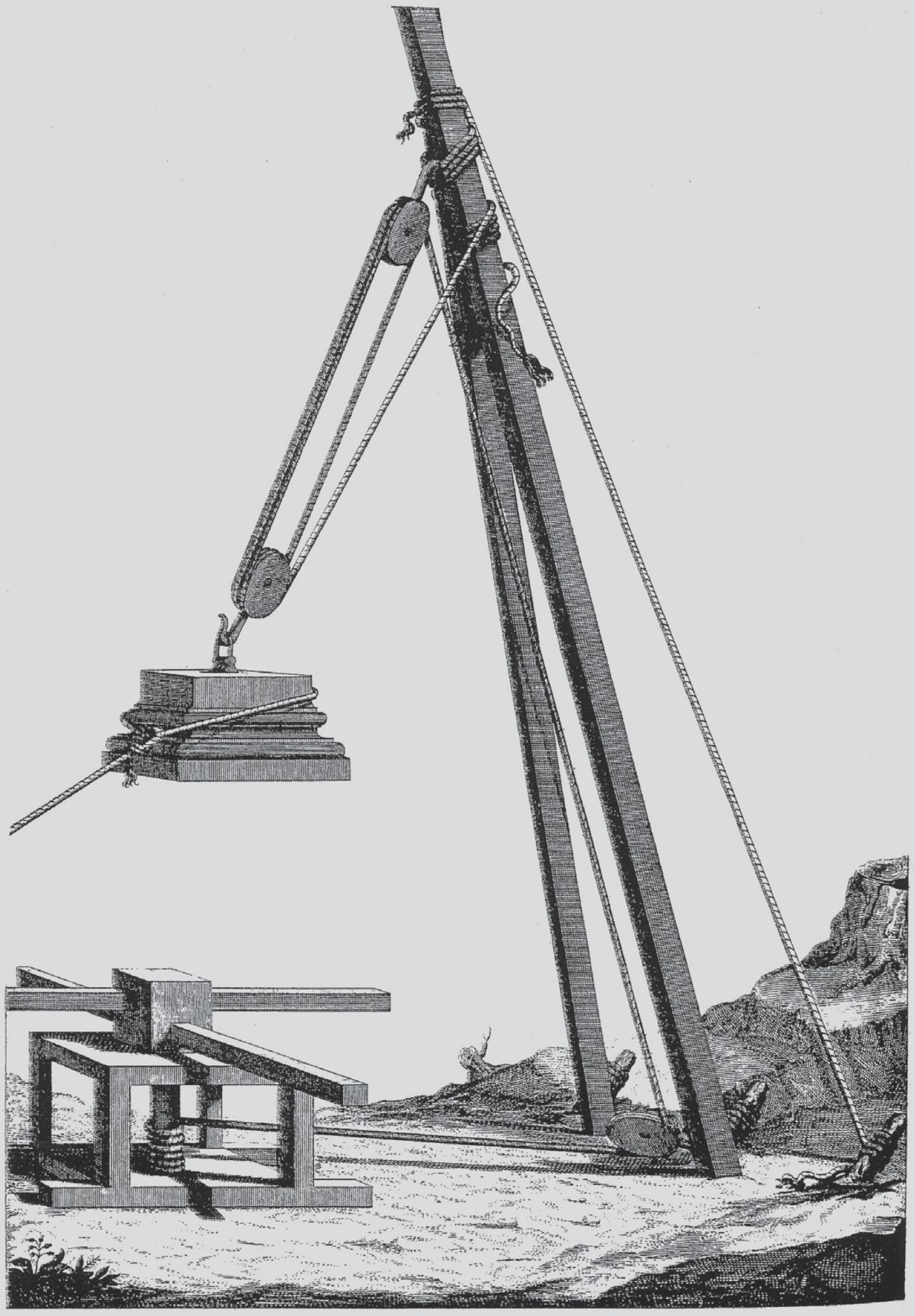
TECHNOLOGY AND CHANGE IN HISTORY – VOLUME 12

Ancient Building Technology

Volume 3 Construction

G.R.H. Wright



BRILL

ANCIENT BUILDING TECHNOLOGY

VOLUME 3

CONSTRUCTION

PART I

TECHNOLOGY AND CHANGE IN HISTORY

VOLUME 12/1

ANCIENT BUILDING TECHNOLOGY

VOLUME 3

CONSTRUCTION

BY

G.R.H. WRIGHT

PART I: TEXT

BRILL

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Front cover: Representation by the French encyclopedists of a classical dikōlos (two legger) crane powered via a massive capstan. This is of interest as it evidences the correct understanding that a crane used in fine stone masonry construction must afford some measure of delicate motion.

Back cover: Sketch of early round house ca 8,000 BC at Mureybit, North Syria, according to excavator's reconstruction. This indicates the surprising extent of building 'know how' at the earliest stage of solid load bearing construction—timber (space) framing, mud brick walls, plastic mud roofing tegument.

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Non modo aedificantibus sed…
omnibus sapientibus

THE LIMITS OF THE ANCIENT WORLD ☞

Considered from three points of view – the history of building, general history, physical geography – some individual entity can be imagined comprising temperate Europe, the Middle East and Africa north of the Sahara together with the Nile Valley and Ethiopia. Regular communication prevailed throughout this region; while whatever external contacts transpired did not influence the development of building within the region.

Natural boundaries closed the region off on three sides. Only there was no natural barrier to the East, neither across the steppes of Central Asia nor by the sea to India. The Ancient World maintained contact with further Asia and India which exercised an influence on building there. However, the only movements of Asiatic people into the ancient world or onto its borders did not in any way affect the history of building within the Ancient World.

Thus the Ancient World as dealt with in this book may be represented notionally by a circle with centre in the Eastern Mediterranean (Crete) spanning about 50° both of latitude and longitude – i.e. with a diameter of roughly 2000 miles (or of three thousand kilometres). From this expanse two areas are removed because of considerations of physical geography: a large segment at the South-West is desert (the Sahara) and the most northerly part is sub-arctic tundra.

Accordingly the most fully developed axis of the Ancient World was NW–SE, from northern most Scotland to Ethiopia and Southern Arabia. To demonstrate the spread of significant building over the expanse so delimited some reasonably well known limitrophic sites are indicated.

subarctic
MAES HOWE
NEW GRANGE
SOUNGIR
STONE HENGE
CARNAC
AY KHANUM
CONIMBRIGA
SURKH KOTAL
LIXUS
CARTHAGE
SUSA
PERSEPOLIS
GHADAMES
CYRENE
MEMPHIS
DILMUN
SIWAH
desert
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2004
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CONTENTS

Efficient construction of a developed building project depends on prior furnishing of directions and information to the builder. These preparatory measures comprise project drawings, written directions (specifications) and detailed estimates of quantities required. Not all these measures necessarily apparent in any one building tradition. Project drawings (and models) considered in Mesopotamian Building; Egyptian Building; Greek Building (noting recent controversy); Roman Building. Specifications limited to literate societies and above all a feature of Classical Greek monumental building (on contract). Prior estimate of quantities vital for carrying out building projects, but all projects everywhere at all times beset by unforeseen increase in costs. Considerable evidence in cuneiform texts concerning this question in Mesopotamian building, but consideration must be given to it in all developed building projects.

Setting out on the ground plans of projected buildings a different operation from surveying (accurately recording existing positions on the ground); but may be preceeded by preliminary surveying of the area. Basic surveying procedures. Position established by measurement of bearing (angle) and/or distance from datum. Triangulation and traverse with offsets. Roman surveying: use of *groma* and *chorobate*. Setting out markings must be clear of area to be covered by building. Different system necessary for rock cut monuments. Setting out in antiquity effected by measurement of distances, not of angles. Basic geometry of ancient building plans (round, rectangular, polygonal, curved). Setting out addressed to concerns of: orientation (geographical and astronomical), line (path and length), angle (how obtained), level (original level plane necessary for all measurements and for all detail in elevation). Setting out practice in ancient world little investigated. Conditioned by geometry of design. Constitutes the vital nexus between design and construction. Illustration of this significance in Egyptian and in Classical Greek monumental building.

Organisation of (monumental) building construction site vital for success of project. Underlying question of terrain (NB Middle Eastern tells). Appearance of monumental public building (massive stone tower) at Neolithic Jericho, ca 8,000 BC. First monumental earth/brick building in Mesopotamia during 5th millennium BC. Simple site development and installations because of portability of material. Earliest monumental stone construction "Bastard Ashlar" with blocks finely dressed only at face. Evolved in Mesopotamia on model of brick masonry during latter 4th Millennium BC. Striking development of this construction at Saqqarah in Old Kingdom Egypt, ca 2650 BC. Blocks not overly massive and construction manageable by manhandling. During mid 2nd Millennium BC this type of stone masonry spread over Eastern Mediterranean and Levant as socle to mud brick or rubble superstructure, thus construction not difficult. During 5th Millennium in the forested regions of Europe wood construction of a monumental nature with large tree trunks, ca 1 ton or more. Earth ramps etc required to set them upright. Such devices and installations gave onto Megalithic Stone building (4,000 BC–2,000 BC) using massive unhewn or roughly shaped slabs etc of many tons burden. This construction prominent in Western Mediterranean and on Atlantic seaboard of Europe. Megalithic Engineering mastered use of the two basic machines: inclined plane and lever. In Egypt during Pyramid Age (ca 2,500 BC) Bastard Ashlar construction supplanted by Pharaonic Masonry. Very large blocks set with a minimum of dressing then finely dressed *in situ*. Construction engineered by large scale earth ramps and fills together with expert levering. Special procedures for pyramid building. In Levant and East Mediterranean during middle and latter part of 2nd Millennium BC building with large unhewn or roughly trimmed boulders termed Cyclopean Masonry. Mainly for fortifications and terrace walling, but NB use for monumental Tholos tombs. Construction based on earthworks.

Organisation and development of monumental building sites revolutionised during 6th cent. BC by introduction of clean lifting in Classical Greek ashlar masonry construction. Installation of mechanical devices incorporating pulleys (block and tackle) together with extensive wooden scaffolding replace installation of earthern ramps, embankments, fills etc avoiding necessity for large gangs of unskilled labour. Types of lifting devices described in ancient records according to rig (one legger, two legger etc.) and also to arrangement of machinery (single haul, triple haul etc.). Power input assisted by windlass, capstan etc. Ideosyncratic administrative arrangements of Classical Greek monumental building.

By 1st Cent. BC building industry in Rome akin to that of modern world in scale, range and diversity, cf organisation of enterprise scope, of projects, types of construction, geographic extension. Augustus, Trajan, Hadrian, the greatest imperial builders. Decline in all forms of building except fortifications and churches from later 3rd Cent. onwards. Exposition focussed on Roman

Concrete building, considered in three typical instances: urban apartment buildings, The Colosseum, The Pantheon. Highly developed works organisation completed large projects quickly, matching present day results in time. Basic to site development and installations was the virtuoso development of timber work of scaffolding, centering and shuttering. Use of cranes of various types, together with tripods and towers to mount block and tackle hoisting with compound pulleys. Large span concrete domes e.g. the Pantheon, which is the largest ever built in traditional materials and a high point of ancient building technology, construction of both standing centering and flying centering on large scale. Monumental building procedure unchanged when Roman Concrete construction lapsed early in the 4th century AD and was replaced by Byzantine mixed brick and stone building. Ayia Sophia was built in early 6th cent. AD in similar manner to Pantheon in early 2nd cent. AD. After Ayia Sophia no further development in building technology until early Renaissance.

Chapter Four: Wood Construction 111

No scientific definition of the substance and discussion includes all vegetal materials, both pliable and rigid, used in construction. Wood traditionally regarded as man's earliest building material, promoting interpretation of some building forms in other materials as derived from original construction in wood. Wood not durable, thus very restricted survival of material remains of ancient wooden building, and most evidence secondary (post holes etc.). Pliable materials (canes, rushes etc.) used structurally (bound up in bundles or interwoven) or as cladding. Notable use of pliable material in Nile Valley during Neolithic period, determining later architectural forms in stone construction. Use of heavy timber (both hewn and unhewn) dependent on capacity to fell large trees—well established by 3rd Millennium BC. Original mode of fixing by lashing (unhewn) and joinery (hewn); carpentry (nailing) a later development (cf in Roman times). Restricted use in load bearing structures (i.e. log cabin style), but always the standard material for framed structures—cf substantial timber framed houses in temperate Europe from Neolithic times onwards. Also "Timber Circles", precursors of Megalithic stone circles (Stonehenge). Wood much used throughout the Levant and Mediterranean in mixed construction both within the same building element (e.g. walls) and for different elements of a building (e.g. roofs as opposed to walls). NB use of wood as foundations, columns, roofs (both flat and pitched). Because of its strength in both compression and tension wood commonly used for reinforcing other materials (e.g. brick and stone masonry). Equally wood the common material for auxiliaries and fittings.

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Development of stone and of brick for load bearing construction closely interrelated. Basic categories of building stone—field stone, quarry stone; small block, large block. Field stone occurs naturally as flat plates and as rounded boulders both used to advantage in building. Early use (5th Millenium BC) of very massive units of unhewn stone in West European Megalithic construction. Development of finely dressed quarry stone construction in Early Dynastic Egypt by mid 3rd Milleniume BC, both small block (Zoser) and large block (Pharaonic). Pharaonic masonry construction highly systematised, affording greatly speeded up time schedule. Proceedure restricted to socio-economic circumstances in Egypt. Small block (Zoser) masonry ("bastard ashlar") diseminated to neighbouring lands ca mid 2nd Millenium BC. Rapid development during 6th century BC of superb finely dressed, dry stone ashlar masonry in Classical Greece, also occurrence there of Lesbian, polygonal and trapezoidal masonry. Stone typically employed as load-bearing construction. Stability promoted by bonding, fixing either with cementious mortar or with cramps and dowels; also by reinforcing with other materials (e.g. timber, metals). Varied application of these measures in rubble masonry, Pharaonic Egyptian building, Bastard ashlar, and Classical Greek ashlar. Stone was employed as framed construction—NB Les Villes Mortes of North Syria in Late Aniquity. Two modes of stone building construction: as all stone building and as an element in mixed construction. Limitation of all stone building because of relative weakness of stone in tension, thus unsuitability as roofing. However occurrence of monumental stone roofing both trabeated (Pharaonic Egypt) and arcuated (vaults and domes) in Classical and Late Antique building. Stone as an element in mixed construction largely for foundations and substructures of walls. Also striking use of stone for columns and piers, even when roof of other material as e.g. in Classical building and in Achaemenid Persian building.

Appendix: Rock Cut Monuments

Introductory historical résumé. *Neolithic origins, ca 8000 BC–6000 BC,* connected with round house building. Hand modelled mud bricks succeeded by form moulded mud bricks, which became standardised for use in rectangular building (in Mesopotamia ca 4500 BC). *Mesopotamian brick masonry.* Brick the material used for all building monumental and domestic. Several distinct forms of brick used, flat square bricks, flat rectangular bricks, long narrow bricks (*Riemchen*), plano-convex bricks. *Riemchen* and plano-convex bricks characteristic of 3rd Millennium BC; square brick characteristic of later times, notably Neo Babylonian. Burnt bricks introduced for special purposes, ca 3rd Millennium, to become increasingly used for general construction (cf Neo-Babylonian period). Varied, highly developed system of pattern bonding during 2nd Millennium BC. Brick arcuated construction from an early age for both arches and vaults, NB corbelled, radial and pitch brick setting. *Egyptian brick masonry* evolved rapidly during later pre-dynastic and early dynastic times (ca 3000 BC). Originally influenced by Mesopotamia, its subsequent development was entirely independent. After introduction of fine stone masonry (mid 3rd Millennium BC) use of brick generally restricted to certain classes of building. Basic brick form rectangular, twice as long as broad (cf traditional modern bricks). Free use of bricks set on edge provided scope for varied pattern bonding. Burnt brick not used as standard construction until late age, notably in Roman period. Early use of brick vaulting for roofing (underground) structures by corbelled, radial and pitched brick setting. Later use of brick vaulting in free standing structures. During Pharaonic times principally in utilitarian buildings, e.g. storehouses; but occasionally brick temples occur (cf Temple of Amun at Malqata). During Roman period brick used for buildings of all description, monumental and domestic, with attendant brick vaulting. Possible influence of Roman construction. *Roman brick masonry.* Obscure origin of monumental building in burnt brick at Rome. Earliest attested use of burnt brick as triangular facing units to Roman Concrete construction (*opus testaceum*) during 1st century AD. However extrinsic evidence that burnt bricks were manufactured and used previously. Roman bricks of square format, thus little scope for developed bonding schemes—in appearance walls are of simple stretcher bond. Although most large span roofing effected in concrete, there are examples of brick masonry domes, e.g. Temple of Diana at Baiae and the Mausoleum of Diocletian at Spalato. Much Roman brick masonry in the provinces. In Anatolia and Greece during 2nd century AD excellent load bearing brick construction (e.g. Kizil Avlu at Pergamum) perhaps owing something to a survival of the Old Mesopotamian building tradition. Whatever the construction, the technique of Roman brick laying superior, with a peak of excellence in the first half of the 2nd century AD. *Byzantine brick masonry.* All monumental brick construction in burnt brick, with square bricks, generally ca 1¼' on a side (ca 15" / 37 cms) as in Roman brick masonry. However aspect of Byzantine brickwork changed through ever increasing thickness of mortar joints which come to exceed that of the bricks. Monumental buildings either all brick construction or mixed brick and stone construction. Mixed construction of courses of brick masonry and courses of stone masonry succeeding each other in some regular pattern. Striking change from Roman practice in large span roofing from concrete to brick construction, erected not over circular plan but over square chambers using structural devices of the pendentive and the squinch. Byzantine brick domes built either with or without centering. Roman background for construction in brick using centering. Sassanian background for dome construction without centering. Abiding question of *Rom oder Orient* applicable to Byzantine brick construction as well as to design. *Late Iranian Brick Masonry*. Parthian Building (ca 100 BC–224 AD). Parthian art and architecture essentially Hellenistic in derivation not traditional Middle Eastern, but this refers to design. Survival of old Mesopotamian tradition of building construction (i.e. brick masonry): General use of burnt brick in monumental building. Square bricks the standard format; an innovation in brick laying is setting square bricks on edge to effect pattern bonding. Where preserved, roofing of rectangular chambers by barrel vaults, little or no surviving evidence of domes or cross vaults. Evidence restricted almost entirely to underground construction (vaulted chamber tombs in Mesopotamian tradition, NB at Assur). Effectively varied brick construction in interest of avoiding centering, both by pitched brick setting and by reducing spans by corbelling out haunches. Very little direct record of brick roofing to free standing buildings. Roofing of Palace at Assur reckoned to be pitched brick barrel vaulting. *Sassanian Building (224 AD–627 AD)*. Sassanian empire geographically extended with varied materials and modes of construction. Rubble construction more prominent than brick. Brick employed almost entirely as mud brick. Brick laying in general carried on Parthian manners. Continued construction of barrel vaulting with vault of ca 26m span over the Iwan of the Palace at Ctesiphon (6th Cent. AD), made possible by great wealth of the Empire. A momentous structural innovation the introduction of the dome carried on squinches over a square chamber. This construction occurred in Iran from the beginning of the Sassanian period (ca 250 AD), and later appeared widely dispersed East and West. Vaults occurred assembled from prefabricated reinforced ribbing. Earliest examples in Median building (8th Cent. BC) but main development in Sassanian building, where material of construction gypsum plaster with reinforcing of pliant canes and rushes etc.

Most significant overall technical advance afforded by Roman Concrete was capacity to roof large areas with cross vaults and domes—free spans of roofing were thus magnified from a few metres (ca 5 m–7 m) to over 40 m, and this advance was maintained but never exceeded until 20th century AD engineering. This revolutionary development in and about Rome during 1st and 2nd centuries AD made possible by expert timber construction of centering and shuttering. Three possible types of centering for large span concrete roofing: standing centering, flying centering, axial tower centering. Shuttering fabricated by timber boarding, but often included brick "lining" and also upstanding brick string courses inset into concrete. Placing of Roman Concrete against and above shuttering, a difficult and little discussed operation, effected from exterior and requiring special access installations. All compartmentalising of concrete mass by way of inset brick work an advantage both in the placing and in the curing of concrete.

Structural behaviour of Roman Concrete domes and cross vaults with their inset brick masonry long a disputed issue, vexed by obscurantist concept of "monolithic construction". Whether or not the dome etc constituted a monolith (i.e. behaved in isolation as a single rigid unit) did not take the structure out of the laws of statics. Thus concrete domes were stressed in tension ("hoop tension") at the haunches and developed vertical fissures in this region when the material of construction was not strong enough to resist these stresses. In later Roman times (3rd and 4th centuries AD) concrete domes incorporated increasing use of brick meridional arches. Difficult to determine whether such arches were conceived as reinforcing to concrete structure or as a brick framed structure with concrete infill. In either event such arches provided strength in compression, and did not function to reinforce the structural weakness in tension at the haunches of concrete. In later times this reinforcing provided by

LIST OF ILLUSTRATIONS

ABBREVIATIONS IN GENERAL REFERENCES

NB References in the body of the text cited in contracted form (e.g. by name of author only) are given definitively in the “General References” at the end of the chapter in question.

AARP	*Art and Archaeology Research Papers*
ABADY	*Archäologische Berichte aus dem Yemen*
ABSA (BSA)	*Annual of the British School at Athens*
ABSP	*Ancient Building in South Syria and Palestine*
AE	*Ancient Egypt*
AJA	*American Journal of Archaeology*
AMI	*Archäologische Mitteilungen aus Iran*
Antiquity	*Antiquity*
Archaeology	*Archaeology*
Architettura	*Architettura*
ASAA	*Annuario della Scuola Archeologica di Atene*
ASAE	*Annales du Service des Antiquités de l’Egypte*
BAR (IS)	*British Archaeological Reports (International Series)*
BdA	*Bautechnik der Antike*
BCH	*Bulletin de Correspondence Hellenique*
BICS	*Bulletin of the Institute for Classical Studies*
CAJ	*Cambridge Archaeological Journal*
GM	*Göttinger Miszellen*
Hesperia	*Hesperia*
HSCP	*Harvard Studies in Classical Philology*
Iraq	*Iraq*
JARCE	*Journal of American Research Centre in Egypt*
JdI (JDAI)	*Jahrbuch des Deutschen Archäologisches Instituts*
JAOS	*Journal of the American Oriental Society*
JEA	*Journal of Egyptian Archaeology*
JHS	*Journal of Hellenistic Studies*
JÖAI	*Jahreshefte des Österreichischen Archäologischen Instituts*
JRA	*Journal of Roman Archaeology*
JRIBA	*Journal of the Royal Institute of British Architects*

JSAH	*Journal of the Society of Architectural Historians*
MDOG	*Mitteilungen der Deutschen Orient-Gesellschaft*
OpAth	*Opuscula Atheniensia*
PBA	*Proceedings of the British Academy*
RA	*Revue Archéologique*
RdE	*Revue d'Egyptologie*
RM	*Römische Mitteilungen*
Thetis	*Thetis*
WA	*World Archaeology*
ZAS	*Zeitschrift für ägyptische Sprache und Altertumskunde*

INTRODUCTION

This volume completes an account of the technology incorporated in ancient building construction—but not of the building science[1] which lies behind it, nor of the structural systems in which it is embodied.[2] On due completion the limitation of the work, both in scope and in execution, is apparent. Its only justification can be in practical utility. It may provide a convenient ready reference for information which otherwise would be far to seek (and thus it would be convenient to have on hand in archaeological field work). To this end an effort has been made to order it in such a way that facilitates consultation on specific issues; likewise to keep the presentation as far as possible at a uniform level, i.e. as elementary as is consonant with some meaningfulness. It might also be noted that this program imports a certain repetitiveness—the same basic matter being restated for each relevant context.

The preparation of the work for submission to the publishers, once more has been carried out by Lynette de Tchérépakhine. She has been the bridge between the author and the printer—an office rendered increasingly onerous by today's greatly changed requirements in this connection, together with (in this instance) the long hand MS of one who cannot type and knows nothing of computers. Fortunately Gera van Bedaf has again been in charge of producing this book, and Brill's senior editor Julian Deahl has continued to encourage the work. Ron Sheriff compiled the index, and Pauline Alys Wright shared in the correction of the proofs.

Recent circumstances have restricted the possibility of work in archaeological libraries, and this has curtailed somewhat the ambit of the last chapters. I thank Gertrude Bolten, Librarian of NINO and Els Koenemann, Librarian of the Archaeological Centre Leiden together with Professor Olivier Aurenche of Maison de l'Orient at Lyon for their good offices in providing essential photocopies. Also J.-C. Bessac of CNRS who has made available some of his own books for consultation.

Finally grateful acknowledgement is made of a subvention provided by the Russel Trust towards expenses of photocopying, typing, etc.

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[1] Cf, e.g. A.G. Gleeson, "Building Science," London, 1965.

[2] Cf, e.g. R. Mainstone, "Developments in Structural Form," Cambridge Mass.

CHAPTER ONE

PREPARATORY MEASURES

A. *General Outline*

Modern exemplifications

The technology of building begins with measures which are preparatory to handling building materials. In the nature of things these measures are threefold in disposition, irrespective of historical developments. Thus it is useful to introduce their discussion in ancient building by reference to present day practice and procedure. In modern times the three kinds of measures which may be taken in order better to ensure that the projected building will accord as closely as possible with what is required are referred to as:

(i) Project Drawings
(ii) Specifications
(iii) Bills of quantities.

Their application may be outlined as follows:

(1) Drawings. Depending on the nature of the project architectural drawings have a wide range in quantity and content; however even for the most minor stereotyped construction no building authority today will authorise any construction without provision of drawings of some sort.

Practice in antiquity

(2) Specifications. These are written instructions expressed in trade terminology instructing the builder exactly how and with what materials he is to incorporate on the ground the indications given in the drawings.

(3) Bills of Quantities. These assume an ever more important role today due to the increasing variety of materials and the great cost of building. They consist of a meticulously accurate itemisation of the quantity of every type of building material to be incorporated—thus affording a summation of the total cost of all the materials of construction.

In very general terms it may be said that evidence of some sort concerning each of these categories survives from the ancient world, but it is very fragmentary, and there is nothing approaching evidence concerning all three of the categories from any one school of building (e.g. Egyptian, Greek, Roman etc.). In fact strong arguments have been advanced that this or that category of preparatory measures did not exist in this or that school of building.

Again in very general terms it may be said that there are material remains of ancient architectural drawings from Mesopotamian, Egyptian and Greco-Roman contexts. There is also literary reference to architectural drawings in Greek and Latin records. So far as something akin to specifications is concerned a surprising amount of information is preserved in Classical Greek building contracts; and some mention can be found in equivalent Roman documents. For the important question of costing by way of calculation of quantities, some information germane to the subject can be found in Egyptian or in Mesopotamian texts.

The following is a brief résumé of this material:

B. *Architectural Drawings and Models*

This subject has received much attention and there are several recent publications which cover the field (e.g. J.-F. Bommelaer ed, *Le Dessin d'Architecture dans les Sociétés Antiques*; B. Muller ed, *"Maquettes Architecturales" de l'Antiquité*). In dealing with this subject it must be born in mind that an important question precedent always arises: are these drawings/models measures preparatory to a building project, i.e. are they, in fact, project drawings/models? The various publications dealing with drawings and models of buildings concern themselves with all these items irrespective of their function. This can be quite other than to convey information to prospective builders and contractors—e.g. drawings can be memorials of existing buildings, while models for the most part are not designed to aid building construction, but are *objets d'art* or, most often, are of religious import. In this way the present lively discussion of drawings and models of buildings may give an inflated impression of what is known about the organisation of building projects.

Drawings & models

The following remarks will deal only with that question and thus e.g. many interesting models will not be mentioned. For the most part these have a religious ambience. Of course these objects may afford very valuable evidence for the history of building form, but that is quite another subject.

Drawings of buildings to serve as project drawings have been made using a great variety of media, e.g. clay tablets; pot sherds (ostraka); stone fragments; stone blocks; stone wall faces; papyrus; parchment etc. and employing the appropriate instrument—scriber, brush etc. together with rule, dividers, compasses etc. The subject matter of project drawings appears to separate out into two classes: plans of buildings and drawings of architectural details. The former of necessity are made to a small scale on portable objects; the latter generally are at natural scale inscribed on standing wall faces of the building concerned. Ancient models are far the most part of terra-cotta, but those intended to serve as project documents, i.e. for reference in constructing buildings, appear to be of stone.

It is probably best to present the evidence by way of the main schools of ancient building: Mesopotamian, Egyptian, Greek and Roman rather than separate it out in the first instance into drawings and models.

1. *Mesopotamian Building* (v Heisel pp. 7–75)

Drawings

Plans inscribed on clay tablets often dimensioned and labelled were of common
1, 2 occurrence in Mesopotamia through much of antiquity—the earliest known ca 2300 BC and the latest in Seleucid times (i.e. after 300 BC). They include representations of most of the common types of buildings of the period: Ziggurats, Temples, Houses—and there are also fragmentary town plans. The standard of draughtsmanship evidenced on these tablets is good. In many instances the drawings are very tidy drawings indeed, often neatly dimensioned and labelled and
2.3 recognisably to scale.

The *raison d'être* of these plans on clay tablets has occasioned controversy. It has often been claimed that they are documents supporting land and titles registration; on the other hand they have been seen as school exercises, i.e. pertaining to the education of scribes. These explanations may hold good in some instances, nonetheless considered generically, these drawings are "project drawings", for reference in constructing buildings.

The modalities of Mesopotamian brick building make for differences in the nature of project drawings from drawings for the stone building of Egypt and Classical Greece. Notable is the fact that whereas well drawn plans dimensioned and to scale are found, there is an entire absence of architectural detail drawings to natural or large scale, which occur in Egypt and Greece. Mesopotamian brick

Drawings & models building is essentially "blocked out" building and any surface articulation is constituted in patterned laying of whole bricks. Thus drawings are not required to set this articulation out since it can be set out directly on the ground by simply arranging whole bricks. In this connection there is, however, a highly individual refinement. At Teppe Gawra, where the early 4th millennium temples exhibit a striking initial development of the niched façade, a strange class of objects were found—model (burnt) bricks at a scale of 1:10. These objects function in the nature of children's building blocks, whereby patterns of brick laying in three dimensions can be mocked up on the ground conveniently and rapidly.

Models

The majority of model buildings anywhere and everywhere are out of clay, and there are a number of model buildings of clay from Mesopotamia. However none of these models give any indication that they were used to guide building projects.

2. *Egyptian Building* (v Heisel pp. 76–153)

Drawings

Surviving drawings of buildings from Ancient Egypt are considerably less in number than those from Ancient Mesopotamia, but it is evident that the practice of using such drawings as "project drawings" to guide construction was established in Egyptian (monumental) building. Nonetheless there are rather striking differences in the nature of the surviving material from Egypt and that from Mesopotamia. This difference may be partly due to the fact that the material used in (monumental) Egyptian building was finely dressed stone, whereas in Mesopotamia it was brick.

Drawings of buildings were made in Ancient Egypt over approximately the same period as in Mesopotamia. The first occurred during the Middle Kingdom (ca 2000 BC) but the bulk are from New Kingdom (from ca 1500 BC) and later, and they do not survive from Graeco-Roman times, except for one or two items from Meroe. As in Mesopotamia the drawings are of all common (monumental) building types but these types are, of course, not identical with those from Mesopotamia. In Egypt the drawings mostly represent temples and tombs, with notable examples of (Theban) rock cut tombs of the Kings.

Several vehicles were used for these drawings. The most substantial was a "slice" or flake of stone (generally limestone) but numbers of drawings were made on 3, 5, 6
papyrus sheets. In general the drawings were freely painted on in colour (mostly 4, 7
red and black). The expression of this brushwork technique is highly characteristic. It conforms with the dimensioning and labelling to give a "quick notebook

Drawings & models

sketch" effect familiar in architects' notebooks. This is markedly in contrast with the carefully "ruled" plans scribed on the Mesopotamian tablets.

Egyptian building drawings can be broadly classified into two groups of building plans and architectural details. Both groups are similar in expression and there is nothing like the full scale details of Greek practice.

The spontaneity and variety of Egyptian building-drawings makes it difficult to be sure of the purpose of the drawings. Not only is it difficult to distinguish what are "project drawings" from those with another purpose (e.g. a record of existing building) but the term "project drawing" may be in itself not definitive. Hitherto it has been understood that a "project drawing" signifies one to guide the builder in materialising the design of a projected building. However whereas numbers of Egyptian drawings were certainly made within the margin of a building project, it is not likely that all of these were intended as guides to construction. Rather it is likely that some are sketches to help formulate the design of the building. 3, 6?

Models

In a land where models were pervasive in a funerary context (e.g. to help eternalise the good life), there is little evidence of their use in building construction. The one example commonly referred to in publication is a model of funerary chambers and passages below a Middle Kingdom pyramid. This was sculpted from a block of limestone. It was found at the Valley Temple of Amenemhet III at his Dashur pyramid complex (ca 1800 BC), which was not used for his burial since it manifested structural failures during building. This very explicit model does not represent the analogous features at the Dashur Temple, but it has been stated that what is represented are the features at Amenemhet's second pyramid at Hawara in the Delta (Maquettes Architecturales, pp. 215–16). A model is in point here since this complex of interconnected chambers at different levels is difficult to render intelligible by drawings alone. 9

3. *Greek Building* (Heisel pp. 154–183)

Drawings

No scale plan has survived which can be considered a project drawing connected with Greek building. However it is within the context of Greek building that there emerges architectural detail of features in elevation scribed to full scale on the standing masonry of the building concerned. The commonsense explanation for this state of affairs is that plan drawings to scale serving as project drawings were made in fugitive materials (e.g. parchment). The necessity of some graphical record to control the setting out of e.g. the lines of the crepis of a temple and in

Drawings & models

turn the upstanding wall plan thereon seems obvious. Beyond this however the existence or nature of project drawings could well be uncertain; and this question could be interrelated with the existence of full scale versions of elevation details inscribed on standing walls.

Although the intention in this study is to report matters of fact, the following developments of the present matter are here noted.

Partly due to this apparent lack of preparatory drawing out for Classical Greek temple building a distinctively new outline has been developed of the procedure for building these temples. The protagonist in this has been J. Coulton (v "Towards Understanding Greek Temple Design," BSA 10, 1975, pp. 59–100; Greek Architects at Work, pp. 51–73; Incomplete Preliminary Planning in Greek Architecture in Dessin d'Architecture pp. 103–122 etc.). This view proposes that the design of Classical Greek temples was one of the mental perceptions and the mental arrangement of inter-connected proportions consequent on choices of basic schemes, e.g. a peristasis of 6 × 13 columns. In this way the design of the Greek temple was worked out in the head, not on the drawing board; and among a group with specialised knowledge and experience it was perhaps better conveyed in words (specifications) than in drawings.

As a first step on this path, it was proposed that details of the design were incomplete when construction of the temple began, and were only finally achieved by and through the construction. In short far from the necessity of design drawings to guide the construction of Greek temples, it was the process of construction which was necessary to finalise the design.

This is not the juncture to discuss in detail these far reaching assertions; however something must be said of them. So far as is evident the practice has always been to design a building on the basis of its plan—and it is the plan which is set out on the ground to control the construction. It is possible that when the construction of the building is begun according to the plan set out, the exact elevation is not yet clearly defined and can only take shape in the process of construction. Thus it is reasonably possible that you begin the construction of an incompletely designed temple by first building the fabric up to the stylobate level in accordance with the designed plan, and then work out the details of the elevation in the process of further construction. However you do not proceed with the construction of an incompletely designed temple by first building the peristasis and then working out the plan of the sekos in relation to it (or, if you so wish, *vice versa*).

This is attested in Coulton's analysis by the fact that all the examples given there of design details worked out in the course of construction are elevation details. Exactly corresponding to this is the fact that the full scale drawing out of architectural details on masonry surfaces of the building under construction are 10
also elevation details—notably columns and pediments as evidenced in Early Hellenistic times at Didyma (v Hasselberger's reports). Here it must be observed that

this was also the case with "optical refinements" in Greek temple building. This phenomenon reckoned crucial to the aesthetics of the structure is entirely a matter of elevation and can only be worked out in the course of construction.

Drawings & models

Thus it may be that the design of Greek temples in plan (the *ichnographia* of Vitruvius) was complete and drawn out—and of necessity, set out—before building was begun; and that detailed design in elevation (the *orthographia* of Vitruvius) was only achieved by drawing it out at full scale on standing masonry) in the process of construction.

Therefore rather than connecting the complete lack of evidence of scale plan drawings in Greek temple building with theories of incomplete design, the reason for their absence is more probably the accidents of preservation. Whereas in Mesopotamia and Egypt building plans were drawn out on terra-cotta and stone which are enduring materials, Greek building plans were most likely drawn on parchment or other fugitive materials which have not survived to the present day, and if it is argued that some Egyptian building plans were drawn on papyrus, then the counter argument is that their survival is due to the special (dry) climatic conditions in Egypt as distinct from in Greece.

Models

There is no surviving evidence in Greek building of models which could have been used as project documents. However it is within the tradition of Greek ashlar construction that project models have been discovered connected with buildings in the Roman Orient (e.g. at Baalbek). 12

It is perhaps possible that there is a literary reference to the use of models in Greek building. Herodotos (V, 62.2) states that the Alcmaeonids being contractors for building the Temple of Apollo at Delphi at the end of the 6th Cent. BC, as an act of beneficience built the temple more lavishly than the *paradeigma* obliged them. However this is very oblique evidence, since the meaning of *paradeignma* is by no means restricted to a three dimensional physical model.

4. *Roman Building* (Heisel pp. 184–218)

Drawings

The question of project drawings in Roman building must be considered together with the same question in Greek building, since there is a continuity between them and thus the Roman evidence has a retroactive significance in Greek building. As in Greek building there is no direct surviving evidence of scale plans serving as project drawings in Roman building. However unlike the Greek situation there is much evidence that such drawings were made and used. The evidence is of two sorts:

Drawings & models

(1) Literary
(2) Surviving building plans which were not project drawings.

The literary evidence is very strong. Vitruvius (I ,2.2) defines three types of architectural drawings—plans, elevation and perspective. These exactly compose the portfolio of drawings required in the submission of a building project today. Furthermore there are a number of passages in different authors stating that various well known persons made such drawings, or that such drawings were submitted in connection with a building project—e.g. Plutarch states that Pompey drew a plan and an elevation; Cicero mentions a project plan in his possession; Seutonius speaks of the project plan for a Gladiator School; Cassius Dio mentions that Hadrian himself drew up plans for a projected building; and Aelius Gellius states that several architects submitted plans for a building project (v Heisel, p. 185).

On the other hand numbers of plans of building or building complexes which
are survey drawings of existing buildings do survive (drawn on stone slabs). These 11
are definitely not project plans, but give evidence that such plans could be made and illustrate something of their nature. There is also abundant evidence of the instruments used to make such drawings, both by way of ancient representations (e.g. on draughtsmen's tombstones) and the survival of the instruments themselves (v Heisel, p. 200; H.W. Dickens "A Brief History of Draughtsmen's Instruments"). These include straight edges, measuring rules, compasses etc., also special templates and French curves.

Also there is surviving evidence of full scale details in elevation inscribed on masonry which continue the Hellenistic mode identified at Didyma and other sites. Here it is to be noted that these full scale details mostly occur in the Roman Orient
in connection with traditional style ashlar building, e.g. at Baalbek and Bziza in the 10
Lebanon (v Heisel, pp. 208–13). No such drawings of elevation details for Roman concrete structures have been observed (e.g. of brick arches in concrete domes). However, there is literary attestation of such drawings in Dio Cassius' account of the snub directed by Apollodoros to (the future Emperor) Hadrian "Go away and draw your pumpkins" (i.e. lobate, "umbrella domes").

The survival of survey drawings incised on stone slabs for public record, together with the survival of architectural detail drawings incised on masonry blocks, whereas, on the other hand, there is no surviving evidence of building plans made as project drawings points to a common sense conclusion. Project drawings (which must be portable) were made on fugitive materials. An obvious vehicle is parchment and there is record of the use of parchment as a vehicle for drawing in Roman times (v Aelius Gellius Attic Nights XIX 10.3; Heisel, p. 200).

Models

Roman building (or building under Roman rule) provides the most telling evidence of models as building project documents. This evidence again relates to traditional ashlar building in the Roman Orient. The well known examples are from Baalbek (v H. Kalayan "Bulletin du Musée de Beyrouth," 22 1969, p. 151) and above all 12, 13 the striking model of the adyton of the nearby Temple of Niha. This model was found within the temple and it can be directly compared with the built structure. This comparison clearly shows it was a "working" model as minor variations were introduced during the construction (v E. Will in "Le Dessin d'Architecture," pp. 277–82).

C. *Specifications*

Written information & instructions

Specifications is the term used in the modern building industry for the written information and instructions supplied by the architect of the project to the contractor to clarify further the intentions and requirement of the party commissioning the building, and for which the contractor assumes responsibility when the contract comes into effect. It is a contract document and thus becomes binding in law when the contract takes legal effect. The earliest historical juncture when significant building projects were carried out on contract was in Classical Greek public building from the late 6th century BC onwards. (Such building was not carried out on contract in the Ancient Middle East or in Egypt.) It seems great care was taken to have the terms of these building contracts readily available for public record in a durable form. Accordingly they were inscribed on stone stelai and set up in the vicinity of the building works. Numbers of these records have survived reasonably intact.

The contents of these contracts are *ad hoc*: they deal with the concerns of the particular building project so that they are by no means all cast in the same mould. However, speaking generally, they contain clauses relating variously to specifications of the items contracted for and payments to be made for goods and services supplied; but there are also clauses concerning e.g. general conditions applying, appointments of guarantors, the time limit for providing what is contracted for; and the satisfactory quality as determined by inspection, together with fines and penalties for infringements (cf A. Burford *Greek Temple Builders*, pp. 91–95, Table I). Here it may be noted that the detail in the specifications varies greatly—in some instances it is minute: e.g. "Mnasikles of Epidauros took up the contract to quarry, cart and set in place the foundation core of the colonnade for 2,400 dr…etc."; and on another occasion for another contractor in another place "He is to dress the rebates as is written above concerning the bed joints and to make no larger margin to the recessing…than a small inch etc." (A. Burford, p. 91).

Specifications & project drawings

Modern specifications are, of course, auxilliary to and explanatory of project drawings. And common sense infers that this is necessarily the case—i.e. as a preparatory measure to building specifications, in the ancient world were associated with project drawings. However since there is considerable surviving evidence of specifications in Classical Greek projects for public buildings and none for project plans, it has been proposed that, in principal, the project was defined by written specifications rather than by a set of project drawings (cf the views of J. Coulton *supra*, pp. 6, 7). In this connection it can only be remarked that in some instances the detail is so precise that such a procedure would be possible, as the following circumstances indicate.

The building contract for the construction of a naval arsenal at the Piraeus during the years 347–46 BC was discovered engraved on a marble stele in 1882 (IG 11^2, 1664). This contract contains an exhaustive and meticulous description of the work to be carried out by the contractor (v M.-C. Hellmann, *Choix d'Inscriptions*…, pp. 46–52). Since that time there have been a number of publications of the contract illustrated by drawings reconstructed from the text. These drawings do not vary greatly. A century later the actual site of the building was identified and its surviving remains excavated (v G. Steinhauer, "La Découverte de l'Arsenal"). The architectural drawings made of the surviving remains again accord closely with drawings based on the text. This taken in conjunction with the possibility of supplementary verbal communication makes it clear that with the precise terminology available in Greek it was possible to erect a significant public building on the basis of written specifications.

There is little doubt that detailed specifications of the contracted work were written into Roman building contracts of the type *locatio conductio* (cf *infra*, p. 87). However the matter is obscure since there is nothing like the evidence accorded by the Greek practice of inscribing the contract for public buildings on stone as a memorial. There is also the fact that with the passage of time an ever increasing proportion of larger building projects was not carried out by contract but directly both by the state and by large scale private enterprise (cf *infra*, pp. 87, 88). In any event the only surviving Roman evidence is in the nature of the Greek inscriptions, the *Lex Puteolana*. This is a lengthy record carved on marble slabs of a contract awarded by officials of Puteoli (Modern Pozzuoli) in 105 BC for some additions and restorations to the Sanctuary of Serapis in that town against payment of 1,500 sesterci. Here the work is specified in the greatest detail—but note that the date is early and the town a former Greek colony (CIL 1968, ILS 5317; J.C. Anderson, *Roman Architecture and Society*, p. 174; R. Taylor, *Roman Builders*, pp. 13, 15).

D. *Quantities*

Bills of quantities

Some prior estimate of quantities (which includes times and cost) is essential for all building projects—but this does not guarantee the execution of the project not outrunning these estimates. Indeed this has always been of regular occurrence. The estimates of quantities have a two fold practical application;

(1) concerning the availability of the required items
(2) concerning the availability of resources to meet the cost of the items.

Inadequacies in either can/will terminate the project. The first application merges into the wide field of building logistics, and will not be considered here. The second is an endemic question in building, but is only discussed here in so far as there is some evidence of the consideration given to it in an ancient building tradition.

It is surprising to find in this latter connection that the fullest record available for ancient building is that for the old tradition of Mesopotamian brick building. This is not to say that the information relates back to the Neolithic beginnings of this building tradition, it obtains for literate Mesopotamian society. However following on this remark, it is in point to note that because the knowledge of estimating quantities in building has not been transmitted to us via literary record, this does not mean that the phenomenon did not exist. Man was certainly numerate before he was literate—and indeed there is contemporary evidence that a high degree of mental "numeracy" coexists with illiteracy (e.g. Gypsies opposed compulsory general education on the grounds that learning arithmetic would drive out their innate awareness of the upshot of involved financial transactions).

Fully developed quantity surveying in building requires the establishment of generally accepted standard measurements for all items concerned in building construction. There must be socially recognised standard units of measure for:

(1) all dimensions (linear, area, volume).
(2) weight
(3) all materials involved
(4) output of labour
(5) prices of all types of materials and labour involved.

In Mesopotamia this "infra-structure" was well established and enforced by the later 3rd Millenium BC. From this period onwards cuneiform texts evidence that prior estimates of quantities were made for building projects—and how they were made (v E. Robson, "Building with Bricks and Mortar. Quantity Surveying in the Ur III and Old Babylonian Periods").

Quantities in Mesopotamia & Egypt

With the standardisation of units of measurement it is possible to calculate (1) the number of bricks required for a building of given dimensions. With the standardisation of labour output it is possible to calculate (2) the number of man days work required to manufacture and set place that number of bricks. This in turn gives the choice of adjusting (3) the labour force or (4) the time schedule for completing the building in the most desirable (or necessary) way. With the establishment of standard wages (in money or in kind) it is possible to calculate (5) the total cost of the building project—i.e. to provide a Bill of Quantities detailing the building materials required (in Mesopotamia very largely bricks), the labour force required, the time required and the total cost of the project.

It also should be noted that Mesopotamian scribes had evolved some ready reckoning rules of thumb for approximate estimating—e.g. the number of batches of bricks (a batch = 720) in the unit volume of a wall (= 18m^2), the proportion that bricks occupied in the volume of a wall (5/6 , i.e. discounting 1/6 for mortar, binders etc.), and the proportion of wall area to the total area of a building (1/3) (cf M. Sauvage, "La Construction des Ziggurats," pp. 55–60; E. Robson, "Building with Bricks and Mortar," *pass*).

Some remarks concerning Egypt may serve as a background to quantity surveying in Ancient Mesopotamia.

Probably no other building in the world has been subject to such repeated quantity surveying as the Great Pyramid at Gizeh. But these surveys are modern ones of a standing structure, not ancient ones of a projected structure. Nonetheless they show that the purpose of estimates for pyramid building is different from the normal.

The quantity surveying of the Great Pyramid is not directed towards costs. The construction of this monument had first call on the total revenue of the land, and costs were not of great concern. When quantities are reckoned up and discussed in modern enquiry into pyramid construction the purpose is the same as that of the ancient Egyptian project directors "Can the monument as designed be completed in a time limit which will accord with a reasonable regnal period for the Pharaoh in view of his age at accession?" There are no surviving texts which throw light on how the project directors based their estimates of quantities in order to arrive at the overall time required for the completion of their project. And thus the question is not discussed here.

Common sense says that they used appropriate global measures and reckoned the time required for these on the basis of recent experience. They had to hand the knowledge of the time required for the construction of the pyramids of Zoser and Sneferu, and they used this as a basis to extrapolate the time required for the larger project.

For a modern attempt to answer this question using estimates of quantities based on unit values derived from modern physics v S.K. Wier, "Insight from Geometry

Quantities in Greek building contracts

and Physics into the Construction of Old Kingdom Pyramids". He reckoned to show that on the basis of physical constants the Great Pyramid could have been constructed in 20 years with a labour force of 8,500–10,000 workers quite irrespective of construction methods and always accepting that no machines were in use to augment the input of manual energy.

If beyond this, there remains a yearning to deal with the "cost" of constructing the pyramid this perhaps can only be significantly expressed in terms of the % of the national income of Egypt. The only historical factor in any way bearing on this question is the abrupt drastic reduction in scale of Menkaura's pyramid. But it is doubtful that this is an expression of "costs". It is not essentially a fiscal matter, it is a political and social one.

The Greek temple building contracts appear to give a definitive account of the question of estimating quantities for these projects. Every building operation required for the construction of the project, together with the provision of the necessary materials is broken up into individual units and the monetary reward for each unit is clearly stated. Thus the addition of these unit payments by the commissioners of the project gives the total cost of the building project. In other words the building contract directly incorporates a Bill of Quantities, and executes it, together with the accompanying specifications of the work as a binding legal instrument.

On the face of it this appears to indicate that the commissioners of the project, employing the services of experts (*viz* master builders and quantity surveyors) defined the materials and work to be provided and the monetary rewards (payments) for the work and material, then entered into contracts with building contractors, suppliers etc. who accepted these offers. This understanding certainly holds good for the specification for the work and materials to be supplied, but does it hold good for the payments detailed.

Clearly the commissioners of these Greek building projects must have had some ideas of the cost of their project, otherwise they were in no position to commission it. They would be acting in bad faith if they were not reasonably assured that they had sufficient resources to cover the costs involved. But are the payments detailed in the building contracts those determined by the commissioners on the basis of what was in effect their quantity surveying to afford a Bill of Quantities? This question cannot be answered conclusively. The Greek building contracts stand in isolation and there is no information on how the payments were determined (v A. Burford, *The Greek Temple Builders at Epidauros*, p. 97).

It is probable that each unit contract for specified materials and work was held out to tender in the manner of today and prospective contractors tendered by offering to provide what was demanded at a named price. The commissioner would accept the lowest (or in their opinion the best offer) to constitute the bind-

Quantities résumé

ing contract (cf A. Burford, *The Greek Temple Builders*, p. 161). In this instance, of course, it was requisite for both the commissioners and the contractors that they could estimate accurately the value in current market conditions of the goods and services concerned.

In brief résumé it can be seen that both specifications and quantities are brought sharply in issue when building work is done on contract. When the work is carried out directly by those sponsoring it then it is possible to some degree to proceed hand over fist and make the arrangements as the work proceeds, but where the work is subject to a contract it is there and then that specifications and quantities must be decided on exactly—so as to determine the success or failure of the project.

In any event, by virtue of the records of Greek building contracts, the question of estimating quantities for a monumental project is clarified better in Greek building than in other ancient building traditions. Only in ancient Mesopotamia do cuneiform texts provide comparable information.

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CHAPTER TWO

SETTING OUT

- A. Preliminary Surveying (Setting out and Surveying)
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A. *Preliminary Surveying (Setting out and Surveying)*

A little investigated basic measure

Setting out, the marking out on the ground of the lines (points) necessary to ensure that a building is accurately constructed according to the projected design, is obviously a very basic measure in any building programme. Yet it is surprising how little investigation and discussion this crucial operation has received in the literature of ancient building. Certainly it is impossible to deal with the question

Surveying & Setting out

by way of a straight forward recital of facts—i.e. this proceedure was used in Mesoptamia, that in Egypt and another in Greece etc. The best that can be done is to raise logical questions and adduce such information bearing on them as can be found, whatever the context.

First it is advisable to make a preliminary observation. Almost inevitably setting out is connected in terms with surveying. And there may be a connection in fact, since on occasion it is necessary to survey an area of land in order to position the building to be set out e.g. to tie it into some sort of town plan (R. Taylor, *Roman Builders*, pp. 62–63). However the two operations are essentially distinct. Surveying is operative over a far greater area than setting out, and partly for that reason may use different proceedures (and different instruments!).

Since surveying is thus only marginally connected with setting out, it is not in place here to treat substantively ancient surveying and topography, which is an extended subject. Only a few remarks will be made to relate surveying to setting out. Surveying consists of fixing the position of various points by accurate measurement in relation to the position of some other points already determined. To fix any position it is necessary to ascertain two such measurements concerning it. These measurements may be either distances or bearings (angles) or one bearing and one distance. On the whole it is a simpler matter to measure distances than to measure bearings, and it is probably fair to say that early surveying proceeded by way of measured distances—which is called chaining in traditional modern surveying. And it may well be that very little use was made of angular measurement until Roman times. Two distances can be measured from two points, one at each end of a base line of known length and the distances can be expressed as the radii of two arcs swung one from each end of the base line. The intersection of the two arcs subtended by these radii then gives the position of the point surveyed. This is called triangulation. The alternative is to drop perpendiculars from each point to a base line (= offsets), and to measure the distance intercepted along the base line together with the length of the offset. This is the method more proper to chaining. Using either of these proceedures or a combination of them, any feature on the ground can be accurately recorded without recourse to measuring angles.

A New Kingdom mural decoration of a Theban tomb (v Arnold, p. 252, fig 6.2) shows a surveying party at work in cultivated fields. They are using a calibrated rope to lay down a line, and measure distances along it. In essentials the scene 14
illustrates the proceeding of any chain survey. On the other hand, whereas from earliest times men were familiar with angular measure, there is no record of men conducting surveys by measuring angles before Roman times.

With the expansion of the Roman Empire a great increase supervened in the requirements for land surveying. This was necessary to provide for communications, services (viaducts, aquaducts etc.) and above all for land settlement and

Roman surveying instruments

town planning. Accordingly proceedure was speeded up by recourse to angular
measurement, and the Romans developed instruments designed for purposes
15 of survey (Adam, chap. 1). These were principally the *groma*, an instrument for
observing and setting out right angles in the horizontal plane, which could be set
up at any desired point and aligned in any direction (Adam, p. 11, figs 3, 4, 5).
16 And the *chorobate*, a level in the form of a long sighting bench provided with both
a water trough and a plumb bob for its horizontal adjustment (Adam, p. 18, figs
16, 17; Vitruvius VIII, V). However neither of these instruments were in routine
use for setting out buildings.

B. *Principles of Setting Out*

1. *Built Monuments*

Setting out control markings must be outside the building limits

The setting out on the ground to control the construction of any monumental building project requires that basic lines and points must be marked in a permanent way outside the area to be covered by the building. If this is not done then there is every likelihood that the marks set out will be destroyed, removed or obscured before they have fulfilled their function by the building construction they are designed to control—e.g. excavation for foundations will do away with the line demarcating the upstanding wall faces. Thus the setting out marks must be made so that they remain available for immediate and convenient checking of the building construction (at least until all the upstanding elements of the building have taken shape).

A simple exemplification of this requirement is the traditional modern practice of
setting out simple construction projects. Open work wooden frames (called sighting
37 rails) are set up at the angles and at the position of cross walls etc., arranged
a metre or two outside the further limits of the building. These devices stand well
above ground level and marks are made on the upper rails so that cords can be
stretched between opposite "sighting rails" to demarcate the various lines of the
building, i.e. faces or axes of the foundations, upstanding walls etc. Such in principle
is the mechanics of setting out lines of projected buildings.

Implicit in this system is the unwelcome fact that very little archaeological evidence of it has ever been observed. The marks are not designed to stand forever, they are destroyed by later building etc.; and, in any event, it has never been a part of excavation programs to investigate the area outside monumental buildings to identify the setting out marks (cf Arnold, p. 11). In short this very important subject has never been properly investigated archaeologically and little is known about it.

2. *Rock Cut Monuments*

Arrangements to control cutting apartments out of rock completely different

There is an exception to this general statement. Setting out is also required for the preparation of monumental rock cut apartments, and considerable evidence of this is preserved *in situ*. It is surprising in every way.

It is not commonly realised how completely inverse are arrangements between monumental rock cutting and free standing building. Buildings can only be constructed from the bottom upwards and rock cut chambers can only be carved out from the top downwards. This conditions drastically the proceedures for setting out. With respect to those for the construction of buildings, setting out proceedures for rock cutting are both upside down and inside out.

In hollowing out monumental rock cut chambers it is the horizontal plane of the ceiling which must first be established, and the plan of the chamber must be marked out on it. Secondly where the fundamental lines and points set out to control the construction of buildings must stand outside the limits of buildings,, this is not possible for rock cut monuments. For rock cut chambers all the setting out lines must be marked out *inside* the chamber limits.

In brief for rock cut monuments the basic setting out proceedure is first to cut 38
a constricted tunnel at ceiling level on the line of the desired medial axis of the chamber. This axis is then marked out on the rock ceiling of the tunnel. At the extremities of this axis transverse tunnels are excavated at right angles to establish the breadth of the chamber, and the "offset lines" marked out on the rock ceiling of the tunnels. The work of excavation can then proceed downwards subject to the control of these lines marked out on the ceiling, which demarcate the front, rear and both sides of the chamber. As a matter of stone dressing technique the work of excavation does not extend completely to the desired rock faces, but is halted slightly in advance of them, leaving a rough coat of surplus rock to be removed by fine dressing. (This resembles the Egyptian mode of final *in situ* dressing of stone masonry.) To effect this terminal fine dressing various methods of control checking are used, e.g. first establishing numbers of "target patches" determined by "boning" inward from the setting out lines (cf Vol. 2, p. 73, Ill 134).

These arrangements have been well studied and explained by observation of the evidence surviving in the Tombs of the Kings on the west bank at Thebes (latter half of the 2nd millenium BC) and the chamber within the Etruscan tumuli of the middle 1st millenium BC (cf E. Mackay, "The Cutting and Preparation of Tomb Chapels in the Theban Necropolis." *JEA* VII, 1921, pp. 154–65; W.H. Seton Kerr, "How the Tomb Galleries of Thebes were cut," *ASAE* 6, 1905, pp. 176–87; J.P. Oleson, "Technical Aspects of Etruscan Rock Cut Tomb Architecture," *RM* 85, 1978, pp. 278–314).

C. *Geometry of Ancient Building Design*

Geometrical forms employed in ancient building

It is obvious that the proceedure for setting out plans of buildings on the ground depends in part on the nature/complexity of these plans. In a basic sense this relates to what geometrical constructions are required to establish their form, with the concern being the simplicity of the required operation. In practice the import of this is that setting out plans by measuring distance is a simpler operation than measuring out various angles. Certainly the equipment required for measuring distances is simpler than that for measuring (sighting) different angles. If the plans of ancient buildings are examined in this light, two generalisations can be made.

(1) It is possible to set out all ancient building plans fairly readily by measuring out distances alone. In no instance is an instrument for sighting out horizontal angles a necessity.
(2) There is an overall chronological development in the geometric construction required to set out plans, beginning with the simplest in earliest Neolithic time and proceeding to the most complicated in Roman times—i.e. there is a uniform development extending over ca 8 millenia.

This is made evident by noting the following analytical categories of building plans according to the geometrical form on which they are based.

(1) Round (circular) building.
(2) Rectangular building.
(3) Non-rectangular, centralised polygonal building.
(4) Non-circular curvilinear building.

These categories come into use one after the other at quite well defined junctures, but do not totally oust one another. Each category has remained in use to some degree. However rectangular building replaced round building as the norm, while polygonal plans and complex curved plans have always been reserved for special types of (monumental) building. This is the background to Vitruvius' insistance that an architect must be familiar with (simple) geometry (I,I,4) and the terms of his remarks indicate that the requirement applies equally to designing buildings and to setting out the design on the ground.

1. *Round Building*

The oldest type of solid (load bearing) building in the ancient world (the Middle East "Round House", ca 8000 BC) was the simplest imaginable building to set out

Round & rectangular buildings

on the ground. All that was necessary was to set a peg into the earth at the centre of the area to be enclosed, attach a piece of cord to it and with a marker at the desired radius of the building describe a circle on the ground to demarcate the single (peripheral) wall. Man was here simulating natural growth. This was nature's economic principle of *multum in parvo*. A round design affords the maximum space enclosed by the minimum construction. The communion here with natural growth (cf of a tree or a bush) was total.

That this mentality was entire is shown in a round house complex. Here not only are the individual buildings round but connecting walls and stretches of barrier walling are also arcs in form. It may be imagined that all this came by second nature and was sometimes constructed hand over fist without any setting out. Just as a modern man can rough out a rectangle by eye, so a round house builder could probably estimate the curvature of a wall appropriate to demarcating a desired space. (For the Early Neolithic Round House v O. Aurenche La Maison Orientale; G.R.H. Wright, "The Antiquity of the Beehive House", Thetis 4, 1997, pp. 7–28.)

2. *Rectangular Building*

The transition from round to rectangular building as the norm for solid load-bearing structures in the ancient Middle East some 8,000 years ago is one of the most striking changes in building history (v O. Aurenche La Maison Orientale). The material question here is how were such buildings marked out on the ground so that they *were* rectangular—i.e. walls mitred at right angles. Some device(s) must have been known, since from earliest times plans were quite closely rectangular. Where plans depart notably from rectangular, it seems generally by design not misadvertance.

Conjecture on the nature of such devices is entirely speculative since antiquity and fugitive materials operate against the survival of material remains of the devices. Any number of set squares survive from Pharaonic Egyptian and Classical times, but these are of small dimensions for use as masons' tools in fine stone masonry. It is always presumed that long sided wooden set squares were used for sighting out right angles in early building construction. Certainly a very effective device of this sort has been imagined with 3 pins set into holes in the wood to act 33
as sights. The virtue of this device is that angular imperfection in its construction can be eliminated in use. The instrument is set up with one arm aligned with the base line and the reading given by the perpendicular arm marked on the ground. The instrument is then rotated etc. so that the other arm is aligned with the base line and the appropriate reading marked on the ground. Any distance between these two readings can be halved to give the true right angle. Such a device used

in this way would give sufficiently accurate results to meet any standards required in setting out.

Regular polygons

It is unlikely however that such a piece of sophisticated carpentry stands at the beginning of rectangular building. In this way the most rational conjecture is that originally builders used a length of rope (cord, twine) to help them set out a rectangular building as they had done previously to mark out round buildings. Every schoolboy knows the geometrical construction to "erect a perpendicular" at a given point. It is to make this point the mid point of a base line and perpendicularly bisect the base line. This is done simply by swinging equal intersecting
22.3 arcs from the two extremities of the base line. If this is effected on both sides of the base line, then there is an additional check that the perpendicular passes through the mid point. Such a proceedure is the simplest imaginable without requiring any instrument other than what was previously used with round building. The drawback is that the operation must be carried out in its entirety.

3. *Centralised Polygonal Buildings*

Buildings with the centralised plans of regular polygons, although restricted in numbers, form a conspicuous class in antiquity. They are Graeco-Roman monumental
17–20 buildings varying in date from Hellenistic times to late antiquity. The centralised plan means, in effect, that their prime axis is the vertical one, thus these buildings can have a transendental significance. The two plans of practical concern are the
19 hexagonal plan and the octagonal plan. In fact the hexagonal plan is more in point with articulating courts. Perhaps the most notable instance of its use is the great court in front of the Temple of Jupiter at Baalbek, first century AD (v Robertson, p. 223, fig 95). On the other hand the octagon occurs to immediately obvious
20 effect in numbers of building plans, notably villas and baths. Since the octagon is the transitional form between square and circle, it also recommends itself as the plan of building associated with transitions, e.g. martyria and Christian baptisteries (cf Krautheimer, p. 145, fig 100; p. 16, fig 24; pp. 176–78).

Both plans are simple to set out, and the hexagonal plan notably so. The radius of a circle steps round the circumference exactly 6 times as a cord. If radii are
23 drawn to the circumferential points then the polygonal figure comprises 6 equilateral triangles, their angles all of 60° and the face angles of a hexagon are 120°. Thus all that is necessary to set out the plan is to mark out one side of the desired hexagon on the desired orientation of the desired length. Erect an equilateral triangle on this side by swinging intersecting arcs from its extremities to give the centre. Describe the circumscribing circle with this centre and step off round the circumference the 6 equal sides of the hexagon.

Regular polygons To describe an octagon is not quite so direct. The face angles of an octagon are each 1 ½ right angles. Theorem: the interior angles of a regular polygon equal twice 23 the number of right angles as the figure has sides minus 4, i.e. 2n – 4. Thus the face angles of an octagon = 16 – 4 = 12 right angles, and each face angle = 12/8 = 1½ right angles, i.e. the face angles of an octagon are 135°. This is easily obtained by erecting a perpendicular at the desired point and bisecting the exterior right angle to give two angles of 45°. The supplementary (internal) angle to 45° is 90° + 45°, i.e. the desired 135°. The simple proceedure for setting out an octagon is then to mark out a side of the desired length on the desired orientation. Construct an angle of 135° at each extremity. Bisect these angles to give the centre of the circumscribing circle. Mark out this circle with the radius so obtained, and step off round its circumference the 8 sides of the desired octagon.

Although simple hexagonal and octagonal plans are straight forward to set out, they depend upon angular (geometric) construction. Thus if they are of complex development with internal compartments, then almost inevitably a regular design will involve irrational linear measurements. Complex designs of this nature occur in later antiquity, e.g. The Church of Theotokos, 484 AD on Mt Gerizim (Krau- 22 theimer, p. 151, fig 118) and the analysis of these plans is very complicated. Such plans are clearly concerned with numbers and proportions. They are products of the intellectual idealism of Neo-Platonism—expressions of the mystique and symbolism of numbers in quest of the "perfect". They are thus more properly concerned with design rather than setting out.

4. *Curvilinear (Oval) Buildings*

Buildings on curved plans other than round buildings are virtually all oval or 24–28 ovoid in form, and they are of Roman date. It is the plan adopted by the Romans for their amphitheatres. 26, 27

The oval is generated as a conic section, a strong point of Greek mathematics. 24 However the oval form never seems to have been adopted into Greek architectural design. The oval curve (or ellipse) is defined as the path traced out by a point moving so that the sum of its distance from two fixed points (the foci) remains the same. The curve varies in appearance from rotund to virtually parallel sided depending on the distance apart of the foci. The limiting forms are a circle and a straight line. When the foci are identical in position (no distance apart) then the curve is a circle (the major and minor axis are identical). When the foci are an infinite distance apart, it is a straight line (the major axis infinite and no minor axis).

There is a well known practical method of drawing an ellipse. Locate the foci as desired. Take a length of cord equal to the combined distance of any point on 25

Orientation

the curve from the two foci. Peg the ends of the cord at the focal points and use a marker held against the inside edge of the cord to traverse the required ellipse. This practical method of describing an ellipse could be used in setting out an oval plan, and probably was so used.

However when closely examined it seems that most oval building plans are not
26 true ellipses but are combined multi-centred arcs—either 3 centred or 5 centred. Such plans are easy to set out on the ground. The centres are located to give the desired form, and the arcs swung from them directly by lengths of cord as radii of the required lengths. It should be noted that where the circumference changes direction the centres must lie on the same straight line so that the change in direction will be continuous (Theorem: the radius is perpendicular to the tangent at point of contact, so that here the radius will be perpendicular to both curves).

D. *Setting Out Concerns*

1. *Orientation*

It is perhaps best to regard orientation together with location as conditions precedent to the setting out of buildings. Given the location of a building the predetermining factor with setting out is its required orientation (if any), i.e. its directional axis.

Generally speaking the exact orientation of individual buildings was not a prime consideration. For most buildings, particularly domestic buildings, the orientation may be preset by e.g. street frontage, or the desideratum is approximate only: e.g. a commanding prospect, exposure to the winter sun, shelter from the prevailing wind, etc. However it was not unusual during antiquity for religious monuments to be oriented rigorously according to considerations other than topographical—i.e. they were oriented exactly according to a "true" bearing (azimuth). This requirement has two distinct expressions which may be termed respectively Astronomical and Geographical.

(a) *Astronomical Orientation*

Numbers of religious monuments, particularly those of early date (significantly megalithic monuments) were designed in the primary instance so that they were axi-
40 ally oriented on some astronomical phenomenon, e.g. sunrise at midsummer's day (the summer solstice) or at the spring equinox etc. Such an orientation demanded only that the monument be built where the astronomical phenomenon (i.e. the specific sunrise) was visible. The phenomenon was observed by the naked eye, and a line towards this direction was marked out on the ground to constitute the axis

Geographical orientation

of the building. Be it noted, however, that this simple proceedure depended on a knowledge of astronomy comprehending the recognition and understanding of the summer solstice, the spring equinox etc. (D. Souden, *Stonehenge*, pp. 110–39, "Ritual and the Heavens"; H.A.W. Burl, *Prehistoric Astronomy*).

(b) *True Geographical Orientation*

Man very early became aware that the configuration of the heavens indicated a notional direction which remained constant wherever he stood on the face of the earth. This was "True North". True North (North-South) is the alignment of the axis of rotation of the globe. At the surface of the earth it is the alignment of part of the Great Circle which passes through the observer and the terminal points of the earth's axis, *viz* the North and South poles, (i.e. a meridian of longitude). It might be thought that this is a geographical feature and is to be determined by geographical observation, but it is not so. There is no record on the surface of the earth which can be used to determine this direction.

Everyone now knows that the earth acts as a magnet and possesses a magnetic field, the poles of which lie in the vicinity of the North and South Pole. In this fashion a pointer of magnetic material (iron) magnetised by induction can be arranged so that it aligns itself with the earth's magnetic field, i.e. points toward the magnetic poles. This device is the freely suspended compass needle. It is reckoned this was unknown in the ancient world; although it is perfectly possible that some intelligent persons may have observed the phenomenon (the wonder is, rather, that they did not). In short the ancients did not possess a device for orienting their buildings on magnetic North-South. Even if they did light on such a device it would not afford an orientation on True North-South. The earth's magnetic field changes its alignment constantly so that the magnetic poles alter their position. Moreover their position is sufficiently distant from the geographical poles, so that dependent on the position of the observer there is a variation between the two directions which is often considerable (e.g. 10° is not uncommon)—and the ancients possessed no record of magnetic variation.

All this is to say that in the ancient world true geographical orientation could only be determined by celestial observation, which explains why Vitruvius layed so much emphasis on the necessity for an architect to possess a good knowledge of astronomy: "From astronomy we find the East, West, South, North, as well as the theory of the heavens, the equinox, solstice and the course of the stars" (I, I, 10; cf IX, I–V).

True Geographical North was indicated by the direction of the sun when at its zenith, i.e. at its highest altitude (elevation above the horizon); or by the position of fixed stars which at night appeared to describe "small circles" about a central point in the heavens. By use of simple devices observations could be made in both instances which records the direction of True North so that a bulding could be orientated North-South or East-West. In short true geographical orientation could be obtained by both solar and siderial observation.

Astronomical orientation

(i) Solar Observation

It is very dangerous to look directly at the sun with the naked eye and to protect the eye modern instruments (e.g. sextants) designed for observing the sun incorporate tinted glass screens through which the sight is made. Accordingly ancient man did not make his solar observations directly on the sun, but noted the changing position of the shadow it cast. The proceedure for this was simple. 42 A post (the gnomon) was set up in the ground vertically to cast a shadow. At its foot on the ground a semi circle or arc was marked of a suitable radius that it was intercepted by the shadow of the gnomon in its passage—i.e. the shadow crossed (into) the arc before noon as it shortened and crossed (out of) it after noon as it lengthened. A cord was drawn between these two points on the arc and the mid point of the cord was marked. This point was where the shadow was shortest, i.e. when the sun was at its maximum elevation in the heavens; and the direction line from the point to the base of the gnomon indicated the direction of the sun at its zenith which was the True North-South direction.

(ii) Siderial Observation

If the axis of rotation of the earth was aligned exactly with a fixed star in the heavens visible to the naked eye, then the problem of determining true North-South would be non-existent. All that would be required is to observe this motionless star and transfer the line of sight to the ground. At the present day there is such a star (Polaris) very close to the North Celestial Pole, so that its direction gives True North with an accuracy sufficient for most practical purposes. However the alignment of the earth's axis "wobbles" about over time and no such conveniently situated star was available during antiquity. In these circumstances it was necessary to observe a star which rose above the horizon and set below it within a reasonable interval, mark the two observed direction lines on the ground and bisect the angle between them. This direction line gave the direction of the star at its zenith and thus the direction True North-South.

41 However it is not common to have a uniformly level unobstructed natural horizon as required for this proceedure, hence it was necessary to provide an artificial one. This can be done by building a wall in the form of an arc directed to the North, with its upper surface absolutely level. The star can then be observed to rise above the top of the wall at a certain point and to sink below it after an interval. The points of rising and setting can be marked on the wall and dropped to the ground where a cord can be drawn between them. The mid point of this cord will

Establishing lines

then mark the position where the star was at its zenith and the line drawn from the observation point to it will give the North-South direction.

No direct evidence survives that this proceedure was used in antiquity; but it is such an obvious one, that it is generally accepted to have been employed.

2. *Line*

(a) *Path*

The basic step in all building is the establishment of a true line; in the vast majority of instances a straight line, in some others a rational curve. The demarcation of a straight line is effected by means of what a builder calls his "line": a length of cord wound in such a way that it is easy to unroll and re-roll. A surviving builders' line from Middle Kingdom Egypt incorporates the sophisticated device of a 29 rotating spindle (Arnold, p. 253, fig 6.3). This cord is stretched out taut between two points and the ground (or other surface) marked according to its course to 34 record the desired line. Sometimes a powdered colour is poured along its length to mark out the line on the earth. In the famous instance of setting out the town plan of Alexandria, no convenient powdered colour was to hand and meal was used instead (which was held to be a good omen). When the line is to be marked on subsisting masonry, a simple and very effective device called "snapping" is used. The line is dusted with red colour and stretched to contact the masonry surface between the terminal points. At the centre of its run it is carefully drawn up or back like a bow string and then released. The impact marks the surface of the masonry with a clean and vivid red line, which is astonishingly resilient. Improbably such lines often survive to the present day, affording valuable archaeological information. However this is rather a matter concerning building construction, not setting out.

The stretched cord is used to transfer a continuous record of a true straight line between two terminal points which define the line. Also regardless of the cord interim points on the determined line, or points extending it can be obtained by visual means. This simple process is called "ranging in" the line, and makes use of rods/poles called "ranging rods". The rods, ca 2m long, are held vertically at the two extremities of the line, at one of which is stationed the observer. At the desired point another ranging rod is moved across the line of sight between the rods and brought to rest when the observer signals that it is aligned with the other two rods, and the ground is marked at this point. Thus any number of points along a determined line can be marked out within visual range.

Egyptian records exist of a proceedure called "stretching the cord" which is one rite within the foundation ceremonies for temple building (Jequier, pp. 33–35, figs 10–13). This is of some technical interest for setting out. What, in effect, the reliefs depicting the rite illustrate is not a single cord stretched out between the rods but a cord looped around the rods so that there is a double strand between the rods (and any intervening pegged out points on the line). This practice records the line very exactly, since the line is exactly between the two strands of the loop. It also permits the line to be extended some distance, since any deviation from the rectilinear is immediately noticeable. This property, however, is not a vital one, since the extension can be ranged in by visual means as previously noted. What the looped cord does is to strengthen the line and provide the means whereby it can be stretched very taut, as also to demarcate the line very exactly (Eisler JARCE XXVI 1989 pp. 193–205).

Determination of length

(b) *Length*

There is often apparent in (archaeological) discussion a confusion between the path of a line (direction) and its length (measure). To establish (mark out) a (straight) line is one thing, to measure along it a certain length is another. They are two different operations performed by using two different instruments. They are not carried out at the same time by using one and the same item of equipment.

To lay out, set out, mark out on the ground (or other surface) a straight line between any two points a long piece of cord (twine) is required which can be stretched out tautly along the ground between the two points, and if the cord is 34, 35 not long enough interim points must be established along the required line (by visual means) which are within the reach of the cord. To measure out accurately along the line so demarcated an exact length some instrument must be used which is calibrated in the units of length to be employed, and is used in such a way that the length measured out along the line exactly equals the arithmetical total specified of the unit of length. This instrument is not the same as the "cord" used for marking out the path of the straight line.

The essence of the "cord" is that it can be "stretched" taut so that it is following the shortest distance between the two points. Thus if this piece of cord or twine is graduated in linear measure the graduations will be continually deformed by "stretching"—i.e. the length indicated beween x feet on the line will become greater than the true length of x feet on the ground. On the other hand the essential of the measuring device is that the units marked on it remain invariable. If this device is of flexible material so that it can be rolled up, then it must be of "non stretch" material and not subjected to tension while being used—e.g. in modern times chains, steel tapes and reinforced linen tapes. Such devices, however, are not perfect and become deformed by stretching. The accurate measuring device, therefore, must be a rigid one: a rule/rod where the lengths marked out on it remain unchanged by use, which is, in practical terms, a wooden rule of limited length e.g. 5' or 10'.

Laying out angles

All this means that if great accuracy is required in marking out a straight line of exact length, the path of the line must be established by using a cord and the length of the line by using an accurately calibrated measuring rule/rod. Since these are inevitably short, then usually a succession of rods must be placed end to end without any disturbance to their position during the operation. This is, of course, a delicate operation but the one method available of accurately measuring out a length using simple devices. It should be noted here that the base line for the Ordonnance Survey of England made in the 18th century was laid out on Salisbury Plain by placing wooden measuring rods end to end in this manner. (For a consideration of accurate measurement of length with cords or with rods v J.J. Coulton, *ABSA*, 70, 1975, pp. 89–93.)

3. *Angle*

The lines of any designed building meet or intersect at specific angles—generally at right angles but on occasions otherwise. It is thus a basic requirement of setting out that the designed angle is exactly marked out on the ground. In modern times there have always been available precision "bearing" instruments so that any horizontal angle can be laid off to an accuracy of, say, 1 minute of arc. However the availability during antiquity of an instrument with a horizontal circle graduated in degrees of arc permitting horizontal angles to be recorded or laid off at any point on the ground is a doubtful matter. Such an instrument (a dioptre) may have existed in Roman times. Even so it is certain that such instruments were not available as a matter of course to those setting out the lines of projected buildings (i.e. they may have been available for special "engineering surveys"). This reproduces the situation in modern times where a theodolite is not to be found normally on building sites. In short, setting out buildings with exact angles as required by their design of necessity made use of other (simple) methods.

The angles incorporated in building design during antiquity were limited. In the vast majority of instances 90°, but on occasions 45° / 135° (for an octagon), 60° and 30°. As has been noted all of these angles could be laid off by simple geometrical construction using only pieces of cord of determined length. The procedure was, in effect, to bisect an existing angle. The construction for erecting a perpendicular is simply to bisect an angle of 180° (i.e. a straight line). This is done by swinging 22.3 equal arcs from points equidistant from the apex of the angle, and joining the apex to the point of intersection (the principle is to establish similar triangles). This procedure is so simple that it was understood from Neolithic times.

Proceeding beyond this it was observed that a triangle with sides 3, 4 & 5 units of length was a right angled triangle (as also, fairly closely, was a triangle with 22.1 sides 5, 5 & 7 units). Thus some device forming a triangle with sides in this proportion 22.2 provided a right angle without the requirement of geometrical construction.

The simplest imaginable device of this nature is a length of rope with successive divisions of 3, 4, 5 marked off on it. The rope can be stretched along the base line 32 with the point where the right angle is to be erected reading 3 or 4 as a convenient, and the right angle will be given by bringing the other two marks together to form the triangle on the ground. Even more direct is to preform the triangle by tieing or splicing the ends of the rope together and then adjusting it taut on the ground (cf M. Sauvage, *La Brique…en Mesopotamie,* p. 75).

Establishing levels

It is accepted that wooden set squares with long arms (e.g. 2 m long) for setting out right angles on the ground were in use from the beginning of monumental building in Egypt. Furthermore as a matter of course, if the designed building included angles of 45°/135° (octagon), or 60° (hexagon) similar wooden devices giving these angles could be fabricated to be used in like manner.

In short either *ad hoc* geometrical construction or the use of prefabricated wooden squares would give an angle of sufficient accuracy for all practical building requirements. Thus to set out accurately on the ground angles incorporated in building was well within the capacity of any ancient builder.

4. *Level*

It would have been more logical to have begun these remarks with a consideration of levelling since all measured setting out must be effected on a horizontal plane.

When concerned with a confined local area the horizontal may be defined as a plane at right angles to the vertical (= a line joining the station to the centre of the earth). There are two ready indicators of this condition:

(i) The vertical is indicated by a plumb line, thus the horizontal is a plane at right angles to the plumb line.
(ii) The horizontal is directly indicated by the plane of the surface of a liquid.

Both these indicia are used in modern precision levelling instruments (sighting devices which may be rotated through 360° on a horizontal plane). In (ii) the optical axis of the instrument is adjusted parellel to a horizontal tube of liquid containing an air bubble (i.e. a spirit level). When the air bubble is central in the tube then the surface of the liquid (and the optical axis) is horizontal. In (i) the optical axis of the instrument is set at right angles to the plumb line. The plumb line automatically assumes the vertical and brings the optical axis into the horizontal plane. In principle both devices were used during antiquity to indicate the horizontal. However in antiquity the bubble mechanism was not available (it was invented in the later 17th century AD), thus the surface of the liquid was observed to coincide with a mark parallel to the optical axis.

Levelling devices The latter system was that of the Roman chorobate. This was a 20' long sighting board (Adam, p. 18, fig 16) used in precision levelling for aqueducts etc. A trough on the surface containing water indicated the horizontal when the surface of the water coincided with a line parallel to the line of sight. (In fact the reading was also checked by a plumb line at the side of the instrument recording the vertical.) However instruments of this type were not normally used for setting out buildings. The type of instrument normally used for this purpose was a plumb line set at right angles to a sighting line, so that when the plumb line showed vertical the line of sight gave the horizontal. Generally this device is in the form of an A frame with a horizontal collar bar. A plumb line is attached to the apex and when this is coincident with the index for vertical on the collar bar, the sighting line is horizontal. A sighting board could be attached to the A frame, or the A frame made to rest on any surface convenient for sighting. 16 30.31 36

In the light of the above, it should be noted here that the use of a levelling device in setting out buildings (as opposed to surveying) is to establish a level building platform, not to establish difference in height between various points. In this way it is only the foresights which are material not the backsights—and so the process is a very simple one. However in special circumstances other (simpler) means of obtaining a level surface have been suggested. The level of the base of the Great Pyramid at Gizeh has been found to be very exact, notwithstanding its extension. Accordingly it has been suggested that this level surface was obtained by sinking a peripheral "moat" in the rock surrounding the pyramid and filling this trough with water: the surface of the water then directly indicated the level building platform desired (Arnold, p. 14; M. Lehner, JARCE, 20, 1983, pp. 7–25). However there are practical difficulties in this stemming from the porosity of the rock! In any event the establishment of a basic horizontal surface is necessary for all building construction. Subsequently, in general, superior horizontal levels (ceilings, upper floors etc.) are established by direct measurement from the basic platform.

E. *Setting Out—Data Provided*

An initial observation may be in order here. It has been the universal habit to build upwards in horizontal registers. In this way it is always the plan which is set out to guide construction. It is logically possible to build from the vertical plane, i.e. first to construct one complete elevation and then complete the building in accordance with it. In this way the setting out for the building construction would be by way of a screen on which were marked the indications for doors, windows, floor levels etc. This, however, has never been the practice anywhere.

Battered walls

In one set of circumstances only has something resembling it been suggested as utilised in the ancient world. This concerns Pharaonic Egyptian building construction. 48 Perhaps the characteristic feature of this building style is the batter (*sqd*) to external walls. It is the feature which invests the style with its air of gravity. On numbers of occasions it has been proposed that this batter (i.e. the inward inclination of wall faces from the vertical at an angle of ca 6°) was controlled by way 47 of building L shaped screen walling outside the external angles of the proposed building and marking on them the setting out lines for the batter (cf Arnold, pp. 11–13, 19; figs 1–8). In fact this was never general practice in Pharaonic building 157, 168 style, and the control was effected in plan not in elevation. The angle of batter can be controlled readily by e.g. measuring outwards from the vertical inner face of the walls. The supposed evidence for setting out the batter by way of profiles marked on external screens (e.g. at Medum) relates to underground construction of massifs (e.g. mastabas, v *infra* p. 150).

It is a misfortune that we know virtually nothing of the actual setting out practices in ancient building construction. Not only is information lacking but the term "setting out" is itself used confusingly in different senses. While the basic usage of the term (when unqualified) is, as here, marking out on the ground controls to demarcate projected construction, the term is often used confusingly for the quite different but closely related, proceedure of drawing out (to scale) the plan of a projected building so as to determine its design. Particularly is this in point 51 when the design of the building is based on some geometrical figure or figures, e.g. equilateral triangle, octagon, ellipse, etc. The confusion lies in that the use of the term in this sense often implies that the same proceedure (cf geometrical construction) was also used for setting out the building lines on the ground. In fact, in some instances it might have been, but this was not necessarily so; and the proceedure of setting out on the ground was always subject to the fact that 52 basic control points must be marked out beyond the area disturbed by building operations. In certain instances of geometrically based plans setting out (on the ground) may have entailed (successive) use of both proceedures, the basic geometrical construction to establish the plan followed by marking out critical points *outside* the plan to control erection of the building according to the plan (R. Taylor, *Roman Builders*, pp. 67–68).

The means and methods available during antiquity for setting out on the ground have been discussed, and it has been shown that only simple proceedures were required. However exactly what markings were set out on the ground in various instances can not be reported as matters of fact. Exposition of this matter is largely conjectural based on common sense and survivals into traditional modern practice.

Setting out, the nexus between design & construction

It is surprising to realise that as at present it is impossible to deal systematically with this vital component of building—i.e. to outline setting out practice according to the different schools of building (Mesopotamian, Egyptian, Classical, etc.), noting the effects of different types of design and of different materials of construction etc. Such treatment necessitates a future research project. At present such questions can be treated only incidentally, e.g. there is an exception to the principle that setting out markings must be outside the area of building. For the framed wooden building of antiquity this is not a requirement and the building lines can be marked out *in situ*, since they will not be disturbed by excavation for foundations, the individual posts being set into the ground directly. Also in this connection it may be noted that with centralised building designs it is axiomatic that setting out proceed from the interior.

Perhaps in these circumstances the best method of discussing what is known of setting out in antiquity is to proceed from its essential rôle in building operations. Setting out is clearly the nexus between the design of a building and its construction, therefore it may be considered from two view points: that of design and that of construction. This may help to bring more clearly into focus the essential question of what actually was marked out on the ground to control the erection of buildings according to their design.

1. *Building Design and Setting Out*

Setting out marks on the ground provide controls for the correctness of the designed plan, which is by no means the complete record of the design. Details of the elevation are as significant in the design of a building as those of the plan: and for the former the setting out provides no guide. Here the designer's intentions must be communicated to the builders and controlled in other ways, be they graphical, in writing, or by word of mouth. How the design of buildings was formulated during antiquity has received wide ranging attention. The focus of this enquiry usually has been the existence or prevalence of design drawings (v *supra* pp. 5–7). In fact surviving records demonstrate the existence of architectural design drawings in Mesopotamian, Egyptian and Classical building (J.P. Heisel, *Antike Bauzeichnungen*, Darmstadt, 1993). However drawings were not the only means of communicating the intended design of a building during antiquity, e.g. in Mesopotamia dimensions of walls could be specified very simply in terms of numbers of bricks of standard format (M. Sauvage, p. 76). Greek inscriptions preserve a surprisingly extensive record of contracts for erecting public buildings (M.-C. Hellmann, *Choix d'Inscriptions Architecturales Grecques*, Paris, 1999). The terms of these contracts include verbal references to the design of buildings, demonstrating in principle an alternative way of communicating building design

Dictates of design

in Greece. (A detailed examination of Classical Greek temple design is given by J.J. Coulton, "Towards Understanding Greek Temple Design" *ABSA* 70, 1975, pp. 59–99, which examines the rôle of drawings.)

In discussing the connection between the design and the setting out of buildings it is, perhaps, advisable to approach the question according to the existence of design drawings. In this way the question may be effectively narrowed down. Buildings may be divided into three classes: those where neither design drawings nor setting out marks are provided; those which have been set out but for which there are no design drawings; and those set out in accordance with design drawings. This classification indicates that setting out is only relevent to buildings which incorporate an exactitude of design. It is possible to build a shed, stable or cabin to keep out the weather hand over fist without any setting out. It is possible to set out a building plan effectively where no design drawing is provided—obviously a simple round building, square building etc. needs only the note of the dimensions for it to be set out effectively. Also it is recognised that in antiquity there were buildings of conventional design. And it may well have been that e.g. a typical Doric Temple with a peristyle of 6 × 13 columns was so standard that only a few supplementary written provisions were all that was necessary for setting out the building. Finally, there is the case where quite elaborate buildings, particularly those of unitary rectangular plan, can be described in words accurately so that they can be set out in accordance with the intended design. Even more readily may this state of affairs obtain when uncertainties in the written description can be supplemented by verbal information as required. The type example of
50 this category is Philo's naval arsenal at the Piraeus (347–46 BC). Normal building contract documents specify exactly the work to be carried out item by item, not the dimensions and form of the building elements; however the document in this instance describes the form and dimensions of the building so that it could be set out accordingly. N.B. reconstructed drawings have been made according to the text information with little dispute (M.-C. Hellmann, pp. 46–52).

It remains now to discuss the setting out of a projected building for which design drawings have been prepared. It is in these circumstances that the little information available and the conjecture are most meaningful. In the first instance something can be said concerning the significant question of who was responsible for the setting out of buildings. The one direct source of information on this subject to be expected are the Greek building contracts which cover so meticulously all the job lots comprised in a building project. They do not mention setting out. This is significant negative evidence. Since no contract was awarded for this work, it can only mean it was the responsibility of the architect who received a daily wage for his duties.

Necessary indication of the design

The architect thus undertook to provide the contractor with lines marked out on the ground in accordance with which the contractor was e.g. "to set in place the stones of the foundation core of the colonnade" (contract 1 for the Temple of Asklepios at Epidauros v H. Burford, "The Greek Temple Builders at Epidauros," Liverpool, 1969, p. 212). Following this he undertook to provide another contractor with the marked out lines in accordance with which the second contractor was "to construct the visible foundation steps and the stylobate" (Contract 5–6). Then he undertook to provide this second contractor with the marked out line according to which the contractor was "to construct the colonnade" (Contract 11–12). The vital consideration here is that these several building lines could only be marked out *in situ* after the preceeding stage of construction had been completed. That is to say the architect was obliged to set out such control points etc. outside the area covered by the building so that they remained available for setting out the various lines of construction when and where required. On the analogy of traditional modern practice this was done by setting out complementary points one beyond each extremity of the building line so that a cord stretched between them dermarcated the line. Angles were then given by the intersection of the lines so demarcated. Thus the device enabled the work on foundations and substructures to proceed without disturbing lines previously marked out. Then when the masonry platform was completed, the detailed plan of the upstanding walls was marked out *in situ* on this masonry. In this way the upstanding walls came to stand exactly as designed in relation to the foundations and substructure.

Setting out was thus a proceedure for making the lines of a design drawing available as required by the progress of building operations. It was not the reproduction at full scale on the ground of the design drawing. Much of the detail shown on the drawing was not set out on the ground and the use of the controls set out on the ground for buildings of developed form had to be used in conjunction with the drawings in order that the construction in all its detail conformed to the intentions of the design. On the other hand when a building was designed in accordance with some grid system e.g. based on modules or the like or on geometrical proportions, e.g. 1:√2, then it is a possible consideration that the skeleton 43
of this system may have been set out on the ground outside the building area as an additional control.

These remarks are very rudimentary ones and are subject to qualification dependent on the geometry of the design (N.B. complex centralised plans) and different considerations apply for special categoriess of building (e.g. Pyramids). However the remarks indicate something of the scope of this important question, which has as yet received so little investigation.

2. *Setting out and Building Construction*

Although it has not been possible to specify in detail the manner of setting out buidings during antiquity, it is possible to make one or two comments on the use made of setting out markings during construction. Contrasting illustrations are afforded by monumental building in Egypt and in Greece. In some way both illustrations concern development in elevation which is not the basic province of setting out the design of buildings.

Construction according to the setting out

(a) *Egyptian Building*

The practice of fine stone masonry in Pharaonic Egyptian building construction is so ideosyncratic according to the tradition derived from classical masonry that considerable note has been taken of it in manuals (cf Petrie; Clarke and Engelbach; Arnold *pass*). The masonry technique of setting large blocks virtually quarry faced and dressing them into the required form *in situ* during and after construction meant, in effect, that the precise building lines of the temple were marked out on the upper bed of each course after setting. Thus it was that Egyptian builders were required to make reference to setting out marks continually throughout the construction of a monument in order to give effect to the intentions of the designer. These circumstances were augmented and intensified by the feature of battered external wall faces, which required the retreat (*sqd*) of the batter to be controlled at every course setting. This incident of setting out in Egyptian building merges with that of masonry technique (v *infra* pp. 150–151). How, then, did Egyptian builders make reference to the original setting out markings so as to control the masonry construction?

The dismantling of Egyptian temple masonry occasioned in considerable part by transfer of monuments to avoid submergence consequent on the High Dam at Aswan afforded opportunities for observation of many markings normally concealed in the construction. These indicated (at least for Graeco-Roman monu-
44 ments) that axes were marked in the stone and carried up course by course so as to be continually available for reference. Final dressing obliterated these markings on exposed faces, but they remained visible on e.g. the upper beds of wall blocks. During the operation for the transfer of the Temple of Kalabsha (G.R.H. Wright, "Kalabsha The Preserving of the Temple") it was hoped to study these markings so as to reconstruct the system employed. However the speed of the operation necessitated by economic considerations did not permit this. Nonetheless passing notice of these matters was published in K.-G. Siegler, *Kalabsha Architektur und Baugeschichte des Tempels*, N.B. figs 23–27.

At this point another feature of Egyptian masonry construction should be noted
63 which is relevent to this question. The device of using earth ramps and fills to

Setting out controls for Classical Greek building

raise up into place the heavy masonry meant that flooring and wall face were in considerable part obscured during construction requiring the necessity for marking the record of axes on bed joints.

In short from primary setting out marks outside the area covered by the temple axes were incised in the masonry construction and raised up course by course so as to be always available to control the setting of the rudely dressed blocks. The faces of these blocks projected far outwards from the eventual finely dressed wall face so that in effect the wall plan of the temple had to be marked out afresh with every course of masonry.

(b) *Classical Greek Ashlar Building*

Of recent years a lively controversy has developed concerning the use made of design drawings by Classical Greek architects in formulating their designs (for temples). Some consider drawings developed more or less *pari passu* with Classical Greek building (i.e. during the 6th century BC), and that Vitruvius' statements concerning architectural drawing (E. Frézouls, "Vitruvius et le Dessin d'Architecture") have an extended anterior reference. Others, notably J. Coulton (Greek Architects at Work chap. 3), advocate that in Archaic and Classical Times (6th–4th Cent BC) Greek temples were designed by mathematical calculation of details based on given standard forms; and that Vitruvius' remarks refer back only to his immediate sources in (later) Hellenistic times (3rd Cent. BC onwards). Theoretically this difference of outlook should not control or condition setting out practice; and nowhere is setting out mentioned in connection with the dispute.

Additionally, consequent on the abnegation of drawings in formulating design, it has been advanced that design of a building was not totally settled before construction began; but that details of design were worked out during the course of construction as they become manifest. At first view this question of "incomplete preliminary planning" might be thought to bear closely on setting out practice. However this is not necessarily so. Although attention is never drawn to the fact, the details of design supposedly marked out during construction all are significantly questions of design in elevation. When construction has incorporated the 19
designed plan according to the setting out controls, such detailing in elevation as is conformable with this construction can be decided on and implemented without prejudice to what has been set out. In short the setting out of a Greek temple refers to the design of the stylobate on which the exact wall plan is marked out in detail. Nowhere does the setting out refer to elements of e.g. the entablature such as position of the triglyphs and metopes in a Doric frieze.

Consideration being given to the above remarks, it is useful to observe one outcome of the setting out of a Greek temple. This concerns the design of the peristyle, a very significant measure indeed.

49 A noticeable feature in Greek temple design is that columns keep in step with the stylobate paving blocks—i.e. columns are set centrally on a stylobate block, they are not positioned at random with respect to the jointing of the blocks. Now the jointing pattern of the stylobate blocks follows the order established in the lowest course of the crepis. Thus the jointing of the lowest course of the crepis determines the positioning of the columns. Since the setting out guide for the positioning of the columns was readily available, the positions of the columns could be marked when the lowest course of the crepis was to be set and the individual blocks of that course dressed and set accordingly. In this way the masonry of the crepis keeping vertical perpends, the columns in due course stood centred on individual blocks of the stylobate as required.

The harmony of Classical Greek masonry

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CHAPTER THREE

BUILDING SITE DEVELOPMENT AND INSTALLATIONS

A. General Background. The Terrain
B. Building Construction Sites
    1. Neolithic Jericho
    2. Mesopotamian Earth (Brick) Building
    3. Bastard Ashlar Construction
    4. European Wooden Building
    5. Megalithic Building
    6. Egyptian Large Block Building (Pharaonic Masonry)
    7. Cyclopean Building Construction
    8. Greek Ashlar Building
    9. Roman Concrete Building

Aspects of site development

The topic of site development is obviously important in ancient building technology, but there is little published material devoted specifically to it. In the nature of things the subject refers to building sites involving the presence of an appreciable labour force comprising variegated skills and competences, together with necessary mechanical devices to facilitate building operations. Significant aspects of site development include:

(1) Organisation of labour
(2) Organisation of supply of materials
(3) Transport of materials to and on site
(4) Preparation of materials on site (workshops, masons' yards)
(5) Excavation, levelling, soil stabilisation
(6) Equipment and devices for erection and finishing masonry (access scaffolding; ramps; hoists; cranes; centering; shuttering etc.).
(7) Measures for clearance and vacating sites.

Information concerning development of ancient building sites may be derived from:

Varried evidence available

(1) Ancient building remains (notably when buildings were abandoned incomplete)
(2) Ancient representations (e.g. decorative and commemorative reliefs)
(3) Ancient literary references and epigraphic records.

The organisation and development of a major building site is a ramified and interesting matter over all ages. It is also in practice a vital matter, for on its efficiency the success of the building project ultimately depends; and great sums of money can be made or lost accordingly. At the present day major construction companies all pride themselves on the "know how" they dispose in this connection. The infra structure which is so significant in the merits of site development comprises essentially matters of administration and economy and will not be discussed here, but will be referred to in the succeeding volume. Here attention will be given only to those aspects of site development which relate directly to the technology of building construction.

A. *General Background. The Terrain*

Presence or absence of Tells

The precise subject of discussion in this chapter is construction site development and installations, i.e. the development and installations on a building site to provide for the proper and efficient erection of a building under construction. In principle it is not the development of a selected terrain to provide the most effective setting for a completed (monumental) building. However to distinguish between these two applications at times may involve splitting hairs. Thus some observations are made concerning site development in the broadest sense.

In this connection a very trenchant matter obtrudes immediately arising from the temporal and regional definition of "The Ancient World". Building sites in the Ancient World are more or less equally divided into those developed on habitation mounds (tells, hüyüks, teppes, koms etc.) and those which are not. As yet no convincing explanation has been advanced to account for this distinction. The explanation should lie either in terms of physical geography or in terms of cultural history. However objections can be made to either instance. In general terms in the Middle East virtually all building sites are located on occupation mounds and in Europe such features are virtually unknown. Yet there are clear exceptions. Typical occupation mounds are the norm in European Bulgaria, while in Asiatic Cyprus occupation mounds are unknown. On the other hand there are areas in Europe with no semblance of occupation mounds yet their physical geography is identical with areas in the Middle East where all settlement is on mounds. Equally there are areas in the Middle East where the physical geography is akin to Europe but settlement is on mounds. The subject warrants penetrating and far reaching investigation.

Tells, occupation mounds

This question is, of course, material to the study of building construction, since buildings on occupation mounds are constructed, by definition, on made-up ground, which modern foundation science will accord no bearing strength whatever as natural foundations. On the other hand the occupation mound is removed from the hazard of swamping, inundation, overgrowth by vegetation etc.

Considering first building sites on occupation mounds. It is perhaps possible to make a distinction between mounds which have accumulated almost entirely out of mud brick building and mounds where the accumulation is largely of rubble construction. Without doubt the former provide the better building sites—or, to put it more cogently, require less in the way of preparation for new building. The very thick mud brick walls characteristic of more monumental building in Mesopotamia with the narrow rooms infilled with fallen or decayed mud brick afford an excellent building platform of compact uniform material. However where, as e.g. in Palestine–Syria walls are in considerable part collapsed rubble with adventitious heterogenous infill, ruined habitation does not necessarily provide a good building platform. It is uneven and sometimes contains voids so that slump frequently occurs. In this way it required and received measures to consolidate the platform for new building. These were based on an expert familiarity with soil consolidation, involving the recognition of the cementitious properties of crushed limestone deposit (*huwwar*) in conjunction with the chemical reaction provided by ash obtained by burning (collapsed roofing materials?) on the surface at intervals.

There were two distinct applications of this technique. The normal occurrence was the consolidation of fills etc. of ruined buldings within the confines of the tell. However on exceptional occasions the decreasing summit area of the tell became too restricted for habitation needs, and required augmenting. In this event there were two alternative measures: either to lay out a new quarter at the base of the tell in the nature of a lower town or to extend the summit area (cf Seton Lloyd, "Mounds of the Near East"; ABSP 1, pp. 155–56). The latter provided more security, but required a great investment of skilful soil science. Sloping layers of earth were fixed with huwwar surfacing and retained by horizontal layers of fill to provide a platform extending out to a new city (retaining) wall (ABSP I, pp. 381–82).

To consider developing the terrain for building where settlement does not follow the pattern of habitation mounds is a well nigh unbounded field, and, in any event, remains essentially unchanged in modern times. Land clearance, demolition and removal of existing structures, levelling of uneven and sloping terrain by cut and fill etc.—all these processes remain standard—only, be it remembered, the ancient world possessed nothing comparable with a bulldozer. There is, however, one severe impediment to building which afflicts many otherwise favorable building sites, and requires onerous remedial measures. Since it was a constant problem to ancient builders it is worth special mention. It is the problem of standing water. It has two common manifestations: marshy terrain with yielding plastic soil; and

Standing water periodic innundation. Vitruvius (II.IX.10; III.IV.2) includes a graphic note on piling with specific timber (alder and olive) plus packing with charcoal in order 53 to stabilise such treacherous sites so as to permit the erection of ponderous stone temples e.g. at Ephesos (cf Pliny NH 36, 95–97). At an earlier period during Bronze Age and Iron Age times settlement sites by lakes and rivers were much favoured and these dwellings were raised up on forests of wooden piles. It was once thought that such arrangements were to develop building above the (protective and productive) waters of a lake etc. (the "terramare"), but it is now generally thought that the piles were to raise dwellings above the level of periodic flooding (but cf Herodotos V.16, Lake Prasias in Thrace).

A singular highly idiosyncratic case of the difficulties incurred by water at building sites is the Nile Valley. The long continued seasonal flooding of the Nile transformed building sites with strong natural foundations into sites submerged below the waters of a vast lake for part of the year and for the remainder the ground was yielding alluvium. By a notable irony the most securely founded buildings were those on settlement mounds, which during the inundation rose above the surface of the flood like islands in the Aegaean as Herodotos remarked (II.97).

While earth works on a considerable scale (site engineering) were associated with tell development in the Middle East during the Bronze Age, there is little evidence of similar works in developing other building sites at an early period. The subject is little studied. It would make sense to treat it in relation with ports and harbour development, but this is beyond present concerns. An early example of urban site engineering is the Achaemenid Apadana, e.g. at Persepolis (F. Krefter, "Persepolis Rekonstruktionen"). This was an extensive and commanding podium 54, 55 raised high above the surrounding terrain by massive stone masonry on which stood residential palaces, reception halls, and administrative apartments etc. A successor to this type of development is perhaps found in the imperial residences at Rome e.g. the Golden House of Nero (Ward Perkins, pp. 214–16). All this is an expression of large scale public works, a function of imperial resources and often embodying the seat of imperial power.

B. *Building Construction Sites*

Since a discussion of construction site development and installations is only cogent in terms of the associated manner of building, it is impossible to deal with the subject within a strictly historical framework. However one (well known) site demands mention initally in virtue of its historical priority. It is clear that site development only comes in issue where building is carrried out with such materials and on a scale which require organisation and capacities beyong the handicraft and physical strength of a few men—i.e. expressed in a polar sense, monumental building.

The first known building of this nature in the ancient world is at Jericho near the Jordan's débouche into the Dead Sea.

Early instance of site development

1. *Neolithic Jericho*

At Jericho excavation revealed the remains of a massive round tower ca 10 m in diameter and standing to almost the same height. It is built against the inner face of a town wall, ca 3 m broad, beyond which is a rock cut fosse ca 3 m deep (K. Kenyon, *Jericho*). Within the area excavated all these features evidence a concerted building project on a monumental scale carried out in the same manner. The stones employed are sometimes of the order of sizeable boulders, on occasion roughly shaped. The tower houses an internal stepped ascent where both the treads and the roofing slabs are of dressed stone. The date of this construction must be in the 8th millenium BC, and the whole complex is in striking contrast to the mud brick round house building of the large settlement it confines. The manner of construction of the tower complex which demands a well organised labour force, skills in manoevering heavy boulders, and some ability to shape stone amounts to what is generally termed Cyclopean building. This is the name given by the Classical Greeks to the ruined fortifications and sepultures of the Late Bronze Age, the massive construction of which seemed to them the work of giants—the Cyclops, titanic artisans (cf Pausanias 2.25.8).

In this manner Jericho stands at the initial stage of two significant ancient building traditions: (mud) brick building and Cyclopean stone building. However whereas archaeology has revealed a continued record of the development of brick building in the ancient world, it has revealed nothing comparable with the Jericho stone construction until the lapse of long ages. Is this simply the accidents of discovery, or was Neolithic Jericho an erratic singleton in the development of building with heavy stones (boulders)?

Although the discovery of this primaeval stone construction at Jericho was made more than 50 years ago, unfortunately as yet no study of the process of construction has been undertaken. Neither the source of the stone, its transport and setting nor its working into steps and slabs. In view of the apparent simplicity required in operations this would seem a profitable occasion for experimental archaeology. In any event since the complex constitutes the world's earliest known example of a monumental building site, something must be said about it, if only to pose questions.

Considering first of all the source of the more massive boulders, there are two possible sources:

cf Cyclopean building sites

(a) immediately to hand in hollowing out the rock fosse
(b) gathered from the valley and foot of the confining scarps.

The first alternative has been suggested; but while it may be possible to bash and pound out a declivity in rock, to break out sizeable units in stone is a very different order. The only process conceivable would be akin to the Pharaonic Egyptian method of quarrying hard igneous rock, *viz* to pound out circumferent channels with very hard stone pounders and then to lever free isolated mass. However nothing suggests such a proceeding at Jericho. If, on the other hand, natural boulders were gathered as occuring in the area, then the problem arises of transport over distances. For irregularly shaped boulders rollers would be impractical, and sleds or such devices would need to be of sturdy construction to permit hauling with ropes. The operation of setting sizeable blocks requires them to be raised up an appreciable height, which at this epoch could only be effected by working them up an incline. In short the circumstances at Jericho are those besetting Cyclopean building very characteristic of the 2nd millenium BC and it is better to discuss 74–76 them in that context. Certainly this work at Jericho demanded a considerable labour force, say 50–100, with the use of stone pounders, wooden levers, ropes and construction ramps. It was a developed building site in the 8th millenium BC.

As noted it is difficult to settle on a framework for dealing with the question of construction site development and installations. The ambit of the question is monumental building together with other building accurately designed and constructed at a reasonable scale. In these circumstances it is equally reasonable to present the subject according to an overall historical succession of different schools of building, or, on the other hand, to arrange the treatment according to different building materials, i.e. schools of building in stone, building in earth, building in wood, building in concrete. The overlap in time is pervasive, while the interrelation in development between building in one material and another is so significant that however the material is presented will incur violence to either history or logic.

It is probably fair to say that the earliest period when building of a type demanding organised building sites with installations became common was ca 5th millenium BC, and during this epoch such building was constructed in earth, in wood and in stone. Whereas monumental building in stone was expressed in different manners across the ages, monumental building in earth and wood tended to retain a certain uniformity of manner, which meant that discussion of construction site development in these instances can be more generalised. Accordingly site development for earth and for wood building will be discussed next.

2. *Mesopotamian Earth (Brick) Building*

Brick construction requires minimal installations

Earth is a most versatile building material equally appropriate for the most rudimentary shelter as for an imposing monument. In this fashion it is perhaps the most widely used building material for domestic and utilitarian purpose in the ancient world. However for distinguished or monumental building brick building always remained the characteristic Mesopotamian mode of building and when it is found elsewhere a Mesopotamian influence is usually evident—that is to say until Roman times.

Perhaps the first Mesopotamian building in brick on a monumental scale occurs in the Tell Halaf period (5th millenium BC)—and it is doubtful that essential site arrangements and installations varied much in subsequent ages (not even when building in burnt brick became common).

Earth construction assumes diverse vehicles, e.g. plastic earth (*tauf*), terre pisé, brick. However to speak of site installations and development in antiquity for earth construction means, in effect, to discuss brick building sites. There are no remains of other types of ancient earth buildings on a substantial scale to warrant discussion of site development.

The versatility of brick as a building material has been observed by everyone. The same units assembled in the same manner constitute a cabin or a castle, a cathedral or a croft. However there is a necessary extension to this meaning which is generally in the mind of those who make the observation. Not only is the material construction of brick buildings great and small identical, but so is the procedure of construction. To build a temple, in principle, requires no more auxilliary appliances and installations at the construction site than to build a workman's dwelling. What differed (and differed greatly) between public and private building in brick was the size of the labour force and the quantities of the materials, with the attendant total difference in scale of logistics, administration and organisation. The picture which can be deduced from the nature of the materials is, in fact, also that afforded by the (scant) ancient records.

Ancient records relating to Mesopotamian building construction are very restricted. There is virtually nothing in graphic art, and literary reference is not a genre in itself of cuneiform literature. However something is to be derived from published studies of cuneiform texts. This comes from two different categories of texts: administrative documents (v H. Neumann, "Der Sumerische Baumeister"), and mathematical texts (v E. Robson, "Building with Bricks and Mortar"). Now all the information contained in these different sources concerns two questions only: materials and labour. They focus on quantities so as to estimate the expenses involved in carrying out projected buildings. And they give no indication that anything other was required than the building material (bricks) and the labour to

Little scaffolding required

produce it, transport it and assemble it, all operations effected directly by human strength and skill. Nothing whatever is said e.g. of conveyances for transport or devices to raise up the bricks often to considerable height.

Perhaps a specific comparison is instructive here. The problem of site development and installations for building pyramids has evoked continual interest and attention. The form and arrangement of ramps for hauling, the use of mechanical devices like the counterpoise and the counterweight, the incidence of levering, to say nothing of possible use of hydraulics—such topics have been discussed and controverted again and again (cf W.M.F. Petrie, "The Building of a Pyramid"; J.-Ph. Lauer, *Le Mystère des Pyramides*; T. Lally, "Engineering a Pyramid"; M. Isler, "On Pyramid Building," etc., etc.). Now there was a closely analagous feature to the pyramid in Mesopotamian building: the Ziggurat. And there has been some discussion on how ziggurats were built (cf Sauvage, "La Construction des Ziggurats"). This discussion is entirely in terms of manpower and materials, their supply and organisation; and there has been no pronoucement whatever on installations and mechanical devices. This, it seems, reflects the fact that no such developments were required to build a ziggurat any more than was required to build a private house.

The virtue of bricks is their portability. Whatever capacity of transport is offering, that modicum of bricks can be apportioned to it. In this way the problem of delivery of material at the necessary height on the wall face does not exist. By almost any means that a man can approach the work in progress, he can do so carrying a supply of bricks on his shoulder, or on his back. Failing this, or alternatively, a basket full of bricks can be hauled up vertically by rope hand over fist, requiring no mechanical contrivance of any sort!

Thus delivery of building material to the wall face is assured by the same means that afford human access to the work. It is suggested that as a general rule in Mesopotamian building brick walls under construction were not completely scaffolded as in traditional modern brick masonry. And it is likely that generally speaking brick laying in ancient Mesopotamia did not proceed from scaffolding. The good reason is that walls in substantial brick buildings are generally very thick. In these circumstances bricklaying was probably more conveniently carried out from the top of the wall, not from its face—i.e. it is paving as much as walling. Modern bricklayers do not like working from inside the wall face, but the circumstances differ.

There is, however, a further consideration here. All mud brick walls were plastered, generally with mud plaster. This can only be carried out working against the wall face and thus some sort of light scaffolding would be necessary. Probably the situation for monumental brick building in Mesopotamia was not unlike that obtaining with Pharaonic stone masonry in Egypt. Construction work was carried on from above the wall, while after its completion finishing work was executed from the lightest possible scaffolding set against the wall face. It is obvious that there are exceptions to this outline. Slight brick walls can not be constructed from above and neither can various forms of ornamental brick facing (v Vol. 2, pp. 117–21).

Plastic earth construction requires no installations

In brief brick construction was arranged so that walk-ways for builders could be readily provided and with the builders the bricks and mortar were walked up to the construction point. Scaffolding was kept to a minimum during construction, and the lightest possible scaffolding or staging was provided for finishing (plastering) the wall faces.

The roofing of Mesopotamian brick building was for the greater part mud terrace roofs carried on logs and poles. However from an early period (end of 4th millenium) the construction of brick vaulting was well understood, and this in a diversity of forms (D. Oates, "Innovations in Mud brick.... in Ancient Mesopotamia").

The rationale of these various forms was to avoid the necessity for temporary support during construction (centering), e.g. by tall parabolic contours for the 354–355 most part corbelled, or alternatively by flat saucer domes of "pitched" construction (v *infra*, pp. 244, 245). In this way heavy wooden centering was not installed in Mesopotamian construction sites. Of course some platform was required for the builder at work, but this would have been lightly constructed (portable) staging.

Since the above discussion has been to emphasize the simplicity of procedure for brick builidng and its relative absence of required installations, it is useful to mention as an appendix the circumstances of building in plastic earth (*tauf, zubur* etc. in the Middle East; puddled mud, cob in English usage). Although there are no remains of substantial ancient building sites employing this construction, it was practiced at the very beginning of load bearing earth building in the Middle East during early Neolithic times (v O. Aurenche, "La Maison Orientale," *pass*). Equally it was prominent as the traditional construction in South Arabia until the 326, 327 early 20th century, expressed in strikingly monumental buildings, skyscapers 20 or more metres high. These are a wonder to behold and more wonderful is the fact that no site developments or installations of any sort were required for their erection. Nor, indeed, were any tradesman's tools!

The system is to set hand modelled plastic mud in place by the handful, to dry and attain rigidity *in situ*. The mud was mixed and rolled into fist sized dumplings 325 on the ground by an assistant who passed them (and subsequently threw them up) to the waller to press and drive them into place by hand, so that they serve both as units of masonry and as mortar (v Vol. 2, Ill 147). The construction proceeded in horizontal registers of ca 50 cms with intervals for drying. When the wall face stood higher than convenient reach, the waller mounted the wall and continued operations standing or sitting on the wall, catching the dumplings thrown up to him by the assistant. When the construction reached ceiling height the floor was set in place, and the sequence of operations continued from this new level. In this way skyscraper proportions were achieved in the same way as a garden wall. These traditionally constructed southern Arabian skyscrapers show clearly that in ancient Mesopotamia it was possible to buld Ziggurats with virtually no site developments and installations.

3. *Bastard Ashlar Construction*

Limited installations required

This type of stone masonry is a very old and rational development, which because of its convenience has remained in use more or less anywhere at any time. Details of the assemblage may vary but the principle remains the same—that is to dress finely only the exposed face of the facing blocks of wall masonry so that they can be set finely jointed, while leaving the remainder of the block (i.e. rising joints, bed joints and back) roughly hewn and splaying inwards so that behind the face the joints gape apart. In this way the masonry combines the convenience of rubble in structure with the distinction of ashlar in aspect. It thus may be regarded as a hybrid, rubble in structure and ashlar in aspect or, in effect, "bastard ashlar", i.e. spurious ashlar.

It was the earliest type of fine stone masonry, evolving from the direct influence of brick. Without doubt the first examples of bastard ashlar stone masonry to occur were in Mesopotamia during the latter part of the 4th millenium BC e.g. the Steingebäude at Uruk (E. Heinrich, *Die Tempel....im Mesopotamien*, pp. 46, 67; J.O. Forest, *Les Premiers Temples de Mesopotamie*, pp. 75–130). However early stone building of this nature according to all archaeological evidence remained very exceptional in Mesopotamia and it was elsewhere that it came into great prominence. Towards the end of the 4th millenium BC mud brick building on the Mesopotamian model and on a monumental scale was introduced into late predynastic Egypt—principally for mastabas, imposing funerary structures with highly decorative niched façades (AAAE, pp. 24–26). In turn during the Early Dynastic period (ca mid 27th cent BC), as a striking innovation such buildings were constructed at Saqqarah in stone (by, it seems, a man of all round genius, Imhotep, the minister of public works of Pharaoh Zoser). The manner of this stone construction was the bastard ashlar style; and it is clear that Imhotep sought to transform the existing mode of 159
brick construction by taking it as it stood and investing it with a new dimension, eternity. In short the new stone construction procedure remained essentially that of the preceeding brick building (AAAE, pp. 30–38).

Bastard ashlar is by nature a facing to ruder masonry, generally coursed rubble—and this is so at Saqqarah. It is façade masonry and quite often false façade masonry with no functional apartments behind it. It is essentially aspectual rather than structural in significance and reproduces the fine aspect of the brick mastabas, *Limited installations required*

as such it is uniform to the full height of the buildings. The format of the stone blocks did not vary overmuch from the mud brick units previously employed (the handier to express the niched façade design) and is "*petit appareil*" in French terminology. All the dimensions are notably less than a cubit (ca 50 cms). Thus the size is of the order of an early Mesopotamian large moulded mud brick; and, what is the material fact, the weight is perhaps something up to ca 40 kgs or twice the weight of a normal mud brick. Now ca 25 kgs is about the upper weight limit of an object (a brick) which one man can handle continually without stress or fatigue. All this means that no essential changes in the site development and installatins were required by the new bastard ashlar stone masonry.

Two men working together could set a Zoser block in position and a party of 4 to 6 men could hand such blocks up a stage or cary them about without need of levering or transport devices (rollers). In short a construction site for building in bastard ashlar proceded on the same lines as one for building in brick—only the setting of blocks was a 2 man job instead of that of a single person, while a working team to keep the masons supplied was probably 4 to 6 men instead of 2 to 3 for brickwork. It is not an obvious matter to determine whether this bastard ashlar masonry was set working "underhand" from the rising rubble core, or whether it was set from a scaffold. The fine dressing of the faces was executed on the bench prior to setting, so scaffolding was not an inevitable necessity for finishing. However in some instances the wall must have been scaffolded eventually since the face bears relief decoration and also engaged columns are fluted. In any event since the burdens were light, the scaffolding required was virtually only workers' access scaffolding (J.-P. Lauer, *Saqqarah*, pp. 86–132).

The convenience in dressing of this type of masonry is such that it has always remained available in the offing. However something like 1000 years after its exploitation at Saqqarah, it provided the basis for the first spreading of fine stone masonry outside Egypt. Somewhere about the middle of the second millenium BC construction incorporating some finely dressed stone masonry spread over the Eastern Mediterranean and the Levant. The finely dressed stone was of the bastard
175–180 ashlar model, and additonally the construction developed into a certain "order" (v *pass*, e.g. G. Hult, *Bronze Age Ashlar Masonry in the Eastern Mediterranean*; S. Shaw, *Minoan Architecture*; Y. Shiloh, *Israelite Ashlar Masonry*; G.R.H. Wright, ABSP, ABC). It was a mixed construction with walls of a stone substructure (about waist high) supporting a superstructure of mud brick or rubble incorporating considerable timber reinforcing. Moreover, quite frequently the bastard ashlar facing
180–181 on the principle faces took the form not of normal blocks, but of tall slabs raised on a projecting plinth termed orthostates. In this instance some of the masonry units (the orthostates) were not "petit appareil". However this construction was not carried up to any height, thus it could all be set in place at ground level and

Orthostates did not involve any special site installations for its construction. This type of bastard ashlar walling flourished during the Late Bronze Age and in some regions (Syria, Palestine, Cyprus) continued in use during the Iron Age. It may be noted 177, 178, also that the orthostate style came to be valued for its aspect, and could become 182–183 the field for relief decoration. In this connection a further development was manifested on occasion: the orthostate facing lost its original structural rôle as part of the socle masonry. It became extraneous applied ornament to the face of a (e.g. mud brick) wall, which in itself was structurally self subsistent—i.e. remove the orthostates and the masonry would remain standing undisturbed. In the instance of Late Assyrian Palaces these ornamental slabs etc. assumed grand proportions. 182–185 However they were not part of the structure and were set in place as a separate *post facto* operation.

The mixed building style of the Late Bronze Age in the Eastern Mediterranean and the Levant plays a significant part in the history of ancient building. As with Mesopotamian mud brick building there is very little information available concerning procedures of its erection. The Bible, for instance, has much to say about the finished state of various buildings at Jerusalem (notably Solomon's Temple), their materials of construction and measurements, but it says nothing about how they were built. In the absence of specific studies on the subject, it is probably fair to say that for both Mesopotamian mud brick construction and for bastard ashlar construction the concern was to keep the process of construction as far as possible in human hands and avoid necessities of special developments and installation on such building sites.

4. *European Wooden Building*

Heavy timber construction long surviving in Europe

Wood (which in this connection is taken to include any appropriate vegetal material) was without doubt the material earliest used by hominids to provide some shelter for themselves, and it has always remained in use for temporary and emergency structures in the form of reeds, rushes, canes, branches and brushwood, etc. Such fabrications do not concern site development. However during early Neolithic times in forested Europe men began to erect quite impressive structures and monuments from solid massive timbers. The utilitarian long houses and barns of this nature survive in the European traditional building through mediaeval into modern 112 times, and something of the manner of the earliest religious monuments remained in evidence with the "stave churches" of Scandinavia. It is with this monumental wooden construction of Neolithic times in Europe that, unexpectedly perhaps, the consideration of building site development and installations should begin.

Wood is a fugitive material, notably so in the damp earth of forested Europe, however evidence of wooden construction is available by way of "archaeology from the earth"—the record of post holes and discoloration from rotting in the soil.

Timber circles require significant installations

This shows not only heavy tree trunks installed as uprights, but also the manner of their installation in the earth. Trunks approaching 1m in diameter are attested in early Neolithic sites, and the wonder is how such trees were felled with flint hand axes. Trunks of consonant length would amount to a burden of well over a ton and could not be manhandled upright. They are thus, probably, the earliest building units requiring some engineering device to set up. At some "wooden circles", e.g. at Arminghall in Norfolk, ca mid 5th millenium (v *infra*, pp. 121, 122) traces remain recognisable in the soil of this operation. Inevitably the trunks were dragged base first to be slid or eased down inclines into prepared post holes. Auxilliary appliances used in these operations included ropes for hauling, and probably long strong poles with a forked end to push up and hold timbers in place.

It is clear that substantial wooden construction of neolithic times required work at considerable height to fix together the solid timber roof framing. Some *locus standi* was required to carry out this work. The work was not continuous like stone or brick masonry, but was localised at intervals of the frames. In this fashion access was provided by ladders set against uprights (the simplest instance being notched tree trunks).

Perhaps the prime interest of these installations is their historical significance. Wood can decay very quickly. Accordingly human understanding appears to have appreciated enduring building material as of a higher order than transient material, and wherever possible men tended to substitute stone for wood in their monumental building. Thus it is possible to see substantial wooden construction in Neolithic Euope as the origin of the forms of Megalithic building. In several instances earlier wood buildings of the same form occur at or near the sites of Megalithic monuments. Moreover some detailing of Megalithic stone masonry is clearly proper to wooden construction. Thus it is reasonable to suppose that the know how for Megalithic construction was nurtured in European wooden construction. And this opens up a long subsequent history.

5. *Megalithic Building*

Problem of definition

It is very difficult to define Megalithic to any useful purpose. The term is used in a descriptive sense; but this is only obscurantist in the present connection, since its principal use in building history is as a technical term. However its use to denote a technical category in ancient building construction is anything but precise. The difficulty is that the term can be thought of as founded both in history and in form. Unfortunately there is large stone building within the historical ambit of the definition which does not correspond to the formal idea; while on the other
56, 158 hand, there is building at many places and times which does. Historically Mega-
152 lithic signifies the type of building in large unhewn/roughly hewn stones current principally in Western Europe from ca 5000 BC to ca 2000 BC. The basis of the

Developed site installations required

formal idea is that Megalithic construction connotes elements standing upright in the ground or spanning these elements as slabs (cap stones). Essentially it excludes stone masonry built up of compact units set one on the other (e.g. in courses). However when considered historically this formal distinction is not absolute and breaks down. 153, 154

The first thing to be said (and most emphatically) is that the site developments and installations for ancient megalithic building were highly evolved, both in scale and ambit. They established a system of handling the heaviest of building units, which has never been relegated from use (on emergency occasions). And it is probably fair to say that the system has never been put into effect more efficiently and comprehensively (F.C. Atkinson, *Neolithic Engineering*; J. Osenton, "Neolithic Engineering Techniques").

To facilitate a brief survey, megalithic construction can be divided usefully into two classes: that where earthworks form an integral part of the finished construction, and that where earthworks are not part of the finished construction. Examples of the former class are dolmens / barrows; while examples of the latter are standing stones (menhirs), stone circles (cromlechs) and Maltese temples. There were two mechanical devices available to Megalith builders: the inclined plane and the lever—and they exploited them both to astounding effect. The inclined plane was fashioned by earthworks, and the levering to height proceeded by chocking and cribbing with wooden members. 153, 154 155, 157 57–59

As a matter of course earthen ramps and embankments were utilised when the design of the monument under construction included an earthen component. The concern here was with the dolmen (= stone table)—a stone compartment formed from great slabs (for the sides as well as the roof). The remains of these structures, still standing in numbers after 5,000 years or so, evoke wonder today. However these visible remains are an "inside out" phenomenon. Originally they formed chambers inside an earth tumulus (the Neolithic chamber tombs, passage graves, round barrows, long barrows etc.) where the enveloping earth has disappeared in the course of time. 154 39

The process of construction of these monuments is obvious. The incipient, earthern tumulus was heaped up to a suitable height, trenches were dug to accomodate the feet of the upstanding slabs and these slabs were hauled up the sloping earth base first to be eased down into position standing upright in the trenches. They were then strutted securely or better the enclosed chamber was filled with rammed earth. The surrounding earth tumulus was then raised to the height of the chamber roof and the capstones were hauled up the bank and then across into position covering the chamber. The chamber was then cleared of its temporary strutting or filling and the earthern tumulus heaped up over it to enclose it completely.

Free standing stones

Quite contrary was the procedure of building other megalithic monuments divorced from earth tumuli—the standing stones (menhirs) and stone circles (cromlechs). Here it would have been practical procedure to heap up *ad hoc* construction ramps of earth and proceed in the manner outlined above. However where the site is extensive and well defined (e.g. Stonehenge) there are indications that this did not take place. No trace of mound building survives at the relevent positions and (even more emphatically) there are no traces of the disposal of the large masses of earth required (R.J.C. Atkinson, *Stonehenge*, p. 134; but cf D. Souden, *Stonehenge*, p. 93).

Standing stones were set up in the following manner. The sunken emplacement for the foot was dug with one face inclined at a suitable angle to form a "slideway". The "menhir" was brought base first up to the emplacement with the foot projecting over the inclined cutting, the stone resting on timber rollers. The far end (top) of
228 the menhir was then levered upwards and the stone slid down the inclined cutting to rest at an angle at the bottom of the emplacement. It was then hauled vertical by ropes attached to its head (perhaps with the interposition of shear legs to engineer a more effective angle of traction) (R.J.C. Atkinson, *Stonehenge*, pp. 131–34).

Horizontal slabs (cap stones) were levered up to the necessary height (eg up to ca 6 m). This could only be done employing the device of "cribbing". A heavy stone slab can be raised up by repeated levering and wedging (chocking / packing) it from below with e.g. wooden chocs. Since the fulcrum for applying the lever must also be raised *pari passu* the packing soon becomes unstable and will not suffice for more than half a metre or so. The process of cribbing then involves building up beneath the raised block a platform or staging so that the levering process can be repeated *ab initio*, and so on until the required height is attained. This seems a tall order, and so it is; but it is carried out with a profuse supply of long and heavy baulks of timber which are laid down parallel at intervals and then another set of baulks are laid across them at intervals. Then a plank floor is laid to provide a
58, 59 working platform. The process is repeated until the raised staging is at the height to lever the cap stone across into place (R.J.C. Atkinson, *Stonehenge*, pp. 134–39; D. Souden, *Stonehenge*, pp. 92–93).

The quantity of timbering required is enormous, but it is not fixed together in any way and is assembled and dismantled without trouble. Thus the one store of timber serves for all occasions when cribbing is required.

In brief the erection of stones of great burden (at times ca 50 tons) was engineered with ample supplies of earth, timber, ropes, grease and manpower. The marshalling of these resources on a construction site and their disposition for carrying out very heavy works involved notable development and installations. Some idea of this is perhaps given by considering the rôle of the engineer in charge of the operations.

Wide knowledge required by master builder

The master builder/controller of a significant megalithic project was a man of varied talents (after the model urged by Vitruvius). He needed an awareness of astronomy exactly for the reasons stated by Vitruvius, as also a grounding in local physical geography within the ambit of the supply of megalithic units of stone. In the instance of Stonehenge the required geographical knowledge extended over the whole of South Western England and Wales. This was a vital concern for routing the haulage tracks for the massive units of stone (which could be the most costly item in the building programme). With this went a knowledge of geology, *sub specie* lithology in order to recognise suitable building stone occuring in outcrops where suitable slabs had been detached by weathering, or could be detached by a minimum of effort. Then followed a capacity in surveying to ensure that gradients of haulage ways were kept at a minimum, and that earth ramps up for setting slabs were negotiable. A knowledge of forestry and joinery was required for construction of transport sleds (and dug out canoes). Finally the engineering know-how to apply manpower correctly to hauling and levering.

It must be remembered that these varied competences were all exercised mentally so far as is known. Neolithic society was illiterate and no graffiti etc. survive which can be considered working drawings for megalithic construction. The development of a construction site with its appropriate installations as the province of a master builder emerges with the Megalithic building tradition in Western Europe during the 5th millenium BC. What relation may subsist between this and similar manifestations at a later date elsewhere (e.g. in Old Kingdom Egypt) is at least a matter for speculation.

6. *Egyptian Large Block Building (Pharaonic Masonry)*

Revolutionary change in building

This system of construction, because of its ideosyncratic nature, has received continued investigation and explanation focussed on site development and installations. The consideration, however, has been accorded to it in isolation (apart, that is to say, from a once current ideology that all monumental construction everywhere was derived from the Pyramids). Since virtually nothing has been said about the origins of Pharaonic Masonry construction, at least some reference to the matter must be made here. The complete change in manner of stone building which occured suddenly in Egypt between the 3rd and 4th Dynasty (i.e. in the middle of the 3rd millenium BC) is one of the most striking (and unaccountable) developments in building history. A small block masonry style emerged with great élan at the Pyramid Complex of Zoser (ca 2650 BC) as a conformable development out 159
of monumental mud brick building, and was constructed with the same processes and installations. Within a century it was supplanted by building with the largest

possible stone blocks constructed in an entirely different fashion, requiring completely new site developments.

Background to Pharaonic masonry

The size of the block and the construction processes of Pharaonic Masonry were similar to Megalithic building of Western Europe. This system had an anterior history of 2,000 years when Pharaonic masonry appeared, thus it is reasonable to look to influence on Egyptian building from this quarter. However there are strong differentiating factors. Pharaonic Egyptian building is out of finely dressed blocks, hair line jointed; Megalithic masonry is out of unhewn (or roughly trimmed) slabs, in principle not bedded one on the other, and with no concern for jointing. Also outliers of true Megalithic masonry occur in regions proximate to Egypt, e.g. Tunisia(?) and Palestine (F. Nel, *Dolmens and Menhirs*, p. 70, fig 10) yet there are positively no occurrences of this type of building in Egypt. Furthermore Cyclopean Masonry, the closest building style to Megalithic Construction, while common in the Mediterranean and in the Levant, is not found in Egypt (N.C. Loader, *Building in Cyclopean Masonry*). In short Egyptian Pharaonic Construction appeared suddenly fully evolved early in Egyptian monumental stone construction, and remained the well nigh unique mode until the end of native Egyptian monumental stone building (ca 2nd cent AD). Building other than in this manner, even monumental building (e.g. palaces and fortifications) was carried out for the most part in brick. These seem to be the facts relevent to possible connections between Pharaonic Egyptian construction and other styles of stone building. What their interpretation may be is not evident. 160, 161

The indigenous background to Egyptian building with large blocks of stone is strange to tell. This building style was essentially devoted to building the Egyptian temple, which was an amalgum of opposites. Its forms were derived from building in the lightest materials—pliant reeds, canes etc. (G. Porta, "L'Architettura Egizia delle Origini…"), but were expressed in the most solid construction ever known. Apparently sometime in the earlier 3rd millenium BC Egyptians came to stand in passionate need of eternity. This need was compulsively expressed in the apalling custom of mummification and in the concept of the "house of a million years". To this latter end was directed Pharaonic masonry construction.

Pharaonic masonry construction was a very coherent system of building designed to effect the assembly of massive units of stone in the quickest possible time. It was based on two complementary factors: the largest possible stone units incorporating the minimal dressing required to assemble them in the solidest structure (v *infra*, pp. 146–151). Fine dressing of stone, particularly of the hard stone favoured by Pharaonic Egyptians is a laborious process which cannot be speeded up. Blocks of the largest dimension progressively reduced the surface area to be finely dressed; while minimising the surface requiring fine dressing prior to setting further reduced

Basic installations, earth embankments and fills

the delay before blocks could be set. The effect was to complete the construction of the monument at an accelerated schedule, leaving the bulk of the final dressing to be effected *in situ* without compromising the schedule of erection—i.e. while the construction of other parts of the building was in progress and also after the erection was complete and the building was serviceable.

To put this system into effect required site development of the highest order with large scale installations.

The basic engineering devices employed in Pharaonic building were those used in Megalithic building: ramps and embankments of earth, together with facilities for levering (B. Cotterrell & J. Kamminga, pp. 75–83, 86–89). However a salient difference between the installations for Megalithic building and those for Pharaonic building was that earthworks did not form part of the design of the latter in the manner that earth mounds/barrows constituted the external form of dolmens. Earthworks in Egyptian building construction were site installations requiring removal before the completion of the programme. On occasion monumental Egyptian building programs were abandoned before completion and on some few 62
occasions, the external earthworks remained *in situ* until modern times as evidence of the procedure (Clarke & Engelbach, figs 87, 88, 89; Arnold, p. 96, fig 3.50).

There is no doubt that such earthworks formed the basic site installations for large block stone building in Egypt. They were not only heaped up externally against 63
the faces of walls but the interior of rooms were completely filled with earth. The necessity of this measure was obvious in the case of the great pillared halls of temples (hypostyle halls) for erecting the columns, but it was also required generally for setting entablature blocks and roofing beams and slabs. The earth fill rose *pari passu* with the courses of masonry (set virtually quarry faced) and was removed when the unit of construction was completed. The speed with which volumes of earth can be deposited and removed by basketting is astonishing (Clarke & Engelbach, p. 91). The overall supply of earth required was, of course, minimised by accurately scheduled construction programs, so that earth filling in a finished apartment was available for use in another apartment where work was beginning.

This eminently practical arrangement is subject to an abiding difficulty. The gradient of the ramps must be gentle (ca 1 in 10) to facilitate hauling; thus to attain 60
the ultimate required height (which was often considerable in Egyptian temple building, e.g. 20 metres) necessitated a long run for the ramp, e.g. 200 m. Now while this might be practical for isolated monuments, it was an unlikely prospect for construction on a crowded building site. Thus the question which hangs over Egyptian site development is the arrangements to gain the necessary height in the confined space available. Here we are speaking of normal building construction. The exceptional circumstances for pyramid construction where some units of

masonry were to be raised ca 150 m have occasioned endless discussion and will be noted separately.

Levering

For this problem besetting construction ramps there is an obvious parallel in step design (i.e. staircases). The expedient here (to achieve height in a restricted space) 63 is to change the direction of the flights of steps at landings: a change through 90° with "quarter landings" and a change through 180° with "half landings". Such a device was practical for construction ramps and must have been used on occasion. Since changing the direction of haulage necessitates levering the block around at the "landing" it is generally supposed that this was combined with levering it up a step, e.g. 50 cms onto the new flight, which would be a further gain in minimising the run.

With this device the question of levering comes substantively into consideration. Although surprisingly, there is no Ancient Eyptian representation of levering masonry blocks (this exists in Assyrian art), abundant evidence of the practice survives in the form of cuttings in massive blocks for engaging levers (in the form of heavy timber baulks). Levering is applied to massive stone blocks in two senses: to move them about horizontally and to raise them up vertically. In the former instance if any sustained motion is required, levering is used as an adjunct to hauling. It is the final adjustment into position on the wall face where levering alone was used to move blocks horizontally. With respect to raising blocks, although there have been proposals in special instances (e.g. in pyramid building) to see levering up used in place of hauling, in general levering up was employed in conjunction with hauling. Proposals for levering blocks up vertically through a considerable height are unconvincing practically—cf the use of "rockers" (Clarke & Engelbach, pp. 94, 95, figs 89, 108). And no one has suggested that large scale cribbing was a standard device of Egyptian masonry construction. The use of levering to raise up blocks then was, in effect, to raise them up a succession of steps. An obvious application 64 of this idea is to work blocks up a wall face of stepped masonry construction. However while in special instances such practices would have been employed, it is not viable as a standard procedure of construction with large roughly dressed blocks—particularly when the external face of the wall is battered.

In short it may be said that in spite of continued consideration (and imagination) no alternative procedure has been established other than earth ramps and fills for raising up the very massive stone temples of Pharaonic Egypt. And here it should be noted that the use of earth devices extends beyond the building site. Generally speaking Egyptian temples were erected by the Nile, so that when 229 building stone was brought to the site from distant quarries it was transported by Nile boat. However this required some overland transport at both ends. In these circumstances, where possible, causeways were constructed for hauling the stone

Inherent problem with embankments

(on sleds). Remains of these causeways (often ramped) are still clearly recognisable extending over considerable distances and several illustrations of them are given in Arnold—e.g. p. 55, figs 3.46, 3.49 (from quarry to Nile) and p. 90, fig 3.42 (from Nile to site). These causeways were often carefully made up with brick walls (and cross walls). Also much use was made of old boat timbers as reinforcing in the construction (cf Arnold, pp. 87–94, figs 3.33, 3.37, 3.38, 3.39). As concerning the plenary use on site of earth construction platforms in monumental Egyptian building, one factor has never been sufficiently emphasized. This is setting in place the massive stone roofing. In the first instance this cannot possibly be carried out over a void; and in the second instance levering about these massive beams and slabs could well disturb and dislodge the masonry beneath, particularly columns. Thus these chambers need to be filled with earth to give the necessary rigidity to permit roofing them with massive stone units of 20–30 tons burden. 60

Here it is reasonable to point out another matter which bears on the use of earth as constructional installations for monumental masonry. For many it may be unexpected to learn that the constituent parts of a developed Egyptian temple were treated as entirely separate units of construction and never bonded into one another, e.g. the Hypostyle Hall masonry abutted on that of the Sanctuary without bonding: the Enclosure Wall abutted on the Pylon. Among other advantages, this sytem of building temples of complex design as independent units of construction facilitated the use of earth ramps and fills. It afforded the most unrestricted access for external ramps (i.e. the possibility of approach from any side), also it economised very greatly on the constructional earth work. The earth ramps and fills required for building the Sanctuary could be basketed away and transferred to the construction of the Hypostyle Hall. Those used in the construction of the Pylon were transferred to the Enclosure Wall and the Court colonnades.

To this appreciation of constructional earth works as the basic installation on a Pharaonic building site recent observations have added possible new light. These observations were made in connection with pyramid building, but nothing gainsays their general application. The situation stands that earth ramps were used in Egyptian construction, but it is often difficult to locate space for them on a construction site because of their gentle gradient. This is assessed as ca 1 in 8 to 1 in 10, i.e. to gain 20 m in height requires a run of ca 200 m, which seems often prohibitive. Now if it can be shown that a much steeper gradient (and thus a much shorter run) is practical for construction ramps, this provides a solution to a besetting difficulty. The accepted practical gradient for haulage ramps devolves from the work against both gravity and friction required to drag a heavy block of masonry over a normal surface. The work against gravity increases directly with the ramps angle of inclination to the horizontal and soon becomes so great in conjunction with work against friction that it is impractical to harness up sufficient men for

"Rockers," or "rollers"

its input. However if instead of dragging a larger flat block up an inclined plane a cylinder is rolled up the inclined plane, then the work against friction is greatly reduced and the haulage team required becomes manageable. The problem then is to transform for the purpose of the exercise an orthogonal block of stone into the semblance of a cylinder.

This measure has been proposed as a possible feature of Neolithic engineering (H. Simpson, *Civil Engineering,* 144, 14); while all readers of Vitruvius (X.10) recognise in it the brain wave of Metagenes for transporting the heavy architrave blocks of the Temple of Artemis at Ephesos from the quarry to the site. Recently the engineer R. Parry has proposed that there is strong evidence for this practice in Pharaonic Egyptian building, if certain material evidence is rightly interpreted. This evidence is in the form of wooden objects for use in building termed "rockers" which have been widely (but errantly) discussed. They consist of two curved sides fixed together by cross pieces so that they resemble cradles, and when set down on their curved sides they are easily rocked backwards and forwards like cradles. Models of these devices together with models of other masons' tools and equipment were discovered as foundation deposits from Hatshepsut's temple at Deir el Bahri, and Petrie proclaimed that they were used to raise up blocks ca a course or so of masonry more conveniently than by repeated levering and chocking. As the cradle was rocked to one side a wedge was inserted beneath it on the other side and so on alternatively until the "rocker" with its burden was set up to the required height (Petrie). Although this idea was taken up enthousiastically by Choisy, it is quite insubstantial. It is inconvenient, disadvantageous and dangerous (cf R. Parry, pp. 102–03). This was recognised by Clarke and Engelbach who tried to validate the device as an aid in dressing Pharaonic masonry (pp. 94–95, 102–03)—but again with little cogency. Latterly these "rockers" have dropped out of discussion. However it is clear that they existed in Antiquity and were designed for use in building.

Parry restored them to notice by seeing in them a completely different significance. They were not "rockers" but "rollers". Parry observed that their form was exactly that of quadruntal segments and thus by affixing one to each side of a block of masonry a complete wheel was framed around the block; and by providing such a wheel at each end of the block it would become possible to roll the block along and up a plane surface freely, instead of dragging it over the surface, working against the resistance due to fricition (R. Parry, *Engineering the Pyramids*, chap. 10).

There are serious drawbacks to this proposal—the great supply of hard wood required; the demanding joinery together with the expenditure of time to fit the contrivances on to the stone blocks. Here it must be noted that quarried blocks are not always of the same size and form, indeed they are rarely square in cross section. Thus to assemble this quadrantal sector into wheels would involve adjustments to

Use of sand

the size and form of the block by way of timber packing pieces. All in all, the device seems appropriate to special (outsize) instances rather than to standard procedure (exactly as Vitruvius reports its use by Chersiphron at Ephesos). Nonetheless the scheme both rationalises the use of the contrivances and also rescues (in principle) the use of ramps from strong negative criticism by more than halving their required length (i.e. by increasing their practical gradient from ca 1 in 10 to ca 1 in 4).

Before leaving the subject of earthworks mention may be made of a kindred subject—the use of sand as a device for transmitting power (in the vertical sense). This operates after the nature of hydraulics. Sand, like liquids (e.g. oil, water) is incompressible and transmits pressure in all directions. Thus to lower a heavy burden (e.g. a sarcophagus or sarcophagus lid!) it is possible to arrange this (with security) down a vertical shaft by filling the shaft with sand. At the bottom of the shaft some escape hatch is provided which can be closed and opened. The sarcophagus or the like is then brought into position on top of the sand filling, exactly above its desired position at the bottom of the shaft. The escape hatch is opened and the sand filling made to escape under control so that the level of the sand filling in the shaft slowly descends bearing with it the heavy stone item. Examples of this procedure can be recognised from the Middle Kingdom onwards in a funerary context (v Arnold, pp. 74–79; figs 3.26, 3.27). An unexpected interest attaches to this device since it is reported to have been used by Chersiphron the architect of the original Temple of Artemis at Ephesos for setting down into place massive architraves too leavy to lift. Whereas this notable emergency procedure was preserved in tradition and related by Pliny (NH 36, 95.9) 500 years later as a brilliant improvisation, it obviously devolved from Chersiphron's aquaintance with Egyptian building practice. Theoretically the reverse procedure is possible. A heavy block can be raised up a vertical shaft by continually ramming sand beneath it. No examples of this practice have been identified in Egyptian stone masonry, but it has been reported as a traditional device known to modern Egyptian villagers (i.e. to raise up heavy objects which have fallen into pits).

Were massive Egyptian temples erected with no other installations than earthworks to raise blocks and expert levering to set them in place? It is a striking conclusion. Did Ancient Egyptian builders possess no device for lifting up a weighty block of masonry from above?

It has long been asserted that Pharaonic masonry was not lifted by the use of block and tackle (Clarke & Engelbach, chap. VIII). This appraisal is based on two lines of evidence—both negative. No indication of attachments to lifting devices are to be seen on blocks, and no material remains of hoisting machinery (cranes, pulleys) have been identified. It is possible to impugn this evidence. Attachments to masonry can be made by slings which leave no indication on the masonry of their use. Also some wooden pulley wheels have been discovered (v Arnold, p. 71, figs 3.16–3.18). However these latter are simple and relatively fragile, they are nothing akin to the compound sheaves of strong metal required for hoisting heavy loads.

Clean lifting, the shadouf

On the other hand close study of Egyptian masonry suggests that on occasion a device for hoisting blocks from above would have been advantageous. When masonry courses are continuous and horizontal, blocks can be levered along them into place. However it is one of the characteristics of Pharaonic masonry (particularly in earlier times) that its coursing is not always regular and continuous—it is sometimes stepped or indented (cf Arnold, p. 155, figs 4.82, 4.83). Here, whatever the procedure for dressing the blocks, their setting requires them to be lowered into place. If they are weighty then this is a problem (which has never received close attention). It is possible that such blocks could be settled down into position by manoevering with levers (Clarke & Engelbach, pp. 107–111), but obviously some device which operates from above is much preferable.

No evidence survives of such a procedure used in any connection whatsoever, thus any proposal is conjectural. The device closest to the known is the balanced see-saw beam: a stout arm raised up on a pivot bearing. The load is attached to one end and at the other end there are ropes for pulling that end down, and so
73 raising the load. This is simply an overhead lever, and the length of the respective arms can be adjusted to give a mechanical advantage. This device is often referred to as a "shadouf", but this is inexact. The shadouf was known (and depicted) in Ancient Egypt (v Arnold, p. 71, fig 3.15) as a device for raising water from irrigation channels; and has survived as such all through the ages. However, properly
72 speaking, the shadouf incorporated a counterweight as the hoisting force, and can be operated by a single man drawing down the attachment arm and then allowing the counterweight to raise up the load.

Given that the Ancient Egyptians used the shadouf for irrigation, it is difficult to think that they did not make use of the kindred "overhead lever" in building. However the fact remains that there are representations of the one but not of the other. It is regrettable that whereas the social-realism genre of Egyptian rural decoration includes scenes of dressing stone masonry, there are no informative representations of setting masonry!

It is now necessary to say something about construction site procedure and installations for building pyramids, if for no other reason than that quantitatively pyramid building accounts for a considerable amount of Egyptian building construction. This is a subject which has caught public attention, and accordingly an enormous and controversial literature has accumulated concerning it (v P. Hodges, *How the Pyramids were Built*, for general engineering background). Within the limits of the present study it is only possible to indicate the bare parameters of this discussion and dispute.

Pyramid construction Perhaps initially some notice should be given of the disposition of the "enormous and controversial literature" presently existing (omitting reference to popular sensation and novelties). Broadly speaking the literature is expressed *via* three different vehicles:

(1) Within general manuals of Egyptian building, e.g. the works of Arnold, Clarke and Engelbach, Petrie, Choisy
(2) In comprehensive treaties devoted to pyramids e.g. those of Lehner, Stadelmann, Edwards, Lauer.
(3) In articles on specific topics, e.g. form, logistics, haulage ramps, stepped approaches, possible lifting devices etc.

The present notice of pyramid building is restricted to construction site development and installations. It is therefore useful as a preliminary to recall the two functions of building site installations:

(a) to provide for the delivery of the building units to the required position for incorporation into the structure.
(b) To provide access for the builders to a working platform for carrying out the necessary building operations.

It is possible that the same installations can serve both purposes, but this is by no means the rule nor even common. Installations affording workers' access are generally of too light a construction for delivering heavy masonry; while installations designed to deliver heavy units of masonry do not necessarily range along the entire wall face under construction, but deliver the material to chosen points only. When the units of material to be set are sufficiently light and portable that they can be freely moved and carried about by one or two men then the whole issue of pyramid construction is simplified and is not discused here (e.g. brick pyramid building).

It is possible to begin remarks with a fact of building construction which has been rarely observed, but which goes to the heart of the issue.

If the aim is to erect a commanding and conspicuous monument dominating the surroundings, then the form easiest to construct is a pyramid.... *But* specifically 69 a stepped pyramid. On the other hand if it is required that this pyramid should be a true pyramid, with faces constituted by plane triangles, then not only is this statement negated but, in effect, it is reversed. A true pyramid is one of the most 70, 71 difficult forms to build. This antithesis is apparent. It is possible to lever quite massive blocks up the faces of steps of restricted height (e.g. 50 cms–60 cms). Thus if a stepped pyramid is formed with steps (courses) where the rise is of this height

Stepped & true pyramids

and the treads sufficiently extended to afford convenient working space, then a pyramid of any height can be erected out of massive blocks without any installations other than the previously erected structure itself. On the other hand if the faces of the pyramid are to be plane and inclined at an angle to the horizontal of ca 50°, then:

(a) blocks can not be levered up into position.
(b) They can not be lifted into position vertically—unless the lift can be made to transfer them horizontally over a distance of roughly the same order as the height they have been lifted (cf F. Abitz, "Shrägaufzug," *ZAS* 119, 1992, pp. 61–82).

Thus they can be raised only by providing external ramps for hauling or steps for levering, both of which involve massive constructions in themselves.

Here it is also to be noted that the antithesis goes not only to the construction but also to the setting out and controlling of the exactitude of the structure erected (cf P. Hodges, *How the Pyramids were Built*, Chap. 5, Setting out).

To set out the plan of a stepped pyramid all that is necessary is to mark out on the ground the lines of a square somewhat larger than that of the designed plan and to put down control points on these lines indicating the alignment of the sides of the base of the pyramid. Thereafter the lines of the successive steps are obtained by direct measurement inwards from the sides of the preceeding step. Equally simply, the elevation is determined by first building the base as a level platform and then directly measuring upwards from the previous level the rise of each subsequent step.

The setting out and control of a true pyramid, however, is a very different matter. The base plan is obtained as described above but controlling the correct construction in elevation is in no way simple.

Local checks on the plane surface of the sides can be effected by applying a straight edge and checks on the correct angle of inclination by applying an appropriate triangle equipped with a plumb bob. However the overall exactitude of the massive structure in elevation is revealed immediately to the eye only at the arrises, the intersections of the four faces. These form four lines inclined upwards and inwards from the base angles to the apex or summit of the pyramid, i.e. they lie on the vertical planes of the diagonals. If these lines deviate in any way, this will be apparent to view (whereas e.g. divergence from a plane surface in the sides of a pyramid is not immediately visible to the naked eye. Thus to control the exactitude of construction of a pyramid some device must be available to check on the rectilinearity of the arrises.

In modern times this would be effected by producing the diagonals of the pyramid and setting up 4 theodolites, one at each extremity of the produced diagonals;

Endemic questions

adjusting the theodolites to the vertical and then sighting back on the arrises. Each arris as it rises must remain a straight line coincident with the vertical datum of the diaphram. In ancient times this check would be made by setting up one or more tall stakes (ranging rods) on the lines of the produced diagonals, ensuring 45, 46 their verticality, and sighting on the arris to see that it conformed to the vertical plane so established. NB It is the frustration of this procedure which renders suspect the use of winding construction ramps which cloak the arrises so that their 65 rectilinearity is not subject to constant visual checks.

Perhaps mention should be made here of an entirely different way proposed for controlling the correct elevation of a pyramid (v A. Bedawy, "The Periodic System of Building a Pyramid"). This is a method suggested for controlling the correct batter of external wall faces in normal building construction. It is to erect at the angles of the structure short sections of walling which meet so as to constitute 47 token upstanding angles, and to mark on their inner faces the true vertical profile of the battered wall as targets for sighting. This, however, does not appear a practical procedure for upstanding building and its application is probably restricted to underground construction (cf *infra*, pp. 150–151).

Some indication is now offered of how these difficulties in construction of true pyramids worked themselves out in practice.

There are several questions which always arise in discussions of pyramid building. They are, of course, interdependent; but it is useful to enumerate them separately so that each may be recognised and kept in consideration.

(1) Installations. The more immediate questions affecting pyramid site installation are those concerning the delivery of the building units, the method of raising them up to the requisite postions for setting
    (a) hauling up ramps
    (b) levering up steps
    (c) vertical lifting by some machine.
(2) Structure. However behind these question (what gives rise to them) is the structure of a pyramid, with its salient division into core and casing. This structural division gives rise to a distinction in modes of construction with, in turn, the installations required for the several modes of construction. And here it will be found that the critical issues centre on the construction of the casing (v P. Hodges, chap. 9 Casing):
    (a) Whether the casing blocks were installed *pari-passu* with the core blocks, or subsequent to the completion of the core blocks.
    (b) The state of the casing blocks at setting—i.e. whether the faces have received their final dressing, prior to setting; or whether the faces are not dresssed (quarry faced); or whether they are partly dressed.

(c) The operation of setting the casing block—i.e. whether these blocks were set working from outside the face of the structure (as is normal), or whether the blocks were set working from inside the face of the structure (underhand setting).

Core and casing

These individual issues are to be kept in mind in the following summary outline of the difficulties in building true pyramids.

Without doubt the most straight forward way to build a pyramid is to build it in a uniform operation, as a single whole from base to summit—i.e. to set the core material and the facing material *pari passu*. This procedure (as noted) is possible and requires minimal site installations when the form of the monument is a stepped pyramid, since it uses the mounting structure of the pyramid for both delivery of the materials and for access by the builders. However when the designed form of the pyramid is with continuous not stepped faces this is no longer possible since the rising structure can no longer be used for delivery of materials. Thence arises a basic conflict!

Either it is accepted to divorce the construction of the casing from that of the core, which procedure may result in considerable difficulty accrueing in the subsequent (separate) construction of the casing; or, if the casing is constructed *pari passu* with the core then the building programme expands greatly since special (external) installations appear to be necessary (*viz* ramps, steps, etc.) for carrying out the project.

First considering the former alternative. It is possible by suitable adjustment of the stepped structure to build the entire core of the pyramid without massive installations, by levering blocks up the faces of the successive steps. This is a consumation devoutly to be wished for. However such a building programme then leaves difficulties in applying the casing material to the standing core.

Here again there are two approaches. It may be just possible to set the casing blocks by levering them up the exposed stepped faces of the standing core construction. However if this procedure is adopted it enjoins that the casing blocks are set quarry faced and thus their faces must be dressed *in situ* to the required continuous bevel (e.g. ~ 52° to the horizontal). This in turn means that some form of scaffolding or other working platform must be installed over the entire face of the pyramid to permit the *in situ* dressing. On the other hand if the casing blocks are to be set finely dressed, incorporating the bevel, then they cannot be levered up since there is no stepped face for them to be levered.

[To this statement there is a hypothetical qualification. The casing blocks might be set with faces finely dressed by being worked up the steps of the core masonry *if* they could be set from the top downwards. This, in fact, is what Herodotos says (II.125) the guides told him was the procedure "The upper portion of the

Limitations of external ramps

pyramid was finished first, then the middle, and finally the part which was the lowest and nearest the ground". This statement is now generally interpreted as referring to "finishing" in the sense of *in situ* dressing of the casing blocks, where the mode specified would be standard procedure. Nonetheless the appositeness of the statement to the problem of setting (not dressing) is such that the (im)possibility of setting blocks from above downwards has received, on occasion serious consideration.]

Now to consider the alternative approach to building a pyramid, *viz* to raise it up as a single unit, core and casing together. In this instance it is obvious that installations are required for carrying on the building operations. Whereas it may be possible to work casing blocks up the faces of the stepped core blocks, it is clearly impossible to work all the building material, core and casing blocks alike, up the narrow steps provided by previously set quarry faced casing blocks. Thus installations are necessary to provide for setting the material even though the casing blocks are set quarry faced; and in this latter instance, installations are also required for the subsequent *in situ* dressing of the casing blocks. Given that the construction of a pyramid necessitated installations of some sort to raise up the building units, it was assumed that the installations were those attested for the construction of normal buildings, *viz* haulage ramps, supplemented to a greater or less degree by steps to facilitate levering. It was also assumed originally that these installations were installed outside and abutting on the face of the pyramid since this was the manner for normal buildings.

In these circumstances much thought was devoted to the nature of ramps, 65 which would serve to raise up blocks in the final instance to almost 150 m. Such ramps moreover had to be lengthened (and strengthened) as they were continually increased in height (cf D. Arnold, *Building in Egypt*, pp. 98–108).

Initially a direct approach type of ramp was accepted (W.M.F. Petrie, "The 66 Building of a Pyramid"; J.-P. Lauer, "Le Problème de la Construction de la Grande Pyramide"). However continued analysis showed this device to be utterly impractical. To achieve a height approximately 150 m such a ramp would come to have the cross section of a pyramid face and a length of a kilometre to a mile. Thus its 67, 68 mass would be greater than that of the pyramid itself. Its operation would also become disastrously uneconomic as it increased in height. This arises from the solid geometry of a pyramid (H.R. Butler, *Egyptian Pyramid Geometry*). The mass contained in a horizontal layer of a pyramid diminishes from base to summit so that the great proportion of the volume of a pyramid is contained in the lowest portion of its height—e.g. half the volume is contained in the lowest 1/5th of the height, and two thirds of the volume is contained in the lowest 1/3rd of the height, while the upper half of the pyramid height contains only 1/5th of the volume, the uppermost 1/3rd of the height contains only 1/20th of the volume and the upper-

Types of external ramps

most 1/5th of the height 1/200th of the volume. In this fashion there soon comes a height beyond which it requires much more material to increase the height of the ramp than is to be delivered into the structure of the pyramid—a situation of progressive diminishing returns.

Finally at the completion of the work there remains the heavy task of demolition and disposal of the ramp material.

In the face of these disadvantages of construction it is interesting to note the functional limitations of such a ramp. It would provide for the delivery of both core and facing blocks. It would not necessarily provide a working platform for the setting of the casing blocks on one face of the pyramid, and would not provide a working platform for the setting of the casing blocks on the other three sides. All told it would be more convenient to set the casing blocks from inside the structure (M.T. Lally, "Engineering a Pyramid"). And in this connection it may be easier to contrive a working space inside the structure if both casing and core blocks were set in the same operation. If the casing blocks were set fair faced, then the pyramid construction would be complete. If not, to dress them *in situ* required an external working platform. This may have been arranged in conjunction with dismantling the ramp, but for one face only, leaving some external working platform to be contrived for the whole expanse of the other three faces of the pyramid.

The uneconomic nature of such a direct approach ramp turned attention to devising other types of ramp reduced in mass and affording greater advantages in setting and finishing the masonry.

In brief the most likely design considered is the winding ramp, i.e. a ramp set
65.C2 against the faces of the pyramid, thus changing direction through 90° at each angle of the pyramid, i.e. at a "quarter landing" (Dows Dunhan, "Building an Egyptian Pyramid"). Such a ramp would deliver the building units to the height required. It might also be arranged to provide an external working platform for setting the casing blocks, and perhaps for the *in situ* dressing of the casing blocks if they were set quarry faced. There are problems with its construction and functioning, but over and above this it is subject to the flaw that it totally conceals the erected structure from view and thus there is no possibility in discerning any building error until the whole edifice has been completed. The upshot of these considerations has been that external ramps are no longer favoured as installations for building pyramids (cf, e.g. P. Hodges, Chap. 2).

The proximate alternative installation to external ramps are external steps to permit repeated levering of blocks up succeeding stages on to a higher step each involving a rise of ca 50+ centimetres. The pitch of such steps is much steeper than the gradient of a haulage ramp (e.g. ca 1 in 4 as opposed to ca 1 in 10), and thus
70, 71 this construction is reduced in scale (M. Isler, "On Pyramid Building"). Nonetheless to build a flight of steps in stable stone masonry ascending to a height of ca 150 m

Internal ramps & steps

against each face of a pyramid is anything but a trivial matter, and would add a considerable item to the construction program. Again such steps would deliver the building units but would supply no external working platforms for setting masonry or for *in situ* dressing of masonry.

In the light of the apparent disadvantages and inadequacies of traditional external installations for pyramid building, more recently speculation has taken another turn: to suggest the provision of necessary installations inside the structure of the pyramid itself (D. Arnold, *Building in Egypt*, p. 101). Both ramp and steps can be contrived within the rising masonry of the pyramid. Here it is advisable to call attention to inadequacies of language. It is a matter of linguistic course to speak of an internal ramp as opposed to an external ramp, but this apposition refers to the location only. It does not import any parallel in construction of the external and of the internal ramp. In this respect the two entities have nothing in common, they are not two species of the same genus. An external ramp is an additional structure requiring additional building material for its fabrication. An internal ramp contrived within a pyramid is a mere passageway recessed within the structure of the pyramid. It requires no extra building material. Rather it subtracts from the total amount of building material required for the project—it does not add to it.

Obviously ramped and stepped passageways can be contrived within a ground mass of masonry in any position and of all dispositions—straight, angled, winding. 65.B2
The most effective disposition for the basic installation for building a pyramid would seem to be a winding ramp parallel to and set somewhat inside the faces of the pyramid so that the core blocks can be delivered on the interior side of the passage way and the casing blocks delivered and set on the exterior side of the passage way. A construction gap is left at ground level for the entrance of building material to the passage way until completion of the building programme. Ideally the casing bricks are set from the inside and fair faced. For an internal ramp so disposed there is some evidence. Tests conducted in 1986 by Japanese physicists on the fabric of the Great Pyramid revealed anomolies close inside the faces. Although not accounted for at the time they were identified subsequently as exactly conforming to an ideal concept of a winding ramp (Brier, Archaeology, May–June 2007, p. 27). 73

In this way, in principle, the circumstances of the construction have been returned to that of a stepped pyramid—i.e. the entire construction can be effected without any additional installations. Variant procedures, of course, will be adopted for special items, e.g. extremely massive blocks. These are introduced into the interior of the pyramid at the lowest possible level and are simply levered up vertically from one course to the next as the core masonry rises.

The foregoing discussion of installations and equipment for pyramid building in massive stone masonry has been limited to installations and equipment attested as used for Egyptian massive stone building in general. It may be possible to question

Report by Herodotos

this approach on the grounds that such pyramid building involved special problems and hence special procedures. Certainly installations have been suggested for pyramid building, which no one has proposed were used in the construction of normal buildings, e.g. hydraulic installations. Often these suggestions were expressed far removed from Egyptological scholarship. However there is one connection where special installations for pyramid building emerge from within Egyptology. This connection is the passage in Herodotos (II.125) recording what the guides told him about the mode of construction of pyramids. Since these accounts were two thousand years *ex post facto*, they are not necessarily of any circumstantiality. The point is simply that they refer specifically to pyramid building. Nowhere does Herodotos (or any other ancient author) refer to the mode of constructing normal buildings, e.g. temples, in Ancient Egypt. Accordingly some modern investigators have attempted to interpret Herodotos' remarks without feeling bound to justify their interpretations as of general use in Ancient Egyptian monumental building construction (and thus based on the study of Ancient Egyptian building).

These modern interpretations proceed on the assumption that the guides' remarks indicate that the pyramids were built using the previously erected (stepped) structure to facilitate the continuing process of construction. Also they assert that the guides' remarks indicate some form of clean lifting of blocks was employed. As for the first of these assumptions it is a common place; as for the second it is by no means a necessary assumption. The guides told Herodotos that the blocks were raised up from one (previously erected) step in the construction to the next higher step by using a device consisting of short pieces of wood. It is quite possible to see these terms as referring to the process of levering—either denoting the levers themselves or, more probably, wooden baulks assembled as chocs to prop up the blocks at each lift. Supposing that Herodotos' remarks indeed refer to devices for clean lifting, two recent proposals for such "machines" are: O.M. Riedel, *Die Maschinen des Herodot*, Vienna, 1980, and F. Abitz, "Der Bau der Grossen Pyramide" *ZAS* 119, 1992, pp. 61–82. The former depends on capstans. The latter is a contrivance with a counterweight mounted on a frame providing for both horizontal and vertical motion, i.e. it provides for lifting into position blocks with sharply bevelled faces. It may be possible to build pyramids with these machines, but there is no corroberative evidence for their existence in antiquity.

The upshot of these general remarks may be summarised as follows. Obviously the *modus operandi* of any significant activity evolves in the interest of economy (of time and material). It would appear that to construct a true pyramid in massive stone masonry the utmost economy is effected by arranging the delivery of material and the working platforms inside the structure, so that no additional material and time is required by way of building installations and eventually disposing of them. If the work of construction is carried on from outside the pyramid structure then it seems unavoidable that such installations must be provided. However it is to be noted that P. Hodges, an experienced master builder, maintained that it was possible to construct a true pyramid working from outside the structure by using the stepped faces of the rising masonry for all constructional operations (*How the Pyramids were Built*).

7. *Cyclopean Building Construction*

Massive rubble construction

This type of construction is little employed for buildings proper, being very largely employed for enceinte walls (which by strict definition are not buildings). The construction procedures for Cyclopean masonry hitherto have been given scant consideration. Thus some notice is taken of the matter here.

Latterly Cyclopean masonry has been defined in various ways so as to restrict its application in the interest of archaeological enquiry (N. Claire Loader, *Cyclopean Masonry*). However for it to serve as a useful concept in a general study of ancient building construction it is better to give Cyclopean masonry the broadest definition so that it may stand in apposition to Megalithic Masonry, Pharaonic Egyptian Masonry, Classical Ashlar Masonry etc. In this sense Cyclopean Construction can be taken as any building with unhewn (or on occasion, crudely trimmed) stones, 173, 174 some of which are very large, i.e. in the nature of massive boulders. A model dimension might be something over a metre in length and something under a metre in thickness and height, i.e. of a volume ca 2/3 m3 and a burden of 1 ½ tons. Such massive boulders were used together with smaller stones to provide secure bedding and to chink up gaps in the fabric. In addition to smaller stones (calcareous) earth could be used to provide better bedding and to chink up gaps, but such filling is not to be regarded as cementitious mortar. The stability of Cyclopean masonry obtains from dead weight.

Cyclopean construction is, in effect, rubble building on a massive scale, i.e. the stone units employed are greatly magnified—on occasion a hundredfold. It was this picture which prompted the Classical Greek to give it its name, i.e. it was like the common rubble masonry of mankind, but as though titanic builders had been at work on it. This, in fact, was a fitting way of accounting for the procedure involved, but is scientifically inacceptable. How then were these massive irregular units of stone raised up and set in place? Good question, as yet substantially unanswered. Perhaps some historical outline of the construction may give an initial lead.

The earliest occurrence of construction of this nature was an idiosyncratic one—the strange case of the Round Tower by the settlement wall at Early Neolithic Jericho, ca 8000 BC (v *supra*, pp. 45, 46). This was followed chronologically by passages of Cyclopean construction incorporated in Megalithic building—e.g. parts of the walling of Maltese Temples such as the Gigantia, ca 3,300 BC (J.D. Evans, *Presence of adjacent earth banks*

Malta, Prehistoric Antiquities of the Maltese Islands). However it was during the middle and the latter half of the 2nd millenium BC that this type of construction became a standard in the Eastern Mediterranean and the Levant, notably in (Mycenaean) Greece, Anatolia, Syria and Palestine. Its principal utilisation was for
74–76 fortification walls, but this extended to Gate Houses; and the construction was also
287–289 prominent in the Mycenaean subterranean "tholos" tombs (for Greece v Lawrence Chaps 6, 7; N. Claire Loader, *Building in Cyclopean Masonry, pass*. For the Levant v R. Naumann Architektur Kleinasiens *pass*; G.R.H. Wright, ABSP I, II *pass*).

To repeat, virtually nothing has been said about the methods used to build up massive walls with these massive stones, sometimes of several tons burden. However manifestly such burdens could not be manhandled about into position, and some site developments and installations were required to assemble them. Perhaps the general historical associations, together with some note of the circumstances in various individual instances may suggest the broad lines of procedure involved. Here it must be advertised that differences of composition among Cyclopean walls are not considered here—the consideration only is with the mode of getting into position the heavy units of such construction.

In the first place heavy blocks of stone were assembled after the manner of Cyclopean masonry in conjunction with some megalithic building. It seems obvious that such blocks were handled in the same way as the megalithic elements themselves. The methods of handling were the same but the form of the units and the assemblage were different. In this way heavy blocks of Cyclopean masonry would have been dragged along the ground and up earth inclines into position on the wall face. This process was supplemented or substituted for where necessary by use of baulks of timber as runners. Additionally where some sort of near vertical displacement was demanded (e.g. working blocks up into position on the wall face), this process was effected by levering. With these parameters in mind it is interesting to reflect how often individual instances of Cyclopean masonry
74–76 construction were associated with rising banks of earth. This is obvious in the case
287–289 of the Mycenaean tholos tombs which were built within emplacements hollowed out in the hillside.

Also in a surprising number of varied instances, if examined enquiringly, it will be found that convenient higher ground was adjacent which could have facilitated the erection of Cyclopean blocks. Alternatively it appears that the masonry construction proceeded in conjunction with building up the ground level *pari passu* by fills and embankments. Informative instances of this have been revealed by excavation on tells in the Levant of fortified city gates. The masonry of these features is Cyclopean in nature, but at times more or less shaped by (hammer) dressing. Here what has often been taken as free standing masonry was the mas-
221 sive foundation of the gatehouse designed to withstand sapping. This consisted of heavy masonry containing packed earth fills, both the masonry and the earth

Parbuckling

rising in unison—which provided the installations for constructing the Cyclopean style masonry of these foundations (G.R.H. Wright, "The Monumental City Gate in Palestine and its Foundations," ZA 74, 1984, pp. 365–71).

Considered within the general ambience a constructional device may be suggested as especially relevent to building Cyclopean Walls, because of the conformation of the stone units employed. These were often large compact stones in the nature of boulders. Whether hewn or somewhat regularised by knocking off excrescences they were usually squarish in cross section, often somewhat rounded off at the angles. Such blocks were more adapted than others to being rolled along, rather than dragged along. Rolling involves a dramatic reduction in the coeffiecient of friction, and thus in the amount of work to be done against friction when moving an object. The practical demonstration of this is that for a certain input of power where dragging a load up a ramp requires the ramp to be at a gradient of 1 in 10, the same input of power can roll the load up a ramp with a gradient of 1 in 3.

The process of rolling an object up or down an incline is termed parbuckling (from the arrangement of the ropes to effect the operation). A rope is passed under and back over the object and the lower end of the rope is fixed at the upper level of the operation. The upper end of the rope is then drawn in or paid out so rolling the object up or down the slope. This process has always been standard for delivering kegs and barrels but is practical for any objects with a cross section not too far removed from circular. Without asserting that it explains everything in Cyclopean construction it seems particularly suited to moving heavy blocks of Cyclopean masonry up and down limited distances where, as in modern use, the trackway can be provided by timber beams as runners. This avoids extensive construction in earth or rubble etc. with the necessity for its subsequent removal. Parbuckling has been discussed in connection with Megalithic building construction (R.H.G. Parry, "Megalithic Mechanics," Civil Engineering 138; H. Simpson, "Further Reflections on Megalithic Mechanics," Civil Engineering, 144, 14). And also in connection with Pharaonic Egyptian Civil construction. In the latter instance it specifically addresses the endemic problem of finding space for gentle gradient "long" ramps (P. Hodges, *How the Pyramids were Built*; Dick Parry, *Engineering the Pyramids*).

The mechanics of the construction of Bronze Age Cyclopean masonry has never been investigated to any purpose and deserves a specific study. The question, is, of course, encapsulated in fortification walls: city walls in the Levant, fortress/citadel walls in Mycenaean Greece. Defence is a vital issue and such strong walls had to be built, and built quickly. It is unrealistic to think that walls constructed with stones weighing over a ton to a height of e.g. 15 m and with a run of several kilometres were as a matter of course provided with a surrounding apron at a gentle gradient as a construction installation to be subsequently removed. Individual circumstances must be considered to arrive at a range of possibilities.

It may be that material evidence survives. It is in Palestine where excavation has revealed (and, to some degree, recorded) the stratigraphy of these walls. Very 74 commonly Cyclopean city walls are in places abutted by or sandwiched between layers of earth which are not habitation layers, they are deposits of some other nature. However on various accounts controversy has arisen concerning this nature. The deposits may be both horizontal and rampant. Are they civil or military engineering?—are they to augment the obstacle or slight it?. . . . Or could they be in some cases surviving evidence of installation for building the walls? (cf Shechem III, pp. 105–07; Ills 10, 59, 68).

8. *Greek Ashlar Building*

Rapid development in new social environment

Monumental building in ashlar stone masonry began in Greece at the end of the 7th century BC and developed rapidly to take its definitive form during the 6th century BC. Its development was thus coaeval with the most significant innovation in building construction since the Neolithic origins of solid enduring building—devices for clean lifting and lowering into position weighty units (notably finely dressed stone blocks). The development of Greek ashlar stone building was also exactly coaeval with the development in the region of a monetary economy, together with a truly individualist, literate society. These factors conditioned the nature of Greek building sites.

Monumental building procedure in contemporary Mesopotamia and in Egypt was essentially unchanged from its age old origins. Monumental ashlar building procedure in 6th century BC Greece was like no previous building procedure, it was an entirely new manner. Whereas a Pharaonic Egyptian building site depended for its functioning on masterly overall direction and organisation of "gang workers", Greek building sites were based on the conjoint activities of highly competent individual craftsmen, each personally responsible for their tasks and working on their own personal account for their own personal profit. There could have been no greater contrast than that between the installations and organisation of a monumental building site in Saite Egypt and a contemporary monumental building site in Greece, in spite of the fact that the inspiration for Greek ashlar building owed much to Egyptian example.

Note of the social and economic factors mentioned above will be taken in the succeeding volume. Here the concern is with the technical aspects of this new manner of building site organisation.

Clean lifting Installations for clean lifting building units to any designed position were the formative factor of Classical Greek building site development;* and a considerable amount of information relating to them has come down from antiquity (for a compendium v Orlandos II, pp. 31–44). It may be classified as follows:

(1) Material remains of such devices. This is very slight and is limited to several pulley blocks (cf Hesperia, 38, 1967, p. 590, fig 1, pl 76). 82, 83

(2) Indirect material evidence for the use of lifting devices by way of cuttings and protruberances on blocks of masonry designed to facilitate the attachment of blocks to the lifting mechanism. Such evidence is endemic in classical ashlar masonry from the later 6th century BC onwards. Be it noted however that the absence of such cuttings etc. on blocks is not conclusive evidence that lifting devices were not employed in their handling. Attachments can always be made by slings and tieing with ropes (cf Martin, pp. 209–19). 95, 93

(3) Ancient representations of lifting devices. A certain number of reliefs and one or two mural paintings, all of Roman date, depict various forms of lifting devices (cf Orlandos II, figs 21–26). 84, 88, 89

(4) Ancient written records. A surprising amount of literary and epigraphic reference to lifting devices exists. Its main divisions are as follows:
    a) References in Greek building contracts and other building inscriptions (v Martin, p. 202).
    b) Expositions in Hellenistic treatises on mechanics preserved in Arabic translation (Hero of Alexandria, ed. Nix Schmidt, Leipzig, 1900).
    c) Discussion in Roman building manuals (Vitruvius X.II).

It might be thought that with such documentation available the functioning of clean lifting devices on Classical ashlar building sites would be clearly apprehended. However this is absolutely not so—and on two basic counts: their mechanical operation and their exploitation within the site organisation.

A clean lifting device (crane, hoist etc.) comprises two distinct elements: the mechanical contrivance which facilitates the application of vertical traction sufficient to raise up a heavy burden (pulley, sheaves, block and tackle); and the housing, mounting for this mechanical contrivance. It will be seen that both elements, jointly and severally, provided for the functional requirements as listed above. The machinery plus the frame jointly were required to withstand all stresses induced

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* It is an obvious surmise that the application of block and tackle to Greek building operations had its background in ships and shipping, since the sea was characteristic of Greek life. The backstays and the halyards to the masthead is a paradigm of the crane in antiquity. Furthermore, all substantial cargo ships required derricks for loading and unloading cargo. However the transition from ships to building sites was not a matter of course. Both the Egyptians and the Phoenecians sailed well rigged ships, but there is no evidence that they likewise developed clean lifting devices for building construction.

The pulley

by the suspended load. These stresses were in the nature of shear, bending or
tension and in general were induced by loads of upwards of one or two tons. The
80 force required to raise up this burden was transmitted by a wheel or wheels with
grooved rim so that a rope for hauling passed around them rotates them on an
axle. This was the pulley or pulley wheel proper (misleadingly the name has no
etymological connection with the English word "pull"). The pulley wheel transforms
the direction of any force applied to the rope—i.e. if the rope were hauled
downwards then the other end of the rope was drawn upwards; if the rope were
allowed to move upwards, the other end of the rope moved downwards. Used as
80 a simple wheel the device gives no mechanical advantage, but confers the great
convenience of permitting a load attached to the other end of the rope to be raised
up by a downhaul (which can be applied more strongly and convincingly than
drawing a rope upwards).

More significantly a series of such wheels can be arranged so that a rope is
80, 81 passed around them all in succession before being attached to the load. Hauling
the rope's end downwards then entails that the same number of ropes as there are
pulley wheels in the system operate conjointly to raise up the load. This has the
result that the system affords a mechanical advantage equal to the number of ropes
acting together to raise up the load. Two or three wheels can be set side by side in
81, 84 a (preferably metal) casing to form a "block", and two blocks can be arranged one
above the other so that a mechanical advantage of e.g. 5 can be obtained for the
force applied. (This means, of course, that the force must move the ropes through
5 times the distance that the load is raised.)

It is possible to apply the input force to the pulley device simply by hauling
down on the rope by hand. However in general clean lifting devices incorporate a
contrivance to render the application of the force more convenient and effective:
85–90 thus a windlass, capstan, treadmill or, indeed, a combination of them. In this way
loads of considerable burden were raised by block and tackle.

That these mechanics were fully understood in antiquity is attested by the treatise of Hero of Alexandria, *Mech. Fragmenta* (ca 250 BC). From this period onward it was customary to designate such lifting devices according to the number of pulleys they incorporated using the Greek verb πάω (= to draw tight, to pull on a cord); thus τρίσπαστος, πεντάσπαστος, πολύσπαστος) (Orlandos II, pp. 39–40, Martin, p. 206). Hence so far as the general issue is concerned, it is evident that adequate machinery to hoist and lower blocks was available on ashlar building sites. However when detailed functional requirements of lifting devices are considered the matter is very different.

To hoist a finely dressed masonry block clear of the ground and then to deliver it into position in fine stone masonry under construction requires that the lifting device incorporates the possibility of delicate motion and instant braking. Without these facilities it is as likely to be an instrument of damage and destruction

Delicate motion & braking

as much as one of construction—damage to the block, to the previously erected masonry, and to the masons. To receive masonry blocks high up on the wall face or by a column when the block can not be lowered centimetre by centimetre in the final instance is a nightmare. So fundamental is instantaneous braking that in most modern lifting devices this is inbuilt—i.e. the device is braked automatically except when it is being operated in one sense or another. Also, although not essential, it is a valuable economy that a lifting device can be operated to give both a normal rate of motion and delicate motion—without delicate motion it is dangerous, without normal motion it is time consuming. Yet in all the subsisting evidence of ancient lifting devices there is no reference to how delicate motion and instant braking was incorporated.

Because of the dire alternative efforts are made to see indications of these functions in ancient representations. There are two bare possibilities manifested in Roman depictions. Where the lifting device is powered via a windlass (winch) some Roman reliefs show a workman hanging onto a wooden staff in the proximity of the windlass drum (Orlandos II, p. 41, fig 22). It might be thought that he is in train of using it as a brake by jamming the drum to prevent it from rotating. However all comments agree that the staff is simply the handspike used to turn 88 the drum. There is also a very commonly illustrated relief of a well appointed crane powered by a treadmill (Orlandos II, p. 43, fig 26). The scene shows the construction of the funerary monument of the Haterii at Rome, ca 100 AD. Below the treadmill with its complement of "treaders" two workmen are shown hauling on ropes attached to the wheel. Again it might be thought that this represented some means of arresting the turning wheel. However, on the contrary, it probably indicates a "starter" mechanism rather than a stopper—i.e. a contrivance to set the 90 wheel into motion for the treaders to work.

If no indication can be found of the incorporation of delicate motion or braking in the machinery of ancient lifting devices, an assessment must be given of the practicality of what is represented. This depends on how the input of power is arranged. If this is simply by direct hand haulage, the machinery is not well adapted for work on ashlar building sites. The situation may be improved somewhat if power is applied through a winch; while if capstans with long bars are provided, 85 the operation of the lifting device might pass muster. If, on the other hand, power is applied via a treadmill, the situation would be horrifying in view of the inertia developed by the turning wheel.

Attention must now pass onto the frame or rig of the lifting device. This must embody the capacity to deliver blocks at the required height and into a location or locations removed horizontally from their pick up point.

Here also a similar picture obtains as with the mechanics. Information is provided in ancient sources, but it does not cover important functional issues. Hero of

Pulley rigs

Alexandra in his treatise on lifting devices classifies them also in accordance with their rig, using terms already current in the Greek building accounts and contracts. These terms specify the number of legs on which the device stands, thus a one legger, two legger, three legger or four legger. The Greek terms are *monokōlos, dikōlos, trikōlos, tetrakōlos* (κῶλον = limb, leg, member).

These four different types of rig are noted and described by Hero in purely formal terms. Because of their transmission through Arabic MSS they have come into modern knowledge in the same formal guise. Summary accounts of them are given in both Martin (pp. 202–05) and Orlandos (II, pp. 36–38), accompanied in both instances by drawings. These drawings are of little account since they are simply diagrams devised in modern times to depict the text. They are not based on any knowledge of classical archaeology or of building construction and therefore are divorced from any functional analysis. In fact it is possible to recognise essential functional distinctions and significance in Hero's forms from experience in using simple lifting devices.

First of all Hero's four forms can be divided into two groups: those which are rigged with (guy) ropes and those which are not. The former group comprises the *monokōlos* (one legger) and the *dikōlos* (two legger) and the latter the *trikōlos* and the *tetrakōlos*.

The *monokōlos* is familiar as the derrick once set about the masts and samson posts of small cargo ships. They were largely hand operated and eminently practical. The single wooden jib carried a pulley attachment at the peak and it could be inclined or swivelled around horizontally by hand held ropes, so that it could pick up and discharge loads anywhere within its radius. The critical requirement was a swivel joint of some sort at its base. Its operation was facilitated by being moored to a strong upright, but this was not absolutely necessary.

The advantages of mobility inherent in the *monokōlos* are commented on in ancient references to it; but the contrivance which secures this, the swivel joint, is not—and it does not appear in any representation. Presumably it was some sort of shallow stone lined socket let into the ground. The operational virtue of the *monokōlos* was apparent in the nautical derrick of former times. It could pick up modest loads from anywhere and deliver them anywhere within the radius of its jib. It was not intended for raising heavy loads to a considerable height. It may well have been convenient in the construction of tholoi and of small ashlar domes.

88–91 Within the same genre as the *monokōlos* was the *dikōlos*. The difference was that the *kōlon* here was not of a simple pole, but of two legs trussed together forming a stronger jib. The jib could be raised and lowered by ropes (themselves operated by pulleys), thus making possible some horizontal displacement of the load, but only in a single linear sense. In the nature of things the device could not be swivelled

Pulley rigs

about horizontally to permit delivery over an area as with the monokōlos. This could only be arranged by setting the *dikōlos* on a swivel base, of which there is neither mention nor depiction. The *dikōlos* could be constructed more strongly and on a larger scale than the *monokōlos* and would have been suitable for raising up heavy blocks to a considerable height for constructing walls. The blocks could be set down at one point of the wall under construction and levered along the subsisting utter bed joint into the required position. The *dikōlos* would also have been effective in setting columns, including monolithic columns, cf the representation of this on the relief showing the funerary monument of the Haterii.

The *monokōlos* and the *dikōlos* are the ancestors of modern cranes, but the evolution into modern cranes which can pick up heavy loads from anywhere within an extended area and deliver them at great height anywhere else within that area was tardy and uneven. It was in Late Mediaeval and Early Renaissance times that rigs were designed to incorporate lateral displacement of a load over an area, and even to incorporate some mobility (on rails) of the "crane" itself. In this connection notable contributions were made by Brunelleschi and Leonardo. However such lifting devices did not become standard until the Industrial Revolution (cf S. de Pascale, *Leonardo da Vinci, Engineer and Architect*, Montreal), 1987, pp. 163–181; B. Gille, in C. Singer, *A History of Technology*, Vol. 2, pp. 639–661.

The second group of Hero's devices, the *trikōlos* and the *tetrakōlos* differ from the first in that their rigging does not depend on guy ropes for its stability. The wooden structure is stable in itself. The *trikōlos* (tripod) is the simplest construction rising to a height which is inherently stable, and has always been used to mount an object or attachment (e.g. a pulley) at some height above the ground. Three long uprights (legs) are jointed at the summit so that each leg can be moved independently. In this way by lateral adjustment of the feet it is simple to bring the summit exactly over any point on the ground. The limitation of the tripod is that it incorporates no possibility for horizontal displacement of the load raised up. Thus suspended loads can only be displaced to a limited degree by hauling them aside with another rope (or tackle). However here it may be added that once upon a time on Middle East reconstruction sites it was not unknown for experienced operators to "walk" the tripod with its suspended load a short distance. The advantage of the tripod is convient storage and instant erection, together with its strength and stability. On the other hand although its legs can be of considerable length (e.g. 10 m–12 m), its working height when mounted is much reduced (e.g. 5 m). In traditional Middle Eastern restoration work, tripods were used notably for work on smaller columns, e.g. taking them down and setting them up.

The term *tetrakōlos* probably can also bear an extended meaning. In the literal sense it is a parallel to the tripod—a wooden tower of four uprights framed with horizontals at the top and cross braced for stability at the top and on 2 or 3 sides.

Multiple attachments & lateral motion

It thus can be made much stronger than the tripod, but lacks the convenience of the latter—i.e. it must be dismantled after use and rebuilt when required. It can not be stored and transported ready assembled. On the other hand it can be built to any strength or height required.

In this fashion the *tetrakōlos* may well have been used for any heavy scaffolding erected to facilitate the raising up into position of massive burdens, which are
94 generally individual items—columns, piers, lintels, architraves etc. Here, to cut short speculation, common sense averrs that this was the only procedure available to ancient builders for clean lifting to height the astonishing burdens they
92 did. They constructed a forest of the heaviest timber scaffolding on which they mounted many attachments to the load—thus keeping the burden on individual attachment within reasonable limits, say 5 tons. In turn the multiplicity of attachments afforded the means of horizontal displacement of the load, since the pulley blocks were mounted on the scaffolding so that the resultant of their combined forces could bring the load into any required horizontal position. Also, in case of need, an additional separate lifting device could be coupled up to the load, e.g. as is attested for the work at the Didymaion (v Martin, pp. 205–06; Orlandos II, p. 38 n1).

In conclusion may be submitted a résumé of the functional use of these various lifting devices—although this is bare rationalisation.

As a general rule in Greek ashlar masonry building blocks were not delivered by building devices exactly into their required position in the masonry structure. They were set down somewhere nearby on the upper bed joint of the preceeding course of masonry. From this set down point they were levered along the bed joint and then levered exactly into the required position. In connection with this operation took place the arrangements for dowelling the blocks into the lower course of the masonry. This procedure is a matter of significance for the operation of lifting devices, viz they were not as a general rule required to deliver blocks to any and every position within a certain range, thus the capacity for horizontal displacement could be limited to one specific delivery point. There were, however, circumstances which were more demanding. The components of columns as also lintels, archi-
94 traves, etc. were to be delivered exactly in position since it was impossible to lever them about. More exigent were the circumstances of arches, vaults, domes. Here
268, 269, voussoirs were each to be delivered precisely into position—i.e. the horizontal
271, 273, motion incorporated in the lifting device required continual adjustments.
298

When exact (or variable) horizontal displacement was required in conjunction with delivering heavy burdens at considerable height, the possible solution is circumscribed. The only rig to achieve the strength and height is strong scaffolding, but this in itself is immovable. With such a framed structure the horizontal trajectory of the load can be effected in only two ways:

Multiple attachments & lateral motion

(i) By use of a travelling pulley attachment to the rig.
(ii) By use of several pulley attachments either operating from the one scaffolding or coupled to several rigs.

The former was the standard procedure in traditional modern building—the block and tackle travelled along a beam which itself travelled backwards and forwards as a bridge between two lateral runners. This arrangement is to all intents practical only with metal beams—and there is no intimation that anything of this nature was known in antiquity. In effect during antiquity horizontal motion must have been applied to heavy loads at height by using at least 3 pulleys—attachments in conjunction, so that by appropriate traction from each device the load could be guided over the required delivery position.

The upshot of these considerations would seem to be that the *monokōlos* was probably used as a maid of all work for relatively light burdens. It might also have been specially adapted for round building, e.g. tholoi or domes. The *dikōlos* may have been the standard rig employed for wall building where substantial loads were to be handled and could be delivered at the one position. The *trikōlos* was probably the device of convenience for localised work, especially for building smaller columns and piers. Finally the *tetrakōlos*, in its literal sense and a *fortiori* in its extended sense, as strong heavy scaffolding, was certainly the only rig which could handle ponderous burdens (e.g. of 50 tons).

The setting in place of ashlar blocks was not the final operation of monumental ashlar building. There ensued (or was scheduled) a work of great significance not only for the aspect of the building but also for the site management and installations. Indeed it is of relevence in connection with the setting of the masonry.

It may be recalled that wall blocks were not as a rule delivered more or less exactly into their required position on the wall face, but rather all the blocks of a given course were deposited at one point on the wall face, and then were levered along the wall into the required position. Also the command of delicate motion in ancient lifting devices has been questioned. In this light it is of interest to note that while ashlar blocks were finely dressed on the bench prior to setting so far as structure was concerned (i.e. the lower bed joints and the rising joints were finely dressed to ensure hair line jointing and thus solidity of structure), the blocks were set not fair faced but a projecting skin of stone was left on the face of the block to protect it from any damage which might be incurred during the process of setting.

Several different systems were employed to effect this purpose. Generally the face of the block was dressed to the final true plane about the margins only (marginal draughting), and the panel was left roughly dressed in advance of the margins. On the other hand a different system was the reverse of this: the margins of the blocks were protected by a residual roll of stone, while the recessed panel

Evidence in building contracts

of the block was finely dressed to the required true face. Whatever system was adopted, the final fair facing of the masonry was carried out ensemble *in situ* for the whole unit of construction (e.g. the elevation of a wall). So far as the aspect of the finished construction was concerned this *in situ* fair facing (cf French *ravaler*) was a vital matter and is reckoned as a separate item in the Greek building contracts and accounts (cf A. Burford, *The Greek Temple Builders at Epidauros*, NB, pp. 214–15; R.S. Stainer, "The Cost of the Parthenon," JHS 75, 1953, pp. 68–76). This work, of course, required the face of a wall to be completely scaffolded; a substantial item which had to be taken into reckoning.

Here it should be noted that in spite of its vital rôle in the building project, surviving evidence shows that quite often this final *in situ* facing (*ravalement*) of ashlar masonry was never carried out. The structure was serviceable as it stood, without it. In this way much technical information about Classical Greek masonry has been transmitted to modern enquiry. The *in situ* facing of Greek ashlar masonry has sometimes occasioned confusion when comparing Classical Greek Ashlar masonry with Pharaonic Egyptian masonry, since it seems to go against the accepted distinction that as far as possible Pharaonic Egyptian masonry was dressed *in situ*, whereas Classical Greek Ashlar masonry was dressed on the bench prior to setting. This distinction, however, is valid. The facts are that blocks of Pharaonic masonry were dressed into form *in situ*, whereas blocks of Greek ashlar were finely dressed into their required form prior to setting and it was only the facing (a non structural matter) which was carried out *in situ*.

Since clean lifting devices operating via the mechanics of block and tackle made Greek ashlar building construction technically possible, it is necessary to consider arrangements for installing these devices on ashlar building sites. These arrangements are contained in the legal and financial parameters whereby monumental Greek ashlar building was carried out. Information concerning this occurs in literary references, but above all in the epigraphic records of the management of individual monumental building projects.

Remains of these records survive to an unexpected degree. They take the form of detailed memorials of the conditions under which the items of work were carried out, as also the "accounting" of the payments made for this work. The surviving records extend across something like three centuries from the 5th to the 3rd century BC, comprehending a number of building sites in the Greek World (i.e. continental and insular Greece and Ionia etc.). These records throw significant light on the economy of Classical Greece, and the part that monumental building played in it. Accordingly they will be considered in detail in the ensuing volume. However in so far as they concern building site development and installations something must be said of them here. As a prelude to this a cautionary remark is necessary. Since the information concerning the organisation of ashlar Greek building comes in large measure from this epigraphic record, there is an unconscious tendency

Evidence in building contracts

to consider ashlar Greek building at large as falling within its frame of reference. This, of course, is not so (for a *mise au point* v I. Nielssen, "Hellenistic Palaces," *pass*). Ashlar Greek building construction took place before and after the period covered by the epigraphic records, and in regions beyond the geographical ambit of these records. Consider monumental ashlar building projects within Greece during the 6th cent BC (e.g. the rebuilding of the Temple of Apollo at Delphi); the completion of the Temple of Zeus Olympios at Athens during the 2nd cent AD; the monumental buildings erected e.g. by the Seleucid and Attalid kings etc., etc. Of the administration of these buildings, however, we possess little record. (For a partition between building on contract and by direct undertaking in Greece v A. Burford, *The Greek Temple Builders*, pp. 110–11, NB Table 11.)

In principle if a public authority decides to erect a monumental public building, two ways of executing the project are open to it. The authority may carry out the construction directly employing its own resources, i.e. the Public Works Department equipment and labour. On the other hand it may contract out the work of construction to a "building firm" working under the supervision of the authority's architect. In principle if the building is a complex one, the contracting body will then arrange that certain aspects of the construction work are entrusted to subcontractors. It may be noticed that the latter alternative is, as a practical matter, virtually restricted to societies with a monetary economy.

The typical procedure adopted among the Classical Greek city states for erecting monumental public buildings in ashlar masonry was a very idiosyncratic one which went beyond these two basic alternatives. The Greek system mirrored the social structure of the *polis* very closely. Here the essential fact was that the citizen body as an aggregate of individuals formed the body politic, i.e. there was no "Leviathen" existing in its own right standing above the individual members of the community. In this way when a public building was projected, an *ad hoc* committee was formed to arrange and oversee the project. And the procedure it adopted was to draw up an instrument governing the work which secured as great a control as possible of the work while limiting as far as possible its own financial responsibility for mishaps in the course of the work. In this interest it endeavoured to distribute the responsibility for carrying out the works comprised in the project as widely as was consonant with efficiency; and above all to fix the liability for failures and imperfections in the work of construction on a broad and reliable collection of interested individuals (each contractor was bound to find a guarantor for the work he took up). As well might be, since there was no supra-ordinate body (the state) standing in the background to bail things out if the project was foundering or had collapsed.

To translate these generalities into more specific terms it is necessary that the remarks have some connotation in modern currency. Such an equivalent is difficult to posit. The drachma was devalued considerably during the course of the 4th cent BC, and the devaluation of modern currencies during the course of the 20th cent has been beyond belief. However the question can be rolled up somewhat. At the beginning of the 20th century the ancient drachma was worth much less than the pound sterling. At the end of the 20th century the ancient drachma was worth more than the pound sterling. Accordingly at an interim period the purchasing power of the two currencies was comparable. This was the case at a period within living memory immediately after the 2nd World War, when £1 st. was a good day's wage for a good day's work and a pay packet of £7–£10 St. per week was very acceptable (cf the architects' salary on various 5th–4th cent BC monumental building projects of 1 dr *per diem*). The sums mentioned in drachma in the following remarks, accordingly, can be thought of as in pounds sterling of the mid 20th century.

Evidence in building contracts

A monumental ashlar building project of the 5th–4th cent BC might vary in total value from e.g. ca 150,000 dr (the Temple of Asklepios at Epidauros) to ca 3,000,000 dr for the Parthenon at Athens (cf Müller-Wiener, p. 38). Construction and ancilliary works (e.g. quarrying, transport and the supply of miscellaneous materials) were divided up into something like, say 50–100 job lots and held out to tender by the commissioners, the individual contracts being worth say a few hundred drachme to a few thousand drachme. Thus the building commissioners retained executive control of the project throughout (or hoped so to do!) and did not become dependent on the calibre of a single contractor. (At any time there were probably something like 20 or so independent contractors at work on the site.)

These contracts were taken up variously by superior craftsmen discharging the work mainly by their own labour or by entrepreneurs (contractors) running some sort of a business and discharging the work through their employees. In either case the commissioner required the contractor to provide everything necessary for carrying out his contract. This picture was that which obtained notably in contracts for setting and finishing ashlar masonry. However as indicated such work depended not only on tools of trade etc., but what might be called site installations, *viz* block and tackle clean lifting devices together with scaffolding of various descriptions. The lively question is who was responsible for supplying this equipment. The project commissioner or the contractor? The epigraphic records do not resolve this question in so many words, but they give some indications.

In the first place it is unlikely that small contractors, working more or less as individual building tradesmen, would carry a stock of capital equipment; however the entrepreneur-contractor well might. Thus it could seem that some contractors, at least, would depend on these installations being available on site. Secondly the epigraphic records on occasion include items specifying the supply and bringing on to site of lifting tackle (pulleys) and scaffolding (e.g. at the Temple of Asklepios at Epidauros, cf Burford, p. 214, contract 29—for supplying tackle; and p. 219 for erecting scaffolding; also pp. 156-57, 186, 188 for comment). Since nothing to the contrary is said, such equipment was at the charge of the project commissioners. In short some at least of the installations necessary for setting and finishing ashlar masonry was part of the building site development. It is, of course, also possible that substantial contractors may have furnished their own additional or special equipment and installations.

9. *Roman Concrete Building*

Modernity of Roman building industry

By the time of the late republic and early empire the building industry in Rome was akin to that of the modern world in its range and diversity. It was varied in every connection: the materials and manner of construction; the range of projects; and above all the socio-economic environments in which it operated. Consider, Roman monumental building was carried out in massive ashlar masonry and/or in flexible Roman concrete utilising both trabeated and arcuated construction. The range of projects became ever more extended—far beyond temple, palace and fortress. Monumental buildings were erected for all civic purposes: political, legal, administrative, commercial, educational, together with recreational and sporting facilities. Moreover all the while there was a constant boom in large scale housing development. In addition to this the Roman building industry was charged with a range of large scale projects which were not "buildings" at all in the strict sense, they were engineering projects for aqueducts, bridges, harbours, roads etc. Finally monumental buildings were erected by Roman authorities or under Roman auspices from North Britain to the borders of the Sahara and the centres of the Ancient Middle East. In some of these regions other renowned building traditions survived, in some building had been much less developed, while in some there was no previous building record whatever.

All this diversity was in complete contrast with the circumstances of monumental building in Mesopotamia, Egypt and Classical Greece. As a result it is not possible in the same short compass to typify Roman construction site development and installations. Only the barest essentials can be mentioned, centering about the typical Roman building construction—Roman Concrete.

There is recognisable an overall history of large scale Roman building as it concerns site development and installations. The information comes in the main from legal and constitutional history, together with surviving private correspondance (e.g. that of Cicero and Pliny the younger).

First in the days of the later republic the wealth which accrued in Rome from territorial conquest found an expansive outlet in building. And to provide for this a flourishing building industry emerged. Master builders, skilled tradesman and unskilled laborers came to Rome in search of work, and men of entrepreneurial

Historical development of Roman building industry & organisation

talent were ready to undertake building commissions. So far as is evident at this period there was little distinction in the organisation of large scale building projects whether considered public or private. The republican state did not maintain a Department of Works, and if some public building project was approved held this out for public tender. This may be thought of as parallel to the Greek City State arrangements for public buildings (e.g. temples). However there were fundamental differences.

In the first instance the command and control of the project was not exercised by an *ad hoc* commission, but was in the hands of appropriate state office holders (magistrates, *censors, aediles*, etc.). Secondly there is nothing to suggest the Greek multiple small contract system whereby the status of contractors was held down to size, so as to avoid the possibility of them calling the tune. So far as is apparent in the Roman world a building contract, whether for a public or private project, was entered into with a single contractor (*redemptor/conductor*) who was free to make whatever arrangements he saw fit to discharge it. Another distinction was that Roman Law provided standard legal forms appropriate for building contracts. The two forms in question were *stipulatio* and *locatio conductio*. The former was the older, a formulaire verbal procedure for constituting binding executory contracts by way of question and answer. "Do you promise to etc., etc.?" "I promise". The other, *locatio conductio*, was the general form for entering into agreements where some possession or property of one person was placed at the disposal of another for some purpose—i.e. an agreement for leasing or hiring. NB very frequently the client in a building contract supplies the building materials for the work, which he thus placed (= *loco*) at the disposal of the contractor. This style of contract was written out in great detail (v J. Richardson, "Roman Architecture and Society," pp. 68–75).

From these beginnings in Republican days there was an overall, long term development in large scale building towards an ever increasing capacity to extend the scale of the work. This development operated both in the private sector and in the public sector.

Private building projects became more and more extensive and lavish—notably urban housing development in the form of the *insula*, the city apartment block with commercial premises (*tabernae*) at street level, well evidenced by the striking remains at Ostia (v Ward Perkins, chap. 12, pp. 279–89). In this connection some enterprising men became building tycoons. Instead of projects being carried out by small contractors and building tradesmen at the behest of individual clients (proprietors), big businesses emerged of the speculative property developer employing numerous tame architects, master builders, skilled craftsmen, clerks etc. capable of carrying out projects of any size. Crassus, the triumvir with Pompey and Caesar, is stated to have become the richest man in Rome, employing 500 workmen in his speculative (and sometimes unscrupulous) projects during the middle of the

Historical & geographical development of Imperial Roman building.

first century BC. Such large scale building construction enterprises were, of course, also well positioned to take up contracts for carrying out major public works, e.g. the erection of temples, theatres, public baths etc.

However parallel with this development in the private sector, the Roman state with its ever increasing wealth and its idealogical programme of "monumentalising" itself, instituted and continually expanded its Public Works Department (*Opera Caesaris*). This development was sealed during the principate by Augustus and made manifest by his appointment of Agrippa as Minister of Works (*aedile*). Equally the expanding state expanded another organisation of builders. The Roman Army maintained a large, highly competent corps of engineers, which was in effect a construction corps. And it was not unusual for this personnel to carry out civil building projects as the occasion demanded.

With these developments the Government of the Roman Empire in the first century AD was in a position to carry out any public works project by direct operation of governmental resources. This is not to say that public building projects were no longer held out to private contract. They were and were effectively taken up, but such contract work continued alongside direct government building.

At this stage another dimension enters into the development of the Roman building industry—that of historical geography. Whereas the Roman government monumentalised the City of Rome during later Republican times by the proceeds extorted from its conquests, the Imperial Roman Government repaid in kind by providing, assisting, supporting public building throughout the provinces of the Empire. The financial mechanism employed was of a fiduciary nature—i.e. it remitted taxes, levied special taxes or sanctioned municipal impositions. It did not make direct monetary advances. However it supplied manpower both professional (architects, master builders) and labour (sometimes convicts or slaves). Also it could arrange for an eminent patron/overseer of the works in the person of some celebrated (and wealthy) dignitary of the region who was thereby bound to oversee the completion of the project. Additionally it could place army personnel at the service of the municipality to direct and carry out the work; and, very significantly, with the Imperialisation of major quarries the Roman government donated prefabricated units of masonry, notably monolithic columns, to monumental building projects throughout the Empire (v *infra*, pp. 212, 213). In this way Roman Imperial building in the provinces has left remains such as are a wonder and amazement at the present day, both in respect of their magnificence and of their dispersal over a vast territory (cf J.B. Ward Perkins, pt 3, "The Architecture of the Roman Provinces"; R. Macmullen, "Roman Imperial Building in the Provinces," pp. 207–17).

The Emperors most active in asserting the humanity, dignity and magnificence of Rome by way of monumental building in the provinces were Augustus, Trajan and Hadrian. However, during the third century AD, the tide of affairs ran

Historical development of Later Roman building

against Roman rule and when Diocletian reestablished and stabilised the power of the state, the situation regarding large scale building was totally changed. Instead of abundant individual, municipal and governmental building enterprise a state controlled economy prevailed where governmental coercion was the mainspring of large scale building. Generalised taxation (often levied in kind), compulsory registration of tradesmen in coporations which were subject to a corvée, together with the binding of individuals to hereditary callings were features of a new centralised order.

Initially the revival of stable central government advertised itself in traditional civic monuments. However the long term changes soon became obvious, instigated by two prime historical facts. The imperial capital was transferred from Rome to Constantinople (304 AD), and not long afterwards christianity became the state religion of the Roman Empire. Henceforth public building was carried on in a new manner within new parameters—and at an overall reduced scale. In the first place the clear distinction between the historic metropolis Rome and the provinces lapsed and Rome with its surroundings progressively became a province so far as building was concerned, while the new capital did not possess a similar distinctive wealth of tradition. Long term change in the purpose of monumental public building was obviously more sharply focussed by the innovation in religion. This acted both directly and indirectly. Very few pagan temples or shrines were constructed after 200 AD and virtually none after 300 AD. Their place in public building was taken up during the 4th century AD by Christian churches and shrines. Outside this obvious substitution other changes are recognisable in the categories of monumental buildings. Vital public works (e.g. aqueducts) continued to be built on a reduced scale, but what might be called "cultural" public building (e.g. theatres, libraries) disappeared from the program during the 4th century. In striking contrast public building resources were taken up by a new category of buildings: those providing for defence—both urban defences together with forts, fortresses and fortified residences of all sorts.

Speaking in general terms, although the incidence varies from province to province and with different categories of buildings, close statistical analysis indicates that compared with the level of public building during the first and second centuries AD, public building in the Roman world thereafter declined by something like 75% (cf Vol. I, chap. 10, Late Antiquity, pp. 129–45). The effect of these changes on building site development is a patent question, and is discussed below.

It is difficult to outline the complexity obtaining when considering the development of the monumental Roman sites. With the limited exception of some projects carried out entirely within the tradition of Greek ashlar building (e.g. the Hadrianic Temple at Cyzicus, the Severan building programme at Leptis Magna) Roman monumental building was in another tradition. Whether or not it is imme-

Significant categories of Roman building

diately recognised as a Roman Concrete building, its construction involved in varying degrees: heavy timber work, brick masonry, mortared rubble, ashlar stone masonry and liberal plasterwork. Furthermore speedy results were a paramount consideration, something like 5 years being the expected term of a major project. In these circumstances the most detailed time schedule must have been drawn up. Indeed it seems impossible that those directing operations did not make use of bar diagrams to establish the rational planning of the enterprise. Where, as here, building involves varied operations of a different nature, then it is obligatory to plan out their sequence so that:

(1) Labour and equipment are continuously employed in the most economic fashion,
(2) Even more significantly, the completion of one operation may not impede or prevent carrying out another.

To bring these matters into closer focus it is best first to attempt some overall classification of large scale Roman building projects, based on the system of construction employed.

The following classification is entirely *ad hoc* and has no rationale other than to facilitate an outline of site development and installations.

A. Large scale urban housing development (residential *insulae*). Here the construction was entirely concrete for walls, with timber framed roofs, and there were no significant ashlar embellishments. No heavy loads were involved and installations were limited to access scaffolding and light (e.g. two legger) cranes. The building material for the walls in the main was readied on the ground and hoisted up by pulleys mounted on the scaffolding. 375 78, 79, 88
B. Public buildings with concrete vaulted roofing. This category may be divided into groups depending on the amount of ashlar stone masonry incorporated in the construction:
   1) Buildings the structure of which was in considerable measure ashlar, e.g. amphitheatres and theatres where the supports (walls, piers, columns) were of ashlar masonry and the roofing was of Roman Concrete. (This distinction draws attention to the fact that Roman buildings did not employ ashlar masonry for vaulted roofing except in the Eastern Provinces where this had a Hellenistic background.) Here the installations were basically those used in Greek ashlar plus the timbering required for the vaulted roofing, which broadly speaking was for passageways not involving large spans. 272, 399 271
   2) Buildings where the structure was basically Roman Concrete but incorporated to a greater or less degree ashlar masonry elements by way of monumental embellishment or which in some instances, had an auxillary

Categories of Roman building. The Insula

structural function—thus markets, basilicae, thermae, temples, tombs. Here 404 the concrete roofing often covered large spans (e.g. up to 40+ m). The impact of this category of Roman building on site development and installations was momentous.

To construct vaulted concrete roofing over spacious halls and apartments required timber work on a grand scale. This timbering comprised (or fulfilled the functions of) scaffolding, centering and shuttering. The purpose here was not to provide devices for lifting heavy loads, but to construct staging of great strength giving form to and supporting the load of the concrete roofing while it was under construction and while it was curing. Details of the arrangement of these extensive timber installations have occasioned continuing and lively dispute. On the other hand lifting devices were required when concrete buildings included notable elements of ashlar masonry by way of embellishment. In numbers of instances the embellishment lay not only in the elegance of the finely dressed stone masonry, 405 but in its grandiose scale—cf the use of Egyptian granite columns 40 to 50 feet high with correspondingly massive entablature blocks. The erection of such units of enormous burden (50 tons or more) required the use of lifting devices totally different from those used in normal ashlar construction (*viz* with a capacity of say 5 tons). The provision in a limited space of all of this timberwork of great 96, 97 strength, filfilling diverse functions, was a condition precedent to monumental Roman Concrete construction. Its deployment so that varied building operations proceeded economically and without hindrance demanded site management of great skill and experience.

A brief indication of this far reaching subject may be provided by noting the varied circumstances obtaining with several typical buildings—e.g. a typical urban apartment block (*insula*); the Colosseum, the arch type amphitheatre; the Pantheon, the ideal concrete vaulted monument.

1. *The Urban Apartment Building (of brick faced concrete, 1st–2nd century AD)*

It is one of the advantages of Roman Concrete construction that walling of this material requires very little in the way of site installations. The masons carry up the facing a limited register in advance of the concrete filling, and when the facing has become competent than the core filling is applied in alternate layers of aggregate (*caementa*) and pozzolana mortar (*materia*). In this way the significant 78, 79 installation required is simply access scaffolding, which here can be "bricklayer's" or "putlog" type scaffolding for economy.

Where the work was on a large scale concreting was efficiently organised by division into registers, both vertical and horizontal so that one compartment was a normal days work for the labour engaged on it. This division also accorded with the time factor operative in the physical process of concreting. With *opus testaceum*

The Insula

the vertical registers were divided one from the other by through courses of bricks the better to compartmentalise the concrete while curing (v Vol. 2, pp. 200–02). The brick layer's work laying the facing and the concretor's work placing the core filling was efficiently organised by being carried on separately in seperate horizontal runs. The masons layed the facing for one run in a day so that it developed strength during the night (or what period was necessary). The concretors then placed the filling in the core during the following day (or after the due interval), while the bricklayers moved on to lay the facing to another run. If the concrete core is placed before the brickfacing has developed the necessary strength, then the brick facing will be displaced by the thrust of the semi liquid mortar during curing.

The delivery of materials for this simple building process was correspondingly simple. A single pulley mounted on the access scaffolding sufficed to hoist up the brick and aggregate, while the pozzolana mortar was made accessible in two manners depending on convenience. Either it could be mixed on the ground and hoisted up ready mixed in a skip, or the ingredients could be hoisted up and mixed close by the work. Both methods are practical and doubtless were practiced (for a detailed exposition of concrete walling procedure v R. Taylor, *Roman Builders*, pp. 97–111).

Finally the overall factor which made for simple construction procedure in apartment buildings was that the upper floors and roofing were always timber framed. Concrete vaulting and domes were not disposed on these buildings, thus no centering and shuttering was required.

The above is ideal building procedure. However as is well known the jerry building of Roman apartment blocks during the first century AD was a favored theme of the satirists (cf Juvenal Satire 3). This state of affairs, of course, specifically refers to Rome where the pressure of population was acute, and the incentive to real estate profiteering was correspondingly high. The apartment blocks at e.g. Ostia were very agreeable and proper buildings (cf J.B. Ward Perkins, figs 28, pl 147–54). 375, 376

2. *The Colosseum, ca 80 AD*

The Colosseum (Flavian Amphitheatre) is of very complicated (not to say intricate) construction incorporating two dissimilar materials: finely dressed stone and Roman Concrete. It is difficult to describe the disposition of this construction in words, and, moreover, even graphically. Perhaps the most telling description is still that of D.S. Robertson in "Greek and Roman Architecture," pp. 285–89 (cf also J.B. Ward Perkins, pp. 221–24, fig 93). Since there is no readily available large scale drawing to make the disposition of the building construction comprehensible at a glance, it is necessary to outline this, as it affects the site development and site installations.

The Colosseum

The Colosseum is a large oval building, its horizontal axes 188 m × 156 m and the outer wall rising to a height of ca 50 m above external pavement level. The 28 plan is formed by a succession of arcs struck from a number of centres rather than a true ellipse and all internal subdivisions parallel this curvature. The vertical supports of the structure comprise piers at the external margin of the plan; pillars 207, 399 linked radially below the middle third of the cavea plan; and slight radial walls at the inner third of the cavea plan. These supports are all aligned radially, i.e. to make straight lines radiating from the centres of curvature of the periphery. There is virtually no continuous load bearing ring walls. The radial disposition of the supports gives a ground plan of the cavea consisting of 4 annular main corridors (ambulatories), 2 at the outer margin and 2 at the inner third, together with a series of radial passageways at the middle of the plan which house stairs. These passageways (*vomitoria*) provide for the vertical circulation and for interconnection between the annular corridors which afford the basic horizontal circulation.

The piers are interconnected in the annular sense by arches and all the corridors and passageways are roofed by vaults (in the main simple barrel vaults). The vaulting over the radial passageways housing stairs is ramped, ascending from a single storey at the innermost to 4 stories at the outer margin. This roofing provides the seating for the ascending rows of marble seats. The cavea floor thus ascends at an angle of ca 30° in the lower circles and ca 40° in the upper circles, and all the space below this provides the manifold circulation necessary to get a full house of 40,000+ spectators into and away from their seats. Finally englobed in a deep pad of site concrete there are also subterranean chambers and passageways serving the (brutal) spectacles in the arena.

All comment has noted the importance of the Colosseum precisely for the light it throws on Roman construction procedure; but without, in fact, transmitting this light very much. Certainly the Colosseum is the one great Roman building to show that Roman builders retained a mastery of Classical Greek ashlar building construction while developing the full potentiality of Roman Concrete construction.

So much for the design of the building. Now is to be considered its construction which was intended to provide for an imposing appearance; structural stability; and also for an accelerated building schedule (something like 5–7 years, an astonishing feat). The scheme adopted by the architect for the amphitheatre to achieve this aim was to employ two basically different building materials in conjunction: 399 meticulously dressed ashlar masonry and Roman Concrete. The ashlar masonry was to provide the imposing aspect and the structural strength of the load bearing supports, while the Roman Concrete was to afford rapid construction where neither impressive aspect nor great load bearing capacity was required. In this way the grandiose façade and outer annular corridors were entirely of limestone and

The Colosseum

the seating was of marble. Whereas the inner pasageways etc. and the concealed flooring of the cavea was of Roman Concrete. All this required ingenious design and very close scheduling of the construction, and this over and above that normally required for amphitheatres because of the great scale of the building.

The construction process of the Colosseum has received attention (cf, latterly, R. Taylor, *Roman Builders*, pp. 133–74) since in view of the vast size of the building, it is a wonder in itself, and there is the added consideration of the reported speed with which it was carried out—ca 5–7 years. It is to be doubted that with today's harnessed power and engineering technology the work could be completed in much less time. Certainly 20 years or so would be a reasonable assessment for the time required in antiquity. Over and above these general questions there is the technical factor that the fabric of the building is very evenly divided between ashlar masonry and Roman Concrete. These two building materials involved very contrasted processes of construction, thus the question arises how they were dovetailed together.

The soul of building construction is in its details, and a mass of details arise for consideration in the construction of the Colosseum. Here it is possible only to make some overall observations.

Heavy ashlar masonry (*grand appareil*) requires powerful mechanical devices to hoist the blocks into place. This requirement is augmented with height, and in the Colosseum the heaviest burdens were set at the highest levels of the building, approaching 50m above the pavement. On the other hand building with Roman Concrete requires virtually no auxilliary devices or installations at all, and proceeds very rapidly. All this, however, refers to walling. With roofing the circumstances are different. It is only possible to construct concrete roofing in the form of vaults and domes—and this procedure requires the form to be previously established in strong timber construction (centering) to bear the load of the material while it is becoming competent.

In this way, to cut short a long analysis, arose the question of a possible conflict in the economic scheduling of building operations. There is relatively little concrete walling in the Colosseum—mainly the low walls of the substructure for the *maenianum primum*. On the other hand virtually all the roofing is concrete vaulting of the cavea structure irrespective of whether the walls were stone or concrete. The only exception is absolutely marginal: the uppermost roofing of all—the roofing of the highest range of seating of the cavea, that constructed of wood (*maenianum summum in ligneis*), or what would be called "the Gods" in English theatrical terminology. This was wooden roofing carried on wooden beams.

In principle, the issues of this conflict may be thought of as follows. The concreting work might be held up because of delay in the demanding masonry work of building up stone walling, and could be obviated by some quicker method of

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building up stone walling. Consideration of this question in the past has centred on the numerous (ca 80) juxtaposed radial passages forming the substructural supports of the *maenianum secundum immus*. These passageways were carried up to 2 stories in height and their wall construction has been the subject of controversy. The first storey of the walls is of sizeable ashlar masonry, but of an idiosyncratic construction. The body of the wall is built of relatively soft and weak volcanic stone (tuff / tufa), but within the run of the walls are several rough piers of hard strong limestone (travertine). Above the vaulted roofing of the first storey the limestone piers continue uninterruptedly up to the inclined roofing which supports the cavea seating. Some writers (e.g. Cozzo) have seen in these piers a rapid structure to allow the concrete roofing to be got under way as quickly as possible, so that the building of the cavea could proceed without delay, leaving the intervals of walling to be filled in with tuff blocks (or *opus testaceum* concrete in the upper floor) without prejudicing the overall scheduling of the building.

On the contrary some have seen a more significant concern to lie in the uninterrupted completion of the vertical passage of similar masonry—i.e. here the stone pillars. Thus they would wish the construction of the stone pillars to their full height without interrupting the work by construction of the concrete vaulting, and then all the vaulted roofing to proceed subsequently (cf R. Taylor, pp. 145–48).

This instance is advanced as an example of the divergent ways possible in planning the building schedule of the Colosseum. In fact the instance does not appear a good one. The construction is surely simply an instance of *opus africanum*, a construction designed to achieve wall strength as economically as possible by stiffening inferior materials and construction through incorporating piers of superior strength in the walling (v Vol. 2, I, pp. 60, II ills, 112–113).

The study by R. Taylor, *Roman Builders*, includes a detailed consideration of the building procedure at the Colosseum, and it should be referred to as a background to the following brief remarks.

The building programme formulated by Taylor is based on the assumed use for ashlar construction of two legger (*dikōlos*) cranes (cf *supra*, pp. 79, 80) which he correctly identifies as the "work horses" of Roman building construction, and which appear on several ancient representations (e.g. the well known relief of the Haterii funerary monument). This in some measure conditions his approach because the multi-floor nature of much of the building programme involved the repeated necessity for dismantling and repositioning the cranes when the area of operation is being roofed. However this assumption of the general use of *dikōlos* cranes is not automatic in view of the ideosyncratic nature of the monument which requires the cranes to be raised up and installed in lofty, cramped positions of the building fabric under construction. Certainly although this type is shown
88, 91 on ancient reliefs etc., it is always shown working on the ground never installed in such a fashion.

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This objection is augmented by the fact that the *dikōlos* crane must be stayed by securely fixed guy roping. Here Taylor makes the reasonable observation that such guy ropes must be continued down to the ground for secure attachment, and as a result can be ca 100 m long. The upshot of this is that although the use of two legger cranes may have been quite in order for building at ground level, they do not appear suitable for use at the higher levels of construction. This is testified to by Taylor's fine drawings of the cranes at work: his fig 82 showing the cranes at work on the ground is convincing, his fig 96 showing the cranes installed at the uppermost level of construction appears improbable. Moreover because of the grand dimensions of the Colosseum cranes would require a long jib (Taylor mentions 20 m) and a two legged crane with such a jib would be a massive contraption to rig up in a cramped, insecure location. There is also a further consideration here. The speed with which the Colosseum was built would only be achieved by multiple simultaneous operations. Now since in most operations more than one crane was required to work conjointly, then the total number of these cranes required on the job must have been very considerable indeed. All this suggests that other arrangements were made for setting the ashlar masonry at higher levels. This, in fact, was the use of what is referred to in the ancient mechanical treatises as the *tetrakōlos*.

It has been noted that the term *tetrakōlos* in the literal sense signifies the square / rectangular tower scaffolding built up around an isolated structure (v *supra*, pp. 80, 81); and in this sense it would apply to arrangements for hoisting into position the monolithic columns forming the colonnade around the uppermost level of seating, nearly 50 m above pavement level. On the other hand the term can well apply to any run of independent standing scaffolding since such scaffolding is composed of successive units formed by four uprights. In this fashion it could apply to the arrangements made for setting the masonry of the ashlar walls. If the "access" scaffolding to the wall faces were made robust, it could also serve as the frame for hoisting blocks into position with the pulley block units mounted on the horizontal timbers at the top of the scaffolding. Horizontal motion is afforded by several pulley blocks installed at different positions, so that the resultant of their differential activation can position the load as desired (v *supra*, pp. 81, 82). If necessary where a heavy block is to be hoisted, the scaffolding can be reinforced by adding members.

When the walling is carried up to the roofing level the robust scaffolding can 400
stand as the basis for the centering and shuttering of the vaulted roof. When this vaulting has become competent, the supporting scaffolding can be dismantled and erected on the floor of the next higher level. The scaffolding against the external wall face of the monument, of course, must rise uninterruptedly from pavement level, a formidable construction. Such a process requires ingenious adjustment but

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it appears more "probable" an alternative to installing cranes in elevated, confined and insecure positions. In addition to the above arrangements, without doubt there were some *dikōlos* cranes on the site—maids of all work performing various tasks. Also it is likely that on occasion a two legger crane was used in conjunction with standing *tetrakōlos* units as recorded for heavy construction work at the Didymaion (v *supra*, p. 81).

The subject of the works organisation and installations at the Colosseum is so extensive and involved that cursory observations are derisory. The structural form of an amphitheatre imposes difficulties. In section it is triangular, a sheer wall face on one side and "roofing" inclined at 30° to the horizontal on the other. The colossal size of the Flavian amphitheatre augments the difficulties. All told it is likely that the structure was built up in horizontal stages, floor by floor, corresponding to the vertical divisions in the seating (the *maeniana*)—as would be expected. It is doubtful that the heavy ashlar walling was all constructed by use of the two legger cranes. It seems likely that a very great amount of standing scaffolding was used for a combination of purposes. To what degree the circulation arrangements of the structure itself could have been used for access of materials is a basic question difficult to answer. Probably the materials for concreting were carried or wheeled up the ramped pasageways wherever possible.

At all events the Colosseum works organisation was a major achievement of ancient building (perhaps to be compared with the Great Pyramid). It can only be dealt with at length, in a monograph by an experienced building construction engineer.

3. *The Pantheon ca 125 AD*

In some ways the Pantheon forms an excellent counterpart to the Colosseum in considering site development and works organisation. The Colosseum in structure and in the incorporated building construction is traditional—ashlar piers and round headed arches, concrete walls and (barrel) vaults of restricted span, roofing, corridors and stairways. However the organisation of the works to build very rapidly intricately designed interpenetrating units confined in breadth and ascending to a great height is a wonder. The Pantheon on the other hand has a simple spacious plan favorable to building work, but its form and incorporated construction are very advanced—a concrete rotunda with one of the widest span domes ever built (cf R. Taylor, pp. 191–211; L.C. Lancaster, *Concrete Vaulted Construction in Imperial Rome, pass*). It is not the building procedure that is of principal interest here but rather the forms and nature of the construction. Accordingly the following remarks are brief and the subject will be discussed subsequently in more detail in the chapter on Concrete Construction.

The Pantheon

As befits its imposing structure and astonishing state of preservation, the Pantheon is a much discussed monument. However much of the discussion has concerned issues which are now reckoned to be false tracks. In the first instance the *rapprochement* of the classical ashlar prostyle porch with the concrete rotunda raised persistent attempts to explain the monument as an agglomeration of several periods of construction. This is now known not to be the case and the monument is the work of a single short period of construction, ca 120 AD–127 AD during the rule of Hadrian. Secondly the concrete fabric of the rotunda was revealed to contain a surprising inclusion of intricate brick arches and ribbing. Accordingly there has been much speculation on the structural significance of this brickwork but this has largely neglected the significance of this brickwork in constructional procedure.

The following brief discussion will touch on:

(1) The ashlar porch and its adjustment to the rotunda with particular reference to the giant Egyptian granite columns.
(2) The inclusion of the brick arches and ribbing in the conrete fabric of the rotunda.
(3) The procedure for erecting the centering / shuttering for the dome of the rotunda.

(1) The ashlar prostyle porch

The juxtapostion of the porch and the rotunda appears illogical, since the lines of the porch do not accord in any way with the string courses on the rotunda which are obviously designed to respond to them. This indeed is so, but the explanation is a relatively simple one. The present design represents the best compromise which could be made with an unfortunate mischance. The porch was originally designed to incorporate 50' granite column shafts, but it was found that column shafts of this dimension could not be incorporated and substitutes of 40' were 96
incorporated instead. When this explanation was first recognised, it was assumed that the reason why the designed 50 footers were not used is that they could not be made available from the Egyptian quarries in time—a reasonable explanation. However a later reconsideration proposes that shafts of this length could not be raised up in the working space available, and thus had to be substituted by shorter ones. This came about through process of construction. According to this analysis it is assumed that 20 granite shafts with a burden of over 50 tons would not be erected by hoisting with block and tackle, but would be set up vertically using a "rotating cradle" or "Adam tilter". This device for which there is no archaeologi- 97
cal evidence whatever was publicised by J.-P. Adam (*La Construction Romaine*, p. 49, fig 98). The defect is that a free linear space at least twice the length of the

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column must be available to operate it, since the haulage must be applied with a reasonable horizontal component to draw down the vertical arm and thus raise up the supine column into the vertial. In the plan of the Pantheon porch there is not the free linear space to lay out the two central columns of the innermost row and operate the tilter for 50' shafts (v R. Taylor, pp. 129–31). These circumstances were discovered too late to make any adjustment to the plan (the rotunda was already built), hence the alternative was to reduce the length of the shaft to 40’ and thereby to lower the entire elevation of the porch and so bring it out of adjustment to the already completed rotunda. However this explanation rests on the categoric necessity of using the Adam tilter to raise up these monolithic shafts, which is difficult to maintain. Certainly the marble columns inside the rotunda were not raised by the tilter. These shafts are roughly the same dimensions as the porch columns, but they are not monoliths (they appear to be composed of two frustra). Presumably they were set in place with a two legger crane.

(2) The Procedure for building the Dome

The wonder of the Pantheon is its concrete domed roof, one of the earliest to be constructed and one of the widest span domes ever constructed in traditional building materials. And it still stands intact after nearly 2,000 years. This wonderful structure was built by virtue of a temporary wooden installation which both gave it its designed form and also supported it while the concrete material was becoming rigid and self supporting. How this wooden installation of great strength was fashioned and set in place climbing to 40+ m above pavement level is a wonder in itself, equal to that of the concrete dome it made possible. It represents a pinnacle of Roman building procedure and something must be said of it here. The installation was designed as a temporary structure, to be removed entirely when it had performed its function, and to leave no trace of its presence in the finished monument. In this way there is no direct archaeological evidence of its nature and discussion of this must proceed from comparitive, historical evidence.

As noted above this temporary installation was multi functional. It provided a surface which delimited the form of the dome, and thus in a general way it may be termed “formwork”. Since the form of the Pantheon dome was hemispherical the wooden installation was “centering”, evidencing that the form was struck from a centre. This is the term applied to form work used for all arches, vaults and domes. However, in addition to defining the form of the dome, the centering was required to support the load of the dome under construction until it became competent—i.e. could support its self load. In these respects the centering for a concrete dome was no different functionally from the centering for a stone masonry dome where the voussoirs required support from beneath until the structure was completed when they were held in place by compression.

The Pantheon Concrete Dome

When the dome was of concrete a further function was demanded of the wooden installation. Since concrete was an aggregate of small stones together with semi-liquid mortar, when applied it was cohesionless and the centering needed to be continuous and impervious so as to confine the material from escaping. This function can be required in any concrete construction (walls as well as roofing) and the wooden installation providing it is called shuttering. Thus the installation for building the Pantheon dome was of necessity both centering and shuttering—the centering provided the form and supported the construction in place for the required interval of time, and in addition the shuttering confined the plastic material while curing until it became fully cohesive and competent. It is now necessary to consider the background to these various functions.

The idea of Roman builders to roof a large open space with concrete (a cohesionless material when applied) was an astounding enterprise. Accumulated experience of ages revealed that neither stone nor brick served well for purposes of traditional roofing. Brick (terra-cotta) was useless, and for a stone beam or slab to span any appreciable distance (e.g. 5 m) it had to be so massive as to be impractical for any except the most monumental structures. The only material generally useful for roofing was wood. Poles or beams could be laid horizontally over a space to support flat terrace roofs or inclined upwards together to support ridged roofing. Also the device of corbelling outwards successive courses of stone or brick until they covered a restricted space was a traditional practice (v. H. Soeder, "*Urformen der Abendländischen Baukunst*" Köln 1964, *pass*). But none of these measures suggested the idea of concrete for roofing—and they were all restricted to limited spans.

In addition to these traditional methods of roofing, from sometime in the latter part of the 4th century BC Greek builders had come to construct arches and barrel vaults in ashlar masonry with radially set voussoirs. Such vaults again were of limited span, but their construction demanded that the voussoirs be supported from below until the structure was completed. This support was arranged by forming 98
stout wooden arches to set as bearers to the stone construction in progress—i.e. the ashlar vaulting was erected by use of wooden centering. Thus when Roman builders began to build spacious concrete vaults and domes during the Augustan period they were familiar in principle with this device. However, what a difference in practice existed between wooden centering spanning a few metres and set a few metres above the ground for centering ashlar masonry vaults and arches and centering arches or segmental arcs 20 m or more in diameter and set at similar 99
heights above pavement level. Furthermore in this connection it should be noted that the first ashlar domes to be erected (again all of a few metres span) can not be dated earlier than the Christian era; that is to say there is no historical priority in the building of (small) ashlar domes over the building of (large) concrete domes. In short in the construction of wooden centering for concrete domes Roman

builders were innovators and leaders in what may be called megaxylic carpentry, a fact which has never been adequately recognised. In this crucial instance of site installations they owed nothing to preceeding Hellenistic builders.

Concrete dome construction

Centering for arcuated masonry roofing takes the form of a sturdy roofing truss with firring pieces attached to convert the triangular (or polygonal) profile into a semi-circle (or other desired arcuated form). One such device supports the construction of an arch; a linear succession of such devices supports the construction of a (barrel) vault; and a group of such devices disposed radially as diameters supports the construction of a dome. Such form work is itself supported in the required position by posts and props rising from the ground; or, on the other hand the rising masonry of the structure to be covered may be provided with corbelled projections (e.g. the abaci of capitals) on which the centering can be set. In order to render the necessary support to the expanse of masonry, these centering pieces or "ribs" are interconnected by boarding (or "lagging") set around the circumference. The lagging may be either contiguous or set at close intervals depending on the nature of the masonry to be supported (e.g. brickwork or ashlar blocks). In principle the fabrication and use of centering is a simple matter and the device remained unchanged from antiquity down into the traditional building of modern times, i.e. arcuated construction in stone or brick always demanded that the form of this construction was first built in wood framing.

The above outline adequately covers the practical application of centering for arcuated masonry construction of limited span, say 5 m or so, but when the spans involved are of a different order, e.g. 20 m or more, or the astounding 40+ m of the Pantheon, then the practical difficulties involved are obviously tremendous. There is no direct evidence of the procedure for this outsize wooden construction neither by way of ancient representation nor literary reference (e.g. Vitruvius does not mention the subject). In this way all modern accounts of it are largely conjectural. Certainly whatever the procedures may have been, they constituted very notable achievements of ancient building technology.

It is impossible here to deal substantively with this subject (for a convenient recent survey v L.C. Lancaster, *Concrete Vaulted Construction in Imperial Rome*, Cambridge, 2005). All that can be attempted in the available space is to outline its scope. Perhaps this may be considered to manifest three aspects: fabricating the centering, setting it in place, supporting it in place. These three aspects are interconnected and interdependent—e.g. the fabrication of the centering depends on whether this is done on the ground or aloft *in situ*; the setting in place depends on its fabrication and how it is to be supported, etc. etc.

Beginning this outline with the fabrication of the centering, it can be stated at the outset that no one has suggested that the "centres" for the Pantheon were constructed as gigantic versions of the centering for modest spans of a few metres, *Concrete dome construction*

i.e. as enormous trussed semi-circles with horizontal ties ca 40+ m long! All discussions envisage segmental trusses (or assemblage of parts thereof) rising from the springing of the dome to the crown—or, to be more precise, since the Pantheon dome has a sizeable occulus, from the springing of the dome to the circumference of the oculus. Each centering rib thus extends across less than half of the circumference of the semi-circular dome (cf the schemes of Viollet le Duc and R. Taylor, v R. Taylor, pp. 197–99, figs 114–116). The question thus arises immediately, "How are these ribs secured in postion at their upper extremities?" This can only be effected by their being put into compression against a compression cylinder marking the position of the oculus—but how was this arranged?

To begin at the beginning with the fabrication of the centering. When the obvious question is posed as to whether the ribs were fashioned on the ground or aloft, the alternatives are not categoric, there are differences in degree. It is unlikely that every baulk of timber was hoisted aloft separately, and then the ribs constructed entirely in the air, so to speak. Equally it is difficult to believe that the complete rib was hoisted up and set in place—such a rib would be of several tons burden. Almost inevitably the arrangements would be that parts of a rib were fashioned on the ground and then hoisted up to be assembled *in situ*. Raising the parts could only be carried out by using cranes or else by the presence of scaffolding on which to mount block and tackle. Cranes perched on the rim of the rotunda drum seem hazardous (but R. Taylor, p. 203, fig 118 to the contrary), thus it seems that the setting in place of the centering requires the presence of a certain amount of scaffolding however the centering was eventually to be supported. In the past this latter question has been disputed in all or nothing terms—i.e. the centering was in effect standing centering, and thus required a forest of scaffolding rising from 400
the ground to support it; or, on the contrary, the centering was flying centering 401
which required no scaffolding.

More recently a sensible and practical middle way has been proposed (v J.J. Rasche, "Zur Konstruktion Spätantiker Kuppeln"; F. Rakob, "Römische Kuppel- 402, 403
bauten in Baiae"). The centering ribs were supported at their lower extremity by scaffolding set against the walls, and at their crown by a central tower rising to the crown of the dome. In the Pantheon this central tower supported a compression cylinder which acted both as shuttering for the oculus and secured in place the 403
upper extremities of the centering ribs.

With the centering ribs fixed securely in position work on the dome was then transferred to the exterior of the building for a succession of demanding operations. These comprised:

(1) Completing the centering –shuttering by connecting the "meridian ribs" with horizontal "parallels" and fixing onto this framework the overall lagging which

Concrete dome construction

constituted the shuttering. Also, since the intrados of the concrete dome of
401 the Pantheon was articulated by a pattern of coffering, the coffer moulds had to be fixed in place on the lagging so as to constitute the required pattern.

(2) Building up any brickwork (arches etc.) to be incorporated into the concrete fabric.

(3) Placing the concrete in alternate horizontal layers of aggregate and mortar against the shuttering and between any brickwork (which to some degree compartmentalised it, and thereby aided in its placing). When all this work was completed and the concrete cured, the dome structure was provided with its cladding of tiles of the required material.

These various operations required secure and spacious working platforms which could only to arranged by scaffolding set in some way against the retreating extrados of the dome under construction.

On the completion of these external operations work was transferred again to the interior of the building. The first task was to remove the massive wooden centering—always a dangerous operation and here, with a span of 40+ m, a very dangerous one. The appropriate drill was to carry it out in two stages: first to ease the centering and then to strike it. In theory centering was always set in place in the final instance resting on folding wedges, and these could be knocked out of position so that the centering subsided a little. If the concrete remained in position, well and good. If, however, it was defective in some way and not self supporting, then it 'failed safe' by subsiding only the few centimetres with the eased shuttering. That was the theory; but in practice the operation remained a dangerous one.

Supposing all was in order with the concrete structure, then the wooden centering was "struck" i.e. totally dismantled and removed. This task was not a light one, and in the Pantheon it must have been very difficult indeed to carry out. Eventually if these operations had gone without hitch, the concluding phase of work on the dome was undertaken—the plastering of the soffite. Plastering is heavy labour and the magnitude of the task in the Pantheon is daunting. The only mitigation was that the oculus reduced it somewhat. From the point of view of installations the plastering was very important. Whatever scaffolding may have been required to build the dome and its centering, total access was required to the face of the dome for its plastering. In this fashion it seems that eventually the interior of the
400 Pantheon was fully scaffolded, i.e. the scene of a forest of rising timbers. This being the case, building programmes designed to avoid this measure by e.g. the use of cranes for setting and holding in place flying shuttering are questionable. On the contrary it is well possible that standing scaffolding rising from the pavement was in use to the necessary (varying) degrees for all required purposes—i.e. for setting the centering in place, and for applying the plaster decoration to the soffite of the

concrete dome when it had become a self supporting structure and the centering had been struck.

Appendix: Large Span Dome Construction after the Pantheon

Discontinuance of concrete dome construction

Large span concrete domes continued to be built by Roman Builders until concrete construction came to an end during Constantinian times shortly after the removal of the Imperial capital to Byzantium (cf, e.g. the Temple of Minerva Medica, 411, 412 span 24 m; The Mausoleum of St Helena, span 20 m, ca 350 AD). Also domes of ashlar masonry continued to be built in the East Roman provinces, but of relatively small span (e.g. ca 5 m–6 m). Never during antiquity was ashlar masonry used to construct vaults or domes of large span. Ancient builders always tried to minimise the self load of domes by using light materials and considered ashlar masonry impossibly heavy (cf C. Mango, "Byzantine Architecture," p. 9). Large span ashlar domes are Renaissance and later in date, e.g. new St Peters in Rome, span 42 m, ca 1560 AD.

With the lapse of concrete as a building material, concrete domes ceased to be built, and the adoption by Christianity of the timber framed gable roof basilica as the form appropriate to monumental church building directed the concern of builders elsewhere for two centuries. It was not until the first half of the 6th century AD that the question of constructing domes of large span again came in issue. This occured in a striking manner, the circumstances forming a parallel to the construction of the Pantheon 400 years previously. The construction of Justinian's Ayia Sophia was bold and novel, and was unmatched by any later Byzantine church building.

Before considering the procedure of constructing the dome of Ayia Sophia (span 32.60 m) and the installations provided for this as a sequel to the construction of the Pantheon dome (span 43.30 m) two basic considerations must be called to mind. The Pantheon dome was built of Roman Concrete and surmounted a round building, factors which were characteristic of Roman domes. On the other hand the Ayia Sophia dome was built of brick and surmounted a rectangular plan. This involved two consequences. The building material of the Ayia Sophia dome, unlike that of the Pantheon, did not require the installation of shuttering to contain it while plastic. That is to say the installation of centering at Ayia Sophia was an issue entirely on its own merits, not involved in any way with the provision of shuttering. Secondly whatever centering was required for building the dome at Ayia Sophia there was the additional consideration of provision for building the pendentives, the "pendant" spherical triangles to convert the square ground plan 298–300

Ayia Sophia Brick masonry dome

into a round one to be domed. Centering required for this purpose inevitably must have been standing centering.

In fact it is possible by various devices to build brick domes without centering, but this was not the procedure at Ayia Sophia which was constructed with the use of centering. Thus the same questions of building procedure and installations arose as with the Pantheon 400 years earlier. Was the centering flying centering or standing centering? Was the work of constructing the centering carried out by way of a forest of heavy timbers rising from the pavement, or could this be avoided and centering installed supported in some way other than from the ground? Mainstone in his comprehensive treatise on Ayia Sophia (Hagia Sophia London 1988) while discussing exhaustively the fabric and the statics of its arcuated construction (cf e.g., pp. 112, 164–5, 172, 204, 207, *et pass*) avoids pronouncing on the nature of the centering used in this arcuated construction. He notes that it is theoretically possible to construct brick domes with flying centering or with standing centering—or with no centering at all (cf pp. 262, 273).

He also notes that there is evidence that both flying centering and standing centering were known and used in earlier Roman construction, including that of large scale concrete domes (cf p. 273). Further he notes that Roman builders had, on occasion, built domes of brick as well as concrete (cf the Temple of Diana
378 at Baiae v Adam, p. 205, fig 450). Thus whatever type of centering may or may not have been used for the construction of the brick dome (and semi-domes) at Ayia Sophia, precedents existed in Roman building of several centuries earlier. In short although Mainstone avoids the subject of the nature of the centering employed at Ayia Sophia, effectively he states that the installation and procedure of domed construction at Ayia Sophia in 532 AD–537 AD were those employed by Roman builders during the first and second centuries AD—i.e. there had been no innovation in the procedure of constructing large span domes in the interim. The building material at Ayia Sophia was different but the building procedure the same as at the Pantheon.

In this fashion the question of the nature of the centering employed at Ayia Sophia stands as it stood for the construction of the Pantheon dome. Failing any detailed study and expert opinion on the subject, a common sense appraisal is that in spite of the enormous trouble and labour involved, a forest of standing scaffolding was
400 the most convenient installation providing for all the requirements of constructing the Ayia Sophia dome, including its centering (cf Vol. I, p. 142) and also for the subsequent decorative plastering of its soffite when the structure was completed.

To the above statement that there had been no innovations in the procedure for building domes since the construction of the Pantheon, a rider must be added—a very strange one, indeed. Only a decade before Ayia Sophia was built (ca 520 AD–530 AD), a monumental tomb had been built at Ravenna for Theodoric the

The Mausoleum of Theodoric the Ostrogoth. Monolithic ashlar dome

last Ostrogoth king to rule there before the region was conquered by Belisarius and returned to Byzantine dominion (v H. Johannes, "Das Grabmal Theodorich zu 301
Ravenna").

The tomb is a well designed monument of heavy ashlar comprising a ground storey in the nature of a sepulchral crypt, and an upper storey serving as an assembly hall. The crypt is a massively constructed decagon in externals, while the upper hall is internally circular. Notwithstanding that the (cross) vaulted roofing of the crypt shows a mastery of vaulted construction in ashlar masonry and that the upper hall is of reasonably restricted span (ca 10 m) so that possibly it might have been roofed with a built ashlar dome, the roof is a monolithic "lid" in the form of a segmental (saucer) dome of enormous burden (far in excess of 100 tons). Details of the masonry show that it has a background in then contemporary Syria, and accordingly the architect is presumed to have been Syrian. However there is nothing like this monolithic dome in Syrian building. Presumably the form of the roof was dictated by symbolic considerations, perhaps connected with Theodoric's Gothic origin.

The constructional history of this strange aberration is reasonably apparent. The block was quarried and dressed near Aquilea, ca 150 miles or ca 230 kms North East of Ravenna around the Gulf of Venice, and a convenient haulage way can be identified from there to its location at Ravenna (a recognised Via Maritima). There are two possible methods for raising the block into position ca 11 m above surrounding ground level. Both are founded on primaeval expedients of engineering practised since Late Neolithic times—the one based on the use of the inclined plane, the other on the use of the lever. The former is the simpler and thus the more likely. The haulage way was brought in to approach the monument horizontally at the required level, and the completed masonry of the monument was englobed externally and internally by an earth mound to secure its immobility. The monolithic dome was then hauled into position atop the masonry walls. Then the earth 100
mound was removed and the monument complete with roofing stood revealed. A more sophisticated alternative has been suggested. The very massively built crypt was constructed and then strutted out to render it secure against displacement. The monolithic lid was hauled into the required position over this masonry. It was then raised up vertically to the required height by repeated levering and chocking, and secured in position by heavy timber props. Then the slighter masonry of the upper storey was built up beneath it (v R. Santillo, "Saxum Ingentum" *Archeologia*, Sept–Oct 1996).

It is impossible to pass judgement on the superiority of one method or the other without being aware of all practical consideration obtaining at the time. Certainly in the abstract today the former method appears more convenient and straight forward.

Consideration of building site development and installation for the construction of Ayia Sophia, the metropolitan cathedral church for the Roman Empire, is a fitting terminal to a survey of building site development in the Ancient World. This is a record extending over five thousand years. It is an outline of the astonishing technical devices of men to bring together, shape and raise up at a time hundreds if not thousands of tons of enduring matter for ends which are not material. Building site development is a mirror of government, and the counterpart to war in revealing essential human nature in action, as is evidenced by the two famous works of Procopius.

Building site development a mirror of the age

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CHAPTER FOUR

WOOD CONSTRUCTION

A. Origin and Development
B. Varieties of Material
    1. Light Pliable Members
    2. Rigid Timber
C. Structural Disposition
    1. Load Bearing Structure
    2. Framed Structure
D. Mode of Construction
    1. All Timber Construction
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A. *Origin and Development*

Historical primacy of wood construction

Since neither wood nor tree are words of precise scientific definition, wooden building construction comprises a miscellany. For convenience all vegetal material employed (e.g. leafy branches, rushes, etc.) is usually included in this category. Perhaps an obvious distinction can be drawn between pliable material (rushes, etc.) and rigid material (wood proper). Building with the former material has suggestions of that type of animal building best known to man—the nests of birds—and has always been considered a "primitive" type of construction.

For whatever reason men never lost the idea of the historical primacy of wood construction, even though little material remains of early wooden construction survive. This is nicely demonstrated by Vitruvius in the philosophical introduction to his building manual. There (Book II), proceeding closely along the path of Lucretius, he ascribes the origins of civilisation to the lessons imprinted on the minds of men by their observation of natural phenomena. The basic steps he mentions all relate to wood. There is first of all man's control of fire which he acquires from his experience of forest fires (arising through acts of nature). The common hearth so formed drew men together into communities and gave rise to the need

Wood skeuomorphs in other construction

to build shelters, which Vitruvius reckons as the beginning of man's handicraft. And the first type of built shelters he mentions are those made of wood (of "green boughs and twigs"). This idea is supported by a recital of wooden building by "undeveloped" tribes living in wooded regions during his day (e.g. in Western Europe, or on the Black Sea littoral).

These suppositions are worth mentioning because they have exercised a direct effect on modern archaeology and building history. They have promoted skeuomorphic explanations of building construction—i.e. the theory that at times the forms manifested when building in a certain material have no logical explanation in the technology proper to that material, but make sense if referred to similar construction in another material. This gives rise to the supposition that the construction was invented in the latter material, and the form then identically reproduced (without functional necessity) when the building material was changed. This analysis is of widespread application beyond building, but when applied to building construction, the original material proper to the form is always wood. And it would be very difficult to adduce some form expressed in wooden building which could be explained through its prior origin in another material. Particular instances of this analysis will be adduced in the following discussion; but men's ready acceptance of the derivation of construction details through their origin in wooden construction is noteworthy in itself.

Availability, workability and suitability for roofing (i.e. for providing total shelter) has made wood always the indicated material for initial, emergency and temporary building. There are, however, limitations to wood as a building material in its durability (particularly as conditioned by inflamability). In this way whereas wood has always remained in general esteem as a material for domestic and utilitarian building, on occasion it has been subject to some adverse discrimination for monumental building. The essence of monumentality is durability and this sometimes has given rise to the concept of a scale of "notability" of materials with a descending order from stone to wood. This idea, however, is in no way of universal application. In fact substantial wooden structures were developed already during the Neolithic period notably in the wooded regions of Western Europe. And these included some public building. It is to be observed, however, that no substantial wooden building has been preserved in integral form from the ancient world. Thus much of the discussion concerning ancient wooden construction is in reality discussion of post holes in the earth and of lodgements in masonry for wooden members. Also some discussion of ancient wood construction has an even less tangible basis, proceeding from the skeuomorphic analysis of construction in other materials. It argues that since some forms manifested in e.g. stone construction can only be explained as being taken over from prior construction in wood, therefore such wood construction must have once existed, even though no material remains of it subsist (because wood is a very fugitive material). However this is, in effect, arguing from a negative, and must be viewed circumspectly.

Pliable reeds, canes etc

B. *Varieties of Material*

As previously noted neither wood nor tree have a scientific definition and thus when used in building construction vegetal material which would not normally be spoken of as wood is generally considered under this heading. Equally the botanical variety of what are always considered trees is very great. These differing trees of all shapes and sizes in turn yield wood manifesting very different qualities. This wide variation in the nature of the different species of wood specifically recommends the use of different types of wood for different purposes in building construction. Scientific understanding of this matter requires some knowledge of botany, but the practical discrimination between different types of wood in ancient building construction is always listed and discussed in any manual of ancient building (or of ancient materials). Thus it is not rehearsed here. Here the use of wood in ancient
104, 105 building is considered under the following categories: light, pliable members; heavy
101 rigid members, both unhewn and hewn to form.

1. *Light Pliable Members*

Pliable woody material was used in ancient building both structurally and as cladding. There are two principal modes of forming structures out of such material: to bind them together; to interweave them. Both modes are employed to fashion both structural members and cladding. The former produces the rigid units (of a frame) but it can also be used to attach cladding. The latter is the mode of production for much cladding (e.g. matting), but it can also be used to constitute the structures.

104, 105 Pliable reeds, canes, stalks etc. can be formed into rigid members by binding them together into a bundle. These units can be used as members of a frame, or as free standing posts, columns, etc. If used for spanning, i.e. as lintels, or roofing members, then they are set as arches not as beams. The appearance of these curves of natural flexure in structures built of other (rigid) materials is often taken to indicate an ultimate origin for the design in constructions out of pliant materials.

As an alternative to constituting pliant material into a structural frame such material can be skilfully interlaced as a self supporting fabric (a shell) which provides a shelter, inevitably taking on a beehive form. Essentially this construction avoids compressive stresses as far as possible and most determinate stresses are tensile, where the pliant units are resilient. This shell may be further clad with appropriate material.

Pliant material used for initial & temporary construction

Broadly speaking the same range of pliable materials which can be used to provide the structure of a building can also be used for cladding that structure in a homogeneous way. Such cladding may be more or less natural in the form of leafy branches, or it can be fabricated—e.g. withies or osiers woven together (= wattling). In either case it is often plastered over with mud or the like, perhaps constituting a mixed material (e.g. wattle and daub). A specialised material of this nature for roofing pitched roofs is thatch.

In conclusion it is to be noted that whatever precise mode is employed in construction out of pliant materials, almost inevitably much rope, cordage or other binding material is required. Construction in such pliant materials remained common into contemporary times and there are ancient representations of such huts and cabins.

One or two glances in historical context at construction out of pliable wooden material are given to support the great antiquity with which this mode has always been invested. The "workability" of such material is eminent and demands little or no technical equipment—i.e. it approximates the circumstances of animal building. However it is evident that virtually no direct evidence (i.e. material remains of such construction) survives over the ages.

A beginning may be made by reference to the Early Neolithic Round House, widespread in the Ancient Middle East. Over the last half century or so excavation of these sites has been prolific. On numbers of occasions a succession of round houses has been observed built over one another on the same emplacement. This succession of the same building form has sometimes revealed a succession of different building materials. Whereas the Neolithic Round House of the Middle East is characteristically built in mud (mud brick or rubble in mud mortar), the earliest structure on the hollowed out emplacement is sometimes shown by the discolouration of the soil proper to organic decay to have been of light vegetal material (branches etc.). The succession has been observed on key sites in Jordan and in Cyprus. (For Jordan, e.g. Jericho, v Ancient Building in South Syria and Palestine, pp. 25, 456–57. For Cyprus, e.g. Khirokitia, Sotira, Erimi, Lemba, v Ancient Building in Cyprus, pp. 42–43; 44–45; 49; 57; 310; 493).

The following observations might be drawn from this material.

Shelters fashioned out of light woody material were known early in building history. However the beginning of the Neolithic Era is no longer considered to be anything like the dawn of building construction. Hence the Neolithic Round Houses can not be regarded as establishing some linear definition in the overall building history of humanity. Within its particular ambit it is an ancient example of the continuing tendency for light woody material to be used if practical at the outset of building in a certain locality, to be later replaced by some more solid material (here load bearing mud and rubble). Also within the terms of the Levant

Pliant material in Nile Valley

area, Round House building excavations have shown that the tradition of the Round House emplacement goes back into the Mesolithic Era, several millenia before the Pre-pottery Neolithic, and it appears that in Mesolithic examples the overhead shelter was, in fact, provided out of light fugitive materials (v ABSP, pp. 23–24). However, in this connection much of the archaeological reporting may be based again on argument from a negative—i.e. there is no surviving evidence of roofing out of solid material (mud etc.) therefore it must have been of light vegetal composition.

Other interesting evidence of early construction out of light pliant material is provided by remains in the Nile valley during Neolithic times (cf the Badarian).

Here the interest particularly turns on the influence of this type of construction on later building in solid material (brick and stone). In Egypt this development is unmistakeable and has been well studied (NB G. Porta, *L'Architettura Egizia delle origini in legno e materiali leggeri*, Milan, 1988).

It has always been a preferred thesis that the earliest settled inhabitants of the luxuriant reed banks and cane brakes of the Nile were essentially of African stock. Certainly the type of dwelling built from this resilient but pliable riverine growth has always remained evident in many regions of Africa—associated almost invariably with a round plan (the beehive hut). Material remains of these Neolithic dwellings in the Nile Valley are not very substantial. They include post holes to show the disposition of woody material, the occasional chance preservation of actual woody members (e.g. long canes), soil discoloration due to decomposition of organic material and also presence of ashes to show the original presence of woody structural members, together with occasional well preserved pieces of matting to indicate the cladding (v Porta, pp. 36–37, 43, 45–46, 51–53, 151–53).

The circumstantiality of the derivation in Egypt of forms in later solid building material (brick and stone) from forms originally expressed in pliant woody materials (palms, canes, reeds etc.) arises not from the superior preservation of the material remains of the ancestral construction, but from the circumstantial evidence peculiar to Egyptian civilisation.

In the first place there are numbers of ancient representations of construction in the original light pliant material, where the identity of the materials is manifest. These representations are very early pre-dynastic or archaic, i.e. prior to the subsequent expression of the forms in solid brick and stone (cf Porta, Pls VI–X). Among them a prominent subject represented is the Nile Boat. These splendid vessels constructed of papyrus bundles, were all furnished with deck cabins manifestly reproducing the form and construction of traditional huts and cabins on dry land. Among the forms here represented are several approximating those renowned in another context. Egyptian ultra-conservatism ascribed certain unvarying forms as proper to several basic religious or hierachic structures, e.g. the *per nu* and *per ur*

Survival of wooden forms in later stone building

sanctuaries, the Heb Zed festival pavilion (v Porta, pp. 68–97). These select forms go back to the original construction in light materials. Moreover lapidiary representations of some of these structures were received into the heiroglyphic script. In this fashion original forms constructed during Neolithic times in pliant woody materials are reliably attested.

Equally the reception of these forms into later monumental construction in brick and stone is made vividly apparent by Egyptian building history. The funerary complex of King Zoser at Saqqarah (ca 2650 BC) is an astonishing world première in monumental finely dressed stone building. And here, as all concerned have pointed out with varying rationales, although the technique of small stone masonry was perfectly mastered, the forms expressed are recognisably those proper to construction in pliant woody material. This includes both overall structural forms and, even more obvious, the ornamental detailing. Thereafter as the logic of constructing in the new solid materials prevailed for the overall form of edifices, nonetheless all the detailing of the structural ornament (i.e. The Egyptian Order) remained transparently derived from the original functional details of construction in pliant vegetal material—e.g. the torus rolls and their decoration, the cavetto cornice, the khaker frieze and the various plantform columns and capitals.

2. *Rigid Timber*

Requisite axes for telling timber

The use of solid heavy timber members in building construction would seem to depend categorically on possessing a tool (axe) capable of felling trees—i.e. of cutting through substantial tree trunks of say 30 cms or more in diameter. With the felled trunk available the earliest stone and wood tools appear quite adequate for converting it into whatever form required—debarked logs or posts, squared baulks, planks etc. (Axe, adze, knife, chisel and auger were available before the use of metals.) However it is not readily apparent to the senses that flint hand axes/cleavers or polished stone "celts" will serve to fell heavy standing timber. It 101, 102 is this common sense proviso which renders suspect some recent assertions that Palaeolithic man built out of wood substantial dwelling places for himself in open country. The wooden structural members Palaeolothic men could procure regularly for themselves are likely to be of very restricted section (i.e. poles) and this, together with the cladding of the frame (generally imagined to be with skins and hides etc.) make these shelters essentially tents rather than solid durable buildings.

On the other hand, there is no doubt that with rapid development of metal (bronze) axeheads men by the third millenium BC were efficient and practiced 103 lumber jacks felling the biggest trees imaginable, e.g. the cedars of Lebanon. It is the use of heavy sections of timber in building during the Mesolithic and Neolithic period which requires convincing experimental archaeology for its explanation.

Nonetheless previous discussion and restoration of Neolithic buildings have at times indicated the use of heavy wooden members in the construction. This matter will be referred to again in the treatment of individual instances.

Fixing of wooden members

Given the use of wood throughout the history of building from earliest times the immediate question arises of the means adopted to attach and fix together wooden members and elements. Here it is possible to give a summary statement which is reasonably valid. For fixing together structural members a distinction exists between unhewn and hewn timbers. For rounded poles and logs the natural (and most effective) means of fixation is by lashing together (if advisable the lashings grooved in). For substantial hewn timbers, it may be said that throughout ancient building they were fixed together by cutting complementary lodgements and engagements (i.e. projections and recesses) in the members to be joined. 114, 115 Thus they were fixed together by what is technically known as joinery. Carpentry (= the use of nails) played a minor part in ancient building construction, and some references to nails, both in ancient records and in modern archaeology, can be misleading. Generally speaking the use of nails with wood did not refer to fixing structural members together—but rather to the attachment of cladding, plating, veneering etc. A notable instance is the attachment of metal sheeting or ornament to wooden grounds (NB also fixing terra-cotta ornaments and revetments to wooden grounds, the fictile revetments of classical temple building). The wholesale use of nails as known in the modern world only appeared during antiquity in connection with the use of wooden shuttering for Roman Concrete.

Two other methods of fixing and attaching wood were practiced in antiquity. Glue (as a by product of the slaughter of hooved animals) was more apposite to cabinet making than to building, but could be used on occasion. And a significant means of attaching planks and boards together was by way of sewing. This may sound somewhat untoward, but if it is referred to ship building, it is seen to have been standard practice.

C. *Structural Disposition*

Wood can be used to fashion both load bearing and framed structures.

Wooden structures

1. *Load Bearing Structure*

In densely wooded regions with suitable trees an "instant house" can be assembled requiring almost nothing except the felling of trees together with the labour resources to pile the trunks horizontally, one on top of another, to head height. With these logs jointed together at the angles a very solid and weather tight

Load bearing & framed construction

dwelling can be constructed—indeed what is virtually a fortress. This type of structure is one of the examples Vitruvius (II.10) quotes to show the ancestral nature of wooden construction—and is the famous "log cabin" dwelling of American pioneers. However this mode of building is not the characteristic one for wooden construction.

2. *Framed Structure*

The strength of wood in tension means that wooden spars are the natural material indicated for roofing (the spreading boughs of a tree are cantilevers stressed in bending). In this way the frame of an entire house (walls and roof) can be assembled by carpentry or simple joinery out of relatively slight sections of timber. This frame can then be conveniently clad e.g. with wooden planks (but also with panels of other suitable non-load bearing material—e.g. wattle and daub). Thus 119
wood is the ideal and characteristic material for building framed structures.

D. *Mode of Construction*

1. *All Timber Construction*

It is self evident that buildings constructed of light woody materials (branches, palms, canes, rushes etc.) are inevitably entirely wooden. And here it may be noted that constructions of such materials could, at times, attain impressive dignity and proportions. This is conveyed strikingly by the modern *mudifs* of the Southern Iraqi marsh arabs. These long tunnel like buildings have been compared with Gothic cathedrals. In fact they could now be taken as the model for the ultra contemporary last word in the design of high speed Railway Stations and Air Terminals. Equally load bearing wooden construction (the log cabin) is necessarily an all wooden building—and one of very striking character.

Wooden framed buildings may be of entirely wooden construction, or may be not. Other building materials can be used to clad the frame, and sometimes the material is quite other than wood and also plays a significant part in the construction, so it is not in order to consider the building an all wooden one.

The evidence for all wooden buildings consists largely of post holes and other traces. Also in the occasional survival of actual wooden members with characteristic cuttings etc. Finally there is, as so often, the oblique evidence provided by "borrowed" forms displayed in other materials.

The most direct evidence of all wooden buildings in the ancient world are the remains of the wooden houses in temperate Europe. Here from Neolithic times

European timber framed long houses

(5th Millenium BC) abundant traces of post holes and other impressions together
113 with the actual survival of timbers (at boggy sites) reveal substantial dwellings of
a standard design and construction, which always remained characteristic in these
regions. Spoken of here are timber frame houses with pitched roofs, the framing
119 of very solid timber and the cladding either of boarding or flexible woody material. The characteristic design is the long house (with evocations of the modern
Dayak long houses in Borneo), but there are other designs (the round house and
the square house).

The framing members from earliest times, may be either unhewn logs or hewn
112 timber, sometimes both are used together. A robust section may be ca 40 cms. The
solid wooden cladding of the wall frames was boarding. These units may be set in
117 position horizontally or vertically. Contrary to modern practice vertical boarding
was perhaps more prominent. It could take the form of a split log palissade which
sometimes left a recognisable impression in the soil. A common alternative to
boarding was "wattling". This was a reversion to light flexible material. Withies,
118 osiers (willow canes) were interwoven in the manner of wicker work. Generally
such panels were daubed over with mud plaster to constitute "wattle and daub".
Sometimes both boarding and wattling were used together in the same building,
the distinction being evident from the impressions remaining in the soil. In some
long houses boarding was used for the panelling of the living quarters at the rear and
wattling to enclose the vestibule at the front providing work and storage space etc.

For the pitched roofing similar alternative teguments were available: shingles
137 (i.e. split wooden "tiles") and thatch (bundles of rushes). Both these materials have
remained in use into modern times.

It is of some interest to review these general remarks on all wooden building in temperate Europe in the light of the recent publication of the excavation of an Iron Age Hill Fort at Danebury near by the river Test in Hampshire, Southern England. This interest arises not from any striking or novel discoveries but from the efficiency of the excavations, together with its sensible reporting which raises general background issues in the limitation besetting present day knowledge of wooden buildings in the Ancient World.

116–118 The site of Danebury was continuously occupied through ca 500 years. Thus it flourished at a period some 4,000 years later than the establishment of the tradition of wooden building in such parts of Europe. The lengthy floruit of the one building tradition is in itself interesting. It long outlasted megalithic construction which developed out of it. And it had a longer life span than, e.g. the long lived Egyptian fine stone masonry tradition (ca 3000 BC–150 AD). Yet in spite of this history much less is known of it in detail than is known of Megaliths in Europe or of Egyptian Pharaonic Masonry. These seldom mentioned things are adverted to in the Danebury publication.

European type site At Danebury the evidence of the wooden buildings (residential, storage and perhaps religious) across a considerable time range is profuse; but, as the report notes, this profuse evidence conveys only very limited information of the original wooden structures. Also, as the report points out, in some circumstances possible wooden building would not even manifest these traces. In short much less is (and can ever be) known about the building history of Danebury than if the material had been stone or brick.

Even so there are matters of interest revealed at Danebury which are little noticed. It has been remarked that wood construction is characteristically framed construction whether the panelling be substantial boarding or light wattling. Nonetheless at Danebury the surviving evidence appears to remove both types from the category of framed construction. The round house dwellings built of wattle and daub ("stake 118
houses") on occasion reveal very clear evidence of the emplacement in the earth of the vertical members (hazlewood withies) for the wattling (Danebury, p. 60, fig 40). This, however, conclusively negates by the absence of larger post holes that any vertical framing existed. Thus this type of round house is not technically framed construction. It can only be described as a stiffer version of the round cabin of light pliant material (e.g. rushes), perhaps best referred to as shell construction.

Equally the one round house out of solid vertical boarding ("plank house") was 117
not of normal framed construction—perhaps as would have been so, if the plan had been rectangular. The solid vertical planks were set continously side by side to describe the complete circular plan, without the existence of vertical framing posts. It is, of course, possible that heavy horizontal baulks were incorporated as a framing of a sort (a stiffening). The reconstructed drawing shows such a presence in the form of a wall plate, certainly required as a seating for the conical roof frame with substantial wooden spars. The distinction between such construction and that of wholly enframed boarding is reminiscent of the two basic modes of wooden ship building: (a) where the ribs of the hull are primary and the boarding is fixed to the ribs; and (b) where the boarding of the hull is primary and the ribs affixed to it. Also boarding, whether horizontal or vertical, or whether set flush or overlapping inevitably requires to be nailed to a frame. The members of the frame are properly set together by joinery, but if clad with boarding, then nailing is the obvious device for any large scale work. There would be a considerable literature on such subjects if ancient wooden building had left traces of the same order as brick or stone building.

Here also it is convenient to recall Vitruvius' (II.8.20) reference to the wattle and daub walling of tenement houses in Rome of his day. He execrates the construction because of its weakness, impermanence and inflamabililty, expressing the wish that it had never been invented. The terms of his castigation suggest that (like Roman concrete) it was a recent development in building construction. Was it introduced into speculative building in Rome from observation of its occurence and utility in the northern provinces of the Empire? It may well be that wattle and daub is better suited to detached building rather than high density urban terrace building.

Appendix: Timber Circles

Neolithic timber circles ancestral to Megalithic construction

In the interest of maintaining a homogenous subject discussion has been limited as far as possible to the dictionary meaning of buildings, i.e. enclosed and sheltered spaces where man may shelter or store their possessions; and in principle other constructions, e.g. roads and bridges, have been excluded. Therefore the following remarks are added rather as an appendix, since they concern constructions which neither enclose space nor provide shelter to man or beast. However they are evidently public as opposed to domestic "constructions". Furthermore they are the direct forbears of renowned stone monuments. Spoken of here are Neolithic "timber circles" of temperate Europe (Britain, Holland, Germany etc.) formed from solid posts or tree trunks set upright in the soil to give in plan a
106 circle or concentric circles. It is possible that they may have incorporated some
107 roofing, but more likely they did not. And while they may have been set within an enclosure (a temenos), it is unlikely that they incorporated enclosure walls in
108 their design. According to recent pronouncement, the essential type of the timber circle is revealed in the stone circle which was its successor (e.g. Stonehenge) both in time and, on occasion, in place.

These timber circles articulated sacred space, they did not shelter it nor enclose it. They are arch-typal examples of the "rural sanctuary" where it is the space which is sacred not any building erected there. This tradition was long lived in the ancient world, e.g. Herodotus (I.131) remarked on it as "subsisting among the Persians of his day—and strange to Greeks". Traces of it can also be seen in the (otherwise bizarre) custom recorded by Strabo (IV.4.3) concerning the priestesses of a temple on an island off the mouth of the Loire. He states that one day each year the priestesses removed the roof of the temple and then set it back in place before the end of the day. This would seem a rite connected with sun worship, but he says the "priestesses of Dionysos".

The "timber circles" are monuments of religious, funerary and ceremonial purpose, exactly parallel to their better known megalithic counterparts; and sometimes
109 (like them) they are associated with "barrows", earth mounds (v Gibson, pp. 81–97). Also in Holland, in the region of Drenthe, waterlogged timbers indicated a small
110 "skeleton" square temple of timber posts and beams (ca 1400 BC). Equally the tradition of skeleton timber construction may be preserved in the wooden skeletons

Setting upright massive timbers

of shrines (or dwellings) set up within the funerary mounds of Skythian chiefs in South Russia, ca 600 BC (v Singer I, fig 213).

These "timber circles" vary in stature and complexity from a single ring of posts, ca 10 m in diameter, to striking monuments with multiple (up to 6) concentric rings and an outer diameter of ca 40 m—e.g. Durrington Walls, Wiltshire (cf Gibson, pp. 155–73 for a gazetteer).

Whatever may be the status of timber circles as buildings, they are important in the history of building. On occasion the timbers were massive items weighing several tons. To raise these truly vertical stably fixed into the ground was not a matter for the combined strength of strong arms. Some mechanical device was required. Since it is known that at the time no means existed of clean lifting (i.e. by block and tackle), then the only practical device was by hauling base first up a ramp (inclined plane) so that the base then slid down a steep declivity into position. This operation was than followed by hauling the post into the vertical with ropes affixed to the top of the shaft. Fortunately the emplacement of some timber circles still preserve on the ground vestiges of these earthern ramps to demonstrate the use of this device (e.g. Woodhenge, Wiltshire v Singer, I, p. 314, fig 202; 108 Arminghall, v Gibson, p. 72, fig 50). In this way the monumental timber circles of Northern Europe are very early attestations of an engineering process which remained standard during several millenia alike for European megaliths, Egyptian obelisks and other monoliths.

2. *Mixed Construction*

"Mixed construction" is a common description occuring in the study of ancient building and its possible ramifications are very spreading. In the interest of conciseness it is useful to make one or two preliminary observations. In the first place the term is used in two different senses.

(1) when more than one material is incorporated in the construction of a specific part of a building—e.g. the walls incorporate both brick and stone. 144
(2) when the several parts of a specific building (e.g. the walls and the roof) are constructed of differing materials—e.g. the walls of the building are of stone, but the roof is of wood. 186

Also it is to be noted that this analysis relates to structural materials, i.e. those which provide the stability of the building. As a general rule it does not refer to ancilliary materials, e.g. surfacing, cladding etc. If a wall is built of brick, it does not become a mixed construction when it is plastered over with lime, gypsum or mud. Nor does it become of mixed construction if it is revetted with wood panelling or ivory plaques.

Wood in Bronze Age masonry —Crete

(1) Mixed Construction of wood and other materials within the same element of a building.

This is the more commonly intended application of the term mixed, and essentially it refers to wall construction. Also to speak in broad terms its regional ambit is the Levant and the Mediterranean. Egypt, Mesopotamia and Northern Europe have typically more uniform constructions. However within the Levant and Mediterranean walls even of monumental buildings are generally constructed from a 186 combination of stone and brick together with a considerable (but varying) component of wood. This mixed construction incorporating much wood is probably best revealed in Bronze Age Cretan building. A surprising amount of wood has 142, 143 been preserved among the remains, and the construction has been closely studied (Shaw, *pass*).

This study has drawn together the traces of use of wood revealed by impressions in mud and plaster, together with recesses cut in monumental stone masonry. Where relevent the latter evidence is very informative. In the developed "palatial" building of Bronze Age Crete (ca 1600–1400 BC) a common masonry ordonnance is a finely dressed stone socle (generally of orthostates) surmounted by a rubble or mud superstructure. The upper bed joints of the dressed blocks evidence small recesses regularly distributed which are obviously mortises to take wooden tenons (some of round section, but generally of rectangular section). Whereas it was once assumed that this device was designed to fix in position blocks of the super-incumbent masonry course, the disposition of the mortises clearly shows that the dowels are to fix wooden stringer beams together with upright posts into the masonry structure.

From this evidence, it is clear that the typical construction of the "palatial" buildings of Middle Minoan III and Late Minoan Crete (so famous from the excavations of Knossos, Phaistos, Mallia, etc.) was a socle of finely dressed stone masonry, above which stood a mud brick/rubble superstructure profusely inset with wooden horizontal vertical and cross strutting. This exactly constitutes the category of mixed construction where dressed stone, rubble masonry, mud brick and wooden members share the load bearing virtue. The one relevent factor in the situation which is not conclusively determined is whether the timbering was fully wrought into a framed structure constituting in itself an independent structure.

A striking fact of comparitive archaeology emerged that this sophisticated building construction also appeared widespread in other localities within the Levant, Anatolia and Mediterranean region. Taken together with the missionising of Sir

Wood in Bronze Age Masonry —Levant

Arthur Evans this led to a Pan-Cretan sentiment, which was prominent during the first half of last century, but is no longer in vogue today. One locality where this Cretan type of building construction occurs and has been accurately studied is Cyprus. Here the chronology is later than in Crete. It is found in the palace buildings at e.g. Enkomi and Kition during LC III, at the end of the Bronze Age in the 13th cent. BC (ABC I, pp. 274–76, 414; II figs 241–50). Very illustrative reconstructions have been made of the construction at Kition. And here the architect O. Callot has 144 restored the timbering into a self-subsistent frame structure (*Kition V.1*).

Very similar building construction has been recognised at the North Syrian town of Ras Shamra (Ugarit) which was closely associated in trade with Cyprus during the latter part of the Late Bronze Age. However, whereas the superstructure of the walls at Kition was of mud brick, at Ugarit the superstructure of the walls was of 145 good rubble masonry. Here also the architect O. Callot has made very illustrative restorations of the construction based on meticulous accurate study (*Une Maison à Ugarit*, 1983; *La Tranche Ville Sud*, 1994). This building style is earlier attested in North Syria than in Cyprus.

In addition to these recent and very notable studies of the wooden component in building construction many notices and records have been made in the past of the significant use of wood in the rubble and mud brick building of the Levant and Anatolia. The subject is thus a ramified one with the wooden component ranging from a framed construction resembling traditional modern "half timbered" constuction to an auxilliary reinforcement of the masonry structure (ABSP I, pp. 363–69, 490; Naumann, Chap. 8). Also many reconstruction drawings of the profuse incorporation of wood into Anatolian mud brick and rubble construction appear in the publications of the Beyce Sultan excavations (S. Lloyd, *Beyce Sultan* 139–141 *I, II, III*).

Wood as an entire structural element

(2) Mixed Construction of wood and other materials used separately in different structural elements of a building.

The use of wood for a certain structural element of a building (e.g. the roof) when other elements are built of stone or brick etc. is obviously a very extended subject since it was widespread in time and place. Perhaps the most notable instances are the use of wood for foundations, for point supports, and for roofing when remaining parts of the building are constructed of other materials. In the interest of conciseness a specimen treatment of the subject is presented according to these categories, although there are other applications.

(i) Foundations. Wooden piles to rectify instable natural foundations.

Wooden piles emerging from marshy ground (indeed from shallow waters) constitute a familiar image, and it is not always kept in mind what exactly is in issue, *Wooden piles*

i.e. what is the function of the piles. Such piles may have been employed in the following interests:

1. To raise a building platform above surface level of
    a. water—e.g. of a lake (“lake dwellings”).
    120 b. land—e.g. low lying areas by rivers or lakes subject to flooding.
2. To improve the bearing capacity of natural foundations either by
    a. providing stable support below buildings which is engineered by
        53 (i) driving the piles down until they encounter solid, unyielding ground, e.g. bed rock (“bearing piles”), or
        (ii) driving the piles sufficiently into firmer soil that the friction between them and the soil provides the necessary stability (“friction piles”).
    b. so stiffening the area of yielding soil by the closely set piles that it acquires the necessary overall stablility to support the load of the building placed on it (“soil stabilisation”).

If the purpose of the piles is to provide a raised building platform, the piles are in effect fulfilling the same purpose as those of a bridge or a causeway. However, because the heads of the piles can be seen standing above present day ground level does not necessarily mean that they were devised in this interest. The surface level can be eroded over a period of time. Equally it should be apparent by the distribution plan of the piles whether they follow the lines of specific buildings are are, so to speak, mass deposed. In fact, although the use of wooden piles driven into yielding, water logged soil to better provide for building in that region is a common fact of anchaeological observation, the precise interpretation of the circumstances has remained in many instances contentious.

When the question relates to prehistoric Europe (Neolithic or Bronze Age) generally raised building/settlement platforms have been reckoned in issue, but there has been sharp disagreement as to whether the settlement has been raised up over the waters of a lake (for security) or whether the settlement has been raised up on low lying ground to minimise the risk of flooding. The latter explanation
53 has tended to oust the former.

On the other hand, in later historic times ancient records give direct information concerning the use of wooden piles and logs to improve the natural foundations for buildings when the site is (unavoidably) in yielding, water logged soil—e.g. the great archaic temple of Hera at Samos.

In this connection the remarks of Vitruvius are revealing. “If however solid ground can not be found, but the place proves to be nothing but a heap of loose earth to the very bottom of a marsh, then it must be dug up and cleaned out and set with piles made of charred alder or olive wood or oak, and these must be driven down by machinery (i.e. *a pile driver*), very closely together like bridge piles, and

Wooden columns with mud brick construction

the intervals between them filled in with charcoal and finally the foundations are to be laid on them in the most solid form of construction... (III.4.2). One can see this at its best in Ravenna, for there all the buildings, both public and private, have piles of this sort beneath their foundations" (II.9.11).

(ii) Columns

Common sense and observation indicate that where a point support was required to prop up overhead construction, the primordial material for this was universally a tree trunk. In this way it is a matter of course that wooden columns and pillars continued to be used in buildings which were not entirely of wooden construction. Evidence for this can be found in all building traditions of the ancient world; 124
Egyptian, Mesopotamian, Mediterranean, etc. This evidence is so manifold that it is useful to orient the discussion in advance by stating what appears to be a general rule, *viz* wooden columns do not long survive into use with monumental finely dressed stone building, nor with baked brick building. However they are commonly found associated with mud brick or rubble building construction. A brief survey of wooden columns in mixed construction is presented on a regional basis.

Egypt. The use of palm tree trunks for columns (posts) in prehistoric times is attested by the subsequent palmiform column, its imitation in stone (Jequier, 123
pp. 96–201). However when in Pharaonic architecture such wooden columns were rendered in stone, it was for "eternal" building—i.e. for temples and tombs in stone masonry. Wooden columns still continued in use for domestic building in mud brick (AAAE, pp. 2, 31), even, surprisingly, for royal palaces (also in mud 122
brick), cf the Theban Palace of Amenhotep III at Malkata (AAAE, p. 169) and the Palace of Akhnaten at Amarna (AAAE, pp. 186 ff, 201). Material remains of these wooden columns have almost entirely disappeared, but they can be recognised in ancient representations: both in mural painting (AAAE, p. 198, fig 68) and even more strikingly in the wooden models of their domestic life which Egyptians opti- 121
mistically provided for themselves in their tombs (AAAE, pp. 92, 93; pl 62).

Mesopotamia. The building of Ancient Mesopotamia has always been characterised as notable for its absence of columns—which is generally ascribed to the lack of both wood and stone suitable for use in building. However closer examination of the archaeological evidence shows that the earliest substantial building developments in Mesopotamia (4th–3rd Millenia BC) were aware of the use of point supports in building construction, and specifically that palm trunks were used for this purpose. Thus in Mesopotamia (as in general) the concept of a column goes back to the primordial use of tree trunks to support overhead construction. Perhaps it is fairer estimate to say that Mesopotamian building is characterised not by the absence of columns, but by the absence of columns used structurally, since in various manners most columns occuring in Mesopotamian building are ornamental in purpose rather than structural. Typically columns are used to flank important entrance ways (for a conspectus v D. Collon, Mesopotamian Columns *JANES* 2, 1967, pp. 1–18).

Wooden columns with metal sheathing

Evidence for the use of wooden columns in the mud brick building of Mesopotamia is (as elsewhere) largely indirect, since (as elsewhere) material remains of wood do not readily survive. In the first place abundant indication that palm trunk columns were an ancient feature of building construction in Mesopotamia is provided by mud brick imitations of such columns. There are many interesting examples of mud brick columns intricately fashioned to simulate the imbricated aspect of the palm trunk given by lopped off branches (D. Oates, "Innovations in mud brick…in Ancient Mesopotamia," WA 21, 1990, pp. 3, 92–98; pls 1, 2; figs 314).

More direct evidence of the actual use of wood columns surviving across the ages is afforded through the practice of ennobling wooden columns by metal (copper sheathing) and this metal plating was decorated to resemble a palm trunk. An early example of this technique was discovered at 1st Dynasty Ur. Even more striking were the remains of palm trunk columns at Al Ubaid in the Early Dynastic III period. Here were found not only fragments of copper plated wooden columns, but also palm logs coated with bitumen overlaid by mother of pearl, limestone and shell bitumen mosaic in palm tree aspect (Hall and Woolley Ur Excavations I, Pls IV, XXXIV.3, XXXV.6.7, XXXVIII). That the device endured in the land is demonstrated by its later occurence in Syria—Palestine and by its adoption by the Hellenistic Greeks during Seleucid times to become an accepted mode of luxury decoration at e.g. Delos and Delphi (Martin, p. 160, Vallois, pp. 299–310).

In quite other manner wooden columns came to be used in Assyrian imperial building as a direct influence (or import) from Neo Hittite North Syria. This can be seen in the occurence of the characteristic decorated stone "bowl" bases, and is also specifically referred to in Assyrian inscriptions, e.g. "A portico patterned after a (Neo) Hittite Palace which they call *bit hilani* in the Amorite tongue I built in front of (the palace) gates. Eight leaves in pairs.… of shining bronze, four ceder columns exceeding high I placed on top of the lion colossi and set then up as posts to support the (palace) entrance" (Ancient records of Assyria and Babylonia I, p. 804; II pp. 84, 367, 883).

The Levant and Anatolia

There was a well established use of columns in the Levant, not wholesale as in Egyptian and classical Graeco-Roman building but as occasional elements. Often these were principally of aspectual significance—e.g. to distinguish a main entrance. As a rule such columns were of wood and remains of stone columns in the area

Wooden column shafts with stone bases & capitals

are virtually non-existant (for an exception in Bronze Age Palestine v ABSP I, pp. 430–31). In the more monumental construction there was a standard ordonnance of a wooden column shaft with stone base and stone capital. Many examples of stone bases in the form of a decorated pot (bowl) survive in the region to give evidence of vanished wooden columns (ABSP 2 p. 431; Naumann, p. 136; Wesenberg Kapitelle und Basen, pp. 87 ff). There is some evidence both archaeological and textual that on special occasions (cf the symbolic columns Jachin and Boaz flanking the entrance to Solomon's Temple) wooden columns were ennobled by metal sheathing after the mode established in Mesopotamia during the third millenium BC (ABSP I, pp. 377–78, 429).

A somewhat unexpected development has been recognised in Late Bronze Age Cyprus. This is, in fact, not a wooden column but a wooden pillar. Stone capitals 125 and bases of simple stepped form have indicated the use of a composite wooden pillar just off square in section formed by securing together four stout timber baulks (ABC I, pp. 429–32).

(iii) Roofs

The roof is perhaps the most salient example of a part of a building constructed out of wood when other parts of the building are constructed of another material, eg brick or stone. Throughout antiquity (and indeed until the nineteenth century) 119, 126, 127–136 if the form of roofing was of plane surfaces, then the structural material employed was inevitably wood. If the use of some other material were preferred (or obligatory) then the roofing assumed a curved form at least in one contour. This fact holds good whether the building is a slight domestic one or an imposing monument. The only exception to this situation in the ancient world was the roofing of the great Egyptian stone temples. These buildings were all-stone structures provided with 255–259 flat, terrace roofs formed from massive stone beams and slabs. However the very high ratio of weight to strength of stone used in this manner made the roofing very inefficient compared with eg the stone walling of the temple. Whereas many Egyptian temple walls still remain intact up to roof height, relatively few stone roofing components have survived intact.

A brief survey of ancient wooden roofing is given with a primary distinction between flat (i.e. virtually horizontal) roofs and pitched (inclined) roofs.

Wooden framed roofs

(a) Flat Terrace Roofs. The flat terrace roof is apposite to a relatively dry climate. Even then an occasional torrential downpour is likely to ruin it; and it certainly needs constant seasonal maintenance to keep it in functional order. It is also unsatisfactory construction on account of its self weight. Very frequently in time the structure sags under its own load and eventually collapses. Nonetheless in all the dryer parts of the Ancient World (The Middle East, the Mediterranean) this form of roofing was universal for domestic building and also was used in some measure for monumental building.

Mud terrace roofing on wooden frames

132 The reason that wood is the structural material for this type of roofing devolves from the properties of matter. A member set horizontally across space will bend downwards in the unsupported run, and this will stress the lower part of the material in tension. The only conveniently available building material which is strong in tension is wood. Thus it is that the load of a terrace roof must be distributed through a wooden frame-work. The construction of such a roof varies in details but the system is constant. The cladding is of earth (applied plastic) often with a surface layer of more impervious earth/clay (which must be kept rolled). Below this the structure consists of a continuous layer of reeds or matting (or both) supported on more or less closely set wooden poles which span from wall to wall (or where necessary are laid over beams). Such roofing, in spite of its defects, remained unchanged in essence over great areas of the Middle East from Neolithic times until the 20th century. It can be reconstructed in more or less detail because, although the organic components (reeds, matting, poles) have generally decayed completely, careful archaeological excavation and observation often reveal their negative impressions left on adjacent earth or clay.

Very recently there has been some question of the ultimate antiquity of this form of roofing. When the pre-pottery Neolithic Round House was recognised as a beginning to solid building in the Middle East, it was apprehended that after light shelters of pliant woody materials the Round House form in mud brick or rubble was roofed by corbelling the solid load bearing material into a beehive structure as is the case with traditional modern round house building. Recently, however, 128 it has been asserted that such round house building of the 8th–7th millenium BC were roofed with the flat mud brick terrace roof proper to the somewhat later rectangular building. Perhaps the basis of this assessment lay in recognising the impressions of poles and reeds etc. as small fragments of clay roofing from round houses. The interpretation of this was further troubled by a very trenchant ambiguity in the use of the word "flat" in English. Flat, where apposite, is often synonymous with horizontal (certainly so when describing a roof), however in general use it also connotes any plane surface as opposed to a curved or irregular one, no matter what the angle to the horizontal may be. It is quite reasonable that small fragments of clay roofing to prehistoric round houses were discovered with a plane (not curved) surface, showing impressions of poles, reeds, etc. This, however, does not mean necessarily that the fragments came from a horizontal roof. It means that they came from a clay roof supported on a pole and reed frame, not from a corbelled mud brick roof; and the contour of this roof was facetted conical in nature rather than beehive.

Monumental mud terrace roofing

Archaeological evidence and modern ethnographic parellels refer generally to the unchanging simple construction of village housing, where the wooden and the woody materials are used in their natural state. However the scheme of the flat terrace roof was also used for roofing more monumental structures in the Ancient Middle East. Here the exposed timbering was hewn square, and the exposed reed or other soffite was plastered and decorated. Archaeological finds (e.g. at Amarna) 129, 130
together with ancient representations (e.g. Theban tomb paintings) provide evidence of such roofing in Egypt (AAAE, pp. 170–72). Evidence of even more monumental wooden terrace roof construction subsists among the ruins of the Bronze Age 131
Cretan "palaces" at Knossos, Phaistos etc. (Shaw, pp. 155–57). Unfortunately no material remains survive of the most imposing flat terrace roofing constructed in antiquity; the like of which in effect can have been rivalled only, in another manner, by the Pantheon and Ayia Sophia. Spoken of here is the vast spreading roofing at Persepolis—seeming acres of ornamental flat ceilings, so high (ca 20 m) and 132
so lightly resting on so many slender widely spaced columns as to be unworldly. There is, however, evidence admitting of its reconstruction.

Numbers of the grandiose stone columns survive including their majestic capitals. Above the construction was timber and earth, destroyed in "Alexander's Feast" and the remains consumed by time. However representations of the details of timber framing for terrace roofs are found carved into the soffite of rock cut tombs in Kurd- 132b
istan (C.J. Edmonds, "A Tomb in Kurdistan Iraq," 1, pp. 18–92). These tombs are probably of Achaemenid date and it is believed that they indicate the construction of the terrace roofing at Persepolis (E. Herzefeldt, "Iran in the Ancient East," p. 283, fig 312). The excavation architect Krefter assembled the varied evidence to provide a sound reconstruction of the Persepolis roofing, and furthermore illustrated this by a series of evocative drawings (F. Krefter, "Persepolis Rekonstruktionen," TF 3, 132a
1971, conveniently reproduced in L. Trümpelmann Persepolis).

The Qizqapan rock cut tomb shows the principal roofing beams to be composite—three massive (cedar) baulks set contiguously side by side. (Since the three elements are not jointed together in some way so as to act as a single unit, it makes no difference in their bearing capacity whether they are set together horizontally or vertically.) The horizontal arrangement is, of course, much more convenient and stable. Krefter considered (sensibly) that the animal protome capitals would be set so as to present their profile to the normal view point, i.e. to the main entrance way (cf the Ionic capital).

(b) Pitched roofs. Bronze Age Greece. Considered on a broad regional basis flat mud terrace roofing would be expected in Bronze Age Greece. Also it was thought that roofing tile fragments never occured in the archaeological remains of this period. Nevertheless the salient development of the double pitched gable roof in

Classical Greek building for the same long house plans found in the Bronze Age made the question contentious (for a brief outline of the debate, v S. Jakovides, *Mycenaean Roofs*, pp. 147–160). In fact more recent archaeological findings (e.g. of abundant tiles and tile fragments) together with careful re-examination of the old evidence has resulted in general acceptance that the standard form of roofing 133 in Bronze Age (Mycenaean) Greece was a gable roof clad with terra-cotta roofing tiles (Martin, fig 58, Jakovides, fig 10).

Pitched mud roofing in Mycenaean Greece

This standard roof was of low pitch (rise to span ca 1: 5–6) with a ridge beam supported by cross wall gables, and principal rafters running up from timber wall plates to the ridge beam. Between the rafters a soffite was formed from contiguous reeds, canes, matting etc., which in turn were plastered over by a layer of mud to form the bedding for the terra cotta roofing tiles (pretty much after the Lakonian style of classical tiles). Thus the pitch of the roof was sufficiently gentle for the mud bedding not to creep or flow. Jakovides observed that at intervals horizontal beams spanned from lateral wall to lateral wall to act as ties. In this event they required to be firmly masoned into their seating—and, in any event, formed no part of the roof structure. This type of roofing is stated to be general for traditional village building in modern Greece (Jakovides, figs 11, 12).

Classical Greece

The historical development of the characteristic gable roof to the monumental buildings of classical Greece is no more an obvious matter than the historical development of the Classical Greek Temple at large. Explanations of the latter phenomenon divide into two main streams:

(a) evolution out of earlier building construction in Greece
(b) diffusion of modes of buildings in the contemporary architecture of other regions (e.g. Egypt).

In the instance of the gabled timber framed roof explanations by way of diffusion do not arise, since no contemporary monumental building style incorporated a gable roof. On the other hand classical roofing is certainly not a blow up in scale of Jacovides' reconstruction of an endemic type of domestic roofing. The fundamental member of the woodwork of classical Greek roofs is the transverse horizontal beam, which acts as the bearer of the vertical prop (post) supporting the longitudinal ridge beam. Whereas in the Bronze Age gabled roofing transverse beams are explained simply as tie beams and have no function in the roofing structure, where the ridge beam runs from gable to gable and the inclined spars (the principal rafters) from wall plate to ridge beam.

Bearer beams & trusses in Classical Greek roofing

When during the 6th century BC classical Greek temple design was standardised as a very sizeable long building with a cella say 10 m–12 m broad × 40 m–50 m long no way could be found to fashion a gabled roof on timber which spanned freely these dimensions, either longitudinally or transversally. A ridge beam was the basic requirement and the obvious way to support it was by a row of columns along the central axis of the building. But this, of course, was specifically destructive to the design. To avoid this, therefore, the Greek designers spanned the cella transversally with horizontal beams and set up upon each at its centre a short post which supported the ridge beam, thus leaving the long axis of the cella clear. If however the breadth of the cella was over 5 m–6 m, then again no timbers could be found to span this dimension freely. The solution was to break the transverse dimension of the cella into three parts by providing two lateral ranges of columns. Then over these three aisles three horizontal beams could be set of manageable spans (i.e. ca 4 m). 134a This solution met all requirements. It supported the ridge beam; it provided interim support to the raking spars via the lateral colonnades, and the horizontal beams supported a horizontal ceiling which concealed the heavy wooden spars effecting the double pitched roof. However the strength of this system rested entirely on the resistance in tension of the horizontal beams at mid span where they were placed in bending by the props of the ridge beam.

To this device an alternative system was available in antiquity which, according to statical analysis, could employ wooden members to roof over very extended spaces. The device was that of the wooden truss and the question is how early this device was used. It was certainly known in Hellenistic building and may be known during classical times in South Italy (Hodge, pp. 38–44 *et pass*).

The principle of the truss is based on the fact that a triangle does not deform 134b, under stress—one side cannot deform individually. 136 All sides share in sustaining the load, thus each member of the truss can be of slighter section. Furthermore the efficiency of the truss can be increased by insetting cross members into the basic triangle thus articulating it into a series of compound triangles, each of which is correspondingly non-deformable. Another way of visualising the statics of the truss is to regard it as a gable. If the statical behaviour of a gable loaded by a roof is examined, it will be found that the lines of force (stress) are not transmitted uniformly downward throughout the area, but follow around the margins of the triangle leaving the interior as a neutral zone. A truss may then be considered as a fretted out gable retaining only the parts of the structure under stress (Sharma & Kaul, pp. 304–16)

3. *Reinforcing*

Wood because of its strength in both compression and tension (i.e. it can serve either as a tie or a strut), its ready availability, and above all, its workability is

Internal & external wooden reinforcing

the naturally indicated material for reinforcing other construction. Recently close observation has shown the surprising development of more or less a timber framing as a constituent element of the "mixed construction" prevalent in the 138–145 Mediterranean, the Levant and Anatolia. However outside of what can be justly called mixed construction, limited items of wood appear set into other materials as reinforcing—almost always as ties to masonry where it was likely to fall apart or be displaced. This use ranges from long runners and through cross pieces to cramps between individual blocks of masonry (v chap. 5 Stone Construction). These instances may be thought of as internal reinforcing. However there was another application of wood as reinforcing of construction in other materials. This was current in antiquity as it is today. It may be called external reinforcing and here the wooden member acts in compression as a strut or a prop.

When masonry shows alarming signs of collapsing—i.e. roofs falling in or walls being thrust out, a short term expedient is to prop the defective element in place by stout wooden baulks. This process is referred to as shoring. It is developed in three ways: vertical from ground to roof (standing shore); inclined from ground to wall (raking shore); horizontal from wall to wall (flying shore). Strangely enough some of the oldest and at the same time best preserved units of wood in ancient buildings relate to this instance. The pyramid tombs of Old Kingdom Egypt (mid 3rd Millenium BC) incorporated extensive chambers and passages beneath and inside mountains of stone masonry. Quite often the massive stone construction of these chambers immediately showed signs of imminent collapse or displacement because of the exorbitant pressure of the enveloping masonry. The dire situation was saved by installing great trunks of cedar as shores. And this emergency installation has remained preserved to this day in the dry air of the crypts (Arnold, pp. 234–36).

4. *Auxiliaries and Fittings*

Non-structural wooden components

The essence of this study is the structure of buildings, and discussion is concentrated on this score. However wood was widely used in ancient building for purposes other than structural—more widely than in contemporary building where metal (and artificial materials) have taken over some of this rôle. An indication of the non structural use of wood in ancient building is therefore included here.

Wood was certainly used as a cladding (revetment) of other materials (brick or stone masonry) in luxury building. Almost no material evidence of this practice survives, but there are literary references to expensive wood panelling (wainscotting). Well known is the specification of the "finish" to the walling of Solomon's temple (I Kngs 5.6–10, 15, 17 etc.): "So he built the house and finished it and covered the house with timber of cedar" etc. Also wood was used for the tegument for (pitched) roofing. Here it took two forms: shingles and thatching. Again 137

Shingles, Thatching, Staircases etc

virtually no material remains of either devices survives. Pliny the elder's categoric statement that shingles were standard roofing material in Roman building until 276 BC (*N H* 16. 34–42) raises questioning remarks. To fix shingles in place, essentially the only device is nailing—and shingled roofing requires large quantities of nails. As for thatching, by its nature, the technology can not vary much and thus modern thatching is always taken as a model for ancient work (Davey, Chap. 1, 137
Thatch). The pitched roofing of ancient buildings is so often reckoned as thatch that a brief explanation of the process is given, notwithstanding that there are no ancient survivals.

However excellent the thatching it will not outlast a century, so its postulated use in antiquity derives from projecting back enduring custom; from the lack of archaeological remains of any other form of roofing (e.g. tiles); and from ancient representations—e.g. temple models from Iron Age Greece and Etruscan house urns suggest by their contour that they were thatched.

The term thatching is used in a variety of senses, sometimes specific to certain materials (reeds) fixed in a certain manner, sometimes generically for all forms of roofing out of vegetal materials—e.g. heather, willow, straw, rushes, reeds, sedge etc. These various materials can be fixed in place in diverse manners ranging from very simple to very sophisticated, effecting a pattern of highly pleasing aspect. Roughly speaking the vegetal material, either simply spread over the roof as a layer or, more properly, worked up in bundles (yealms) can be fixed by holding it down with rods laid across it, or by securing it with ropes stretched over the surface with their ends tied into pegs or weighted down. Yealms of thatch can be fixed directly to the wooden structure of the roof by sewing into the battens or nailing to the rafters. Finally the bundles can be interwoven into their grounds.

A very significant use for wood in ancient building was for staircases. Here the incidence divides up fairly neatly Monumental building in dressed stone fashioned its steps or stairs in stone masonry. For wooden buildings and buildings of mixed construction the stairs, staircases incorporated were of wood (NB Callot Tranche Sud *pass*). Archaeological remains of such wooden staircases survive e.g. at Pompeii and even more notably at Herculaneum (Adam, pp. 217–22).

An obvious use for timber in ancient building (as it is today) is the framing for doors and windows. This can be integrated with the general timber framing and 142
thus take on something of a structural role, cf in Cretan palace building (Shaw, pp. 173–85).

Finally there is to be mentioned "fittings"—i.e. doors, windows and shutters. In the normal run of buildings these were of wood in ancient times as they are today. In monumental construction door leaves were occasionally of stone (e.g. in funerary monuments) and in very grand building door leaves were cast in metal (Vol. 2, figs 273–77). The design of wooden doors has remained in essence unchanged since

Roman times (Adam, pp. 320–23; Sharma and Kaul, pp. 217–21; E.G. Warland, pp. 300–302). Before the introduction of glazing (or where it could not be afforded) wooden windows could be provided. These consisted of wooden lattices or grilles which admitted a modicum of light, but acted as a bar to intemperate weather (heat, wind, driving rain).

Window frames

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CHAPTER FIVE

STONE CONSTRUCTION

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A. *Origin and Development*

Developments in use of stone interrelated with use of brick

Stone is a conveniently occuring material which can be used conveniently to build various structures, but the earliest "buildings" (i.e. habitable shelters for men) were certainly not built of stone. Rather the earliest use of stone in building was for barrier walls and for terracing. However there was a continuous development in stone building which is closely connected with developments in earth construction. This has an interesting pattern (O. Aurenche, *La Maison Orientale, pass*).

Field stones were used either dry or drowned in mud to constitute low barrier 328
walls. From this emerged the concept of hand modelled mud bricks in the image
of such field stones and as a substitute for them, the supply of which could be con- 320, 331
trolled. In turn these gave rise to form moulded mud bricks, with their advantages
of regularity and mass production. The advantages of such mud brick construc- 334
tion led to the perception that stone could be dressed into the regular form of
moulded brick, thus giving rise to finely dressed quarry stone / dimension stone
masonry. It is also possible to extend this chain another link. The advantages of 195, 196
durability inherent in stone masonry eventually promoted and fostered the use
of burnt brick in place of mud brick—first as a special material, then as a general 349
all purpose building material.

In addition to this line of development shared with earth, stone afforded an alternative usage of its own. Properties of matter (e.g. cohesion) restricted the size of bricks to small units. However stone also occurs naturally in large units—or such units can be extracted fairly readily. Thus it was possible to use stone as a 153, 154
building material in a different way from brick.

With this recital the parameters of stone as a building material have been established: field stone masonry; quarry stone masonry; small block masonry; (very) large block masonry. A skeleton chronology of this categorisation may now be proposed.

Field stones were used for building low barrier and enclosure walls in Mesolithic
times. The first use of field stones in upstanding load bearing masonry was at the
beginning of the Pre-pottery Neolithic era in the Middle East, ca 8th Millenium 146
BC. The use of finely dressed regularly shaped blocks of stone developed in Egypt
from early in the third millenium BC. This development refers to stones of limited 150
size (which can be handled by one man), i.e. small stone masonry. Quite distinct
was the use of large units of stone, e.g. units weighing several or many tons. 153, 154

Unexpectedly something of this nature occured at Jericho at the beginning of stone building (8th millenium BC). Large boulders were used in constructing a terrace wall and a tower ca 10 m high built up solid which housed an internal stepped passage ascending from base to terrace roof. Nothing approaching it has been reported from elsewhere at this period. The connected history of very large stone building (megalithic construction) began during the fifth millenium BC, 152 centred on the Atlantic Coast of Western Europe. It is a truly astonishing phenomenon. In essentials the largest possible units of stone were procured weighing e.g. 30–40 tons. These could be furnished by natural processes of exfoliation, or by levering away from fissured bed rock. Two forms were utilised: great flat 153–157 slabs and pillars. With these were constructed artificial caverns within a tumulus of earth (dolmens), together with monumental standing stones (menhirs). Such construction was current ca 4,500 BC–2,000 BC; and because of their massiveness striking remains endure to this day of these monuments (R. Joussame, *Dolmens for the Dead*; G. Daniel, *The Megalith Builders of Western Europe*).

Extensive knowledge of properties of building stones

Megalithic construction is an enigmatic phenomenon both historically and geographically. After ca 1500 BC it was never resorted to again in the Ancient World. 56 However in disparate regions outside the Ancient World (e.g. India, Korea, etc.) where no connection by diffusion can be imagined megaliths occur at later dates (R. Joussame, *Dolmens for the Dead*).

B. *Varieties of Material*

The first concern in stone construction is the choice of material, since the varieties of stone are very numerous. Field stones come in many shapes and sizes and the physical composition of all stone is extremely diversified. The physical nature of any stone depends on its chemical components and the processes of its formation. These questions today constitute the sciences of lithology and petrology—the first concerning the geology of rock outcrops, and the second the chemistry and crystalography embodied in any item of stone. About these matters the ancients had no knowledge. Nonetheless already in e.g. Old Kingdom times at the early stages of large scale quarrying the Ancient Egyptians possessed close discrimination between the qualities of various stone outcrops; and organised expeditions to quite remote localities to obtain supplies of specially suitable stone. The close knowledge ancient man possessed of all natural phenomena was obtained by long sustained observation—by nature study rather than by science. Moreover man's initial awareness of the qualities of stone pertinent to building was developed in part by his prior familiarity with stone working in Neolithic times to produce stone vessels and objects.

Certainly a very extensive knowledge of the physical varieties of stone is required to build in stone to the best advantage. Stone is used for the widest variety of purposes in building construction—to constitute the structure of a building in whole or in part and to constitute its aspect in whole or in part. Thus virtually every physical type of stone imaginable is useful for some specific purpose, and accordingly virtually every physical type of stone has been used in building construction. Furthermore from the beginning of fine stone masonry (in the third millenium

Use of field stone

BC), so long as any given physical type of stone was available and useful for building construction, it could be worked.

To illustrate man's increasing command over stone as a building material, i.e. the various sorts of stone he was able to employ, some historical sequence may be asserted for the basic categories of building stone mentioned above, i.e.:

> Field stone / rubble (non-dimensioned stone); finely dressed stone / quarry stone (dimension stone).
> Small block stone masonry; large block stone masonry.

However to speak in such terms is "typically speaking" only. The subject is almost unbounded, and hard and fast distinctions difficult to draw. Nonetheless it is reasonable to begin a survy of building in stone with the use of field stones—i.e. small block rubble.

Gathering field stones for building construction demands a study. Quarrying latterly has emerged as a much favoured "special subject" yet the supply of field stones for building has been totally ignored. NB It is worth noting that the period when field stones began to be used for building was co-aeval with the development of agriculture, which required clearing fields from stoney encumbrance.

The detachment of field stones from bed-rock is effected by the geological process of disintegration—i.e. mechanical (physical) weathering. Here the form of the material only is changed, not its chemical composition. To effect the latter is the process of chemical erosion (decomposition) whereby the original minerals are changed and replaced by new minerals. Two parallel / alternative operations are involved in disintegration: exfoliation and spheroidal weathering. Exfoliation is the splitting off from the bed rock surface of flat layers of rock which subsequently break up into angular plates. This is the result of insolation—the repeated expansion and contraction due to marked changes in diurnal temperature. Spheroidal weathering proceeds by way of surface decomposition which material then falls away in concentric stages, leaving a rounded core of unchanged stone. Both these processes operate over a wide range of scales. The detachment brought about is the prelude to the transportation of the fragments in various manners. When stones are waterborn, i.e. by rivers or along sea shores, they are rolled and ground together so that they quickly lose all irregularities (G.H. Dury, *The Face of the Earth*, London 1962, chap 2, Rock Destruction).

Again speaking in the broadest terms, the upshot of these natural processes was that stones of varying size littering the surface of the earth tended to fall into two forms—flat angular fragments (i.e. thin slabs or plates); and rounded compact 147
units (rubble, boulders, etc.). There was also the climatic consideration that flat 146, 148,
angular plates were of frequent occurence in hot, dry regions. Both these classes of 149
field stones had specific advantages for use in building, and both were employed

from the beginning of building in stone. The advantage of the compact unit was strength; that of the flattened units, stability in setting. There was a consequent distinction in the mode of use, compact rounded field stones needed to be set in thick beds of (mud) mortar; while the flat stones could well be set dry (without mortar) if desired.

Use of field stones

Record of this distinction occurs in the remains of early Neolithic building. Where rounded stones are used the manner is not so much mortared rubble as rubble in (mud) mortar. Mortar was not used to fix the stones in position, but solid stones were inserted into plastic mud construction to stiffen and strengthen it (this is sometimes referred to as drowning the stones). On the other hand early Neolithic round house building in arid regions, e.g. at Beidha in Southern Jordan was fashioned with expert dry stone walling—sometimes evidencing lodgements for posts to further stabilise the construction (another instance of the anteriority of wooden construction). Thus two contrasting methods of building in stone were virtually aboriginal.

Perhaps it was in later Neolithic and early Chalcolithic times that a development in rubble walling became general and has remained the standard way in the Middle East of traditional walling with field stones. The process is as follows. Substantial stones of compact regular form (with principal dimensions ca 30 cms–40 cms are chosen as facing material to constitute the two faces of the wall. If necessary one side of the block is trued up somewhat by knocking off excresences. These stones are then carefully set in place contiguous to one another on a bed of mortar and with mortared rising joints, thus defining firmly the breadth of the wall. The core between them is then spread over with smaller irregular stones of all shapes and sizes and mud mortar is slopped over the fill to drown it. This assemblage constitutes something of a course, and the process is repeated *da capo* until the desired height is achieved. Usually only several "courses" at most of such construction remains for archaeological observation. For the most part the remains constitute foundations or a low socle, but on occasion they form the rising wall masonry. In modern village work such walling, in the interest of speed and economy, is carried out by two builders, one working at each wall face. This is a very effective system of construction and it is interesting to observe that it stands behind developed Roman Concrete practice. Undoubtedly the impetus to this sytem of field stone rubble walling was the development of form moulded mud bricks. The mass production of this material promoted building—and such mud brick walling required a stone base, not for stability, but as a protection against rising damp.

An alternative to this basic style of rubble walling can be observed on occasion. It probably emerges about the same period—i.e. the Chalcolithic Age ca 5th–4th millenium BC—and arises from the conformation of the field stones available. When these are more or less ovoid in form, they can be conveniently and stably

Megalithic construction

assembled by setting them on end inclined to one side. Succeeding rows are inclined alternatively in opposite directions to produce an interwoven fabric known as "herring bone" formation. Such an assembly with suitable stones is also stable set dry stone. It is, of course, closely related to the introduction about the same time of plano-convex mud bricks in Mesopotamia.

Further development in rubble masonry inevitably involves additional shaping of the stones and is probably for the most part an affect of fine stone dressing.

It should be noted emphatically here that the manner of construction with field stones discussed above refers to domestic building. The stone units are portable and the building operations can be carried out by one or two skilled men and at the most several assistants. The buildings are addressed to the material needs of the living, and can be encompassed by a family group. It is an expression of that secular progressive temperament which stands behind what is often termed the Neolithic Revolution.

The development in stone building which succeeded this in point of time is momentously other. It is a mutation in every respect. It is not addressed to the material needs of the living. It accomodates the dead and the destiny of the group. It is momentous public building on the grandest scale. The construction demands the regimented highly organised resources of a sizeable community (a tribe, a clan), and the direction of some men of great talents. This megalithic building tradition of Western Europe (centred on the Western Mediterranean and the Atlantic coast during the fifth to the third millenium BC) is one of the vicissitudes of history most difficult to account for. No stone building like it occurred previously anywhere in the Ancient World, and previous building in the region was not stone at all, but wood. Some complete change in human (social) values found direct expression in stone building. In place of one or two men assembling together stones a few kilos in mass, companies of men transported, set up, and raised up to considerable height units of stone many, many thousand times the weight of a typical field stone. To what end? No man dwelt in such structures and they provided no defence against hostile groups. Such construction was unknown in the Ancient World prior to ca 5000 BC and was little practiced there again after ca 2000 BC. However the technology may be explained, the conceptual change involved is stupendous—and this took place in a region reckoned to lag several millenia behind the eastern part of the Ancient World! (C. Renfrew, *The Enigma of the Megaliths*, chap VII, Before Civilisation London, 1973; A. Sherrat, "The Genesis of Megaliths World Archaeology," 22, 1990, pp. 148–65).

Megalithic masonry construction has been characterised here as it is generally thought of—a homogenous and disassociated phenomenon: rude stone monuments on a gigantic scale, dolmens and menhirs which have survived the millenia to present a spectacle unlike any other building in the ancient world (G. Daniel, *The*

Diversification of Megalithic construction

Megalith Builders of Western Europe, London, 1958). However, when examined in component detail other considerations appear.

The supply of great slabs and pillars of crude stone can not be imagined as invariably the result of the natural process of rock disintegration. On occasion this must have been supplemented or augmented by human intervention. In short some activity akin to quarrying was at times involved. Next, although dolmens and
153, 154 menhirs are the predominant expression of megalithic construction, they are not exclusively so. Other monumental forms fall within the megalithic tradition, notably
155, 157 the Maltese temples and the Stonehenge "Stone Circles". When these monuments are included it is surprising to realise how many apparent innovations in stone building are comprehended in the Megalithic tradition. Both the Maltese temples and Stonehenge incorporate much dressed masonry, and in addition the Maltese temples incorporate a considerable expanse of masonry bearing relief ornament.
251 Also the roofing of megaliths is not invariably that of a single great slab (a table
252 top). At times (e.g. at New Grange in Ireland) the principle of corbelling was employed. Viewed in this light the question thus occurs did megalithic construction, even though there is nothing later akin to it in form, directly influence subsequent development in stone building elsewhere in the ancient world?

The Megalithic tradition of Western Europe slightly overlaps in date the development of finely dressed quarry stone masonry in Early Dynastic Egypt. Nothing approaching the megalithic style occurs in Egypt but the abstract question at least admits of consideration. Certainly the devices of construction for handling the massive units were the same in both instances: hauling up ramps and/or levering and cribbing.

Whatever substance there may be in such speculations, it was the appearance of a god on earth which established large scale quarrying of building stone, and thereby utterly transformed stone building construction. Thereafter any monumental building project could be designed at will and accurately constructed with statical properties comparable to those of bed rock. Moreover a suitable type of stone could be chosen from a variety of different rock formations. This was clearly an attribute of divinity. Quarries in Egypt belonged to the Pharaoh, and in due course were inherited by the other god on earth—the Roman Emperor.

The history of Egyptian construction in finely dressed quarry stone is unexpected. The oldest remains of large scale monumental construction of this nature are the
159 famous funerary complex of Zoser at Saqqarah (ca 2650 BC) encompassing the Stepped Pyramid. The expert stone masonry here is of relatively small blocks and only the face and its adjacent perimeter are finely dressed. This narrow margin adjacent to the face is finely dressed normal to the face to secure the appearance in elevation of fine jointing. The remainder of the other surfaces are splayed apart to the rear so that the block is in essence not a parellelopiped, but a truncated

Egyptian dressed stone construction

pyramid. In this way when the blocks are set together the masonry appears finely jointed ashlar at the face but the construction opens to (squared) rubble inside the wall. Such blocks are thus essentially facing. When disposed to build a free standing wall the faces appear largely stone, but the core of the wall is to a considerable degree mortar. Since the facing of the wall is regularly coursed and finely jointed whereas the core is not solid stone, the correct trade name for this type of masonry is "bastard ashlar". Its excellent aspect, coupled with economy of construction is such that it has always remained in use. When finely dressed stone masonry was introduced in other lands (e.g. Crete, Palestine, Cyprus) this 175–178
was the form employed.

In Egypt, however, within a short time this "small block" masonry was replaced as the standard construction in stone by an utterly different system which survived throughout the history of Egyptian monumental building—i.e. from ca 2,500 BC to ca 150 AD. This style of masonry is known as "large block", or Pharaonic Masonry. 160, 161
It is a truly ideosyncratic system of finely dressed stone masonry and as a system was never put into practice outside Egypt. Whereas "small block" (Zoser) masonry followed on from rubble stone masonry and form-moulded mud brick masonry, Pharaonic stone masonry turned its back completely on this line of development. If any analogy can be suggested to explain its *ratio*, then it can only be to transfer an outcrop of rock to the building site and dress it *in situ* into the required building form—i.e. it was the rock matrix which was constructed and the building was carved out of it. Of course Pharaonic masonry varied in details so that it approximated in varying degrees to this idealised character (Arnold, *pass*). However such was the underlying nature of the process, as has always been recognised since the time of Petrie (cf Petrie; Clarke and Engelbach *pass*).

What stood behind this *volte face* in Egyptian stone construction is not apparent. Perhaps there was some (religious) imagery at work; perhaps on the other hand it was a socio-economic development. The characteristic quality of Egyptian civilisation was the high degree of centralisation it assumed, with a consequent social discipline and predeliction for efficient works organisation on a large scale. All these factors bear on Pharaonic stone masonry and may explain it is as simply the most economic method of monumental stone construction.

In brief the most advantageous quarries were exploited no matter how remote the location, the largest possible blocks were extracted from them and were transported to any building site in the land very largely by virtue of the Nile. On site well drilled (and contented!) gangs piled up earth ramps (or wholesale fillings) very rapidly so that these massive units of stone would be hauled up and levered up and about into position high above ground level. This system involved great saving—saving in stone, in labour and, above all, in time.

In situ *dressing of Pharaonic masonry*

The saving in stone dressing under the Egyptian large block system is cumulative and very great—and this meant, in effect, a saving in time, a speeded up schedule of construction. There is no doubt that this was a desideratum. There are several records where an official lauds his performance of major building work, and always the celerity of the work is mentioned as an outstanding achievement. There is furthermore the basic instance of the grandest of all construction work—the pyramid. In the nature of things a schedule was required so that this work could be completed well within one regnal period—i.e., ca 10–20 years. The saving in stone and the saving in (skilled) labour was efficiency, but there was no shortage of stone or skilled labour. It was the saving in time which was of paramount consequence.

In Pharaonic masonry correlated with large blocks was the system of *in situ* dressing. As much as possible of the fine dressing of the large blocks was carried out in conjunction with, and after their setting in place. 163–169 Only the fine dressing which was required to set a block in place was effected before its setting. In fact the fine dressing of the various surfaces of the block may be divided into three categories:

(a) that required to set the individual block in place
(b) that required to construct the stone matrix of the building
(c) that required to "finish" the building.

The fine dressing of these three categories was carried out in corresponding stages:

(a) prior to the setting of the block concerned
(b) in conjunction with the setting of the masonry
(c) after the completion of the stone matrix of a building unit.

The processes of Pharaonic masonry construction may be considered in more detail according to this analysis.

The saving both in stone and in time in quarrying large blocks is obvious, but the saving in time of dressing large blocks instead of small blocks is more pronounced. If the fine dressing of one block of stone, a cube 1 × 1 × 1 is considered, then the total surface area to be dressed is (1 × 1) × 6 = 6. Now supposing each dimension of the cube is divided into half, giving a total of 8 smaller blocks, then the total surface area to be dressed will be (1 × 1) × 6 + (1 × 1) × 2 = 8—i.e. an increase of 33%. Thus in this instance the use of one large block instead of 8 smaller ones effects a saving in time for fine dressing of 33%. So much for the size of blocks.

Form of dressed blocks in Pharaonic masonry

However the saving in time of erection effected by the system of *in situ* dressing is equally great. To dress finely a simple block of ashlar masonry requires at the very least three times as long as setting. If the block can be set in place with less than half its surface expanse finely dressed, then obviously the schedule of construction is further speeded up.

The expression of this sophisticated programme is revealed in the many surviving examples of Pharaonic masonry. The picture revealed differs greatly from modern stone masonry which is derived from the classical tradition.

Blocks are large to very large, often several metres long and weighing many tons. They are set dry stone with the very finest possible joints between them (Arnold, p. 123). However in elevation these large blocks are not necessarily rectangular, and may not be quadrilateral. The bed joints may not be horizontal and the rising 161, 162
joints may not be vertical—nor may the face, the bed joints and the rising joints be perpendicular one to the other. Furthermore the bed joints may not be continuous but may be stepped or indented so the block has more than four sides. Strangest of all, perhaps, is the appearance of the face of the blocks! In some parts of the wall this may be finely dressed (and often bearing relief decoration); in other parts 169
it may not be dressed at all.

The inevitable wonder is how such large blocks of irregular delimitation and appearance can be so perfectly set together one against the other, the adjoining surfaces entirely in contact. In fact, notwithstanding the closest study, this wonder in part remains. Outlines of the proceedure appear evident, but the precise means adopted to effect even the basics are still controverted. In principle the only surface which must be dressed true before setting the block is the lower bed joint, while the face need not be dressed at all at any stage of the building, since no other surface comes into contact with it. Its dressing is entirely a matter of aspect, not structure.

A question remains why the rising joints are so often oblique both in the vertical and in the horizontal sense. This has generally been accounted for as a measure of economy—i.e. to save cutting much stone to waste when the block was delivered from the quarry irregular in outline (cf Clarke and Engelbach, fig 107). On reflection, however, this argument is difficult to sustain, and it may be that the oblique rising joints producing irregular dihedral angles were specifically designed to strengthen the masonry by improving the bond. It would certainly operate against displacement forces, approximating to some degree the effects of polygonal jointing.

Construction in large block Egyptian masonry where blocks are dressed into form as they are being set and after they have been set has evoked great interest. The principles were early perceived by Petrie and by Clarke and Engelbach; while latterly there has been a comprehensive study by Arnold. Moreover the transfer

Procedure of setting Pharaonic masonry

of monuments occasioned by building the Aswan High Dam during the 1960's afforded profuse opportunity for observing details of masonry construction (G.R.H. Wright, Kalabsha 2). In this way there is a considerable literature available on the subject, some of it conflicting. It is not so much the processes and their order which remains in question, but how they were carried out. Perhaps the basic matter is that Egyptian large block masonry is not as homogenous as is generally assumed. In the present connection it is of significance whether or not the coursing is continuous—i.e. the bed joints are not stepped or indented. Also some monumental Egyptian masonry appears as published scarcely to fit the Pharaonic category at all; unless, that is, there is some extraneous evidence of *in situ* dressing (cf Deir el Bahari, Arnold, fig 4.85). The puzzling question is how the *in situ* dessing in conjunction with setting was carried out. This question is not unique to Pharaonic Egyptian masonry, something like it operates with Cyclopean masonry and substantial polygonal masonry. However the dimensions of Pharaonic blocks accentuate the question. To the practical difficulty of dressing very large blocks of irregular form so that the joints between them are extremely fine when the wall face is elevated above ground level there are in outline two approaches: i.e. either to bring the wall face down to the ground or to bring the ground up to the wall face. In general the earlier commentators on Pharaonic masonry proceedure (e.g. Clarke and Engelbach) thought of the former approach—i.e. they tried to make the setting of Pharaonic masonry conform as far as possible to the familiar process of setting modern large block masonry (i.e. masonry in the classical ashlar tradition). To this end they mooted a preliminary mock up setting on the ground. The blocks of a course were all first assembled in position on the ground where all the necessary dressing for their setting had been carried out and afterwards the dressed blocks were delivered (by ramp) to the wall face and then duly set in position. Such a proceedure is theoretically possible but, of course, involves every block being set twice over. Latterly another approach has been more or less the favoured one. The earth ramps, platforms and fills for the Pharaonic masonry construction were so developed and all present that something like an earth hill rose in and about the construction so that there was reasonable space available adjacent to the wall at whatever course level for carrying out the dressing required in conjunction with the setting. In this fashion the proceedure for setting Pharaonic masonry is divorced completely from that for normal ashlar.

In general when thus considering the problem of dressing blocks to form in conjunction with setting, it is the dressing of the rising joints which is envisaged since they are very often doubly oblique, i.e. neither normal to the bed joint, nor normal to the face. The proceedure for obtaining the fine jointing is obvious: either a bevel is taken from one block and applied to the requisite face(s) of the other, or the blocks are brought in close proximity to each other on a true bed

Battered external wall faces

and a convenient constant offset is measured from one to the other at each of the four angles of the rising joint. When the rising joint of the second block has been dressed to the plane so established, the setting is a straightforward matter of levering the second block into position.

The circumstances, however, are markedly different when the bed joints are not horizontal and/or not continuous. Particularly in the latter instance (because of 161
the indented bed) there may arise difficulties in setting which require a block to be lowered into position. When the block is a massive one weighing several tons then the proceedure to effect this is not obvious. As yet no practical study of these questions is published.

It is now necessary to direct attention to a salient characteristic of Egyptian monumental masonry: the battered external face of outer walls. It is this feature 48
which gives Egyptian monuments their air of grave repose. As the wall face rises it inclines inward from the vertical at an angle of about 6° (or with a retreat in the proportion to the vertical height of ca 1:10). To obtain this inclination has often been considered as requiring specific devices of some complexity, e.g. L shaped constructions erected beyond the angles of the building on which the profile of the battered wall face is painted in red. Thus the line of the wall face at any height can be obtained by sighting or by running a cord from one painted profile to the other at the opposite end of the wall. Such devices undoubtedly existed, but it will be found that all the literature relating to them (e.g. W.M.F. Petrie, *Medum*, London 1892, pp. 11–13) refers to underground structures, massifs rather than walls.

Alternatively it is suggested that the batter was controlled by measuring inwards from a plumb line or other vertical erected at the foot of the wall. Instances are reported where this proceedure was used to cut at intervals rising channels in the rough masonry face of walls defining the required angle of batter so that the intervening panels could be dressed true by reference to them.

In fact, however, the problem is virtually non-existent.

If one rising joint is dressed true prior to setting the block and for this purpose the adjacent marginal draught on the face of the block is cut, then this marginal draught will incorporate the angle of batter (obtained by applying a bevel at the correct angle). Thus since at least one rising joint on each block is cut to incorporate the angle of batter, then this is provided everywhere for the wall face. If, on the other hand, no marginal draught is cut at the rising joints prior to setting blocks, then the retreating line of the outer face of each course is very simply obtained by directly measuring out the breadth of the wall at the upper bed joint of each course. This is given by the formula b—s, where b is the breadth of the wall at the 167, 168
upper bed joint of the preceeding course and s is the *s q d*, the inward inclination from the vertical = the diminution in breadth of the wall. This is measured and marked out on the angle blocks at each extremity of the wall. A sighted line

between these marks defines the breadth of the wall and thus the retreat of the wall face from the vertical. Better to facilitate the final dressing of the upper bed, the line of the outer face is marked on two small projecting tabulae at the angles. Thus the record remains available until the dressing of the bed is concluded, and is only removed at the final *in situ* dressing of the face after the construction of the wall is complete (cf Kalabsha 2, p. 74; fig 88).

Pharaonic masonry restricted to Egypt

It is impossible to encompass the ramification of construction in Pharaonic stone masonry, which is, in effect, a major triumph of human inventiveness. It turns to the best practical advantage the virtues of Ancient Egyptian society to produce a rather astounding phenomenon: the transformation into massive stone-work of building forms evolved in construction out of light pliable material—rushes, canes, palms etc. It is also of interest to note how quickly this transformation was accomplished. Roughly speaking it was the work of three or four generations of men centred about 2,600 BC. In this it was a precursor by two thousand years of the development of Classical Greek Ashlar masonry, where to all intents this triumph of human inventiveness was the work of three or four generations of men centred about the 6th century BC.

Whatever may be the range and variation of Pharaonic masonry practice it is possible to make the statement that as an integral system of building construction it was never exported to regions outside Egypt. It was tied to its socio-economic environment. Indeed it was not until towards the middle of the 2nd millenium BC (ca 1600 BC) that any systematic construction in finely dressed stone masonry emerged in lands other than Egypt.

Those regions where this type of masonry was prominent were subject to the historical phenomena of the break up of the Bronze Age world and an ensuring "Dark Age". The possible survival of this type of masonry across "the Dark Age" is an important question. In brief it would appear that the record varies in the different regions. In Greece the fine stone masonry of Mycenaean times seems to disappear completely with the end of the Bronze Age. On the other hand in Cyprus
177 and Palestine it appears that the tradition survived into the Iron Age. The obvious importance of this question is to what degree (if any) the Bronze Age bastard ashlar tradition influenced or affected the development of Classical Greek ashlar.

That a monumental building could be constructed out of sizeable blocks of stone closely jointed together was clearly demonstrated to the Greeks by their observation of stone temples in Egypt. However in no way did Classical Greek builders assimilate the technology of Egyptian dressed stone construction. The other system of finely dressed stone masonry which came under Greek observation was the
175, 176 "bastard ashlar" construction to be seen in e.g. Cyprus, Palestine, Syria. However, although superficially to outward view this gave an impression not dissimilar from Greek ashlar masonry, in essence the two types of construction were totally differ-

Classical Greek ashlar masonry

ent in concept. Bastard ashlar construction was essentially a facing to a disparate core, Greek ashlar construction was uniform throughout the entire structure. Was then the ordonance of Classical Greek ashlar essentially an expression of Classical Greek rational idealism?

Greek ashlar masonry was assembled out of sizeable blocks—the average wall block of the order ca 1.0 m × 0.5+m × 0.5–m (or ca 3'–4' × 2' × 1.5'). This gives a total mass of ca 0.25 m3 or a burden of 0.5+ ton, which is about the upper limit that one or two men can budge or lever about, but which can not thus be lifted and placed in position. Such blocks were finely dressed on the bench into orthogonal form with each surface truly planar admitting of dry stone, hair-line jointing between adjacent blocks. This hair-line jointing was effected with great discrimination. At the bed joints where the compressive stresses in the masonry were transmitted the contact was total, but the rising joints where no compressive stress was transmitted were dressed so that contact was made only at the periphery (anathyrosis). On the other hand to provide against displacement at these joints through exceptional tensile forces the blocks were tied together by an overall system of metal cramps and dowels. Moreover the blocks were set together in effective bonding systems which afforded in elevation patterns very pleasing to the eye. 198–201 202 202 198–203

Finally, although it is not exactly in point to speak of the matter here, there was more than meets the outer eye in the monumental masonry of Classical Greece. Not only was the jointing uniformly fine throughout the structure whether visible or not, but the "intervals" between the joints everywhere were made to conform to an overall pattern—i.e. they were everywhere "in harmony", so that e.g. the record of jointing preserved in a lower course of the crepis enables the jointing of the stylobate to be reconstructed and thus the scheme of the peristasis. These things were for the eye of the mind, they were an expression of rationalist idealism. 49

Truly shape and fashion these;
  Leave no yawning gaps between.
Think not because no man sees
  Such things will remain unseen.

Let us do our work as well,
  Both the unseen and the seen;
Make the house where gods may dwell,
  Beautiful, entire and clean.

Classical Greek ashlar masonry was as much as Classical Greek sculpture superb idealist art. Like Classical Greek sculpture it had observed antecedents in Egypt and Western Asia, but was the product of Greek mentality and society—both very different from what obtained in Egypt and Western Asia.

The meticulous precision of detail and the consequent solidarity of Classical Greek ashlar masonry was standardised at a level never afterwards achieved. When the Romans used ashlar masonry construction (*opus saxum, opus quadratum*), the fineness of jointing deteriorated. 205 Above all they began to be more concerned with aspect than structural solidarity. The greatest possible visual effect was sought from fine dressing, thus more and more blocks were set so that the surface of the greatest area was the face rather than the bed. 204, 206 This attitude culminated in the practice of revetting walls with marble facing slabs, which gave an impressive aspect but added no solidity to the construction. Martin pp. 445–447 offers a nuse en seene of this development, which is the basis of the statement of Augustus that he found Rome brick and left it marble (Vol. 1 p. 113, ill 45; Vol. 2 p. 68, ills 106, 110, 111).

Optical refinements

EXCURSUS. OPTICAL REFINEMENTS

> By the latter part of the 19th century it was universally recognised that some of the superb religious monuments of Classical Greek architecture incorporated subtle refinements of design. Although the adjustments in form involved were very slight, by careful mensuration with optical instruments they could be recorded and objectively established. The upshot of these adjustments was that some straight lines were transformed into slight convex curves and some verticals were given a slight inward inclination. 233 Much discussion ensued concerning the rationale of these measures—and it was agreed that their effect was to impart a "life" to the structure which was lacking in a mechanical rectiliniarity. Also it was reckoned that these adjustments "corrected" three dimensional appearances brought about by the modalities of vision (optics) (cf Lawrence, Chap. 15, pp. 169–75).
>
> These recondite matters pertain to design and are outside the concern of the present study. However it must be noted that virtually no discussion exists on how the "optical refinements" were worked into the masonry construction. The slightest consideration of this matter indicates that they must have occasioned very difficult additional problems and processes to the masonry work. This subject is too uncertain and far reaching to be taken up here. Only it may be observed that the overall effect in some instances was to create a curious parallel with the normal process of Pharaonic Egyptian masonry—i.e. the comprehending masonry mass was built up and then the finished lines of the structure were "carved out" of this mass *in situ*. In this connection it is also possible to make a further observation. It is always understood that these optical refinements are absolutely specific to Classical Greek ashlar masonry. Nonetheless there have been hints that something similar is found in Pharaonic masonry. Whereas the peripheral lines of the base of a Greek temple (the stylobate) are given a slight (upward) convex curve in elevation, it has been asserted that the peripheral lines of the base of an Egyptian temple are on occasion given a slight (outward) convex curve in plan. This is a question that is in no way settled and awaits further investigation. Only it may be noted that if a three dimensional drawing is made to illustrate (by exaggeration) the effects of Greek optical refinements, the eye has difficulty determining whether the convex curves of the stylobate are upwards or outwards, (Vol. 1, ill 34).

Coursed orthogonal ashlar (isodomic or pseudo-isodomic) was not the only type of finely dressed stone masonry used in Classical Greek construction. Two or three

Non-orthogonal coursed masonry

other types have been recognised: Lesbian, polygonal and trapezoidal masonry. 188–192 Unfortunately there has been considerable obfuscation concerning them, because manuals always refer to them in the first instance with reference to their historical instance. It is possible that these types of masonry may on occasion afford some chronological evidence, but their essential significance is functional not chronological.

The matter is clearly demonstrated by Lesbian and polygonal masonry. There is no essential distinction between these two types of maosnry; they differ in that (some of) the sides of the Lesbian masonry are curved not rectilinear (the name Lesbian is misleading, there is no distinctive geographical association with Lesbos). A block of polygonal masonry has more than four face angles, sometimes including 188–190 re-entrant angles. When the jointing is exact and very fine, each unit interlocks tightly with adjacent units. Thus polygonal masonry is the strongest type of masonry to resist disruption by horizontally applied pressure and shocks. Accordingly if an exhaustive count could be made, it would be found that virtually all examples of finely dressed polygonal masonry in Classical Greek building comprise barrier walls, retaining walls, terrace walls. The genesis of finely dressed polygonal walling in Classical Greece is obviously by way of technical development from uncoursed rubble masonry used in similar circumstances. A block of trapezoidal masonry is 188 quadrangular but only two sides of the face are parallel, the other two are not. The 191 two parallel surfaces of the block, as a routine matter, are the bed joints, the two non-parallel surfaces are the rising joints, thus finely dressed trapezoidal masonry can be seen as developing from coursed rubble masonry. (There is also a strange echo of Pharaonic masonry block forms.) Finely dressed trapezoidal masonry 192 does not constitute such a clearly recognisable class of masonry in Classical Greek building but numbers of examples exist (ca 100 were recorded two generations ago). Whether as with polygonal masonry its occurence is very largely confined to barrier and retaining walls has not as yet been assessed. On the face of things this seems doubtful. The matter warrants investigation.

The best survey of Lesbian, polygonal and trapezoidal masonry is still R. Scranton, *Greek Walls*, chaps II, III, IV, pp. 26–78. Scranton himself states (pp. 23–24) that his classification of the styles of Greek masonry is based on the form and coursing of the blocks, the dressing of the faces, and the treatment of the joints. He does not approach the classification of masonry from the function of the walling. In fact, although it is not made explicit in the title, Scranton's encyclopediac study is essentially of the masonry of Greek fortifications. However this does not always appear clearly in the discussion; and the functional distinction between such walling and the walls of buildings is not discussed. Within the ambit of his study (the masonry of Greek fortification) Scranton is concerned to establish a chronological sequence for the various styles he recognises. In brief, he sees a sequence of

Resumé of varieties of ancient stone masonry

Lesbian—Polygonal—Trapezoidal, with Lesbian restricted to Archaic times (before the Persian wars), Polygonal common in the Classical Period (5th–4th century) and Trapezoidal appearing more markedly in later Classical times (4th century). Thus his overall view (pp. 137–42) is that ashlar masonry progressively takes over from Lesbian, Polygonal and Trapezoidal masonry, so that these latter styles are more or less totally ousted in Hellenistic times. To what degree this picture is applicable to Classical Greek finely dressed masonry in its totality is not discussed, and the possible distinction is not mentioned.

To summarise the preceeding account, the main varieties in which stone was used in ancient building construction were:

(1) Rubble field stones
  (a) as angular plates (to maximise the surface area)
  (b) as compact stones and boulders of all sizes sometimes roughly trimmed and squared up.
(2) Megaliths—great rude slabs or pillars of rock, natural products of disintegration.
(3) Bastard Ashlar. Relatively small blocks of quarry stone, dressed at the face into standard rectangular form so as to permit the appearance of finely jointed regular coursed (ashlar) masonry, but with the other surfaces roughly dressed so that the joints splay open to the interior of the wall to constitute mortared rubble.
(4) Egyptian Pharaonic Masonry. Large blocks of quarry stone, finely dressed (*in situ*) so that all joints are hair line but the form of the block is not regularly orthogonal.
(5) Classical Greek Ashlar Masonry. Large blocks of quarry stone, finely dressed to orthogonal, parallelopiped units set with hair line jointing at all surfaces.
(6) Polygonal Masonry. Sizeable blocks (mainly field stones) dressed into irregular polygonal forms with re-entreant angles so as to interlock one with the other.
(7) Facing (or Revetting) Slabs. Thin slabs of ornamental stone (e.g. marble) finely dressed and fixed to the face of walls to provide a distinguished aspect.

Rubble field stones are set in beds of cementitious mortar, but generally finely dressed quarry stone is closely jointed and set dry stone. There is a geographical and historical sense to the occurence of these different varieties of masonry but over and above this there is a functional explanation for their use in some cases—e.g. polygonal masonry is designated for terrace walling where the masonry must resist horizonal forces. There is also an abiding distinction in the relevence of large block and small block stone masonry. As for the distinction in physical composition between various stones used in ancient building, all manuals of ancient

Stone predominantly used for load bearing structures

building give the names of different stones (and often mention lithological formations). However for these names to be informative some elementary geological knowledge is required (in the branches of lithology and petrology). Unfortunately there is no conveniently available study of ancient building stone proceeding from this basis.

C. *Structural Disposition*

Stone is generally used to fashion load bearing structures, but on occasion it has been employed to build framed structures. Stone is the quintessential load bearing material, since it comes to hand naturally in a form (i.e. field stones) which is 208
adapted to this function. Here it must be noted, however, that these considerations extend beyond 'buildings'. They embrace engineering construction (i.e. *Tiefbau*) in addition to architectural construction (*Hochbau*); and as such are marginal to the present study. On the other hand, a frame is a structure which is largely open work, i.e. to support roofing it must incorporate members which span across space. Because of its limited resistance in tension, stone is not overly effective for lintels, beams, etc., and thus is of limited worth for framed construction. However important stone framed structures exist in ancient building. There are also quite 214–217
numerous passages of ancient stone masonry where, because of the incomplete survival, it is not possible to state definitely whether the construction was (or was intended to be) framed construction. Here the question extends into the wide 212, 213
ambit of stiffening and reinforcing of masonry construction.

1. *Load Bearing Structure*

When considering load bearing stone structures it is perhaps advantageous first to speak in a summary way of the "engineering" constructions mentioned above—i.e. constructions which do not support a roof and thus do not come within the category of "buildings" as strictly defined. A prime instance of these are free-standing enclosure barrier walls and retaining walls.

Stone has always been the preferred material to construct robust and imposing enclosure walls—temenos walls, fortress walls, city walls. The study of such construction is highly developed and it is clear that the technology evolved in such connections influenced or was carried over into the construction of buildings. There is also the important consideration of barrier walls, not to bar the passage of men but to bar the flow of water—i.e. dams, sluices and the like. Such constructions can also be considered as retaining walls. They retain the accumulated water, exactly as terrace walls retain the earth banked up behind them. As such it is evident that these walls are load bearing walls, *sui generis*, since the load they bear is a thrust, a horizontal pressure. This, of course, influences both their design and construction, since such pressure increases rapidly with the depth below the surface of the retained mass (T. Reynolds and L.E. Kent, Chap. XVI, pp. 31–64). Very material in this connection is the type of masonry bonding employed better to resist lateral deplacement. Thus reference to retaining walls is inevitable when discussing polygonal and Lesbian masonry. However, again it must be stated that these considerations are highly specialised ones, they relate to engineering works not to building construction and will not be treated substantively in this study.

The rigidity of load bearing stone construction

Also it may be noted that there is reason to mention these matters at the beginning of load bearing construction because of the historical instance. In the earliest building of pre-pottery Neolithic times (the Round House) solid stone walls were not used to support the roof. They were used as barrier or retaining walls to enclose the sunken floor emplacement. Roofing was rigged up on a light wooden framing of some sort (Vol. 1 pp. 18, 19).

Stone in its characteristic use as a load bearing material raises the issue of solidity, stability of construction—i.e. rigidity, the resistance to deformation. There are several measures in building construction which severally or in combination augment the rigidity of stone walling ("stiffen it"):

(a) Bonding
(b) Fixing
(c) Reinforcing

(a) *Bonding*

Bonding is the process of setting masonry units together in such a way that the pattern militates against the deformation, damage or collapse of any part of the structure. The principle is that the disposition of the units distributes evenly throughout the structure loads applied to it unevenly, i.e. concentrated at certain points. However the common understanding of bonding that it is of general efficacity in this connection is errant. Bonds familiar in traditional masonry which presume setting units in uniform continuous courses are conceived to resist normal forces transmitted vertically downwards through the masonry, i.e. those induced by bearing the load of upper floors and roofing. If such a wall is subject to horizontal forces (e.g. those induced by human battery, or by earthquake) then the continuous joints running horizontally through the masonry at the beds of each course constitute a weakness. The actuality of this is made familiar in field archaelogy, where quite often the articulated remains of walls can be seen which have toppled over en masse at a certain course of masonry or indeed have been displaced horizontally at a certain bed joint. The type of masonry which best resists such horizontal courses is polygonal masonry which by definition avoids as far as possible all continuous horizontal bedding.

Bonding of rubble stone masonry

The bonding of masonry is a subject which has a more ramified development in brick masonry than in stone masonry, and accordingly will be examined in more detail in the next chapter. However bonding is a significant matter in ancient stone masonry as the following discussion indicates.

It is a simple matter to set well bonded masonry in the run of a wall, but it can be very intricate to keep a good bond at the stopped ends, intersections and angles of walls. The difficulties here with stone masonry are not so acute as with brick masonry, since stone can always be cut to required dimensions; whereas with brick masonry the units are of predetermined size and special adjustments required can only be met by trimming bricks into smaller units.

Bonding in stone masonry has two distinct contexts which are basically quite different in their application

(i) Rubble Walls (particularly faced rubble walls)
(ii) Finely Dressed Stone (Ashlar) Walls

(i) Rubble Walls

Here the concern is entirely with maintaining the integrality of the structure across the thickness of the wall—i.e. to avoid blocks falling away at the face of the wall. Particularly is this concern in issue when the construction of the wall consists of three separate elements: two faces and a core, e.g. ashlar faced rubble. In this connection Vitruvius (II.8) animadverts bitterly against the absence of such care in the Roman (concrete) construction of his day. To effect this binding together the facing blocks should include at regular intervals "headers" tailed well into the core, or better, if possible, running through the entire thickness of the wall (*diatonoi*). Where walls are very massive (e.g. barrier walls) and it is not possible to provide header blocks long enough to unite the two faces, then alternative arrangements are made to provide the necessary transverse bonding, e.g. several blocks are set overlapping one another to run through the thickness of the wall, thus utilising friction to effect the tie. In place of this a bonding transverse "wall" (itself of two faces and a core) can be built across the structure—obviously such a device is more proper to "engineering" structures, where special strength and stability is required (e.g. dams). It should be noticed also that this transverse bonding not only ties the wall together, but it also compartmentalises the core and thus reduces its outward pressure on the wall face (ABADY IV 1987 pp. 63–78, figs 9, 10).

Another factor to be noted in this connection are measures taken to anchor the bonding stones into the face of the wall. In run of the mill instances this is effected by the header and stretcher bond of the face, but where maximum fixity is impor-

Bonding of dressed stone masonry

tant the bonding headers may be treated as bolts—i.e. they are made to protrude outwards beyond the face of the wall and given a larger head which serves to bolt the wall in. The aspectual pattern formed by such arrangements may be strikingly ornamental (ABADY IV 1987 pp. 79–96, figs 18, 19, 21–23).

(ii) Dressed Stone (Ashlar) Walls

With finely dressed (dimension) stone masonry bonding assumes an ambit comparable with that it occupies in brick masonry—although, as previously remarked, there is more latitude in its application since blocks of stone can be conveniently dressed to size and shape.

As a preliminary observation it is to be noted that the significance of bonding varies inversely to the size of the masonry concerned. The aim of bonding is to restrain the displacement of masonry units, and the larger the unit the more stable it is because of its dead weight. The force required to displace an object at rest on a horizontal surface is directly proportional to its weight modified by the co-efficient of friction (μ), a value derived from the nature of the surfaces in contact (here stone upon stone). In this way the question of bonding does not enter into megalithic masonry and only to a limited degree in Egyptian large block masonry. 170–173

185A Bonding blocks of standardised form into a pattern uniform throughout a wall, perhaps, first comes to notice in “Israelite” masonry of the Iron Age (8th–7th centuries BC) seemingly mentioned in the Bible. This masonry is not impeccable ashlar masonry. Blocks vary in fineness of dressing according to their position in a wall, and generally the dressing is fine only at the exposed faces of blocks to give an outward appearance of fine dressing—i.e. the masonry is in the Bastard Ashlar tradition. However the material factor is that blocks can be recognised as approximating to standard proportions and the disposition of blocks in the wall accords rationally with these proportions—i.e. bonding pattern can be observed (NB If the reader is not familiar with modern brick bonding, it would be useful at this stage to consult a manual of modern building construction on this subject).

Various biblical references to fine stone masonry indicate that (some) blocks were cut according to given dimensions (i.e. they were “dimension stone”). Moreover they suggest that these dimensions could be standard ones—*viz* “the measure / the measures of hewed stones” (1 Kings 7. 9–11). This passage refers to Solomon’s monumental building, but probably reflects the masonry of Israelite times, e.g. at Samaria. The significance of the biblical references has been interpreted (v TA 3, 1976, pp. 74–78) in the light of the archaeological record of surviving remains of Israelite masonry (e.g. at Samaria) as inferring the solid bonding of these blocks as headers and stretchers was facilitated by or governed by their standardised dimensions. “The building block was approximately two cubits long, 2/3 cubit thick and 1 cubit high. The wall was built of uniform blocks that were 3 times as long as they

Bonding in Israelite masonry

were broad, and the length of which was equal to the thickness of the wall. Thus the same block could serve either as header or stretcher, and the thickness of the wall consisted of one header or three stretchers (TA 3, 1976, p. 75).

In short the dressed block was cut to the length, breadth, height ratio of 6:2:3 which is that of a modern English 9" brick set on edge, and the bonding pattern of the interchangeable units is recognisable in terms of modern brick bonds. The alternation of headers and stretchers in the one course (TA 3, 1976, p. 76, fig 1A) aligns the system with Flemish Bond. Indeed if the face of the blocks had been used as the bed then the proportions of length to breadth would have been 2:1, exactly as with modern English bricks (including the mortar joints) and the bond of alternate header and stretcher would be exactly a Flemish Bond wall. And such a bonding system where the length / breadth ratio is 2:1 and a header course alternates with two stretchers set back to back across the thickness of the wall can be seen at Tell Dan (BA, 1980, p. 178). Walls of considerable thickness (e.g. of two cubits thickness) follow the principle of double Flemish bond (TA, 1976, p. 76, fig 1E), only they require three headers in parallel between the face stretchers instead of two. 185A, 2E

The variants where two headers alternate with a stretcher (TA 3, 1976, p. 76, Fig 1B) suggest in aspect the decorative intention of modern bonds employed generally on non-load bearing walls, e.g. the various types of Flemish Garden Wall bond (*viz* Sussex Garden Wall Bond etc.). Here, however, several stretchers (2, 3 etc.) are set in a run between two headers and the strength of the bond is thereby diminished, whereas the Israelite walling with two headers to the stretcher the strength is increased. 185A, 2B, D

Another type of bonding occurs in Israelite masonry which is interesting. Here the blocks are set as as to leave cavities in the heart of the wall which can be filled with rubble and masonry debris (TA 3, 1976, p. 76, Figs 1C & D). This bond resembles a modern 13" Quetta Bonded wall (where the cavities are grouted and sometimes take steel reinforcing). A85 A, 2D, E

The preceeding comments on bonding in Israelite masonry are to a degree conjectural and based on a limited archaeological record. However they are of considerable interest when seen as precursors to Classical Greek Ashlar masonry. Here the blocks are accurately cut to dimension, while the surviving record of their setting in regular pattern is very extensive. The bonding of Classical Greek Ashlar walling embodies the fullest development of bonding known in stone masonry. However generally it is treated as a matter of aspectual rather than of structural interest (e.g. Scranton, *Greek Walls*). In the following some note is taken of the latter concern.

Bonding in Classical Greek ashlar stone masonry

As is well known Greek ashlar walls are categorised (following Vitruvius) into Isodomic and Pseudo Isodomic masonry, terminology which is meaningless and inept on every count. It can only refer to the aspect of the masonry but is notably misleading in this respect. The usage signifies walls where all the courses are of equal height and those where all the courses are not of equal height—i.e. Isodomic and non-Isodomic masonry. 198–203 Non-Isodomic masonry is not "false" (pseudo) isodomic masonry since it does not purport to be isodomic, or indeed anything other than what it is. Moreover this terminology takes no account of the vertical component, i.e. the aspectual pattern afforded by the rising joints of the blocks. Over and above this the terms do not connote anything at all regarding the internal structure of each course—i.e. the course plans. What they signify is simply masonry set in continuous horizontal courses where, on the one hand, the courses are all the same height and, on the other, where they are not.

A much more revealing classification in every way would be walls where all 199 blocks were of the same form (like modern bricks) and walls where they were 201 not, i.e. walls where blocks of 2 (or more) different forms were set together in regular patterns.

To intimate briefly something of the bonding schemes of Greek ashlar masonry it is necessary to generalise by way of type examples showing:

(i) the form of ashlar blocks
(ii) their disposition within the structure of the wall

(i) The Form of Greek Ashlar Blocks

Speaking in the broadest terms two forms of ashlar blocks were current. One was a compact rectangular faced block where there was relatively little difference between 196A the breadth and the height, while the length was two or three times these dimen-196B sions. The other form was a flat slab where the breadth was greater in proportion to the length, so that the length was only up to one and a half times the breadth.

It must be emphasized that these generalisations refer to normal blocks used in the run of the wall masonry. In addition to these blocks various specially shaped and dimensioned blocks were ued to effect special passages of wall masonry (e.g. stopped ends, intersections, angles etc.). Also a very common device was to set 203 a course of large upstanding slabs at the base of the wall, which are now termed orthostates. These orthostates are a carry over from the mixed masonry traditions 179–185 of the Bronze and Iron Ages, notably in the Levant, where they are functional in providing a solid structure at the base of the walls. However this consideration does not obtain in Classical Greek masonry and their presence there is by operation of tradition and relates to aspect not structure.

Bonding in Classical Greek ashlar masonry

(ii) Disposition of Blocks (the masonry pattern)

As a fundamental all blocks, (whatever their form) were set in the wall (whatever its construction) so as to keep the rising joints of alternate or intermittent courses exactly in vertical lines (cf the "perpends" of brick masonry). Next it may be observed that generally in Greek monumental ashlar masonry, the thickness of the walls was made to acord either with the width of one ashlar block or with its 198
length. For slight walls of the former class bonding was circumscribed. Isodomic 199
walls were constructed of blocks set in stretcher bond. If the variety of pseudo-isodomic masonry was desired different courses could be set with blocks bedded on different sides. However with the usual form of blocks this did not give much 198b
distinction in course height. More effective was to use blocks of two different forms affording a greater contrast in course height.

With more substantial walls, a block length in thickness, blocks could be set as 199
headers and stretchers in the same wall. Here developed bonding patterns were employed presenting the several aspects of Stretcher Bond, English Bond and Flemish Bond. If the additional variety of pseudo-isodomic masonry was desired, then blocks of another format were introduced at regular course intervals. When 200a–c,
a strongly pseudo-isodomic aspect was desired then flat slabs rather than compact 201c
blocks were employed. If the dimensions of the blocks permitted these multiple 200c
block walls could be completely solid construction. However where two stretchers back to back did not equal the length of one header central cavities occured; and 200, 201
these were often filled with rubble. Ill 202 gives a conspectus of different forms of blocks disposed in different manners in a typical passage of Greek Ashlar masonry of the 5th century BC (the Temple of Poseidon at Sounion in Attica).

Little attention has been given to these bonding patterns in Classical Greek Masonry and it has not been made clear e.g. what chronological evidence they offer. Scranton (*Greek Walls*) bases his chronology on modes of facing the blocks (e.g. margin draughted, bevelled, bossed etc.), however this is entirely a matter of aspect with no effect whatever on the structure of the masonry. Perhaps the strongly patterned use of headers and stretchers—e.g. three stretchers to a header in one course (Flemish Garden Wall Bond), or three courses of stretchers to a header course (English Garden Wall Bond) is more a Hellenistic feature, ca 3rd century BC (*Greek Walls*, p. 140).

There is little detailed record conveniently published on the bonding of Roman *opus quadratum*. Also in this connection the looseness of the term Roman is particularly vexing. Let alone a possible restriction regionally to parts of Italy, does it mean building known to have been carried out in some way under 'Roman' direction or simply any building during Roman rule? Obviously in buildings erected during Roman rule there is a great difference between those in provinces where Greek ashlar construction was current and those where no tradition of fine stone masonry existed.

In any event it may be possible to say that speaking generally fine stone masonry (*opus quadratum*) under Roman rule tended to develop away from the sophisticated pattern bonding of Hellenistic ashlar towards a simple stretcher bond which continued into Byzantine times. With this development (indeed as part of it) *opus quadratum* construction developed away from uniform finely jointed masonry throughout the thickness of a structure towards a facing to other material—and thus to an element in mixed construction. But this field is too extensive to survey here (cf supra, p. 155). *Fixation of blocks* 204 399

b. *Fixing*

During antiquity two dissimilar means of fixing stone masonry were practiced. They and the manner of their application both were constant throughout the ancient world (and indeed remained so in after times). They were:

(i) Cementitious mortar
(ii) Inset couplings (of wood or metal)

Cementitious mortar not only provides the desired adhesion between units of masonry, it also provides the bed on which the units rest stably. The inner couplings between blocks secure them one to another where the form of the blocks themselves provides the necessary bedding. Cementitious mortar can be prepared from several substances and its composition is characteristic of the type of masonry where it is employed. The material (wood, metal) of the couplings and their form imports both geographical and historical distinctions, and is of considerable archaeological significance.

(i) Cementitious Mortar

In connection with building the term mortar is used loosely for any plastic earthy substance employed in masonry in conjunction with the masonry units (stone, brick). It may serve two distinct functions—often both combined, but not necessarily so: as a lubricant to facilitate the setting in position of masonry units, and as an adhesive to fix the units together when it has "set". The following remarks are concerned with the latter function—hence the term cementitious mortar. The uniformity in the manner of use of such mortar is striking. 164–166

In brief, cementitious mortar is used with rubble masonry, not with finely dressed (hair line jointed) ashlar masonry which is set dry-stone (Orlandos II, pp. 99–100). More specifically when rubble masonry is random, irregular and little shaped the type of cementitious mortar employed is "mud mortar". On the other hand where another type of mortar is used with stone masonry, gypsum based mortar is strongly preferred to lime based mortar (which is always used with burnt brick masonry). A reason for this distribution (as is obvious) is economic: to fill the 149

Fixation of blocks by cementitious mortar

interstices of random rubble masonry require a great quantity of mortar, thus the cheapest serviceable substance is mud. Gypsum (or lime) based mortar however is relatively expensive and therefore only to be used when the quantity required per masonry unit is relatively slight.

From Early Neolithic times, mud mortar has always been used in connection with rubble masonry construction (Vol. 2, p. 95; O. Aurenche, *La Maison Orientale I*, 149 p. 72). Mud is very glutinous and adhesive when plastic, however thereafter time appears to deal differently with different mud mortared masonry. In some the plastic mud after drying out remains compact so that the construction is stable well bedded masonry. On the other hand, in some instances, the mud mortar becomes dessicated and loses all adhesive virtue. Not only this, but it loses its cohesion as well and trickles away from the interstices of the masonry. Deprived of fixing and also of adequate bedding the units of rubble collapse or are easily displaced and the building becomes ruinous—a convenient source of supply for later building in rubble. Presumably the root of this diversity is the composition of the soil used for the mud.

The traditional preference for gypsum based mortar in fine stone masonry is unfortunately not elucidated in manuals of building construction or building materials. Some physics or chemistry should stand behind this, but there is no consideration of the matter conveniently available for the study of ancient building construction. Also ground up stone dust, a favoured ingredient for mortar used in modern fine stone masonry, is likewise rarely mentioned in connection with ancient building, but cf the use at Karnak in New Kingdom Egypt of gypsum and stone dust (Arnold, p. 291).

For long reference in archaeological reports on ancient building to gypsum or lime were worthless since the observer lacked the capacity to discriminate between traces of the two materials. In more recent times scientific understanding has been applied to this question with the result that regional zones have been postulated in the ancient world where one of the materials was much more commonly used than the other (O. Aurenche, *La Maison Orientale*, Vol. 2, pt 2, ill 198; O. Aurenche, I, p. 28, Cartes 1 & 2). However it is not generally appreciated that this analysis is based almost entirely on the use of the materials in plaster (Vol. 2, pp. 159–74), not in mortar (Vol. 2, pp. 174–77).

The primary question is the field of use of cementitious mortar in ancient fine stone masonry. It is not used with large block masonry (*grand appareil*) such as Pharaonic Egyptian (Clarke & Engelbach, p. 78; Arnold, pp. 291–92) or Classical Greek ashlar masonry since the dead weight of the individual block provides its own fixing. Hence the field should be finely dressed small block masonry (*petit appareil*). This, in effect, should equate with ancient "bastard ashlar" where it may be imagined that gypsum based mortar was employed at the finely jointed faces of the blocks leaving the roughly jointed tails and rubble interior of the wall to be set in mud mortar (cf the analagous question of *opus incertum* and *opus reticulatum*). However there is virtually no discussion of this question in manuals or reports.

Fixation of blocks, in dressed stone masonry by cramping & dowelling

Nonetheless in one connection there is both ancient discussion and surviving evidence of the use of gypsum based mortar in ancient stone masonry. The Greek philosopher Theophrastus (Aristotle's successor as head of the Lyceum) wrote a treatise on stones (*Peri ton Lithon*—ca 300 BC) wherein he notes that a highly cementitious substance was prepared from gypsum which could be used to cement other materials together. In particular it was used as a mortar so strong that the blocks of stone would break apart before the mortar joint would fail. What Theophrastus was evidencing here is most likely the masonry of city walls, a special case where normal considerations of economy took second place to human survival against siege warfare—cf the walls of Tyre which resisted Alexander's battery for so long (Arrian, *Anabasis* 2, 21, 4). Evidence of the use of gypsum in this connection exists in the contemporary circuit walls of Dura Europas, where the blocks, both dressed facing blocks and core rubble are fixed with gypsum mortar (J.-P. Adam, *La Construction Romaine*, pp. 59, 69; J.-C. Bessac & P. Leriche, "Les Dossiers d'Archéologie," 171, 1992, pp. 70–81).

This subject in general is inadequately investigated.

(ii) Inset coupling between blocks (cramping and dowelling)

The practice of fixing blocks of masonry in place by dowelling and cramping is the counterpart (i.e. is inverse in its application) to that of fixing by cementitious mortar. Whereas the latter is used with roughly jointed or rubble masonry, the former is used with finely dressed stone masonry ("dimension stone" blocks) set dry jointed. The practice thus has a limited usage in the ancient world. To all intents it is limited to Pharaonic Egyptian masonry and Classical Ashlar masonry. Thus it does not occur in small block "bastard ashlar", e.g. Zoser masonry. This is a matter of some pragmatic importance, since it serves to identify mortises for dowels in the upper bed joints of bastard ashlar, not as evidence of dowelling for another course of such masonry, but as arrangements for anchoring timber beams used as re-inforcing for a superstructure of a different type of masonry, e.g. mud brick or rubble.

The device of cramping together blocks of finely dressed masonry is of considerable interest in the history of building technology. Its history extends over the entire period of building in finely dressed masonry in the ancient world and it appears to bring into focus general issues. Cramps occur with the earliest Egyptian Pharaonic masonry (ca 2500 BC) as in the earliest classical Greek ashlar construction (ca 600 BC). The device thus constitutes one feature in Classical Greek building which is patently derived from Egypt—although the precise mechanics of the diffusion are

Cramping & dowelling in Pharaonic masonry

not demonstrated. Moreover this particular instance bears out to the full the general nature of such transmissions—i.e. the device was certainly taken over from Egypt, but it was developed in an entirely Greek manner. In Egypt the wooden material and swallow tail form of cramps remained current from the Pyramid Age (ca 2,500 BC) to the end of Pharaonic building (ca 2nd century AD). On the other hand the changing form and substance of cramps in Greek ashlar masonry is a favorite chronological indicator in classical architectural history. 164–167, 170

Cramping masonry in Egypt and Greece forms a continuous history and must be considered in conjunction. In the overall it is the study of a feature introduced to provide for special circumstances, which developed into standard general construction.

When the first building out of large finely dressed, closely jointed blocks appeared suddenly in Egypt at the middle of the 3rd millenium BC, this masonry incorporated the use of swallow tail cramps (both of wood and of metal) in positions where some special measure of fixing appeared necessary. Was it an *ad hoc* invention (a brilliant one) to give this masonry greater strength and stability? Hardly. Such inventions usually show primitive traits with a subsequent history of formal development. The swallow tail cramp appeared in definitive form which remained unchanged throughout the history of Pharaonic building. The obvious inference is that it was developed in another connection—perhaps that of piecing together stone statuary. The ancient Egyptian builders discriminated nicely between Pharaonic masonry which was closely jointed throughout the entire wall thickness and Zoser masonry (bastard ashlar) which was finely jointed only in aspect at the face. For the latter they did not supply cramps. They recognised cramps were a supplement to fine jointing, not a device in themselves for providing solidity and strength. For cramping to be effective there must be no play in the joints. This was the knowledge of experience.

It is only possible here to speak in summary terms concerning the history of cramping and dowelling in Pharaonic masonry (for a more detailed review v Arnold, pp. 124–28). In the first place the massive nature of the blocks (generally speaking) reduced the need for this measure. Thus in the overall cramping remained confined to positions of special stress, while dowelling was always rare—generally associated with fixing columns and entablature. It has been noted that routine general cramping of blocks appear to be associated with masonry of Graeco-Roman date. Here it is quite possible that this feature represents the influence of Classical Greek masonry, since although the design of Egyptian temples was not subject to Greek influence, elements of construction were (e.g. foundations). However recent knowledge has clothed this feature in mystery.

The possibility of examining course by course the masonry of several Graeco-Roman temples in Nubia was provided by the necessity of dismantling and transferring them occasioned by the building of the High Dam at Aswan during

Cramping & dowelling in Greek ashlar masonry

the sixties of last century. This revealed that uniformly recesses for swallow tail cramps were cut in all wall blocks. However, quite amazingly, apart from vestigial (wooden) survivors, these cuttings were devoid of any cramps. The only possible explanation is that the wooden cramps were set as a temporary measure to enhance the solidity of the masonry during the process of construction (NB the massive blocks were not clean lifted into position, but were hauled along and levered about and into place). The cramps were then removed from their lodgements when the course was completed and before being rendered inaccessible by the setting of the superincumbent blocks. (Wright, Kalabsha 2, p. 76). However from all practical points of view this explanation seems derisory. Nonetheless a similar phenomenon has been noted in the (Greek) ashlar masonry at Leptis Magna in Tripoli, and the same explanation advanced (Ward-Perkins, *Leptis Magna*, pp. 92, 96). The date here is late 2nd century AD and neither the masonry nor the province has any connection with Egypt!

The history of cramping and dowelling in Classical Greek ashlar was in startling contrast to the static picture of Egyptian usage extending across two and a half millenia. It was one of dynamic development. Within a few generations of men (at most ca 600 BC–ca 400 BC) an occasional auxilliary to fine stone masonry became a coordinate component to the stone. There were at least the same number of metal cramps, together with at least the same number of metal dowels as there were finely dressed blocks contained in the structure. These cramps and dowels
202 of evolved and differentiated forms connected each block of stone to contiguous blocks of stone in the same course, as also each block of stone to contiguous blocks of stones in the courses above and below—and the distribution of the cramps and dowels was as systematic as the setting of the blocks.

This development of total cramping and dowelling in ashlar masonry can only be reckoned an expression of Classical Greek rational idealism—the perfect building construction to correspond with the perfect building design. And with this went an empirical effort to determine the most effective form of cramps and dowels to secure this perfection of construction: metal succeeding wood and the most effective forms proper to metal succeeding one another.

Over all this development arches a question which is never broached in the manuals. Given that total cramping and dowelling of dry stone ashlar masonry was the perfect form of fine stone masonry, the Greeks of the 5th and 4th centuries BC achieved it. But it must be added at great cost. It would be interesting to calculate what fraction of the total cost of such masonry construction was incurred on cramping and dowelling. Did cramping and dowelling augment the strength, solidity and stability of the masonry sufficiently to warrant this added expense? This is a question of great interest and worth detailed investigation. Pending such investigation it is worth while to remark on the sequel.

Reinforcing of less solid stone masonry

After the decline of Classical Greek ashlar construction in Antiquity, the complete systematic usage of cramping and dowelling disappeared and was never renewed. Abandoned entirely in mediaeval stone masonry, cramping and dowelling were re-introduced only where special circumstances demanded special fixing. In contemporary ashlar masonry (or reconstruction work) the use of ferrous cramps and dowels is eyed askance, because of the inevitable rusting and consequent cracking and splitting of the stone work. Did the builders of classical antiquity possess some specific device for nullifying this development?

(c) *Reinforcing*

At all times and in all places the practice was current of reinforcing some stone masonry so as to increase its strength and stability. Manifestly this practice is applicable in the main to stone masonry which is relatively weaker and less stable. In this way reinforcing devices were not associated with the strongest of all stone masonry: sizeable blocks set dry stone and finely jointed throughout the thickness of the wall, i.e. Egyptian large block (Pharaonic) masonry and Classical ashlar masonry.

According to modern statical analysis reinforcing of ancient stone masonry can be recognised as falling into two categories according to the stresses it provides against, *viz* compression and tension. However it is unlikely that ancient builders ever thought about the matter in this way.

(a) Reinforcing against compressive stress

Here the required material must be strong in compression. This in effect is stone or stone masonry which is of a stronger nature than that comprising the wall. Broadly and briefly speaking it takes two forms which may be termed for convenience: *opus africanum* and Coigning and Framing.

(i) Coigning and Framing. This is the less well attested mode in antiquity, but was renewed in Renaissance times to become a prevalent construction for Neo-Classical Villas etc. of the 19th century, notably in Greece and the Eastern Mediterranean—thus often in localities where it had been known in Classical Antiquity (e.g. Cyprus). This mode of reinforcing walls was in no way restricted to stone walls, indeed it was more commonly associated with mud brick. 210

A nice display of ancient ashlar coigning and facing to rubble walls is at the Sanctuary of Apollo near Kourion in Southern Cyprus (*Ancient Building in Cyprus I*, p. 173 & II, figs 269–270). There several buildings reveal passages of this construction accurately restored almost to ceiling height. With the ashlar elements standing slightly proud of the plastered rubble these buildings must have presented the attractive appearance of their Neo Classical successors (the mode was adopted for public building in the earlier days of the British Administration, cf Praktika, 2000, Vol. 1, p. 420, fig 21). 209

(ii) *opus africanum*. In the present context it is reasonable to extend the field of this term so as to include its antecedents which were unknown when the term was coined. The Romans applied the term to the striking construction they observed of widespread occurence in the Phoenecian settled provinces of North Africa. In this region the standard type of wall (both domestic and monumental) was a pier and panel construction, where the piers, spaced at suitable intervals, were of finely dressed stone masonry, while the panels between them were stone masonry of lesser strength and stability—rubble of varying types. The integrality of the wall was effected by careful bonding together of the ashlar piers and the rubble panels (Adam, pp. 130–31, figs 276–79). The effectiveness of this type of masonry is evidenced by the numerous survivals to considerable height which can be seen today all about the countryside. It should be noted here that the dressed stone reinforcing serves two ends. It directly provides the wall with additional strength in compression and also it augments the stability, rigidity of the construction by compartmentalising the rubble and so reducing its outward pressure. 211–213

Reinforcing against compressive stress

What was unknown to those who devised the term *opus africanum* has been latterly revealed by 20th century Palestinian archaeology. Although excavation has been restricted in Pheonecia, in the adjoining areas of Israel and Canaan numerous examples of this general type of construction have been discovered of Iron Age date—thus antedating the examples in Punic North Africa (where the construction remained endemic under Roman rule). As might be expected the Palestinian Iron Age examples are of ruder construction and the piers of varying degrees of fine dressing. Also according to the revealed evidence the Palestinian Iron Age examples appear to occur in domestic building rather than in monumental building as is often the case in classical North Africa. Nonetheless the device is clearly one and the same in both regions. In the light of this knowledge perhaps nowadays *opus punicum* might be a more revealing designation. *Opus africanum* wall construction is clearly at times on the border line with stone framed construction (cf the Italian appelative, *opere a telaio*). It would become framed construction if the roofing beams were everywhere lodged on the wall piers, or even more exactly if the wall piers were all spanned by load bearing architraves. However although examples of *opus africanum* are preserved to considerable height, few are preserved in situ to roof level so as to clarify the question. 150, 151 213

(b) Reinforcing against tensile stress

Walls of buildings ideally are not subject to tensile stresses, however on occasion they are—obvious occasions being human battery, and, even more patently, earthquake shock. In this way tensile reinforcing in walls of buildings in the Ancient World is usually considered to be a measure directed against earthquake damage. However it is not evident that provision of tensile reinforcing in walls is limited to earthquake zones. Perhaps it served against the effects of uneven settlement of

Reinforcing against tensile stress

foundations. Damage to masonry occasioned by failure in tension means splitting apart and horizontal displacement. Massive units of masonry are less subject to this damage because of their dead weight, hence tensile reinforcing in stone masonry is not associated with large block masonry but with smaller block rubble masonry. It goes with cementitious mortar (particularly mud mortar) as a binding device as opposed to finely dressed dry stone masonry secured together by cramps and dowelling.

Obviously the materials used for this type of reinforcing must be strong in tension, which in ancient building indicates wood; also to a lesser degree in classical times metal (iron).

(i) Wood Reinforcing in Stone Construction

The use of lengths of timber inset into stone construction the better to hold the masonry together is a familiar expedient. English lacks an effective term to describe (functionally) this practice, but the French *"chainage"* is very expressive.

The matter has been outlined above in chap. 4 Wood under the sub-headings "Mixed Construction" and "Reinforcing" (pp. 124–135). This indicates that the inset wooden members vary in extent from occasional stringer beams along bed joints to stringers, cross ties, and vertical posts—where because of limitations in the surviving remains it is difficult to determine whether or not the reinforcing constituted an independent frame. Apart from this, the posts were essentially not designed to add strength in compression but to tie the masonry together vertically as the stringers operated horizontally. These wooden members also compartmentalise stone masonry defective in coherence so as to limit prospective displacement and to localise the effects of actual displacement. Wood reinforcing is thus intended to increase the coherence of stone masonry. It is therefore proper to rubble and, to some degree, to bastard ashlar, which in structure (not in aspect) approaches rubble. However it should be noted that although often present in conjunction with a bastard ashlar socle, the wood reinforcing generally figures in the rubble superstructure, not in the bastard ashlar socle.

The Biblical specification of three courses of hewed stones and a course of cedar beams (1 Kings 17.12) for the masonry of Solomon's Temple indicates more monumental masonry. However the masonry in question (cf surviving Israelite masonry of a somewhat later date) was essentially bastard ashlar rather than entirely fine jointed ashlar. Regrettably no masonry survives which accords with the biblical specification. Speaking broadly wooden reinforcing is not found in Classical Greek Ashlar nor in Egyptian Pharaonic masonry. However evidence subsists of the incorporation of wood in finely dressed stone masonry. But this is not reinforcement, it is by way of protection. The feature extends from protection of specific elements exposed to damage (e.g. qusins) to revetment of entire wall faces. This issue is only marginal to construction, and cannot be dealt with duly here. It is well surveyed by Martin pp. 443–445.

Finally mention is made of a specialised usage of wood reinforcing, the reinforcing of stone fortification walls in military engineering. Here in addition to all other functions, the wooden reinforcing absorbs and distributes the shock of battery, i.e. it increases the resiliance (elasticity) of the stone construction, cf the precepts of Philo of Byzantium 1, 12.

Metal reinforcing

(ii) Metal Reinforcing in Stone Construction

During Classical times the forging of iron became reasonably practical, and in addition to using iron for cramps and dowels, the Greeks made use of inset cross bars as reinforcing in stone masonry. Because of its great strength in tension iron was always used like wood to increase the tensile resistance of masonry, but in exact contradistinction to wood, iron bar reinforcing, because of its expense, was used (like metal cramps) with the finest ashlar masonry. This use had two main applications: in upstanding masonry and for spanning members, i.e. architraves, beams etc. stressed in bending.

(a) Upstanding Masonry

The crepis of a Classical Greek temple was the basic platform on which depended the stability of the upstanding structure. If the crepis deformed in any way, then that movement could occasion damage to the entire superincumbent masonry. To ensure against this possibility two courses of the crepis of the Theban Treasury at Delphi were entirely secured together by a framing rectangle of wrought iron (6 m × 13 m) set into their upper surface. This consisted of four long iron bars (9 cms × 10 cms in section) with overlapping halved joints at the angles. A fine example of blacksmithing—and very expensive (W. Dinsmoor, "Structural Iron," pp. 149–50).

(b) Spanning Members

The soffites of such stone blocks are put in tension and thus liable to crack or fissure. Greek builders recognised this weakness and on occasion provided against it by wrought iron bars set into either the upper bed (The Propylaia at Athens) or the lower bed (The Temple of Zeus at Akragas) which could resist the entire load and transmit it down through the columns (Vol. 2 pp. 252, 253). The strength in tension of iron is vastly greater than that of stone (e.g. up to 90 times greater) and the Greeks stressed their iron reinforcing to the limit (W. Dinsmoor, "Structural Iron," figs 2, 3, 5, 6 *et pass*).

2. *Framed Structure*

Stone framed construction existed in the Ancient World although of minor significance compared with load bearing stone construction. Yet this appraisal requires some qualification. To determine that the construction is a fully framed one, requires surviving evidence up to roof height—and this is not very common. Without this evidence it is not certain that the entire load was transmitted

Stone framed construction

exclusively to the piers: the definition of a true framed structure being one where the frame provides for the strength and stability and the infilling panels are closures not required to bear any loads. That is if the panels are removed the structure will continue to stand. The latter circumstance occurs in some ancient stone buildings and in these instances it can be stated that they are of true framed construction.

Stone framing is the logical fulfillment of *opus africanum* construction and, exceptionally, at the prosperous provincial Roman town of Cuicul (Jemila) in the Algerian uplands (v Ward Perkins, pp. 486–90) evidence survives to show that a true framed construction was aimed at—i.e. the wall plate is of blocks spanning from pier to pier. Also, although it may be pushing logic too far, perhaps the connection between piers and infill may give an indication of a framed structure, since if the piers are not bonded into the panels, then maybe this is a sign that they are intended as an independent structure.

Framed construction is essentially economic construction, as is attested by its entire predominance in present day building. As such its obvious expression is dressed stone framing with rubble panels as occurs in North Africa (e.g. at Cuicul). 213, 214
However by far its most striking survival is in the rocky uplands of North Syria, the region about Aleppo and Antioch, during late antiquity (ca 500 AD). Here the preservation of gaunt, powerful stone frames standing stark above the deserted rocky terrain has bestowed on their agglomerations the term "Les Villes Mortes". 216, 217
However the building style was a uniform one common both to houses and public buildings. And it exhibited a mode quite different from *opus africanum*.

Each individual frame is a trilithon of three more or less identical "baulks" of stone. These are sizeable and weighty enough to be structurally stable by their own dead weight so no cramping or dowelling was employed. The baulks were squarish in section (something under 50 cms × 50 cms) and approaching two metres in length. Thus they verged up to one ton in weight. A typical horizontal range was a series of ca 10 piers enclosing 5 bays, and very frequently there were two such ranges superimposed vertically one above the other. The general appearance of such structures suggested to casual observation that they were porticos (cf Krautheimer, p. 140). In some instances they were; closed at the bottom with a balustrade of the typical ornamented Byzantine closure slabs (like those used in the chancel screens of Early Byzantine Churches). However many are now devoid of any panelling, and in these instances traces on the uprights indicate that the infill was of normal dressed stone masonry blocks to constitute a complete wall. It is evident that this ponderous framing was lifted into place by block and tackle, set on heavy scaffolding, the attachments to the stones by way of ropes (slings).

This highly ideosyncratic construction has been illustrated and commented on since the 19th century. (H.C. Butler, "American Expedition to Syria"; H.C. Butler, "Princeton Expedition to Syria"; G. Tchalenko, "Villes Antiques"; J.-P. Sodini, "Déhès.") However little attention has been given to explaining its historical background and development, and why it became endemic in the region during late antiquity. There are two obvious background considerations. When the late antique building of North Syria was re-investigated in 1976–78 (J.-P. Sodini, "Déhès"), 217 the French archaeologists had difficulty in distinguishing between pillared porticos and framed wall construction. They also thought to recognise fore-runners of this framed construction in the area, going back to the Early Roman Empire. In this way, they established the line of development of the striking framed stone construction evidenced in Les Villes Mortes during later antiquity. This evolved 215 out of the Portico House Type of the Early Empire, e.g. at Banaqfur, 1st Cent AD; Benabil, 2nd Century AD (cf Ward Perkins, pp. 428–30, fig 161). The other strand relevent was the stiffened wall masonry called *opus africanum* but perhaps better termed *opus punicum*. However ultimately these considerations merge in an original pillared construction.

All stone building

D. *Mode of Construction*

More or less on a par with wood, stone construction can take two modes: "all stone" buildings and as a contributing material in mixed construction. This statement, of course, must be understood as referring to building structure. A building does not cease to be an all stone building because, e.g. the doors, windows etc. are of wood.

1. *All Stone Building*

There are numbers of all stone structures in several different contexts in the ancient world and there would be many more if the physical properties of stone admitted of convenient trabeated roofing out of stone. However this is not so, and thus "all stone" building is virtually limited to monumental building where the roofing, if trabeated, is on a grandiose scale (Egypt) or else it must be of vaulted construction (later Graeco Roman).

(a) *Trabeated Roofing* (v Arnold, pp. 183–260; Clarke & Engelbach, pp. 151–61) The inexpediency of trabeated stone roofing is manifest and it is demonstrated by the surviving record in Egypt To roof any reasonable span by stone beams 255–259 or slabs requires such massive units that their burden is great, e.g. some 20 tons. There is difficulty in getting such units in position 15 m or more above the ground; and equally the wall construction must be very strong to support this load. In any event the results in Egypt were not notably successful—very few massive stone beams have survived intact across the ages. Also it is a striking fact that nowhere else in the ancient world was an attempt made to emulate this Egyptian

Stone roofing

system of stone roofing. It was not practical without the great centralised resources of Egypt.

(b) *Arcuated Roofing* (v T.D. Boyd, "The Arch and the Vault in Greek Architecture," *AJA* 82, 1978, pp. 83–100).

In contrast to the foregoing arcuated stone roofing became widespread in the international Hellenistic-Roman world. Stone domes covered centralised tombs 298A
and temples, and stone vaults roofed basilicae in the Eastern Roman Empire. Also 271
some apartments of bath buildings were provided with stone domes where wooden roofing was contra-indicated because of the humidity.

With respect to arcuated roofing, there is an important practical distinction which is seldom, if ever, noted. This is the distinction between normal free standing building construction and underground construction (which is to say, in general, tombs). There is no lexical difficulty here: a built tomb is, according to English usage "a building"—and because of the constraints of physics, stone is highly appropriate for underground building. Indeed the only comparable alternative material is burnt brick; mud brick and timber being much less resistant to decay in the earth. In this fashion underground built tombs in the ancient world were very frequently "all stone" buildings, e.g. the Mycenaean tholoi; the burial vaults 286–289
at Bronze Age Ugarit, Iron Age built tombs in Cyprus etc. All these funerary 263–266
stone buildings were of arcuated construction (they were roofed by way of domes or vaults, generally corbelled). Indeed arcuated construction was appropriate to underground building, since no problem by way of thrust supervened, because of the buttressing effect of the earth emplacement.

Stone Roofing

The question of stone roofing to monumental building is of great importance in the history of building construction and must now be taken up in some detail—especially as concerns arcuated roofing. This is one instance where explanation in terms of statics can not be avoided (entailing a lengthier than usual discussion).

The use of stone as a structural material for roofing buildings is limited by physics. Stone is the natural material which has the most adverse strength/weight ratio in tension imaginable. Thus its use for roofing is contra-indicated unless it can be kept almost entirely in compression (which, in effect, means some form of arcuated roofing). Here it may be emphasized that this statement refers to structural use. Stone was used for cladding roofs (i.e. as a tegument). On occasion the normal terra-cotta roofing tiles of Classical Greek temples were replaced by marble tiles—at great cost, and to little aesthetic advantage. In the light of these remarks a brief review of stone roofing may be presented under two headings: trabeated roofing and arcuated roofing.

Trabeated stone roofing

(a) *Trabeated Roofing*

This type of roofing was limited to monumental buildings in stone, since the great load of the massive roofing units necessitated very strong supporting masonry. To 250–252 all intents it was limited to Megalithic Building (floruit ca 4,500 BC–2,500 BC in 253–259 Western Europe); and to Pharaonic Egyptian Building (floruit ca 2,500 BC–150 AD)—the former out of rude (or roughly shaped) slabs, and the latter from finely dressed masonry.

(i) Megalithic Roofing

The characteristic form of Megalithic roofing is the rude stone slab supported 259 by similar slabs as walling (= the Dolmen). The burden of some Megalithic slabs 154, 251 is very great, indeed up to 100 tons (e.g. the Mount Brown dolmen in Ireland). Bearing in mind that dolmens were not as a rule "al fresco" structures but were the interior component of earth tumuli, the method of construction appears evident. Earth slopes as starters of the tumulus were heaped around the designated emplacement of the dolmen. The wall stones/slabs were then hauled up these slopes base first and slid down into position, to be raised vertical with raw-hide ropes. Next the chamber was filled with earth to consolidate the standing stones and the roofing slabs were hauled up the earth slopes and across the filled chamber to be set into position capping the wall stones. Finally the chamber was emptied of its earth fill and the enveloping earth tumulus completed. (A proceedure which was essentially that of Egyptian Pharaonic masonry construction in general.) Many such megalithic structures have survived over the millenia to the present day. And while many more have collapsed, there is little evidence of the capstones failing in bending (tension) to break apart and fall. The reason for this is probably that the spans involved were restricted (say 3 m or so, in gallery graves). Where greater spans were involved (e.g. for the circular chambers of passage graves) some form 252 of corbelling was adopted (cf New Grange in Ireland), but the construction proceedure remained essentially unchanged).

(ii) Pharaonic Egyptian Roofing

Here the roofing differed from Megalithic roofing in two essentials: the blocks 255 were finely dressed, and the spans required were on occasion considerable, ca 4 m–7 m. The lesser spans, e.g. of pylon chambers, were roofed by contiguous slabs spanning directly from wall to wall. These slabs of necessity were of considerable depth (verging up to 1 m) to provide the strength in tension to resist the bend- 257, 258 ing stresses. The greater spans (e.g. that of Hypostyle Halls) required "double" roofs, *Arcuated stone roofing*

i.e. massive columns supported beams and the roofing slabs spanned from beam to beam. Very often these roofing beams were composite, i.e. of two beams side 254 by side, and even two beams one above the other giving a total of 4 elements).

It was a general rule that such slab roofing was also paved with substantial stone blocks, so that the combined burden of slabs and paving was very great (always 256 of the order of several tons per square metre). This involved two consequences. The upstanding supports (walls and columns) were of massive construction; and (because of the weakness of stone in tension) the roofing slabs and beams were stressed often beyond safe limits and failed in tension. Thus relatively few roofing slabs have survived in position intact to the present day.

In turn the upshot of this is that Egyptian style slab roofing for monumental building was never a feasible proposition in other parts of the ancient world. Its structural heritage is to be found outside the Ancient World as here defined, *viz* in Hindu monumental stone building—particularly in the Dravidian style of Southern India.

(b) *Arcuated Roofing*

(α) Terminology

Any attempt to outline briefly the use of stone to construct arcuated roofing confronts an inital obstacle in the very ambiguous use in English of the relevent terminology. This can refer indifferently to: geometrical form; statical functioning; and type of building. Thus the one term can be applied in three senses, so that where it correctly indicates the nature of an item in one sense, it is erroneously applied in another.

First a substantiation of "arcuated". This is a convenient generic term to comprehend arch, vault and dome. Strictly speaking the arch is hardly to be considered as roofing since the dimension other than the span is restricted and thus it cannot cover a signifiant area. However since the arch is the generating form of the vault and the dome, the three forms are properly considered ensemble. A vault is the linear extension of an arch; while a dome is generated by the revolution of an arch about its vertical axis. Here it is to be emphasized that the concern is with geometrical form not with construction or functioning.

When spoken of in this fashion the geometrical form of the arch (and hence of its derivatives) is always understood as curvilinear. However when considered in connection with building construction, a curvilinear profile is not a *sine qua non*, nor indeed is it the essence of the matter. An arch can be constructed so that it is flat (horizontal) or triangular. On the other hand a beam can be shaped so that 260, 261 it is of curvilinear profile. What is in issue here is thus not geometrical form but structural mechanics. In this sense the essence of an arch is that its component parts are stressed in compression, whereas the essence of a beam is that it is stressed in bending (i.e. partly in tension). Thus structurally a flat arch is not a beam even though it is rectilinear in form; and a hollowed beam is not an arch even though it is curvilinear in aspect.

Arcuated stone roofing—definition

There is also a further ambiguity. In English "vault" is often used for subterranean apartments (e.g. of a tomb, or of a bank) even though neither their geometrical form nor their statics conform to this term. In other languages the term for the cathedral church of a city is "Dome" (*Duomo, Dom*) even though the building is neither domical in aspect nor in construction.

Finally to be noted is the term for the component elements of an arch, vault or dome. In English these are called voussoirs (taken directly from French). However some effort has been made to distinguish the component element of a dome by the use of the term *vousson* (again taken directly from French). Whatever may be the correct or current usage in French, the latter term has never gained significant currency in English.

In view of this multiplicity of reference it seems preferable to begin a survey with some account of historical occurrence, and on this basis then proceed to an analysis of form and function of structure.

(β) Early History

If an attempt is made to assess the overall historical development in the use of stone for arcuated roofing, it would seem that this can be largely equated with progression in the nature of the stone employed, i.e. from random rubble to roughly dressed stone and bastard ashlar, to finely dressed ashlar masonry. It is also advisable to observe a distinction between free standing structures and those below ground or covered with earth. This latter distinction has a structural basis. Arcuated construction exerts a lateral thrust, which is, of course, effectively taken up by the earth surround. (NB the use of vault for a chamber tomb, whatever its construction or situation.) Finally, as an overall consideration, it is possible to make the suggestion that the use of stone in arcuated construction derived in some measure from prior experience in using clay (brick) for this purpose.

The earliest use of stone for arcuated roofing may be found at the beginning of substantial building construction—in the "Round House" of the Neolithic Middle East (cf Aurenche, *La Maison Orientale*, *pass*). To the degree that the entire construction embodied rubble (rather than the superstructure was entirely in mud brick on a rubble substructure) then it was considered that these structures constituted
280 rubble domes—corbelled it was said, although this term can have little significance when applied to rubble and earth construction (v *Ancient Building in South Syria*

Arcuated stone roofing—the round house

and Palestine I, pp. 282–3; II fig 202–80; *Ancient Building in Cyprus I*, pp. 305–10; II figs 152–55). However recently it has been advocated that the manifest incurving of the surviving walls is illusory or misleading; and that these round houses were 281 more or less cylindrical buildings roofed with flat mud terrace roofs as normal for rectangular building (The Beehive House, pp. 1–28 at pp. 12–14). Some Neolithic Round Houses may have been constructed in this way but surviving evidence seems to indicate others were "beehive domes" in form (The Beehive House, pp. 17–28). In the historical record the next class of buildings which raise the issue of arcuated stone roofing are the so-called "Vaulted Tombs of the Messara" (Lawrence, p. 20). These are free standing circular structures of very substantial rubble stone construction, numerous on the Messara plain in Southern Crete. They are provided with an entrance compartment in front of a massively built door in the nature of a trilithon. The circular burial chamber varies considerable in size (with an internal diameter of up to 13 m). The surviving stone walling exhibits an inward inclination, but nowhere is preserved to a height of more than ca 3 m, i.e. to the level of the door lintel. The original investigator unhesitatingly took the profile of the wall to have continued into an arcuated roof. However, subsequently, the 282, 283 nature of the roofing has been much disputed. Latterly it is generally accepted that it took an arcuated form, but was not necessarily constructed conformably with the stone walls—e.g. it may have been of mud brick or wood framed.

These (sometimes monumental) free standing buildings are of chronological interest. They are Middle Minoan in date (ca 2500 BC–1800 BC). It is thus possible that they could in some measure derive from the late survival of the Neolithic Round House in (Western) Cyprus to the middle of the 3rd Millenium BC (S. Hood, "Cyprus and the Early Bronze Age Circular Tombs of Crete"). On the other hand, these tombs, still standing intact, could have influenced the striking development of the monumental tholos which supervened at the middle of the 2nd millenium in Mycenaean Greece, which is now to be discussed.

At all events it seems that after the Tombs of the Messara fell into desuetude, for a long age stone roofing was employed only in subterranean construction. This is rather a surprising statement: but there are, however, relevent considerations. Principally there is the structural issue. Arcuated structures exert a lateral thrust and develop tension zones at their outer surfaces. This is restrained by the inward pressure of the surrounding earth—i.e. underground arcuated structure is naturally favoured. There is also man's familiarity with natural caverns and the strongly symbolic effect they have for him. It seems fitting to return his dead to the hollow earth. There were three possibilities to effect this: natural caverns (cf Gen 23); to excavate such hollows in solid rock; or to build the semblance of caverns under the earth. All three possibilities were utilised. Subterranean built caverns varied greatly in size and display from the utilitarian to the monumental. Occasional underground stone built tombs with arcuated roofing can be found in the Levant, when, for some reason, intra-mural burial was required. They are set down into the occupational levels of the tells in default of chambers cut into (soft) bed rock for the standard extra-mural burials. They are small and constructed of boulders and field stones.

Arcuated stone roofing—Mycenaean tholos

However for two centuries between ca 1500 BC and 1300 BC a type of underground stone built tomb referred to as a tholos flourished in Mycenaean Greece (v Lawrence chap. 6). These tombs developed in size, masonry technique and ornament to become, in some instances, very imposing monuments. The earlier 285 tombs (1500 BC–1400 BC) were built of random rubble or roughly square rubble. The chambers vary in size upwards from ca 8m in diameter. These tombs progressively develop in size to ca 14m in diameter and roughly of the same height from floor to peak of the pointed dome. Equally the masonry passed from rubble to uniform bastard ashlar (i.e. entirely fine jointed at the surface). They were of uniform design, a long narrow dromos was excavated in the slope of a hill until sufficient height was available in which to set a chamber of pointed domical form. The walls of the dromos and of the chamber were built in stone masonry and earth packed back behind them to the scarp of the excavated emplacement. Then the peak of the chamber was buried in earth to the level of the hill top. The chamber portal at the end of the dromos was given monumental treatment, and the lintel was of megalithic disposition and surmounted by a relieving triangle in the masonry. The finest of these tombs were revetted on the interior with, e.g. decorated 286–289 metal plating. Foremost among these tholoi were the two tombs at Mycenae and that at Orchomenos, well known today as the Treasury of Atreus, the Treasury of Clytemnestra and the Treasury of Minyas. (NB the term "treasury" was used by Pausanias for the grave of a hero, where the vital forces resident in his *soma* were treasured up for the welfare of the community.) Parallel to the Mycenaean tholoi another type of arcuated stone tomb was developed in the Eastern Mediter- 203 ranean—the underground vaulted tombs of Late Bronze Age Ugarit. These were bourgeois rather than princely, but very well constructed in bastard ashlar. The blocks were corbelled out and their faces dressed to give a pointed profile to the vault. The form was thus arcuated but not the construction.

Returning to the Mycenaean tholoi, it is clear that they were entirely stone built domes in form, but the statics of their construction are subject to varying assessment. The individual blocks were finely dressed bastard ashlar—i.e. the jointing at the face was very fine, but the joints, both bed joints and rising joints, opened apart to the interior, also in general they were set in regular courses with horizontal beds. Thus in general they did not constitute what is understood by voussoirs, i.e. wedge shaped blocks where the planes of both the rising joints and the bed joints radiate from a "centre". This disposition increases the state of compression (both

Arcuated stone roofing—structure

horizontally and vertically) of the constituent blocks—and thus such construction has been referred to as a "true dome". When the blocks are set in horizontally bedded courses, each course oversailing the lower, the construction has been referred to as "corbelled vaulting" or "false vaulting". However subjected to rational analysis it is not at all apparent that wedge shaped voussoirs are a *sine qua non* of a "true dome". If a horizontal ring of masonry is complete, the form puts the construction in compression without concern for the angle of the bedding, and if each course is in compression horizontally, this will be sufficient to ensure the compression of the entire dome. Vertical compression is an additional force and is not mandatory—e.g. the crown of a "true dome" constructed with radial voussoirs may be incomplete, since an "oculus" may be left open for lighting etc. Thus the domical form of Mycenaean tholoi can be also reckoned a "true dome" in the 289
structural sense since the inward pressures exerted by the earth backing negates tension. Further consideration of this question will follow when discussing later ashlar domes (v *infra*, pp. 188–193).

(γ) Structural Analysis

Having in the preceeding account raised variously questions of form, construction and functioning, it is opportune now to attempt some analysis of these questions before discussing the further development of arcuated roofing in finely jointed stone.

Without doubt among the several types of arcuated construction the greatest attention has been accorded to domes. In a measure this proceeds from the inference that the dome is the most 'advanced' form of arcuated construction, and what holds good for it, *a fortiori*, holds good for the others. This is, in fact, not so, and there is trenchent difference in structural mechanics between the dome on the one hand and the arch and the vault on the other. To make this clear the simplest example can be taken: a comparison between the hemispherical dome, the barrel vault, and the semi circular arch. In section all these manifest the same form—a semi-circle. However the statical analysis is not uniform.

Between the arch and the vault there is no essential distinction. A barrel vault is the elongation of a semi-circular arch. This is demonstrated in practice by the fact that a barrel vault can be constructed as a series of contiguous arches. And, although it is not the strongest form of construction, this is sometimes done to save trouble and cost incurred on centering—i.e. when one arch is constructed the centering is moved along to construct another arch beside the former. In this fashion it can be seen that the statical analysis of the vault is similar to that of the arch. It proceeds by examing the forces operating in a vertical sense, i.e. the units (voussoirs) are held in place by compression operating vertically.

Arcuated stone roofing—structure & construction

The statics of the dome, on the contrary, resolve into a horizontal analysis. The units (voussoirs) are held in place by compression operating around successive horizontal "parallels". Thus the elemental form of a dome is not a vertical semi-circle like the arch and the vault, but is a complete horizontal circle (a ring). A moment's observation of many domes makes this clear. The vertical slice (the meridian semi-circular arch) is not complete. It is interrupted at the crown by a space, the oculus, left free for lighting or other reasons. In such case no compressive force at all is transmitted along the vertical semi-circle, yet the dome remains structurally stable. 296

(i) The Vault and the Arch

In form the vault is simpler than the dome—i.e. it is curvilinear in one plane only (the vertical), whereas the dome is curvilinear in two (the vertical and the horizontal). For this reason the vault will be discussed first. As distinct from the detail of form (e.g. semi circular, parabolic, pointed, etc.) vaults are distinguished by their construction. There are basically three methods of constructing a vault: out of a slab; out of corbels; out of radially set units (voussoirs).

The initial and limitrophic case is a vault, or a seeming vault, created by hollowing out the soffite of a beam or slab. This is often done for aesthetic reasons (or to give greater head height). However it raises the question of terminology. Is it correctly termed a vault? It would seem a vault in appearance only, i.e. a vault in form but not in function. The beam remains a beam; it is stressed in bending, in spite of its arcuated soffite.

A common method of constructing a vault is by corbelling. Each successive course of masonry is made to project somewhat beyond the face of the course below. The extent of the projection is governed empirically by whether the projecting blocks remain in equilibrium. If construction is carried on in this way from both walls, eventually the projecting blocks will abut or can be spanned by a closing block. In this way the space between the wall is covered by blocks shorter than those required to span across the space directly. The extent the courses project beyond the course below will govern the height of the vault and the profile will be presented as a series of steps. The projecting parts of the blocks will be stressed in bending not in compression. However it is possible to dress the succession of steps into a continuous curve of one form or another, so that the construction is vaulted in appearance. 263, 266

The stone vault appears to have taken form in Egypt—and in interesting circumstances, which may evidence a conflict between structure and symbol. One of the earliest expressions of Egyptian monumental building in stone was the massif—the pyramid. The design of these monuments called for extended passages

Arcuated stone roofing—Egyptian vaults

as also for chambers overlain by an enormous burden of stone. The builders soon became aware that slab roofing was inadequate to bear the massive loads, and they hit on two devices to deal with the situation: corbelling and the triangular 261 arch. They used both devices either to relieve the load above a slab roof or indeed in place of slab roofs. Both devices proved effective structurally, and accordingly were adopted in a normal building, significantly for circulation passages and corridors. However they gave a rectilinear aspect: in the first instance a series of steps; in the second an isoceles triangle. Where in a massif these devices roofed a relieving space above a flat slabbed roof not exposed to general view, their aspect was acceptable—and evidence of them survives. However where these forms were exposed to view over apartment generally accessible, a new factor intervened, appearance not construction.

For Egyptians the roofing (more properly the ceiling) of a compartment symbolised the sky. In the normal flat slabbed roofing, this symbolism was expressed by painted decoration, e.g. by stars and the sky Goddess Nut hovering in vulture form. However the exposed stepped or triangular form conflicted with this symbolism. The matter was adjusted in both instances by carving the sofite into a continuous curved form—the sky vault. Finally it would seem during the Late Period (ca 8th century BC and later) Egyptian builders realised the possibility of directly constructing vaulted roofing by the use of radially set blocks with their faces dressed in curvilinear form (i.e. voussoirs). This involved the use of some form of temporary support (centering) for blocks until the construction was completed. (Specific instances of all these stages are conveniently illustrated in Arnold, pp. 183–201, figs 4.114–4.143.)

Here may be a convenient juncture to mention a very individual example of Egyptian stone vaulting that in the small funerary chamber of (the god's wife) Shepenupets I at Medinet Habu, ca 700 BC. Its radially set voussoirs were in the 262 form of thin slabs set on end so as to comprise a series of arches. These arches of conventional (paraboloid) profile, however, were not set vertically but were inclined slightly backward to rest against the upstanding rear wall of the chamber. This technique was exactly that of "pitched" vaulting in mud brick which avoided the 354, 355, necessity of centering by a combination of friction plus quick setting mortar. It is 371 difficult, however, to see what structural advantage was aimed at in its use with finely dressed stone masonry. Perhaps it was thought that the inclination placed the voussoirs in some horizontal compression which better held the finished construction in place (v Wesenberg, fig 6).

The above discussion of Egyptian roofing may seem sufficient to account for the origin and development of radial stone vaulting in general—however it is doubtful that it is the complete story in itself. In the first instance all the examples of Egyptian stone vaulting are of very restricted span—two to three metres only.

Also, perhaps, as a corollary of this, the overall incidence of radial voussoir stone vaulting in Egyptian building is of an extremely minor order. Accordingly since large scale brick vaulting was well established in the Ancient Middle East, it has been suggested that here was the essential background to the development of stone vaulted roofing in the Classical Greek and Roman World, which has remained an important feature of building ever since.

Arcuated stone roofing—Classical Greek vaults

Vaulted stone roofing constructed out of voussoirs set on radially inclined bedding appeared suddenly as a fully understood technique in Greek building during the latter half of the 4th century BC. It was employed in Macedonia at and about Vergina (the ancient Aegae, a traditional burial centre from Iron Age times onwards) to roof underground built chamber tombs which were as a rule surmounted by an earth tumulus. Evidently these tombs were of members of the ruling dynasty—e.g. including possibly Phillip II, the father of Alexander. The construction is in all respects proper practice: the units (voussoirs) are finely dressed to give dry stone close jointing; the bed joints are disposed radially; and the blocks have the greatest development in length so that they are set as stretchers. The inner face of the voussoir is finely dressed to give in section the arc of a circle, the back
268 of the blocks is left roughly dressed as not exposed. The construction is employed for underground building, so that the only aspect of the vaulting is an internal one. It thus conforms to the idea of the natural cavern, and there is nothing in the external aspect which conflicts with the established rectilinear form as proper for monumental building. There is a coherence in these attributes, nonetheless the sudden (post classical) manifestation of this construction, and in the marginal region of Macedonia has occasioned varied explanations—or emphasis in explanation.

Since the date of these tombs roughly coincided with Alexander's campaigns in the Middle East, it seemed a convenient idea to draw a connection between the two. Accordingly it was proposed that the genesis of the construction was to be explained by the aquaintance Alexander's military engineers gained with the imposing brick vaulting of the Middle East, e.g. the Hanging Gardens of Babylon (T.D. Boyd, "The Arch and the Vault in Greek Architecture," *Diss*, Indiana, 1976; *AJA* 82, 1978, pp. 83–100). However it was determined that some of the examples of stone vaulting antedated Alexander's campaigns and this was siezed on to impugn the thesis (v M. Andronikos, "Some Reflections on the Macedonian Tombs," *BSA* 1987, pp. 1–16; R.A. Tomlinson, "The Architectural Context of the Macedonian Vaulted Tombs," *BSA* 82, 1987, pp. 305–12). This argument seems somewhat adventitious, since Greeks had considerable knowledge of the Middle East before Alexander's conquests. Nevertheless the tendency has been to discount the influence of Middle Eastern Brick Vaulting in the development of stone vaulting in the Hellenistic and Roman World. Here it may be observed that the format of the brick units and of necessity their bonded setting differs from that of stone voussoirs.

Arcuated stone roofing—origin of Greek vaulting

On the other hand it is to be noted that Greek builders since Classical times had been familiar with arcuated stone construction in the horizontal plane, e.g. the circular tholos buildings (v H. Lauter, "Die Architektur des Hellenismus," pp. 176–79 *et pass*). Now the form of a voussoir for a barrel vault is essentially that of a wall block for a tholos or a semi-circular exedra. Thus Greek builders possessed 267 the basic technics of arcuated construction and it was only the inspiration to apply them in the vertical plane which was required. Accordingly it might appear that the stone vaulted Macedonian tombs of the later 4th century BC drew largely on existing Greek masonry expertise plus Greek capacity for intellectual analysis. To what degree knowledge of earlier Egyptian stone vaulting contributed to developments is an open question (cf Wesenberg, pp. 252–58). This is a particular instance of the endemic question of the indebtedness of Classical Greek ashlar masonry to Pharaonic stone masonry (cf G. Hölbl, "Ägyptischer Einfluss in der Griechischen Architektur," *JÖAI* 55, 1984, pp. 1–18).

In sum it may be said that whatever ultimate origins may have been, from the third century BC onward vaulting in stone increased in the Hellenistic and Roman world. And it is only latterly that its incidence in Hellenistic building has been adequately recognised (v Lauter, pp. 59–62). This development follows in a direct line from constructional developments in Greece and Macedon during the later 4th century BC, and thus these may be considered its direct progenitor. However this does not mean that the process was entirely oblivious to the previous widespread practice of vaulting in other materials and techniques—only that such was much more remote. Here something may be conveyed by considering the form and setting of the blocks used in stone vaulting, for this evokes ultimate traditions. Such blocks can take two forms: the normal solid ashlar masonry block with a length 2 or 3 times its thickness or height (which are not dissimilar); or the flat slab (the French *carreau*). When the normal compact block is set as a stretcher on radial beds, this betokens direct derivation from the tradition of classical ashlar masonry construction. When the compact block is set as a header, this betokens adherence to the tradition of corbelling. When the thin slab (*carreau*) is set as a facing slab, it betokens an ultimate background in the triangular (dihedral) arch. And when the thin slab is set as a header, it goes back to pitched brick construction.

It is in point to make some concluding observations specifically regarding stone vaulting in the ancient world, since this subject is always considered together with domes; whereas, in fact, there are different applications between the two.

Whatever the circumstances with domes may be, all indications are that the impetus for stone vaulting was in underground construction (or within the core of massifs). This in itself provided the abutment for any lateral thrust exerted by the masonry. Thus the use of the term vault for underground apartments in general has a reasonable etymology. These were the circumstances in Egypt from

Arcuated stone roofing—Roman developments

the Pyramid age onwards, and they were paralleled in Greece two thousand years later. The practice of sepulchral stone vaulting as evolved in Egypt spread beyond Egypt into the Levant where Egypt maintained at various periods some political standing. An interesting record of stone vaulted tomb chambers occured in Cyprus. This extends from the Late Bronze Age down through Graeco-Roman times. During the earlier period (Late Bronze Age—Archaic) the chambers were
264–266 triangular vaulted or corbel vaulted. Here Egyptian influence is evident, either direct or through Phoenecia. During the later Hellenistic-Roman period ashlar
269 radial vaulted chambers are found. (For a concise account, *Ancient Building in Cyprus I*, pp. 343–349, II Figs 195–211.)

However in the Graeco-Roman world from ca 300 BC onwards new building types gave another impetus to stone vaulting. These were public buildings providing recreation and entertainment etc.—i.e. places of large scale popular assembly (such as theatres, amphitheatres) requiring sophisticated provision for circulation
277, 399 involving corridors by the kilometre. These corridors and passageways were roofed by vaulting. Another application for stone vaulting lay in the passageways through city gates. Here the distinction between arch and vault is in issue. It is in name only. Perhaps a convenient yard stick is that where the depth of the passage is greater than the span, then we can speak of a vault.

Graeco-Roman developments in building programs brought the stone vault above ground, and they also concurred in defining the character of the vaulting. In the first place the spans were all relatively narrow, and secondly the function of the vault was to provide a ceiling for the space below and at the same time, a support
270 for overlying construction. Thus it is very rarely that the extrados of stone vaulting was exposed to external view. All this contrasted markedly with the old tradition of (mud) brick vaulting which roofed great spans, and sometimes assumed a very
392 monumental aspect (e.g. the Taq-i-Kisra at Ktesiphon, Vol. I, ill 55; Vol. 2.2, ill 101). Equally while providing added demands for vaulted construction, the spread of Roman rule and influence opposed the proliferation of dressed stone vaulting in favour of concrete and brick construction.

During Imperial Roman times and Late Antiquity the survival of dressed stone vaulting seems to be limited regionally. It is to be found mainly in the Greek speaking provinces of the East, e.g. Cyrenaica, Syria, Anatolia. An illustrative field for the continuance of dressed stone vaulting until the end of the Ancient World is the
271 Greek speaking province of Cyrenaica. This devolves from two considerations: no other form of vaulting was developed there (neither brick nor concrete), and the almost total cessation of building after the Arab Conquest, with the consequent preservation of vaulted remains in the wooded countryside (v "Christian Monuments of Cyrenaica," *pass*).

Arcuated stone roofing—cross vaults

To facilitate comparison the previous discussion has been carried on in terms of the simplest form of vaulting—the semi-circular barrel vault. However more developed forms of vaulting did occur and are now briefly mentioned.

In the first place it is possible to say that all the instances adduced follow in the line of development manifested in Greek masonry as spoken of above. This is of some interest itself, for if e.g. intersecting stone vaulting was built in Egypt, then according to the norm its final form would have been worked *in situ*. And seemingly this would have been a more straightforward operation than the stereotomy of cutting groin blocks on the bench before setting. In this way it would be possible to adduce it as a formative stage in the development of such vaulting. However (at least in reasonably accessible publication) there is no record of stone vaulting of this description in Pharaonic Egypt. On the other hand where numerous passages and galleries were required in Hellenistic and Roman public buildings, it is apparent that this gave rise to the intersection of passages, as also for their change in direction. Both eventualities involved the interpenetration of the curved surfaces of their vaulted roofing so that the intersection itself formed another (and different) curve. 277 There are two different solutions available for these circumstances in practical masonry: the groined vault and the ribbed vault. In the first case the block (voussoir) at the intersection in each course has two exposed faces and the arris between them must form part of a continuous curve, the groin, when the dressed block is set in position—i.e. the groin must not "wave". The second method is to determine the curved profile required at the intersection and build arches with this curvature at the lines of intersection, and then set the remainder of the vaulting to accord with these arches.

The distinction between the groined vault and the ribbed vault is reckoned to be a principal discriminant in the formation of the Gothic style of Mediaeval architecture (ca 1200 AD), and the question is discussed at great length in that connection. There it is obvious that the distinction has two applications of equal importance: the aspectual and the structural. Ribbed vaulting provides a "nervous" linear aspect; whereas groined vaulting gives a calmer aspect of surfaces. On the other hand groined vaulting is a load bearing structure whereas ribbed vaulting is a (curvilinear) framed structure where the loads are transmitted (principally) by the arches, and the other blocks are panelling infill only (or can be in theory). It is perhaps within the margin of this concern of a later age that most notice has been given to the question of intersecting vaulting in the Ancient World (cf, e.g. Frankl Gothic, "Architecture," pp. 1–4). In any event it may be said that intersecting stone vaulting of the Ancient World was groined not ribbed. There are very few examples where rib arches are used in association with stone vaulting, and they are never used for their aspectual virtue.

Arcuated stone roofing—rib arches

Groined "cross vaulting" was developed in the Graeco-Roman World to provide for the intersection of two vaults or for the change in direction of a vault. Additionally its structural virtues became apparent so that the device was used
278, 279 not only for these purposes but also as a solution in itself to roof a rectangular
414 (square) space, where it functions in parallel to the dome.

This may be the occasion to note roof construction involving arches which is difficult to classify. Although rib arches did not play a significant rôle in stone
273 cross-vaulting, they appeared in connection with barrel vaults. Here, however, questions of terminology arise. With early (5th cent BC) instances at Ephyra and Delos (v Boyd, *diss*, p. 180, fig 14; p. 183, fig 17; also *AJA* 82, 1978, pp. 96, 97, fig 13) and a famous manifestation at the Temple (Fountain House) of Diana at Nîmes (Robertson, pp. 237–38), examples of this type of construction pass from the category of vaulting to a type of slab roofing. Nonetheless the structural basis remains the same: a succession of arches (v Besenval, pp. 68–69 for comparative structural analysis). In the first instance the lacunae between the arches is covered by stone vaulting, so that the more solid arches break the vaulting up into smaller compartments giving additional (lateral) seating to these compartments, and in the overall provide a stiffening to the entire vault. This construction is clearly a
273 (reinforced) barrel vault. There is then the well known construction at Nîmes, where the bays between the arches are covered by slabs, spanning from one arch to another. Whether these slabs function in any way as vaulting in themselves is not clear. They are certainly slabs, but slabs carried by arches not beams and thus have the profile of a barrel vault. There is finally a type of roofing which became common in the basalt region of Jordan and the Hauran, during Nabataean and Late Antique times (Robertson, pp. 238–40, 314). Here the arches were built up
274 at the spandrels to give a horizontal seating for the slabs set between them. Thus the roofing is a flat slabbed roof, and can not be considered vaulting.

Since consideration has been returned to the barrel vault, a final development in this connection may be mentioned. The passages and corridors in buildings of public assembly (theatres, amphitheatres etc.) were very clearly an important factor in the development of barrel vaulting. Moreover in the functional nature of such buildings these passages were frequently not horizontal but inclined. The vaulting was thus roofing to stairways (and equally support for stairways above). There were two solutions to this problem: to build the barrel vaults as a stepped succession of horizontal vaults (stepped vaulting) or to build the vaulting continuous on the incline (ramped vaulting). Both solutions were adopted, the simpler construction of stepped vaulting being more commonly preferred.

Arcuated stone roofing—the Dome

ii. The Dome

The historical development of the domical form does not begin underground. A very early (Mesolithic—Neolithic) form of shelter was the "round house", a beehive cavern in form. Originally built of pliable vegetal materials, during the early (Pre Pottery) Neolithic Period it was constructed in solid mud brick or mud 280, 281 brick and rubble—thus the domical form appeared first in materials other than stone. Pharaonic Egyptian stone building never accepted the round plan. Egyptian planning remained entirely rectilinear, so that the stone dome never ocurred as a building form in Ancient Egypt.

The stone dome made its appearance in underground built tombs of the Bronze 284 Age Levant and swiftly developed into monumental form during the Late Bronze 285, 289 Age as the Tholos Tomb of Mycenaean Greece (v *supra*, pp. 179, 180). The masonry construction was horizontally coursed corbelling, but since the chamber was buried within an earth tumulus the surrounding earth exercised the inward pressure necessary to restrain any deformation by outward thrust, so that the assemblage functioned as a "true" dome—i.e. the component blocks of each course (or 'parallel') were held in compression. However with the downfall of the Mycenaean civilisation, this genre of corbelled domical construction disappeared in Greece. On the other hand, in a way not easy to account for tumulus tomb chambers similar to the Mycenaean tholoi occured during the mid first millenium BC in various regions under Greek influence—Etruria in the West and the Pontic region 290 (Thrace and the Crimea) in the East. Moreover these corbelled beehive chambers 291–293 show a formal development over the Mycenaean Tholoi, which they resemble in essentials. Not only were the beehive domes raised over circular chambers, but they were also constructed over square chambers. Here the transition from the square plan was made by corbelled out arcs of masonry set in the angles. These devices 290 were designed and functioned in exactly the same manner as the spherical triangle pendentives of the 'true' masonry domes constructed with radially set voussoirs half a millenium later (v *infra*, pp. 191, 192). An extended résumé account of 298 these beehive domed tumulus tombs is given in Orlandos 2, pp. 201–17.

At all events when during the latter part of the 4th century BC Greek builders began to build arches and vaults from radially bedded voussoirs, they did not likewise dress voussoirs for building domes. This development did not take place for another 300 years, and then all the surviving evidence indicates that the earliest dressed stone domes were built in the heartland of Oriental Hellenism—Palestine, Syria, Southern Anatolia—not in Greece. For this fact no convincing explanation 298 is readily available.

In considering the Graeco-Roman ashlar stone dome there are two distinct structural questions at issue, i.e. a second issue over and above matters relating equally to the vault. There is the question of the form and setting of the voussoirs composing the dome proper as a parallel issue to the form and setting of

The Dome

the voussoirs comprising a vault. However whereas a vault is set directly on any rectilinear plan, a dome can only be raised on a curvilinear base (almost always a circle, but it is possible to build domes over an, e.g. elliptical plan—although there is little evidence of such construction in the ancient world). Therefore since the great majority of domes were raised over a rectilinear (square) plan, the question 298 arose of accommodating the circular base of the dome to the square plan of the underlying chamber.

The construction of the dome proper will be dealt with first.

In dealing with Graeco-Roman ashlar stone domes attempted analysis of stresses will be avoided. The roughest rule of thumb guide to design is that deforming stresses in a dome (e.g. outward thrust at the haunches) increase according to the square of the span and diminish directly according to the height (the "rise"). It is thus not possible to identify an optimum geometrical form which is applicable to all domes irrespective of scale—i.e. if the span to be covered is doubled, the rise should be increased fourfold to maintain the same statical properties. This can be put in categorical terms as follows. The thrust in a dome is directly proportional to the load (dead weight of the construction) and to the square of the span; and is inversely proportional to the rise. Thus to minimise the thrust for a dome of given span it must be as light as possible and have the maximum rise feasible.

Statical information of this and more detailed nature was not available at the time. The architects and builders then had at their disposal knowledge of solid geometry necessary to set out any curved form, and they had possibilities of reference to experience in other regions of the construction and behaviour of domes out of materials other than stone. In this way they knew that the greater the span the more difficult it was to construct a stable dome; and they knew that a dome tended to push outwards at its haunches involving vertical cracks and fissures in this region (signs of "hoop tension"). To minimize this behaviour they knew of two obvious measures, constructionwise. The dome should be as light as possible and as tall as possible relative to the span.

These simple considerations, however, had complications in practice. To gain overall lightness meant differentially reducing the weight of the upper registers of the dome, since here the self load was much less than at the base. This could be effected in two ways: using lighter material at the crown, or reducing the thickness of the wall section at the crown. Both devices were practiced in domes constructed from other materials (e.g. clay), and both could be incorporated in stone domes. The thickness of the wall section was progressively reduced by striking the curves 295 of the extrados and the intrados of the dome from different centres (that of the extrados from a centre below that of the intrados). It was also possible, though unusual, to build the upper part of the dome from the lightest possible stone—e.g. pumice. However when consideration was directed to the optimum tall profile, it was apparent that this optimum directly conflicted with the optimum of minimum overall weight. The taller the dome was built in relation to the span, the heavier the load.

In addition to the above background when Graeco-Roman builders began to construct stone domes, they had available to them several centuries experience of building stone barrel vaults. The upshot of this situation was that although it was evident that dressed stone domes could be constructed 'tholos wise' by corbelling out horizontal masonry courses of circular plan, they chose unhesitatingly and immediately to build their domes of hemispheral form out of wedge shape voussoirs set on radially inclined beds (i.e. in the same overall manner as barrel vaults). 297, 299 Although the matter is seldom noted, some account should be given of this choice. This account raises the condition precedent of the protracted delay in taking up the model, but it is better to discuss that factor in the sequel.

The first issue bearing on the choice of voussoir domes is that of statics. A development in statical efficiency can be asserted. The common failing of domes 296 is thrusting outwards at the haunches. Now with finely dressed dry stone masonry units the resistance offered to movement is friction at the joints. In horizontally bedded corbelled domes the units can slide relatively easily on the horizontal surfaces (i.e. the coefficient of friction is at the minimum). When voussoirs were set on a radially inclined bed, spreading movement entailed pushing the block upslope, with a corresponding increase in the coefficient of friction. Thus the voussoirs were more securely fixed in position by stronger friction. This was not important when the dome was surrounded by earth, but it came into consideration when the dome was free standing and subject to no centripetal pressure.

Nevertheless it is doubtful that the introduction of the hemispherical stone dome was motivated by such a neatly formulated theoretical consideration. The form was chosen (came in) automatically because it was the most convenient and economic to construct in fine (closely jointed) stone masonry. In the classical ashlar tradition each unit was dressed to form on the bench prior to setting in position on the wall face. The geometrical setting out of a voussoir block for a dome was not the simplest of matters, but the circular curve was the easiest one to trace; and 299 all the voussoirs were standardised in form. On the other hand, to dress blocks for a corbelled tholos dome with a visible extrados would involve much more individual treatment of blocks, especially for any profile other than a tall pointed one. The form was also economic in its structure. A hemispherical dome involved a rise equal to half the span. This was a mean between a flat profile dome (e.g. a segmental dome) which exercised considerable thrust but was a "light" load, and a tall profile dome (the Mycenaean tholos had a characteristic rise equal to the span, i.e. was twice the relative height). This exercised less horizontal thrust but involved a much heavier load.

The Dome

Of equal significance to these factors was the aspect. The stone dome, unlike the vault, was designed to present an external aspect. A tall "vertical feature" was such a violent contrast to the overall horizontal lines of classical architecture as to constitute an unpalatable shock. On the other hand the hemispherical form has
295 a restful disposition.

With these latter remarks in mind it is now appropriate to say something of the protracted delay between the acceptance of the vault and the acceptance of the dome in Graeco-Roman monumental building. This manifestly has little to do with masonry technology. The stereotomy of a dome voussoir is more complicated than that of a vault since the intrados and the extrados are curved in two dimensions (i.e. horizontal as well as vertical), and the bed joints as well as the rising joints diverge radially. However the incorporation of these features is simply by extension of the features in setting out a vault voussoir. The acceptance of the hemispherical dome was governed entirely by questions of aspect not structure. This change in aspect was an image of a changed "world view". Much has been written on this subject, falling within the philosophy of history. A striking characterisation of the issue is contained in Spengler's Decline of the West; while Baldwin Smith's The Dome rehearses all the ramifications of symbol and image relating to the domical form. The delay in the introduction of the ashlar dome into the Classical World attended on a change in society and its values away from the "dear city of Cecrops".

It is now necessary to attempt some explanation of the second problem which is endemic in the construction of domes: the adjustment between the circular
300 base of the dome and the square plan of the chamber over which it is set. There are two circles which coincide at some points with the square: the inscribed circle and the circumscribed circle. The inscribed circle coincides with the square at the mid points of the sides. The diameter of this circle is thus the same length as the side and the radius of the circle is half the length of a side of the square. The circumscribed circle coincides with the square at the angles and its radius is thus half the length of the diagonal of the square. Since the ratio of the side of a square to its diagonal is $1 : \sqrt{2}$, the ratio of the radius of the inscribed circle to that of the circumscribed circle is also $1 : \sqrt{2} = 1 : 1.1414$ or $< 10 : 14 \sim 5 : 7$. Neither of these circles, however, makes the necessary adjustment. A dome raised on the circumscribed circle oversails the chamber on all 4 sides, and a dome raised on the inscribed circle leaves uncovered a considerable (triangular) space at each of the four angles of the chamber.

The problem is thus to cover these angle spaces in a way which facilitates transition into a dome raised on the inscribed circle. This may be done more or less
290, 293 hand over fist in a number of ways, but the rational (monumental) solution is to occupy each of the angle spaces with a spherical triangle of masonry which "hangs down" to a point in the angle of the chamber and is thus called a pendentive.

The Dome (A spherical triangle is part of the surface of a sphere enclosed not by three straight lines, but by three arcs of circles.) In this instance the spherical triangles are formed by building those parts of the circumscribed dome which fall within the space enclosed by the square chamber. These pendentives thus rise from an apex at the base to a horizontal arc which extends from the mid point of one side to the mid point of the adjacent side of the square. At this level these arcs abut on each other and form the continuous inscribed circle, the radius of which is 5/7th of the radius of the circumscribed hemisphere. The dome construction can either be completed on the same curvature, or discontinued and a new hemispherical dome be constructed on the base of the inscribed circle. The former construction gives a flat segmental dome with a rise of only 2 (i.e. 7–5) on a span of 10—i.e. a rise of 1/5th only. This is called a continuous dome on pendentives, or a saucer dome. The latter is called an independent dome on pendentives, which has a rise of 1/2 the span thus giving a taller overall construction of 10 (i.e. 5 + 5) instead of 7. It is heavier construction but more stable as exercising less horizontal thrust.

The latter solution is the one generally adopted. It manifests a rationally satisfying form. Each side wall is arched at its upper limit, the angle spaces between the arches are occupied by arcuated forms, and there is a transition from a square with half diagonals of 7 units to a circle with a radius of only 5 units sustaining a dome. Reference to the illustrations supplied will clarify this verbal description. A final qualifying remark should be made here. The overall symmetry of the ashlar dome on pendentives together with the precise elegance of its masonry detailing, combine to give this construction great distinction. However it should be noted that the spectacular triumphs of domical roofing in antiquity were not achieved in ashlar stone construction. The sublime dome of the Pantheon at Rome (ca 120 AD) with a span of 43.30 m was built in Roman concrete, while the dome of Ayia 405
Sophia at Constantinople (537 AD) with a span of 32.60 m was constructed of 385, 386
fired brick.

* * *

Mastery of the technique of constructing ashlar stone vaults established in Classical Antiquity was an important development in the history of architecture. This expertise was never lost and until very recent times remained a touchstone of nobility and distinction in monumental architecture. However the automatic projection backwards in time of this appraisal to the Graeco-Roman world involves some misconception.

The theory of vaults and domes provides that a far greater unencumbered floor space can be roofed than is possible by trabeated construction—i.e. with beams and slabs. In this fashion it is generally assumed that ashlar stone vaults and domes were introduced into Graeco-Roman building in order to roof spaces

The rubble masonry dome

impossible to encompass with beams. This is not so. No Graeco-Roman ashlar stone vaulting was designed to span spaces in excess of the spans of stone beams used in Egyptian and Greek architecture. The extreme spans of stone beams in antiquity was something like 7.5 m, whereas the spans of ashlar stone vaults and domes never exceeded ca 4–5 m. The novel virtue of arcuated stone roofing was its convenience. To roof considerable spans with stone beams required special stone, dressed to lengths difficult to transport and to raise up into position, whereas the voussoirs of a dome or a vault could be cut from any reasonable building stone (available locally); and their bulk was, in general, less than standard wall blocks. The introduction of ashlar stone domes and vaults meant a convenient extension (to roofing) of standard ashlar stone masonry where this was standard practice.

Heretofore discussion of true stone vaults and domes has been advanced in terms of ashlar masonry construction—i.e. built of finely dressed units (voussoirs) set closely jointed. This indeed is the typical countenance of arcuated stone roofing in classical building. However it is possible to construct "true" stone vaults and 275, 276 domes out of rubble masonry. Spoken of here are structures where the units are set radially, not corbelled. This also serves to distinguish the construction from concrete vaulting where the "*caementicia*" (rubble) is spread in horizontal layers like that in wall masonry. In the main rubble vaulting is employed for utilitarian structures (generally underground), the most prominent instances being cisterns. As a rule the rubble units are secured together in cementitious mortar and plastered over at the surface with similar material.

Such arcuated construction in non-dimension stone masonry (rubble) assumes a rôle in the eastern regions of the ancient world—*viz* Mesopotamia and Iran, the sometime eastern limits of Hellenistic expansion. It is now accepted understanding that whereas Parthian rule (141 BC–224 AD) marked a political resuscitation of the Ancient Middle East, its cultural expression was essentially Hellenistic. In this way Parthian monumental building employed as a norm the arch and the barrel vault, embodied variously in dressed stone, rubble or brick. However it is not apparent that it likewise made use of the dome, least of all the ashlar masonry dome. It was the succeeding Sassanian regime (224 AD–637 AD) which turned its back on Hellenistic culture and resumed eastern modes. In this way the dome figures as a standard form of roofing in Sassanian building, generally of brick but on occasion of rubble construction.

The Sassanian usage, however, involved an individual characteristic: an alternative device to the pendentive for adjusting the rectangular plan of the chamber to the circular base of the uprising dome. This, in English, is termed the squinch (> scuncheon > *escoinson*) or squinch arch. In theory it can be any succession of 393–396 oversailing courses set in the angle of a chamber so as eventually to constitute the side of an inscribed octagon. However in practical terms it means a succession of

The Sassanian rubble masonry dome on squinches

oversailing arches which constitute a niche set in the angle, the crown of which is at the mid point of alternate sides of an inscribed octagon. The squinch thus transforms a square compartment into an octagonal one, whereas the pendentive transforms a square into an inscribed circle. Whereas the latter thus provides the exact base of the dome, the former (the squinch) provides only an 8 point approximation to the circular base. It is thus more appropriate for rubble construction than for ashlar construction, since the final adjustment to the circular base can be made easily in small rubble masonry.

Essentially the squinch is more adapted to brick construction and will be discussed more fully in that context. It was prominent in Islamic and later Byzantine building but was of secondary importance in the earlier age considered here, when stone domes were commonly of ashlar construction.

2. *Mixed Construction*

Stone has always figured as a component in buildings of mixed construction, generally in conjunction with earth/clay used as mud brick or burnt brick. In such circumstances stone is found where its strength in compression is advantageous, as also in positions subject to mechanical damage where its hardness is appropriate, and finally its relative durability prompts its use on occasion. Not only does the presence of stone reinforce the structure in other materials but both the appearance and, by extension, the prestige of stone ennoble the aspect of buildings according to widespread traditional values. A summary resumé of the use of stone in mixed construction is given here, since the various circumstances have been mentioned in other connections.

(a) *Foundations*

> *Note. As a matter of taxonomy the following consideration of stone foundations is partly out of place here, since it includes reference to foundations in all stone Egyptian building and to foundations in Greek and Roman building which is, except for the roofing, all stone building. However it seems preferable to take in the entire ambit of foundations in one discussion.*

Understanding of the term "foundations" is very loose both in technical and common expression. Etymologically the root (*fundus*) signifies that which is at the bottom, by extension, what is underneath. With reference to buildings a degree of precision has been imported by the use of two terms "natural foundations" and "artificial foundations". Natural foundations refers to the material of the earth's surface underlying (underneath) a building; while artificial foundations refers to the lowest part of a building lying at or below surrounding ground level, designed not primarily for habitation etc. but to provide more favourable conditions for the upstanding structure. This is very often taken to equate with providing a secure base for the structure so that it will not move to the detriment of the construction. However in addition or alternatively to this foundations may e.g. act as a damp proof course to prevent damage to the upstanding masonry by rising damp, or may withstand battery from disturbances at ground level. *Stone foundations*

The nature of artificial foundations to a building is governed by two factors: the nature of the building and the nature of the ground on which it is erected (the natural foundations). Stone, because of its rigidity and strength in compression, is in general a suitable material for foundations, and was so regarded in antiquity. With respect to the pattern of its use among building of differing construction a general preliminary statement can be made. Stone is rarely used as foundations for wooden buildings. It is very commonly employed as foundations for buildings of mud, brick or stone with the following distinction. For buildings of mud brick or rubble the stone foundations are invariably of rubble; but for buildings of dressed stone (ashlar) the foundations are usually, at least in part, of dressed stone. 218–220 221, 222, 224–227

The nature of the ground on which buildings are constructed (the natural foundations) varies dramatically from the ideal to the worthless—from outcrops of strong bed rock to shifting soil and marshy swampy ground. On the other hand the location of buildings is controlled by many factors other than the merit of the "natural foundations" in the area. In this way very often buildings, including massive buildings, are constructed on very unsatisfactory natural foundations and require in compensation significant artificial foundations.

Unfortunately, in addition to *ad hoc* instances of this nature, buildings in the ancient world comprehended two important regions where unsatisfactory natural foundations were endemic. It is well known that the habit of settlement over the expanse of the Middle East was the tell. Settlement in a favoured site having been established, it persisted on that site and continually rose up on the ruins of older habitation (tell = ruin heap). In short whatever the merits of the natural foundations where the settlement was first established, in later times the natural foundations available to builders on the tell were made up ground—which in modern foundation science must be allowed no strength at all!

Over and above this the long lasting history of building in the Nile Valley was beset by a strange historical development with regard to foundations. Egypt's continued prosperity was characterised as "the gift of the Nile", which was in effect the continued deposit of alluvial soil by the annual inundations. While this ensured fertile fields, it involved increasingly inferior natural foundations. In the very location where Old Kingdom buildings were founded securely on rock, stiff sand or gravel, later (New Kingdom—Ptolemaic Roman) buildings were founded on metres deep accumulation of fine soil which was annually transformed into

Stone foundations glutinous yielding mud. And it may be said in advance Egyptian conservatism meant that development in artificial foundations did not keep pace with this deterioration of natural foundations.

Before attempting to outline the use of stone for foundations in antiquity, it is worth remarking that modern foundation science is, in fact a recondite study which can not be broached here. A classic presentation of the subject is contained in the works of K. Terzaghi (cf K. Terzaghi *et al.*, "Soil Mechanics in Engineering Practice").

As a preliminary it is possible to roll up somewhat the question of ancient stone foundations. The extreme worthlessness of natural foundations is ground which is intrinsically instable—i.e. subject to flow, creep or slump etc. irrespective of load. Measures taken to remedy this are in the nature of soil stabilisation. These do not involve stone, but are either chemically based soil science (e.g. intermixing ashes and lime to bind plastic soil together and make it rigid) or involve timber piling which mechanically compresses the soil and promotes immobility by increased friction. The former was practiced on tells in the ancient Middle East, and the latter was common in Roman building and engineering. 53

The earliest use of stone in monumental construction occurs in the megalithic monuments of Western Europe during the 5th Millenium BC. The massive slabs and baulks used as uprights in these monuments do not rest on artificial foundations. It is interesting to note that they are treated exactly as heavy wooden baulks or posts—i.e. they are sunk to a considerable depth in firm unyielding soil to guarantee their stability. And here it is apposite to recall that megalithic building proceeded from a background in wooden structures, e.g. there were wood henges 228 as the immediate predecessors of Stonehenge.

In fact the first appearance of stone foundations was in the predominantly mud brick building of the Ancient Middle East, but it was not an original component of this construction. The earliest pre-pottery Neolithic habitation (ca 8th Millenium BC) was an emplacement of round plan sunk ca 50 cms or more below ground level surrounded by a mud brick barrier wall to a certain height (= The Round House). Here, it may be appreciated, the concept of foundations was extraneous. However there followed an ecumenical evolution away from the original "round house" style of building, whereby the round plan gave place to a rectangular plan; flooring at surface level was substituted for sunken emplacements and the original barrier walling became a load bearing structure supporting the roof. The sum of these developments imported that the mud brick walls were provided with one or more courses of rubble stone as footings at ground or below ground level (Aurenche, *La Maison Orientale I*, pp. 95–101). This transformation was fully established by later Neolithic and Chalcolithic times, i.e. by ca 5th Millenium BC. Thereafter it was the norm for mud brick walling to be based on rubble footings. 218

Stone foundations

It must be stated at the outset, however, that the common provision of rubble footings to mud brick walls in the ancient world is little conditioned by questions of secure transmission of loads. Although in considerable measure mud brick (or rubble) building was localised on the accumulated decay, destruction and refuse of previous building (the tell), the vast majority of such mud brick building (i.e. housing) involved negligeble loads. The strongest of natural foundations—i.e. outcrops of igneous bed rock, have a bearing capacity of more than 33 kg/cm2, and good natural foundations, e.g. stiff sand or gravelly soil, have a bearing capacity of ca 4.5 kg/cm2. On the other hand an ancient mud brick or rubble house would develop a load of only a fraction of 1 kg/cm2. Thus in the absence of some patent deficiency this load would be well within the bearing capacity even of the made up ground comprising tells. This is to say that only with more monumental 219, 221 structures (e.g. city walls, gates, towers, temples, palaces) would any significant load (i.e. approaching the bearing capacity of natural foundations) come into consideration.

In this latter connection some idiosyncratic stone foundations are revealed through excavation of tells. These may be partly conditioned by the circumstances that building on tells involves foundations on made up ground (both by way of accumulation, and also by way of extension). In the main the concern is with city walls, enclosure walls etc. where considerations other than architectural are manifested. However a notable instance is city gate houses, and these while involving military engineering are very definitely buildings as defined for the present context.

Stratigraphic sections on occasion show a close succession of layers of small rubble set in resilient mortar. These were very often interpreted as a raft, or mat foundations for heavy walls, towers, etc. Several concerns may be in issue here. At times these may be a concern for drainage. However their capacity to absorb differential stresses appears to suggest that they were concerned in the interest of stabilisation (cf the Egyptian practice of setting discrete layers of small stone blocks in a matrix of clean sand). This feature is associated with “built up” foundations rather than foundations set into the ground. It may also be in point to note that this “make up” forms a close parallel to Roman Concrete.

A specific instance of specialised foundations on tells which is related to the above are the foundations for some city Gate Houses or Gate Towers in Palestine. These are perhaps the most monumental type of buildings in the region, and are, of course, to be found at times high up on high tells. They are required to be tall buildings to provide good look-outs and fighting platforms. And they must be very strongly built with solid foundations to withstand battery and sapping. On occasion excavation reveals the following structural succession:

Stone foundations

(1) a cobbled area or pavement
(2) set directly on this the (dressed) stone structure of a gate tower
(3) surmounted by the remains of the stone structure of another gate tower of identical design.

Interpretation of this sequence has given rise to head on debate. Stratigraphic archaeology asserts here an original gate tower set directly on the rubble paving (i.e. without foundations) followed by a (later period) rebuilding of the gate on the original lines. This has been countered by the structural interpretation of a stone gate house with strong foundations of (dressed) stone beneath the upstanding 221 walls. These foundations are carried down to a rubble mat or pad, the interstices being filled with rammed earth (The Monumental City Gate in Palestine and its foundations, *ZA* 74, 1984, pp. 267–89).

In general, however, the utility of rubble stone footings to the majority of mud brick walls must have rested on considerations other than the load they imparted to the ground on which they stood. Such considerations include to provide a level bed for the convenient setting of upstanding masonry; to resist mechanical damage prevalent at or immediately above ground level; to resist erosion from e.g. standing or running water at or immediately above ground level; to prevent deleterious effects on upstanding masonry by "rising damp", i.e. to function as a damp proof course (DPC). In this connection it is relevent to observe that although the setting of courses of rubble at the base of mud brick walls became normal practise, it was not completely exclusive. Excavation reports note than on occasions brick walls (both mud brick and burnt brick) were set directly on or into the natural foundations (as will be discussed in the following chapter). There is also the revealing circumstance where foundations for mud brick walls are also of mud brick (i.e. set below ground level) but above these brick foundations at ground level are two courses of rubble. Here these rubble footings can not be invested with any statical functions, but are clearly intended to serve as a D.P.C. etc. as noted above (cf Naumann, p. 56, fig 30).

In view of the marginal relevence of statical considerations it is rather surprising how general in the ancient world were rubble footings to mud walls. It is perhaps only in Southern Mesopotamia that excavation reports indicate that they were often dispensed with and mud bricks set directly into the soil.

Perhaps the first building style where the distribution of loads onto natural foundations became of significance was the Pharaonic stone masonry of Old Kingdom Egypt—i.e. about the middle of the third millenium BC. It is out of place to discuss this matter in the present context of "mixed construction", since whatever the virtue of foundations in Pharaonic masonry, the construction was an all stone one and thus by definition the foundations were of stone. The ancient

Stone foundations in Egypt

Egyptian builders appreciated the load bearing strength of good natural foundation
(bed rock and desert sand or gravel) and sought these out whenever possible for
the emplacement of e.g. pyramids. In this connection the material virtues of sand
doubled its symbolical significance as providing a "pure" (i.e. uncontaminated)
building platform recalling the original island-mound of creation. However both
223 virtues required the sand deposed to be effectively confined and isolated, which
did not always follow. There is also the suspicion that Egyptian builders when
faced with the necessity of supplying strong artificial foundations, confounded the
strength of the materials with the strength of the structure—i.e. blocks of excellent
sandstone or granite do not in themselves constitute strong foundations; this is
achieved by good construction of the foundations (e.g. close jointing etc.). Moreover
in the overall, natural foundations in Egypt were constantly vitiated by the rising
alluvium and inundations which also sapped artificial foundations.

A type of mixed construction widespread from Middle Bronze Age times
incorporated a stone sub-structure to mud brick walling and the foundations
were more substantial than simple rubble footings. The stone sub-structure was
generally of bastard ashlar masonry with very frequently orthostates part of
the ordonance. These orthostates invariably stood on a plinth course of dressed
220 stone which formed a euthynteria at and below ground level and below this on
occasion were substantial blocks of quarry stone as foundations. (G. Hult, *Bronze
Age Ashlar Masonry, pass.*)

Nonetheless it is probably true to say that "foundation science" began with Classical Greek monumental building in ashlar masonry. Not only were the solid ashlar walls a significant burden, but the heavy timber framed gable roof added considerably to the load. In this way Greek builders were as concerned with the structure of the foundations as with that of the upstanding masonry. Fortunately Greece is rocky territory and quite often the weighty loads of ashlar monuments could be founded on bed rock. The principal class of Greek ashlar monuments were temples, and the design of the monuments was worked out in association with providing strong artificial foundations.

The "founding feature" of the design of a classical Greek temple is the crepis
225 (Martin, pp. 326–56). This is, in effect, a three stepped building platform which
somehow appears to rise naturalistically from the earth, yet at the same time affords
monumental distinction to the building. Equally it consolidated the foundations
of the temple, so that while each load bearing element of the temple is provided
226 with separate and appropriate stone foundations these individual foundations are
unified by compacted filling. Not only does the stepped crepis spread the load of
the temple, but jointly and severally wherever possible this foundation assemblage
is taken down to bed rock. The treatment of the crepis by Martin (pp. 322–56),
with its numerous analytical tables, is penetrating and exhaustive.

Classical Greek stone foundations—The crepis

Over and above the systematisation of the crepis it is possible to make some general observations and note odd details which demonstrate the concern given by Greek builders to stone foundations in monumental ashlar construction.

Only in very exceptional circumstances was a raft of continuous masonry provided as foundations—always the norm was to provide individual foundations for each individual load bearing element of the structure (at times even for each column); and no foundation masonry was wasted beneath non load bearing space. The type of stone employed for foundations was generally different from that used for upstanding masonry on rational grounds of both aspect and structure: the stone was invisible and it was not exposed to weathering. Very frequently old *disjecta membra* including column drums were reused. Structurally foundations were always assembled in order; material was never dumped down into a trench from above. Where foundations were carried down to a considerable depth an orderly development from below to above is manifested. At the bottom smaller odd fragments of all sorts are compacted together then with height the blocks become larger, more regular and are set with care, eventually even cramped (Martin, pp. 308–22). Finally it may be noted that wherever a building contract survives it demonstrates that 225 foundations were not left to the "know-how" of the builders but are treated in the specifications with exactly the same precision as the upstanding masonry.

There were no radical new developments in stone foundations for monumental building to be associated with Roman as distinct from Greek building. There was, indeed, much technical concern with foundations in Roman construction, but this was in engineering work—roads, bridges, harbours, etc., and thus essentially outside the scope of the present study. Monumental building construction in Roman Concrete was pervasive and it employed concrete foundations. Monumental building in ashlar stone was for the most part in commemorative building, temples, tombs and in this connection there was a development which impinged on foundation practice. As is well known the Roman temple assumed an attitude other than that of a Greek temple emerging from the ground on its stepped crepis. The Roman temple sought dominance lifted up prominently to axial view on a podium. Thus the podium in construction as in design was the counterpart of the crepis. It is 226 doubtful that any specific study of the construction of the Roman podium has been made and clearly this varies according to size and other factors. However, in principle, as with the Greek crepis, the main load bearing elements of the upstanding structure were treated independently, and carried down by independent stone foundations within the podium (cf exposed foundation masonry of the republican Temple of Cori, Robertson, fig 93). The die walls of the podium thus act as retaining walls for compacted filling between the individual masonry foundations of the load bearing elements—which sometimes can be concrete (Adam, pp. 115–16; figs 241, 242).

Roman stone foundations—The podium

On the other hand when the podium assumed grander proportions, this enclosed volume below the monument invited exploitation for a variety of purposes, utilitarian (e.g. storage) and otherwise. In this connection it is worth recalling the story of Apollodoros' critical assessment of Hadrian's early architectural pretentions in temple design. Apollodoros drew attention to Hadrian's lack of forethought in not raising the temple up on a higher podium thereby to provide needed storage space for theatrical props (Dio Cassius, LXIX, 4.1–5). Thus developed the concept of the vaults below a building—foundation vaults, subterranean vaults etc. 227 The ramifications of this concept are very great but one outcome is of technical importance in the subsequent theory and practice of foundations, *viz* foundations by subtraction as opposed to foundations by addition. The greater the voided area below the upstanding structure, the less the pressure exerted on the natural earth foundations, so that in theory by adjusting the vaults/cellars below a building it is possible to negate entirely the "pressure bulb" it generates on the soil and thus do away entirely with the need for artificial foundations!

(b) *Walls*

The use of stone together with other material in walls of mixed construction is a basic widespread device and has been referred to on many occasions in this study. It will be noted only briefly here.

In general stone is used together with mud brick in ancient walls. Frequently it may be regarded as an upper extension of foundations, so that many of the considerations mentioned in stone foundations also apply in this connection. It is possible to define three principal modes of mixed stone and brick masonry, and it is to be noted that all apply principally to monumental or semi monumental construction.

(i) *Solid Stone Socle to Brick Superstructure*

The prominence of bastard ashlar stone masonry in Bronze Age Mediterranean Aegaean and Levantine building has been noted (v *supra* p. cf Hult, *Bronze Age Ashlar Masonry pass*). This type of masonry is almost invariably expressed as a socle to walls with a mud brick superstructure (or on occasion with rubble superstructure). 176 Prolific remains of this construction subsist e.g. in Crete, Cyprus, The Levant, 179–181 Anatolia. At times this construction is expressed in the form of orthostates.

(ii) *Stone Facing to Brick Construction*

On some occasions (perhaps to be regarded as a variant of the above) a mud 182 brick wall is provided with stone facing as a socle. The standard expression of this 183–85 mode takes the form of orthostates, typically bearing relief ornament of human or supernatural figures invested with religious significance. This style centres about North Syria, Assyria and Anatolia during the later second millenium and early first millenium BC. The use of this mode in Late Assyrian Palaces, Gate Houses etc. is on the grandest monumental scale (Frankfort, AAAO, pp. 77–78).

(iii) *Stone Coigning and Framing of Mud Brick Walls*

This is a different and counterpart measure to the stone socle for giving increased solidity to (mud) brick walls; and is found sporadicaly in different regions and on different scales. It occurs commonly in more or less domestic mud brick building in Egypt, principally in New Kingdom and later times (Arnold, p. 128, fig 4.42; G. Höbl, "Altägypten R.R.I.," p. 53, fig 45). However on the grandest of monumental scale it provides the articulating structural mode of Achaemenid Palaces. Here the scale and form is megalithic; and this framing and coigning is partnered by 186, 187 grandiose stone columns. The measure of the significance of the solidity afforded to the mud brick construction has been revealed by time. Today the mud brick construction has entirely disappeared, and only the megalithic stone framing and stone columns survive (v Trumpelmann, *pass* and figs 27, 29).

In conclusion it may be observed that the above discussion is all relevent to the construction of city walls, where mud brick ramparts rest on stone socles, are faced with stone, and are provided with gates and gatehouses built of stone. However this extensive field of consideration is not strictly within the ambit of the study of buildings. Also mention can be made of stone facing to some Middle Kingdom brick pyramids (Arnold, fig 4.27).

(c) *Columns*

Columnar supports / point supports, their presence and type, are a basic feature of building and have always been recognised as such. However the attention devoted to them has been focused on their aspect, which sometimes has been chosen as the representative feature of "style"—the "order" of building. In this way the construction of columns has been accorded only incidental attention, although in fact it is an important characteristic of building. How columns are raised up to support loads is a sensitive indicator of the manner of building since to ensure that a considerable load is transmitted downward through a considerable distance while remaining within a restricted cross sectional area is not a simple matter. Furthermore a cursory observation reveals that the manner of constructing columns may change completely, even though their form (their aspect, their "style") remains the same.

It is obvious that the material exemplar of columns is the long straight trunk of a tree, a single unit; but to provide the functional equivalent of this unit in another 121–124

Monolithic columns

material is again demanding. The most appropriate material statically (i.e. strong in compression) available in the ancient world was stone, and the question was how stone could be given the form of a tall shaft with a height something like 10 times that of its diameter. In basic terms there were three (or perhaps four) solutions:

(i) as a monolith
(ii) as a vertical succession of drums (i.e. units the height of which was not greater than their diameter)
(iii) as several (e.g. three or four) frustra (i.e. incomplete portions of shaft)

The two schools of building in the ancient world where stone columns (piers, pillars) were important constituents were Egyptian building and Classical (Greek and Roman) building. A survey of the construction of Egyptian and of Classical columns gives a coverage of the issues involved—and it is of interest to note how parallel were developments in the two fields. The developments were manifested in two closely related instances: the nature of the units and the manner of their erection.

It stands to reason since the prototype of stone columns was the tree trunk,
that the earliest stone columns should be in the form of monoliths—which in fact
was the case both in Egyptian and in Greek building. Early palmiform columns
230 in Egypt of the pyramid age are monoliths, whereas other very similar columns
of this type in a later age are built of ca 8 drums (Jequier, figs 121–25). Equally
some early stone Doric columns in Classical Greek building are monoliths, e.g. at
232 Corinth, ca 540 BC or earlier; while later columns of similar design are constructed
232 of 8 or 10 drums, but cf early examples with drums, e.g. at Paestum and Selinus
(v Robertson, p. 88; Durm, pp. 84–86, fig 65).

The size and mass of the early Egyptian and of the early Greek monolithic
columns are reasonably comparable—*viz* height ca 8–9 m and burden ca 20–30
tons. The production of such monoliths demands developed quarrying expertise
together with practical transport devices. Some record of these matters subsists
for both Egyptian and Greek columns. Whereas the characteristic practice of
Pharaonic masonry was to get on site and set the masonry blocks with as little
dressing as possible, the opposite practice was apparently favoured for monolithic
columns. They were finely dressed to finished form in conjunction with the quarrying process and transported to the site ready for erection (v Isler, MDAIK, 48,
1992, pp. 45–55). Numbers of ancient representations show such finely dressed
229 columns on transport sleds and also, together with sled, on Nile boats (Arnold,
fig 6.37). Concerning Greek monolithic columns, ancient literary references subsist of "inventions" to facilitate the transport of such inconveniently long burdens

Mono-lithic columns

(Orlandos, II, pp. 26–28; Martin, pp. 169–70). They could be slung lengthwise between two sets of wheels so as themselves to constitute a chassis, but this was limited by the necessity for restricting the axle loading to a reasonable burden (v Orlandos, II, fig 13). On the other hand Vitruvius (X, 2, 11–12) refers to various devices for constituting the long blocks themselves as axles for the pairs of wheels. This proceedure, however, required a broad carriage way which was a significant expense (cf Orlandos, II, figs 10–12).

With respect to the raising up into position of monolithic columns Egyptian monoliths were doubtless hauled base foremost up an inclined earth ramp and then slid down an abrupt incline into position more or less in the same manner as 228
an obelisk (v R. Engelbach, *The Problem of the Obelisks, pass*; Arnold, pp. 67–70). The early granite piers in the Pyramid temple of the 4th dynasty were embedded well down into the ground which alleviated the process of erection somewhat (Arnold, p. 67, fig 3.9; Clarke & Engelbach, fig 164). The early Greek monolith columns were of the period (6th cent BC) when it is now reckoned that clean lifting by block and tackle was being introduced (J. Coulton, "Lifting in Early Greek Architecture," *JHS* 94, 1974, pp. 1–18). It is possible they could thus have been lifted into position, and only in extremity were hauled up ramps to be set into position after the Egyptian manner. Pliny's story (N.H. 36.14) of the use of this system by Chersiphron to raise up the architraves of the Temple of Artemis at Ephesos in the mid 6th cent BC as something wonderful betokens that some other method was already standard practice. However the question of the date when clean lifting was introduced is not settled. Note that arguments based on the presence of cuttings in blocks for attachments as necessary evidence for lifting is not valid as it is always possible to lift blocks by slings or by tying ropes around them to provide attachments to the lifting ropes. Thus the absence of cuttings on blocks before say 515 BC does not negate lifting blocks before that date.

There is, of course, a hypothetical device clearly indicated for erecting monolithic columns. This is a heavy wooden cradle with two arms set at right angles and strongly braced together. The monolith is roped to the supine arm with its base 96
at the fulcrum. The vertical arm is then hauled down into the horizontal to raise the other arm with attached columns into the vertical. This appears a practical and convenient piece of machinery, but there is no record of its use in antiquity. Formerly when it was required to re-erect monolithic columns during restoration work—at out of the way places—with only the simplest traditional equipment, the work was carried out by lifting using tall metal tripods.

The high level of socio-economic organisation entailed with the early Egyptian practice of ready to erect monolithic columns brought from distant quarries is obvious. On the other hand it was requisite that early Greek monolithic columns could be won at nearby quarries.

Columns built from drums

In succession to early monolithic columns the development in both Egyptian and Greek building was parallel. By the Middle Kingdom (2nd millenium BC) in Egypt and by the 5th century BC in Greece, columns were normally built up in drums. 233, 234 Several factors were involved in or promoted this change (not all the same in either instance). In the first place construction from drums greatly diminished difficulties of quarrying, transport and erection of columns. Indeed the Greek practice of building up columns out of drums was closely connected with / was an expression of the introduction of routine clean lifting of stone masonry units by block and tackle. This was fully achieved by the 5th century BC (cf Orlandos, II, pp. 32–33; Martin, pp. 202–06; Coulton, *JHS* 94, 1974). The burden of a sizeable column drum was 2 to 3 tons, and this was a convenient mass to handle by block and tackle (more convenient in every way than a monolithic shaft weighing over 20 tons!).

Building up column drums by whatever means adopted is not routine masonry work. The proceedure for constructing columns in Pharaonic masonry was clearly by way of continually rising earth fill in the columnar precinct. Whatever device of construction may have been used for building walls, there is virtually no alternative available for column construction. It is clear from the plentiful evidence of unfinished work that the drums (or semi drums) were, as a rule, set in draught form, to be fair-faced *in situ*. In this way verticality was secured by setting the drums by the central axis, and guide lines to this end can sometimes be seen scored on the upper bed. Semi drums are easier to position.

Setting column drums (or frustra) by a hoist is skilled work. The units can not be set down on adjacent masonry where convenient, and then levered into position. They must be deposited exactly into position by the hoisting device. This demands a control of delicate motion and also that the attachment of the hoist must be moveable (preferably in all directions). In general terms there are several obvious ways of arranging for such movement—and these may be noted as a basis for discussion.

(1) Moving Bridge. This is the optimum arrangement but involves sophisticated mechanics. Scaffolding is erected to constitute a tower about the column emplacement and raised to a sufficient height to permit the setting of the drum. At the top of the tower two parallel beams are set on opposite sides to act as runners, and athwart these beams a transverse beam is placed, free to run backwards and forwards along the runners. The hoisting head is attached to the moveable bridge, so that it, itself, is free to run backwards and forwards along the moveable bridge. In modern devices the runners and the bridge are structural steel beams, and the movement of the bridge and hoist head is arranged by trolley wheels set on the flanges.

Erection of columns by clean lifting

In this way the head of the hoist can be brought directly above any position within the area covered by the tower, so that the drums wherever situated on the ground can be attached, hoisted aloft and then brought directly over the column emplacement.

No evidence of such a device is known from the ancient world, and its existence has never been discussed. It is possible, however, that something like it might have been developed in imperial Roman times.

(2) Moveable jib arm. This device is now familiar on all construction sites where powerful cranes with long jibs are in operation. The jib can be rotated into any direction and the lift can be moved outwards or inwards any distance up to the length of the jib. Such a device may have been available in ancient times, with a wooden jib controlled by ropes. The limitation here is the strength of the wooden jib to resist the bending moment of a heavy load on a long arm.

(3) Attachment to multiple hoisting units. A scaffolded tower is arranged to cover the area of the operation and at the top of the tower several hoists can be positioned so that the drum can be lifted by one hoist to a convenient height, then attached to the other hoist, and by differential control of the hoists, the drum can be brought vertically above the column emplacement. Such a device could have been arranged in antiquity. Skilful control of the hoists is necessary, otherwise the load can swing dangerously on occasion.

(4) There is also a makeshift proceedure when the load is not great. The drum can be lifted from any convenient position by a hoist, raised to the required height, then dragged into position above the column emplacmeent by ropes fastened to it, and then lowered into position by the hoist. This, at best, is a hit and miss operation with risk of chipping and jarring. It would not be employed for heavy loads or positioning finely dressed masonry.

This outline can be super-imposed over what is known of ancient Greek and
Roman lifting devices. Representations of these occur in Roman decorative
reliefs (Adam, pp. 46–47, figs 87–90) and the subject is discussed by Vitruvius 88–91
(X.2) and in a treatise by Hero of Alexandria (Mechanicorum fragmenta III ed,
Nix-Schmidt, Leipzig, 1900). Both sources classify lifting devices according to the
supports or frames to which the hoist (pulley block) is attached—enumerating the
single leg (limb) *monokōlos*; the two legged/biped *dikōlos*; the three legged/tripod
trikōlos; and the four legged/quadruped *tetrakōlos*. The discussion indicates that 85, 86,
the *monokōlos* and *dikōlos* devices were stayed in position by auxilliary guy ropes, 89
so that the lifting head could be pre-set at a distance from the base of the device,
i.e. directly above a given emplacement. Nowhere, however, does the discussion
clearly indicate arrangements by means of such ropes for changing the position of

Erection of columns —Egypt & Greece

the lifting block when charged with the load, which is a fundamental requirement for setting a column drum.

On the other hand some mention is made of lifting heavy blocks by the above named hoists in the building accounts for the construction in Hellenistic times of the great oracular temple of Apollo near Miletus. (Inscriptions of Didyma, Didyma II.) It states that a special four legger was built and used in conjunction with a two legger available on site. This amounts to erecting a scaffolding tower about the emplacement and employing at least two hoists in conjunction. Thus with this system massive columns could have been erected. (Martin, pp. 200–19; Orlandos, II, pp. 31–44; Adam, pp. 44–52). At the other extreme it is possible that minor column drums could be set by controlling their lowering into position with hand held ropes. It must be born in mind, however, that to set drums dowelled together by polos and empolion would require command of very delicate motion in the hoisting device (and no record of this matter survives from antiquity).

The drawback of drum construction is that columns are best finely dressed *in situ*. This meant employing highly qualified stone dressers on the building site to perform a difficult operation (especially when the columns were fluted or incorporated diminution and entasis). However construction of columns out of drums was without doubt the standard method throughout most of the history of both Egyptian and Greek monumental stone building. There were differences between Egyptian and Greek column drum construction. Since Egyptian columns were frequently ponderous, the drums were reckoned to be adequately fixed by dead weight. Indeed such Egyptian drums were often built up out of two semi drums. This was never the practice in Greece, and Greek column drums were always fixed one to the other by an idiosyncratic system of dowelling. In its classic development (5th–4th century BC) a cuboid emplacement was hollowed out at the centre of both beds of each drum into which was set a wooden block (the empolion). This in turn was bored to receive a centering pin or dowel (the polos) of either hard wood or (more generally) metal. (v Martin, pp. 291–96, figs 135–37; Orlandos, II, pp. 113–15, figs 125–28). Later in Hellenistic times additional dowelling arrangements of this nature were incorporated towards the periphery of the drums (Durm, p. 289, fig 206; Martin, pls XXI, XXV).

Although construction out of drums is often taken to be the one alternative to monoliths, this was not so. Another method existed of constructing columns in the ancient world. However it is virtually restricted to Greek building and is almost never found in Pharaonic building (but little notice has been accorded this distinction). In reasonably monumental columns the height of the drums is usually something less than the diameter of the column, thus there are usually ca 8 to 10 drums constituting a column shaft. However Greek and Roman column shafts

Columns built out of frustra of all descriptions are sometimes built up out of several tall segments, e.g. 4 to 5 in number, each much taller than the diameter. These units are termed *frustra*. They are not simply a qualitative variation of drums, but constitute a different system of column construction. They occur in two distinct instances. During later Hellenistic and Roman times the use of columns in "non-monumental" building became common, i.e. in more oppulent domestic building such as villas, which are often provided with peristylar courts. Such columns are generally relatively slight and simple (not fluted). Drums would be flimsy items, and thus these columns 239, 240 are usually built up out of 4 to 5 frustra. This is a purely utilitarian matter of little consequence in the history of building construction. And such minor *frustra* were dressed on site like drums. However *frustra* are used in quite contrary circumstances which are significant.

It may be possible to trace the use of *frustra* in early monumental building 238 among the Eastern Greeks, i.e. in the formative Ionic style or even in the pre-formative period. However in the great Ionic temples of the 6th cent BC (at Samos and Ephesus with their multitude of peristylar columns) the columns appear to have been constructed with drums (Lawrence, fig 76), perhaps taller than Doric column drums, as reflecting the taller, more slender proportions of the shaft. In view of this, a striking mutation in column building appears to have occured in 236 the great Achaemenid palace halls at Pasargadae and Persepolis. Whereas the proclamatory building inscriptions announce that the master masons and stone dressers employed on these programmes were East Greeks from Ionia (Frankfort, AAAO, pp. 214–15), the stone columns at Pasargadae and Persepolis were not constructed out of drums on the model of the Ionic columns of similar stature at Ephesus etc.

Herzefeld (Iran, p. 238), wishing to stress the independence of Achaemenid monumental building from Classical Greek building, states that the basic concept of the tall columns at Pasargadae and Persepolis was traditional wooden columns. Thus wooden columns were used in these programs wherever it was possible to supply items of the required height, and only when the height demanded exceeded the limits of tree trunks was stone used. Presumably he did not mean that both wooden and stone columns were used in the same building, but that stone columns were specified for the loftier halls. The question then arose of how to provide stone columns of a height of ca 18 m or 50'. Such columns are among the tallest known, exceeding the height of tall Roman columns, e.g. at the Pantheon.

Unfortunately conveniently published photographs of the soaring columns of Persepolis do not make the construction of all these columns apparent. However it is clear that they are not built up of drums, but are either monoliths or assembled from several tall frustra. This extreme example brings into sharp focus the inter-

Monumental columns out of frustra

related questions of providing the required stone units and of how to raise up securely into position these heavy but instable units.

If the columns are monoliths then the quarrying and transport of such units of stone was a prodigious undertaking; if the columns were assembled from ca three or four frusta then their quarrying and transport was alleviated somewhat. However when their erection is considered, it is difficult to assess which construction (monoliths or frustra) presents the greater difficulty. Certainly in either case the difficulties were enormous and as Herzefeld said their erection is a mystery and a wonder. To erect monoliths two processes were known: hauling base first up ramps or clean lifting. Both processes would present enormous difficulties in the circumstances. To erect tall frustra it would appear only clean lifting was feasible. In this connection it is interesting to note that columns built of frustra are virtually unknown in Egypt. Also to the difficulty of lifting these frustra into position (involving loads of say up to 50 tons), there is the added demand of their fixation. To bed securely such items must have involved perfect and perfectly horizontal jointing. The great bending moments induced by any displacement from the vertical would render dowelling insignificant. It might be suspected that the complete array of such columns would require interim strutting during construction until the roofing was complete to weight down and secure the entire inter-acting structure as a space frame. The Achaemenid building proclamations (at Susa) mention that both Egyptian and Greek master masons had charge of the stone construction (Frankfort, AAAO, pp. 214–15). It is possible that in the unique circumstances of the Achaemenid Empire there was a fruitful collaboration of two different building traditions to produce a unique result.

Perhaps the most striking columns constructed with frustra surviving from the Ancient World are the enormous peristylar columns of the Temple of Jupiter
237 Heliopolitanus at Baalbek erected under Augustus (v Robertson, pp. 222–27, fig 95). This grand temple, although a Roman podium temple in design, incorporates a megalithic element in its construction. The die wall of the podium includes the famous "trilithon", blocks of ca 800 tons burden, virtually the largest units of masonry handled in the ancient world (E. Will, "Du trilithon de Baalbeck…"; Adam, pp. 31–32, fig 36). These columns are over 2m in lower diameter and ca 20 m in overall height. If monolithic their burden would have approached 150 tons. As it is the shafts are constructed of 3 frustra with heights ca 5–6 m, and with a burden of say 30–40 tons. There is no doubt as to the process of their erection. The frustra were clean lifted by block and tackle, set up on a forest of the heaviest timber scaffolding using multiple hoisting devices.

This example illustrates the difference between construction of monumental columns with frustra and construction with drums. Each frustrum of the Baalbek

Fabrication of columns by lathe

columns is more massive than a normal monolithic column, thus in many ways such construction is more allied to monolithic column construction. In this fashion it is not surprising that there is evidence for the pre-fabrication of monumental frustra under the Roman Empire at major Imperial quarries (M. Waelkens, ed., *Ancient Stones* Leuven, 1990, p. 73, fig 4).

It is doubtful whether any specific attention has been given to the construction of monumental columns out of frustra. However the record that column frustra were prefabricated at quarries raises an interesting question. The ratio of prefabrication of columns at quarries is the economy of centralised mass production—especially in the disposition of skilled labour. To dress a column (or its components) truly cylindrical is demanding work. There is, however, a mechanical device which can effect this operation very truly, and is of reasonably simple functioning. This, of course, is the lathe.

There is no doubt that smaller stone objects were turned on the lathe in antiquity. However the use of the lathe for fabricating ancient columns or their components is a controversial matter. No specific record of this proceedure survives. On the other hand traces of tooling and also the nature of some detailing make it evident that the lathe was used in fashioning columns during antiquity. There are two applications: the incorporation of details (e.g. horizontal chanelling of Asiatic column bases, also annulets and necking grooves etc.), and dressing the form of the column. The latter is the present concern. There are (as might be imagined) various technical problems in turning a full length monolithic column, but frustra of reasonable length are well adapted to turning. Were frustra fabricated en masse at quarries, fashioned on the lathe further to economise in skilled labour? It is a subject for future enquiry. One observation can be made here. All types of stone are not equally suitable for working on the lathe. Medium and softer stones are more amenable than hard stones (e.g. marble, granite); also the stone must be compact, otherwise it can shatter. On the contrary columns fabricated at quarries are usually of harder (decorative) stone. Nonetheless the question subsists. A summary account of the possible use of the lathe during antiquity in the present connection is given by J.C. Bessac ("Le Tournage des origines…," ed., M. Feugère *et al.* Montagnac, 2004). Possible reconstructions of proceedings are given in T.F.C. Blagg, "Tools and Techniques of the Roman Stone Masons…," Brittania 7, 1976 at pp. 165–70). 248, 249

A few words may be interpolated here concerning building up columns out of normal masonry. Pharaonic Egyptian columns of New Kingdom times and later are frequently assembled not out of drums but out of semi-drums (v Clarke & Engelbach, figs 77, 78, 153, 155, 161). This practice has the distinct advantage of facilitating the use of dowelling as a mode of fixation, which is otherwise difficult to incorporate in Egyptian construction since it involves lowering a drum into

Reversion to monolithic columns in later antiquity

position. However dowelling drums together was not standard practice in building Egyptian columns.

In fact when speaking of constructing columns out of normal masonry, it is small block masonry which is generally in mind. Such construction is found at times in Egyptian columns (v Clarke & Engelbach, fig 156), but for the most part it occurs by way of repairs to damaged columns (v Clarke & Engelbach, figs 166, 167). Structurally speaking columns can be built up well enough out of small units of masonry as is evident from brick columns, which are common. Nonetheless small stone masonry columns are very rare, and probably derive from imitation brick construction.

Construction of columns out of drums which became the dominant proceedure in the 5th century BC did not remain so throughout antiquity. As developed in Classical Greek monumental architecture the column was a functional element. The purpose of columns was to double that of walls in supporting the roof. Developments tended to turn the column away from this character.

Changes in demand and in supply both interacted and worked together to change the construction of columns from assembled drums into monoliths. Beginning in Hellenistic times columns became more and more items of display both by way of stature and costly aspect. In other words the formation of columns tended to become a separate concern apart from normal structural stone masonry. This development coalesced with the building revolution of Roman concrete construction where the material was not stone and construction not trabeated. Thereby stone columns became adventitious ornament. Remove the ornamental marble columns from e.g. the halls of the great imperial thermae etc. and the building would continue to stand unconcerned. In these conditions where the stone masonry was virtually a sub-contracted item, the rational economy of monolithic column construction became manifest. It is evident that the amount of fine stone dressing in a column shaft constructed of 8 to 10 drums is vastly greater than that of finely dressing a monolith. Also if the capacity exists to raise a monolith, then this is a shorter (and sweeter) operation than setting and fixing together 8 to 10 column drums.

Parallel with this changed demand there were changes in supply even more patent. Augustus decreed Egypt an imperial province and thus inherited by conquest the Pharaoh's ownership of Egyptian quarries. Whether or not this served as a model, the successors of Augustus extended the Imperial domaine over all large scale quarries in the Roman Empire. Not only did this measure alter the economics of supply but it altered the form of quarry stone supplied.

Quarries fall into two classes: occasional and standing. Ancient quarrying was of simple technology which required few installations, and given suitable outcrops of stone, it was always possible to "open" a quarry as occasion demanded, and close down the operations after the demand had been met. On the other hand where convenient outcrops of particularly good quality stone existed, then it was in every way preferable to exploit them on a standing basis. To develop the most efficient installations together with the most experienced and skilled permanent labour force was the obvious way to exploit such quarries if the market sufficed.

Fabrication of monolithic columns at the quarry in the later Roman Empire

Hand in hand with increased efficiency in quarrying out stone at such estab-
lishments went the overall economy of, to some measure, dressing the blocks at
the quarry site, since a standing labour force of stone dressers were assembled
there possessing the advantage of great experience in working that particular type 242
of stone. In this way in the market conditions of imperial Rome, it was customary industrial development for standard production items of stone, including architectural elements to be dressed in draught form at the quarry (J.B. Ward Perkins, "Quarrying in Antiquity," PBR, LXII, 1971, pp. 137–58; M. Waelkens, ed., "Pierre Eternel…," Brussels, 1990, *pass*, NB Chaps 5, 8, 9; M. Waelkens, ed., "Ancient Stones" Acta Archaeologica Lovaniensia, Vol. 4, Leuven, 1990, *pass*).

With the exercise of eminent domain over major quarries by the Imperial admin-
istration this development was progressive and it is probably reasonable to say that
stone dressing at the quarry progressed with the lapse of time towards an ever
finer finish (N. Ashgiri, "Objets de Marbre fini… du Proconnèse" in *Pierre Eternel*,
pp. 117–24). In short supply of building stone from central quarries passed from
including e.g. draughted Ionic bases (Ashgiri "Observations on two types of quarry,
items from Proconnesus. Column Shafts and Column Bases" in *Ancient Stones*,
pp. 73–80) to including during later antiquity job orders of finished columns (bases, 244
shafts and capitals) prefabricated ready to erect In this way e.g. Justinian's great
ecumenical building programme was articulated very frequently by an imperial
donation of a consignment of marble columns (from e.g. Proconnesos quarries) 245
to a church built by local masons out of local limestone in a distant province,
e.g. Cyrenaica (cf J. Reynolds ed., "Christian Antiquities of Cyrenaica," *pass*, NB,
pp. 27–30). In this connection it is interesting to note that it was not economic to
prefabricate normal column drums at the quarry and to transport them to the site
for re-erection. Dressing such column drums was site work and when economics
told against this, monolithic columns became the rule. In Byzantine church build-
ing the alternative to monolithic columns were masonry piers, i.e. a wall pierced 246
by arches. Be it noted that in Byzantine churches columns were internal features,
they were no longer seen as part of the external fabric of construction.

The upshot of all these considerations was that in the ancient world construction
of columns by drums was outmoded during the 2nd century AD—and thereafter 235
columns as a rule again took on a monolithic form. The renewed use of monolithic 242
columns in part depended on transport facilities over wide ranging lines of com- 243
munication. Construction of monumental columns out of drums did not again 245

become a norm until Romanesque building of post 800 AD, by which time the inter-regionalism of the ancient world order had lapsed.

Spliced columns in Byzantine cisterns

A final remark may be included to demonstrate the changed rôle of columns in later antiquity. It concerns "column engineering" and bestrides the category of monoliths and of frustra. Population growth in the great capital cities brought problems of water supply, and extensive covered cisterns were required. The roofing of these cisterns was generally vaulting carried on a forest of columns. The capacity of such cisterns was achieved by their depth, which, in turn, meant very tall supports. Such cisterns at Constantinople have survived in functional order until the present day, and reveal a surprising device to obtain the requisite height. At this period construction of columns out of drums was long outmoded, and for any large scale columnar construction a matching set of prefabricated monolithic columns was supplied from Imperial quarries. In the instance of the Binbir Direk cisterns from the time of Justinian, the builder ordered two sets of matching monoliths 247 and at each emplacement mounted two columns, one on top of another, giving a total height to crown of vaulting of ca 50' (ca 18 m).

The instability of such an arrangement would appear manifest, but the assemblage has survived to the present day. The builder did not attempt to dowel together the two superposed columns but provided a doubly socketed stone sleeve to encompass their bedding and so "splice" the columns together (v C. Mango, p. 20, fig 93). It would seem probable that the assemblage of columns was held in place by scaffolding until the vaulted roofing was constructed to stabilise them. Presumably the work was carried out colonnade by colonnade including the vaulting. In spite of its antiquity, it was an unqualified success since the structure remains in functional order to the present day as a factor in the city's water supply.

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Appendix. Rock Cut Monuments

Rock cut premises are not built

The following remarks are included as an appendix not because they are of marginal significance to ancient building technology, but in deference to the "logic" of the English language. The concrete noun "building" in English denotes a construction comprehending an interior which can be entered to provide shelter for man or beast or mortal remains or goods and chattels. Thus while a building must be built, many things can be built other than buildings, e.g. aqueducts, roads, bridges, groins, wharves etc. The latter have been excluded substantively from the present study since although they are built they are not of the form envisaged by the concrete noun. On the other hand rock cut chambers and apartments, although of the form designated by the concrete noun, do not meet the *sine qua non* that they are

Some rock cut features are notable monuments

built/constructed—which verb signifies “to put together”, “pile up”, or “assemble” units. On this account rock cut monuments are not buildings; and indeed it is very difficult to find a general verb in English to designate their creation—“to fashion” is used in these remarks.

However rock cut apartments etc., very often of monumental nature, play a significant role in ancient architectural development; and unfortunately no comprehensive general study is available concerning them. Accordingly a brief outline is provided here.

In the interest of concision some preliminary general remarks are useful:

(1) The subject treated is solely the technology of fashioning the rock cut apartments. The treatment does not concern their design development as such.
(2) Rock cut chambers etc. are patently of two grades: what might be termed (a) utilitarian and (b) monumental. No categorical dividing line can be drawn between the two, but in fact the division is clear enough as constituted by the scale and by the form of the cutting. Both grades are considered here.
(3) The fashioning of rock cut features can not be discussed in detail, and in fact discussion here is limited to considering the two basic methods which are practiced: dressing away the rock to waste, and quarrying it out in the form of masonry blocks.
(4) It is assumed that both methods infer that the relevant technology was at the time independently in possession of the society concerned.
(5) It is useful to recognise 3 broad types of rock cut monuments:
    (a) The hypogeum, where the entire feature is hollowed out below ground level. 302, 311
    (b) The “speos” or façade type, where the cutting is made in a cliff face, and the façade is exposed to view as a feature. 312
    (c) The free standing monument, where the whole feature stands above the surface and is exposed to view. 321, 323, 324

Men first acquired the technique of hollowing out solid rock in connection with mining. And it is not generally appreciated how early this came about. Quite extensive mining for flints was practiced in Neolithic times (ca 5th and 4th Millennium BC), both open cut and underground—cf the well known flint mines at Grimes Graves in South East England. Hand stone mauls and antler picks were adequate to cut out in the soft rock (e.g. chalk) shafts ca 10 m deep and galleries ca 12 m long deep below the surface of the earth. This work proceeded according to the curved contours of Neolithic understanding, and the rock was cut to waste according to the fashion of mining (v Vol. 2, pp. 39–40, ills 56 a & b).

Megalithic rock cut monuments

At exactly this period occurs the first monumental rock cutting. The Hypogeum 302 at Hal Saflieni in Malta (not far from Valetta) is an astounding monument, the first and one of the most striking of all rock cut monuments. A complex of galleries, precincts, halls, chambers, alcoves etc. descend in 3 successive levels to ca 18 m below the surface. These features comprehend a total floor space of ca 380 m^2 and something like 1,500 m^3 of limestone must have been cut out of the solid rock. The complex includes several finely dressed compositions with "ordered" façades, so as to constitute a rock cut subterranean version of the Megalithic temples of Malta, several of which stand in the vicinity.

The design concept of this great work falls entirely within the Neolithic "round house" mentality. There is no way in which the units could have been set out prior to cutting, and thus the work must have proceeded directly from Neolithic empathy with the forms of natural growth. The rock was broken away with hard stone pounders and hand axes. Salient spoil heaps must have accumulated about the mouth of the hypogeum, and presumably the material was removed to be used for rubble structures or field boundary walls. Nothing of it was observed in modern times—unfortunately, since it would have given detailed information on the method of rock cutting.

A simpler example of rock cutting in Western Europe occurs in the South of France, near Arles. A form of megalithic tomb common in France (and other parts of Western Europe) is the Gallery Grave (Allée Couverte), comprising a long (e.g. 15 m) straight gallery—structurally a simple dolmen longitudinally extended (v G. Daniel, *The Megalith Builders of Western Europe*, pp. 90–98, fig 6, Pl VI). At a site 303, 304 by the side of the road from Fontvieille to Arles is a group of several megalithic graves where this form is expressed by way of rock cutting—i.e. the gallery is hewn out of bed rock but covered by megalithic type (dressed) roofing slabs similar to the built form. In the past when megalithic monuments of Western Europe were given a much later chronology as supposedly deriving from eastern models (e.g. Mycenaean tholoi) it was stated that these rock cut gallery graves were the background to built megaliths of this form. However in the light of the present chronology it is much more likely that rock cut gallery graves are a specialized derivation from built megaliths. Built gallery graves were current in France from 305 the later 4th millennium BC and the date of these rock cut versions near Arles could be ca 3000 BC.

These monuments have a special significance for rock cutting, although this fact is seldom brought to notice. The rock walls of the galleries are smoothly and evenly dressed and give little information how the galleries were excavated. On the other hand the deep and massive roofing slabs are quite accurately squared 154, 305 up (as are those of some of the built Gallery Graves, A). However these roofing

Non-monumental rock cut chamber tombs

slabs were won, the presence of massive squared up slabs above an excavated rock gallery can not but suggest that the gallery might have been quarried out and the roofing slabs won from this process. The form of the gallery in section speaks to the contrary, since it was wedge shaped, splaying outward to the base. This matter deserves investigation.

At this historical juncture something is to be said of the simple non-monumental rock cut chamber tomb. These tombs are perhaps the most conspicuous relics of all the ancient remains in the East Mediterranean, Levantine, Anatolian region of the Ancient World (cf ABSP I, pp. 324–27; ABC I, 333–42). The formal types of these rock-cut graves have been studied for the light they throw via burial customs on social and ethnic history (cf, e.g. E. Bloch Smith, "Bronze and Iron Age Burials and Funerary Customs in the Southern Levant"). However no concern has been shown for the method of fashioning these tombs, i.e. the manner of such cutting adopted. And this in spite of the fact that preparing these rock cut tombs must have constituted a very significant factor in the economy of the communities concerned.

The type of the simple rock cut chamber tomb developed during the later 4th Millennium BC in these regions, then totally devoid of finely dressed stone masonry. From a simple pit cut into the rock a bipartite form evolved consisting of an approach shaft or passage (the *dromos*) and a sealed off burial chamber (the 306 *spilion*). In the earliest examples these formal elements were rounded as is natural to primitive cutting or hollowing out. With the passage of time rectangular delimitation of the cutting became common but, generally speaking, the confines were not accurately and precisely demarcated (v ABSP II, ills 266–73; ABC II, ills 176–86). There is little doubt that such rock cut chamber tombs of whatever formal type were fashioned without prior measurement or setting out by cutting the rock to waste, working hand over fist. Moreover such tombs were cut where possible in the soft secondary limestone (*huwwar*) which could be dug away virtually as stiff earth. Here it may be observed also that in traditional modern practice all activities connected with *huwwar* were reckoned women's work.

Although it is regrettable to speak in such sweeping terms, it is possible to say that, in all their varied forms developed during the 3rd and 2nd millennia BC (i.e. the Bronze Age), the non monumental rock cut chamber tomb was fashioned with pick axes etc. by cutting the rock matrix to waste. This work was carried out by specialist "tomb diggers" who through experience carried in their heads the forms 307 to be hollowed out and how to achieve them, so that no prior design or setting out was required. It was only in the later Iron Age and, above all, in Classical 308 times that the non-monumental chamber tomb was cut to precise measure and accurate rectangular form. This infers prior design and some sort of prior setting out, factors which may indicate that the rock was not cut to waste but quarried out (cf, e.g. ABSP II, ills 279–280, ABC II, ills 190–94; ABSP I, pp. 328–29, ABC I, P. 352).

Egyptian monumental rock cut chamber

In Egypt early in the 3rd millennium BC rock cutting was transformed in scope and in nature to achieve the monumental. At this juncture the resources of urban civilisation supported extensive quarrying with the consequent building construction in finely dressed stone masonry. “Quarry” is derived from *quadro,* to make square and it infers the accurate squaring up of masonry blocks and hence of dressed stone construction. In this way rock cutting also proceeded on a rectangular basis and required accurate setting out in this form. Since the work of rock
38 cutting proceeded from above downwards, the lines of the cutting were marked out on the ceiling, which was thus the first surface of the compartment to be dressed true, so that it became the surface of reference for subsequent cutting. This setting out procedure was effected by first driving into the rock a narrowly confined axial gallery (the *cuniculus* or “pilot gallery”) immediately below the projected ceiling level. However, whereas in surface work ancient setting out always proceeded by way of measured distances, setting out of rock cut features necessarily involved angular measurement—i.e. laying off angles. Also since rock cut features of the hypogeum type involved development at different levels, this in turn necessitated laying off vertical angles as well as horizontal angles.

The required technology for these operations was quickly developed during the Pyramid Age in Old Kingdom Egypt, to be continued on an extended scale in the New Kingdom rock cut Tombs of the Kings at Thebes. NB Here it is to be noted as an aside that this technology of underground surveying developed for rock cut premises as discussed here became fundamental in connections other than that of building, *viz* engineering—mining engineering, hydraulic engineering, i.e. for subterranean aqueducts, viaducts etc. But this is too large a field for brief, incidental mention.

Where apartments to be hollowed out of bed rock were reasonably large and of accurately dimensioned rectangular form, then the most economic method of abstracting the rock was to quarry it out in the form of masonry blocks—i.e. to treat the desired apartment as a subterranean quarry. This conferred the benefit of transforming the spoil into a valuable yield, *viz* blocks ready for use in fine stone masonry. In this way as far as practical there was every incentive to form chambers in bed rock by quarrying out the rock rather than by cutting it to waste. The factors governing this question were both intrinsic and extrinsic. Intrinsically it was necessary for the chamber to be reasonably large and of rectangular form, while the rock matrix was to be suitable for use as building stone. There were then extrinsic factors: possession of the technology of quarrying, possibility of removing the quarried blocks from inside the compartment, operations to be in a region where the masonry blocks were usable.

Quarrying out of rock cut monuments

The balance of these factors was such that from the earliest stages of rock cutting in Old Kingdom Egypt sizeable chambers were hewn out by quarrying. The hypogeum type of rock cut premises (as associated with Pyramids and the New 309 Kingdom Tombs of the Kings at Thebes) presented some unpropitious circum- 310–312 stances, cf steeply inclined passage ways, but this was not prohibitive. In fact very little close investigation has been made in hypogea to determine the incidence of quarrying out these premises.

It is rather the other type of rock cut monument, the "speos", or façade monument cut in the cliff face where circumstances were entirely favourable for quarrying. Here surviving *in situ* evidence shows it to have been practiced. Such monuments at Aswan and at Beni Hassan are in regions noted for quarrying, and 312–314 the wide, open porches align these monuments with underground quarries. Moreover it is this type of rock cut monument, rather than the hypogeum variety which spread beyond Egypt notably in Anatolia, the Levant and Cyrenaica to produce spectacular vistas at sites such as Caunus (Caria), Cyrene, Petra and Medain Saleh, 315, 319 etc. At the latter sites where the rock cut façade monument is most prolific close observation recently by J.-C. Bessac has assembled much *in situ* evidence of the 316–318 quarrying procedures (v J.-C. Bessac, "Le Travail de la Pierre à Petra").

It now remains to speak of the third division of rock cut monuments in the nature of buildings, i.e. the entirely free standing monuments. These monuments as fully developed are spectacular, but their floruit does not fall within the Ancient World as here designated. Rock cut monuments of the façade type found increase in Anatolia, initially in Lycia, Phrygia and thence spread eastward through the 319 mountainous region of Urartu, Media to be developed in Achaemenid Persia (cf the Royal Tombs in the cliffs backing Persepolis). Hence rock cutting found its way into India where it flourished in all forms with spectacular examples of the free standing rock cut type in Buddhist (e.g. Ellora) and early Hindu (Mahaballipuram) 323, 324 times. This fell chronologically within the Ancient World but lay geographically beyond its boundaries. When free standing rock cut monuments were fashioned on a notable scale within the geographical region of the Ancient World (e.g. The Cappadocian Rock Cut Churches), it was in a later (Mediaeval) Age (cf P. Brown, Indian Architecture chaps 5, 13, 15; G. de Jerphanion, Les Eglises Rupestres de Cappadoce).

Nevertheless some instances of free standing rock cut monuments ("Monolithic buildings") occurred in the Ancient World, in the eastern region rather than the western region. For brevity the following representative instances may be adduced:

(1) The Tomb of Pharaoh's Daughter at Silwan. 320
(2) The "Jin Blocks" at Petra. 321
(3) The East Fort at Apollonia in Cyrenaica. 322

Free standing rock cut monuments

The rocky slopes of Silwan facing Jerusalem across the Kidron Valley was a long enduring cemetery area of rock cut tombs. Among these the Tomb of Pharaoh's
320 Daughter is a striking monument cut to stand free of the rocky terrain. It is from the period of the later Monarchy and consists of a rock cut cube on a side ca 5 m containing a small funerary chamber crowned by a built masonry pyramid. The latter has been despoiled over the ages but can be restored by the cuttings for its seating apparent in the rock. It has the form of small pyramidal tombs found at Thebes in the New Kingdom times. It was detached from the rock slopes by quarrying, so that it stands absolutely free on three sides, but is largely engaged at the rear. The interior chamber is again a cube on a side of 2.5 m with a gabled roof (a complication in rock cutting). It is of very confidently executed workmanship (v, in brief, ABSP I, pp. 326–27; II Ill 277).

321 The Jin Blocks standing in the mouth of the Siq, the rocky defile leading into the bowl of Petra, are now well known to phalanxes of tourists. They are, in fact, both in their nature and their siting very impressive monuments. In form they belong to the category of Hellenistic Tower tombs well established in the Levant and East Mediterranean area: only they are not masonry structures but fashioned by carving out the bed rock. Since they are sizeable monuments, ca 8–9 m in height, a very great amount of rock must have been removed to expose their form. In the nature of things this could have only been effected economically by surface quarrying—unlike the underground quarrying practice to fashion hypogea and façade type monuments. They received the architectural ornament proper to their monumental nature, partly by the insetting and addition of elements of classical entablatures etc. in fine stone masonry (v Indian Summer at Petra).

Of a quite different nature but germane to the present issue are the remains
322 of a coastal fort one kilometre to the East of the Cyrenaican Apollonia. These remains exemplify the functional practice of carving the confines of fortresses out of upstanding bed rock wherever practical. In this instance the rock cut North (Sea) Wall of the fortress, encompassing a range of loop holes, still stands to a height of 2 m above the internal floor level.

The rocky outcrop on which the fortress stands was the venue of prior quarrying, both surface and underground; and the external walls of the fortress were likewise defined by quarrying out (v D. White, *Libyan Studies*, 29, 1998, pp. 3–23).

For comparative background purposes attention has been drawn to the striking floruit of rock cut monuments in Southern India during Late Antiquity and Early Mediaeval times, ca 3rd Century BC through the 1st millennium AD, ie encompassing the Hellenistic period to the end of the Ancient World in the West. Accordingly as a conclusion some remarks are made to indicate the culminating development of rock cut monuments. This is the culmination of a process which began in the Ancient (Western) World but only achieved its ultimate possibilities outside this region in Asia. For this purpose brief reference is made to the sites of Ellora in Maharashtra

Indian free standing rock cut monuments

30 kms NW of Aurungabad, and of Mahabalipuram/Mamallapuram on the Coromandal coast 50 km south of Madras.

The world famous site of Ellora in Western India includes rock temples of all periods cut into the cliffs from Early Buddhist times onward until this activity lapsed at the end of the 1st Millennium AD. The standard form of monument is of the speos type with a colonnaded façade, yet unlike the generality of this type of monument in Ancient Egypt, the interior is also carved out in a detailed reproduction of a built temple. However a few temples surpass this scheme. Here a sizeable area has been cut out of the cliff from above to fashion an entirely free standing temple, the sovereign example being the Kailasa (or Shiva's Paradise). 323

This is an astounding piece of Baroque virtuosity, and a world wonder. Fashioned during the 8th century AD, it draws on all the resources of a 1000 year long tradition, and extends over an area of half a hectare so as to embody an entire temple precinct. Since it is only recently that this type of rock cutting has been clarified in the West, it is of interest to remark that the process was previously well understood by investigation in India as demonstrated by the following remarks.

"The first stage of the work (at Kailasa) was simple. It consisted in excavating out of the hillside three huge trenches at right angles, cut down vertically to the base of the hill, thus forming a rectangle 300 feet by 175 feet. This operation.... left standing in the middle a large isolated mass, an "island" of rock over 200 feet long and 100 feet wide and 100 feet high at the apex. Beginning at the top, the process of rough hewing the irregular mass into shape was next undertaken, but those employed on this.... were immediately followed by the sculptors, for each portion of the carved detail appears to have been completely finished as the work proceeded downwards, thus avoiding any need for scaffolding...the Kailasa is more closely allied to sculpture on a grand scale than to architecture...being obtained by the process of cutting down as distinct from building up.... Authorities have shown that this method of production by excavation involves much less expenditure of labour than by building but on the other hand the general effect is marred by the rock production always appearing in a pit, a disadvantage from which the Kailasa obviously suffered " (P. Brown, "Indian Architecture," p. 74).

Here are rehearsed all the elements of the procedure for fashioning rock cut monuments. Only it may be questioned whether the initial separating trenches were necessarily carried down to rock bottom before the detailed work of carving out the rock architectural elements began.

Something further now follows with respect to Percy Brown's final observation on the Kailasa, viz that the aspect of such rock cut temples suffers from always appearing in a pit. This is not the case as is strikingly evidenced by the group of rock cut monuments at Mahabalipuram to the south of Madras. 324

These early Hindu shrines of the Pallava dynasty (ca mid 7th Century AD) reveal an exquisite fancy and imagination; and this together with their siting by a deserted seashore make them one of the most winning groups of monuments in existence. They are the quintessential development of free standing rock cutting since their siting is entirely natural, undifferentiated from that of any built monument. Great ingenuity was expended in totally eradicating from the aspect the false note of a rock matrix. They may be compared with the Jin blocks in the mouth of the Siq at Petra but 7 hundred years older. The complex consists of a handful of shrines of modest dimensions each reproducing the (different) design of original buildings constructed of fugitive materials (principally wood), together with several animal guardians (lions, elephants). All the features are carved from a small hump backed ridge of hard rock (granite) outcropping along the shore (v P. Brown, pp. 79–81).

Evans' Hypogaeum at Knossos

Addendum

302A A striking example of early rock cutting is the "Hypogaeum" at Knossos excavated by Evans during the early stages of his work there, now nearly 100 years ago. Unfortunately the published accounts of this feature are not sufficiently definite or consistent to make possible any critical account of it. Recently a brief survey has been made of the references to this feature both published and unpublished (P. Belli, *The Early Hypogæum at Knossos*, in P. Betancourt *et al.*, Meletenata (Aegæum 20), pp. 25–32, Liege, 1999). This is a valuable record of previous conjecture, but does nothing to advance knowledge of the feature itself. The best that can be done here is to try to roll up somewhat previous discussion of the feature.

The issues arising are:

(1) Its form.
(2) Its fashioning.
(3) Its function.
(4) Its chronology.

Of these issues only its chronology has been reasonably elucidated. This is because it can be established independently of the other issues, since the feature, whatever its nature, at a later time was sheered through near its summit and filled with extraneous earth. This filling contained only Middle Minoan pottery, and thus the feature must date to the beginning of Middle Minoan times or to the Early Minoan Period, i.e. before ca 2500 BC. Next to chronology the issue most discussed is its function, but opinions on this score are frequently oblivious to the details of its nature. In this latter connection it can be said, that its form has not been defined in detail, while nothing whatever has been said of its fashioning.

Evans' Hypogaeum at Knossos

The form of the Hypogæum as shown in the drawing published by Evans (The Palace of Minos I, pp. 103–06; Bell "Prehellenic Architecture in the Aegæan," London, 1926, p. 31) is a very large domical chamber (maximum diameter ca 10 m, height ca 16 m) drawn as a perfectly regular geometrical form in both plan (circular) and section (an ellipse truncated at the base). This is shown as entirely rock cut with its peak a metre or two below the surface of the rock. However super added to this chamber is a winding stairway cut into the rock enveloping a quadrant of the chamber plan. This stairway descends from 2–3 m below the peak to give access to the floor of the chamber. These winding rock cut steps were not cut as a lateral extension of the chamber—i.e. the steps are not internal steps. The stairway was an external stairway separated form the chamber by a rock wall ca 1 m or so thick. However the partition was pierced by a series of 6 apertures affording intercommunication between the stairs and the chamber. Entrance from the surface to this winding stairway is shown as a horizontal passage (a "dromos", ca 20 m long) cut into a vertical face of the bedrock. As drawn, this assemblage is amazing to impossible, i.e. impossible to fashion. Therefore before speaking of the function of the Hypogæum, it is necessary to consider its fashioning, about which, hitherto, nothing has been said.

In the first instance it is necessary to remember that, in principle, rock can only be cut (excavated) from above downwards. Thus if the chamber was entirely rock cut (as shown), initial access to begin the work could only have been gained via the winding stairs through the highest interconnecting aperture. This is such an improbable scenario, that it is to be presumed that the chamber was cut down vertically from the surface; and at least its summit was enclosed by a built rubble dome (this appears to be shown in the Evans photograph published for the first time by Belli). Next if indeed the stepped passage was cut in the rock separately and outside the chamber but closely enwraps it, then to control its cutting would be a taxing job for a modern mining surveyor. Finally it must be noted that Evans' drawings do not distinguish surviving remains for restoration of destroyed remains.

With this as a background, it can be said that proceeding on comparative evidence, the most likely function of the Hypogæum at Knossos was a completely or largely subterranean granary.

The oldest known granaries are those found in PPNA round house villages. These take the form of the round dwellings—i.e. they are semi sunken and are to be distinguished from the house by their smaller size (e.g. diameter ca 2 m) and by their taller, steeper profile. The virtue of sunken or semi-sunken grain storage was such that this tall, conical form survived across the ages to become a standard form of built silo in later antiquity, and is frequently represented in ancient graphic art—e.g. Egyptian mural painting and in Assyrian wall reliefs. This form is an 'al fresco' version of the Knossos Hypogæum. However there are no surviving remains

The Hypogaeum at Knossos, a granary

of entirely subterranean rock cut versions of the form in these later ages (although they may have existed). Underground storage facilities in plenty existed during later ages, indeed into modern times, but the standard form appeared as small bell shaped or bottle shaped pits, accessible from above with their mouth closed at surface level by a slab (v, in general, G.R.H. Wright, ABSP I, pp. 298–304, II figs 238–240; ABC I, pp. 317–21; ZAW, 82, 1970, pp. 275–78).

The preferred functional arrangement for free standing silos of this form is to fill them from apertures in the walling near the peak, and to empty them from at or near floor level. This required some means of external access (i.e. ladders or inset rungs etc.) to fill the silo, whereas emptying was straight forward. With an underground silo of the form and dimensions of the Hypogæum the descending stairway was a functional device for both filling and emptying. The chamber could be filled from the uppermost communicating part, and emptied from the successive parts progressing downwards.

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CHAPTER SIX

BRICK (EARTH/CLAY) CONSTRUCTION

A. General Outline of Development
B. Neolithic Origins
C. Mesopotamian Brick Masonry
D. Egyptian Brick Masonry
E. Roman Brick Masonry
F. Byzantine Brick Masonry
G. Late Iranian Brick Masonry

A. *General Outline of Development*

Range of earthen materials discussed on Vol 2

Human inventiveness has been notably successful in manufacturing a great range of building supplies out of earth. These include primary structural materials, e.g. brick; secondary materials, e.g. mortar; revetments / cladding / teguments, e.g. roofing tiles (designed intrinsically for protection, water proofing etc., but inevitably acquiring an ornamental significance) as also items entirely of ornamental virtue, e.g. acroteria etc.; additionally there are important items connected with the auxiliary services essential to functional buildings (heating, water supply and drainage etc.). The gamut of these products of earth and clay—their nature and function—have been discussed in detail (v Vol. 2, Chap. 4). Accordingly in the present connection of construction discussion will be limited to structural considerations alone.

325–327 The earth materials concerned are plastic earth (*tauf* / puddled mud); compressed earth (*terre pisée*) and brick. However, in fact, the treatment resolves into a discussion of brick construction. Although there are indications that brick construction 328 evolved from a prior use of plastic earth, and construction in plastic earth survived strongly into modern times, yet there is little surviving material evidence of plastic earth construction in the ancient world to justify any detailed discussion of the subject. Similarly although there is literary evidence of *terre pisée* construction in Roman times and the use of *terre pisée* has survived strongly into contemporary building construction, yet there is virtually no reported archaeological evidence of *terre pisée* construction in the ancient world to justify any discussion on this score. To repeat, the following remarks will deal with ancient brick construction.

Mud brick An obvious statement continually repeated is that brick is the most versatile of building materials—meaning that it is equally effective for building a small cabin as for building a great cathedral. Considered in a little more detail this means that the same small prefabricated earth units of roughly standard form conjoined with a building procedure which is of the simplest and most uniform (v Chap. 3, pp. 49–52 *supra*) serves for all construction projects. Since this statement applies generally in the ancient world wherever brick construction was practised, it suggests that the widespread development of brick construction in the ancient world was brought about by diffusion.

As distinct from the multiple functions served by other earthern building materials, structural brickwork is used in two instances: as upstanding load bearing masonry, and as devices for spanning across an open space. In the former instance significant construction procedure resolves into the question of bonding, while in the latter there is a possible choice between three procedures: corbelled brick, pitched brick and radially set brick.

1. *Neolithic Origins*

Neolithic evolution Whatever prior use may have been made of mud plaster or mortar (cf Vol. 2, pp. 90–96), the use of mud brick as a structural material evolved contemporaneously over a wide area of the Ancient Middle East (the Levant to Iran) at the beginning of the Neolithic Age contemporary with round house building, ca 8th Millennium BC (O. Aurenche, "L'Origine de la Brique dans le Proche Orient Ancien," *pass*). There is surviving material evidence to show that at this period bold experimentation was afoot (cf P.B.L. Smith, "Architectural.... Experimentation at Ganj Dareh"); but, in 329
effect, the standard product adopted was the hand modelled mud brick, obviously 330, 331
conceived in the image of field stones of various forms previously found convenient for building purposes. Following this there was no great delay (i.e. still in Early Neolithic times, ca 7th Millennium BC) before the first form moulded mud bricks appeared in various parts of the region (v O. Aurenche, *La Maison Orientale*, I p. 294). The replacement of hand modelled mud bricks by form moulded mud bricks did not proceed uniformly, and in some areas (e.g. Cyprus) hand modelled mud bricks long remained in use where elsewhere form moulded bricks were cur- 332, 333
rent. The progress in building construction afforded by form moulded bricks was very significant indeed, since the standardisation of form facilitated the close and regular bonding of the mud brick in load bearing walls (cf Sauvage, pp. 105–07). As to roofing the early round house structures there is sufficient indication to show that this could be by corbelling inwards to produce the long lived Beehive House 281
form. Additionally it is possible that round house structures were also roofed by mud plastered timber framing of various forms (v G.R.H. Wright, "The Antiquity 128

Diffusion of mud brick

of the Beehive House"; ABC, pp. 309–10; Ill 152, 153, 339). The upshot of all this is that mud brick very early in the Middle East became the standard construction for domestic building. And from this origin and development mud brick as the medium for domestic building spread to all parts of the ancient world where it was climatically relevant—i.e. in reasonably dry regions (cf, e.g. A. Guest Papamanoli, "L'Emploi de Brique dans l'Egéen à l'Epoque Neolithique," BCH 102, 1978, p. 241). It is possible to suggest a closer chronology for the diffusion of mud brick for domestic building. Although the evidence assembled is only incidental, it would appear that mud brick construction spread widely only after the introduction of form moulded mud brick, since in areas outside the original development discussion of mud brick construction is always in terms of form moulded brick, and hand modelled mud brick is not mentioned. This suggests a date for the general spread of mud brick construction as beginning ca 5000 BC.

2. *Mesopotamian Development*

Development of varied forms of bricks

The previously discussed mud brick construction was essentially that of domestic building—Neolithic settlements were essentially villages where buildings were almost entirely family dwellings, and public buildings for specialised functions were minimal. However from the 5th Millennium onwards society began to approach an urban style, it became diversified and accordingly its buildings became diversified to include some public buildings constructed on a grander scale than domestic dwellings. In short, some social capital was available. This development was in full swing during the fourth millennium and it was the Mesopotamian region where the process first advanced. Accordingly the first advance in brick construction took place in Mesopotamia (Sauvage, pp. 109–14).

Symptomatic of this general development was the invention in Southern Mesopotamia during the 4th Millennium BC of Burnt (Fired) Brick. This curiously delayed invention (it was open to all immediately on the invention of pottery) was certainly first achieved in Mesopotamia, and thus its eventual ecumenical use would seem to go back ultimately to diffusion from Mesopotamia. The main reason for the delayed appearance of burnt brick as a building material, as equally for its slow and sporadic advance is economic. The cost of production of burnt brick was vastly greater than that of mud brick. Southern and Central Mesopotamia led the Ancient World in the accumulation of the necessary communal wealth.

This wealth was manifested in the type of monumental brick building prolifically developed in Mesopotamia from the third millennium BC onwards. The characteristics of this brick construction were:

Characteristics of Mesopotamian brick work

(i) extremely thick walls with varied bonding patterns—NB the herring bone bonding employed for plano-convex bricks (Sauvage, pp. 115–124). 341 342

(ii) roofing where desired of pitched brick construction (D. Oates, "Early Vaulting in Mesopotamia," pp. 183–91). 354

Here a significant observation must be made. Whereas individual aspects of developed Mesopotamian construction (e.g. pitched brick vaulting, use of burnt brick etc.) spread to other regions beyond Mesopotamia, the Mesopotamian manner of brick construction was not disseminated abroad as a complete entity.

3. *Egyptian Development*

Mesopotamian derivation

The striking development of mud brick construction (cf the mastaba) in late Predynastic and Early Archaic Egypt has always been recognised as of Mesopotamian origin (v AAAE, pp. 18–25; Spencer, pp. 5–6).

However, in spite of apparent initial Mesopotamian diffusion, the development of mud brick construction in Egypt took on a totally different character from that of Mesopotamian brick construction. This was manifest equally in the destination of brick building as in the technique of brick construction. Whereas brick construction in Mesopotamia was all purpose for all monumental (and domestic) building, in Pharaonic Egypt finely dressed stone masonry outranked brick in the scale of nobility of materials—so that virtually all temples and built tombs were constructed with finely dressed stone masonry, brick was reckoned appropriate material for building human residences. These included, not only 'domestic' building, but also quite monumental (royal) palaces. Brick was the standard material for utilitarian building, notably store houses and the like. Brick was also reckoned 371 proper to massive boundary walls—not only defensive walls but also enclosure 364, 365 walls to precincts. The upshot of this division was that an appreciable amount of mixed construction occurred, e.g. mud brick palace with stone columns; mud brick walls with stone gates, etc.

Equally, although there were undoubted generic resemblances between Egyptian and Mesopotamian brickwork, considered from the technological view point one would never be mistaken for the other. The brick formats used in Egypt are 356 noticeably more restricted in variety than those used in Mesopotamia—cf the 338 notable case of Mesopotamian plano-convex bricks, for which there is absolutely no equivalent in Egypt (although Egyptian brick layers were very well aware of the advantages of diagonal setting of bricks). In this way the elaborate bonding patterns of Egyptian brick masonry are less extravagant than those of Mesopotamia. There is also the salient circumstance that whereas burnt brick assumed a progressively greater role in Mesopotamian brick masonry culminating in its use

Specific Egyptian developments

as a general all purpose material in Neo Babylonian times, burnt brick played no significant role in Egyptian brick building before Roman times. On the other hand two notable devices of Egyptian brick work were entirely unknown in Mesopotamia; the construction of enclosure walls undulating in plan ("wavy walling"), and the setting of bricks in such walls (and some others) on beds alternately concave, convex and/or horizontal ("pan bedding"). 364–366

With respect to the brick work of spanning members Egyptian practice may have been more extensive and diverse than that in Mesopotamia (v Spencer, pp. 123–27; A. Bedawy, "Vaults and Domes in the Gizeh Necropolis"). 368–373

A concluding remark reverts to a concurrence between Mesopotamian and Egyptian brick masonry. Although aspects of developed Egyptian brick masonry may have spread to neighbouring regions (e.g. Palestine), developed Egyptian brick masonry as a system was never exported (diffused to other regions of the Ancient World).

4. *Roman Development*

Use of burnt brick from 1st Cent. BC

In the light of previously outlined developments it is now timely to observe that by Neo Babylonian times (ca 500 BC) every aspect of brick masonry (as extending down to modern times) had been mastered. Yet it is equally just to remark that Roman burnt brick masonry as developed 500 years later transformed brick building in the Ancient World. This singular fact has never been closely enquired into—and, indeed, most observations on the development of Roman burnt brick masonry have little coherence. Questions are patent. The development of fine brick masonry in Rome distant 500 years in time, and on the other side of the Ancient World from the age old centre of brick building; the discrepancy between the archaeological record of Roman burnt brick construction and of the history of Roman brick production; the geographical distribution of Roman brick construction; above all the relationship of Roman load bearing burnt brick masonry to brick faced Roman Concrete (*opus testaceum*). All these questions require conjoint resolution, which they have not received.

In the first instance burnt brick construction played no part in the Classical Greek building tradition (cf Martin, pp. 63–64; Orlandos I, pp. 67–68). Thus it is generally considered that Roman awareness of burnt brick masonry was acquired from contact with Hellenistic building in Latium, Magna Graecia and Sicily—where it had spread from Seleucid Babylon via a Hellenistic Koine (Dellbrueck II, pp. 95–97). Be this as it may the first archaeological evidence of the use of burnt brick in Roman building, and the earliest indication of a significant (burnt) brick making industry at Rome are roughly contemporary, in the later 1st Century BC (v Anderson pp. 151–65). Burnt brick at this stage is evidenced not as a general purpose building material, *As load bearing structure & as facing to Roman Concrete*

but as used for special occasions and connections (NB bath buildings). Some such date (and no later!) for the inception of burnt brick construction is requisite, since all accounts of the development of *opus testaceum* concrete during the 1st century AD refer to the brick facing as originally from reused roofing tiles and burnt brick 381 masonry but with very little evidence for the supply of pre-existing burnt brick (Vitruvius 2.8.19; cf Vol. 2, pp. 116, 199).

With the dominance of *opus testaceum* concrete the rationale of the Roman brick industry became ever more diffused. There is evidence to show that on occasion square burnt bricks were shaped into triangular facing units either by sawing apart diagonally, or by dressing away (Vol. 2.2 ill 239). There is also evidence that the Roman brickyards continued to produce square burnt bricks. One thing is certain. Roman brickyards did not produce square bricks of varying sizes, so that subsequently 374 these bricks were to be laboriously sawn apart etc. for use as triangular facing units to Roman Concrete. Where Roman Concrete was faced with new brick units, common sense says that these units were supplied pre-fabricated, ready for use by the brickyards. NB The exposed side of the triangular brick facing units to *opus testaceum* was the hypotenuse. If the units were old brick divided up, the tooling should be exposed to view on the elevation of the wall. If they were new specially moulded bricks then equally this should be visible.

However the supply of brick facing units was arranged the floruit of *opus testaceum* construction meant that the aspect of Roman building was transformed into one of brick masonry. And it is accepted that during the second century AD (Trajanic, Hadrianic and Antonine times) this brick masonry was of the highest possible excellence—a sort of equivalent to 5th Century BC Classical Greek ashlar stone masonry. These circumstances are one of the justifications for stating that Roman brick construction transformed brick building in the Ancient World.

Following on this statement it may sound strange to assert that precisely these circumstances are the occasion for a lacuna in the published accounts of Roman brick work. Theoretically the fine aspect of the brick masonry of this age could represent quite different categories of construction—e.g. solid load bearing brick or *opus testaceum* Roman Concrete. The difference in construction is, of course, fundamental: load bearing brickwork formed of entire square bricks bonded together; *opus testaceum* formed of triangular brick segments applied without any bond. Obviously in discussing Roman brick construction it is imperative to know which construction is employed in any given instance. Such a state of affairs, however, is not the case in publications. Adam (Chap. 5.7, La Brique, pp. 157–63) systematically avoids any distinction in building construction and applies his remarks concerning Roman brickwork generically to all building manifesting a brick masonry aspect. Ward Perkins, also, repeatedly discusses buildings in terms of their brick masonry aspect, but neglects to specify the construction (e.g. pp. 284–89). Furthermore

this matter is not a simple dichotomy between Roman Concrete and solid brick
masonry. Whether or not the core of walls is concrete or brick, some of the brick
375 facing commonly illustrated—e.g. the façades of some buildings at Ostia, cannot
be formed out of triangular segments although reference is not made to this question (cf Ward Perkins, pl 152).

Burnt brick building in the Roman provinces

The other moiety of the transformation effected in ancient building by Roman brickwork is Imperial brick building outside Italy. Bricks made in Roman brickyards, as evidenced by the stamps they bear, have been found in many provinces of the Empire (cf Vol. 2, pp. 138–39; J.C. Anderson, "Roman Architecture and Society," p. 163). For the most part these are provinces where Roman Concrete construction was little developed or absent. Thus such stamped bricks bespeak solid brick construction in these regions. Special consideration has been accorded solid Roman burnt brick construction in the East—e.g. in Greece and, notably, Asia Minor (v Ward Perkins, pp. 388–89; H. Dodge, "Brick Construction in Roman Greece and Asia Minor," pp. 106–10; "The Architectural Impact of Rome in the East," pp. 115–18; M. Waelkens, "The Adoption of Roman Building Techniques in the Architecture of Asia Minor," pp. 101–02).

It is of interest to note the same development of solid brick masonry in both Greece and Asia Minor—since, on the one hand, burnt brick construction had never formed part of Classical Greek Building (Martin, pp. 63–64; Orlandos I, pp. 67–68), whereas, on the other hand, in Anatolia burnt brick construction occurred under Babylonian influence and it is reckoned that this tradition continued through Persian and Hellenistic times. The possible interplay of the two traditions has been discussed (cf Vol. 2, p. 117; H. Dodge, "The Architectural Impact of Rome in the East," pp. 116–18). The one circumstance in common between Greece and Asia Minor is that in neither region was construction in Roman Concrete developed to any degree. Thus the occurrence of solid burnt brick construction in Greece and (particularly) Asia Minor is of great significance in explaining the development of Early Byzantine building construction, which entirely ousted and superseded brick faced Roman Concrete (cf Ward Perkins, "Building Methods of Early Byzantine Architecture," pp. 52–104; M. Waelkens, p. 102).

5. *Byzantine Development*

Relation to Roman Concrete

Burnt brick construction enjoyed a notable development during a millennium of Byzantine history, with many refinements particularly of ornament. However during Early Byzantine times to the end of the Ancient World the establishment of the tradition appears to reveal the negative impression of Roman Concrete. For socio-economic reasons Roman Concrete construction was not appropriate or practical in Constantinople, the newly established capital city of the early 4th

Load bearing burnt brick replaces Roman concrete construction

century—and it was not resorted to. (Moreover at the same period Roman Concrete construction was discontinued in Rome.) In Constantinople the place of Roman Concrete was taken up by mortared rubble and by burnt bricks, often used in conjunction as in Roman Concrete, but in the guise of a mixed construction, not so as to constitute concrete. Often in a general way the external aspect of Early Byzantine construction resembled that of Roman Concrete, but the structure was different. Walls were built of courses of mortared rubble and courses of burnt brick in alternating registers of varying proportions, e.g. a register of 5 courses of burnt brick supervened after a register of mortared rubble, say 4 times the height 384 of the burnt brick courses. Such a construction in aspect was reminiscent of *opus mixtum* concrete (cf Mango, *Byzantine Architecture*, pp. 9–10, figs 1, 5). On the other hand buildings were constructed basically or entirely of load bearing burnt brick (cf Mango, Figs 2, 3). Such buildings presented the external aspect of *opus testaceum* Roman Concrete, but the internal structure was entirely different, being uniform coursed brickwork.

In general Byzantine brick masonry differed from Roman brick masonry in that the thickness of the mortar jointing (in proportion to the thickness of the bricks) 377 was greater, and tended to increase with the passage of time (eventually considerably exceeding that of the bricks).

Perhaps the more striking distinction between the use of burnt brick in Byzantine and in Roman construction was in large span roofing. Whereas in Rome for nearly three hundred years this had been carried out in concrete, in Constantinople the same roofing forms were constructed entirely of burnt bricks, employing much 385, 386 the same construction procedures as Roman Concrete.

6. *Iranian Development*

Parthian brickwork

At the period when Roman (concrete) buildings were clad with fine burnt brickwork and buildings of load bearing burnt brick were erected in Roman provinces (e.g. Anatolia and Greece), there was prominent monumental building in another region of the Ancient World. This was Mesopotamia and Iran, where an Iranian people, the Parthians, had come to rule over the Eastern half of the Seleucid Empire (250 BC–224 AD). The Parthian rulers accepted the hellenised cast of expression in the region. This included the design of buildings and to some degree their structure which had replaced the Ancient Mesopotamian building tradition. However, while the forms of buildings were changed, the brick masonry construction incorporated in them remained traditional Mesopotamian brickwork, both mud brick and burnt brick (cf O. Reuther, "Parthian Architecture," *pass*).

Parthian brick masonry retained only the square brick form which had become 387, 390 virtually universal by Neo-Babylonian times. The bonding for such bricks was

Sassanian brickwork

limited and mechanical. The one variant much favoured by Parthian brick layers who advanced it to a standard device was to set bricks upright on edge in association with normal horizontal bedding. As spanning devices Parthian brick layers employed the arch and the barrel vault. The latter was generally constructed by pitched brick technique already prominent in the Ancient Mesopotamian tradition of brick masonry. This construction is well evidenced in underground building, i.e. vaulted tomb chambers. However sufficient material evidence survives to show that it was also employed in free standing, above ground buildings. Thus there was nothing innovative in Parthian brickwork.

This however was not the case during the succeeding Sassanian regime (224 AD–627 AD). On the contrary Sassanian brick work has entered ecumenical architectural 393, 394 history in connection with the structural form of the dome carried on squinches (cf O. Reuther, "Sassanian Architecture," *pass*). This device was in use throughout the Sassanian period, and the two obvious questions of ecumenical application are its derivation and its wide spread diffusion, both East and West. Sassanian brick construction also has another mark of the highest distinction. In carrying on the tradition of barrel vault construction in the Palace at Ctesiphon, the Taq-I-Kisra (6th century AD), Sassanian builders achieved a long standing world record: by far the greatest span known (ca 26m) until contemporary engineering (v Vol. I, ill 55).

B. *Neolithic Origins*

The Round House

During the years just prior to the Second World War the curtain was lifted a little on a surprising archaeological feature: standing at the beginning of Middle Eastern settlement history in Neolithic times was a tradition of building men's dwellings on a circular plan, the so called Round House (v P. Dikaios' excavations at Khirokitia and other early Neolithic sites in Southern Cyprus; cf M. Mallowan, "Excavations at Tell Arpachiyah"). Then soon after the Second World War excavations carried out by Kathleen Kenyon at Jericho (1951–55) brought into light the ecumenical nature of this tradition, and established its unsuspected ancient chronology (8th millennium BC).

In the sequel to the Jericho excavations many excavation programs were taken up extending across much of the Ancient Middle East to investigate this cultural tradition of the Neolithic Round House, so that in the intervening half century this very ancient tradition has become one of the best recorded periods of Middle Eastern Archaeology. As well it might be since it reveals the Ancient World origins equally of sedentary society and of solid, load bearing building construction. Of recent years the extensive archaeological record of this age has been digested and

The Round House, hand modelled mud bricks

systematised by O. Aurenche (*La Maison Orientale*) and M. Sauvage (*La Brique en Mesopotamie*) to which works reference should be made for all matters of detail. Here a final observation may be added concerning the significance of this material. Repeated intimations have been made that the circumstances of this age provide any *realia* existing behind the "Golden Age" of humanity; i.e. that the egalitarian life of Early Neolithic Round House Communities saw human nature and energies developed to their best effect before authoritarian society, and its adjunct authoritarian religion, coerced the majority of mankind into an automated acceptance of an established pattern of social life.

It is in the ambit of this "round house" building tradition of the ancient Middle East (ca 8th–6th millennium BC) that men first made bricks by modelling plastic earth by hand and setting them in the sun to dry out and become rigid so that they could sustain loads (i.e. resist compressive stress). This modelling practice was unknown previously and it did not survive into use during later ages and in other regions. The extensive and widespread excavation programs have shown that hand modelled brick making originated independently in several areas (e.g. Palestine, Mesopotamia) within the Neolithic Round House continuum and there are also indications of its somewhat later spread to other areas in the region (e.g. Anatolia). Equally there are indications that bold inventive experiments were essayed on the most effective manner whereby earth could be preformed into building units before the simple device of hand modelled mud bricks became the general mode (v O. Aurenche, "L'Origine de la Brique dans le Proche Orient Ancien," for a convenient summary).

There is no structural requirement in building round houses (beehive houses) which necessitated the use of hand modelled mud bricks. Round houses can be 330A
built of other materials, e.g. vegetal material or rubble in mortar etc. Indeed close study of the remains of earliest round houses indicates that hand modelled mud brick appeared subsequent to earlier (more primitive) construction in plastic earth, e.g. mud plastered "*branchage*", or "*tauf*" (balls of plastic earth). In short 329
the practice of brick making evolved out of prior familiarity in using plastic earth for building.

Building in hand modelled mud brick was thus the earliest substantial step in man's continued progress in manufacturing artificial building materials which afforded advantages in supply and in use over natural materials. It proceeded from experience in building with other materials. In this way hand modelled mud bricks were assembled after the manner of the ancestral field stones, i.e. as stiffeners to mud mortar, not as a closely integrated fabric—there was little question of bonding with hand modelled mud brick (cf Aurenche, "L'Origine," figs 3, 5, 9).

The wide ranging excavations in the Early Neolithic levels of the Middle East have shown that the Round House Building tradition (PPNA) was fairly soon (e.g.

Form moulded mud brick

330B, 331 after a millennium) joined and eventually ousted by the tradition of rectangular building. Parallel with this basic evolution in designing buildings there occurred a basic development in mud bricks as a building material—*viz* the manufacture of form moulded mud bricks. The standardisation and regularity of form of these bricks effected a revolution in building construction. Unfortunately it is still not possible to provide an overall account of the occurrence of form moulded bricks in the Neolithic Middle East. This is due to the fact that previous excavators noting the use of mud bricks generally did not specify whether the bricks were modelled or moulded. However it is probably fairly reasonable to assume that when they spoke of mud brick without any qualification, the bricks were form moulded.

There is an obvious ideal consonance between rectangular building and the use of form moulded (i.e. rectangular) bricks; and at first this was widely assumed to exist. However with the accumulation of published data it appears that this consonance was not as close in actuality as once assumed.

The first reports of form moulded bricks are isolated occurrences at various sites in Mesopotamia and Syria, ca 6500 BC; but the earliest occurrence where form moulded mud bricks appear as a standard feature is at Samarra on the mid Euphrates, ca 5500 BC, and form moulded bricks became the exclusive construction employed in the Ubeid and Uruk periods, ca 4500 BC (v O. Aurenche, *La Maison*, I, pp. 64–67; Sauvage, pp. 91–101). On the other hand it is evident that 330B, 331 e.g. at Jericho in the Levant hand modelled mud bricks long continued in use after the appearance of rectangular building (PPNB) ca 7000 BC. In this fashion it is possible to suggest that the general use of form moulded mud bricks began in the eastern moiety (Mesopotamia) of the ancient Middle East and spread to the western (the Levant). However this is putative and subject to excavation findings. There is perhaps still a measure of correspondence exhibited between rectangular building and the use of form moulded mud bricks. It may be possible to say that form moulded mud brick was never used with Round House building; but the contrary was not the case. Hand modelled mud brick continued to be used on 382 occasion with rectangular building. Thus it long continued in use where the Round House building tradition survived, e.g. notably on the Island of Cyprus into the third millennium BC, at which period construction with form moulded bricks was virtually universal in the Middle East (ABC I, pp. 36–68; 305; 308–10; 379).

The above account of the Neolithic origins of mud bricks gives rise to a significant observation. All the evidence shows that at the beginning of the Neolithic Age, ca 8000 BC, hand modelled mud bricks evolved independently in several areas of the Ancient Middle East, and their use spread over much of the region. Then a millennium or so later form moulded bricks were introduced as building material and replaced hand modelled mud bricks. This process occurred irregularly and disjointedly over the succeeding millennia, but in broad terms by ca 3000 BC all

Diffusion of form moulded mud bricks

mud brick construction in the Middle East was carried out with form moulded bricks. With this history in mind it is then to be noted that in other regions of the Ancient World outside the Middle East (e.g. Egypt, the Mediterranean) and in later times mud brick construction developed and flourished. Although little direct attention has been given to the matter, speaking broadly it is possible to say that in none of these later instances of mud brick construction has there been any report of hand modelled bricks. Such mud brick construction is always taken to be of form moulded bricks, and there is nothing to suggest that it evolved locally out of earlier hand modelled mud bricks.

In short the succession of hand modelled and then form moulded mud bricks operated only in the original development of mud brick construction—i.e. that of the Early Neolithic Middle East. All later developments of mud brick construction began with form moulded brick work. This is surely an argument of some account that all mud brick construction in the Ancient World in some measure can be ascribed to diffusion from its origin in the Neolithic Middle East.

C. *Mesopotamian Brick Masonry*

Diversification of types of building

From ca the 5th millennium BC onwards settlements in Mesopotamia were no longer an agglomeration of family units (i.e. villages) but provided a means of public life and work, necessitating public buildings of various sorts in addition to private dwelling places. Such public buildings were developed in plan and were constructed of form moulded mud bricks. These circumstances may be taken as constituting the opening stages of a specifically Mesopotamian tradition of brick masonry. This tradition was to be the most highly developed brick masonry in the Ancient World, enduring unbroken for say 5,000 years, to survive the Persian conquest of Babylon, 539 BC, and continue under Persian and Hellenistic rule.

Investigation of Mesopotamian brick building was begun by the architects of the German Oriental Society (D.O.G.) at the end of the 19th century. However they directed their expertise toward the study of design form, and largely ignored building construction. Fortunately during recent years an exhaustive study of Mesopotamian brick masonry has been published, M. Sauvage La Brique et sa Mise en Oeuvre en Mesopotamie (Paris 1998). This can be referred to on all questions of detail. Here only basic structural issues are considered with discussion ranged on upstanding load bearing masonry and masonry spanning (cf Vol. 2, pp. 96–121 for auxillary aspects of brick construction devices). Manifestly Mesopotamian brick masonry developed uninterruptedly from the Neolithic moulded masonry of the region. There is little indication of the use of square bricks during Neolithic times, and the inference is that in general Neolithic moulded bricks were rectangular in form (v Sauvage chap. IV). Subsequently Mesopotamian brick masonry during its long history made use of a number of brick forms alternatively or, at times, in conjunction. The principal forms are: *Brick forms*

(1) Flat square bricks
(2) Flat rectangular bricks
(3) Long narrow bricks of square cross section (*Riemchen*)
(4) Plano-convex bricks.

The incidence of these forms has both a chronological and geographical significance—and initially some general observation must be made in this connection. Rather surprisingly it is the idiosyncratic brick forms 3 and 4 (*Riemchen* and plano-convex) which are prominent at the outset, 4th and 3rd Millennia BC; while square bricks increase during the later and latest periods (2nd and 1st Millennia BC). Reasonable attempts have been made to rationalise these circumstances.

341, 344 *Riemchen* (= little strap) is said to be a German builders trade term, but it makes no sense (and is unhelpful) used in the present context. Some term incorporating "bar" or "rod" would be more apposite in English expression. Riemchen bricks are standardised in their proportions, being long and of restricted cross section with the proportion of length: side ~ $2^{1/2}$: 1 (v Sauvage, pp. 109–12). This form would seem to have its prototype in Neolithic hand modelled long bricks, e.g. the cigar shaped type. The virtue of *Riemchen* bricks is obviously ease of handling and rapidity of assemblage. They can easily be picked up in one hand and set in place without concern for bed or side (which are all one). The *Riemchen* is naturally laid as a header, notably in the construction of massive walls. This assemblage is tied together longitudinally by a row of stretchers as a facing. Also if the wall is massive, there may be additional tie rows of stretchers within the thickness of the wall. Such a construction is clearly appropriate to periods of great building activity. Thus *Riemchen* brick masonry is prominent during Late Uruk, Jemdet Nasr and Archaic Dynastic times—the period when towns were being established and expanded.

The other brick form prominent during the earlier periods of Mesopotamian history (*viz* the third millennium BC) is the plano-convex brick. This is a completely idiosyncratic form of brick, used only in Mesopotamia. Whereas bricks approximating the *Riemchen* in form may occur elsewhere on occasion (e.g. in Egypt, v Sauvage, p. 113) nothing like plano-convex bricks appears outside Mesopotamia. In essence the plano-convex brick is a form moulded rectangular brick, but a surplus of earth remaining above the top of the mould is not scraped away but modelled by hand into an upstanding 'mound'. The brick is thus plane at base and sides, but convex on top (v Sauvage, pp. 115–122). The correspondence 342, 359 351

Brick forms, historical development

in form with early Neolithic hand modelled bricks (e.g. the hog backed form) is obvious and it has been suggested that some later plano-convex bricks may have been substantially hand modelled.

The line of descent of plano-convex brick goes back to field stones of this form and this demonstrates its advantages in construction. It naturally of its own accord falls into an interlocking pattern when set together—the herring bone bond. This assemblage of bricks set on end and leaning obliquely one against the other can be contained and compartmentalised by bricks laid horizontally on their flat beds. In short they are to some degree self bonding which facilitates and speeds up their assemblage (P. Delougaz, *Plano Convex Bricks*).

Given that both *Riemchen* and plano-convex bricks made for simplicity and speed of construction, it is an obvious question to rationalise their predominance during the early stage of Mesopotamian building and their abandonment and displacement by other brick forms in later periods.

It has been proposed that the rapid urban development during the third millennium BC severely taxed building resources to keep up with the demand, so that procedure was geared in the first instance to rapid construction. And this was certainly promoted by *Riemchen* and plano-convex brick masonry (v Sauvage, pp. 109–13).

Equally the subsequent lapse and disappearance of *Riemchen* and plano-convex brick masonry has been put down to the fact that later development and systematisation of the building industry caught up with the demand, and emphasis then shifted to solidity and durability of brick construction, which was served by more intricate bonding of square and rectangular bricks (Sauvage, p. 123). This overall 339, 340
idea is a reasonable one.

If *Riemchen* and plano-convex bricks be regarded as in some measure a carry over from the Neolithic brick tradition, then speaking broadly the 2nd Millennium BC saw in the establishment of fully developed Mesopotamian brick masonry. This involved the use of both rectangular bricks and square bricks, as also the increasingly generalised occurrence of burnt bricks in both public and private building. 347

During this period brick bonding became very advanced—it was varied, intricate and effective, and brick layers of the time were masters of their trade. As a norm in one passage of masonry bricks of more than one format were utilised set both
on bed and on side and as headers and stretchers. These permutations and com- 345, 346
binations afforded striking aspectual patterns together with the most diversified breaking of joint within the structure.

It is of some interest to comment on this highly developed bonding in terms of
traditional modern brick bonding. In their fundamental outlook the two are quite 334–337
opposed—and Mesopotamian brickwork is none the worse for that. Traditional modern bonding seeks to obtain structural strength by the utmost possible uni-

formity in the pattern of setting. This it achieves by the clever use of "closers" at angles and stopped ends etc., which ensures that joint is broken throughout the complete passage of masonry. On the contrary, as stated above, Mesopotamian bonding obtains its structural solidity by variety in the pattern of setting bricks. Also, although information regarding ancient bonding is most often restricted to the run of the wall rather than at angles and ends etc., it seems that "closers" were not used to break joint but rather bricks of different format (or special format, e.g. L-shaped bricks) were set at the ends and angles (Sauvage, p. 63). Allied with this is a very salient fact. Whereas in traditional modern bricklaying the bonding unit is the individual brick, in many instances in ancient bonding the unit is not the 344 individual brick but a composite group of a number of bricks, forming a dwarf pier or the like. Within this pier joints were "broken" between individual bricks, but jointing between individual piers was "straight".

Bonding

The ultimate development in Mesopotamian brickwork culminating in Neo-Babylonian construction, 6th Cent BC, went the other way as concerns bonding. 348 Square bricks became ever more general, this being in a measure associatied with 349 increasing practice of burnt brick (exclusively square in form). And square brickwork admits of only the simplest and obvious bonding. In a certain respect this makes a strange story. The intricate and striking aspectual patterns of mud brick bonding during the 2nd and early 1st Millennium BC were never visible, since uniformly plastered over with mud plaster. On the other hand the simple uniform body of burnt brick in e.g. Neo-Babylonian monuments was exposed (but then the aspect was frequently decorated with figural relief, cf the Ishtar Gate). These circumstances inevitably suggest some idealist rationale (cf, e.g. bichrome *opus reticulatum*).

> Think not because no man sees
> Such things will remain unseen

Of recent years it has become apparent that from an early time Mesopotamian brick masonry made considerable use of arches and vaults. This was formerly not well appreciated and something should be said about this, since it can be misleading. Reconstruction drawings of buildings and building complexes appear in general works. Most of them show universally flat terrace roofing—i.e. they accept that any arcuated roofing construction was not expressed externally. This may be justified in the instances recorded, but it is not necessarily of universal validity. Also the reconstruction shown of the roofing is often a subjective one. These general surveys of Mesopotamian building may be leafed through to ascertain the incidence of arcuated construction in Mesopotamian brick building across the ages. This yields the following general picture:

Arcuated brickwork

(1) Most gates and major entrance doorways have arched lintels. Generally these features comprise two or more successive archivolts; and are of burnt brick even though the general fabric is of mud brick (cf Vol 1, ill 17)
(2) Nothing relating to other arched construction occurs in connection with temples.
(3) There are references to vaults in connection with secular buildings (palaces), but it would seem relating to subsidiary rooms or passageways, not to principal apartments (e.g. throne rooms).
(4) The most prominent representations/references concerning vaulted roofing 355 relate to underground structures—notably tombs (i.e. funerary vaults).
(5) Little direct information is provided concerning details of construction.

In fact arcuated construction in Ancient Mesopotamian brickwork is a subject which can not be set out clearly and definitively in the limited compass available here. For an itemised survey of the evidence reference should be made in the first instance to Heinrich's lengthy article *Gewölbe* in the Lexikon der Assyriologie 3, pp. 323–340. Here individual instances are ordered under the categories of structural form (arches, barrel vaults, domical vaults); process of construction (corbelled, "pitched", radially set); materials of construction (mud brick, burnt brick, gypsum mortar, lime mortar, bitumen mortar); and, above all, architectural disposition (utilitarian constructions, underground constructions, free standing buildings). Heinrich seeks to arrive at an outline statement of arcuated construction form this itemisation, but in the upshot his statement is very generalising—and may well reflect the facts of survival—obviously the roofing of underground features is more likely to survive than the roofing of free standing buildings. However his comments are worth attention.

He states that Mesopotamian brick-layers were able to fashion arches and vaults by corbelling and by 'pitched brick' construction, and that construction in these 354 techniques required no temporary support during construction. On the other hand they could also fashion arches and vaults from bricks set on bed radially ("true" arches and vaults) but such construction necessitated some form of temporary support (centering) during construction. Such brick work was effected in both mud brick and burnt brick, but whereas normal construction in mud brick used mud mortar, arcuated construction (particularly pitched brick construction) was generally fashioned with lime, gypsum or bitumen mortar to increase the adhesion and speed of setting.

In principle these techniques were available from Uruk times onwards, but the earliest instances very largely concern utilitarian constructions like ovens, wells, silos etc. Otherwise the earliest instances in the nature of buildings are underground constructions, e.g. graves. With respect to vaulted roofing of free standing buildings Heinrich's observations are significant. He states that the demonstrable

Arcuated brickwork

mastery of arcuated construction by Mesopotamian brick-layers at an early period (i.e. 4th–3rd Millennium BC) has led to a division among archaeologists into a maximalist and a minimalist view of arcuated construction in Ancient Mesopotamia. Maximalists have restored large and imposing halls and chambers in monumental buildings with vaulted roofs; whereas minimalists can find no evidence to support such restorations. They accept vaulting in free standing buildings only in small scale, non monumental construction, or in secondary apartments of monumental buildings, e.g. service rooms and circulation passage ways or spaces. Heinrich himself is a minimalist and summarises his conclusions with the telling remark that building in Mesopotamia never acquired an overall arcuated aspect until Parthian times.

In this way aspectual history of Ancient Mesopotamian building parallels that of Classical building. With the abeyance of the Early Neolithic Round House tradition a trabeated aspect was reckoned proper to all monumental building and arcuated forms were only tolerated for more or less out of sight utilitarian construction. Then a revolution in values occurred in the first centuries of the Christian Era so that arcuated construction became the very sign of monumentality. Since this change occurred more or less contemporaneously in the Western and in the Eastern part of the Ancient World we have to do here with a basic change in spiritual images.

Finally it may be noted that if this overall assessment is correct, arcuated construction in Mesopotamian brick building was less accepted in aspect than in Egyptian brick building. On the other hand it is to be noted that the forms of arcuated brick construction were the same in both regions: domical vaults and barrel vaults with no evidence whatever of cross vaulting. Also both Mesopotamian and Egyptian building favored the use of flat square bricks in arcuated construction.

D. *Egyptian Brick Masonry*

Sudden appearance, ca 3000 BC

The development of brick construction in Egypt was markedly different from that in Mesopotamia. Whereas in Mesopotamia four millennia or so of solid load bearing brick building preceded large scale public building out of brick, such buildings appeared suddenly in Egypt at the end of the Pre-dynastic age and the beginning of Dynastic times (ca 3,000 BC) without any surviving traces of antecedents. That brick building in Egypt and in Mesopotamia were more or less at an equal stage of development ca 3000 BC, one after a lengthy historical background (v Aurenche, *La Maison*, *pass)* and the other without any significant antecedents (v A.J. Spencer, *Brick Architecture in Ancient Egypt*, Chap. 2) in itself raises a presumption of Mesopotamian influence on the origin of brick building in Egypt. There are points of detail to support this view (notably the niched façade), and it was adopted without question in the earlier part of last century by the founders of

Mesopotamian influence

comparative Middle Eastern Studies, e.g. by Childe and Frankfort (v The Origin of Monumental Architecture in Egypt). More recently there have been opinions limiting this influence (cf W. Stevenson Smith AAAE Chap. 2) but there can be no gainsaying it.

The Egyptians as other people originally gained their experience in building with earth by using it as a secondary material—here mud plaster to stanch and waterproof flexible vegetal material—reeds and canes abundant in the brakes of the Nile. Remains of such buildings survive from earliest (Egyptian) Neolithic times, ca 6000 BC (v G. Porta, "L'Architettura Egizia della Origini in Legni e Materiali Leggeri"). However little or no evidence survives of formative stages in mud brick construction—i.e. building in *tauf* or in hand modelled bricks. Instead from ca 3000 BC there are well preserved remains of monumental building out of form moulded mud brick, and brick building in this tradition continued in Egypt throughout Antiquity.

The incidence of brick building in Egypt is quite other than in Mesopotamia. In Mesopotamia brick was to all intents the universal, all purpose building material throughout antiquity. It seems this was the state of affairs in Egypt for several centuries only. Then during the third Dynasty (ca 2650 BC) this situation was revolutionised, and thereafter whenever possible building for timeless ends (e.g. temples, monumental tombs) was carried out in finely dressed stone, while building in brick served for ends limited in time, e.g. for human residence or for utilitarian purposes.

These circumstances notwithstanding, the remains of mud brick construction survive in Egypt from earliest Dynastic to Roman times so that is is possible to make an overall assessment of Egyptian brick masonry practice, v the excellent study A.J. Spencer, *Brick Architecture in Ancient Egypt*. This incisive analysis classifies its material as from funerary building, religious building, administrative building, domestic building, military building—presenting the evidence from each division chronologically. This is the product of Egyptian brick construction. It then examines brick construction as embodied in walls; foundations; floors; arch vaults and domes; massifs (e.g. pyramids) etc. This is the process of Egyptian brick construction, which is the concern of the present enquiry. The following remarks will be limited in the main to the construction of upstanding masonry (walls) and the construction of spanning devices (arches, vaults, etc.). Ideally this may indicate a distinction between the practice of brick construction in Egypt and in Mesopotamia.

A basic distinction between Egyptian and Mesopotamian brick masonry lay in the form of bricks employed. As recounted above several contrasting brick forms were developed in Mesopotamia across the ages. On the one hand this afforded some chronological indication of the brickwork, but on the other it permitted the

Form & bonding

concurrent use of more than one (contrasting) brick form in any passage of brick
356 masonry. In Egypt only one standard brick format was in general use across the
ages for building walls. This was a rectangular brick, as a norm something like twice
as long as broad, and with its breadth greater than its height in the proportion of
something like $1^{1/2}$: 1. These proportions align Egyptian bricks rather closely with
the traditional modern 9″ brick (= $9'' \times 4^{1/2}{}'' \times 3''$).

However in developed passages of Egyptian brick masonry the bonding patterns
employed were not those employed in traditional modern brickwork. Structural
stability was obtained not by overall uniformity of the bond but by complicated
and varied patterns of bonding. These involved much use of brick set on edge, as
also bricks of differing dimensions and proportions. The effect of these devices
358 was frequently to set up a bond between composite units of brickwork rather
than between individual bricks. Another different and surprising device was fre-
361 quently to set bricks in the thickness of the wall obliquely rather than as headers
or stretchers. All this, of course, is to say that Egyptian bonding procedure was
much more akin to Ancient Mesopotamian procedure than to traditional modern
procedure. This observation is not a surprising one, but when the resemblances
between Egyptian and Mesopotamian bonding are considered in detail, matters
are not straightforward.

Proceeding along the lines indicated by Oliver Myers (in The Bucheum)
A.J. Spencer established a corpus of Egyptian brick masonry bonding for general
reference. Based on this an attempt can be made to outline briefly the nature and
development of Egyptian brick bonding across the ages (i.e. from ca 3000 BC
to the end of the Ancient World). Apart from the ubiquitous and unavoidable
stretcher bond for slight (half brick) walls, Spencer set out his corpus as contain-
357 ing 4 groups:

A. English style bonding.
B. Flemish style bonding.
C. English style bonding making much use of bricks set on edge as headers (i.e. using flat bricks).
D. English style bonding making use of clustered headers set on bed and on edge.

362 Of these groups A and C are subdivided into numerous subsections, whereas B and
D are of little overall account. Therefore the two major styles of Egyptian bonding
359 are his group A and group C: English style bonding and English style bonding
360 effected with headers set on edge. Stated thus it would appear that Egyptian bond-
ing practice was simple and restricted. However both these styles of bonding are
susceptible to a striking and characteristic development which accounts for their
many subdivisions.

Bonding In traditional modern brick laying English bond comprises courses of two sorts: of stretchers and of headers. In normal wall bonding these courses alternate; but in (generally) non-load bearing, enclosure walls one course of headers is followed by 3 or 5 courses of stretchers. For obvious reasons this type of bonding is called Garden Wall bond and the aim is to economise on headers.

As opposed to this, Egyptian bonding sometimes makes use of 3 different sorts of courses or of 2 sorts of courses set in varied patterns of succession (e.g. a, a, b, b; a, b, b, b; a, b, b, b, b, b etc.). The latter recall English Garden Wall bond, but are set so as to produce striking and characteristic patterns in elevation. Here setting of bricks was not calculated to break the vertical joints at each course but rather in part *not* to break them. In fact the aim was to let them run up continuously through several (3) courses so as to constitute a discrete unit of bricks (4 or 6), which often appear as a row of "dwarf pillars". This arrangement is strange to eyes 358
accustomed to traditional modern bonding. However it is instructive to compare these patterns in elevation of Egyptian A and C bonding with course plans in modern bonding. Egyptian bonding was more concerned to break the jointing in the horizontal plane than is modern practice, which indeed specifies on occasion that jointing should be continuous throughout the thickness of a wall.

A very notable singularity of Egyptian brick bonding is the use of bricks set diagonally in the horizontal plane (v Spencer bonds A17, A18). This is reminiscent 361
of Mesopotamian plano-convex brick bonding, but the departure from orthogonal is in the horizontal plane not the vertical plane as in Mesopotamian herring bone bond. The bonding shown in A18 is structurally speaking very superior. Indeed there have been recent proposals to revolutionise modern brickwork by the adoption of bricks of parallelogram form in plan so that the jointing in plan is *never* normal to the face of the wall!

According to the dating of individual instances of bonding the simplest form of English style bond (Group A), *viz* non patterned bonding, occurred at the beginning of Egyptian brickwork (ca 3000 BC) and survived in use throughout subsequent ages. The pattern bonded examples of this group have a random occurrence but likewise may have been in use throughout the ages. The use of bricks set on edge (Spencer' Group C) gave more emphasis to pattern bonding and was a late feature prominent during Roman times. Other developments e.g. the occasional use of Flemish style bond, the occasional use of square bricks, the use of burnt bricks, all were similarly late features and their occurrence was predominantly during Roman times.

This outline chronology immediately suggests two observations. Firstly whatever may be the explanation of the origin of brick building in Egypt, the subsequent development of brick bonding in Egypt did not follow the development of brick bonding in Mesopotamia. Neither the dominance of plano-convex brickwork during

Individuality of Egyptian brick masonry

early Mesopotamian history (3rd Millennium BC); nor that of square bricks during later (e.g. Neo-Babylonian) times had any parallel in Egyptian brick building. Secondly most of the later developments in Egyptian brick masonry are ascribed predominantly to the period of Roman rule. Now while the use of square bricks and of burnt bricks is compatible with their age since these features were endemic in Roman brick masonry; however the intricate developments in bonding ascribed to Roman times have no relation whatever to Roman brickmasonry.

Surviving Roman brickwork is in large part *opus testaceum* facing where, strictly speaking, no question of bonding arises. Also where solid brickwork can be identified the bricks are square bricks, so that inevitably bonding is of the simplest form, *viz* stretcher bond and certainly no question arises of setting bricks on their sides. The manifest conclusion from these observations is that if the earlier development in Egyptian brick masonry did not follow that in Mesopotamia and if developments during the period of Roman rule have little relation to Roman brick masonry practice; then what ever its origin may owe to foreign influence, brick masonry development in Egypt must have been of largely autonomous inspiration.

Some brick masonry in Egypt certainly comprehends devices unknown elsewhere. The most notable of these is the alternating (or rotating) of bedding between flat
365 and curved (both concave and convex) which is effected in a series of horizontal "runs" of the wall. Associated with this in both theory and practice is the device of
364 building a long wall on an undulating plan as opposed to a rectilinear plan. Both these devices stiffen the masonry against deformation (fissuring and collapse); the former in the vertical sense, the latter in the horizontal sense. They embody the principle of corrugation once familiar in the traditional building materials of corrugated iron and corrugated asbestos sheets. The devices are regularly incorporated in long and massive enclosure walls (about sanctuaries). They remain visually striking in their preservation from earliest dynastic times (cf Spencer, pp. 114–117; Jequier, pp. 64–65).

Again the occurrences of these devices at the very earliest stages of solid brick construction in Egypt (ca 3000 BC) indicates that if the introduction into Egypt of large scale construction in brick masonry was influenced by the prior existence of this building construction in Mesopotamia, its subsequent evolution in Egypt owed nothing to foreign influence since nothing like curved bedding or wavy walls occurs in Mesopotamia.

When attention is shifted to spanning devices in Egyptian brick construction, it is very clear that, once established, brick construction in Egypt required no external models for its development. The realisation that space can be entirely enclosed by small pieces of sun dried mud is a very significant step in material progress. And the circumstances of Egyptian archaeology are such that an extensive record is preserved of the earliest stages in the development of spanning devices in Egyptian

Origin of brick vaulting

mud brick construction. This is due to the profusion of late pre-dynastic and early Dynastic pit burials and to their effective excavation. Many of these pit burials (or shaft graves) were roofed over. Originally (during late Neolithic times) this measure was effected in one way or another with wood. However at the focal period 367 of ca 3000 BC numbers of instances are revealed showing the transition between providing the roofing in wood and providing it in mud brick.

A point of departure in late pre-dynastic times are brick lined pit graves roofed over with wooden boards carried on log bearers. In some instances the boarding is covered by a layer of bricks. Here the bricks are a tegument only, and have no structural purpose. However they served to associate the idea of brickwork with roofing. As a parallel to this are the small earthen mounds as a sign of a burial. Here on occasion the visible mound was secured by cladding with bricks. Again the brickwork was non structural, resting on the earth profile—but it took the form of a vault. An interesting memorial of a false departure is provided by the roofing of a pit grave (3036) at Saqqarah (Spencer p. 18, fig 11). Here the wooden bearers take the form of closely spaced poles. However instead of covering these with boards or the like, the interspacing has been infilled with bricks and the whole assemblage covered with a layer of bricks. This, in effect, constitutes an alternative to standard mud terrace roofing—but it is an inefficient device if exposed to any wear.

In any event in the immediate sequel during the 1st dynasty at Saqqarah there appeared the earliest surviving examples of such a pit grave roofed over not with wood, but by a brick vault (subsidiary grave to Tomb 3500). According to the diagram supplied by Spencer (p. 11, fig 3). the grave was also marked by an earthen mound which was clad with brick. The feature thus comprehended both an instance of a structural and a non structural brick vault. In much the same (funerary) context many examples of corbelled vaults are recorded at the Naga ed Der early dynastic cemetery. These are of the 2nd Dynasty (Spencer, pp. 12–14). However the succession may well represent the accidents of discovery rather than a significant chronological development. Certainly by the 3rd Dynasty mud brick vaulting constructed by all procedures was well understood and practised in underground tombs (Spencer, pp. 22–23). This evidence for the early development of brick vaulting construction in Egypt is at least far more extensive than any similar evidence in Mesopotamia.

More complex developments in vaulted mud brick construction are revealed in Old Kingdom cemeteries. At Gizeh during the 4th Dynasty barrel vaults were constructed with special moulded bricks. These bricks, in form like two modern bull nosed bricks joined together laterally, give the section of reed bundles set side 368 by side, thus affording a lively impression of an original vault built out of flexible bundles of reeds (cf the modern mudhifs of the South Iraq Marsh Arabs). Mud brick is thus used here skeuomorphically to reproduce the prior Neolithic con-

Incidence of brick vaulting

struction of canes, reeds etc. plastered with mud (v A. Bedawy, "Vaults and Domes in the Gizeh Necropolis"). The assemblage of these bricks as voussoirs required some form of centering. This cemetery also included a very rare mud brick dome over a square chamber where bricks in the form of crude pendentives round out the angles (v A. Bedawy Figs 113, 114).

This rapid development of arcuated brick construction for funerary purposes during late pre-dynastic and early dynastic times apparently served to establish a command of arcuated construction in Egypt—notwithstanding that very basic ideological concepts were set against its use. With the introduction of finely dressed stone masonry (Pharaonic masonry) during the pyramid age, building in finely dressed stone was considered to outrank in dignity brick building. Equally in post Neolithic "round house" times flat (horizontal) roofing was considered proper for rectangular building (i.e. intellectually designed building). Thus arcuated brick roofing in theory was of limited application in Pharaonic Egyptian building. It was acceptable when not exposed to view, i.e. in underground construction and in the interior of massifs. Also it was deemed in character with utilitarian construction for workaday purposes, where dignity was perhaps inappropriate. This basic outlook remained dominant until Roman rule was established in Egypt, at which time such symbolical concepts swung round full circle in the ancient world. Nonetheless for one reason or another in practice there was much brick building in Pharaonic Egypt (e.g. if there was no time to build a funerary temple for a Pharaoh soon and suddenly stricken, then it had to be built in brick).

Unfortunately there is no published resumé along these lines of arcuated Egyptian building, and a brief abstract is given here. For this purpose Egyptian building can be set into three functional categories: utilitarian, residential and religious. In Egyptian understanding a principal constituent of the distinction was the time factor. For the former two the (all too) short scale of life was applicable; for the latter a very long period frequently specified as a million years. With this guiding concern Egyptian understanding classified all "earthly dwellings" in the short term building category—artisans' houses, noblemen's houses, and rulers' palaces. For all such mud brick construction was appropriate. For the religious category of building, temples of gods and divine kings, tombs housing the magically conserved (mummified) dead, stone was indicated as the appropriate building material.

The clearest of all distinctions was that of utilitarian buildings, which again for the sake of brevity can be focussed here on the vital storage buildings for the staff of life—i.e. granaries. Here not only was brick reckoned adequate, it was enjoined. The two design forms universally adopted in the Ancient World for storage premises were the tall round house (the beehive house) which was specifically for grain
371 storage (a silo); and the sets of long narrow galleries in parallel, also for grain storage but as well for other comestibles. The construction of the silo granaries was

Incidence of brick vaulting

a corbelled dome, or a pitched brick dome (cf Brinks LÄ II s v Kuppel col 883, fig 5; Arnold Architecture s v Silo, pp. 99–100, fig C; Jequier, pp. 12–13, fig 4). The long gallery store room construction was typically pitched brick, cf the repeatedly illustrated store rooms set about the Ramesseum at Thebes (v Brinks LÄ III 361
s v Gewölbe col 590, fig 4; Arnold Architecture s v Grain store, Silo, pp. 99–100, fig A; s v Vault, p. 252; Jequier, pp. 15–16, fig 6).

Human dwelling places (residential buildings) of whatever development were not constructed of finely dressed stone masonry, but of less enduring (and less imposing) material—rubble and/or mud brick and wood. However they were of varied construction, both trabeated and arcuated as also mixed trabeated and arcuated. The prejudice in favour of flat roofs for buildings of significance was partial in its application. Moreover in later, i.e. Roman and Byzantine times, it came to be extinct. The upshot of this is that some Egyptian residential buildings are (partly) roofed by arcuated brick construction.

There is no succinct general treatment available of this issue; here it is only possible to outline some leading considerations. Basic lower class housing in Pharaonic Egypt, whether of mud brick or rubble construction (cf workers' villages at Deir el Medineh, Kahun, etc.) appear as a rule to have been roofed by flat mud terrace roofing carried on a timber frame. However ancient representations, generally in the form of models show some small houses with arcuated roofing elements (cf A. Bedawy, A History of Egyptian Architecture… The Middle Kingdom… Los Angeles 1966, p. 16, p. 13 pl 1). Thus Old Kingdom and Middle Kingdom houses may have carried vaulting on occasions, but generally their roofing was flat terrace roofing. This is the picture presented at Lahun, the Pyramid Town of Sesostris II (ca 1880 BC) which comprised mainly workers' houses together with some larger houses or mansions for officials. In both instances flat mud terrace roofs were standard but in both instances there were occasional barrel vaults (v Arnold, *Architecture* s v Kahun, pp. 118–19).

Direct information regarding the roofing of dwellings is more frequent in New Kingdom times—with the outstanding case of Amarna, the "instant" capital of Akhnaton. The Amarna upper class house was of developed and characteristic plan, incorporating both dignified reception halls and living rooms as also adequate service apartments and facilities (v Spencer, pp. 94–95). Taken together a characteristic distribution of roofing construction is indicated. Speaking in general terms this distribution is also reproduced at e.g. Deir el Medineh funerary workers' village and at Medinet Habu, priests' houses (cf Spencer, pp. 95–96). The principal apartments are with flat terrace roofing, but service apartments, communication facilities (e.g. stairways), and above all cellars, were vaulted. This distribution adheres to the basic ideology that venues for dignified living should be flat roofed, and vaults are only for utilitarian premises.

Incidence of brick vaulting

Several royal palaces of the New Kingdom have been excavated, e.g. Amarna, Medinet Habu and Malqata (v Spencer, pp. 84–89). In all these buildings some brick barrel vaulting occurred. In the Palace of Ramesses III at Medinet Habu occurred the possibly unique arrangement of mud brick barrel vaulting to (stone) columnar arcades, i.e. springing from (stone) architraves (Spencer, pp. 86–87)—however the basic construction (walling) of the Palace was mud brick. On the other hand
130 in the Palace of Amenhotep III at Malqata quite monumental versions of flat terrace roofing were constructed (Spencer, pp. 87–88, Smith AAAE pp. 160 ff, fig 60, pls 120–22).

A very different general impression of vaulted housing is afforded during late, post Pharaonic Egypt. In Roman / Byzantine / Coptic settlements the general aspect of remains is closely packed, multi-storied housing—the unmistakeable image of a proletarianised society. Rather astonishing standing remains of this nature are preserved in Egypt (Spencer, pp. 98–103), notably in rather idiosyncratic localities such as the Faiyum (Karanis, Dimais, etc.) and Elephantine; but also in tells (e.g.
370 at Edfu). Here vaulting is endemic, most markedly for cellars and lower stories so that a flat terrace is available for the roof tops. Spencer (pl 55) gives an idea of the vivid impression afforded by the vertical section of piled up mud brick ruins
363 looking as if they were ruins of abandoned modern villages, rather than relics of the ancient world. Unfortunately, although the overall aspect is familiar, constructional details of this mud brick vaulting are not commonly reproduced.

The most “ideologically charged” use of vaulted brick roofing in Ancient Egyptian building was for temples. Here the “conflict” with stone slab roofing is manifest. In origin large block “Pharaonic” masonry was a “hieratic” construction—it was developed specifically for religious building. Its use in temple building could thus co-exist with the use of other types of construction (e.g. arcuated brick roofing) for other (non religious) types of building (e.g. dwellings). However in principle it did not co-exist with other types of construction (e.g. arcuated brick roofing) for religious building. Such use was exceptional and to be explained in some way or another.

But now it is to be observed that Ancient Egyptian Religion did not continue in vigour until the end of antiquity—and parallel with this, neither did the traditional Egyptian Temple. With the inception of Macedonian rule (332 BC) Egyptian religion and Egyptian temple building remained in full vigour, but another type of religion and another type of temple building also became current in the land. With the inception of Roman Rule (30 BC), however, this situation changed. During the 1st Century AD erection of traditional Egyptian temples in traditional construction continued, but from the second century AD onwards the Egyptian religion declined in its vigour and only repairs and reconditioning were carried out on Egyptian temples. No new Egyptian temples were erected in traditional large block Egyptian

Incidence of brick vaulting

masonry, and no religious buildings were again roofed with grandiose stone slabs weighing many tons. Ancient Egyptian religion, the Egyptian Temple type and Pharaonic stone masonry fell into desuetude at the same time—and behind them all and conditioning them all so did Egyptian hieroglyphics.

This outline story gives occasion for the possible occurrence of arcuated brick roofing in Egyptian religious building at three separate junctures.

(1) Very exceptionally in traditional Egyptian temples during Pharaonic and Ptolemaic times.
(2) In temples of Egyptian religion during early Roman time (i.e. 1st–2nd Centuries AD. 373
(3) In religious buildings (other than Egyptian temples) during later Roman and Byzantine times (from ca 4th century AD onwards).

Spencer (pp. 59–82) gives brief notice of the individual occurrences of arcuated brick roofing in Ancient Egyptian building which can be summarised in accordance with the above distinctions.

So far as concerns brick vault roofing in traditional Egyptian temples there is virtually nothing recorded. Brick masonry often occurs in such temple precincts, but in outworks and auxiliary buildings—not in the "holy" premises, e.g. the Hypostyle hall and the Sanctuary of the developed New Kingdom Temple. One exception noticed in Pharaonic times is of a surprisingly wide span (7.70 m!) pitched brick vault in the mortuary temple of Amenhotep, son of Hapu, at Medinet Habu. However the locale seems to be a secondary hall (Spencer, p. 67). Another exception is the brick built mamisi juxtaposed to the (stone) Ptolemaic temple at Deir el Medinah. The roofing vault here is of double "barrelled" pitched brick construction and again is of considerable span (Spencer, p. 80).

An interesting record is that of the second division: mud brick vaulting to temples of the Egyptian religion built during Early Roman times. These temples are more or less of the traditional disposition in design, but constructed not of stone but mud brick. A concentration of them occurs in and about the Western 373
Desert Oases, Dhaklah and Khargah. A surprising number of temples were built in this region for the most part in mud brick. So far as is evident from the surviving remains, the roofing was often brick vaulted, but flat mud terrace roofs also 373A
occurred (Spencer, pp. 81–82). A good illustrated account of these buildings is given in Hölbl III, pp. 35–101).

The final division concerns roofing to Early Christian (Coptic) Churches; and this is rarely considered in conjunction with its historical background in the roofing of Egyptian temples. A good number of Early Christian churches survive in Egypt, particularly in Upper Egypt and in outlying regions. The remains show

Arcuated brickwork, résumé

them to be roofed uniformly with mud brick domes over square compartments, the transition effected by way of squinches. There is absolutely no record of squinches in traditional mud brick building of Pharaonic times, so this feature in Christian Churches is in any circumstances derived from ecumenical early Christian building outside Egypt. There is, however, an important qualifying factor to this picture. More recent research questions that the surviving domes on squinches are the original roofing of theses churches. In some cases the domes appear to date from (mediaeval) Arab times. This does not necessarily settle the nature of the original roofing, which could have been wood or wood framed (v Hamilton, *Byzantine Architecture*, pp. 152–56; Krautheimer, *Early Christian and Byzantine Architecture*, pp. 110–17, 304–08).

Conveniently published records of mud-brick building in Egypt are not uniformly explicit concerning arcuated roofing construction. The jist of what is specifically stated may be summarized as follows.

369 *Form.* By far the most common form of arcuated roofing was the barrel vault.
370 Domes were unusual until late (Roman, Byzantine) times. A shallow domical vault
372 (dish vault) was known and was typically employed for roofing cellars dug below
houses in late times. Early Christian (Coptic) Churches of a type found mainly in Upper Egypt are commonly roofed with a dome (rather domes) carried on squinches. This device betokens an external influence, but the antiquity of this roofing has been called into question.

Construction. As in the nature of things, 3 modes of construction were employed to build mud brick vaulting: corbelling; pitched brick; and radially set bricks. The former two modes dispensed with the requirements of support by centering during construction. The latter mode was built both by bricks (usually square) set on bed, or set on edge. For significant spans this type of arcuated roofing required the temporary support from below of centering. Some evidence survives of two types of centering. The most basic and simplest method was to fill the chamber or compartment with sand, and to fashion the required arcuated profile on and out of the sand filling. This, in effect, was a special (total) form of standing centering. However for larger spans, on occasion flying centering was utilised. Lodgements survive in walling below the springing of the vaults for inset timber beams to support the centering frames. These lodgements were generally blocked up with mud after the construction of the vaulting was completed and the centering removed (Spencer, p. 87).

Historical Development. Almost co-aeval with their adoption of substantial load bearing mud brick construction during Late Pre-dynastic and Early Dynastic times Egyptian builders appear to have gained a command over arcuated brick construction. Although this was first developed in (underground) funerary contexts, it came to be used in free standing building of all types (utilitarian, residential

Arcuated brickwork, historical résumé

and religious). Surviving evidence of these applications greatly increases in New Kingdom times, while during late (Roman-Byzantine) times arcuated roofing became common in mud brick building of all natures. Speaking in general terms this historical development was of native Egyptian inspiration. Egypt was truly a significant centre for the development of arcuated construction, and this development had its prime expression in mud brick.

E. *Roman Brickmasonry*

Load bearing brick and opus testaceum *facing*

Compared with the great amount of detailed information available concerning ancient brickwork (Mesopotamian and Egyptian brickmasonry), there is little concerning Roman brickwork. That is concerning the setting in place of bricks—brick laying, which is, effectively, bonding. Roman bricks were square, and this limits 374 the range of bonding, compared with rectangular bricks. However the prime consideration here is the still open question of how much building there was in load bearing burnt brick at Rome.

This question comes to the fore in the ever quoted statement of Augustus that he found Rome brick and left it marble. Was he referring to mud brick or burnt brick? If he was referring to mud brick then he was limiting the statement to non-monumental domestic building; but then he certainly did not leave the tenant housing of Rome marble. It was the public building of Rome that he left marble clad, but then where are the remains of pre Augustan monumental building in burnt brick?—the buildings that are postulated to have supplied the scrap material re-used as facing for *opus testaceum* construction? This issue remains still under discussion.

The tandem question is that it is often difficult to determine in general pub- 375, 382 lications whether elevations of burnt brickwork are *opus testaceum* construction or are solid brick masonry. For the most part the inference is that they represent *opus testaceum* facing; but on occasion their nature infers that they are solid brick 377 masonry.

In either event no evidence survives of developed pattern bonding as found in e.g. Mesopotamian brickwork. As for facing to *opus testaceum* no structural bonding of any description obtains—and there is no ornamental development of the facing. Equally when appearances suggest that solid brickmasonry is in evidence, then only simple stretcher bond occurs—e.g. the square bricks are not in part set 377 on edge as pattern bonding in conjunction with normally bedded bricks (as common in contemporary Parthian brickwork).

Here it should be noted that whether as brick facing or as solid brick construction the technical competence of Imperial Roman brick laying was extremely

Arcuated brick construction

high, with a peak of excellence under Trajan and Hadrian. Its impeccable cours-
ing and close jointing contrasts with later brickwork. One aspect of this technical
competence worth special mention is curved plan brick laying—extending to the
376 demands of curve on curve construction (which in stone masonry would entail
significant problems of stereotomy).

Further information on Roman brickwork is available from brick vaulted con-
struction. This is somewhat unexpected since almost all published discussion in this
383 connection relates to the use of brick as a subsidiary material in concrete vaulting
(here treated in the following chapter). Nonetheless some striking evidence survives
of Roman load bearing brick vaulting.

Roman builders used burnt brick for constructing e.g. small barrel vaulting to
niches at the very beginning of their use of the material (cf Adam, pp. 192–95).
However during the period of constructing large span concrete domes (ca early
1st century AD to the beginning of the 4th century AD) three large domes built
of burnt brick are conveniently illustrated in manuals. They employ different sys-
tems of construction and demonstrate Roman builders' command of load bearing
378 brick construction. They are the so called "Temple of Diana" at Baiae (probably
the nymphaeum of a bath building) ca 2nd half of the 2nd century AD (v Adam,
379 pp. 204–05, fig 451); and the Mausoleum in Diocletian's Palace at Spalato, shortly
after 300 AD (v Robertson, pp. 255–57, fig 108) together with the contemporary
380 Imperial Mausoleum, that of Galerius at Salonica (E. Hebrard, BCH 44, 1920,
pp. 15–40 at p. 15).

378 The Temple of Diana is one among several domed buildings in that region, which is highly thermal with many hot springs. For whatever reason these domes are for the most part exceptional. They are of very large span and/or they are not of concrete, but built of rubble etc. The dome of the "Temple of Diana" is 30m in diameter, making it one of the largest of Roman domes. Its system of construction is the simplest possible, consisting of corbelled square bricks coursed horizontally. This gives it a (somewhat flattened) beehive form. It thus reverts to the oldest of all traditions of domical construction. The reason for the unusual choice of material and construction was clearly to avoid the use of centering. Such a dome could be constructed hand over fist from access scaffolding with only a piece of string to control its contours, which forms a profound contrast to the construction of the Pantheon, a generation or so previously.

379 A greater contrast is provided by the construction of the brick dome at Spalato (v Robertson, pp. 255–57, 346, fig 108). This construction also largely avoided centering but by using one of the most intricate systems of brick construction imaginable. The dome was of hemispherical form, with a diameter of ca 14m. The shell of the dome was composed of 2 skins each ca 33 cms thick, i.e. each of 1 square brick 33 cms × 33 cms. The details infer that each skin was built separately,

Late Roman brick domes

so that the inner skin served as centering for the outer skin. The brickwork of this inner skin was astonishing.

The brickwork of the dome at Spalato is divided into 2 registers. For the lower two thirds of the arc, where the stance of the curve is more or less vertical, the bricks are laid to form a circuit of contiguous arches repeated in zones one above the other. For the upper one third of the arc to the crown the bricks are laid in normal radial fashion. The ratio of this arrangement is that centering was required only for the upper one third of the dome construction. The device thus corresponds to the simple expedient employed in barrel vaults to narrow the span requiring centering, corbelling out the shoulders of the vault (cf *infra* pp. 262–263). In the case of the Mausoleum dome, however, the device was anything but simple, both in theory and in practice. The basic theory was to build the circular dome by way of a series of inscribed polygons. The inscribed polygon was 12 sided (a dodecahedron) at the base of the dome, but thereafter was transformed to 24 sided. Each successive polygon was inscribed in the one previous so that its angles were at the mid point of the sides of the preceding polygon. Thus each side of each successive polygon "cut a corner" of the preceding polygon.

On the sides of each polygon segmental arches were built up. Thus these arches since they cut the corners of the outer figures were exactly squinch arches (v. *infra* pp. 263–265); and thus the dome in that register was an overall squinch dome. At the period concerned (ca 300 AD) the dome carried on 4 angle squinches was the standard (exclusive) form of dome construction in Sassasian Iran. However it is not easy to imagine any diffusion operating in Dalmatia. The construction of the dome of the Mausoleum of Galerius is of similar intent but limits the span where 380 centering is required by maximising the shoulder zone of the dome profile where the brickwork can be safely corbelled without centering. It does this by erecting a second dome of smaller radius immediately above the shoulder zone of the first dome, thus providing two cumulative zones where the curvature is of more or less vertical stance.

Whatever practical device was adopted to set out the squinch arch construction of the dome at Spalato, there lay behind it a remarkable knowledge of spherical geometry. There is nothing *ad hoc* about the construction, it is entirely regular. And to adjust the span and rise of each successive zone of small segmental arches so that the overall contour of the domical surface they form is hemispherical seems quite remarkable. Nothing else like it survives from antiquity. But this is not the end of the story. The construction anticipated a later age. The arch headed facetted structure of the dome at Spalato took shape again in Islamic domes, where the construction was expressed as ornament, with its intricate ramification difficult to analyse structurally.

When reproduced graphically this curvilinear patterned brick construction is undoubtedly ornamental, and its squamous motif seems appropriate to a domical form. However presumably it was never visible after the construction was completed, as it would have been plastered over and decorated in some fashion. The same comment thus obtains here as with some Roman concrete brick facing (e.g. *opus mixtum*).

F. *Byzantine Brick Masonry*

Origin & characteristics

Byzantine brickwork was to have a long and interesting development in post-
antique times (Mid and Late Byzantine Periods) but during antiquity (Early
Byzantine Period) it can be reckoned as complementary to Roman brick masonry.
As in Roman building all monumental construction was carried out with burnt
bricks. Byzantine bricks retained the format of Roman times with square bricks,
generally on a side of ca 14″–15″ (ca 37 cms) = $1^{1/4}$′. Thus a 'two brick' wall was ca
30″ (75 cms) = $2^{1/2}$′ in thickness. Monumental building (churches) were constructed
either wholly in load bearing brick (church of St Mary Chalcopetria, ca 450 AD) or
384 of mixed stone and brickwork. Little evidence remains of Roman buildings wholly
in load bearing brick construction, while in Roman times brick and stone were
conjointly employed in concrete construction. Thus the extended use of bricks in
Byzantine building is consequential on the sudden complete lapse of concrete as
a building material at the foundation of Byzantium.

Square bricks in themselves are not conducive of elaborate bonding and Early
Byzantine brickwork, as Roman brickwork, is expressed externally in simple
stretcher bond. There is, however, a striking difference in this expression. Whereas
Roman brickwork exhibited a technical excellence in bricklaying with universal fine
and regular mortar jointing (exactly as modern brickwork), Byzantine brickwork
increasingly departed from this norm. Instead of the mortar joints appearing to
377 casual view as a linear pattern only, the thickness of the joints came to equal and
then exceed that of the bricks. In this fashion later Byzantine brickwork came to
exhibit a diametrically opposite aspect from Roman brickwork. The thick mortared
joints fostered the development of ornamental brickwork giving a picturesque
impression rather than an impeccably precise one as for Roman brick masonry
of the 2nd century AD (S. Casson, JRIBA, 1934 pp. 865–72).

Mixed masonry construction was common in Early Byzantine building and
381 continued so. However here Roman brick facing to a rubble core (*opus testaceum*)
384 gave place to courses of stone masonry and courses of brick masonry succeeding
each other in the one wall according to some regular numerical pattern (Mango,
Byzantine Architecture, pp. 9–10).

Large span vaulted roofing

The most striking shift in Byzantine brick masonry from Roman practice was
in large span roofing. Whereas this was carried out in Roman building almost
entirely in concrete, in Byzantine building it was largely effected in brick. There 385, 413
were several instances of sizeable brick domes of Roman construction, but these
were clearly exceptional. However in the heartland of the Byzantine Empire (Anatolia,
the Balkans, Greece and Italy) vaulted roofing in burnt brick was the norm.
There was moreover a most significant difference between the few Roman brick
domes and the Byzantine domes. The former roofed a circular plan, the latter were 378
constructed over a square chamber (the circle of heaven over the four corners of
the world). Effecting a transition from a rectilinear plan into a circular plan is
a tentative affair in Roman concrete domes, it is the essence of Byzantine brick 411, 413
construction—a fact little noticed. Byzantine builders employed both the pendentive
and the squinch to effect this transition. The pendentive was used during the
first century AD as a device in ashlar stone masonry vaulting in lands where the 299, 300
Hellenistic tradition of stone masonry obtained (e.g. the Levant); the squinch first
appeared during the 3rd century in Sassanian Persian dome construction. 393, 396

From the beginning of constructing brick domes Byzantine builders appreciated
that vaulted construction in brick was equally possible with or without centering.
The model for constructing brick domes on centering was the Roman practice for
building concrete domes—with the possible choice of either flying or standing 400, 401
centering. Here the square bricks could be set radially (voussoir fashion which
increased the resistance to the dome spreading at the haunches). The two methods
of building vaults of any nature without centering were by corbelled brickwork or
by pitched brickwork. In the first instance the bricks were set horizontally, each
course projecting beyond the lower. The bricks were thus cantilevered with consequent 370
subjection to tensile stress induced by bending. However in a dome the
units were in compression horizontally which worked to hold them in place. In the
second instance the flat square bricks were set inclined at a constant angle from 391
the vertical, so that the mortared jointing of very quick setting mortar combined
with the resistance due to friction prevented them from sliding out of position
during setting.

Byzantine builders did not make use of corbelled construction for domes with
its characteristic steep profile, but they knew of pitched brick construction. In
conclusion to exemplify the mixed nature of Byzantine building construction the
crowning achievement of Ayia Sophia may be adduced: the structural materials
employed were ashlar masonry, rubble masonry and burnt brick, while the brickwork 385
of the dome was pitched, but centering was used.

G. *Late Iranian Brickmasonry (ca 250 BC–627 AD)*

Parthian brick masonry

With the conquests of Alexander the age long autochthonous, autonomous building tradition of Mesopotamia came to an end. There were no more temples to Ea or Marduk, no more palaces for Naram Sin or Nebuchadnezzar, both with their massive brick walling and their vaulted passageways. The king was dead and the god gone away. However square bricks, both sun dried and kiln fired remained the staple building material in the region, though now used on occasion to construct quite other design forms than previously. These developments have been treated in manuals of architectural history, but a seldom asked question is whether the methods and manners of brick construction changed when the traditional material was put to new uses.

Something has been said of the possible effect on Imperial Roman building construction (in e.g. Asia Minor) by the use of brick masonry as surviving from the old Mesopotamian tradition (e.g. in the Kizil Avlu at Pergamum). It now remains to consider briefly the survival of traditional Mesopotamian brickwork among the Iranian successors to rulership in the Hellenised Orient.

Of recent years both Parthian and Sassanian archaeology have received considerable attention, but this has not been focussed on building construction. Information of this nature derives mainly from publications of the earlier part of last century. One Parthian site where details of brick masonry are available is Assur, the old religious capital of Assyria, where a Parthian town flourished notably during the 2nd Century AD. Detail drawings of brick construction show that square bricks were employed very similar to those used in Assyrian or Babylonian time; indeed in domestic areas it is often difficult to distinguish Parthian building from remains of 500 years earlier. However in more monumental construction there is one idiosyncracy of Parthian brickwork. As a regular practice use is made of square
389 bricks set on side (edge). These upstanding bricks are incorporated in the bond both as "carreaux" (stretcher slabs) and as headers. In this way, taken in conjunction with square bricks set normally on their beds, very striking pattern bonding eventuates. Similar arrangements were not unknown in traditional Mesopotamian bonding employing rectangular bricks—but the categoric use of the device with square bricks seems a Parthian novelty. Apparently nothing like it exists in Roman brickwork using square bricks.

A more significant issue is the question of arcuated construction. According to the dictates of survival this resolves largely into a consideration of underground tombs. With Parthian building as e.g. with Classical building, the story of arcuated construction appears to be one of vaulting eventually emerging from underground into the light of day. At several localities in Mesopotamia excavations have been made of Parthian underground built tombs. These consist of an entirely under-

Parthian brick vaulting

ground, brick built chamber with barrel vaulted roofing, entered by steps descending from ground level. This tomb type follows an old Mesopotamian tradition well known from Andrae's excavations at Assur, which revealed at the one site both 353 Assyrian and Parthian tombs conforming to the same type. The brick vaulting of these tombs is effected in several different manners so far as the published drawings indicate. Square bricks set radially on their beds, square bricks set upright on edge (side) in successive discrete arches—whether vertical or canted backwards is not always made clear (v A. Haller, *Gräber und Grüfte von Assur*, Berlin, 1954; W. Andrae, *Die Partherstadt Assur*, Berlin, 1933). In this connection an illustrative Parthian grave is one published from a cemetery at Ctesiphon (v S.R. Hauser in 389 BM 24, 1993, pp. 325). The cemetery was excavated ca 1930 by a German Expedition and the original drawing of the grave shows the brickwork of the vault in definitive detail. The barrel vault with a span of ca 2.40m and a rise of 1.20m was divided into a lower (shoulder) half and an upper (crown) half, each with a rise of ca 60 cms. The flat square bricks (ca 30 cms × 30 cms) were set radially on their beds in the shoulder zone, (thus continuing the brick setting of the wall to give a total rise from the floor level of ca 1.20m–1.25m); thereabove in the crown zone the blocks were set on their edge as pitched brick vaulting. This pitched brick vaulting, however, has an unusual constructional detail. The pitched bricks are inclined not backwards against the rear wall, but against the front wall. Also they do not extend from front to rear of the chamber, but at both front and rear the radial vaulting of the lower zone is carried up to the crown thus forming two complete arches (ca 40 cms deep) between which is inserted the pitched brickwork. All this betokens great experience and mastery of brick vaulting practice.

Two conveniently published graves from Assur provide further information on Parthian vault construction (v Andrae, *Die Partherstadt*, Taf. 50). Vault 13971 is of traditional long house plan. The unusual low pointed vault is half destroyed. It 390A is constructed of bricks set radially on their beds in the lower part, but could have had bricks set on edge at the crown. Vault 13972 is of broad room plan. Again the vault is half destroyed. It is a semi circular barrel vault and the bricks appear 390B to be set on edge, but vertically not pitched.

This distinction in the manner of setting square bricks between the haunches and the crown of barrel vaults goes back to the old Mesopotamian tradition. It was in the interest (or supposed interest) of avoiding the necessity for centering. In the lower zone of the vaults bricks set radially on their beds are not at sufficient inclination to require support during construction. Thus pitching was reserved for the crown of the vaults where bricks set on beds would require centering.

There is little direct record of brick roofing in free standing Parthian building. What exists is confined to barrel vaults. Detail drawings of the brick roofing to the Palace at Assur are published by Reuther in his account of Parthian Archi- 388

Sassanian dome on squinches

tecture in Pope's Survey of Persian Art (Vol. 1, pp. 424, 425; figs 100, 101). They represent a triple aisled hall with barrel vaulted roof supported on arcaded brick pillars. Reuther's text refers to pitched brick construction. The vaults could have been constructed in this manner, although the brick for brick detail in the drawings does not show it so. The arches between the pillars must have been constructed as shown—i.e. by semi-circles of bricks set on edge vertically. However these drawings were not made directly from the surviving material evidence, but are interpretations of Andrae's written reports.

Building during the Sassanian regime (224 AD–627 AD) as dispersed over a very great area does not constitute a uniform category, neither historically nor geographically. In any event the characteristic building material employed is not brick but rubble. However it has long been popularly understood that a structure of general architectural significance, the dome carried on squinches, originated in Sassasian building construction. Although this structural form is by no means confined to brick building, it is closely connected with brick building. In this way it is appropriate to discuss the structural form in connection with vaulted Sassanian brickwork.

There is no general study of Sassanian brickmasonry. Accepted statements are that it carried on Parthian practice in brick laying (e.g. alternation or variation in brick courses set normally on bed with brick courses set upstanding on edge). Also, and more significantly, that roofing was always in arcuated brickwork. In this latter connection a marked progression or difference was exhibited from Parthian brickmasonry—and this in two instances.

Parthian building construction accepted and developed the brick barrel vault. However its significant development was in underground construction (vaulted tomb chambers). Vaulted roofing occurred in free standing buildings (e.g. the Palace
388 at Assur) but this was not general practice. As opposed to this a stupendous barrel
391–392 vault with a span of ca 26m remains standing at the present day over the reception hall (iwan) of the Sassanian palace of Ctesiphon, near Baghdad. Secondly it has been observed that Parthian vaulted construction was confined to the barrel vault. Herein lay a striking difference, for from the beginning of the Sassasian regime (mid 3rd Centry AD) Sassanian builders employed the dome to roof square chambers, carrying it
393–396 on squinches, and very frequently constructing it of brick. It is this fact (alone) which has brought Sassanian brickmasonry into general consideration (as stated above).

The dome carried on squinches appears to have occurred in Sassanian building earlier (3rd Century AD) than elsewhere, while later examples of the dome on squinches can be found dispersed widely to East and to West—e.g. in Central Asia to the borders of China, and in Anatolia, Greece and Sicily (v Reuther, "Sassanian Architecture," pp. 500–03; Hamilton, pp. 46–48). In these circumstances it was generally accepted that the dome carried on squinches was first developed by Sassanian builders. Various generalised concepts were adduced in support of

The squinch

the verisimulitude of this idea. The Sassanian Dynasty sought to demonstrate in all ways its ethnic Iranian character, as opposed to the Hellenised character of the Parthian regime; domes were native in the domestic building of the Iranians (in the East!) etc., etc. In fact there are further observations to be made concerning squinches—not least the precise form of the device.

The squinch is popularly understood as a structural device inserted in the angles of a square chamber so as to transform the plan of the chamber at ceiling level from a square into an octagon, thus providing for an inscribed circle 4 additional points of support to the original 4 mid points of the sides of the square. This definition corresponds well with the English term squinch, the etymology of which is associated with corner (coin) and goes back (via Scuncheon) to the old French "escoinson"—i.e. in essentials the squinch is a "decornering" device. However the modern French term which is equally correct in technical usage adds to this sense. *Arc de trompé* specifies that the device is constructed by means of arches, which fact is not indicated in the English term. Thus taking the English and the French term together, one is given to understand that a squinch is a device of arches set in the angles of a square chamber, which provides 8 points (the mid points for an inscribed octagon) to "carry" the circular base of a dome set above the square chamber. Here it should be noticed that unlike the companion device 'the pendentive", squinches do not provide a complete circular plan on which to base the dome, but only 8 discrete points on this circle. The use of squinches thus requires further masonry adjustments to be made for building the dome. 393

This understanding of a squinch is not sufficient to deal with all the complicated facts of its structural behaviour. However this statement refers very largely to the development of the squinch (and the pendentive) in Islamic building construction—circumstances which are not considered here. Nonetheless something of the further analysis required by these later developments is relevant to the question of the Sassanian dome on squinches and is mentioned *pro tanto*.

The definition (or description) given above derives from a consideration of form; whereas in discussing the squinch there are other factors to be considered: its construction (including material of construction) and its function(ing). There is also the question of its aspect, which is a significant one in Islamic building when the squinch became an important architectural ornament in itself. However this has no application to Sassanian building (v Jones & Michell, "Squinches and Pendentives").

It has been advanced that the Sassanian dome on squinches evolved out of a construction referred to as the "squinch vault" (v Reuther, "Sassanian Architecture," p. 501, fig 130), said to be endemic in Khorassan villages. This consists in constructing squinches at each of the angles of a chamber and continuing the construction until the faces of the 4 squinches (in form half cones) about against one another at the centre points of the sides).

Reinforced plaster vaulting

Finally there is to be noticed an unusual and isolated phenomenon in connection with vaulting but one which falls squarely within the Iranian world. Its origins
397 are in Median building of the 8th century BC, but its fully developed form occurs
398 in Sassanian building. The phenomenon is a type of moulded plaster vaulting component; but one which is reinforced. The superficial resemblance to an analogy with pre-fabricated, reinforced concrete units is obvious; the only examples of this known in ancient building. However the material is unlikely to behave as true concrete, i.e. to react to stresses as a single substance (v D. Huff, "Fertigteile im Iranischen Gewölbebau").

Across the ages the material changed, but the idea of the form remained constant. The Median examples were of mud plaster (i.e. mud bricks of special format), the Sassanian examples were out of gypsum plaster. The 'reinforcing' was of pliant wood or rushes etc. The units were cast in the form of curved 'ribs' of rectangular cross section, which could be assembled contiguously one after the other as arches to form a barrel vault. The typical rib unit was ca 1m long with a section ca 20cms × 10cms. The arches formed with these units were high pointed (2 centred) arches, or high parabaloid arches. The units could comprise one complete side of an arch
298.1 meeting at the crown, or units forming the shoulders of the arch and a special unit
298.2 for the crown (parabaloid arch).

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CHAPTER SEVEN

ROMAN CONCRETE CONSTRUCTION

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A. *The Significance of Roman Concrete in Building History*

Scope of treatment

Much of the essentials of Roman Concrete construction has been discussed previously—cf Vol. 2, Chap 6 . (the *in situ* formation of the material) and *supra*, Chap. 3 (the installations for its construction).

Here, as far as possible, repetition will be avoided. Accordingly discussion will be directed towards characterising Roman Concrete construction by the innovations

Prime importance, large span roofing

it imported into ancient building construction in general—changes which outlasted the use of the material as such.

Although Roman Concrete construction has always been regarded as a highly individual development, in fact the formation of the material (and indeed some concrete constructions) are not radically distinct from building in other materials. *Opus incertum* walling is structurally (and aspectually) little different from many earlier random rubble walls (a core of irregular smaller stones drowned in thick beds of mortar and faced with more regular field stones). Equally there is little difference
in construction between some *opus testaceum* walling (notably where the core is 381
made up largely of broken brick fragments) and some later brick masonry walls of flat bricks set in thick beds of mortar. Also there were other highly cementitious mortars besides that from Pozzolana, e.g. gypsum and bitumen mortars evoked comment in Antiquity for their strength.

Notwithstanding that it is rarely spelt out, by far the most significant effect
exercised by Roman Concrete construction on the history of building was the 404–413
capacity to roof over very large areas of unencumbered floor space (cf R. Mainstone, p. 116).

Before the development of monumental buildings in Roman Concrete during the 1st cent AD, the maximum "carry" of monumental roofing across unencum-
bered floor space was something up to 7 m, as born on prodigiously massive stone 255–259
beams, difficult to fabricate and to set in place. If, on the other hand, a background
was sought in dressed stone arcuated roofing of Hellenistic times, the carry was 269
not extended—indeed it fell short of this figure. The only advantage lay in the convenience in fabricating and setting the relatively small units (voussoirs). Thus whereas previously ashlar vaulting of any nature erected with the aid of heavy wooden centering was limited to spans of a few metres only, within a generation or two Roman builders were able to roof floor spaces of something up to ten times that span (e.g. 40 m) with Roman concrete supported on similar wooden centering (cf R. Mainstone, p. 116—"a revolution").

Moreover if precedent is sought for Roman Concrete roofing not in Classical Ashlar building, but in older traditional building modes which did not make use
of centering (e.g. the mud brick construction of the ancient Middle East, or the 354, 355,
dry stone corbelling of the Western Mediterranean) then the situation remains 369–373
unchanged. Such roofing was all restricted to spans of a few metres only.

The aftermath of Roman Concrete roofing tells an equally emphatic story. The revolutionary development in scale effected in Roman Concrete roofing was maintained after the discontinuance of Roman Concrete construction (post 330 AD) and its replacement by brick construction employing essentially similar procedures (e.g. the roofing of Ayia Sophia 537 AD). Moreover the spanning capacity attained in Roman Concrete roofing although maintained in later ages (e.g. the Renaissance dome of St Peter's) was never exceeded until the revolution in building materials of the present day. Surely this was the prodigious achievement of Roman Concrete building—before nothing like this, after it always something like this, before it impossible, after it always possible.

B. *Structural Forms*

In principle Roman builders employed three structural forms when erecting concrete roofing:

269, 270 (1) The Barrel Vault
278, 279 (2) The Cross Vault
295–300 (3) The Dome

Barrel Vaulting

In general terms, they did not employ the simple barrel vaults for "display architecture", i.e. roofing expansive assembly halls, e.g. in *thermae*. Roman builders used the barrel vault for utilitarian purposes, e.g. roofing circulation passage ways in the substructure of amphitheatres. Here the span was limited and, in fact, for the most part on the same scale as ashlar construction (NB The Colosseum contains vaulted circulation passageways in both ashlar and Roman concrete, and if 399 anything the ashlar barrel vaults are of larger span). Another utilitarian application of the barrel vault was also out of general viewing as cisterns or the like in substructures. Higher in social standing are the clusters of barrel vaulted chambers found in business and administrative premises, e.g. Trajan's Markets (cf *in extenso* L.C. Lancaster, *Building Trajan's Markets 1 & 2; Concrete Vaulted Construction*, pp. 98–106). However although the sum of these apartments are impressive and even on an imposing scale, the span of the individual barrel vaults is in the nature of 4 m–6 m which is nothing innovative in measure. NB It is interesting here to compare the contrasted destinies of brick vaulting in the Middle East as culminating in the Sassanian Palace (Taq-I-Kisra) at Ctesiphon. Here the vast mud brick barrel vaults built without centering which roofed the pavilion halls were flung across a span of 26 m, which remained something of a world record until modern 392 times (v Vol. 1, p. 143). Perhaps with the Taq-I-Kisra attention should be drawn to the Basilica of Maxentius at Rome on the Palatine (v D. Robertson, fig 111). The nave of this building is roofed by cross vaults with a span of ca 24 m and quite exceptionally the nave cross vaulting is buttressed by barrel vaults of similar span set transversally over the compartmentalised aisles. The background to this is little discussed. Is it connected with a possible orientalising trend discussed in the Rom oder Orient controversy? In short it was not in their employment of barrel vaulting that Roman builders were innovators. Here they continued the usages of Hellenistic ashlar construction.

Domes & Cross vaults

It is the reverse of this state of affairs which is surprising. To roof over in concrete the expansive halls of monumental public buildings the Roman builders employed the (hemispherical) dome and the cross vault. When during the first century AD Roman builders constructed domed and cross vaulted concrete roofing of ever larger and larger span, it is popularly assumed that they were always proceeding on the model of earlier domed and vaulted ashlar masonry construction. However this is not at all the case. When the Roman builders constructed concrete barrel vaults they did indeed have the model of Hellenistic ashlar vaulting to guide them. Such vaulted roofing erected on centering was current in the Greek world from the later 4th century BC onwards—mainly for monumental underground tombs (cf the Macedonian Royal Tombs at Vergina, v *supra*, pp. 183, 184). However for the other arcuated forms of roofing there was no chronological priority in ashlar masonry construction (cf R. Mainstone, p. 115). The earliest surviving ashlar masonry domes (in Anatolia and in the Levant) are not earlier than the first century AD (v *supra* pp. 189–193). Thus ashlar domes are no earlier than Roman concrete domes (and are much reduced in size). Moreover the lobate dome form (the umbrella dome, the pumpkin dome) was altogether & novelty of concrete construction. Nothing like it is known in stone or brick masonry. It was, perhaps, Handrians brain child. As for ashlar cross vaults, the earliest surviving examples are probably 2nd century AD (from Pergamum, cf Adam, p. 207) whereas cross vaulted concrete roofing appears in Rome during the middle of the 1st century AD (L.C. Lancaster, *Concrete Vaulted Construction*, p. 106). What the 1st century AD Roman builders of monumental concrete vaulted roofing took from Greek precedent was not similar structures in ashlar masonry, but familiarity with the geometry of such forms. 404–414

C. *Centering and Shuttering*

Prerequisite carpentry

Whatever structural form was adopted by Roman builders for roofing large areas, the basis of the undertaking was the same—the provision of a strong wooden framing which

(1) defined the form of the soffite of the concrete roofing and
(2) supported the load of the concrete roofing until it became a rigid self supporting structure.

Additionally for concrete construction a sheathing of impervious materials was required immediately below the soffite of the vaulting to prevent the escape of the liquid content of the concrete while curing. These two features, the former “centering” and the latter “shuttering”, in general are formally and functionally quite distinct; but in the case of vaulted construction they are conflated in position, and this sometimes occasions confusion in references. In any event the nature and disposition of both centering and shuttering in Roman concrete roofing have occasioned dispute. Some reference has been made to this question (in Vol. 2, pp. 188, 189), and only a summary statement is presented here.

1. *Centering*

Standing & Flying Centering

Although the function of centering is constant, the construction to support a dome 40 m in diameter is of a different order from one supporting an arch spanning 4 m. The following remarks pertain to centering for expansive structures.

There are two systems for installing centering: standing centering and flying
400 centering. Standing centering is held in position by vertical supports rising up from the ground. Flying centering has no contact with the ground but is made to spring
401 from some sort of lodgement in upstanding walls. If the vaulted construction is high above the ground, standing centering requires a great quantity of timber for the uprights, and it obstructs circulation at ground level by a forest of timbers. Flying centering leaves the floor unimpeded and is more economic in the timber required. However its construction is more demanding.

There is no installation necessary for installing standing centering. It provides its own installation. It is assembled *in situ*, timber baulk by timber baulk, thus requiring no hoisting of heavy burdens. On the other hand flying centering can only be installed in the form of prefabricated units. In the nature of things where the span is great, these are ribs similar to bow string trusses (segmental trusses). Such members for the centering of a large concrete dome constitute weighty burdens (ca 5–7 tons), and require installations and lifting devices to install them Thus the economy calculus for standing centering and flying centering is not clear. Saving in timber with flying centering may be outweighed by demanding construction with its own necessary installations.

Centering for wide span concrete roofing has been considered mainly in connection with large domed monuments (e.g. the Pantheon), where in a number of instances, much of the dome structure survives. In general it may be said that little detailed attention has been given to the provision of "standing centering" for such monuments. At the middle of the 19th century Viollet
401 le Duc in his Dictionnaire (*s v* Voute) illustrated a project for flying centering structured on trussed segmental ribs. And this approach has remained influential (v Adam, p. 176). That centering of this basic type was known in Antiquity is well demonstrated by the Pont du Gard (ca 5 AD). Here projecting corbels in the haunches of the arches etc. are clearly lodgements for flying centering (for a reconstruction v Adam, p. 176, fig 421).

It is regrettable that all the reconstructed drawings of such centering include the finished masonry structure together with the reconstructed centering. This gives a false impression suggesting that the centering is suspended or attached in

Axial Tower centering

some way to the masonry rather than the prime fact that the centering was built free standing and the dome was later built up over it. In this way the difficulty of engineering the structural stability of the ribs is concealed. Stability can only be achieved when the two opposite ribs are united into a meridional arch, stable in compression. This, of course, is not an easy thing to achieve without support and access installations.

To better provide for this difficulty a modified type of centering has been proposed recently which may be called "Axial Tower" centering. This system introduces a strong tower-scaffolding (or space frame) on the vertical axis of the dome, at the summit of which are facilities for linking together the ribs, e.g. a compression ring subsequently incorporated into the *oculus* of the dome (v F. Rakob, "Römische Kuppelbauten im Baiae", J.J. Rasch, "Zur Konsruktion spatantike Kuppeln"). 402, 403

The above summary account of speculation on the centering employed for large concrete domes reflects an inherent limitation. The question is always approached as if when the concrete structure was rigid, the centering was struck and the builders work was terminated. This, of course, was not so. Much work remained to be carried out on the monument after the concrete structure had solidified. And this fact was material in discussing the type of centering employed.

The fabric of Roman Concrete was never exposed internally but was always plastered—and on occasion was plastered very heavily with ornamental plaster work. In some instances this formed a substantial project in itself, cf the coffering of the Pantheon dome. The execution of such work required all the internal wall faces of the monument to be entirely scaffolded to the crown of the dome with substantial scaffolding.

Now if flying centering has been employed for concreting, an antinomy arose here. This flying centering would have to be dismantled and removed to permit the installations of the scaffolding for the plaster work. On the other hand if the centering for the concrete dome were standing centering, then this forest of timbers could well be adapted to provide the scaffolding necessary for plastering. This fact that the timbering for standing centering could be adapted to provide the scaffolding necessary for finishing work is an advantage which should be considered when seeking to reconstruct the centering used for concrete domes.

2. *Shuttering*

If consideration of centering for concrete roofing was initially conditioned by the 19th century proposals of Viollet le Duc, consideration of the shuttering long rested on the proposals of Choisy (L'Art de Batir chez les Romains) of similar date. These proposals were ingenious and practical.

414 Choisy's system employed "lost" brick shuttering bestriding light open work planking (the shell of the centering). The combined strength of the brick and the planking provided the support and form for the soffite of the concrete, while the brick tegument sealed off the plastic concrete placed above it, so that there was no drainage away of moisture content to vitiate the curing of the concrete. When this process was complete, the centering was struck, including the openwork planking, but the brickwork now mortared to the concrete remained in place as lost shuttering to form the soffite of the vaulting. Also incorporated in this brick revetting were upstanding "strings" of bricks on edge which penetrated into the concrete. These elements, of course, served to key the brick revetting into the concrete structure. *Shuttering*

Choisy undoubtedly based this "system" on observed evidence, but whether he was justified in elevating his observations into general application has been contested, In fact Choisy's system has been discounted by some recent authorities (cf L.C. Lancaster, *Concrete Vaulted Construction*, pp. 26–31). They point out that in many instances the soffites of concrete vaults show clearly the impression of continuous wooden boarding which thus constituted the shuttering. Also they note that when bricks are found adhering to the soffite these bricks do not reveal the nature or pattern postulated by Choisy. Thus their function was not to economise on the wood required for shuttering, but to facilitate the separation of the concrete from the wooden shuttering. In this way the criticism repeats the general criticism of Choisy's work: that he tended to idealise his limited observations. In this instance the critics also point out that he was strongly influenced by a building technique current in Spain and Southern France known as "timbrel vaulting". This was indeed economical as Choisy claimed for his system, but in fact different from it.

Adam (pp. 178–181) appears to offer a reasonable "overview" of the position. He recognises the acuity of Choisy's observations and indicates that several different practices obtained in shuttering concrete roofing. In these he recognises a certain gradation in complexity. The simplest arrangement was to set the concrete directly on wooden boarding as observed by Choisy's critics (cf L.C. Lancaster, figs 32, 35, 38). A more complex arrangement was that proposed by Choisy—i.e. of lost shuttering composed of two skins of flat bricks (v Adam, figs 425–427). Finally Adam spells out that the upstanding strings of brick set on edge formed coffers which, of course, were vital in facilitating the placing of the concrete (v *infra*, p. 277).

D. *Construction Procedure in Concrete Roofing*

The process of constructing concrete roofing is entirely different from constructing concrete walling (or foundations). There are no *opus incertum* roofs or *opus testa-*

Placing Concrete

ceum roofs. Concrete wall construction has long been discussed, but the practical details of placing concrete to build arcuated roofing are not examined in relevant publications. Spoken of here is the construction of an exposed vault or dome as a structural form, not a vaulted or domical ceiling overlaid by mass concrete. Such passages of construction are often illustrated (cf) obviously here the placing of the concrete follows the normal procedure.

As might be expected the earliest concrete vaulted structures are seen to detach themselves from mortared rubble vaulting. The rubble aggregate is set radially, and the only factor which distinguishes them as concrete is probably the cementitious pozzulana mortar (cf niches at Palestrina ca 110 BC, Adam, p. 17, fig 424; in general R. Mainstone, p. 115, L.C. Lancaster, p. 59).

From these beginnings the line of development is to assimilate the placing of the concrete in vaults to the normal process of alternate horizontal layers of aggregate and mortar as far as possible in view of the totally different spatial context of the structure—not a simple process. Within this development a part was played by inset brick work, which in some way, may be compared with the through courses of brick in *opus testaceum* walls. It is well to say in advance that the following remarks are elementary observations only, since virtually no consideration of detail appears in publications. Also it may be noted that much comment does not distinguish clearly between construction and structure, i.e. between the process of building and the properties of what is built.

Whatever the manner of their fabrication the centering and shuttering were raised up into position from inside the building. However when they were completed they sealed off all access to higher levels of construction from within the building. Thus placing concrete above the shuttering required a new access for workmen and materials to be arranged from outside the building. There are theoretical qualifications to this statement. Communication from within the building with higher levels was perhaps possible through the oculus of a dome if such existed. Also there is a further contingency—although it is a remote one. It has been suggested on occasion that concrete domes were built up in stages. In this way the entire centering was not completed first and then the dome concrete placed over it. Rather the centering for, say, the lower third of the dome was set in place and then the concrete placed in position over this and left to solidify. This operation was then repeated for, say, two more successive stages so that the dome was built up piecemeal. The motive for this proposition was economising in the supply of wooden centering. The centering for the limited construction could be dismantled when the concrete had solidified and then reused for the further stages of construction. In fact such a procedure is an unhandy one and has nothing to recommend it (cf L.C. Lancaster, *Concrete Vaulted Construction*, p. 48). It would, however, permit access for the concreting work from within the building.

Placing Concrete

To all intents then, when the centering was set in place, operations for the concreting were transferred to outside the building, and new access arrangements from that quarter had to be provided.

Concreting arcuated roofing was not straightforward work. The basic procedure for placing concrete is to lay down a succession of horizontal layers, alternately aggregate (*caementia*) and mortar (*materia*). However the unit to be constructed was delimited neither horizontally nor vertically—it was inclined at an ever-changing angle. And the only restraint to the plastic concrete was provided by the shuttering, and that was at best (at the springing) "one sided". In the nature of things it was impossible to confine the plastic concrete at the extrados, that is, unless the extrados was given a stepped profile. Such stepped rings were sometimes provided 401, 404 at the base of domes, where they also performed the statical function of minimis- 406, 407 ing thrust (v L.C. Lancaster, p. 141, fig 225).

In view of this situation the placing of concrete in arcuated roofing is difficult to envisage unless some form of compartmentalisation exists to provide a measure of lateral restraint (and thus definition) to the plastic concrete. Thus these remarks bear directly on the question of brick arches and ribs inset into the concrete fabric. 383, 412, 413 Speaking in this generalised manner it can only be emphasized that the more brick "ribbing" present, the more feasible was the process of placing the concrete. Inset brick ribbing was thus very significantly a device in the interest of construction, whatever other function it possessed (cf R. Mainstone, p. 119).

Associated with this is the still open question of how the brick units themselves were constructed. In principle were they constructed *pari passu* with the concrete—i.e. keeping just ahead of the latter? Or were they constructed in their entirety and the concrete then placed to accord with them? This is a ramified question which has received little attention (v R. Mainstone, p. 119).

Inset brickwork also may serve constructional interests in a different context—not in placing the concrete but in its curing. This connection has long been noted. The process of curing whereby moisture evaporates and a plastic mass becomes solid causes changes in volumes and pressures. Compartmentalising the mass clearly reduces these changes quantitatively and localises their occurrence. It is therefore reasonable to suppose that brick insets into concrete fabric regulated possible damage and distorting to the solidifying mass (cf D.S. Robertson, chap. 15).

Something must now be said concerning the basic proceeding for constructing concrete domes. This has been left to follow on some statement of the work entailed. The question is how access was afforded for the work—and no conveniently published discussion of it exists.

On the face of it placing the concrete was in practice a very difficult operation to arrange. It was carried out at very dangerous heights above the ground, with a very confined horizontal surface available only at the margins of the area. For the rest there was no footing whatever. Workmen could not walk, clamber nor crawl about the sheer domical surface of the shuttering. Clearly some form of stepped wooden staging must have been supplied for carrying out this work. Perhaps the simplest installation would be something akin to putlog scaffolding. To a certain degree relevant installation may be sought in the construction arrangements for traditional modern reinforced concrete domes. Here it is not so much the placing of the concrete which is the analogy, since modern concrete is "poured" not placed. However the installation of the steel reinforcing affords something of a parallel—and this is generally effected from scaffolding. In this connection it must also be remembered that whatever means of access was provided, this access remained necessary for finishing work on the dome—e.g. tiling of either terracotta, marble or bronze.

E. *Structural Behaviour of Concrete Roofing*

Monolithic construction?

In the past confused and misleading statements have been published concerning the structural behaviour of Roman Concrete roofing in the guise of domes. Accordingly since domes are also the most common form of concrete roofing, the following remarks on structural behaviour of Roman Concrete roofing will be presented in the first instance in terms of domes. Further an attempt will be made to rationalise some past comment.

When Roman Concrete domes were first discussed in manuals during the later 19th century, the basic point at issue appeared to be "Did the material of construction (concrete) *ipso facto* determine the structural behaviour of the dome (e.g. as opposed to domes of ashlar masonry or of brick masonry)?" Also, since some Roman Concrete domes were observed to contain set within their fabric a considerable amount of brick masonry, "What was the function of this inset brick masonry?"

Two opposing attitudes were manifested:

(a) Concrete because of its physical nature behaves in a different way from masonry construction. It acts as a "monolith", and therefore concrete domes do not spread at the base and thrust outward their supporting structure. In this event the brick work inset into the concrete does not perform any structural service in resisting this outward thrust.

(b) Concrete domes do not function as monoliths which transmit all loads vertically downwards but behave in a manner akin to masonry domes and tend to thrust outwards at the haunches. Thus the brick masonry built into the concrete fabric is intended to strengthen the structural behaviour of the dome.

Inset brickwork

Stated crudely like this, it is evident that the comment was in terms of hypostases not realities. Little more than common sense is required to apprehend the following state of affairs:

(1) In principle a Roman Concrete dome will behave structurally in the same way as a dome of any other material (e.g. of ashlar stone construction). It will tend to crack apart in the tension zone so that the radius of its base increases and consequently it will tend to thrust outward so as to displace its supports and abutments. This behaviour will be prevented, restrained or mitigated
  (a) if the strength in tension of the concrete is greater than the tensile
  296 stress = (hoop tension) developed in the haunches. In this event the concrete will not crack apart and thus it will not spread and tend to thrust out its supports,
  (b) if the resistance to thrust of the dome's supporting masonry is so great
  411 (either by virtue of its mass, or by virtue of the buttressing applied to it) that it will remain in position, and accordingly tend to prevent the cracking and spreading of the haunches of the dome (cf L.C. Lancaster, Chap. 7).

It now remains to examine the modification in the structural behaviour occasioned by the incorporation of brickwork within the concrete fabric.

In principle the brickwork inset into the concrete domed monuments takes the form of relieving arches and/or rib arches (= meridional arches).

(a) Relieving Arches. This is the standard device for re-routing compressive stresses away from frailer structural members onto stronger construction (e.g. away from lintels onto their imposts etc.). In general relieving arches are inset into the masonry of walls, and they appear in the rotunda wall supporting domes exactly as in other walls. On the other hand it is theoretically possible to insert brick relieving arches into the concrete fabric of the dome itself, in order to direct the load of the dome away from the weaker parts of the rotunda wall
404, onto the stronger parts (i.e. away from niches onto solid piers of masonry).
406–408 This is not a usual proceeding but it is stated to occur in the dome of the Pantheon and is shown on several analytical drawings. Adam, however, questions the existence of these arches.

(b) Rib Arches occur in all forms of concrete roofing—barrel vaults, cross vaults and domes. They may be either entirely set into the concrete or stand free of it to a greater or less extent. Their function is to reinforce in some way the
383, 407, strength in compression of the concrete roofing to resist the compressive
412–414 stresses applied to it.

Inset brickwork Only a signpost to this ramified subject can be given here. Brick rib arches were incorporated into all forms of arcuated concrete roofing: barrel vaults, cross vaults and domes. They were not an original component, but their use developed during the later stages of concrete roofing (3rd and 4th centuries AD). In this fashion it must be assumed that their introduction and use was prompted by experiment and that Roman builders recognised brick ribbing to possess functional virtues.

The obvious theoretical question is whether brick rib arches were reinforcing to a load bearing concrete structure or whether they constituted in themselves a framed structure, so that they transmit the loads while the concrete is simply infill panelling. To this question there is an immediate response that sometimes the ribbing was designed so that it could have functioned as a framed structure, cf The Temple of Minerva Medica (L.C. Lancaster, pp. 201–02; pl XI); and sometimes it 412
was designed so that it could not have functioned as a framed structure, cf "the 413
Tor de' Schiavi" (L.C. Lancaster, p. 99). The evidence spoken of here is the disposition of the arches (or the major arches) so that they discharge onto the solid piers of the supporting structure and are not directed above the weaker parts, e.g. the niches. For a survey of this question v L.C. Lancaster, *Concrete Vaulted Construction*, Chap. 5; cf R. Mainstone, p. 119).

This evidence, of course, does not necessarily establish that the brick ribbing in practice did function as a framed structure, Adam (pp. 194–198) believes that it did, at least to a significant degree; and that it gave an extra stiffening and rigidity to the structure. The only way to determine the question would be to subject the structure to some form of stress scanning. Certainly 18th & 19th cent drawings of 412
the Temple of Minerva Medica (when the rib arches survived intact but much of the concrete fabric had fallen away) gives the very image of a framed structure.

When the inset ribbing does not constitute a framed structure, but is reinforcing to the load bearing concrete, an interesting question arises in view of the properties of Roman Concrete. Does the reinforced construction constitute a compound structure or a mixed structure? A compound structure signifies that the concrete and the brick elements have become unified and react as one substance to stress; a mixed structure indicates that the concrete and the brick elements retain their individual properties and behave separately when reacting to stress. Again this question demands close investigation of the individual circumstances.

The above outline indicates that the brickwork inset into concrete roofing serves to canalise and/or better resist compressive stresses set up in the concrete. However it is not in the nature of domes to fail in compression. Concrete like stone is strong in compression but weak in tension, and concrete domes generally fail in tension so that the haunches spread and thrust outwards. To reinforce the tensile strength of a dome it is necessary to inset within the tension zone a circumferential hoop of material strong in tension. Brick is weaker in tension than concrete and is

Inset brickwork

thus no use here. Thus inset brickwork in Roman Concrete domes is not directed against the principal structural weakness of domes.

Roman builders understood that their concrete domes were liable to crack and spread at the haunches, but they did not develop the technique of reinforcing this zone with hoops or chains of material strong in tension (e.g. metal). They attempted to contain the behaviour in two ways:

413 (a) Minimising the self load of the dome by using increasingly light weight material as aggregate (e.g. in the upper part of the dome) and/or employing amphorae as building material in the dome wall (v L.C. Lancaster, Chap. 4).

404 411 (b) Maximising the stability of the dome supports by very heavy wall construction and judicious buttressing (cf R. Mainstone, pp. 118, 195; L.C. Lancaster, Chap. 7).

In spite of such measures surviving evidence reveals that Roman Concrete domes cracked in the tension zone sometimes soon after construction. Clear record of this behaviour (e.g. in the Pantheon) is revealed by date stamps on bricks used in repairing the fissures. In fact according to modern calculations of the strength of materials the concrete used to construct Roman domes should have been strong enough to resist the tensile stresses induced. However the accidents and limitations of the curing process were such that often in practice it did not develop its strength to full capacity and consequently cracked when stressed (cf R. Mainstone, p. 118).

The structural behaviour of concrete domes is not a simple issue and it is beyond the capacity of this book to resolve it. The following is an attempted recapitulation.

The surviving evidence indicates that Roman Concrete domes cracked and spread outwards in the tension zone (some shortly after construction). It is also clear that the builders were aware of this shortcoming and provided buttresses etc. to resist structural displacement. However never did they attempt to inset brick (or any other material) in the form of a peripheral hoop at the base of the dome as tensile reinforcing to restrain outward thrust.

On the other hand the question of the structural functioning of inset brick arches in arcuated concrete roofing is not settled. The proliferation of brick ribbing is a later development, therefore it would seem to be based on experience as fulfilling a necessary or desirable function The disposition of the arched ribbing in some instances clearly indicates that the builders intended the ribbing to transmit the load with prior effect to the concrete (cf R. Mainstone, p. 117). However the disposition in other instances clearly shows that no such structural functioning was intended. No question of chronology arises here, so the distinction is difficult to account for.

Inset brick ribbing in cross vaults

The question of ribbing is usually discussed with reference to domes, but this is an occasion where cross vaulting adds to the picture (v L.C. Lancaster, pp. 106–08, figs 91, 92; J.-P. Adam, pp. 191–95). The intersections of the cross vaulting are much easier to define and construct if they are demarcated by ribs (in concrete as in ashlar masonry) and here again, as with domes, ribbing appeared at the intersections in later concrete construction. In cross vaulting there is a *prima facie* structural rationale for ribbing at the intersections, for there the compressive stresses are the greatest. However it is difficult to assert categorically that ancient cross vaulting is here repeating the development of mediaeval Gothic construction, i.e. from groin vaulting to rib vaulting. This would entail that the ribs were built first as structural members, and the concrete added subsequently as infill (v K. Alexander *et al.*, "The Structural Behaviour of Mediaeval Ribbed Vaulting"). 278, 279

At this point a curious feature is to be mentioned. In most of the published illustrations of brick ribbing, the brick ribs are clearly to be seen projecting below the concrete soffite, which emphasises their structural role (cf L.C. Lancaster, figs 84–95). However this aspect is surely adventitious. The vaults were constructed on centering, and therefore must have been built with a flush soffite, both ribs and concrete. If the ribs now stand below the concrete then this must indicate that the brick "lost shuttering" or "lining" has fallen away.

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CONCLUSION

The technology of building construction is one of the salient factors defining a civilisation (the term which goes best for signifying the broadest geographical context). To share in the same technical resources for constructing premises serving the public and private needs of society is the most salient outward and visible sign of community. Accepting that the geographical expression, "the Ancient World" connotes a "community", it is thus a priority to demonstrate the consequential unfolding of the various significant items noted here. This has become an issue since in recent years dates obtained by physical tests have upset inter regional chronologies based on deduced reckoning from style, social theory etc. On the other hand if a consequential history is derived from the significant items in the record of the technology of building construction in "the Ancient World", this is a corroboration of its accepted community. And very profitable knowledge would be gained by comparing the technology of building construction in "the Ancient World" with that obtaining in other quarters of the globe, e.g. in India and South-East Asia, in China and Japan, and in Central and Southern America etc.

Based on the material in this book it is not possible by way of conclusion to set out a coherent story of the development of building technology in the ancient world. It is possible to recognise and isolate salient items which are comprehended in this development, but not to show necessary interconnections between them. Individual items are widely separated in time and place and there has been little close consideration of their possible diffusion. All that can be done here is to set down these conspicuous items. In due course others may sustain a connected story of the developments.

To provide a background framework for these items it is useful first to reconsider the prime factors governing building—i.e. the mental and material possessions required for building construction.

(1) An understanding of the behaviour in accordance with natural physical constraints of elements of a stable structure.
(2) Some understanding of the properties of matter as they condition the strength of the building materials.
(3) The capacity to indicate/demarcate/set out what is to be built.

(4) The possession of any tools which may be required for the construction.
(5) The provision of any equipment or installations which may be required for the construction.

Statics and the Strength of Materials

The first two factors are closely interrelated and it is possible to take conjoint notice of them. In view of the great achievement of Classical Greek mathematics, it comes as a surprise that man's knowledge of statics and the strength of materials was entirely based on experience throughout antiquity—initially on general experience of life, in later times on building experience. Builders came to know by experience which assemblages of materials were stable, and which materials were strong and which weak when used in various circumstances. However ancient builders were never able to quantify this knowledge and construct buildings in accordance with scientific mathematical calculations. The calculations provided by Classical Greek mathematics related to the form of buildings; to the areas and volumes it incorporated, not to the statics (i.e. the structural behaviour), nor to the capacity of the various materials of construction to resist the stresses induced in them as part of the structure. The Pantheon and Ayia Sophia, complicated structural designs, were created on the same experiential basis as the simple structural forms of the Parthenon and the Pyramids. Experience became ever more involved, but it remained adequate for ordering building construction in the 6th century AD as in the 6th millennium BC.

Experience, however, is not altogether the obvious process generally imagined. If some construction was inadequate for the function required of it and consequently failed, this experience was unmistakeable and prompted a stronger construction. Yet how did experience work in the opposite direction? How e.g. did Classical Greek architects of the 6th and 5th centuries come to realise that for the loads they were to support, the stone columns of their Doric temples were over massive and could be much reduced in diameter. They progressively rectified this excess, but it was certainly not done on the basis of calculation of load and of the strength in compression of the limestone and marble employed.

Measured Setting Out

If man was himself the measure of all things, he was certainly the measuring animal. All the evidence of prehistoric metrology indicates that from earliest Neolithic times man set out his buildings according to rational dimensions, quite exact rectangularity (when desired), and some significant orientation (when desired). With the advent of Megalithic building in Western Europe (ca 4500 BC) some of these measures are reckoned to have been very involved, not to say abstruse; and this was continued with the 4th Dynasty Egyptian Pyramids. In this fashion both e.g. Stonehenge and the Great Pyramid have been reckoned to have functioned as observatories. Thus from his earliest buildings man appears to have understood measure in theory and practice, and he was always able to measure out what he devised to build. Man's acquisition of this faculty is a mystery which goes far beyond construction of buildings, but building must have been a principal activity in the exercise of this faculty.

Tools

There is no overall study of the role of tools in ancient building construction. Thus it is rather surprising to observe on the one hand how in its earliest stages building was carried out with a minimum of tools; and on the other how soon a full set of trademan's tools was available to ancient builders. The background to the latter observation is that tools used in ancient building were also used for other purposes which, speaking broadly, were anterior to building—e.g. fabrication of utensils and weapons. Summary notice of the role of tools in building construction may be provided by considering the question with reference to the major building materials used—wood, stone, earth.

Very few tools were required for building even large and imposing structures out of earthern materials—indeed in some techniques none at all. Early Neolithic building in hand modelled mud brick (from ca 8000 BC) required virtually no tools. The bricks were formed by hand and set by hand in a matrix of mud mortar which could be slapped on by hand. Tauf (puddled mud) construction required absolutely no tools of any sort. The balls of mud were formed by hand and thrust into place by hand so that they constituted at the one time both bricks and mortar. Form moulded bricks (from ca 6,500 BC) required only the use of a wooden frame to manufacture the bricks and some simple device for applying the mud mortar. And these circumstances obtained irrespective of the scale of the building.

The use of tools in wooden building showed the typical pattern. On the one hand flint axes and knives etc. felled trees, severed and trimmed branches etc. in the very earliest building; while on the other the tool chest of Egyptian carpenters and joiners by the early 3rd millennium BC included all the essential wood working tools of traditional modern tradesmen (except the plane).

These tools permitted fastidious work on a standard higher than required in building construction.

The significance of tools in stone masonry construction is more pronounced, and has been recognised. Indeed of recent years attempts have been made to identify schools of masonry on the basis of the tools used (cf H. Kalayan A History of Architecture through the Tools used *Al Mouhandess* 1–11, Beirut pp. 3–15). This, however, falls within the instance of finely dressed stone masonry. The overall picture is seldom discussed. Obviously tools are more significant in finely dressed masonry then in field stone, random rubble building. In the latter instance tooling can be restricted to knocking away irregular excrescences etc (e.g. with a stone hammer or pounder).

The following are outline observations on the rôle of tools in fine stone masonry.

It is not commonly realised the fine dressing in stone building began not in the Middle East but in Western Europe. Although Megalithic Building (Dolmens, Menhirs etc) as a class was in rude stone, there were striking exceptions. It is difficult to think of Stonehenge and the Maltese temples as not pertaining to the category of Megalithic Building. Yet these famous monuments incorporate passages of finely dressed (and ornamented) stone masonry.

The tools employed were hard stone pounders and chisels, and antlers for the punched ornamental work. This use of stone tools for fine dressing stone masonry marginally preceded the development of Pharaonic stone masonry in Old Kingdom Egypt, ca 2600 BC. However the Egyptian stone mason of this epoch possessed a full range of masonry tools such as is encountered in modern times. These tools were of metal (copper, bronze) although for working hard (igneous) stone, e.g. granite, Egyptian masons used stone hammers and pounders of very hard basic rocks.

From this plenary beginning it may be said that thereafter in the Ancient World variations and limitations in the tools used by different (regional) groups or schools of stone masonry may have been more a matter of adjustment than of deprivation. Here may be noted the publicized distinction between those groups which favoured the "struck" percussion tools (chisels, punches etc.) and those which favoured the "striking" percussion tools (hammers, axes, adzes etc.)—Egyptian and Greek masons preferring the chisel and point etc., with Middle Eastern and Roman masons preferring the adze and axe etc.

Finally is to be mentioned the important development constituted by the general replacement of bronze tools by iron tools during the latter part of the first millennium BC manifested in Classical Greek and in Roman stone masonry.

Equipment and Installations

There is a great difference in the equipment and installations required on a building site depending on the material of construction in use. Where the units are small, e.g. bricks, they can be hand portered or hauled up hand over fist to the working position required. Thus no equipment or installations other than providing for human access is necessary. This is the fortunate circumstance of brick building irrespective of the scale of the structure. The flimsiest of scaffolding is adequate for access. Moreover, in Ancient Mesopotamian building the walls were often so thick that it was not necessary at all to scaffold the wall face to provide access for the bricklayer, since this work was carried out from above the rising wall in a manner resembling paving floors. With puddled mud (tauf) construction even slighter walls are constructed without access scaffolding of any sort. The waller stands or sits astride the top of the wall, while the assistant throws the balls of mud up to him from the ground or lower floor.

As opposed to this, building with the most massive of units ever known occurred early in building history. Megalithic Building which flourished in Western Europe (the Atlantic Seaboard) from well before 4,000 BC to ca 2,000 BC made use of slabs and blocks of stone of many tons burden (on occasion exceeding 100 tons). Thus the equipment and installations required to set in position the weightiest burdens of all times were realised in what has been generally regarded as a marginal area of the Ancient World, early in the history of building. Surviving evidence indicates that two types of installations were employed:

(a) Earthwork ramps and embankments.
(b) Levering and cribbing.

Perhaps the most numerous class of Megalithic monuments were Dolmen chamber tombs of various designs heaped over with a tumulus of earth. Thus there was every advantage in using earthworks as installations for construction. Upright stones were hauled base first up the earth ramps to a suitable height, allowed to slide down a steep incline into position, and then hauled upright with ropes (using shear legs to better vector the traction). Capstones were hauled across the top of the earth filled chambers, and the earth fill subsequently removed.

Alternatively where there was no tumulus standing stones were levered and chocked into an inclined position and then hauled upright; while capstones/lintels were levered up horizontally and a cribbing of open work logs was built up below them in successive stages. Both these installations were employed in large block Egyptian construction—and are still resorted to in emergencies today.

The other method of raising up heavy burdens is to clean lift them into position by ropes and pulleys (block and tackle). All surviving evidence indicates this procedure was only introduced during the 6th Century BC by Classical (Archaic) Greek builders, presumably under the stimulus of a nautical background. The economy and rapidity of clean lifting ousted ramps and levering except in special circumstances.

Subsequently only one major type of building installation was developed. This was the curved profile timber staging erected to position and support arcuated (vaulted) roofing during construction. It appeared in Greece during the 4th Century BC for ashlar stone masonry construction, but continued to be used for rubble, concrete and brick construction. This was the counterpart to building arcuated roofing in brick and stone by way of corbelling or pitched brick construction known from earlier times.

The history of installations for building parallels that of tools. The most replete building can be constructed with virtually no tools or installations. Yet on the other hand when building construction required sophisticated tools and installations, they were available surprisingly early in the history of building.

As predisposed by these factors the significant items in the history of ancient building construction may be resumed as follows.

Initial Development of Solid Load Bearing Construction

Of recent years much has been published concerning building in Late Palaeolithic times (or even earlier v Vol. I). Some of it has the doctrinaire aim of reducing the "myth of the caveman". Where there is any coherent account of building construction it is difficult to imagine anything more than temporary framed shelters (tents or cabins). The subject, in fact, pertains more to archaeology than to building construction.

The account of building construction (as it is presently known) begins in the Ancient Middle East in Early Neolithic times somewhere about 10,000 years ago. In it can be traced a development from a sunken shelter (pit dwelling) protected from encroachment by a barrier wall and shielded from the elements by an independently supported canopy into a solid load bearing structure with walls of mud brick and/or field stones supporting either a corbelled roof or a mud terrace roof on wooden bearers. This might pass for a description of the construction of a rudimentary domestic dwelling in the region down to the Second World War. In one sustained historical process evolved all that was necessary to construct a stable weatherproof domestic dwelling place adequate for the elemental needs of human society for many thousands of years. This was the work of an individualist and inventive age unfettered by traditions or by all pervading authority.

The Brick Mould

Speaking in terms of the then time scale, it was not long (a millennium or two) after the agricultural communities of the Middle East began to house themselves in solid buildings of rubble and earth, that a device was invented which remained in use until within living memory. This was the (wooden) brick mould. Its direct effect on building construction was, of course, great, but in addition it exercised a far-reaching "symptomatic" effect on the history of building technology. Form moulded mud bricks replaced mud bricks modelled by hand to resemble field stones found to be convenient building material. The introduction of identical units rigorously parallelopiped in form is clearly of an imagination compact with the replacement of round building by rectangular building, although these two developments do not always proceed exactly in parallel at every site and region. The two innovations (one in construction, the other in design) mark man's assertion of his own intellect as the controlling factor in the world he makes for himself. No longer is his life guided by "*participation mystique*" with natural phenomena. He imposes on nature the categories of his human intelligence, brought into full consciousness.

With form moulded mud bricks his building construction immediately gained the added strength of pattern bonding (binding individual units tightly together) and of reducing the (weaker) mortar content to a minimum. These structural advantages of form moulded brickwork were readily apparent. However this construction still harboured a defect—its limited durability in contact with water. To remedy this defect it was expeditious while maintaining the advantages of the regular form moulded units to replace where necessary the water soluble mud brick material with a much harder relatively insoluble material. In this way not only burnt brick but also small block stone masonry (both appearing in Mesopotamia during Chalcolithic times) were developed in the train of the brick mould, a device which, historically speaking, thus incorporated *multum in parvo*.

Solid Wooden Framed Construction

In point of systematics if not in point of time the earliest evidence of substantial durable building in wood should be mentioned next. This took the form of long houses of solid timber framed, ridge roofed construction. Wood is a fugitive material, and as such does not provide as distinct archaeological evidence as construction in stone and clay. Thus the earliest remains of these structures may not be established firmly. However present indications are that such building was first established in western continental Europe before 4000 BC and remained common in the region throughout antiquity (and later). The regional association was so readily accepted that, when efforts were made a century ago to explain the origin of the classical Greek Megaron Temple (a ridge roofed structure) the popular theory was that the form was originally of wooden construction and was brought into Greece by migration of people from Northern Europe (Dorians etc.). If nothing else such speculations show a fond desire to make a coherent story out of building construction in the Ancient World.

Megalithic Construction

The next item is the most inexplicable and the most striking in the record of ancient building construction. It emerged during the latter part of the 5th millennium BC at the extreme western margin of the Ancient World. The buildings concerned were all monumental ones, and had no connection whatever with the domestic building construction of the community. They took the form of large unhewn stones/detached slabs of rock set up as standing stones forming avenues or circles (menhirs); or they were capped by other slabs so as to form chambers or galleries constituting artificial caves heaped over with earth (dolmens). The full range of their functions is not yet determined. They were jointly or severally communal graves, temples, time and/or space markers etc.

The engineering of these ponderous constructions was a wonder—it is doubtful that any more economic or efficient procedures would have been available before the Industrial Revolution. The capacities of those in charge answer to the demands of Vitruvius, and they deserve to rank with the famous early 19th century engineers of genius. Who were they? Were they of a single definable origin? Freemasons? A caste? Preachers of sermons in stones? With Megalithic Building it is particularly apparent how episodic is present understanding of the story of ancient building construction. No convincing source for megalithic building has been determined and no detailed study has been made of its influence on later building construction, e.g. on large block Egyptian (Pharaonic) Masonry or on Cyclopean Masonry.

Finely Dressed Large Block Stone Masonry

The introduction of large block monumental stone building in Egypt, sometimes referred to as Pharaonic masonry, is another item of prime importance in the history of ancient building construction. This manner of building replaced the small block "facing" construction of the funerary complex of Zoser (ca 2650 BC) to become immediately the characteristic building style of the Pyramid Age and remained the characteristic building style until the end of traditional Egyptian monumental building (1st–2nd Century AD). At its introduction it appeared fully developed, and its technical excellence has never been surpassed. The blocks were massive, as a rule ranging from several tons to many tons in burden. They were as a rule not regular parallelopiped in form—their joints were not orthogonal and sometimes were stepped. This evidences that as much as possible of the dressing was effected *in situ*.

These massive units were set in place by the same procedures as was Megalithic masonry, i.e. the use of earthwork ramps, banks and fills, together with expert levering; but the nature of the masonry units was entirely different from those of megalithic construction. Whereas Megalithic masonry was largely unhewn, Pharaonic masonry was finely dressed so that all the joints between blocks were "hairline". Thus the construction was of the greatest possible solidity. This mastery of the art of fine dressing large blocks of stone remained a principal factor in building construction throughout antiquity down to very recent times when reinforced concrete and steel framed construction has rendered finely dressed load bearing stone construction virtually obsolete. The invention of this practice is seen in 4th Dynasty Egypt—and no forerunners are to be seen. On the other hand, as stated above, the construction procedures of Pharaonic masonry were those of Megalithic Masonry. The development of Megalithic Masonry in Western Europe was a good millennium prior to that of Pharaonic masonry, however they overlapped historically. Megalithic construction was flourishing when Pharaonic construction was introduced and both remained contemporary for a millennium or more. Very little has been said about any possible connection or influence.

Clean Lifting by Block and Tackle

During the 6th Century BC Greek builders developed to perfection a style of Ashlar Masonry which has remained the academic norm, and has never been surpassed in its detailing. However the basic idea of finely dressed large block masonry was derived by Greek builders from the example of Egyptian monumental building (past and present). It was a specific item in the building procedure of this Greek ashlar construction, reversing and outmoding Egyptian procedure which constituted a most significant development (innovation) in the history of ancient building technology. This was clean lifting by block and tackle—i.e. a device of a "block" in which were housed one or more wheels around which wheels a rope could be passed serially. Each wheel reversed the motion of the rope and the number of wheels in the system progressively increased the mechanical advantage of the input of energy, so that ultimately loads of many tons could be raised vertically by the input of a limited traction (which could be augmented with the aid of e.g. windlass or capstan).

Many detailed factors and appliances operate in such a system each of which needs to be sufficiently strong to support the stress induced in it by the load, and the practical details of such systems of clean lifting very heavy loads in antiquity are by no means clearly determined. Indeed some of the loads clean lifted by block and tackle in Roman times beg modern understanding. However, in principle, the mastery of clean lifting heavy burdens attained by Greek builders in the 6th Century BC and augmented by imperial Roman builders transformed construction procedure for good and all, as witnessed by today's mammoth tower cranes and mobile cranes seen all about us.

Centering for Vaulted Construction

During the latter half of the 4th Century BC Greek builders began to construct arches and barrel vaults in ashlar masonry "turned" on wooden centering. Much has been written concerning this development endeavouring to explain its origin by showing how Greek builders at that time acquired familiarity with arches and vaults from observation of arcuated construction in the Ancient Middle East. This discussion mistakes what is, in fact, the significant issue. It is not knowledge of the form of arches and vaults which is the novel development. Arches and vaults were endemic in the ancient building tradition of the Middle East, and Greek builders could not help but be aware of these forms. The novel development lay in the procedures of construction—i.e. the use of timber centering.

Unfortunately there is no published study of the history of this device. So far as is apparent the vaults of the Ancient Middle East were generally constructed without the use of centering. For the most part they were of brick, and the technique employed was "pitched brick". This relied on a combination of factors to mitigate the operation of gravity: light weight units; maximum bed area to volume; quick setting, very adhesive mortar; and, above all, inclination of the bedding away from the vertical. There were, of course, other devices to construct arches and vaults, e.g. corbelling. However, prior to the 4th Century BC Greek developments, there is no record of the construction of arches or vaults from sizeable finely dressed blocks of stone, wedge shaped in form and set with radial joints. The construction of arches and vaults from these units required the use of centering, both to establish the true form of the intrados, and to support the units until the profile was complete. This was the innovation of the Greek builders in the 4th Century BC, not adoption of a structural form with a long background in another region.

The immediate effects of this innovation were not, in fact, visually striking. The expression of the barrel vaulting was for the most part hidden underground away from passing view, and the span of the vaults was no greater than was customary with stone beams and slabs. However the construction was stronger. The load bearing capacity was greater per sectional area, since stone (or brick) arches of this nature were stressed in compression (where they were strong, rather than in bending as were beams and slabs where they were weak in tension). What made this development of great significance in the history of building construction was that it provided the basis for later construction in Roman Concrete of vaulted roofing of very wide span.

Very Large Span Roofing

The latest item of major significance in the history of ancient building construction, the capacity to roof very large areas of unencumbered floor space, is unexpected—or rather its late date and its venue, Rome during the first and second centuries AD, are unexpected. This is a clear instance of the primacy of social factors in the development of ancient building construction. The secular trend in Roman society coupled with the political necessity of pampering the city mob required the construction of spacious halls for public concourse of the multitude by way of public entertainment centres (*thermae*) and also for public affairs (*basilicae*). The enormous wealth of the capital of a great empire made possible building on this scale. In this fashion were constructed Roman Concrete domed and cross vaulted roofs of many times the span of previous roofing, whether slabbed or arcuated.

It is to be noted that this achievement was not based on technical developments. The great increase in the freely supported area of the roofing was not due to the use of Roman Concrete. Once the carpentry was available to build the centering, the roofing could be construction in brick or stone as well as in concrete—and was so constructed in Byzantine and later times. What is of interest technically is that the Roman builders extended these roofs to the technical limits. This is evident in that although the greatest spans in Roman Concrete roofing were maintained in other materials during later times, it was never exceeded until the post World War II revolution in building materials and design.

* * *

The above mentioned items are the epoch making ones in ancient building construction—not many and widely separated in time and space. Yet somehow with the invention of each the command of construction it afforded was never totally lost—the essence of it always remained available or was recollected if needed.

There are conflicting explanations for this, but none has been pursued in detail. Perhaps the last words of this outline of ancient building construction may be focussed on this issue.

A survey of different modes of building found across the ancient world gives rise to the same issues endemic when other material remains of the past are considered comparatively across broad fields—the perennial question of evolution versus diffusion. When similarities are observed between different building styles sometimes the evidence suggests the origin lies in independent evolution, sometimes it indicates diffusion—and remarks in this connection are often conflicting and inconclusive.

As an example, a small block "bastard ashlar" masonry strikingly present at Saqqara in the funerary complex of Zoser ca 2650 BC is derived in the ultimate instance from the brick building tradition of Mesopotamia. On the other hand what was the origin of the so different Pharaonic type large block masonry which soon ousted it in large measure? The only prior mode of building construction which resembled Pharaonic building was the Megalithic building mode originating on the Atlantic coast of Western Europe, which certainly extended its field to the eastward, a development notably manifested in Malta. But to what degree can it be imagined that Egyptian Pharaonic masonry construction derived from the example of Megalithic masonry? Only perhaps the idea that it was possible to build monumental structures using very large units of stone—and also perhaps that methods of raising up and installing these large stone units in place might have been in some measure derived from knowledge of practices in Megalithic masonry. In all other respects the two systems of large unit stone masonry building differed completely, e.g. in the winning of the stone, its dressing and its setting together.

In similar fashion the dramatic development of classical Greek ashlar building construction during the later 6th Century BC has always been referred back to the Pharaonic building in Egypt at the time experiencing a renaissance under the Saite dynasty. However when details of construction are compared, they appear to be pointedly different. What then can be said was diffused from Late Dynastic Egypt to Archaic Greece. Again the idea, the concept that it was possible to build monumental temples out of sizeable blocks of finely dressed stone. The detailed expression of the idea is for the most part pointedly different.

These observations relate to the geographical transfer across the ancient world of building construction procedures. Similar reflections are possible in connection with the transfer across time of building construction procedures. It was individual elements only which may have been diffused, and the same can be said regarding transfer over the ages. The mode, the school of building construction had a limited time span, but this does not mean that when the mode lapsed, all technical procedures appertaining to it disappeared from men's knowledge. In fact many individual items survived or could be regained if necessary. It was the idiosyncratic combination of all the technical elements which lapsed. Traditional modern stone dressing employs exactly the same processes as Classical Greek ashlar masonry; but this does not mean that Classical Greek building construction has survived into modern times. Overall types of building construction are time bound, they have their entrances and their exits.

This latter fact in turn gives onto an occasion where the circumstances of building construction appear to illustrate clearly a general historical issue of note. Megalithic style building construction obtained over several millennia, say from the 5th millennium BC to the 3rd millennium BC; Egyptian Pharaonic building construction say from the 3rd millennium BC to the 1st century AD. Mesopotamian massive brick building construction had an even longer life span. However Classical Greek ashlar building had a drastically reduced life cycle of somewhat over only half a millennium; while Roman Concrete construction endured for still less a period, say for under half a millennium. Is this another record for the speeding up of the process of change (= time)?

Finally it may be in point to say the obvious. Ancient building construction is patently in the first instance an expression of human thought. Thus the study of ancient building construction in the first instance is the study of the thought of man in a setting of time. It is a long process whereby the "fixed action patterns" of emerging hominids became the (relatively) free thought patterns of (some) men. The new "bastard" ashlar masonry at Saqqarah did not grow up out of the soil. In this instance the innovation was so striking that the thinker of it was deified by later men, and remembered by his name—Imhotep. Thus the modern study of the building construction of the funerary complex of the Pharaoh Zoser (ca 2650 BC) is the study of Imhotep's thought—very strenuous thought. "The thoughts of men are light and fleeting." These were monumental thoughts. They are history.

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(Compiled by Ron Sheriff)

Note: numbers in bold refer to the Illustrations in Part 2

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ANCIENT BUILDING TECHNOLOGY

VOLUME 3

CONSTRUCTION

BY

G.R.H. WRIGHT

PART 2: ILLUSTRATIONS

BRILL

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Front cover: Representation by the French encyclopedists of a classical dikōlos (two legger) crane powered via a massive capstan. This is of interest as it evidences the correct understanding that a crane used in fine stone masonry construction must afford some measure of delicate motion.

Back cover: Sketch of early round house ca 8,000 BC at Mureybit, North Syria, according to excavator's reconstruction. This indicates the surprising extent of building 'know how' at the earliest stage of solid load bearing construction—timber (space) framing, mud brick walls, plastic mud roofing tegument.

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LIST OF ILLUSTRATIONS

ABBREVIATIONS IN CAPTIONS

A A A E	W.S. Smith, *The Art and Architecture of Ancient Egypt*, Harmondsworth, 1958.
A A A O	H. Frankfort, *The Art and Architecture of the Ancient Orient*, Harmondsworth, 1958.
A B A D Y	*Archäologische Berichte aus dem Yemen.*
A B C	G.R.H. Wright, *Ancient Building in Cyprus*, Leiden, 1992.
A B S P	G.R.H. Wright, *Ancient Building in South Syria and Palestine*, Leiden, 1985.
Adam	J.-P. Adam, *La Construction Romaine*, Paris, 1989.
A f O	*Archiv für Orientforschung.*
A J A	*American Journal of Archaeology.*
A M I	*Archäologische Mitteilungen aus Iran.*
Archéologia	*Archéologia.*
A S A E	*Annales du Service des Antiquités de l'Egypte.*
A St	*Anatolian Studies.*
Andrae	W. Andrae, *Die Partherstadt Assur*, (WVDOG 57) Berlin, 1933.
Arnold	D. Arnold, *Building in Egypt*, Oxford, 1991.
Aurenche	O. Aurenche, *La Maison Orientale*, Paris, 1981.
Baalbek II	T. Wiegand *et al., Baalbek II*, Berlin, 1923.
Bailey	D.M. Bailey, "Honorific columns, cranes…," in D.M. Bailey, ed. *Archaeological Research in Roman Egypt*, Ann Arbor, 1996, pp. 155–68.
Barsanti	*Les Temples Immergés*, G. Maspero, *Les Temples Immergés*, Cairo, 1911, pp. 45–83.
B C H	*Bulletin de Correspondence Hellenique.*
B d A	A. Hoffman *et al.* ed., *Bautechnik der Antike*, Mainz, 1991.
Bedawy	A. Bedawy, "Vaults and Domes in the Gizeh Necropolis", in Abu Bakar, *Excavations at Gizeh*, Cairo, 1953.
Beehive House	G.R.H. Wright, "The Antiquity of the Beehive House," *Thetis* 4, 1997, pp. 7–28.
Bessac tournage	"Le Tournage Antique," in M. Feugere *et al., Le Tournage des origines à l'An Mil*, (Colloque dl Niederbronn, 2003) Montagnac, 2004.

Bessac Petra	J.-C. Bessac, *Le Travail de la Pierre à Petra*, Paris, 2005.
Blagg	T.F.C. Blagg, "Tools and Techniques of the Roman Stone mason in Britain," *Brittania* VII, 1976, pp. 152–72.
Brier	Bob Brier, "How to Build a Pyramid," *Archaeology*, 2007, pp. 23–28.
Brown P.	P. Brown, *Indian Architecture*, Bombay, 1965.
Butler	H.C. Butler, *Early Churches in Syria*, Princeton, 1929.
Choisy	A. Choisy, *L'Art de Bâtir chez les Romains*, Paris, 1873.
Christian Monuments of Cyrenaica	J.B. Ward Perkins & R.G. Goodchild, *Christian Monuments of Cyrenaica*, London, 2003.
Clarke & Engelbach	S. Clarke & R. Engelbach, *Ancient Egyptian Masonry*, Oxford, 1930.
Crema	L. Crema, *L'Architettura Romana*, Turin, 1959.
Danebury	F. Cunliffe, *Danebury*, London, 1993.
Davey	N. Davey, *A History of Building Materials*, London, 1961.
Dessin d'Architecture	J.F. Bommelaer *et al.*, *Le Dessin d'Architecture dans les Sociétés Antiques*, Leiden, 1985.
Dikaios	P. Dikaios, *Khirokitia*, Oxford, 1953.
Dodson	A. Dodson, *Egyptian Rock Cut Tombs*, Princes Risborough, 1991.
Dufay	B. Dufay, "Du monument tel qu'il est au monument idéal: basiliques paléochretiennes," in *Dessin d'Architecture*, pp. 309–24.
Durm B d G	J. Durm, *Die Baukunst der Griechen*, Darmstadt, 1892.
Durm B d R	J. Durm, *Die Baukunst der Etrusker, Die Baukunst der Römer*, Stuttgart, 1904.
East and West	*East and West.*
Frankfort	H. Frankfort, *The Art and Architecture of the Ancient Orient.* Harmondsworth, 1958.
Gibson	A.M. Gibson, *Stonehenge and Timber Circles*, Stroud, 2005.
Ginouvès	R. Ginouvès, *Dictionnaire Méthodique de l'Architecture Grecque et Romaine I, II, III*, Paris, 1985–98.

Golvin ASAE 68	J.-C. Golvin *et al.*, “L’Edification des Murs de Grès en Grande Appareil à l’Epoque Romaine,” *ASAE* 68, 1982, pp. 162–85.
Golvin ASAE 70	J.-C. Golvin *et al.*, “L’Edification des Murs de Grès en Grande Appareil à l’Epoque Ptolemaique,” *ASAE* 70, 1984–1985, pp. 371–81.
Hasselberger	L. Hasselberger, “Architectural Likeness.... in Classical Antiquity,” *Journal of Roman Archaeology* 10, 1997, pp. 79–94.
Heinrich	E. Heinrich, *Tempel und Heiligtümer im Alten Mesopotamien*, Berlin, 1982.
Heisel	J.P. Heisel, *Antike Bauzeichnungen*, Darmstadt, 1993.
Hellmann	M.-C. Hellmann, *Choix d’Inscriptions Architecturales Grecques*, Lyon, 1999.
Hesperia	*Hesperia*.
Hölbl	G. Hölbl, *Altägypten im Römischen Reich I–III*, Mainz, 2000–2005.
Hodges	P. Hodges, *How the Pyramids were Built*, London, 1989.
Huff	D. Huff, “Fertigteile im Iranischen Gewölbebau,” *AMI* 22, 1990, pp. 145–60.
Isler	M. Isler, “An Ancient Method of Finding and Extending Direction,” *JARCE* XXVI, 1989, pp. 191–206.
Jakovides	S. Jakovides, “Mycenaean Roofs. Form and Construction,” in P. Darcque & R. Treviz ed. *L’Habitat Egéen Préhistorique (BCH supp XIX)*, Paris, 1998.
Jequier	G. Jequier, *Manuel d’Archéologie Egyptienne. Les Eléments et l’Architecture*, Paris, 1924.
Jericho	K. Kenyon, *Jericho III*, London, 1981.
Kalabsha 1	K.G. Siegler, *Kalabsha Architektur und Baugeschichte des Tempels*, Berlin, 1970.
Kalabsha 2	G.R.H. Wright, Kalabsha *The Preserving of the Temple*, Berlin, 1972.
Kalabsha 3	G.R.H. Wright, *Kalabsha III The Ptolemaic Sanctuary*, Mainz, 1987.
Knossos	Sir A. Evans, *The Palace of Minos I*, London, 1921.
Kraeling Ptolemais	C.H. Kraeling, *Ptolemais City of the Libyan Pentapolis*, Chicago, 1962.
Krautheimer	R. Krautheimer, *Early Christian and Byzantine Architecture*, London, 1986.
Krefter	v Trumpelmann.
Lancaster	L.C. Lancaster, *Concrete Vaulted Construction in Imperial Rome*, Cambridge, 2005.
Lauer	J.-P. Lauer, *Saqqarah*, Paris, 1977.

Lawrence	A.W. Lawrence, *Greek Architecture*, Harmondsworth, 1957, 1973.
Lehner	M. Lehner, "Some Observations on the Layout of the Khufu and Khafre Pyramids," *JARCE XX* 1983, pp. 7–32.
Lloyd	S. Lloyd v Seton Lloyd.
Maquettes Architecturales	B. Muller ed, *Maquettes Architecturales de l'Antiquité*, (Colloque de Strasbourg 1998), Paris, 2001.
Mango	C. Mango, *Byzantine Architecture*, London, 1986.
Martin	R. Martin, *Manuel d'Architecture Grecque*, Paris, 1965.
Megalith Builders	G. Daniel, *The Megalith Builders of Western Europe*, London, 1959.
Naumann	R. Naumann, *Architektur Kleinasiens*, Tubingen, 1971.
Nel	F. Nel, *Dolmens et Menhirs*, Paris, 1950.
Oakley	K.P. Oakley, *Man the Toolmaker*, London, 1961.
Op Ath	*Opuscula Atheniensia.*
Orlandos	A.K. Orlandos, *Les Matériaux de Construction et la Technique Architecturale des Anciens Grecs I & II*, Paris, 1966–68.
P B S R	*Papers of the British School Rome.*
Plommer	H. Plommer, *Ancient and Classical Architecture*, London, 1956.
Pope	A.U. Pope ed, *A Survey of Persian Art*, London, 1938.
Pope Persian Architecture	A.U. Pope, *Persian Architecture*, New York, 1965.
Rakob	F. Rakob, *Römische Kuppelbauten in Baiae*, RM 95, 1988, pp. 259–301.
Ragette	F. Ragette, *Baalbek*, Park Ridge NJ, 1980.
Rasch	J.J. Rasch, *Zur Konstruktion Spätantiker Kuppel vom 3. bis 6. Jahrhundert*, J d I 106 1991, pp. 311–83.
Rea	R. Rea, *Anfiteatro Flavio*, Rome, 1988, fig 7.
Robertson	D.S. Robertson, *Greek and Roman Architecture*, Cambridge, 1954.
Sauvage	M. Sauvage, *La Brique et sa mise en œuvre en Mesopotamie*, Paris, 1998.
Seton Lloyd	Seton Lloyd, *Beyce Sultan I, II, III*, London, 1962–72.
Shaw	J.W. Shaw, "A Double Sheaved Pulley Block from Kenchreai," *Hesperia* 36, 1967, pp. 389–401.
Shechem III	G.R.H. Wright, *Shechem III.2*, Boston, 2007.
Siegler	v *Kalabsha I.*
Singer	C. Singer *et al.* ed, *A History of Technology I & II*, Oxford, 1954–56.

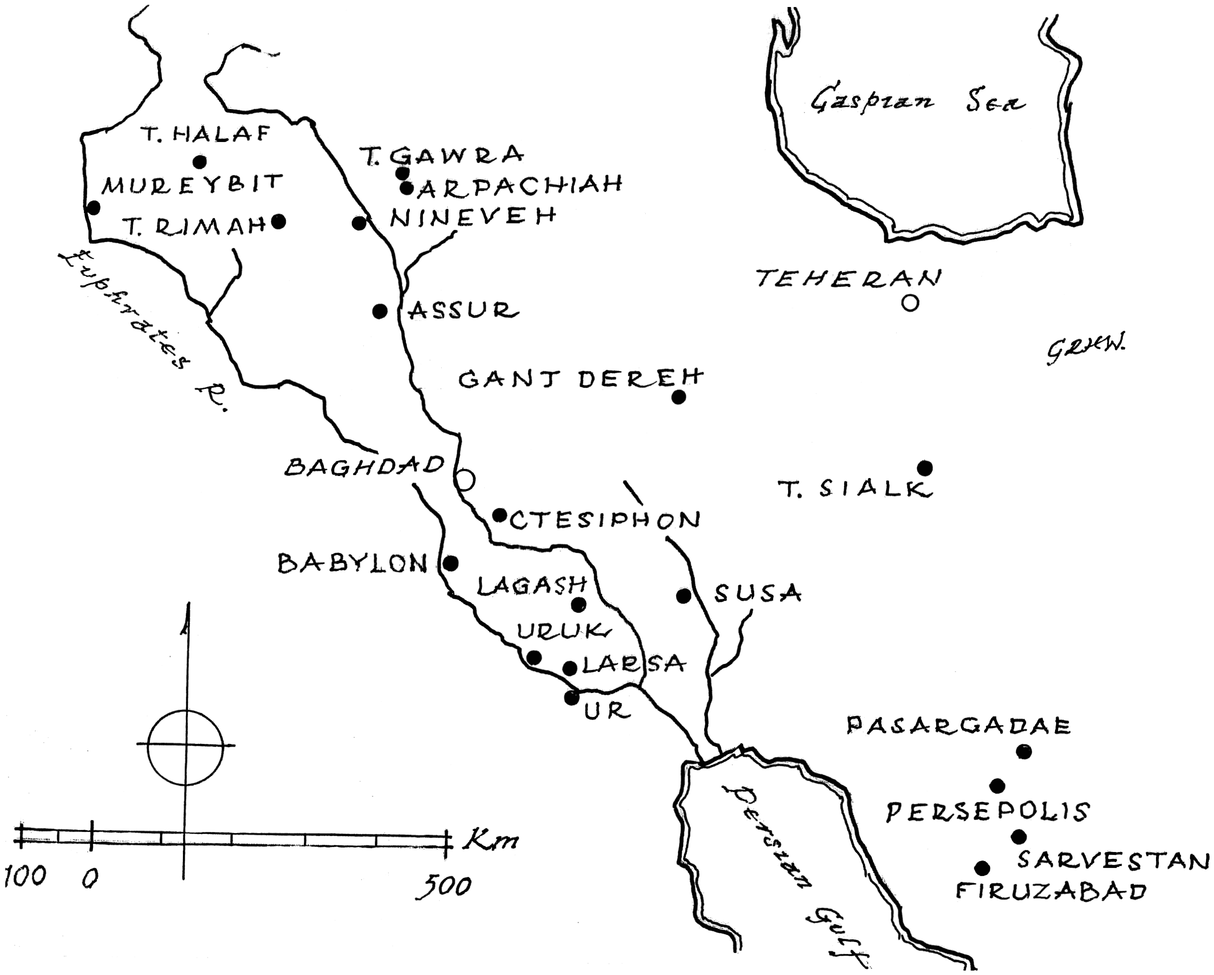
Souden	D. Souden, *Stonehenge*, London, 1997.
Spencer	A.D. Spencer, *Brick Architecture in Egypt*, Warminster, 1979.
Stadelmann	R. Stadelmann, *Die ägyptischen Pyramiden*, Mainz, 1985.
Taylor	R. Taylor, *Roman Builders*, Cambridge, 2003.
Thesiger	W. Thesiger, *The Marsh Arabs*, London, 1976.
Trumpelmann	L. Trumpelmann, *Persepolis*, (with Krefter's drawings), Mainz, 1988.
Tuleilat el Ghassoul	A. Mallon, R. Koeppl, *Tuleilat Ghassoul 1*, Rome, 1940.
Vandier	E. Vandier, *Manuel d'Architecture Egyptienne II Architecture*, Paris, 1954.
Viollet le Duc	Viollet le Duc, *Dictionnaire Raisonné*, Paris, 1868.
W A	*World Archaeology.*
Wilson Jones	M. Wilson Jones, "Principles of Design in Roman Architecture: The Setting out of Centralised Buildings," *PBSR* 57, 1989, pp. 100–51.
Ward Perkins	A. Boethius & J.B. Ward Perkins, *Etruscan and Roman Architecture*, Harmondsworth, 1970.
Warland	E.G. Warland, *Modern Practical Masonry*, London, 1953.
Wesenberg	B. Wesenburg, Zur Entstehung des Griechischen Keilsteingewölbes, *B d A*, pp. 252–58.
Z A	*Zeitschrift für Assyriologie.*

INTRODUCTION

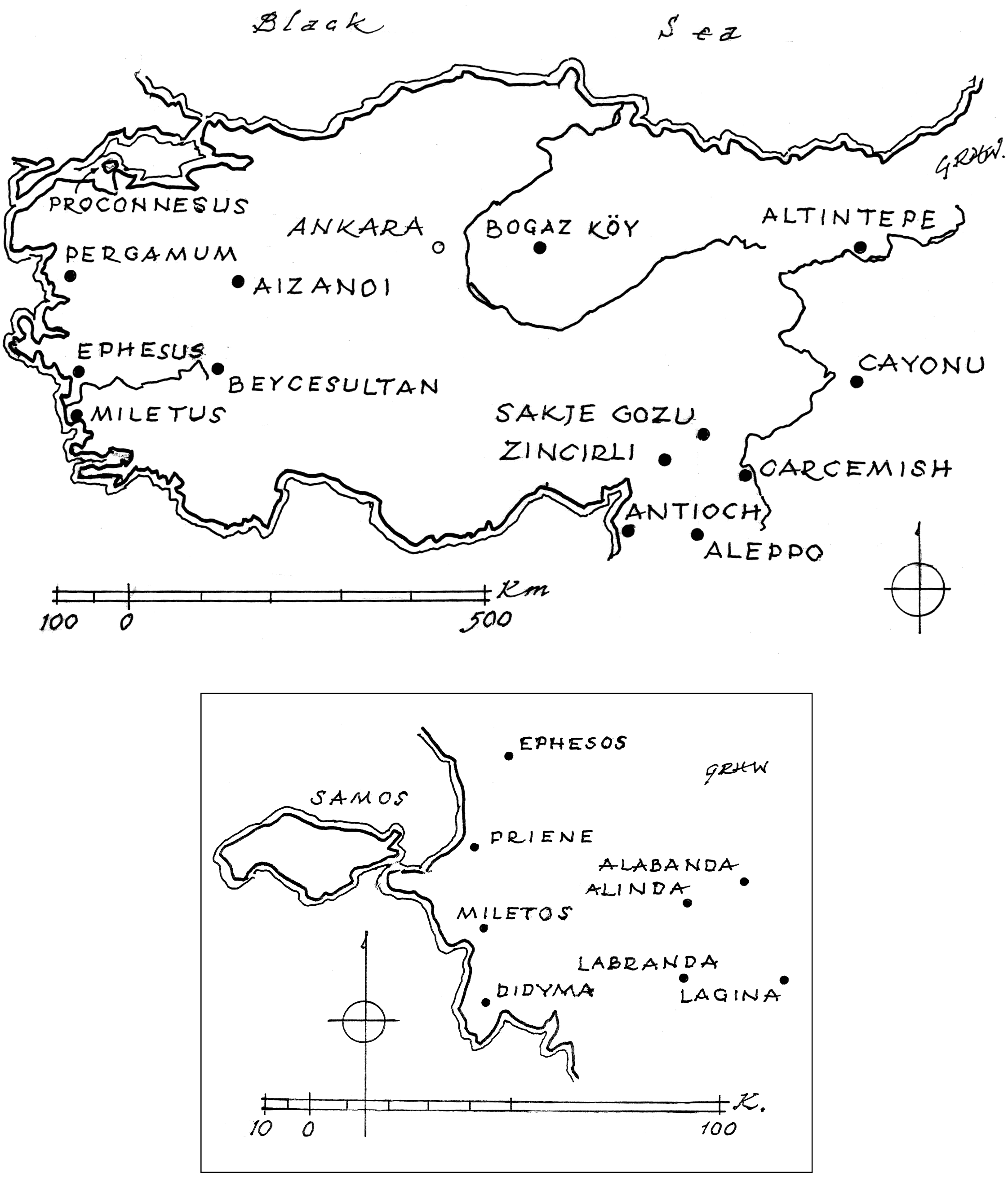
The illustrations have been conceived as of equal weight with the text in the composition of Vols 1 and 2, but with this volume on Construction they are of special significance. Building construction is more effectively represented graphically than verbally. Indeed the traditional students text books of building construction (McKay, Mitchell, etc.) take the form of sheets of detail drawings with accompanying notes, rather than an illustrated text. It is hoped then that Part 2 of this volume may parallel in some degree such text books of traditional modern building construction.

There is no lack of effective illustrations of Ancient Building Construction, rather the difficulty is to limit the choice from those available. Here it may be said that any merit the present submission may have lies not in striking "novelties" among individual illustrations. Photographs of building construction detail are not selected for their art content; and drawings are chosen above all for their simplicity and directness of expression, not as examples of fine draughtsmanship. The virtue aimed at here resides in the selection and its ordering, so that the individual items cast light on one another to form a collective account of Ancient Building Construction, which in some way is a readier reference than the text. If this aim is achieved in any degree then the present part of Vol 3 may possess its own independent utility.

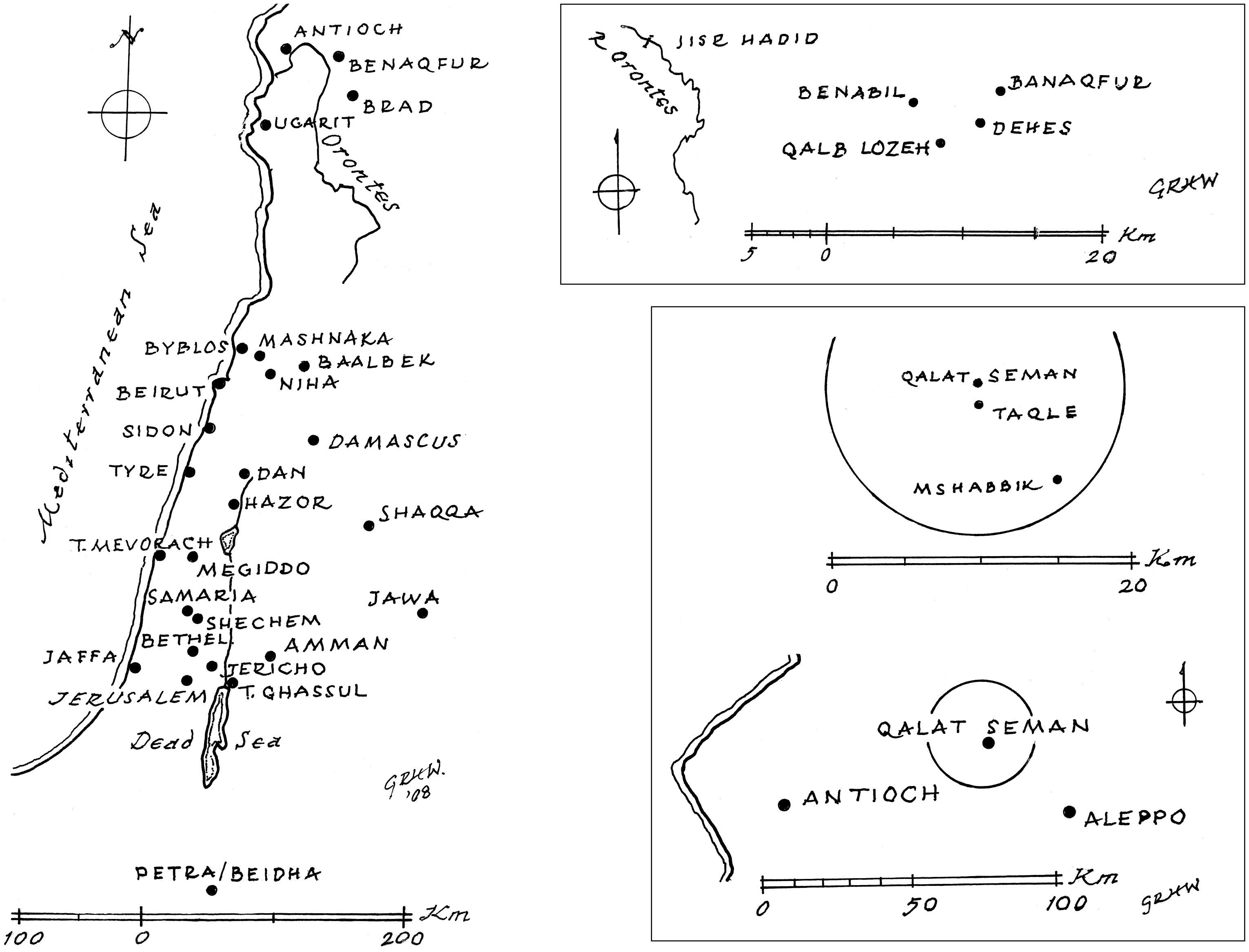
ILLUSTRATIONS



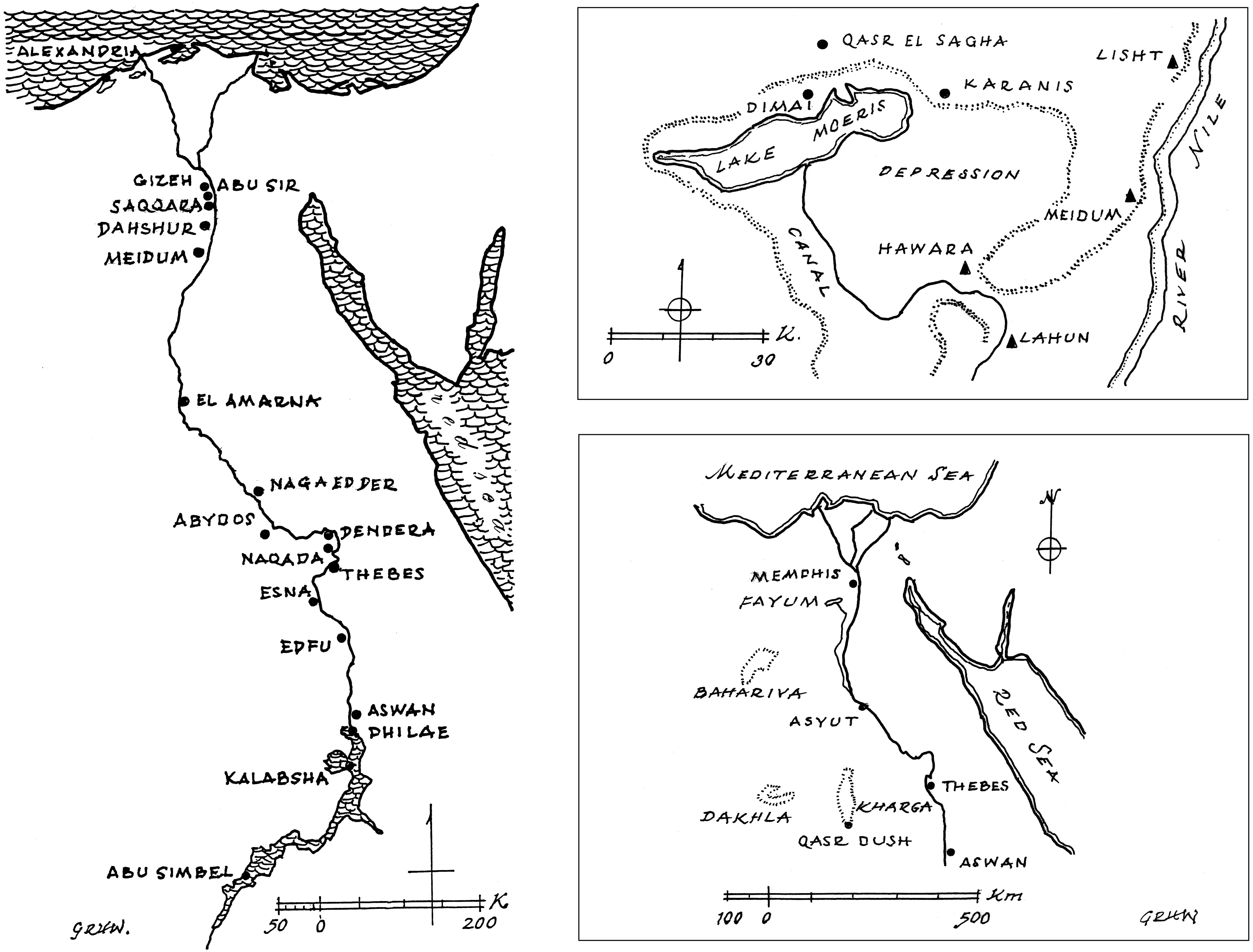
1a. Location Map of Sites and Monuments. Mesopotamia and Iran.



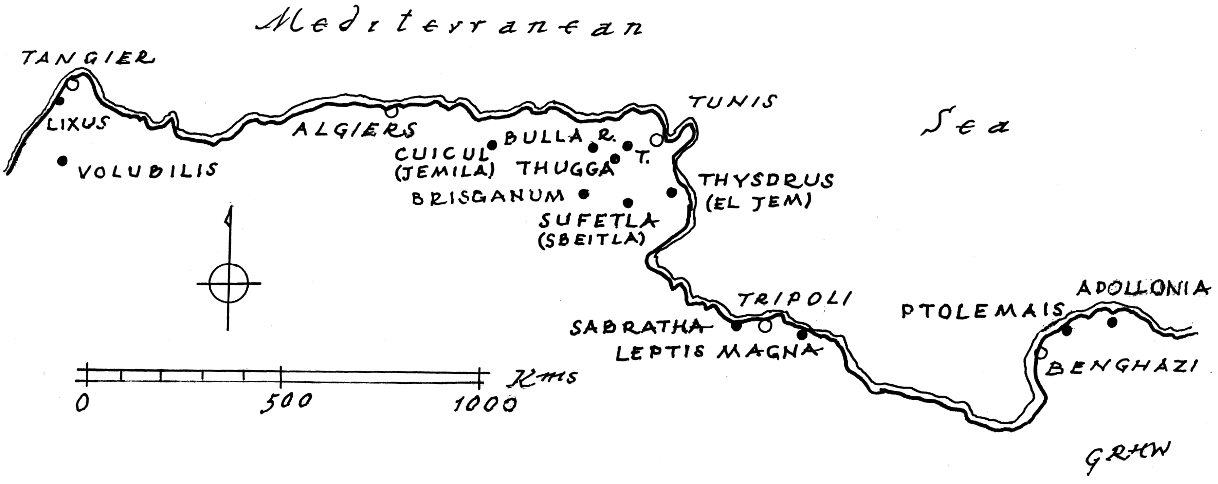
1b. Location Map of Sites and Monuments. Anatolia with inset Ionia.



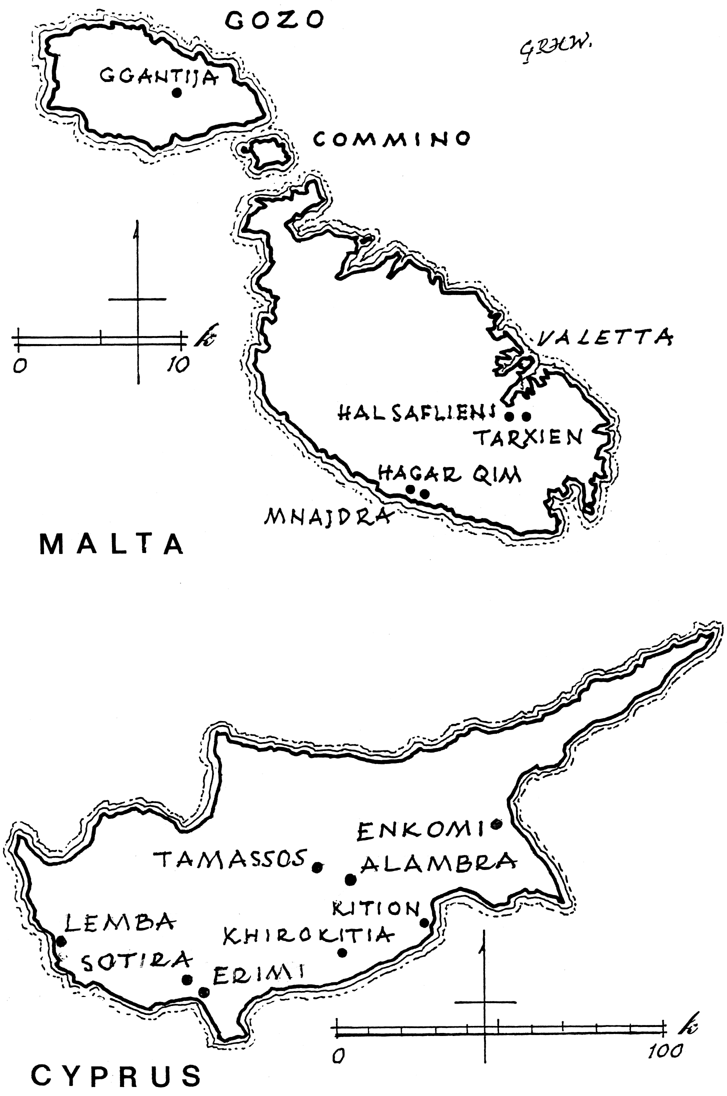
1c. Location Map of Sites and Monuments. Syria and Palestine with insets North Syria.



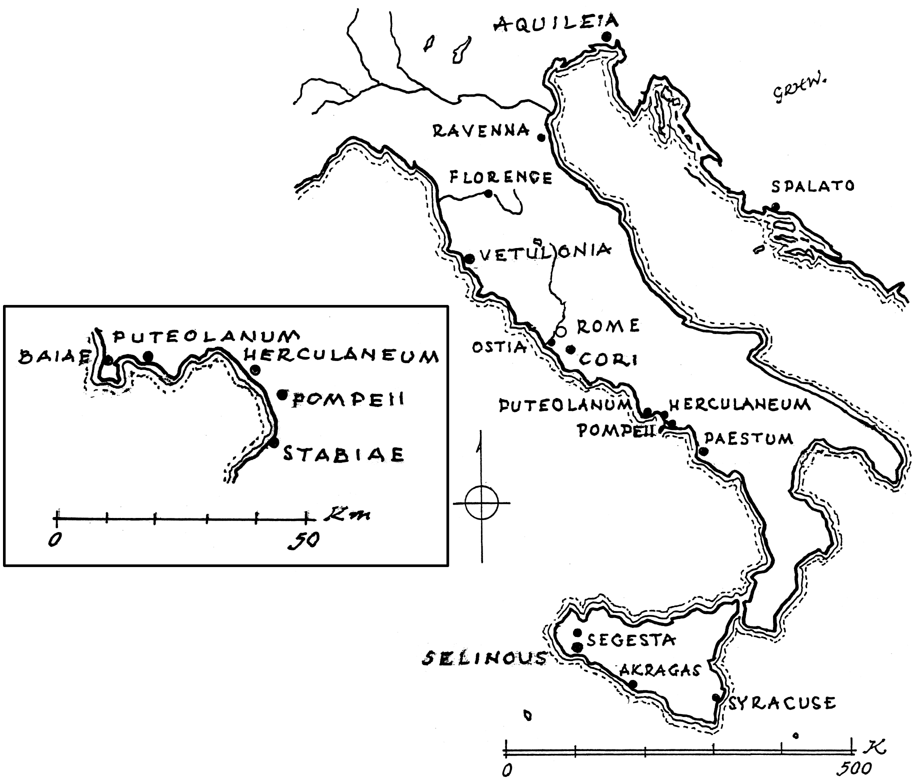
1d. Location Map of Sites and Monuments. Egypt with insets The Faiyum and Oases.



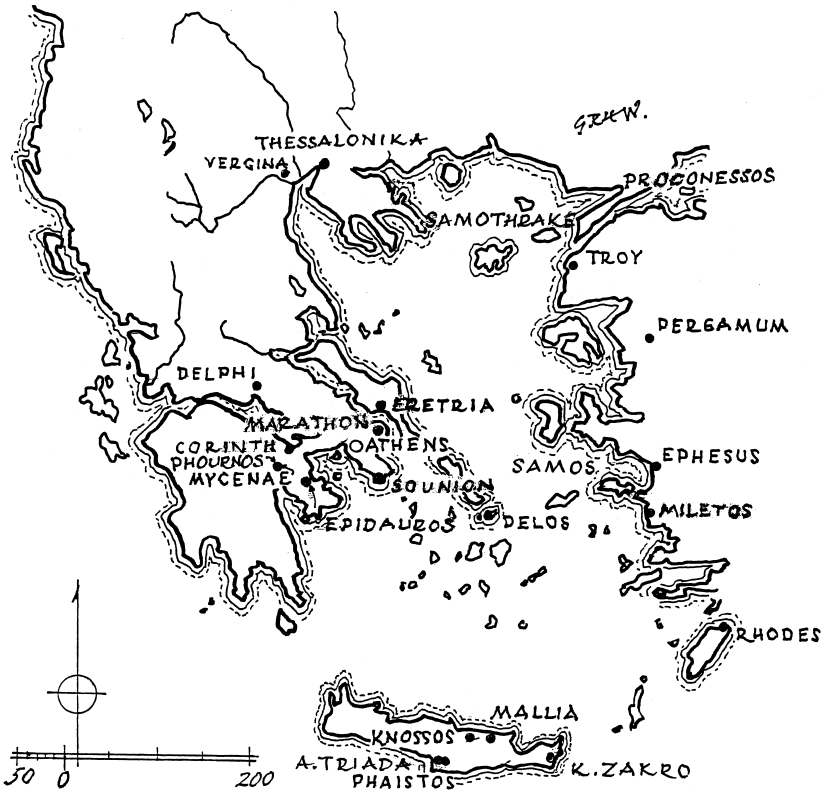
1e. Location Map of Sites and Monuments. North Africa.



1f. Location Map of Sites and Monuments. Cyprus and Malta.



1g. Location Map of Sites and Monuments. Italy with inset The Bay of Naples.



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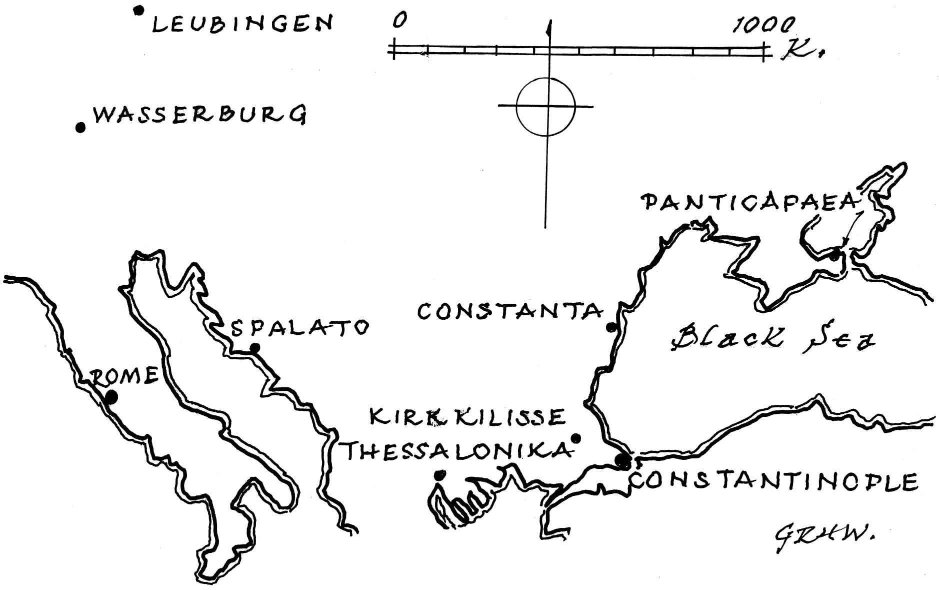
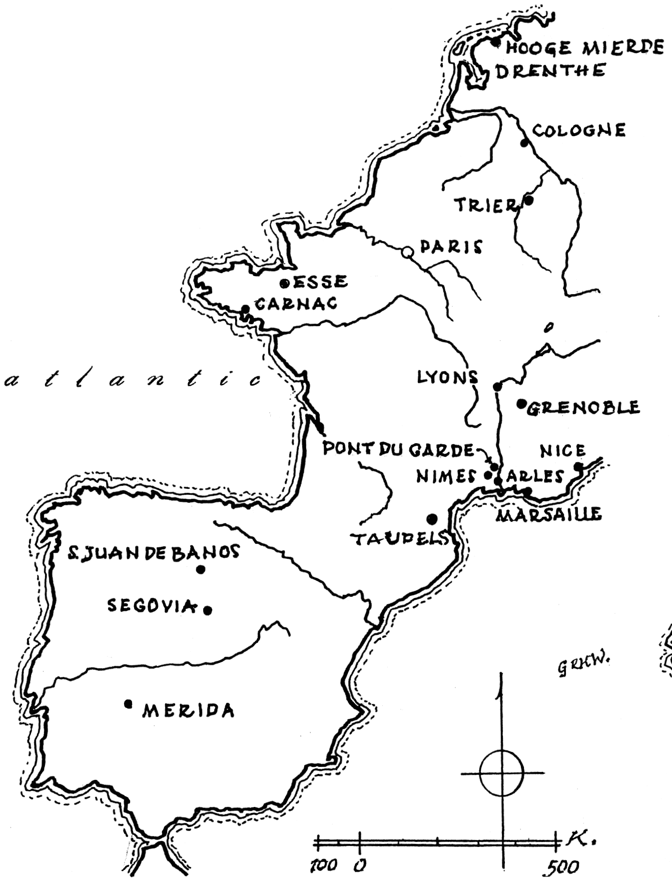
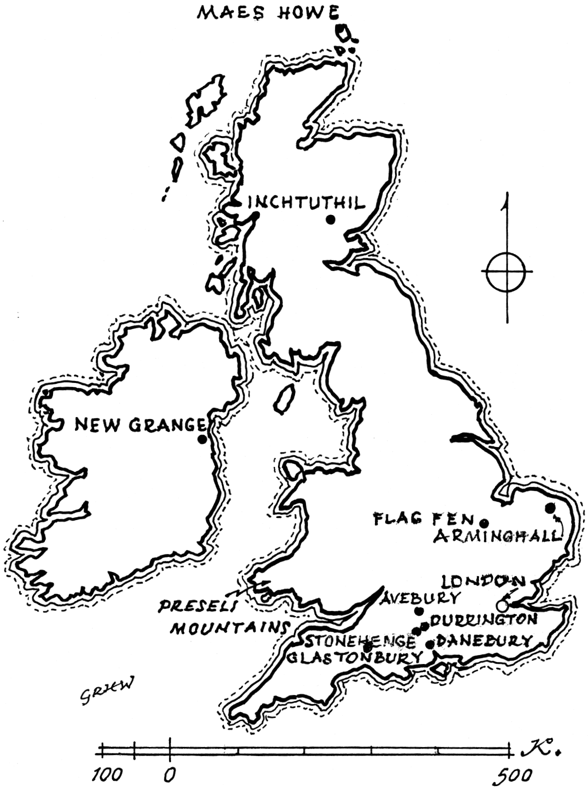


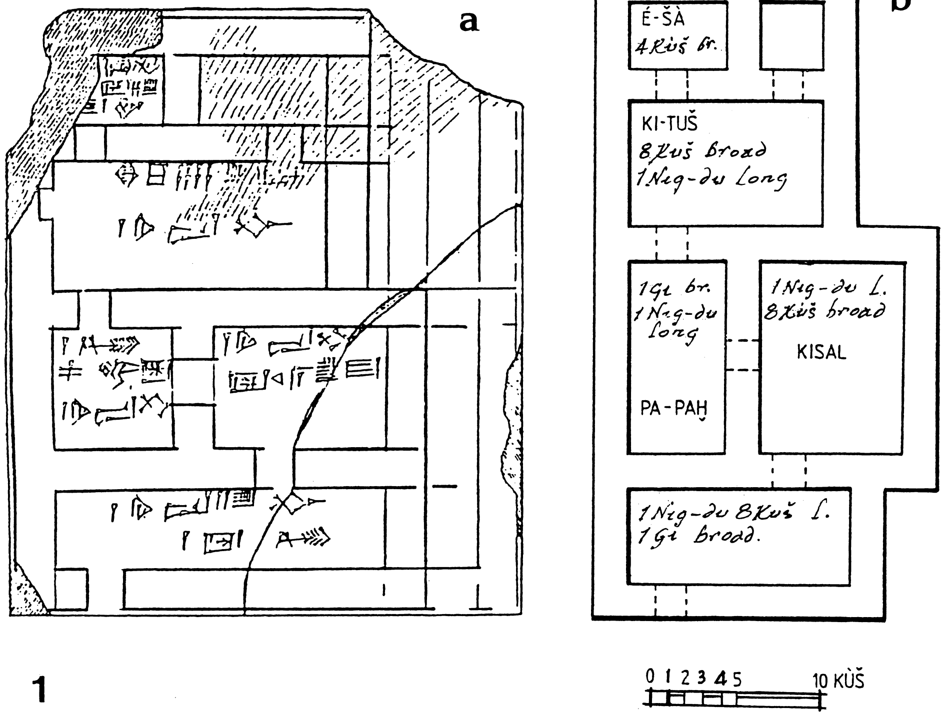
1j. Location Map of Sites and Monuments. Eastern Europe.



1k. Location Map of Sites and Monuments. Western Europe.



1l. Location Map of Sites and Monuments. The British Isles.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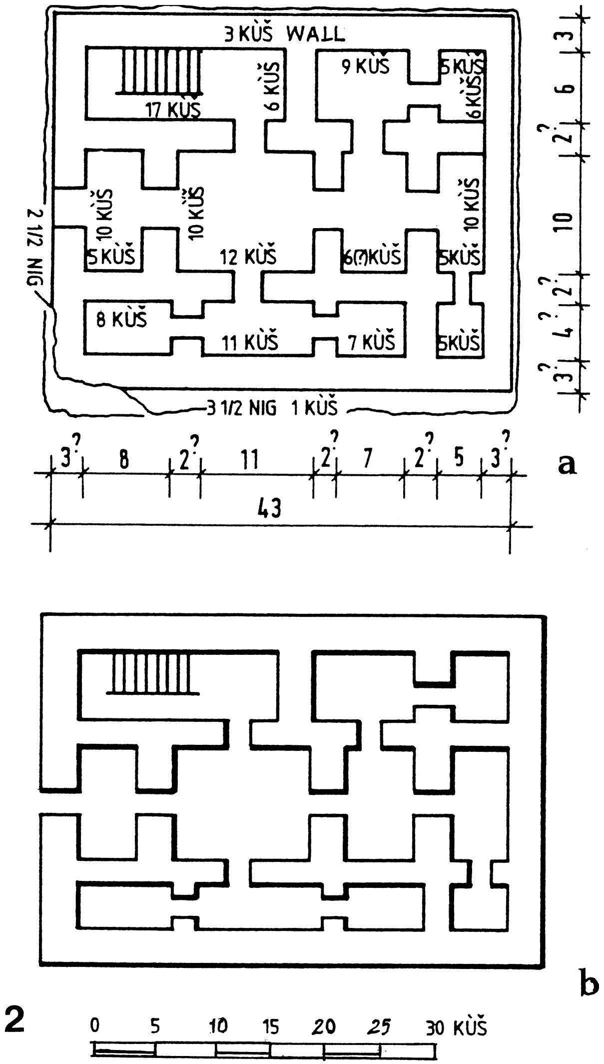
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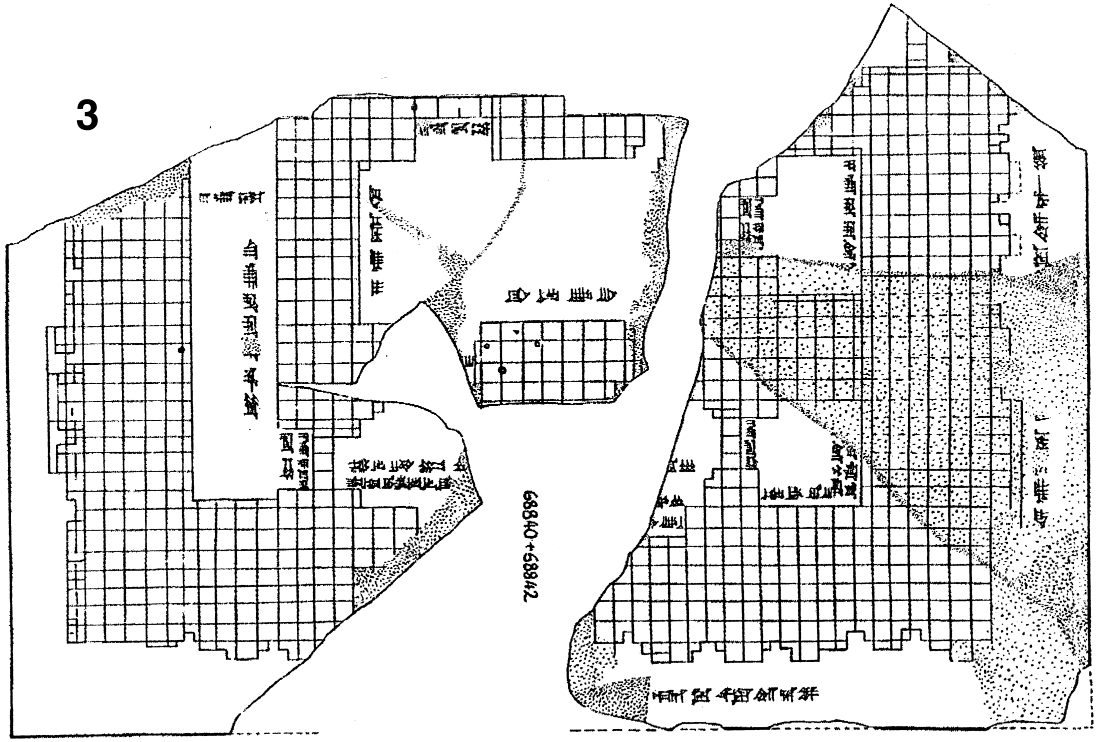

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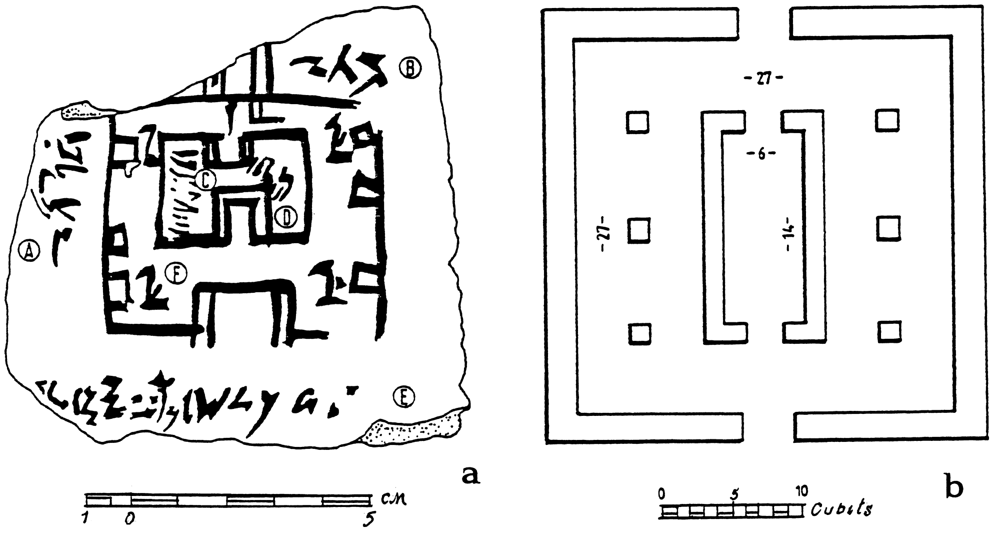
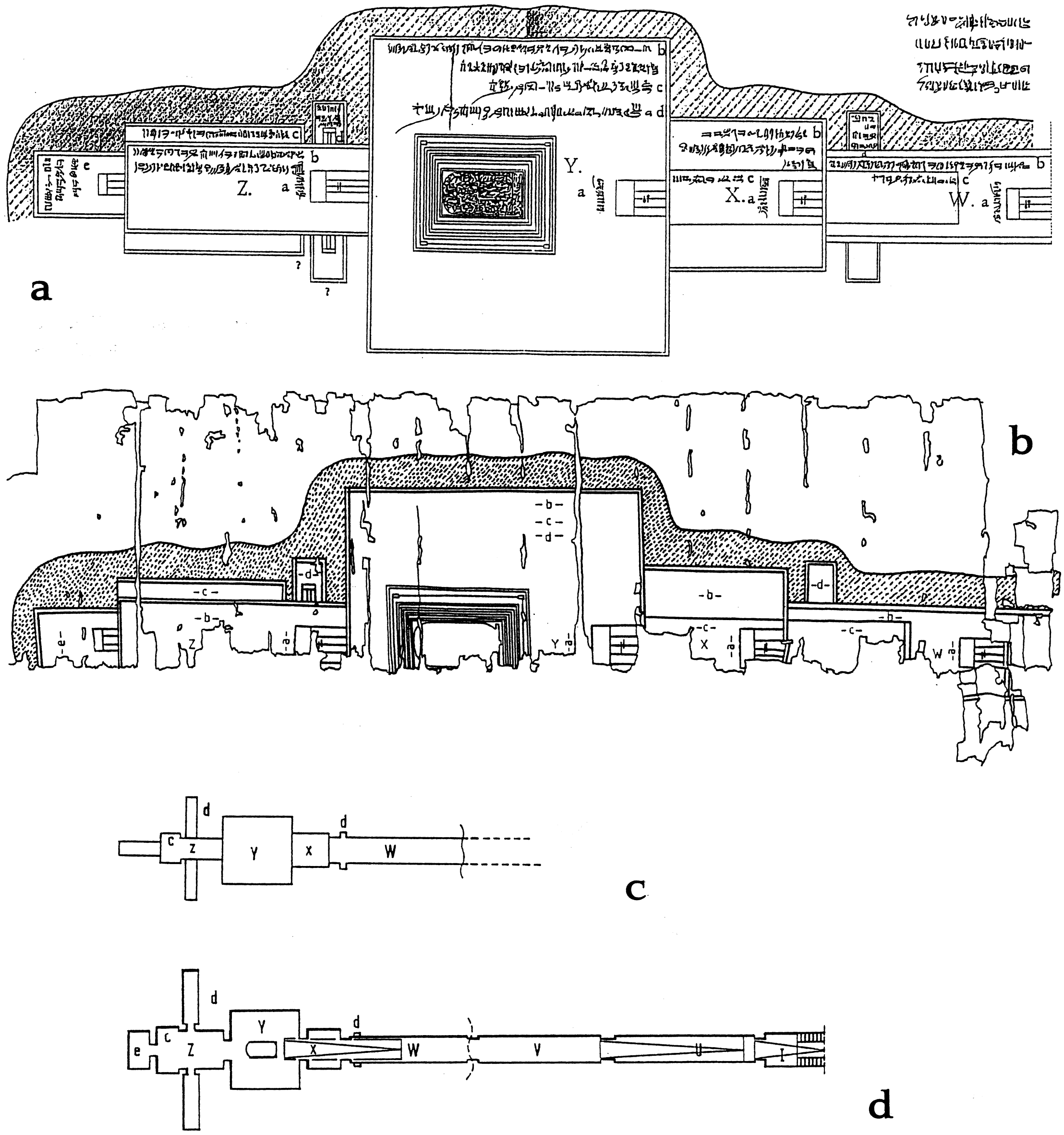
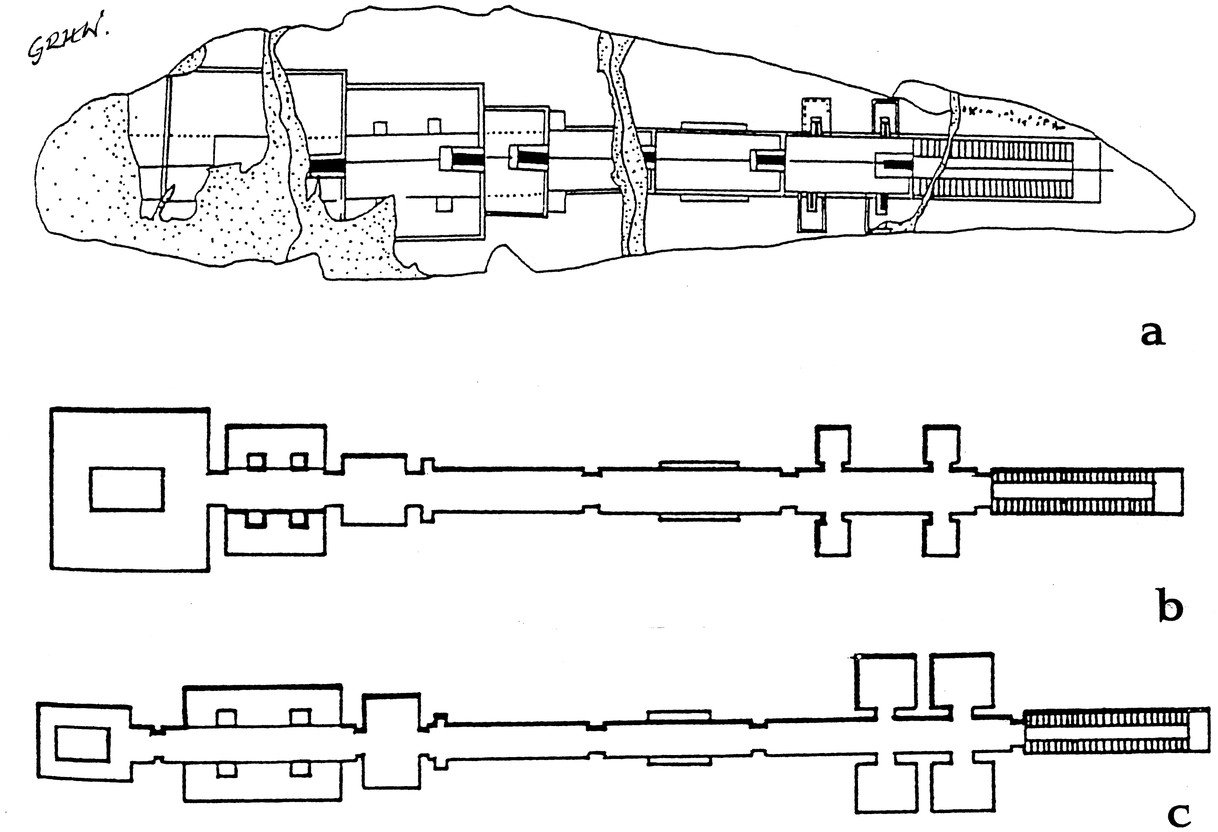
2. Mesopotamian Architectural Plans. All such plans in Mesopotamia are incised on clay tablets and generally give principle dimensions in cuneiform script. *Key*: (1) Plan of house or temple from Tello/Lagash (Akkadian). a. Incised tablet with dimensions; b. Modern drawing to scale according to the specified dimensions (with translation of the cuneiform. After Heisel p.10, fig M1; (2) Plan of Temple (?) Late Sumerian; a. Original plan with translation of cuneiform; b. Modern drawing to scale. After Heisel p.21, fig M14; (3) Dimensioned brick for brick plan of building constructed of square bricks 33.33 cms = 1 long foot. In addition there are notes concerning the special bricks reequired (half bricks, quarter bricks, L-shaped angle bricks etc and the bonding. The builder could thus set out the plan both from the overall dimensions and from the indicated assemblage of individual bricks. After Sauvage, p. 75, fig 61.



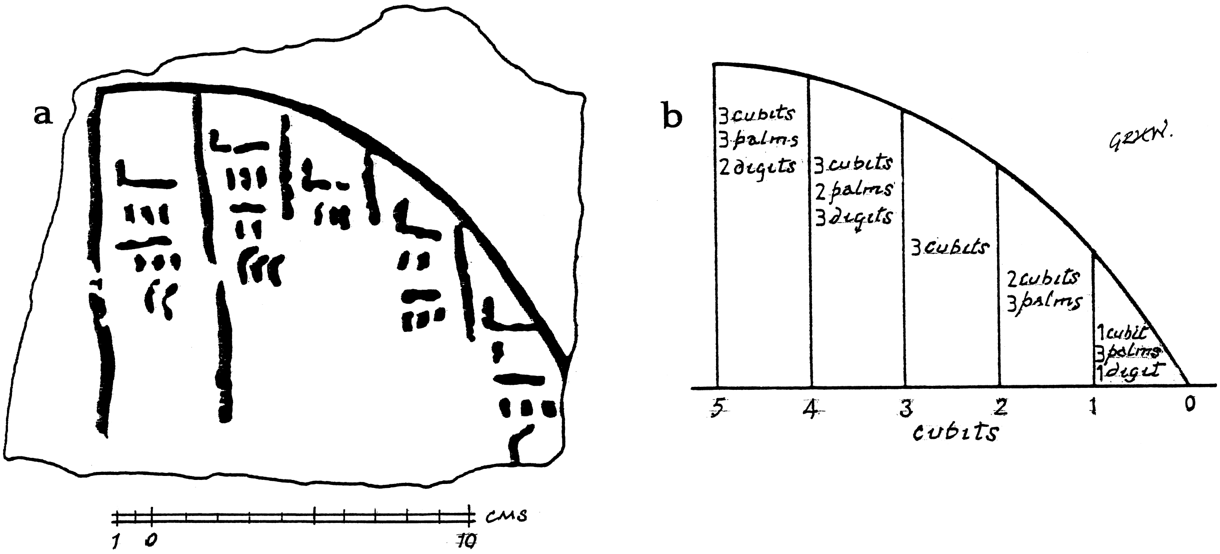
← 3. Plan of a chapel. Paint on limestone. Deir el Bahari 18th–19th Dyn. (a) Drawing of object. *Key*: A. Length 27; B. Breadth 27; C. Length 14; D. Breadth 6; E. Who stands here he rests in the west; F. Sign for "support"; (b) Reconstructed drawing of plan. After Heisel p. 92, fig 7.



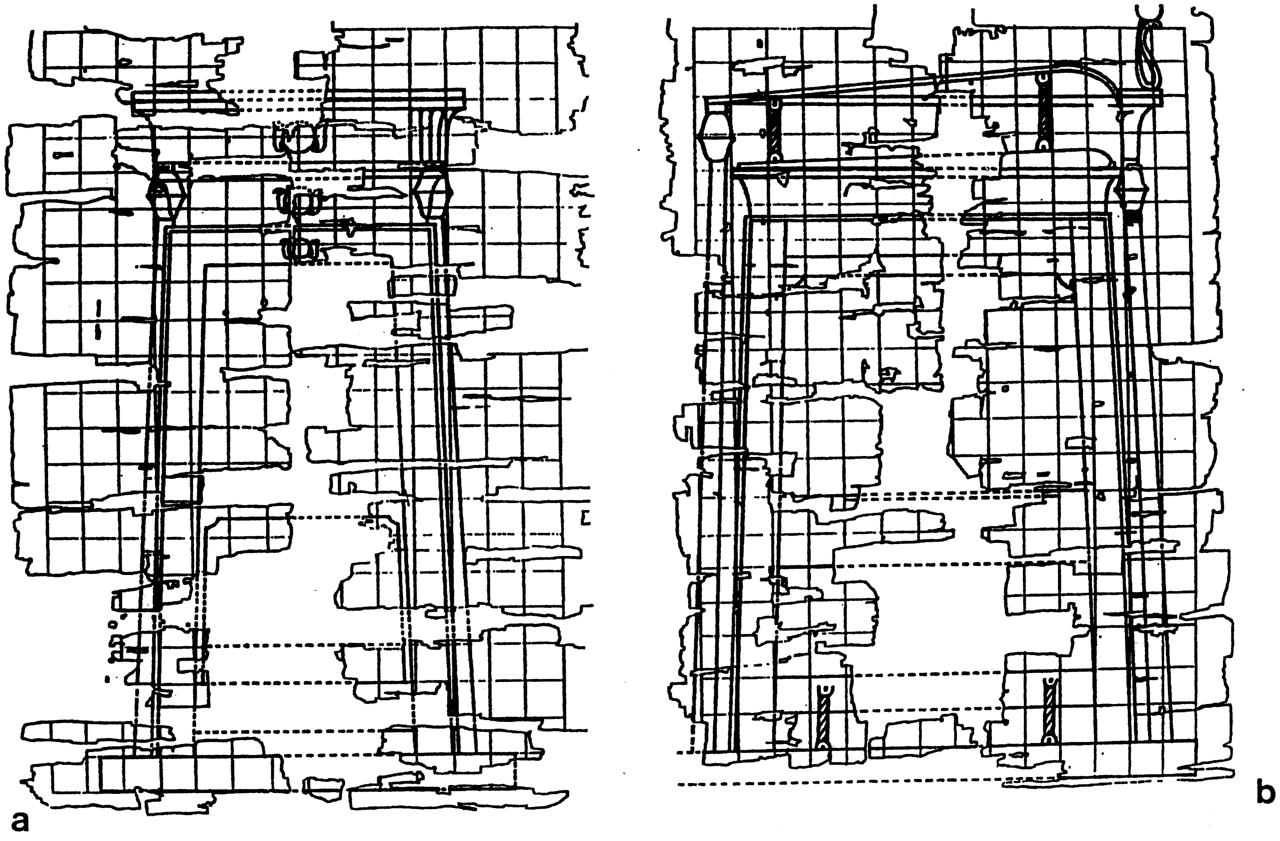
4. Plan of Tomb of Ramses IVth. Paint of several colours on papyrus. Thebes 20th Dyn. a. Reconstruction and transcription of papyrus; b. Papyrus with key. *Key*: Y: Tomb chamber; Ya: Its door is shut; Yb: The golden house wherein he rests; 16 cubits long; breadth 16 cubits; height 10 cubits; set out hewing out with a chisel, filled in with colour; prepared and furnished with the equipment of his majesty (he lives is blessed and sound) all around with the divine Ennead in the underworld; Yc: Beginning from the 1st Corridor to the Golden House in total 136 cubits, 2 palms; Yd: Beginning from the Golden House to the Treasury of the Innermost: 24 cubits and 3 palms; breadth 5 cubits; total 160 cubits and 5 palms; Z: Treasury; Za: Its door is shut; Zb: The corridor of the Shabti Place of 14 cubits and 3 palms; breadth 5 cubits; height 6 cubits, 3 palms, 2 digits. Set out, hewn out with the chisel, filled with painting and made ready. The southern aspect front exactly similar; Zc: The resting place of the Gods of 4 cubits and 4 palms long; height 1 cubit and 5 palms; depth 1 cubit, 3 palms and 2 digits; Zd: The left side treasure chamber of 10 cubits (long); breadth 3 cubits, 3 palms; Ze: The Treasury of the Innermost of 10 cubits (long); breadth 3 cubits, 3 palms; W: Corridor; Wa: Its door is shut; Wb: The 4th corridor of 25 cubits long; breadth 6 cubits; Height 9 cubits and 4 palms; set out hewn out with the chisel filled with colouring and made ready; Wc: The ramp of 20 cubits long, breadth 5 cubits, 1 palm; Wd: This chamber of 2 cubits (long); breadth 1 cubit, 2 palms; depth 1 cubit, 2 palms; X: The Ante Chamber; Xa: Its door is shut; Xb: The ante chamber of 9 cubits long; breadth 8 cubits; Height marked out, hewn out with the chisel, filled with colouring and made ready; Xc: End of the sarcophagus roof; 3 cubits. (c) Modern scale drawing according to the dimensions. (d) Survey Drawing of the actual tomb as discovered. After Heisel p. 98 fig 12.



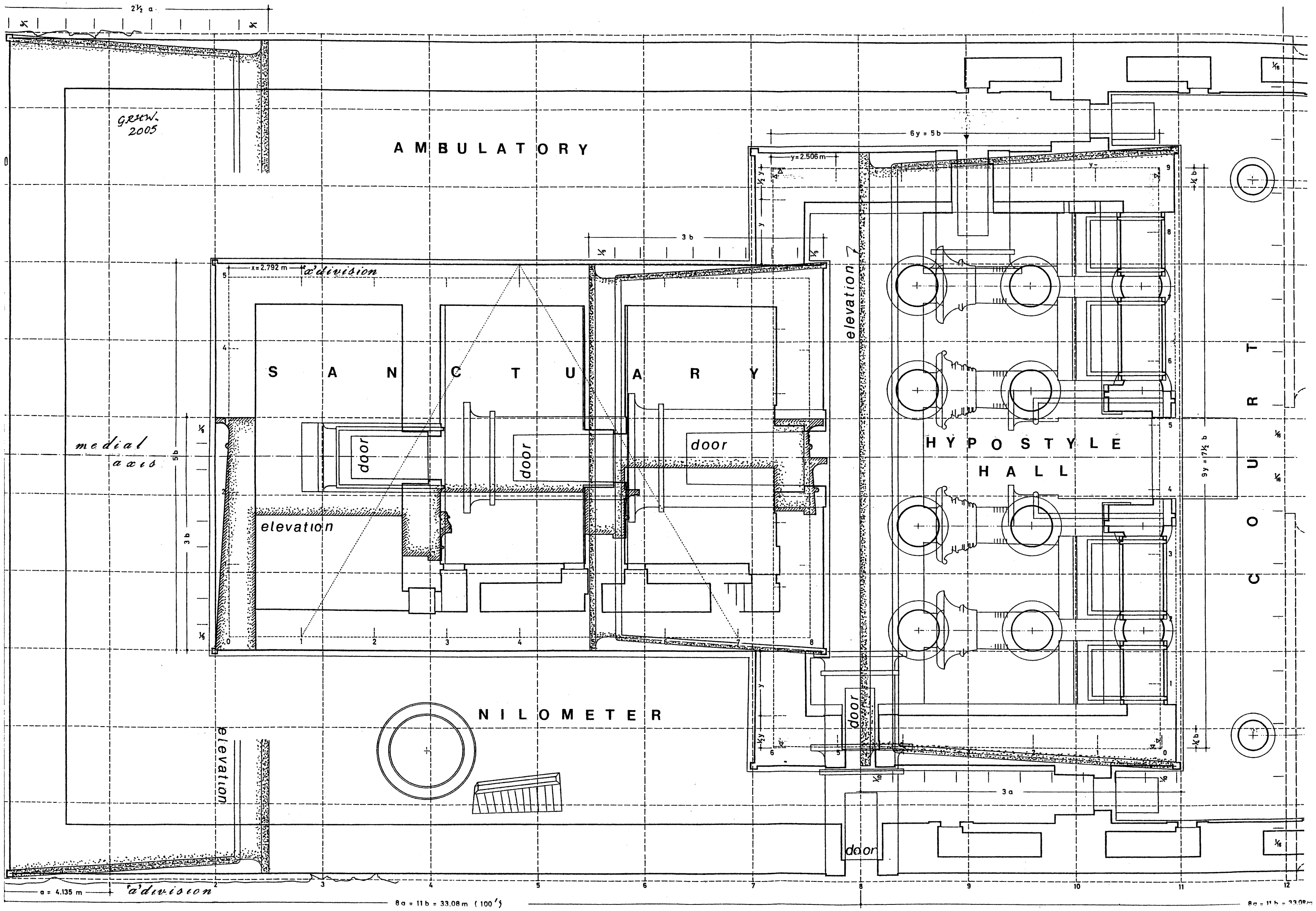
5. Plan of the Tomb of Ramses XI. Thebes 20th Dynasty. *Key*: (a) Plan on Limestone of Tomb according to Egyptian graphic convention; (b) The above original drawing redrawn according to modern graphic convention; (c) Modern Survey Plan of the tomb. After Heisel.



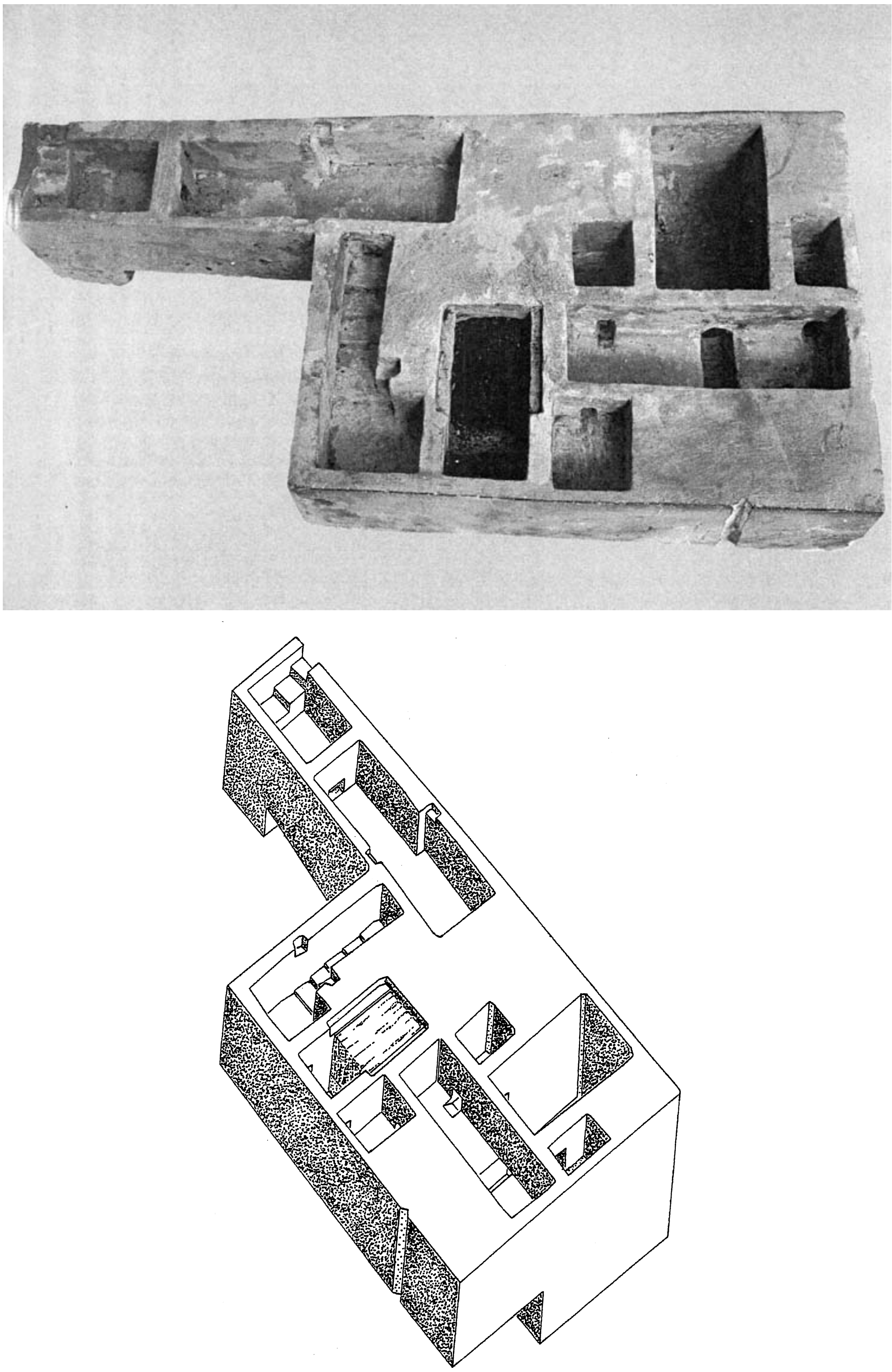
6. Working drawing for the curve of a vault. Red colouring on limestone. Sakkara 3rd Dynasty. (a) The original stone giving the dimensions for the rise at (evidently) 1 cubit horizontal intervals, i.e. the coordinates of the curve; (b) Scale drawing with translation of dimensions. After Heisel p. 130 fig A 18.



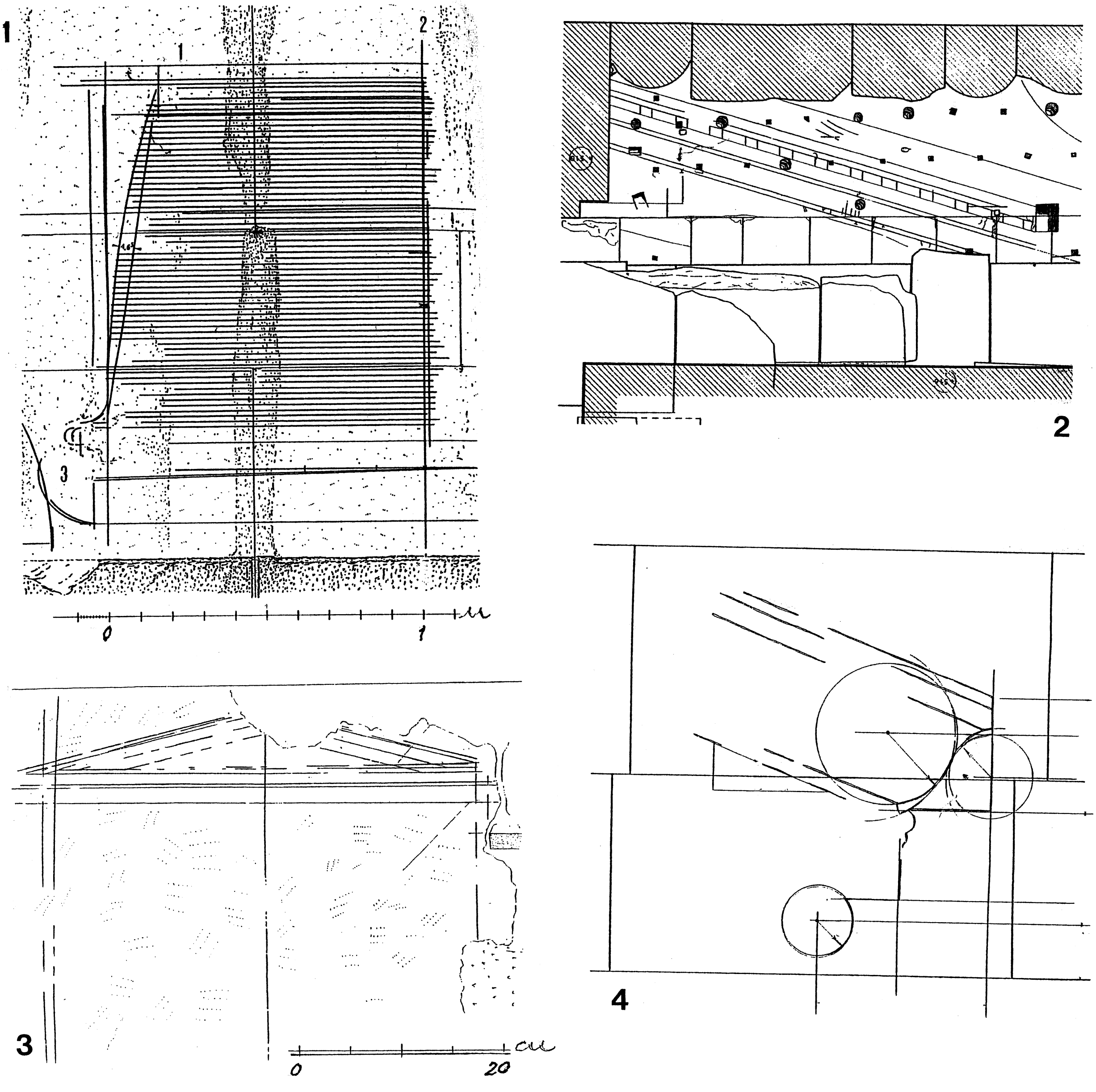
7. Front and Side Elevations of a (wooden) shrine. Red and black ink on squared papyrus. Ghorab, 18th–19th Dynasty. (a) Front elevation; (b) Side elevation. After Heisel fig A 19.



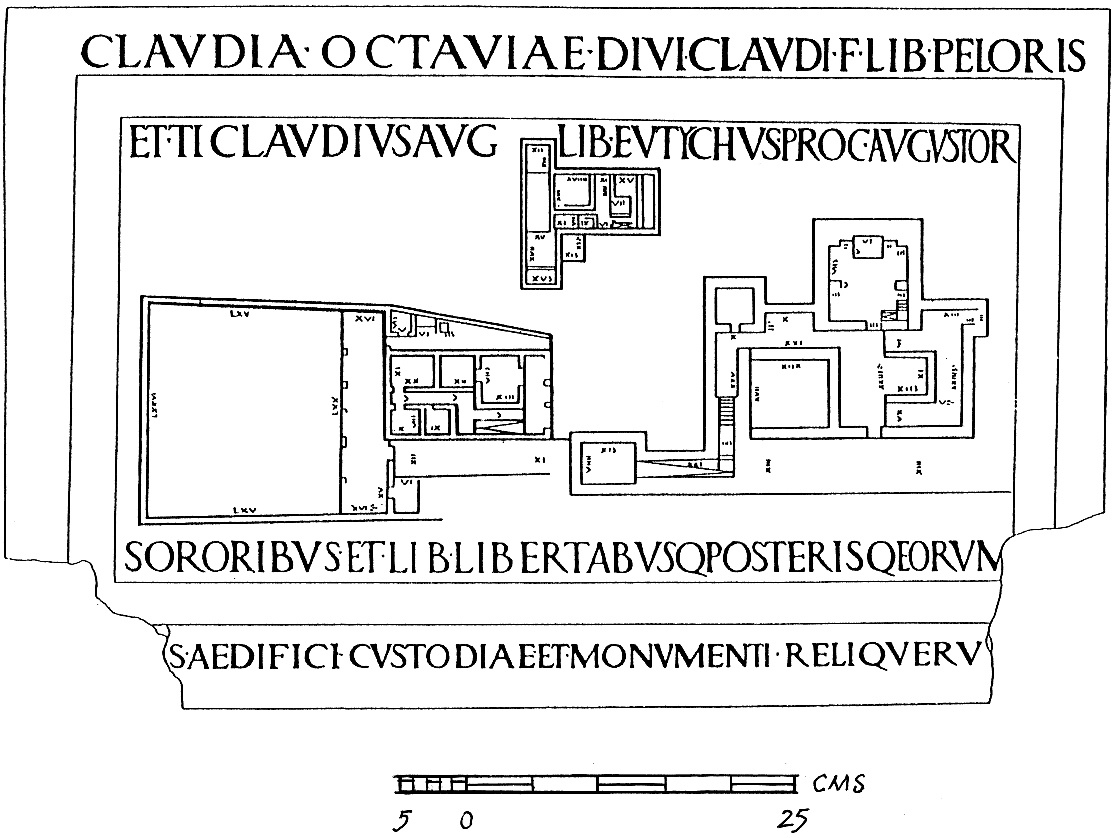
8. Modern use of Ancient Egyptian convention for architectural drawings. The Ancient Egyptian convention of erecting elevations and sections directly on the plan so that both are represented in the same drawing has striking advantages. These are demonstrated in this analytical drawing of the proportional design of Kalabsha Temple (1st Century AD). The drawing shows the grid used for constructing the proportions of the building and Egyptian style drawing immediately reveals that similar proportions governed both plan and sections (stippled).



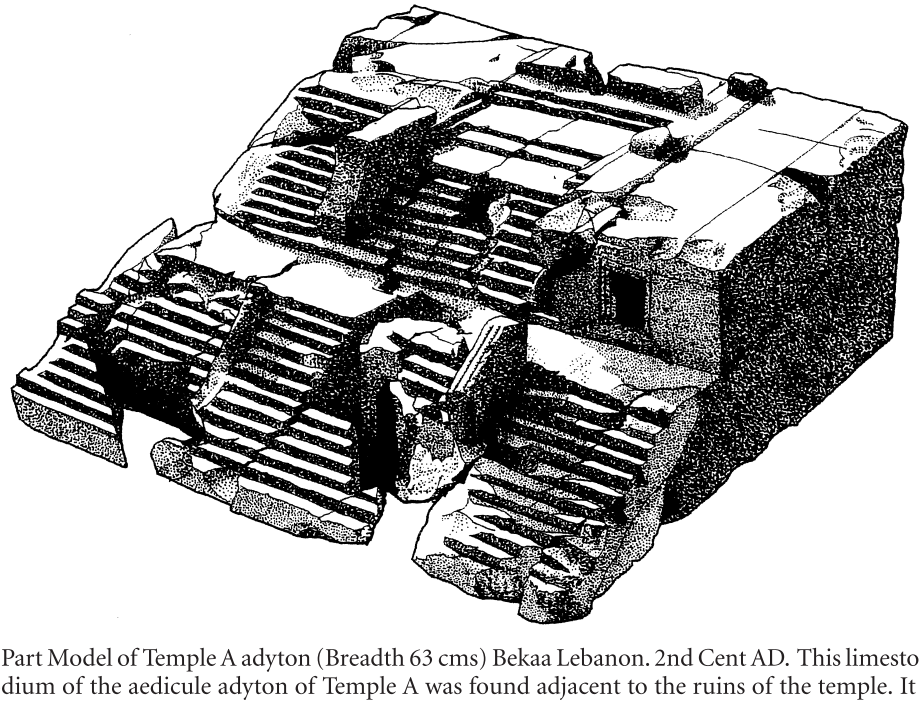
9. Drawing and photograph of stone model of funerary chambers below a pyramid. Dahshur Amenemhet III ca 1800 BC. The chambers in question appear to be those of Amenemhet's pyramid at Hawara rather than his pyramid at Dahshur where it was found. There is a good reason for the use of a model in this instance, since the existence of chambers at different levels, and the complicated circulation between them make their representation in a drawing very difficult. After Maquettes Architecturales p. 215, fig 1.



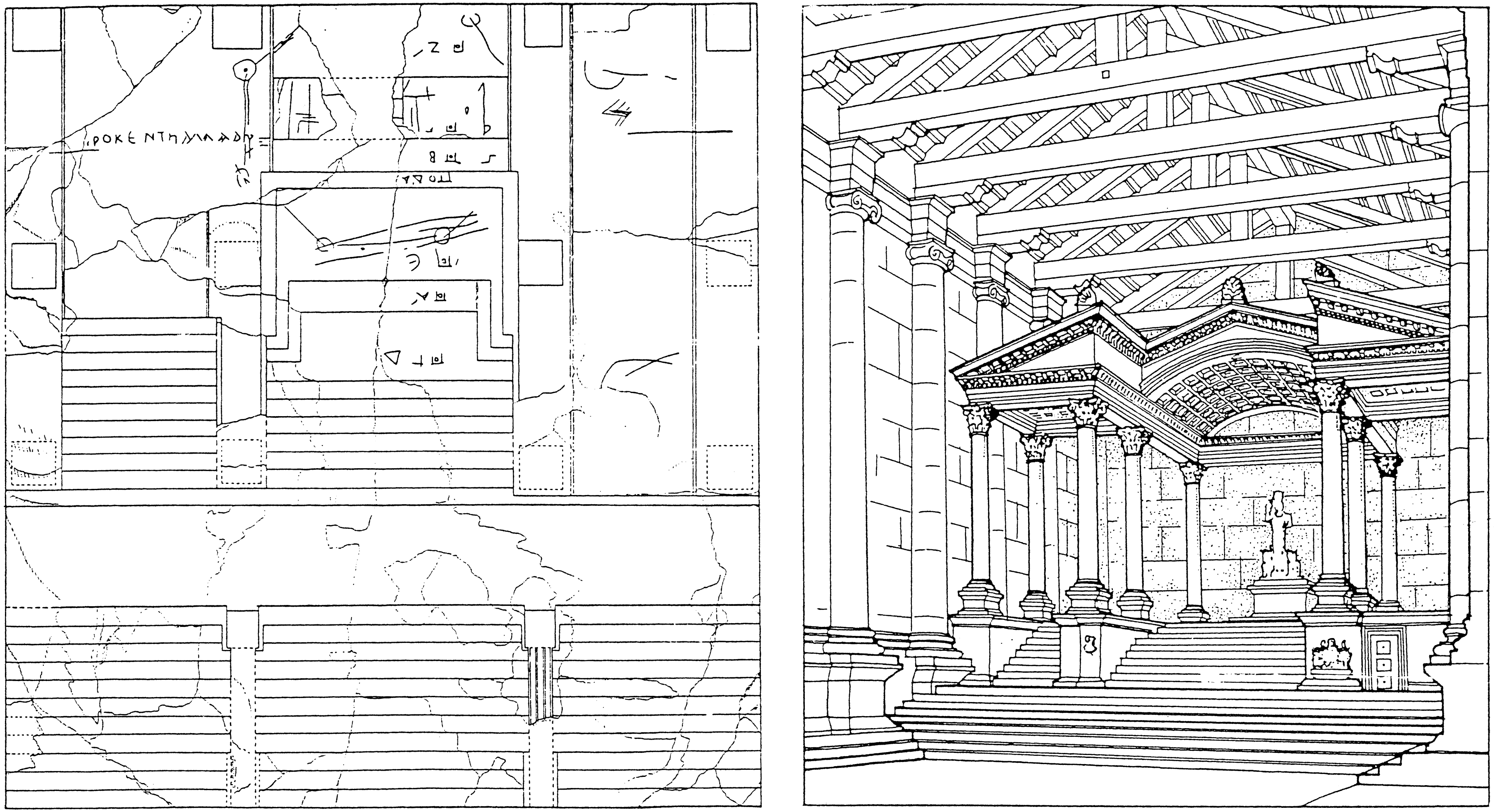
10. Architectural detail drawing scribed out on the face of standing masonry. Levant Oriental Hellenistic-Roman. (1) Didyma Sanctuary of Apollo. Setting out of Columns. Horizontal scale 1:1, vertical scale 1:16. For convenience of access the vertical scale has been greatly compressed. The vertical intervals are successive integers of the unit of measurement employed. *Key*: (1) Upper extremity of column shaft; (2) Central axis of column; (3) Torus moulding of base. Near Miletus, ca 300 BC; (2) Baalbek. Working drawing for the pediment of the Temple of Jupiter Heliopolitanus scribed on the bed of one of the enormous podium blocks (the Trilithon). Central Lebanon. Early 1st Cent AD; (3) Priene. Working drawing for elevation of pediment scribed on marble block built into Temple of Athena. Exceptionally the drawing is made to a smaller scale than natural size. Ionian Coast. Ca 340 BC; (4) Bziza. Profile of angle of pediment scribed on Temple wall. North Lebanon. Roman ca 2nd Cent AD. NB. All these details are those of elevation – i.e. of construction yet to be carried out when the standing walls on which they were drawn out were already built. This is a facet related to the controversy concerning working out details of design during construction. All the instance mentioned in this controversy are elements of the elevation, which can be adjusted without varying the initial plan already built.



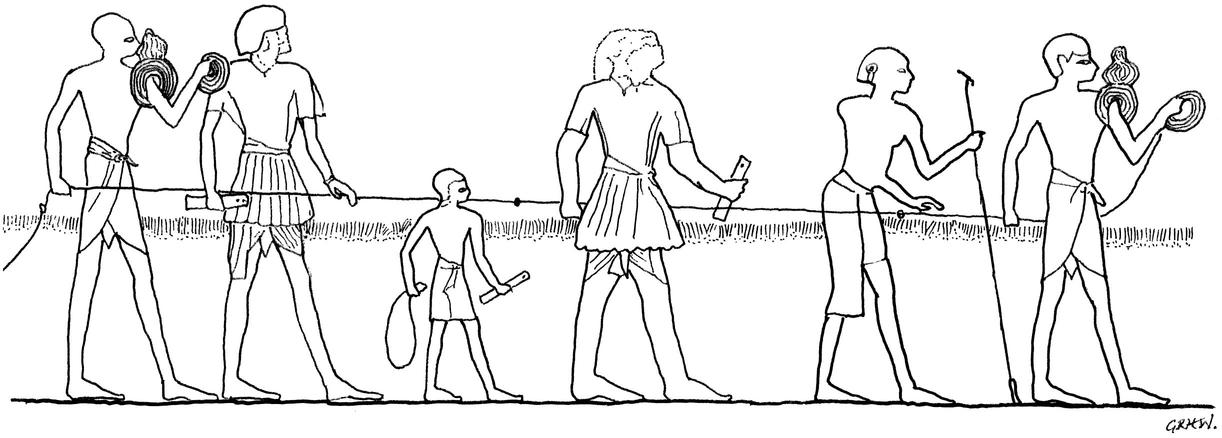
11. Plan of Funerary precinct chiselled out on marble slab. Roman 1st Cent AD. After Heisel p. 189, fig R3.



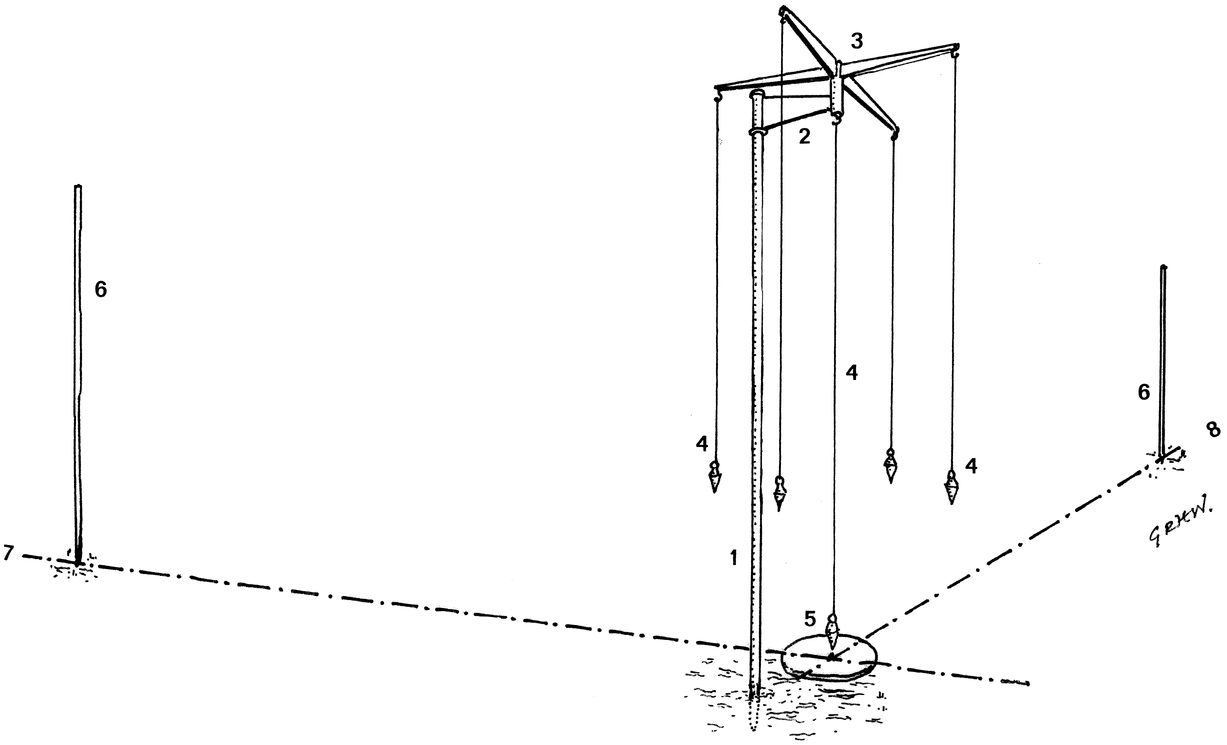
12. Niha. Part Model of Temple A adyton (Breadth 63 cms) Bekaa Lebanon. 2nd Cent AD. This limestone model of the podium of the aedicule adyton of Temple A was found adjacent to the ruins of the temple. It may well have formed the lower part of a composite model of the complete adyton, the upper part forming a separate block to be lifted off. In this way it is likely that the model was made to serve as a *prosketema*, i.e. a presentation document for the project design and to guide building construction. After Hasselberger Fig 5b.



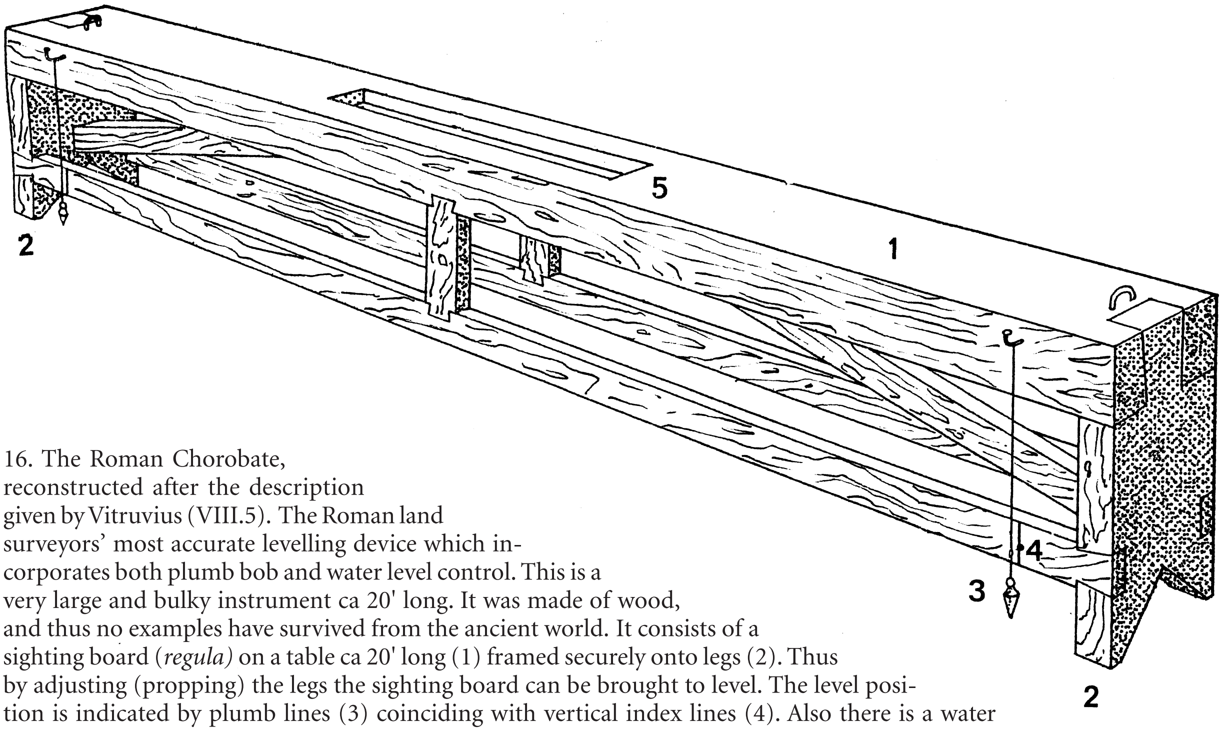
13. Niha Temple A. Syrian Aedicule Type Adyton. Bekaa Lebanon. 2nd Cent AD; *left*: Limestone model giving plan of adyton (Scale 1:24); *right*: Perspective reconstruction of adyton as eventually built. Discrepancies in detail indicate that the model was prepared as a presentation document, not as the definitive “working drawing”. Design details were finalised during the process of erection. After Wilson Jones p. 55, figs 3.10, 11.



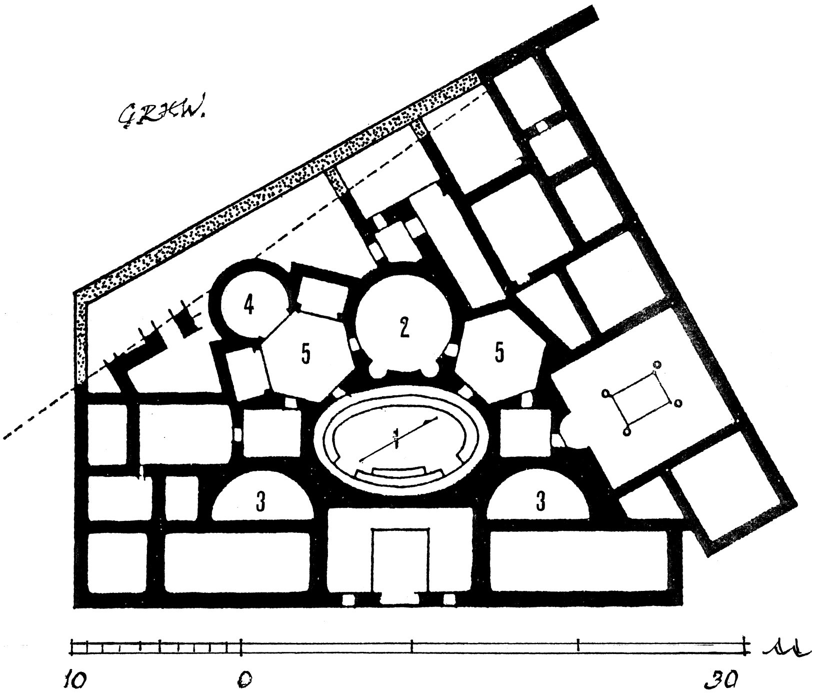
14. Egyptian Land Surveying. Thebes. New Kingdom. This tableau does not depict building site operations but shows land surveying procedure which is the exact equivalent of traditional modern chaining. The chain is a coil of rope, tagged apparently at 10 cubit intervals. This provides sufficient accuracy for demarcating agricultural field boundaries etc. However the stretching of the rope and the inexactitude of the knots make it inappropriate for setting out buildings.



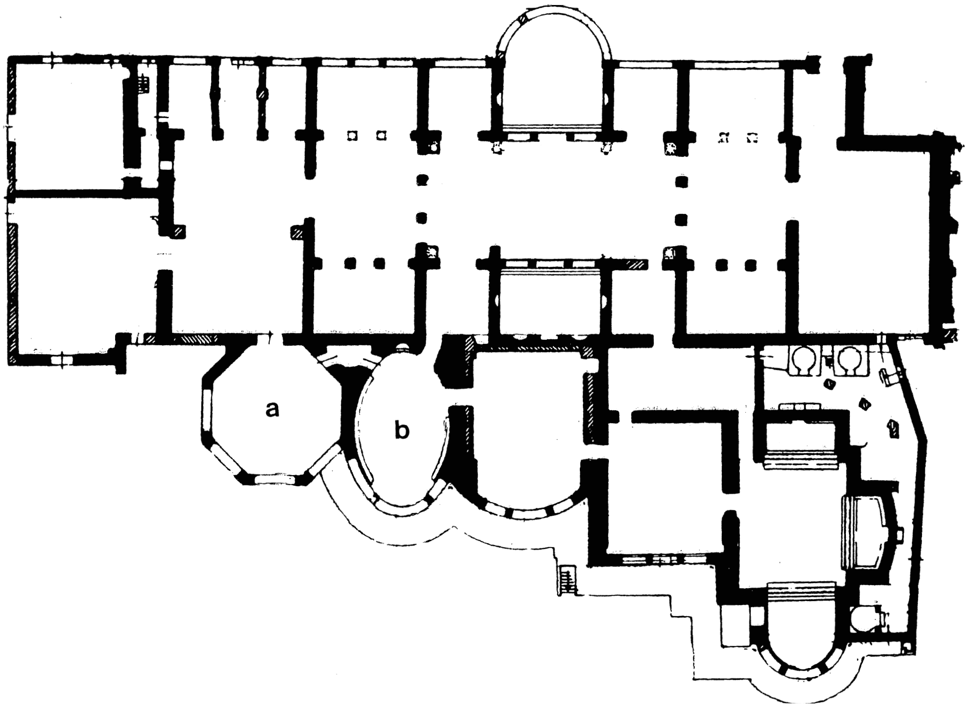
15. The Roman Gromma, restored from ancient remains and representations. This Roman land surveying instrument for e.g. setting out fields (centurisation) or urban development would not have been normally available for setting out building lines (unless the building complex was a very monumental one). However it indicates that an optical device was available in Roman times for setting out right angles on any required bearing. The gromma was of metal and consisted of: (1) The vertical support provided with a spiked foot for setting into soft ground; (2) A rotatable fitting to offset the operation of the sighting device so that the line of vision was not interrupted by (1); (3) A rotatable device of 4 arms set at right angles provided at the centre and the extremities with hooks for suspending; (4) 5 plumb bobs permitting the intersection of the lines of sight to be centered over the datum or station point (5); The suspended plumb lines permit sighting onto rods (6) so that the two lines sighted out (7 & 8) are set at right angles on whatever orientation is required (cf the modern optical square). There are several virtues to this design. The composite parts are all detachable and thus the gromma can be easily transported. Also the suspended plumb lines give a great field for sighting since both distant and nearby targets are equally visible. Finally the suspended plumb lines give truly vertical lines of sight irrespective of the exact verticality of the frame.



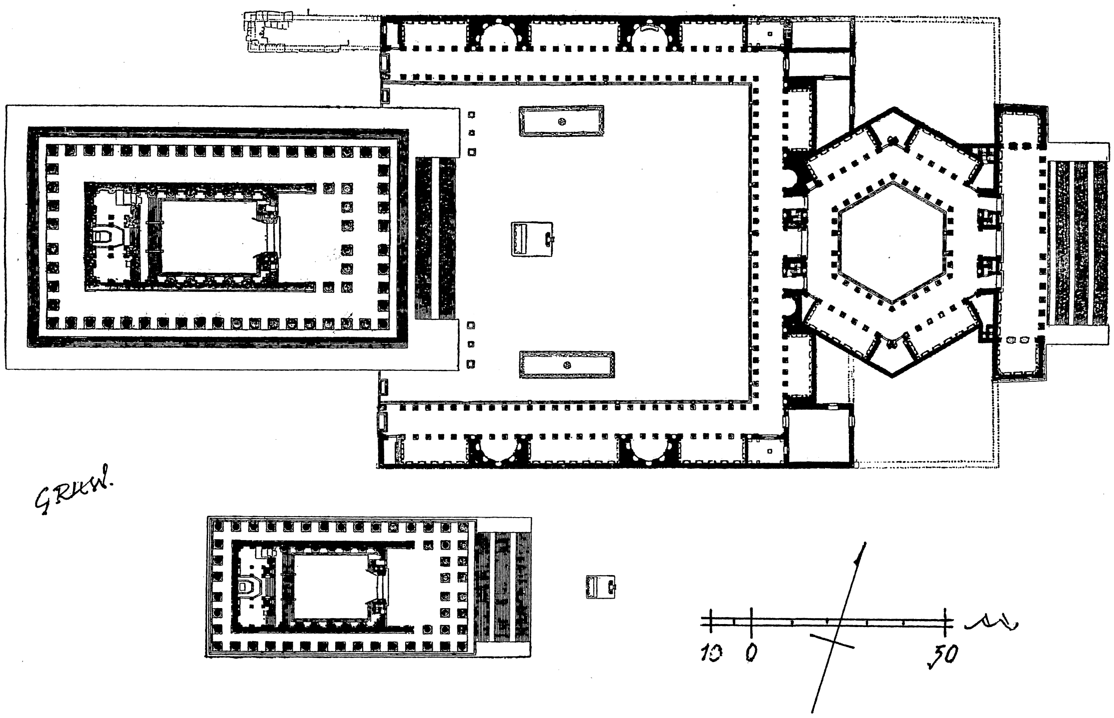
16. The Roman Chorobate, reconstructed after the description given by Vitruvius (VIII.5). The Roman land surveyors' most accurate levelling device which incorporates both plumb bob and water level control. This is a very large and bulky instrument ca 20' long. It was made of wood, and thus no examples have survived from the ancient world. It consists of a sighting board (*regula)* on a table ca 20' long (1) framed securely onto legs (2). Thus by adjusting (propping) the legs the sighting board can be brought to level. The level position is indicated by plumb lines (3) coinciding with vertical index lines (4). Also there is a water trough (5) sunk into the top of the sighting board. As a check for level this can be filled with water, so that when the surface of the water coincides with the horizontal sighting board then the latter is level. The size indicated by Vitruvius accords with the necessity for great accuracy (e.g. to control the fall of an aqueduct), but there is no reason why smaller instruments should not have been constructed. It is unlikely that the chorobate was commonly available on building sites. After Adam p. 18, fig 16.



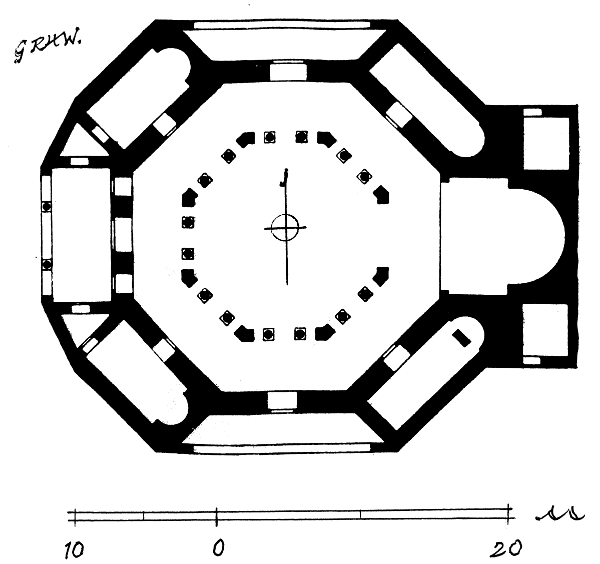
17. Marathon. Roman Baths. Varied room forms to be set out in Roman planning. Greece ca 2nd Cent AD. In addition to basic rectangular planning the following room forms are employed: (1) Ellipse; (2) Circle; (3) Semi circle; (4) Segmental; (5) Hexagonal. After Ginouvès Pl 1.2.



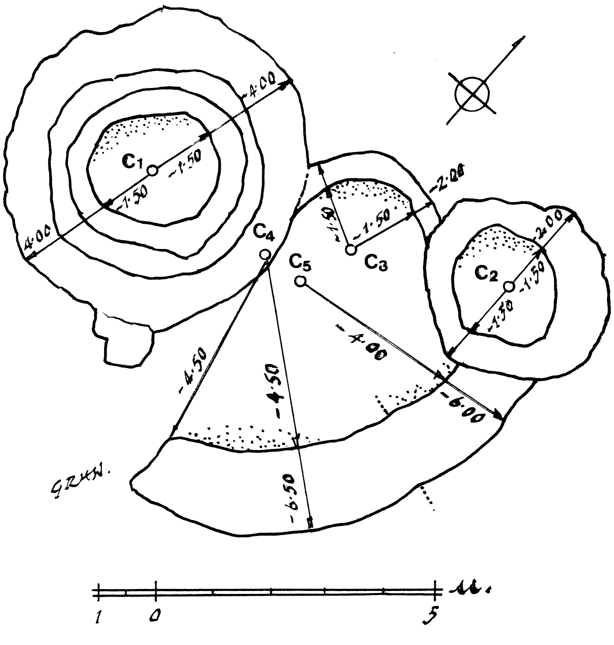
18. Ostia. Baths near forum. Variety in planning. Port of Rome 160 AD. Basically rectangular planning but varied room forms include octagon (a) and ellipse (b). after Crema p. 406, fig 497.



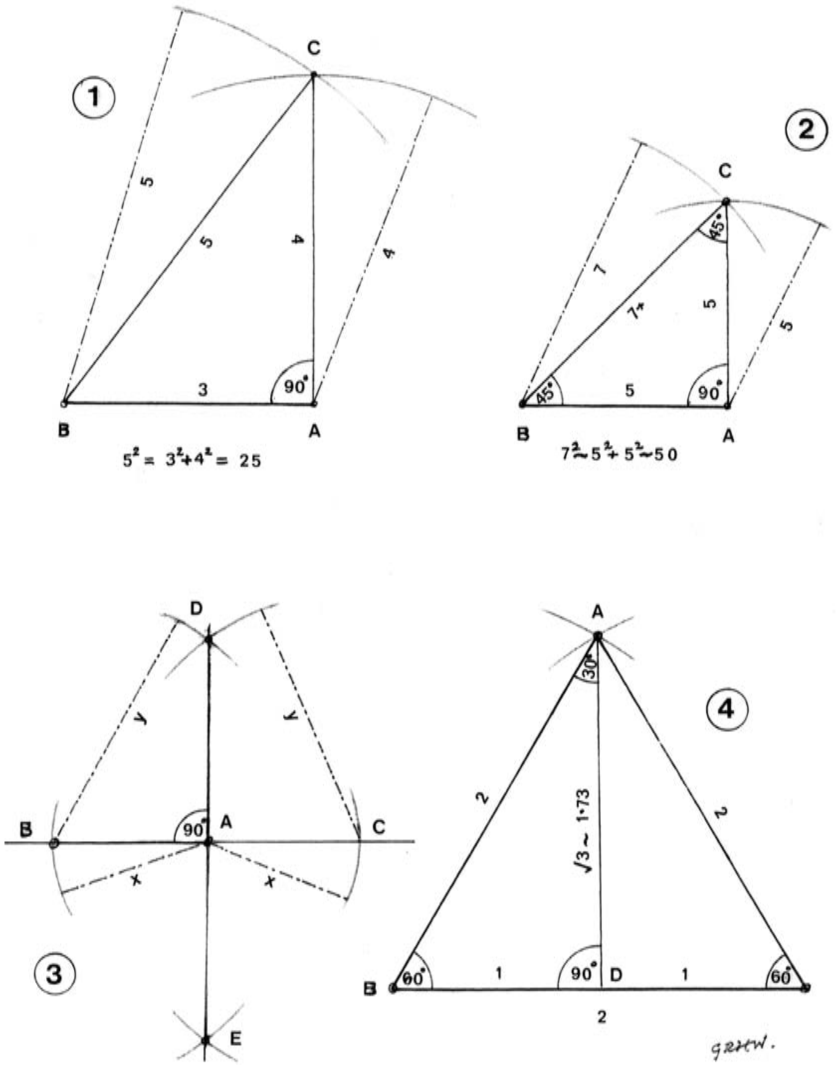
19. Baalbek. Temple of Jupiter Heliopolitanus. Hexagonal entrance court. Bekaa, Lebanon. 1st Cent AD. After Robertson, fig 95.



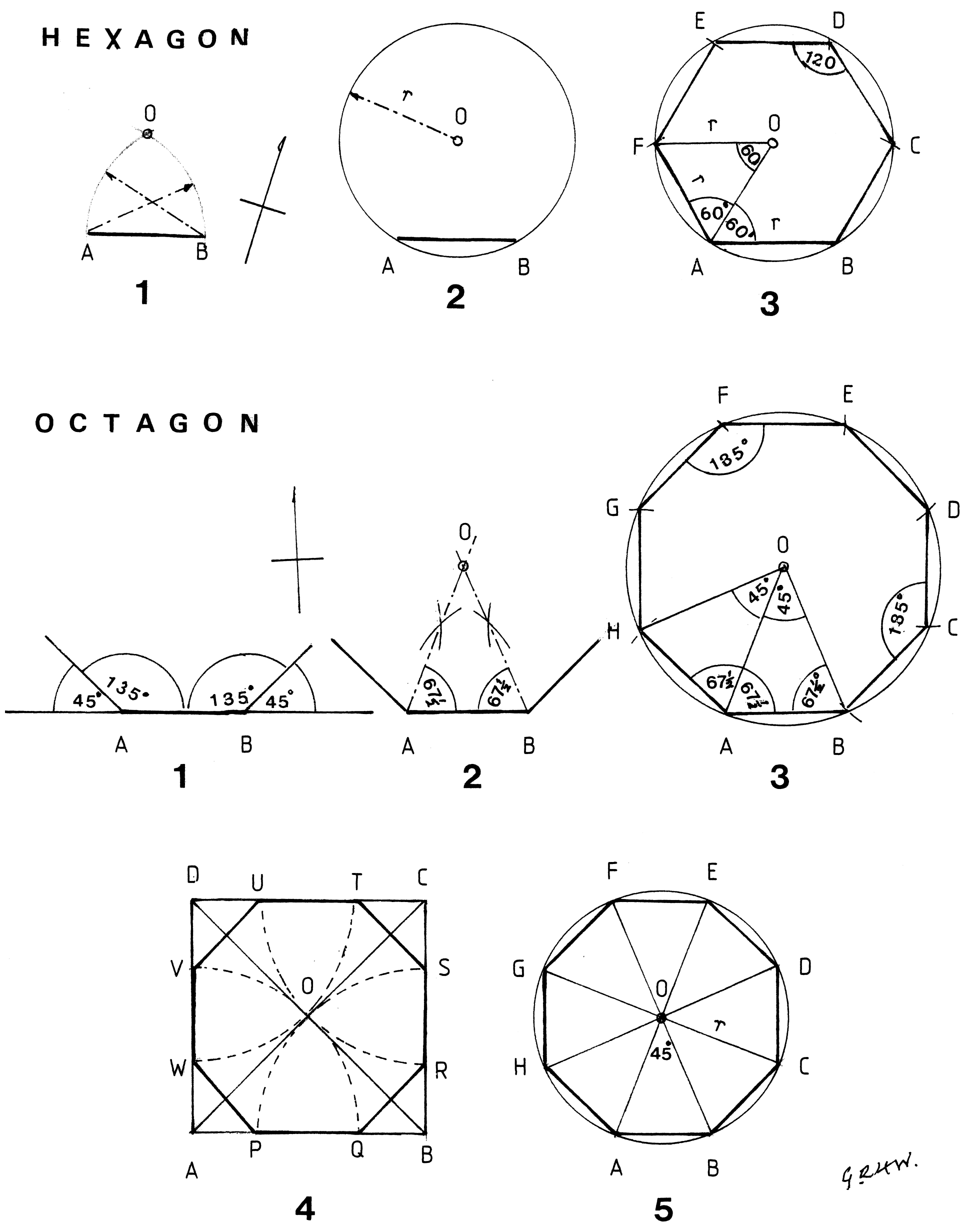
20. Mt Gerizim. The octagonal Church of the Theotokos, near Nablus, Palestine. 484 AD. The basic setting out of this church was to establish the primary octagon. The details of the plan are complicated to analyse since they show a concern for numbers and proportion in the Neo-Platonic tradition. However this concerns design rather than setting out. After Krautheimer p. 157, fig 118.



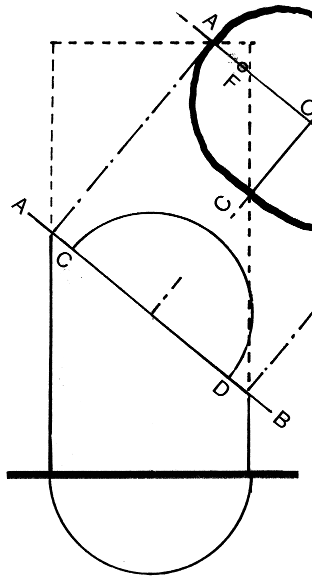
21. Khirokitia. Early Neolithic Round House Complex. Cyprus 7th Millenium BC. When as here round house units are set together in a complex, the conformity of the designer's mentality with the workings of nature is clearly demonstrated. The Neolithic planners did not think in terms of a straight line as the shortest distance between two points. They thought of any structural form as necessarily defined in the image of natural growth, i.e. with a curvilinear periphery. Modern mentality adjusts readily to the centralised design of circular buildings, but finds it irrational that a stretch of boundary wall should be curved. As a practical matter of setting out, that for round building is the simplest construction of all ! A peg is fixed in the ground at the designated centre, a cord attached to it and with this cord the building line is traced out as an arc described by the chosen radius. That this procedure was often used is clear from the regularity of the curve (and also by the fact that the length of the radius was often a rational measurement). However it is probable in some instances that a reasonable arc corresponding to a certain radius could be described instinctively. After Dikaios Khirokitia, fig 75.



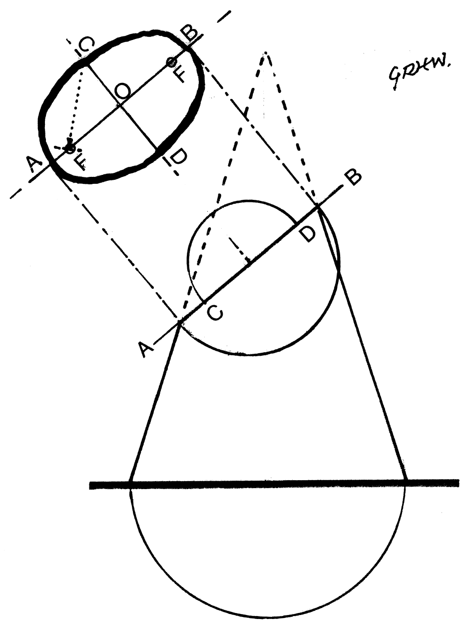
22. Simple Geometrical Constructions for Rectangularity. From Earliest Neolithic times when rectilinear building became dominant the angular setting out was generally quite accurate. This could be obtained by simple linear measurement without any recourse to sighting devices to give the correct angle. The following linear constructions are apparent to any child and are practical to carry out on the ground. (1) A triangle with sides in the proportion of 3:4:5 gives a right angle opposite the longest side. To construct a right angle at A, AB is laid off 3 units in length and ropes are held at points of origin A and B. The point C at which the 4 units mark along the A rope coincides with the 5 units mark on the B rope gives the right angle ∠ BAE, since the square on the hypoteneuse equals the sum of the squares on the other two sides (Pythagoras' Theorem); (2) It soon became evident that the proportion of the diagonal to the sides of a square was 1.414 and this in practice approximated to 14:10 or 7:5. Thus to construct a right angle at A, AB was marked off 5 units in length. A rope indicating 5 units was held on A, and one indicating 7 (or 7+ a small fraction) was held at B, and the point C where the two indications coincided gave the required right ∠ BAC; (3) The simplest of all methods (where space was available) was to produce the line BA and mark off BA = AC any convenient length (X). Then from points B and C ropes were held marked identically with any convenient length (Y). The point where the two indications coincided (D) gave the required right angle ∠ BAD. If space were available the procedure could be repeated on the other side of line BC so that the line DE intersected BC perpendicularly at A (vertical bisection); (4) For the greater part of antiquity the only significant angle required in setting out buildings was a right angle. There was, however, an exception when a concern developed for proportion in the design of buildings. Surprisingly this very often was not arithmetically based (i.e. 2:1; 3:2; 8:5 etc), but geometrically based – and here the 60° angle came into issue. The angles of an equilateral triangle are 60°. If the vertical angle at A is bisected, it divides the base BC into two halves – BD, DC. Allowing the length of the sides of the triangle to be 2 units, then the proportions are obtained of 1, √3 (~ 1.73), 2 – and these proportions were often used in design. The describing of other angles (i.e. other than 90°, 60°, 45°, 30°) only entered into calculation with the introduction of the buildings designed as regular polyhedrons (e.g. octagons, hexagons etc). This, to all intents, was a development of later Classical Antiquity.



23. Simple Methods of Setting Out Regular Polygon Centralised Plans. These plans became common in Roman Architecture, the octagon in association with domical roofing. As a matter of practical planning it is very often required to proceed from the dimension and orientation of one side of the figure. This gives on to laying off the face angles of the figure as the next step. The face angles of any regular polygon are given by the obvious formula that they are equal to twice the number of right angles as the figure has sides minus 4, divided by the number of sides (= number of angles). The two regular polygons employed in ancient building were the Hexagon and the Octogon. These have respectively face angles of $1^{1/3}$ and $1^{1/2}$ right angles, i.e., of 120° and 135°. In the absence of precision instruments with graduated horizontal circles it is not possible to lay off these angles directly on the ground. However there are reasonably simple geometrical procedures to obtain them, using only lengths of cord. *Hexagon.* This is very simple to set out. The figure consists of 6 contiguous triangles with angles of 60° - i.e. equilateral triangles. Thus the radius of the circumscribed circle = the length of the side of the hexagon. The procedure is (a) to lay down one side (A-B) with the required orientation and dimension; (2) with this as base construct an equilateral triangle (ABO), the apex of which (O) is the centre of the required circumscribing circle; (3) step the length of the base (= radius) exactly 6 times around the circumference of the circle to give the required hexagon (A, B, C, D, E, F). *Octagon.* The regular octagon is not straight forward to set out, given only the length of a side. The face angle is 135° (i.e. 1 ½ right angles). A practical procedure for setting out such a figure on the ground devolved from setting out the supplementary angle to the face angle, i.e. 45°. The side is extended in both direction and perpendiculars erected at its extremities. The external right angles are then bisected to five two 45° angles and the interior supplements to these external angles are the required 135° face angles (1). These face angles are then bisected and the intersection of the bisectors gives the centre (O) of the circumscribing circle (2). The angular points of the octagon (A, B, C, D, E, F, G, H) are obtained by stepping the length of the side (A-B) 8 times around the circumference (3); On the other hand if it is not the length of a side which is basic to the design of the octagon but the overall dimensions of the figure, then other simple geometrical constructions are available. However in this event if the overall dimensions are rational numbers, then the length of the side of the octagon will be irrational. The two practical instances are the octagon inscribed within a square on a given side (4) and an octagon inscribed within a circle of a given diameter (5). In the former instance (4) the diagonals A-C, B-D of the square A, B, C, D are drawn and quadruntal arcs swung from the angles with length half the diagonal to intersect the sides of the square A, B, C, D at points P, Q, R, S, T, U, V, W giving the required octagon. In the latter instance (5) draw the circle with given radius. Draw two diameters AOE, BOC intersecting at right angles, then bisect these quadrants by two further diameters HOD, BOF. The 4 diameters intersect the circumference at A, B, C, D, E, F, G, H to give the required octagon.



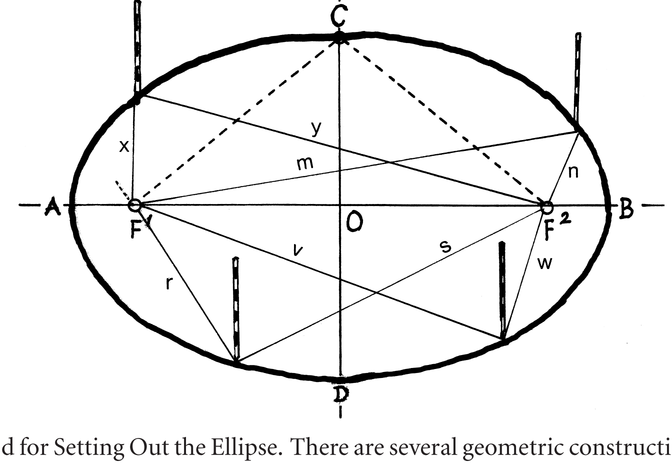
CYLINDER



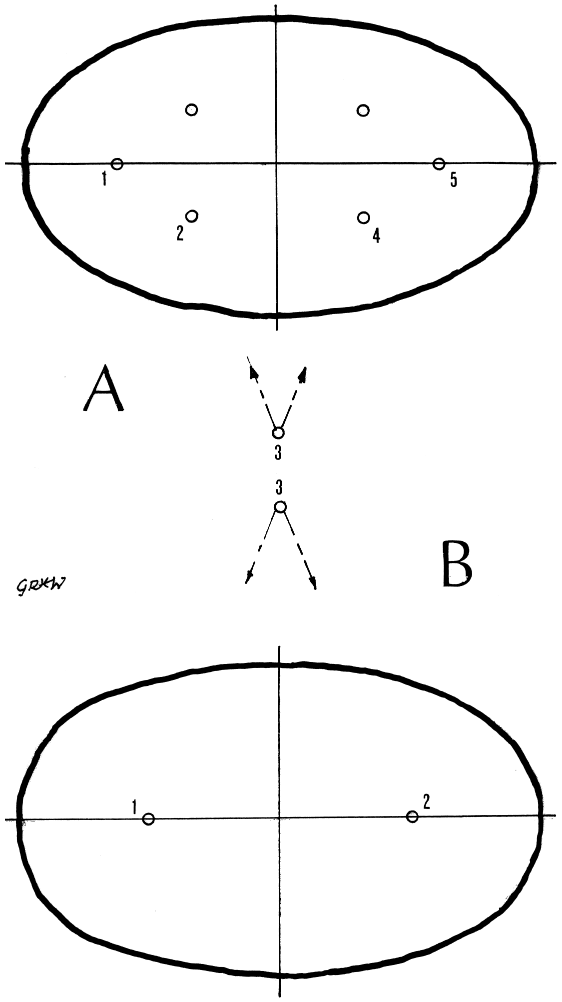
CONE

GENERATION OF ELLIPSE

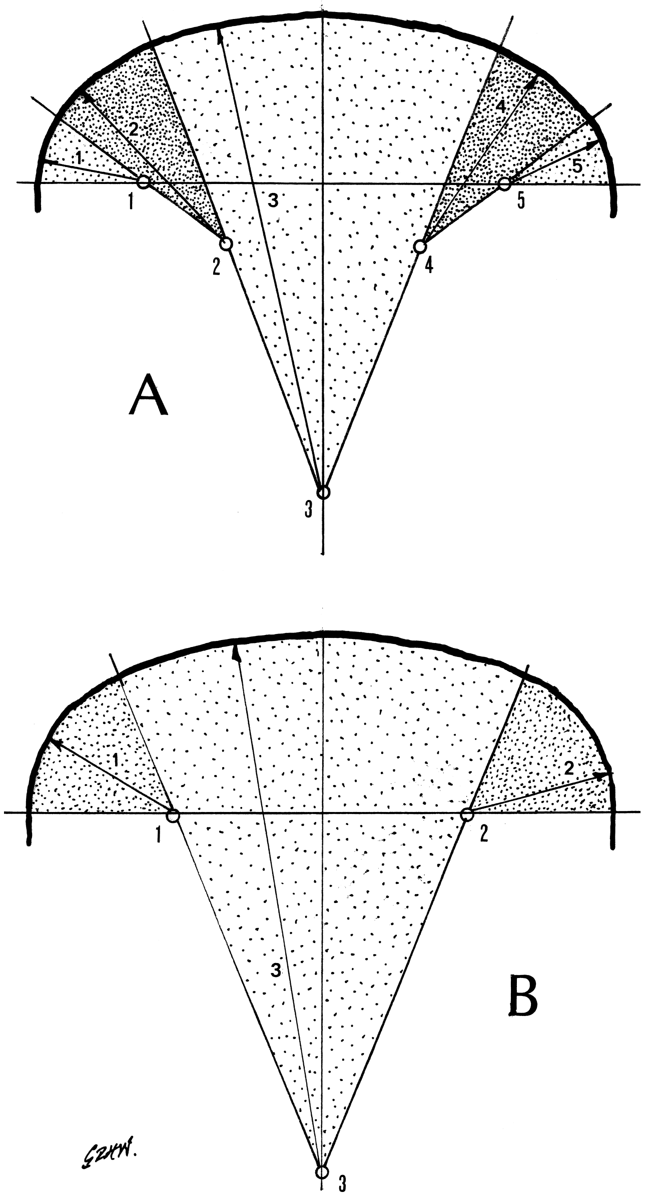
24. Generation of the Ellipse. The ellipse is a curve generated from the intersection of a cone or cylinder by a plane inclined to the horizontal at a lesser angle than the inclined surface of the cone. It has two axes, the length of the major axis (A-B) being the greatest linear dimension of the figure and the breadth of the minor axis (C-D) being the greatest linear dimension perpendicular to the major axis. The curve which passes through these 4 points (A, B, C, D) is generated from two focal points, the foci (F, F) on the major axis, located so that their distance from the extremities of the minor axis (C-F, D-F) is equal to half the major axis (AO, BO). The curve of the ellipse is then the locus of a point moving so that the sum of its distances from the two foci (F, F) remains constant and equal to the length of the major axis (A-B).



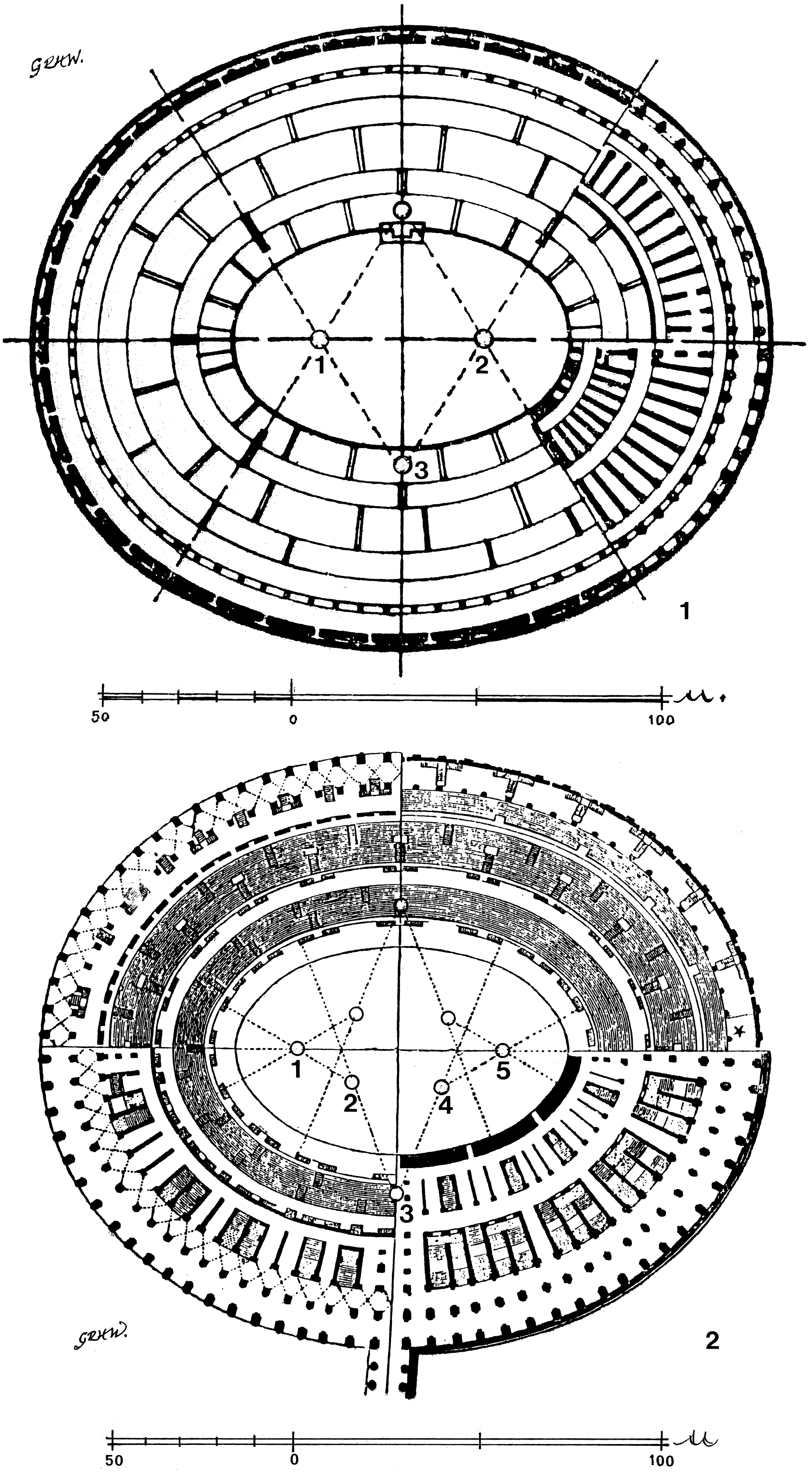
25. A Practical Method for Setting Out the Ellipse. There are several geometric constructions for the ellipse, but an empirical method can be used on level cleared ground to set out quite a large ellipse. Position as desired the major and minor axis giving the desired length (A-B) and breadth (C-D) of the figure. From C (or D) locate the two foci (F^1, F^2) by swinging an intersecting arc with radius C-F^1 / C-F^2 equal to half the length of the major axis (A-O, B-O). Take a length of cord (rope, twine, etc) of length C-F^1 + C-F^2 = A – B and peg the ends at F^1 and F^{2}. With a marker held against the inner edge of the distended cord describe the curve A, C, B, D so that x + y = m + n = r + s = v + w = AB (major axis).



26. The oval plan set out as two multi centred arches. In practice the oval plan was rarely set out as an ellipse, as two identically opposite multi centred arches gave a close approximation of the curve. The designed arches could be 5 centred (A), or 3 centred (B).

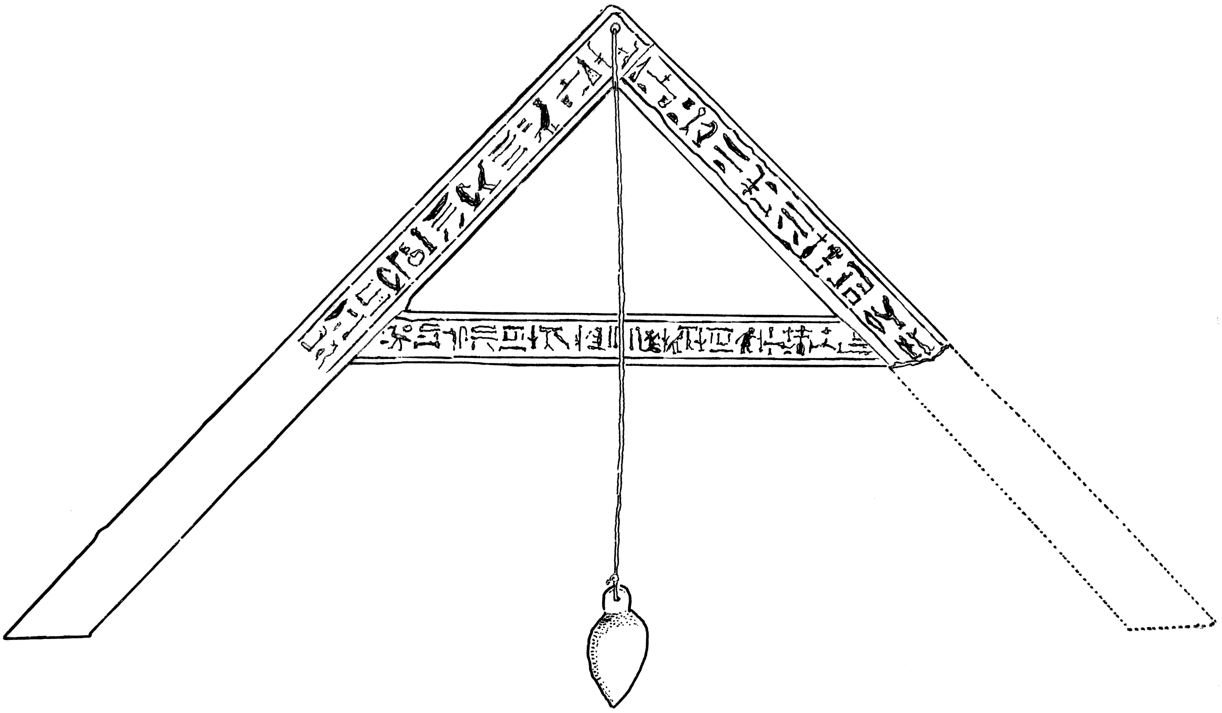


27. Construction of multi-centred arches (arcs). To ensure continuous unbroken curvature the centre of adjacent arcs must be on the one straight line – i.e. since the tangent at point of contact is at right angles to the radius, the tangent will thus be at right angles to the radii of both arcs, and the arcs will be continuous. For clarification, the sectors of the arch are distinguished by varied stippling. A. 5 centred arch. Centres 1 & 2 lie on one straight line; centres 2 & 3 on one straight line; centres 3 & 4 on one straight line; and centres 4 & 5 on one straight line; B. 3 centred arch. Centres 1 & 3 lie on one straight line; centres 2 & 3 on one straight line.

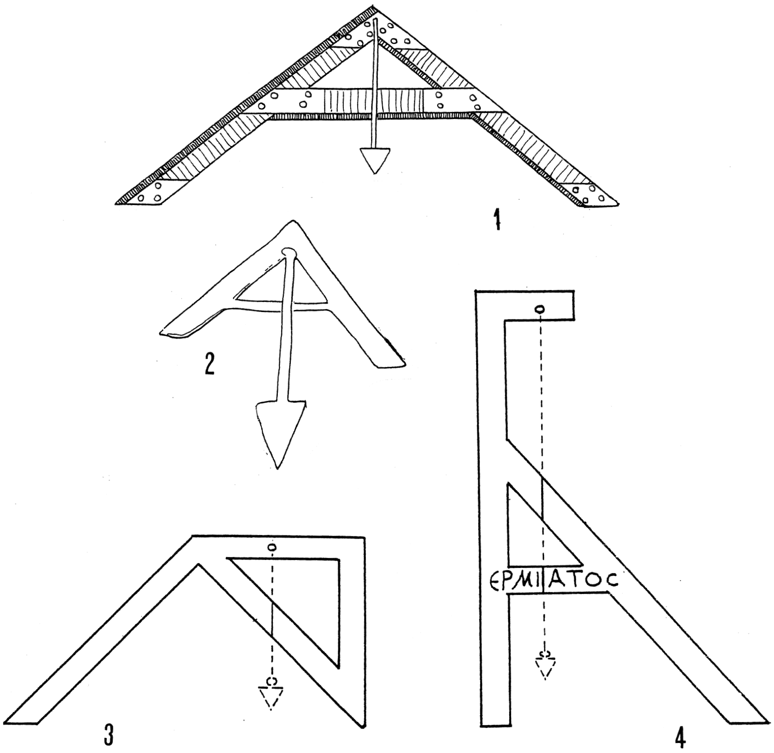


28. Setting out the oval form of a Roman Amphitheatre. Rather than being set out as true ellipses, amphitheatres were usually set out as two multi-centred arches. (1) Analytical plan of the Colosseum at Rome set out as two identically opposite 3 centre arches; (2) Analytical plan of Colosseum at Rome set out as two identically opposite 5 centered arches.

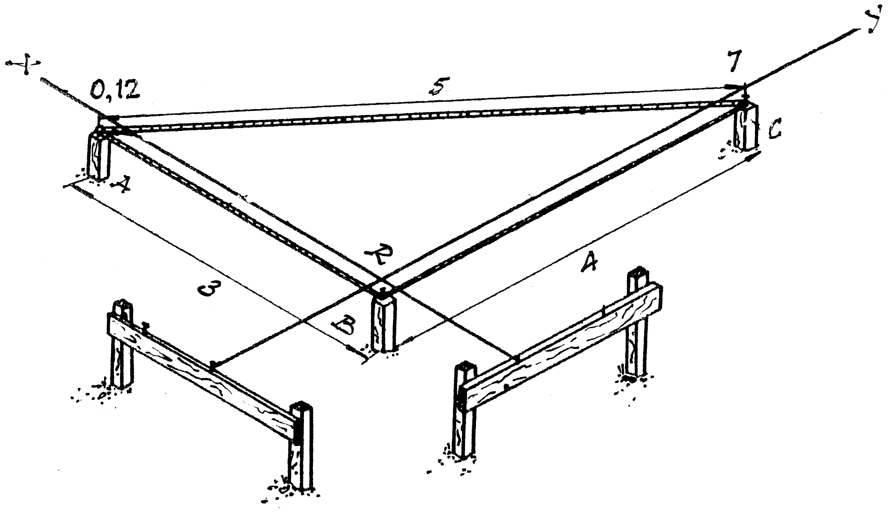
29. Egyptian Mason's line from a Middle Kingdom tomb at Deir el Bahri. The thin cord used by masons to establish the line for the faces of masonry construction can either be stretched and fixed in place so that the bricks etc are set in line against it, or it can be used to mark the required line, e.g. on the upper bed of a lower course of masonry. This is done by dusting the line with red ochre powder, stretching it in position along the masonry, then drawing it away from the surface and letting it "snap" back again to mark a perfectly straight line in red; This mason's line incorporates the sophisticated device of a rotating spindle. After Arnold fig 6.3.



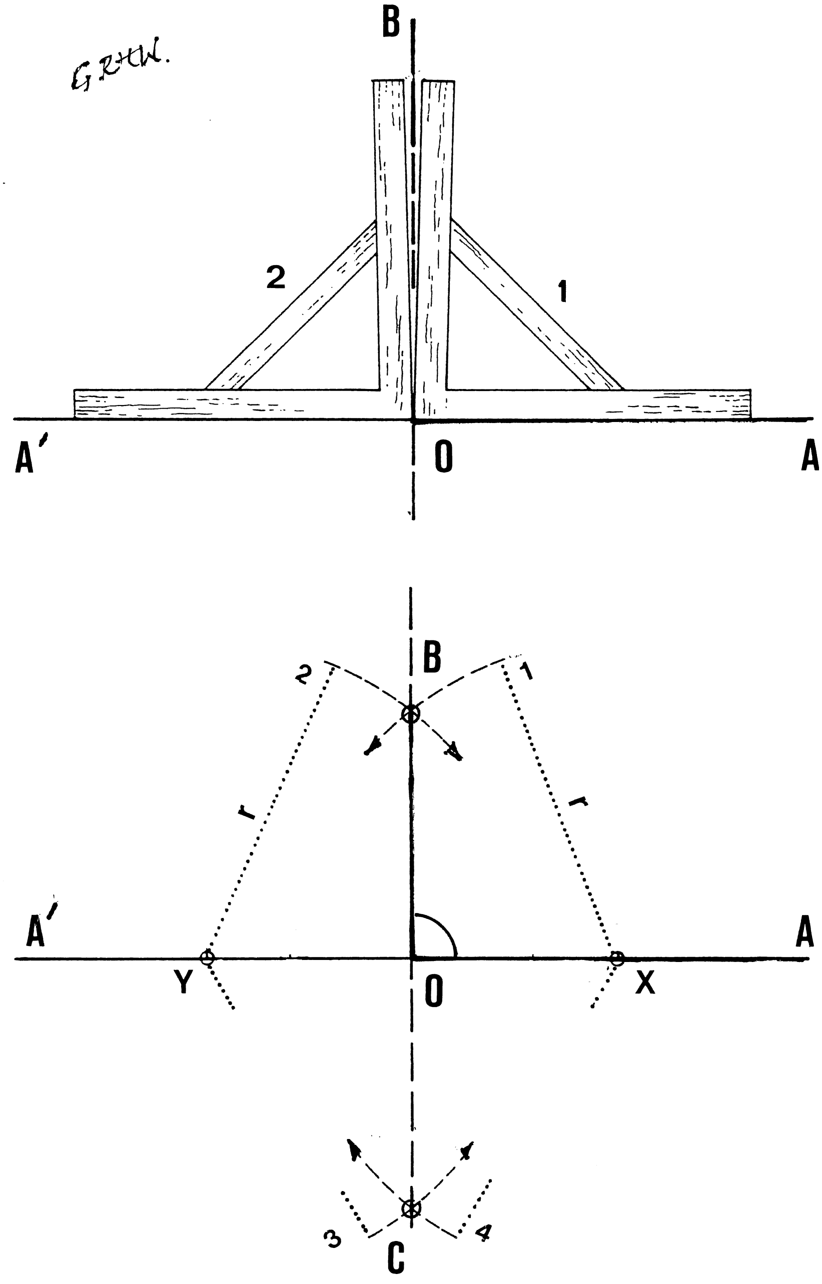
30. Pharaonic Egyptian 'A Frame' builder's level. From a tomb at Deir el Medinah. This obvious device depending on establishing vertical by plumbing was early apprehended and conserved without change throughout antiquity. When the plumb line coincides with the central index on the collar bar, the feet indicate the horizontal. This device as illustrated is not an instrument for setting out buildings, it is a builder's combined square and level for testing true construction. However it can be easily adapted to serve as a sighting device for levelling. Indeed the principle has been incorporated in modern (self levelling) builder's levels, replacing the traditional 'spirit level' system.



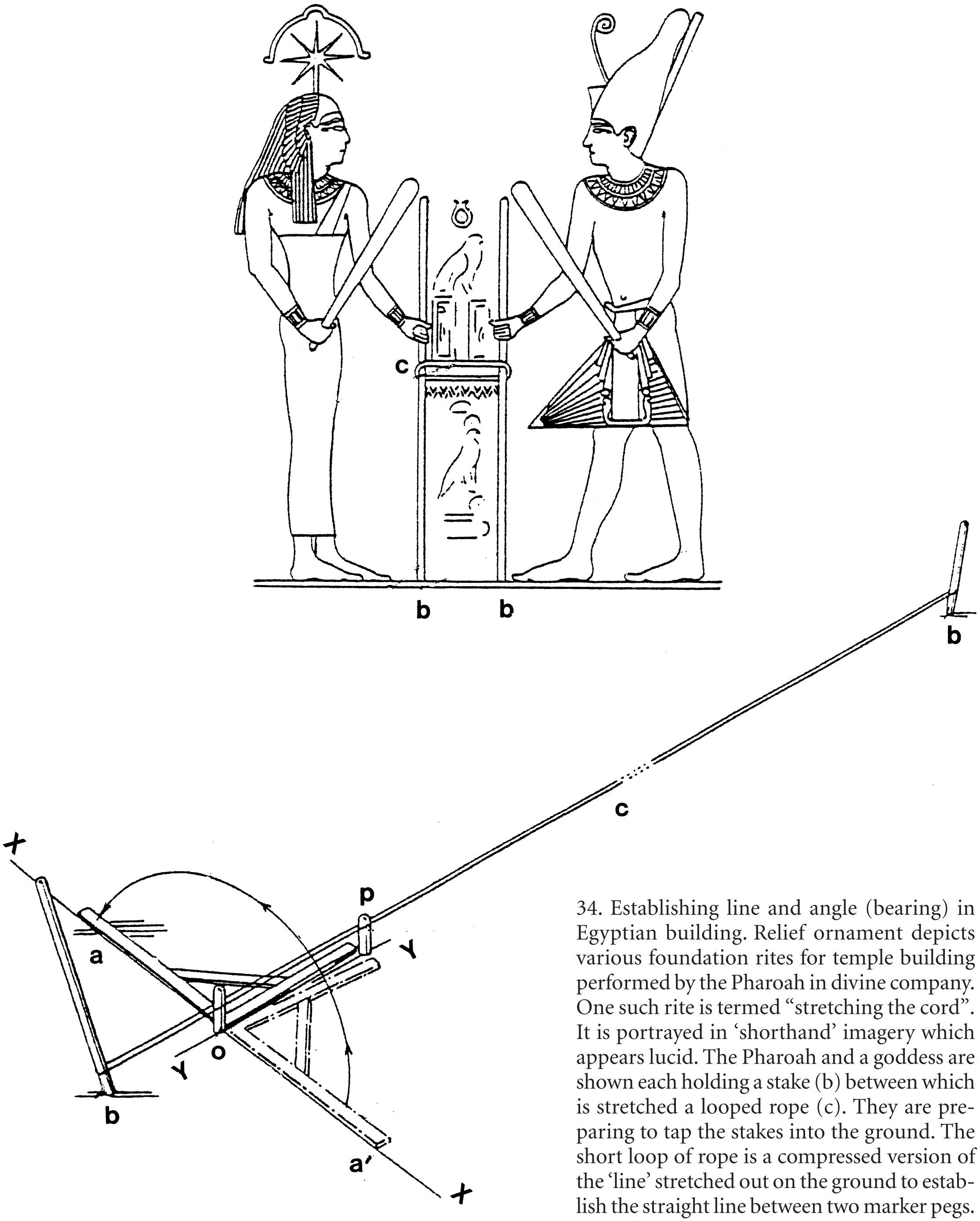
31. Roman 'A Frame' square levels. 1. Depicted on a Pompeian Mosaic in Naples Museum; 2 Crude representations as found on innumerable funerary stele (from Pompeii); 3. Convenient design for conjoint use as level and square. From tile now in Louvre; 4. Design adapted for use in difficult positions. Avignon Museum.



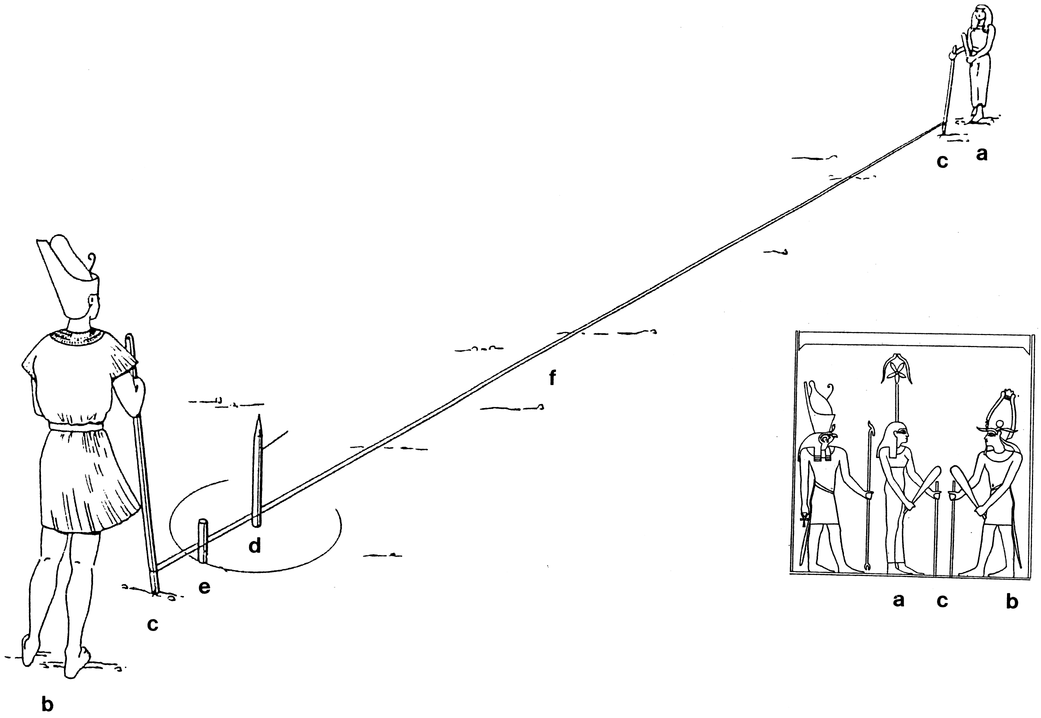
32. Construction of right angle by forming a triangle with appropriate sides. Sketch from modern bricklayer's manual; Line X is the given base line and B is the point at which a line at right angles is to be laid off. Point A is taken as the origin with length AB = 3 (or 4). A measuring tape is extended from the point of origin to B and then looped around B so that the distance 12 is made to coincide with the zero at the point of origin. The distance 7 is then drawn taught and a mark made at the point C. Thus AD = 3, B-C = 4 and C-A = 5, so that the ∠ R = 90° (by Pythagoras' theorem); "Sighting rails" are shown set up beyond the area of construction so as to preserve the trace of the building lines X and Y from interference during building operations. NB The breadth of the walls indicated by nails in the sighting rails.



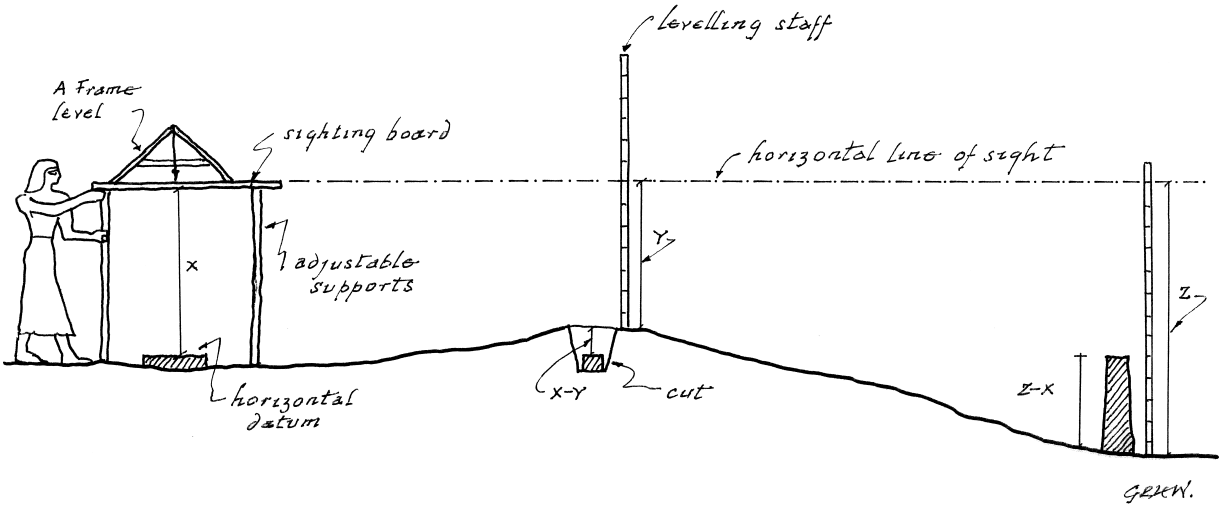
33. Simple methods of setting out a right angle on the ground. A right angle can be constructed geometrically by perpendicularly bisecting a line (= bisecting the ∠ 180° to give two equal adjacent angles of 90°). To construct a right angle at Pt O. If O lies within the line A – A', mark off on the line OX and OY so that OX = OY. If O is at the extremity of the line produce it to A' and then mark off OX= OY. From points X and Y swing 4 arcs of equal radius to intersect at B and C. Join B and C passing through O. The ∠BOA = ∠ BOA' is a right angle; If many right angles are to be set out, then this procedure can be used to construct a wooden set square with long arms (*above*). Any slight defect in the right angle can be righted in use by applying the set square to the line in reversed positions (1 and 2). The error will then be equal and opposite, and can be rectified by taking the mid point between the two indications as shown.



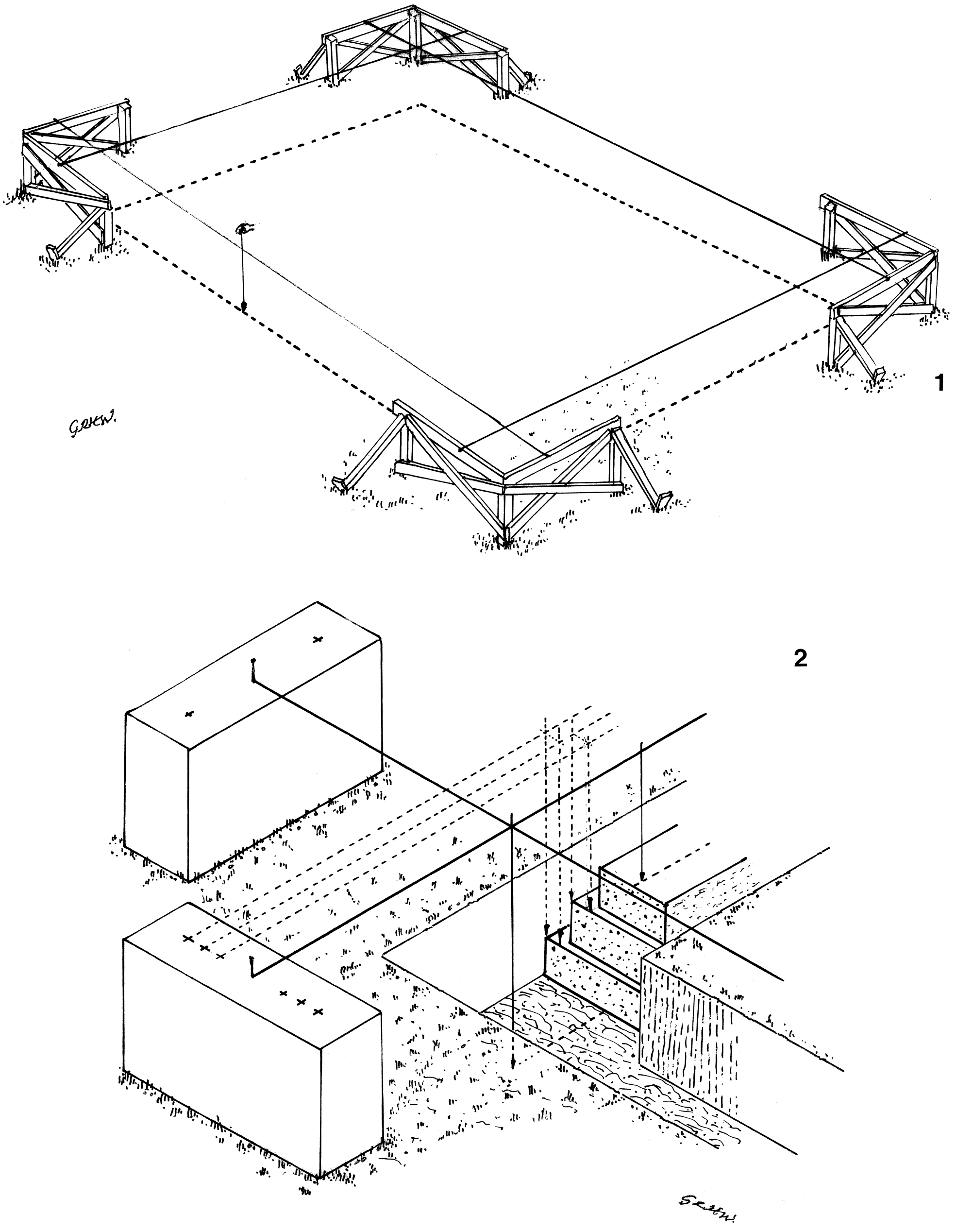
34. Establishing line and angle (bearing) in Egyptian building. Relief ornament depicts various foundation rites for temple building performed by the Pharoah in divine company. One such rite is termed “stretching the cord”. It is portrayed in ‘shorthand’ imagery which appears lucid. The Pharoah and a goddess are shown each holding a stake (b) between which is stretched a looped rope (c). They are preparing to tap the stakes into the ground. The short loop of rope is a compressed version of the ‘line’ stretched out on the ground to establish the straight line between two marker pegs. The superior Egyptian practice consists in substituting a double or looped line for the customary single cord used in the process. A single cord is held against one side of pegs, and when it is stretched a considerable distance it is very liable to be bent out of true alignment. The Egyptian practice of a double cord which was looped around the pegs or stakes and could be levered taut avoided such possible deviations; A reconstructed version of this practice is shown below in connection with setting out a line at right angles to an existing line using the long sided set square, generally presumed employed to establish the angle; At point O in the line X-X a line is to be marked out at right angles. One arm of the set square is aligned with X-X and the position of the extremity of the other arm marked out on the ground. Since the angle given may not be exactly true, error is avoided by flipping the set square over (a'-a) and repeating the process. Any discrepancy between the two marks is then halved and the true perpendicular line marked out (Y-Y) and pegs driven into the ground (O, P). Line Y-Y is then extended to the required length (b) by the device of stretching the looped cord (c) with stakes (b, b) as described (*below*). After Isler JARCE XXVI figs 15, 18.



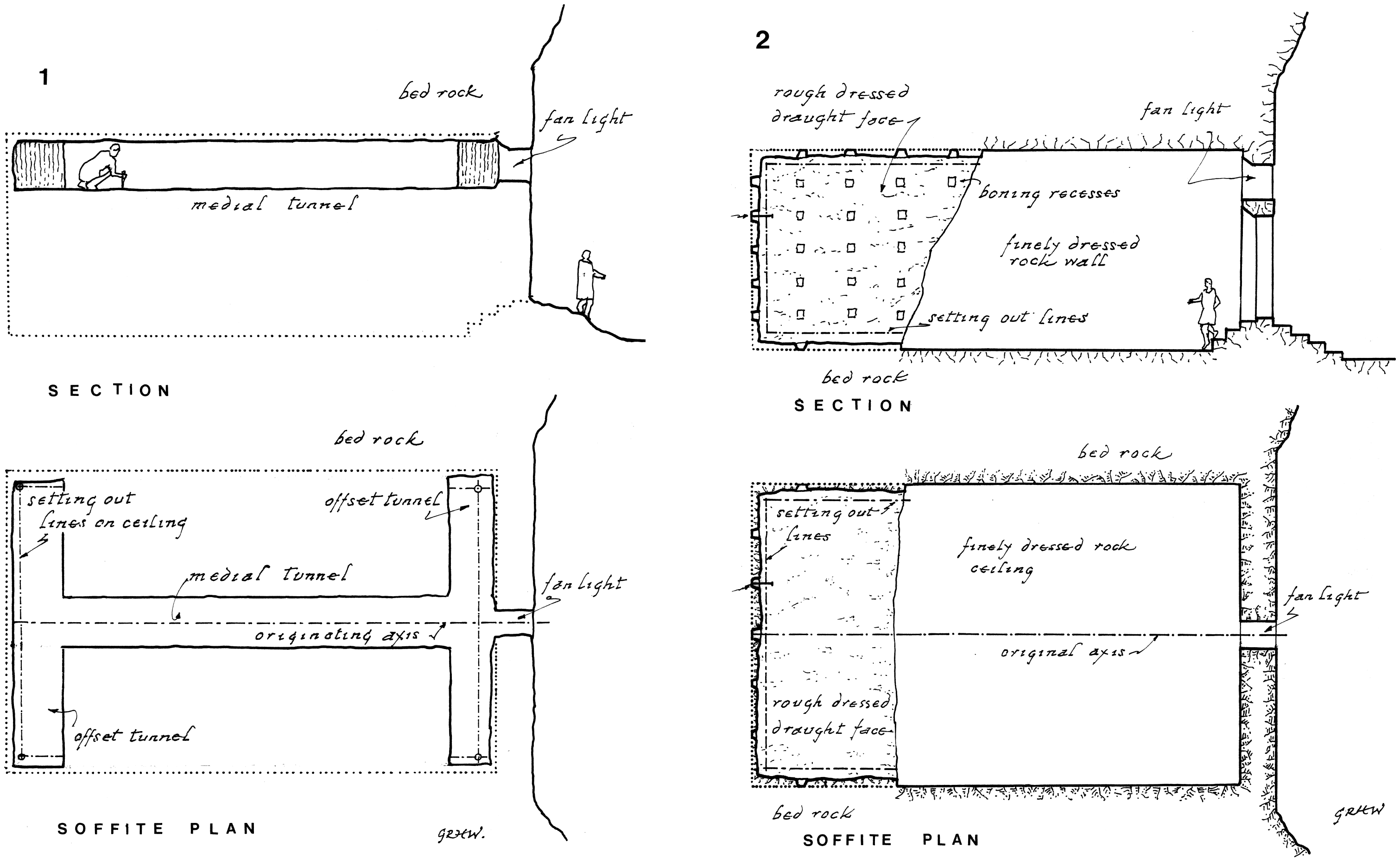
35. Establishing and extending North-South orientation on the ground in Egyptian building by stretching the cord. Egyptian relief decoration representing foundation rites for temple building shows the Pharaoh (b) and the Goddess (a) under the supervision of Thoth, staking out a line (c-c); A reconstruction shows the looped cord (f) as extending the true north orientation (e-d) established by using a gnomon (d) to record the moving shadow of the sun intersecting an arc (e). The orientation (e-d) is then marked out on the ground by tapping in stakes (c-c). After Isler, fig 14.



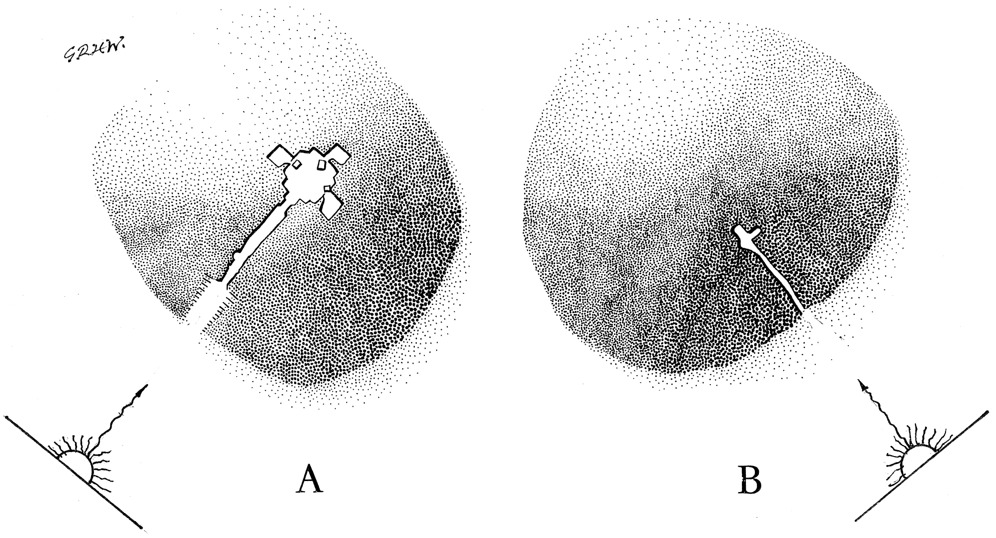
36. Egyptian optical level as used for establishing levelled points in setting out buildings. There are many obvious ways in which the simple A frame square-level can be adapted for use as an optical levelling instrument. Here is shown the simple expedient of setting it on a plane sighting board or table, which can be adjusted so that the surface is registered as horizontal. It can then be used to give a horizontal line of sight in any direction. The height of this line of sight ("collimation height") above a datum set below the table is given by direct measurement as here (x) – or by taking a "back sight" on a datum set elsewhere. Another bench mark of the same height as this datum can be established anywhere within visual range of the naked eye (ca 50 m) by taking a 'foresight' on a levelling staff. The difference, plus or minus, gives the ground level at the spot and a bench mark of the same height as the original datum can be marked or constructed either below or above the ground level as the case may be by applying the "rise" or "fall" (here x-y or z-x).



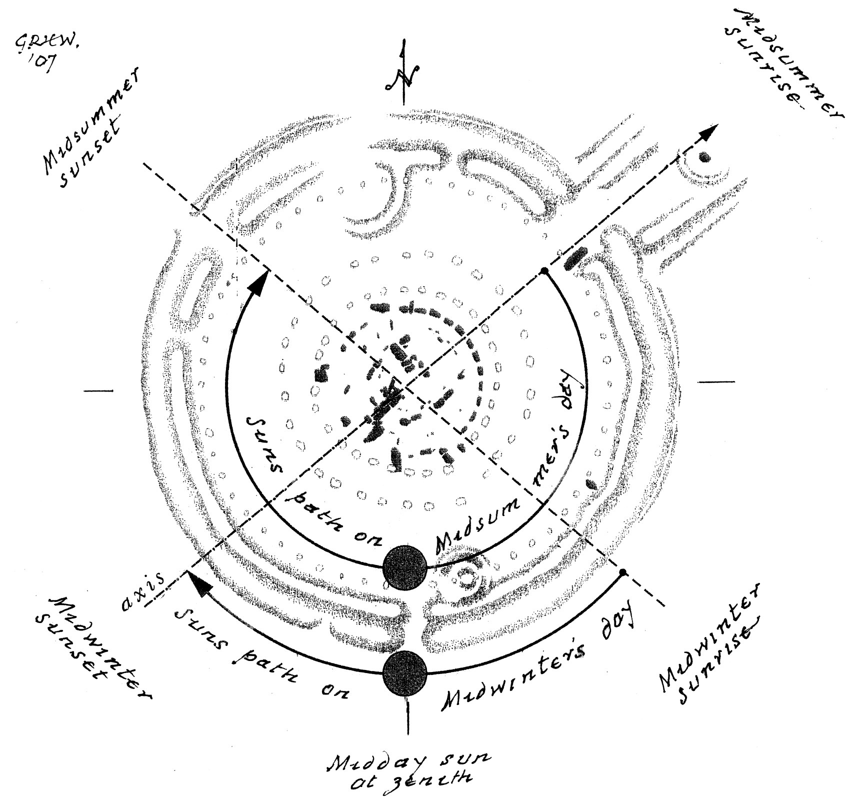
37. Traditional modern setting out arrangements. (1) Illustrated here are wooden devices used in Europe where timber is cheap (and reusable). To provide permanent control points removed from disturbance due to building operations or casual passage wooden frames are built outside the external angles etc of the building. These are positioned to parallel the required setting out lines so that the trace of the building lines can be marked on the wooden rails (by incising etc). Hence the devices are called "sighting rails". The sighting rails stand well above ground level so that cords can be stretched between the marks clear of any obstruction on the ground, and the trace of the building line can be marked at any level by plumbing from the stretched cord – e.g. down to the bottom of the foundation trench, or at plinth level well above the ground. They are also used to give a datum point for levels (i.e. a bench mark) so that e.g. the level can be directly transferred to the fabric of the building by using a plank held horizontally as determined by a spirit level. (2) Detail of traditional modern setting out arrangements. Here instead of wooden frames, solid brick pedestals are shown. On these pedestals are marked the various building lines required for external walls – e.g. the axial line, the lines for excavating foundation trenches, the lines of the socle of the upstanding walls, etc. By stretching a cord and plumbing these lines can be marked out at the appropriate level, rechecked or re-established as may be necessary.



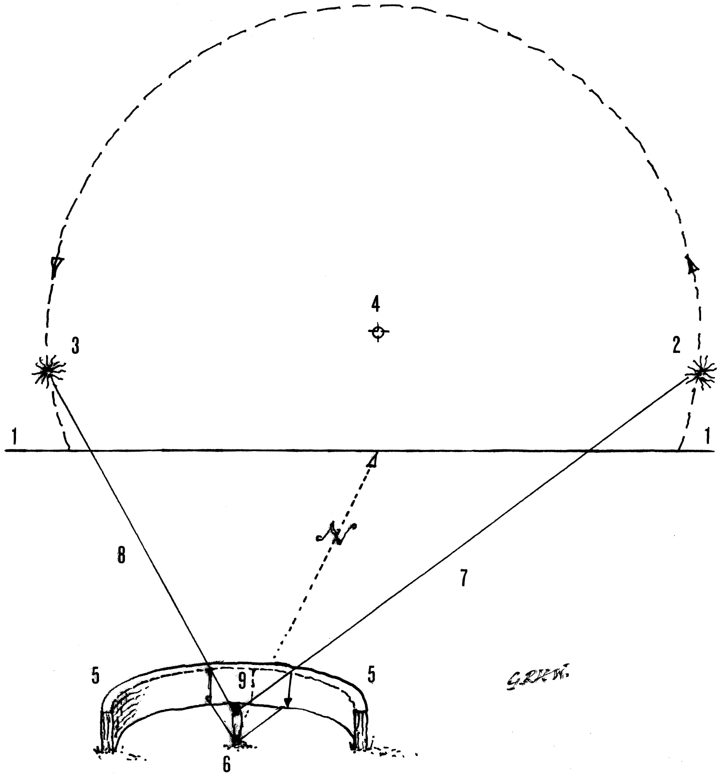
38. Simplified and idealised arrangements for setting out rock cut premises. As opposed to arrangements for setting out *al fresco* building, where the controls are placed outside the limits of the building, the controls for setting out rock cut features must be organised within the desired confines. There is also the very salient contrast that all work must be carried out in an upside down fashion so that setting out lines must be marked on the ceiling not on the floor; In some way access to the chamber must be gained close to roof level, and a tunnel driven into the rock (the cuniculus) along the desired axis of the building. The axis is then marked out on the ceiling of this tunnel. The line of lateral walls is then established by cutting tunnels for offset lines of the required length and marking these lines on the tunnel ceilings (1). The body of the chamber can then be quarried out down to floor level, subject to the control of the lines marked out on the ceiling (2). As a matter of convenient practice the rock is not cut away to the ultimate fair face desired. Instead, as for much ancient masonry construction, removal is halted so as to leave the surface of the rock somewhat in advance of the desired true face. This protective coating is then removed as a separate process (fine dressing or *ravalement*); Unfinished work indicates the method employed for this process in Egypt. Plumb lines are suspended at intervals to give the plane of the preliminary faces. The plane of the final fair face is then determined by 'boning in' from these lines. This is effected by the master mason sinking a series of recesses subject to the control of the boning rod. When the correct depth has been reached, the rock at the rear of the recess is painted with black paint. The protective rock coating can then be dressed away easily subject to the control of these regularly spaced black painted "targets".



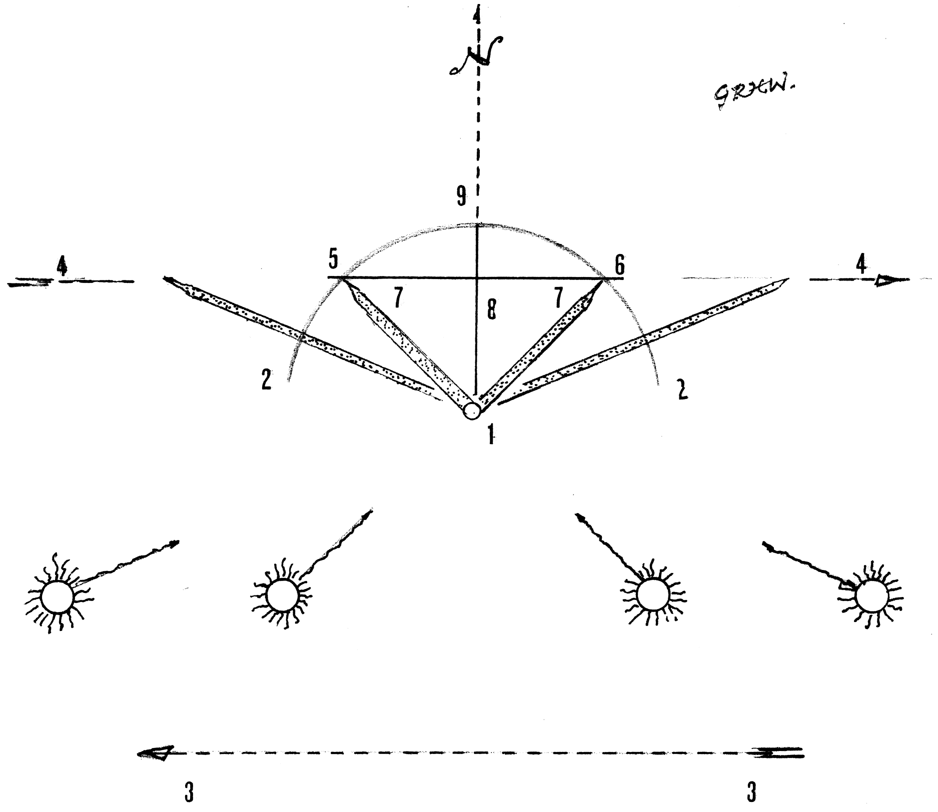
39. Orientation of Neolithic Round Barrow Chamber Tombs. British Isles 4th Millenium BC. A. Maes Howe, Orkneys; B. New Grange, Ireland; These great monuments are oriented by direct alignment with astronomical phenomena, Maes Howe on midsummer sunset, and New Grange on mid winter sunrise. True North is not shown on these plans since it played no part in the orientation of the monuments.



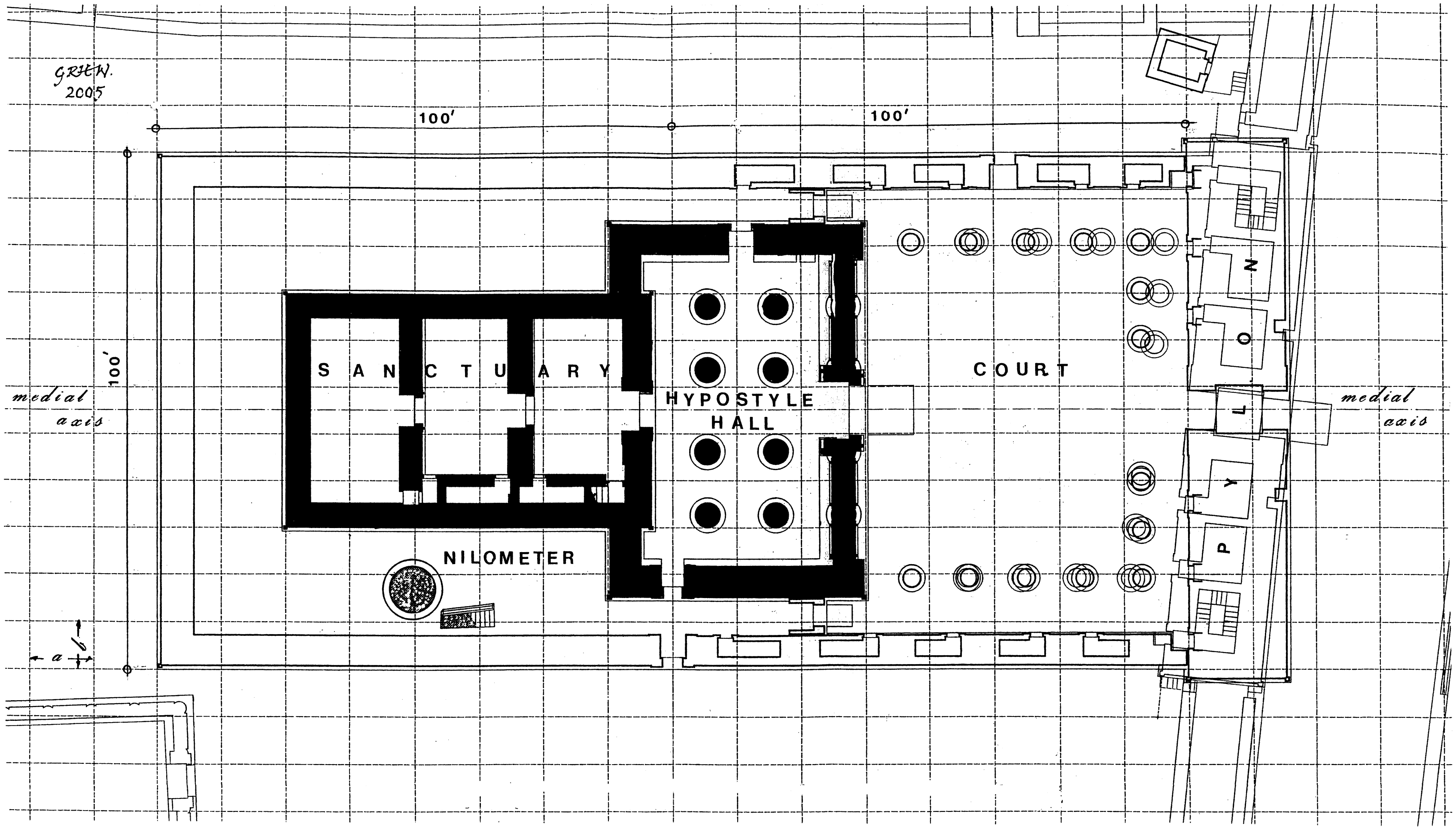
40. Stonehenge. Astronomical Orientation. Southern England 3rd Millenium BC. The access of the circular monument defined by its approach way was oriented on the azimuth of the sun's rising at the summer solstice (which here coincides with the sunset at the winter solstice). Also the position of various isolated stones serve as marker of other astronomical phenomena (both solar and lunar). Such astronomical phenomena were identified and understood by continued observation over the centuries – e. g. the astronomical fact that at this latitude the azimuth of sunrise on midsummer's day and of sunset on mid winter's day were one and the same; In addition to testifying to these matters of empirical knowledge, Stonehenge has been seen by some modern astronomers as witnessing to advanced astronomical knowledge – e.g. the predetermination of eclipses. Such theories are controversial. After Souden p. 120.



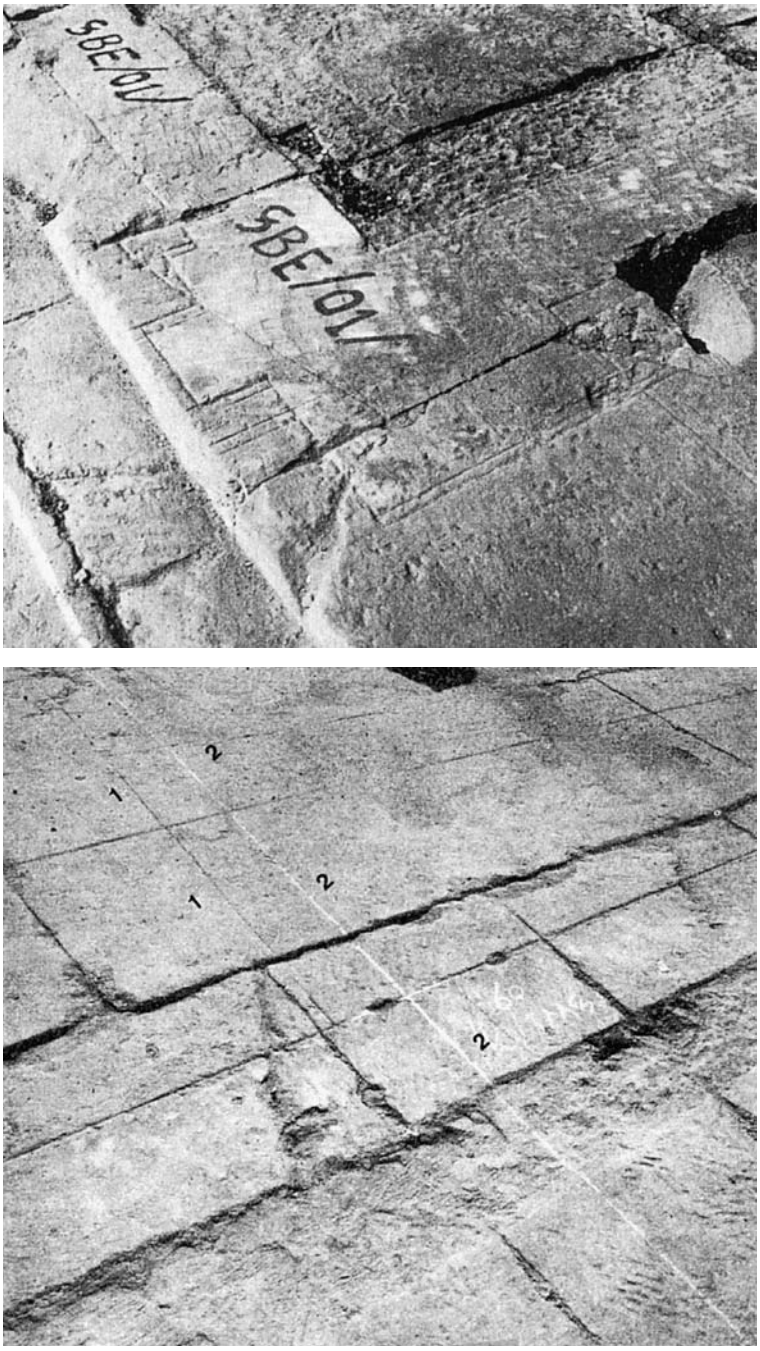
41. Simple method for determination of True North by direct observation of the azimuths of the rising and setting of a near circum polar star marked on an artificial horizon. (1) Natural horizon; (2) Rising star; (3) Setting star; (4) Elevated (North) Celestial Pole; (5) Artificial (level) horizon; (6) Observer; (7) Marked sight on azimuth of star rising above artificial horizon; (8) Marked sight on azimuth of star setting below artificial horizon; (9) Bisection of angle between (7) and (8).



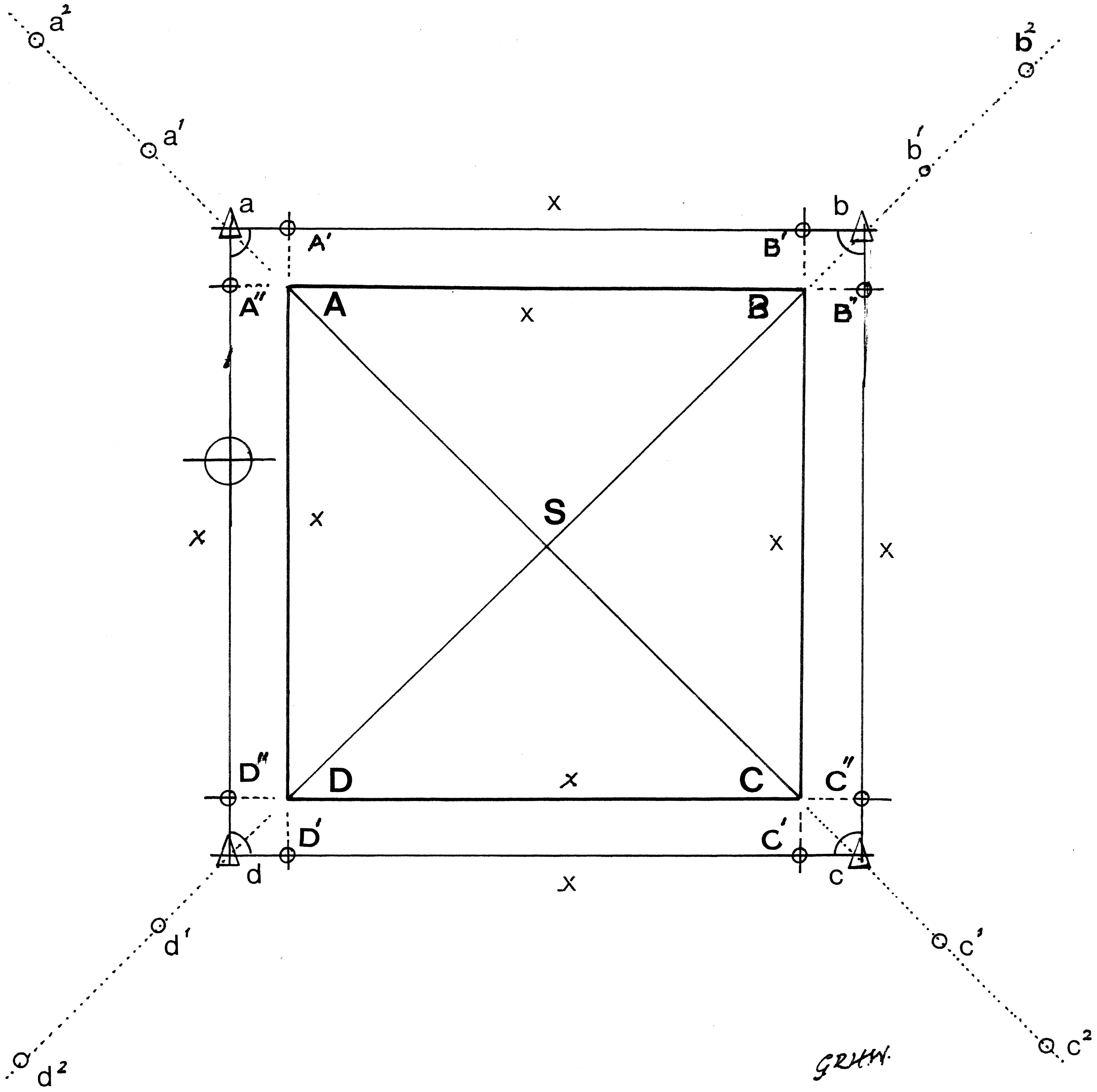
42. Simple method for determination of True North by observation of moving shadow of upright pole (gnomon) cast on ground by the sun's movement across the heavens. (1) Gnomon (vertical pole); (2) Arc described on ground with centre gnomon and radius suitable for intercepting the track of the shadow cast by extremity of gnomon; (3) Path of the sun from East to West across the heaven (Northern Hemisphere); (4) Path of the extremity of gnomon's shadow from West to East across the surface of the earth. (In general the actual path is in the form of a curve.); (5) First intersection of extremity of shadow with the arc; (6) Second intersection of extremity of shadow with the arc; (7) Cord drawn between the two intersections; (8) Bisection of cord (and angle between the two intersections); (9) Direction of True North.



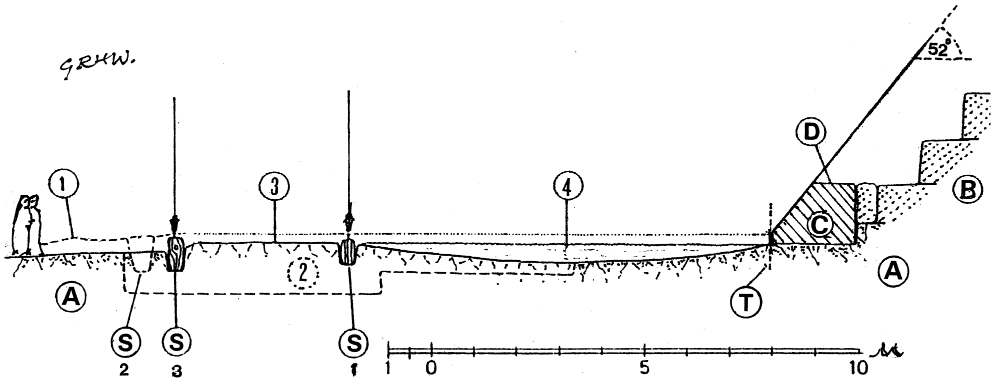
43. Kalabsha Temple of Mandoulis Nubia. 1st Century AD. Setting out and Grid Design; Researches into this Graeco-Roman Temple attendant on its transfer to avoid submergence in Lake Nasser established that it was designed as a double Hekatompedon on a grid system based on the Fibonacci series (1, 2, 3, 5, 8 etc). This instance is of interest in connection with the general question of what guide lines actually were set out to control construction; In this instance it may be that it was the grid (or a skeleton version of it) which was marked out beyond the limits of the building so as to control setting the socle course of the wall masonry. When the upper beds of this course were finely dressed (*in situ*), control markings to demarcate the plan of the upstanding walls were then inscribed directly in the stone bed of the socle. NB. The Pylon has been skewed out of grid design so as to include a Ptolemaic structure within the temple enclosure. After K. C. Siegler. Kalabsha 1 Abb. 24.

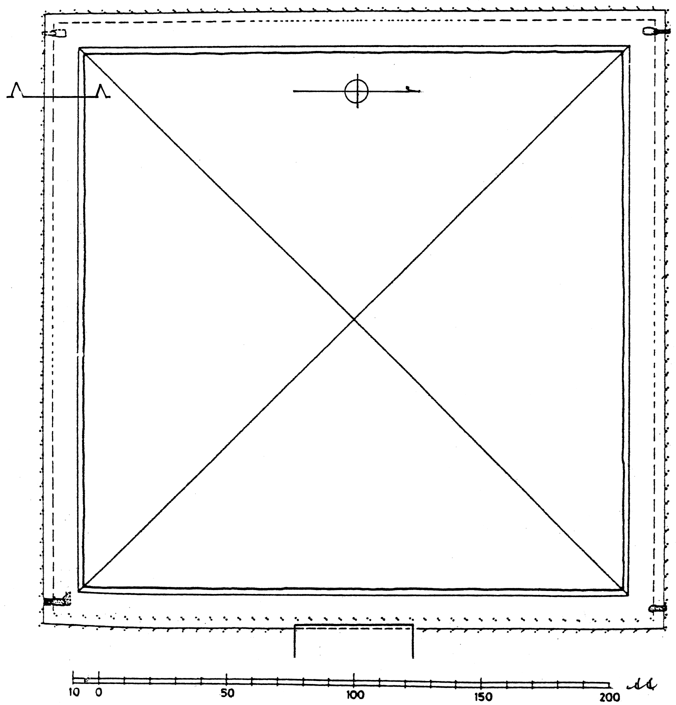


44. Kalabsha Temple of Mandoulis Nubia. 1st Century AD; Setting out lines incised in stone on upper beds of (non visible) foundation courses revealed by the total dismantling of the Temple (1961–62). Controlled by the primary markings outside the area covered by the temple, the lines necessary for building the temple according to the plan were incised in the masonry. These included both axes and wall lines. Because of the system of *in situ* dressing these lines remain preserved only on non visible surfaces; *Below*: Medial axis of the Temple (1) incised on upper bed of foundation raft i.e. below the paving blocks. The white painted line to the right (2) is an axial line belonging to the system of axes set out to control the dismantling of the Temple in 1961-62. The indication of the axes was carried up course by course but for the most part has been removed by final *in situ* dressing of upper beds; *Above*: Demarcation lines for the upstanding masonry of walls incised on the socle course of the sanctuary (the lowest course to be dismantled). These markings are only preserved in the projecting socle course. Such markings existed also on the upper bed joints of the upstanding walls but were no longer apparent as the masonry had been dressed back to the face markings they indicate. After Siegler Kalabsha 1 Taf 24.

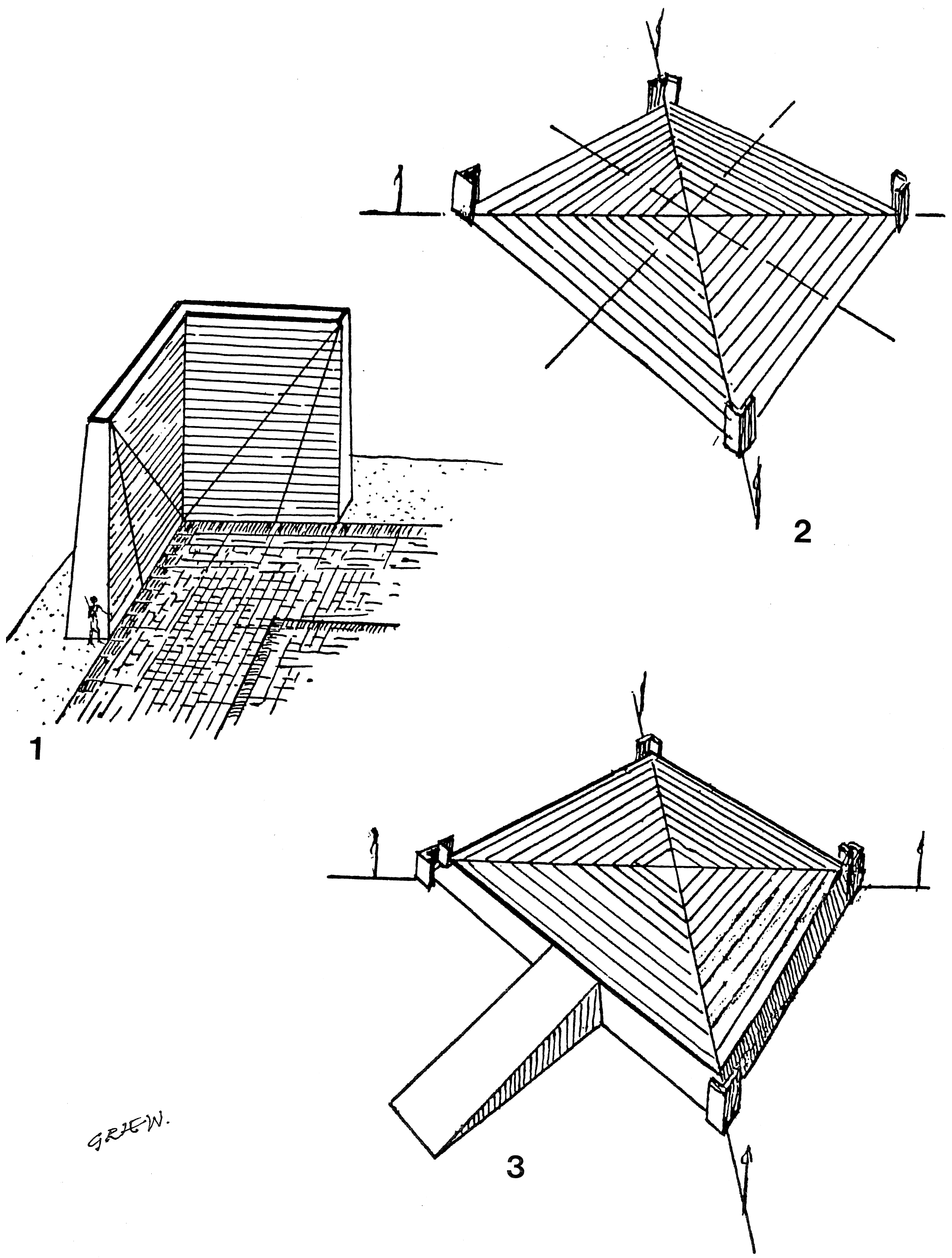


45. Ideal scheme for setting out and controlling the erection of a true right pyramid A, B, C, D, length of side X; Line a d is laid down oriented true north, of length somewhat greater than x. Lines a b, c d, e d, d a are then constructed and laid down so that the interior angles are all right angles constituting a square with length of sides x+ and oriented N-S, E-W. On line a b points A', B' are marked off so that A' B' = AB = x; and on line b c points B", C" are marked off so that B" C" = BC = x etc. The intersection of line A' D' and line A" B" determines the position of Pt A etc to establish the ground plan of the desired pyramid; The diagonals of the square a b c d are then produced externally so that the intersection of these diagonals determines both the centre of the base of the pyramid and the summit of the elevation of the pyramid vertically above it. During the erection of the pyramid vertical markers are set up at points a^2, a^1, b^2, b^1 etc. and sighting along these markers controls that the arises of the pyramid AS, BS etc remain in a straight line on the one vertical plane. In this fashion the arises will meet at the point S, the summit vertically above the centre of the base. This gives an overall check that the masonry construction has remained true and out of twist.

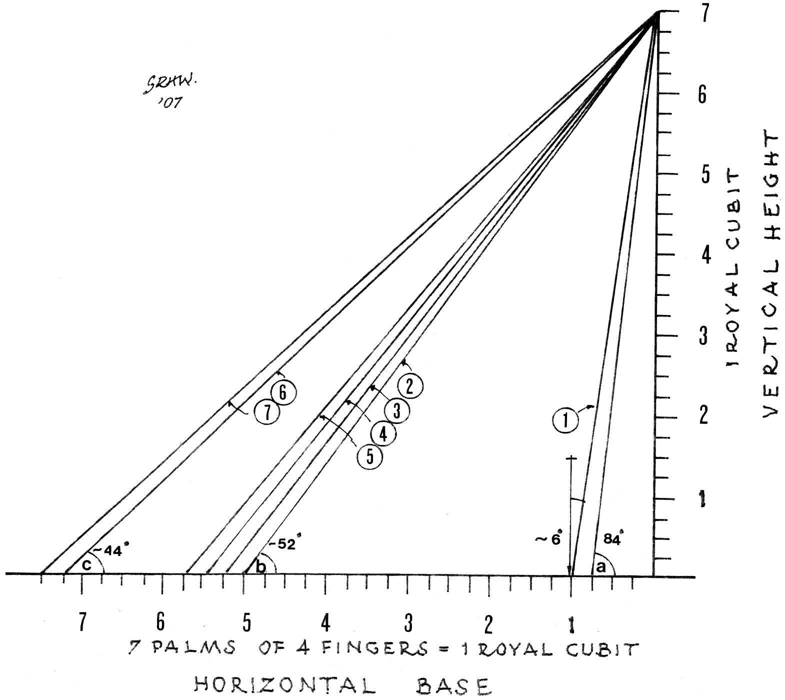




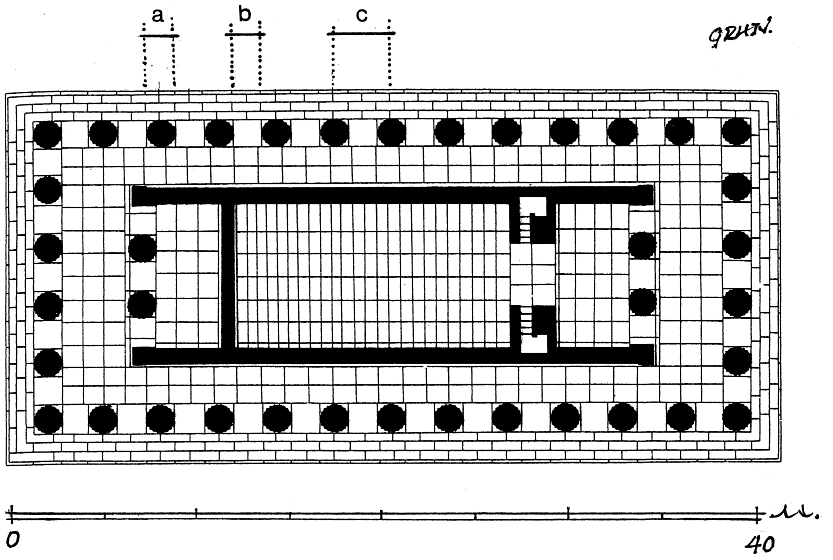
46. Pyramid of Khafre. Evidence of Setting Out. Details. Gizeh 2500 BC; The establishment of the plans of the colossal 1st and 2nd Pyramids is astonishingly accurate in all respects (i.e. for line, length, orientation, angle and level). Repeated checking with modern surveying instruments has verified that the % error is well within the strictest standards required for modern structures. How this was effected has always been of interest, since the site of the Pyramids was originally uneven sloping rock and the core of the Pyramid was a residual rock mass which blocked off all direct access and view from one side to another. In recent years the area of bed rock about the base of the pyramids has been closely examined for evidence of the setting out procedure. Information has been revealed which is in line with basic practice. However in view of the vast scale the basic procedure is elaborated. The Pyramid of Khafre affords a fairly coherent picture. The first operation when the bed rock had been roughly levelled in the region about the required base of pyramid was to cut 4 trenches about 10m outside the intended 4 angles of the pyramid. These served to adjust a preliminary setting out of a square about 10m outside the required base plan. Alignment of holes set in the rock at intervals of roughly 1m indicate that these setting out lines were measured accurately with measuring rods, while at extremities of the lines right angles were laid off by erecting perpendiculars. The accuracy of this square depended on the equal length of the sides and the exact angular traverse, since there was no possibility of measuring the diagonals because of the intervening rock hillock. In the normal course of events this enveloping square would constitute the setting out device for the base of the pyramid. However in these exigent circumstances it seems the whole procedure may have been repeated two further times about 4m outside the original square each time refining the accuracy, and the base plan of the Pyramid was marked out by reference to the refined square. When the first course of casing blocks were set to this plan, their upper bed joints were dressed *in situ* to a continuous horizontal plane which provided the level datum for all measurements in elevation. The remaining control required was to ensure that the arrises of the pyramid remained rectilinear. This could only be obtained by backsighting along the lines of the extended diagonals. Evidence for such sighting stations was not located as lying outside the area of the base of the Pyramid, however it is interesting to note that the original trenches terminated where they would have abutted on the extension of the diagonals. *Key to Section*: A. Bedrock; B. Pyramid Core blocks; C. Pyramid Facing blocks; D. Probable plane of horizontal datum for measurements in elevation; S^1, S^2, S^3 One of the holes cut in the rock to house wood stakes or pegs to define the path and length of successive setting out lines for determining the exact position of one side of the pyramid; T. Line of Pyramid base laid off from setting out line (S); 1. Original surface of rock; 2. Trenches outside angles of pyramid for locating position of setting out lines; 3. Rough dressing of bed rock to give points for panels for setting out line; 4. Rough dressing of bed rock into shallow trough between setting out lines and pyramid base. (This sometimes has been interpreted as a water trough to provide the basic horizontal level datum for the pyramid.) After Lehner JARCE XX 1983 pp 23,24.



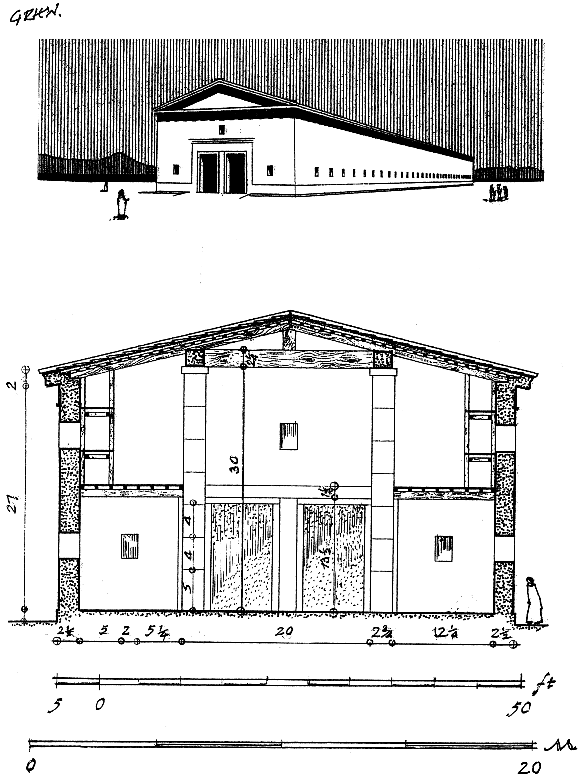
47. Setting Out Pyramids, Control of Elevation. Aspectually the form of a pyramid in elevation is much more significant than its form in plan. Thus some device must be available to establish and control exactitude in elevation over an extended passage of masonry. One device suggested is the "angle placard", sometimes proposed as an illustration for controlling the batter in normal building. This consists of a vestigial angle on the inner faces of which is marked the inclined lines of the intended battered wall faces. In the case of a pyramid this means that the apothem is available at hand as a reference or a check; In spite of its theoretical value, it is very unlikely that such a device was employed. It is simply more trouble than it is worth in upstanding building. The evidence for its application in building is most probably restricted to underground construction where it is perfectly reasonable and practical. *Key*: (1) The "placard" constructed in brick set up outside the angle of a pyramid; (2) View showing the placard installed and used as a sighting device to check arrises; (3) View during construction of a pyramid with the lower courses of the casing blocks set. NB. The original drawings 2 & 3 are not explicit. After A. Bedawy JEA 63, 1997 figs 1, 3.



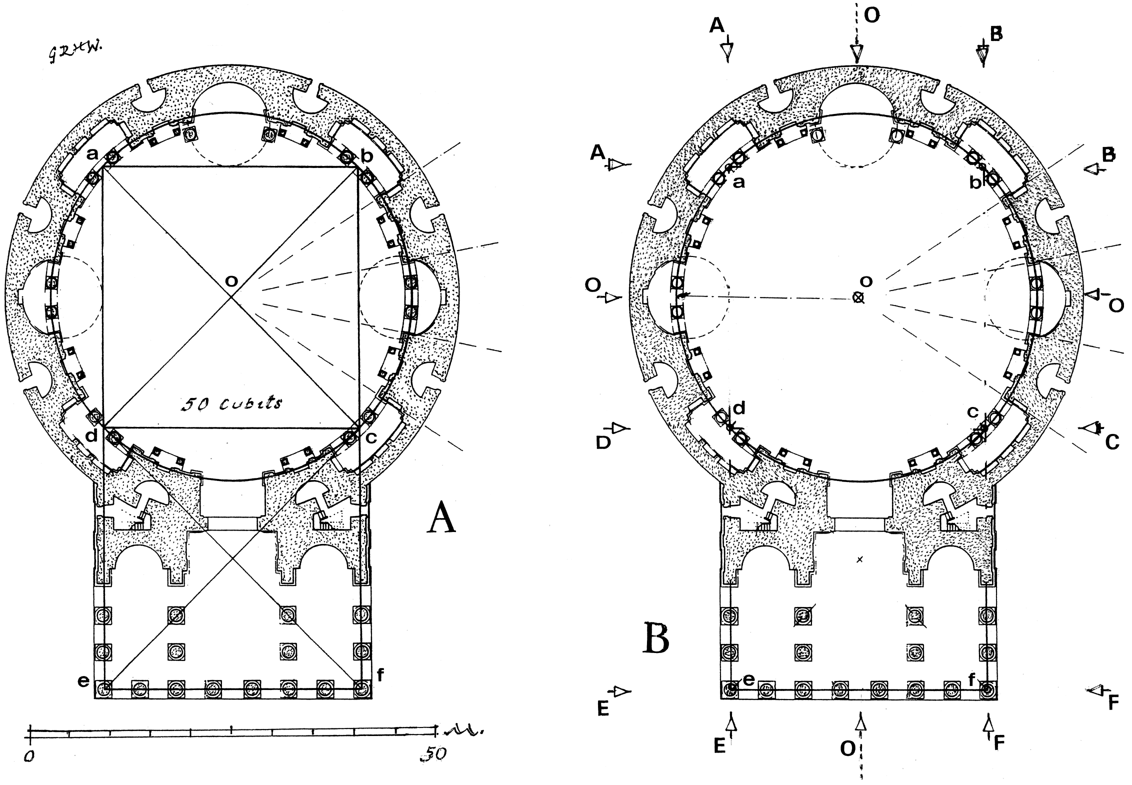
48. Diagram showing the inward inclination (batter) of the external faces of monumental masonry in Egyptian building (= s q d). The ancient Egyptians reckoned the s q d as so many palms or fingers to the vertical height of 1 cubit (= 7 palms). This diagram illustrates the characteristic s q d of various constructions (1) The external walls of monumental buildings, e.g. temples; (2) Abu Sir pyramid of Queen Khantkawes II (Dyn 5); (3) Gizeh 2nd Pyramid, of Khafra (Dyn 4); (4) Gizeh Great Pyramid of Khufu (Dyn 4); (5) Abu Sir Pyramid of Sahure (Dyn 5) [the average angle of inclination of Old Kingdom pyramids is thus ca 52° to the horizontal]; (6) Dashur Bent Pyramid of Sneferu, upper (Dyn 4); (7) Dashur Red Pyramid of Sneferu (Dyn 4);.



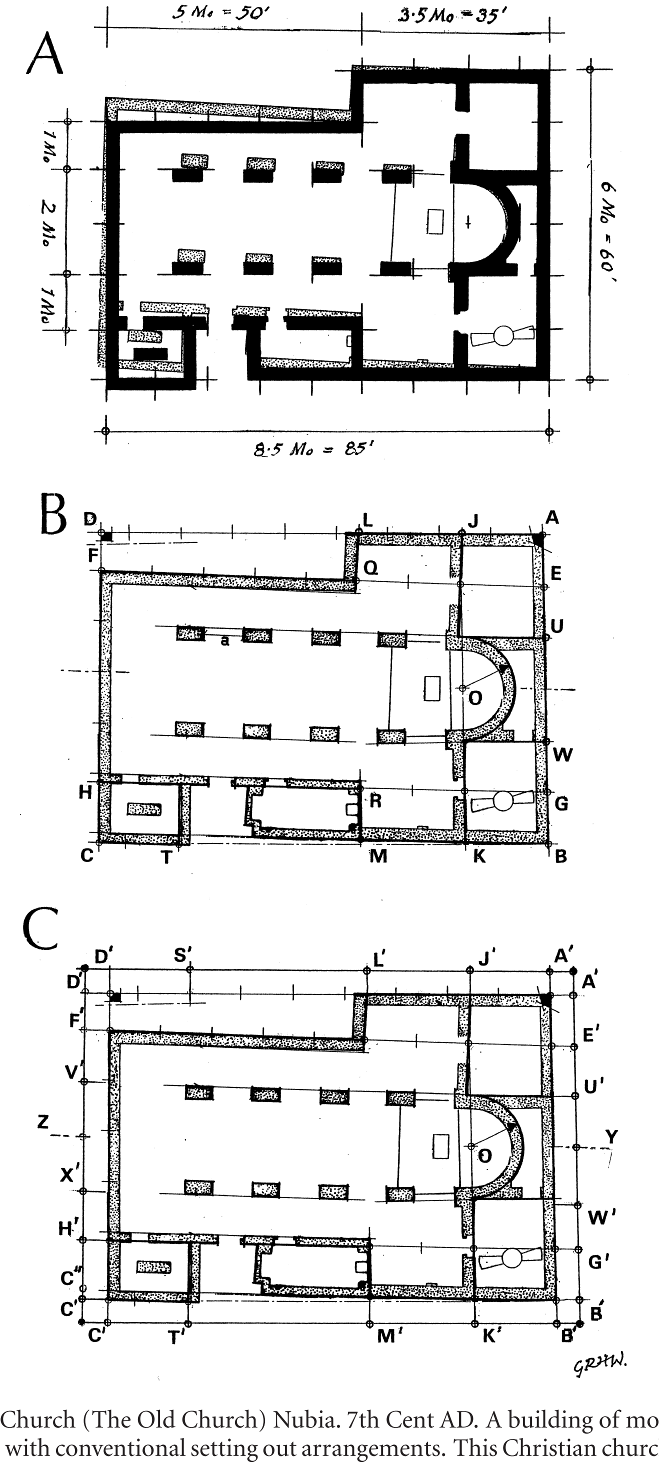
49. Agrigentum Temple of Hera. Sicily ca 470 BC; Setting Out and Masonry “Harmony”. The crepis of the Classical Greek Temple was a very characteristic feature and its masonry construction was punctilious. In this temple the rising joints of the blocks in alternate courses kept exact step (like brick masonry with its vertical perpends). Thus the setting of blocks in the lowest course of the crepis conditioned the pattern of the blocks constituting the stylobate, the uppermost course of the crepis with its visible upper bed jointing. In this way the desired pattern of the stylobate masonry was known and applied to determining the exact length of the finely dressed blocks of the lowest course of the crepis. However the visible masonry pattern of the stylobate blocks was not an end in itself. This pattern was of prime significance because of the rule that the peristyle columns kept step with the stylobate block, *viz* the columns stood centrally each one on one stylobate block with the alternate blocks of the stylobate occupying the space between the columns. Now the axial distance and intercolumniation of the peristyle columns was probably the most significant design feature of a Greek Temple. Accordingly these dimensions were already settled when the masons were given the (exact) dimensions for dressing the blocks of the first (lowest) course of the crepis, or even the euthynteria, the first visible course of upstanding masonry; This does not mean necessarily that the mason’s yard was supplied with a stone for stone plan of the masonry course of the crepis – nor even that such drawings existed for the architects reference. Indeed the facts can be regarded from the opposite view point, *viz* that the setting out of the design details was controlled in part by the accuracy of the fine stone masonry. *Key*: (a) Stylobate blocks bearing columns and corresponding blocks in alternate lower courses; (b) Stylobate blocks occupying intercolumniations and corresponding blocks in alternate lower courses; (c) Interaxial spacing of 2 stylobate blocks. In these closely set columns the base diameter is approximately equal to the intercolumniation = 1 stylobate block and the interaxial spacing = 2 stylobate blocks.



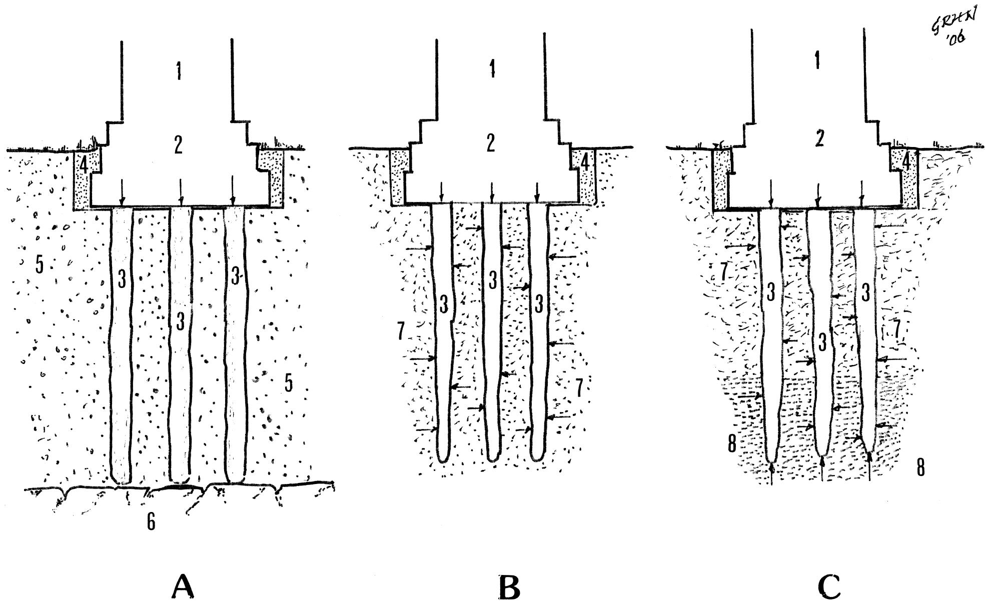
50. Piraeus Naval Arsenal. Athens 347-46 BC. Reconstructed Cross Section and Perspective View. A surviving inscription gives a detailed description with dimensions in Attic feet of this building project to be awarded on contract. Whether design drawings of the building were also available is not known, but it would have been perfectly possible to set out and construct the building solely on the written information supplied. The information covers equally the details in elevation. These do not figure in the setting out markings on the ground so that after the plan of the building has been established further construction work proceeded either on written information such as contained in this document or on dimensioned elevation drawings such as reconstructed here –or on both combined. After Hellmann Figs 7, 8.



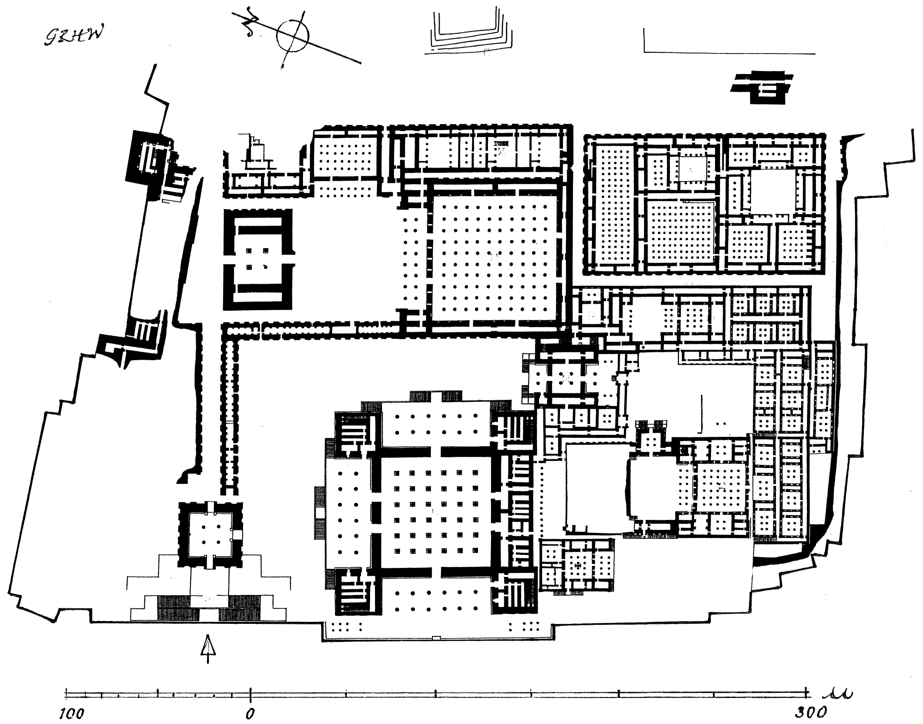
51. Rome. The Pantheon. 125 AD. Geometrical Construction of the design and indication of possible setting out controls marked on the ground. The term "setting out" is applied variously and is often used to denote the geometrical construction set up to design a monument (A). It is possible on occasion that this construction is laid out on the ground to determine the position and orientation of a monument by locating its critical points. However the initial marking out of these points on the ground does not constitute an effective "setting out" of the building on the ground. This is demonstrated here by the obvious fact that points a, b, c, d, e, f will be obliterated by the first construction work carried out (e.g. excavation for foundations). Some control marks must be established on the ground outside the area covered by the building so that they remain available for reference as required throughout the building operations. A hypothetical scheme of such "setting out" control marks on the ground is indicated (B). NB. There are other geometrical analyses proposed for the design of the Parthenon. After Wilson Jones. Principles.



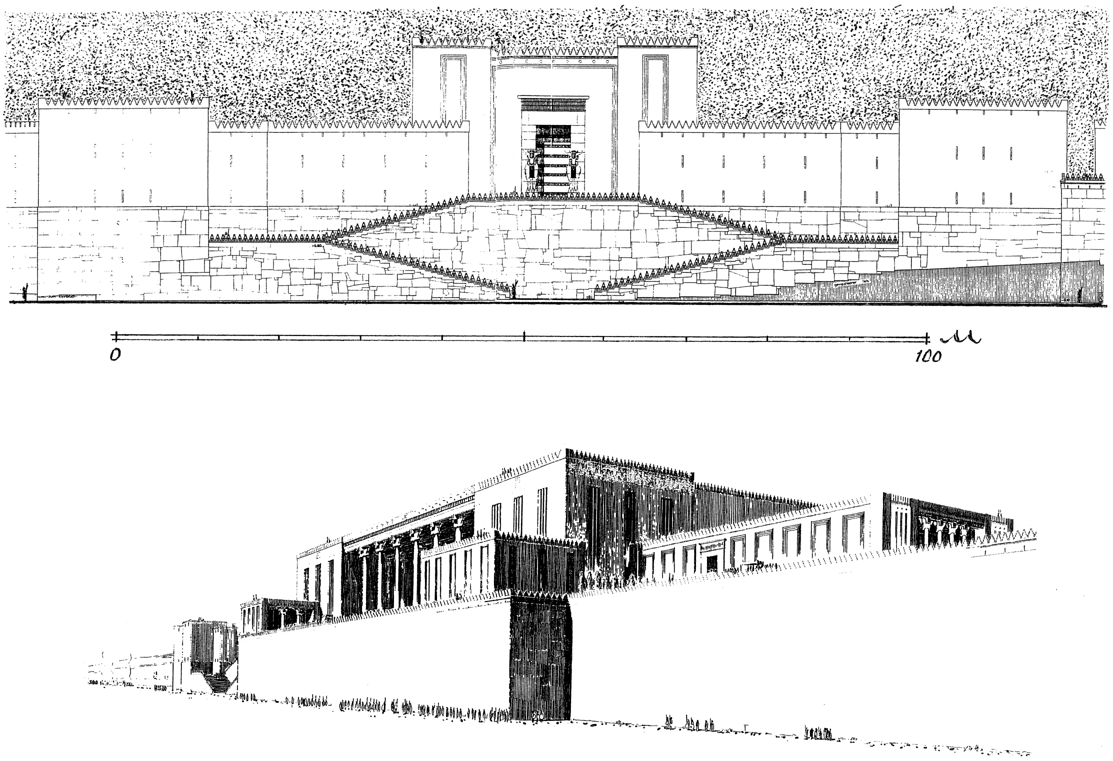
52. Dongola Basilican Church (The Old Church) Nubia. 7th Cent AD. A building of modular design adjusted in construction shown with conventional setting out arrangements. This Christian church from the latest years of the Ancient World was regularly designed on a module of 10 feet (of 31+ cms), however for some reason it was skewed slightly in its orientation which affords a useful illustration of the distinction between design drawing and the setting out data for construction. A. The church as designed (black) with indication of the church as constructed (stippled); B. The church as built with critical points necessary to establish the plan (A-T); C. The church as built with setting out markings located outside the area covered by the building so as to be undisturbed by the construction work. Cords are stretched between the pairs of corresponding points (e.g. A^1 – B^1, B^1 - C^1 etc) to give the line of the walls, and the intersection of two cords gives the critical points of the design. The building plan cannot be controlled by setting out Pts A, B, C, etc directly as, e.g. excavation for the foundations will disturb or destroy them. After Dufay in Dessin p. 316, figs 4, 5.



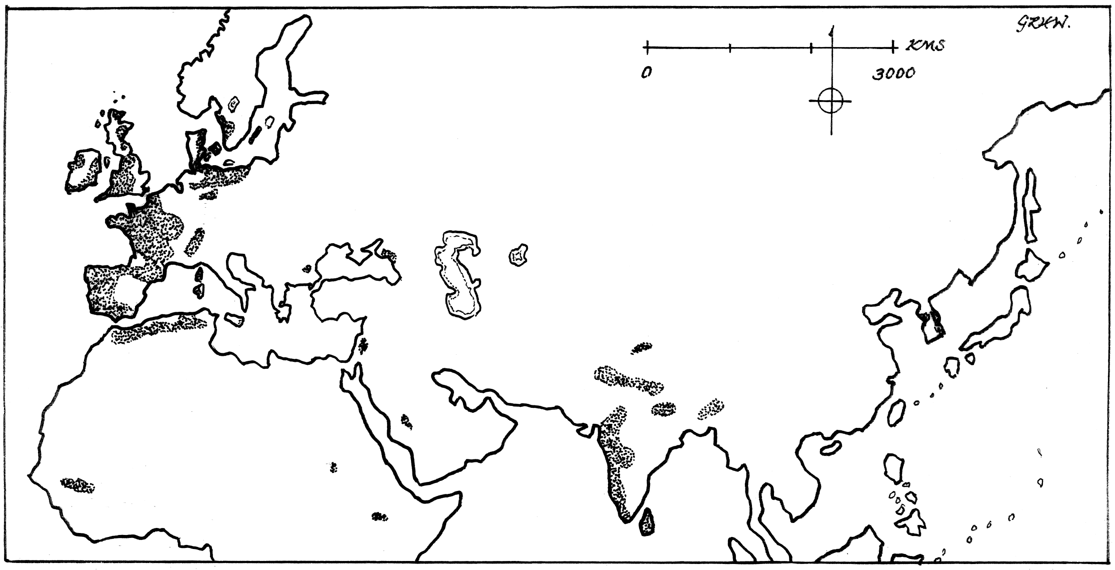
53. Piled Foundations. Wooden piles to stiffen insecure ground (natural foundations) were a common device in ancient building. They had three broad applications. A. Bearing piles (piles driven down to solid footing); B. Friction piles (piles immobilised by lateral friction); C. Friction and Bearing Piles (piles immobilised by combined friction and resistant footing). *Key*: 1. Wall; 2. Masonry foundations; 3. Wooden piles; 4. Foundation trench; 5. Loose uncompacted soil; 6. Bed rock; 7. Semi compact soil; 8. Stiff, compact soil.



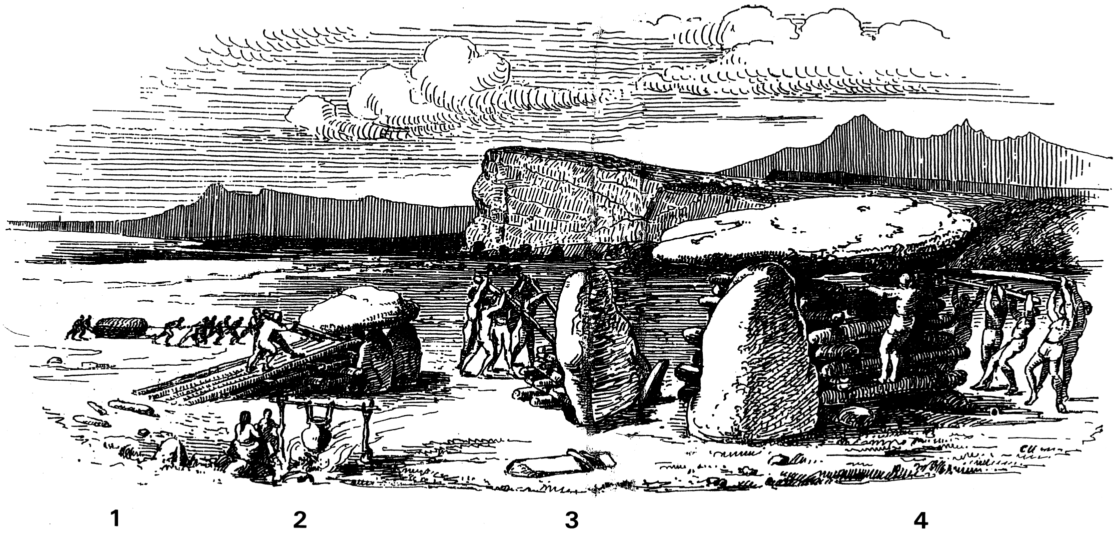
54. Persepolis. The Dynastic Seat (Takht) of the Achaemenid Empire as constructed by Darius and Xerxes. ca 500 BC. This inspired complex of monumental buildings is the outstanding example of site development (creation) in the broadest sense surviving from the Ancient World. A grand terraced podium backed by cliffs and fronted by a far spread plain was raised 11m above the level of the plain on a massive platform of masonry. The area is ca 12 hectares, that of a large ancient city. All the individual buildings set on it were of monumental aspect and proportions. After Frankfort AAAO fig 110.



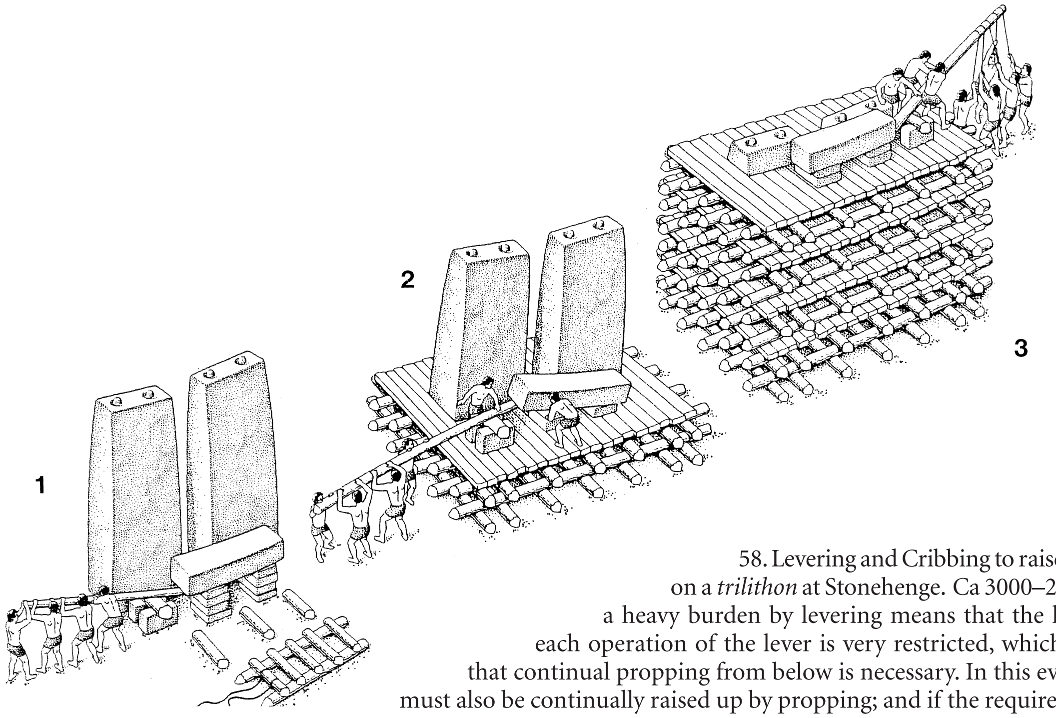
55. Persepolis. Reconstructed Views by Krefter of the Achaemenid seat of Empire raised up above the plain of Marv Dasht, the homeland of the Persians. ca 500 BC. *Above*: Elevation of the ceremonial entrance mounting by a Palladian stairway to the Gate of all Nations. *Below*: A perspective view showing the retaining wall of the terrace with the throne hall and approach stairway to the left. After Krefter in Trumpelman Persepolis pp 67, 76.



56. World Distribution of Megalithic Monuments (shown stippled). Included here are all unhewn stone monuments which can be reckoned Megalithic in type according to their manner of construction. In addition to the monuments in the Western Mediterranean and by the Atlantic shores of Europe which constitute a "class", there are sporadic examples of Megalithic construction in e.g. West Africa, Ethiopia, The Hejaz, Palestine, India, Ceylon, Korea. Because of their disassociation in space and time it is impossible to rationalise these latter monuments into a valid historical category of building. After Nel Dolmens and Menhirs fig 10.

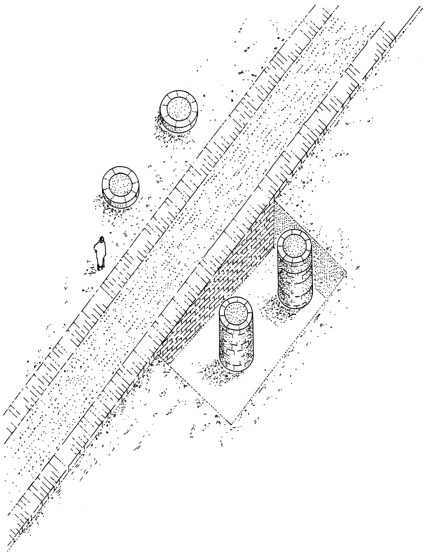


57. Site Installations and procedure for erecting Western European Megalithic Monuments by wooden ancillaries. This imaginative 19th Cent drawing shows an understanding of the technology available in Neolithic Europe. It emphasizes that the technology of megalithic building in Western Europe evolved out of the technology for building massive wooden structures – i.e. those formed from the boles of great forest trees (some above 1 ton in weight). Thus devices for raising up into position massive stone slabs were based on the use of timbering in various ways to facilitate hauling and leverage. The following operations are depicted in the drawing as indicated. (1) Hauling a megalith across level ground mounted on a wooden sled and/or on rollers; (2) Levering a megalithic roofing slab into position up an inclined plane (ramp) of wooden construction; (3) Raising upright the wall slab by levering and progressively supporting in position the oblique standing blocks by timber “chocking”; (4) What appear to be the sophisticated device of first raising up into position the massive roofing slab (by levering and cribbing) so that it is secured in position by temporary propping, then setting the wall slabs into position beneath it.

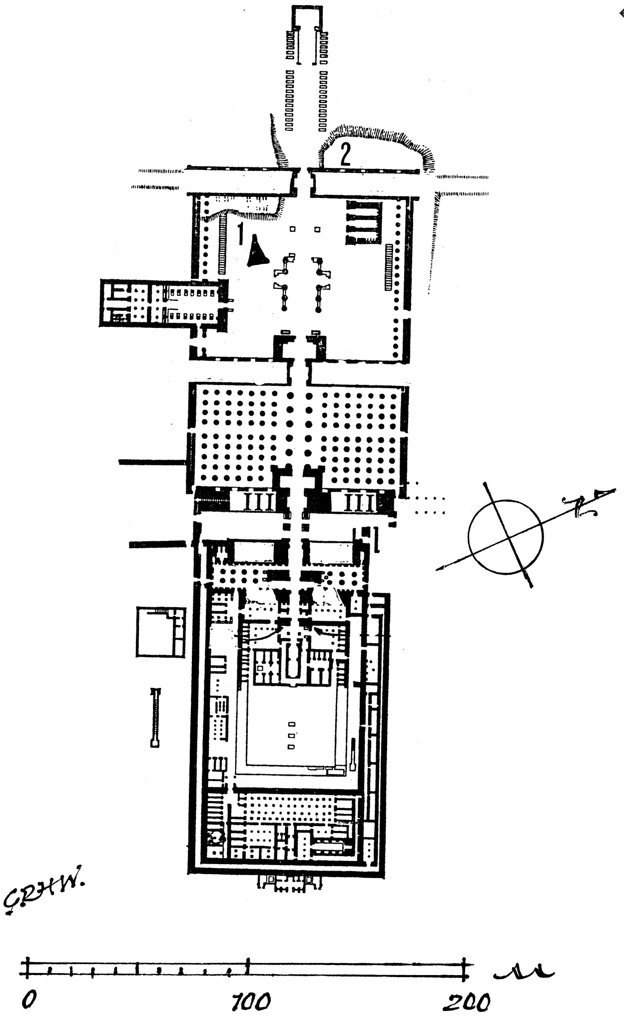


58. Levering and Cribbing to raise lintel into place on a *trilithon* at Stonehenge. Ca 3000–2500 BC. To raise a heavy burden by levering means that the height raised by each operation of the lever is very restricted, which in turn means that continual propping from below is necessary. In this event the fulcrum must also be continually raised up by propping; and if the required height is great then also a raised staging is necessary for the men levering. Such a staging (constructed from timber logs, baulks, planks) is called a crib. For any significant operation this required a large supply of heavy timber. In emergency the procedure is still practiced today. This illustration from a popular account is schematic only and defective in details.

59. Modern Cribbing for Emergency Field Construction Work. To make good a mountain road destroyed by explosives a working platform has been fashioned in the blasted cliff face by laying spaced out logs in courses alternatively set at right angles. This provides a stable and solid support for any building operation, and itself requires nothing beyond human energy to build. After P. Hodges p. 12, fig 12.

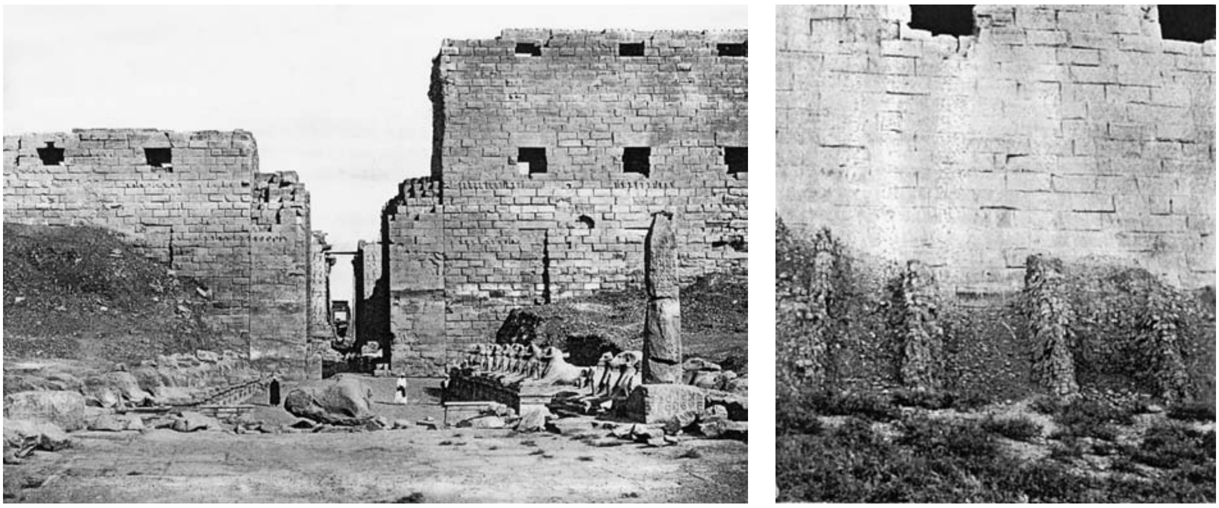


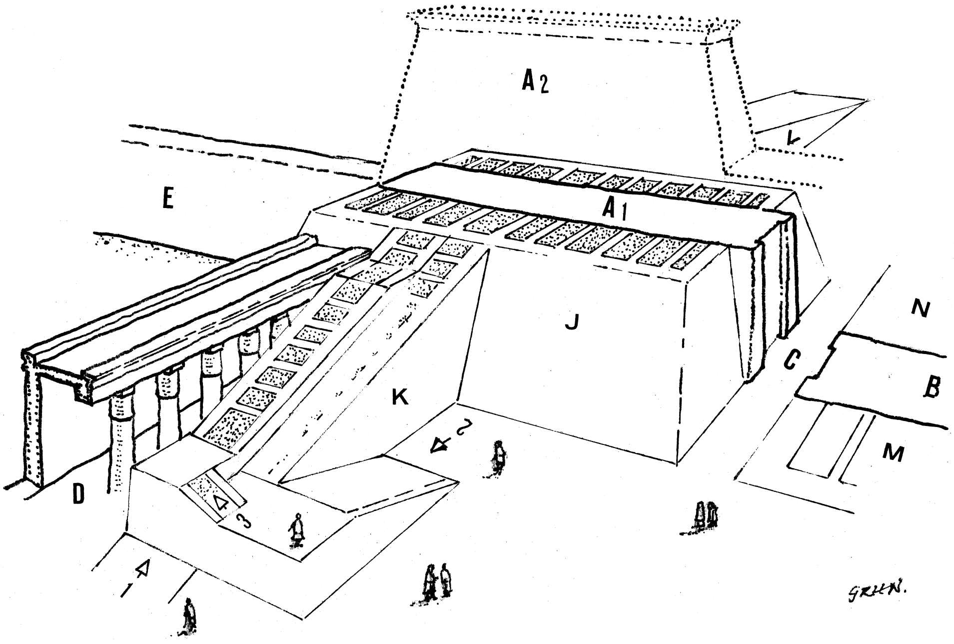
60. Pyramid of Senusuret I at Lisht. 12th Dyn. Ca 1920 BC. Transport haulage ramp ascending slope from Nile to Plateau. The ramp was 3.85m wide with brick retaining walls. The going is at an inclination of ca 8° or a rise of 1:6·5 which is relatively steep. Excavation revealed in one area the presence of 4 substantial brick "bollards". Although it is not clear from the publication how such constructions were combined with wooden posts (as suggested), their disposition by the haulage ramp so clearly parallels the stone bollards by the descending slipway from the Pentelic Quarries in Attica that it infers they were similar in function. Thus it is apparent that massive blocks were hauled up from the harbour. Four ropes were used for haulage, several men hauling at the bight of each rope while others behind this may have somehow looped the fall of the ropes around the pillars so as to provide a safe braking device throughout the haulage to prevent the blocks slipping back out of control down the ramp. In this way the haulage could be carried out in discrete stages with rest pauses in between. Whether this mode also admitted the use of rollers to reduce friction is an open question. In general the use of rollers beneath massive blocks is potentially dangerous with a rise steeper than 1:10. After Arnold figs 3.42 & 3.43.



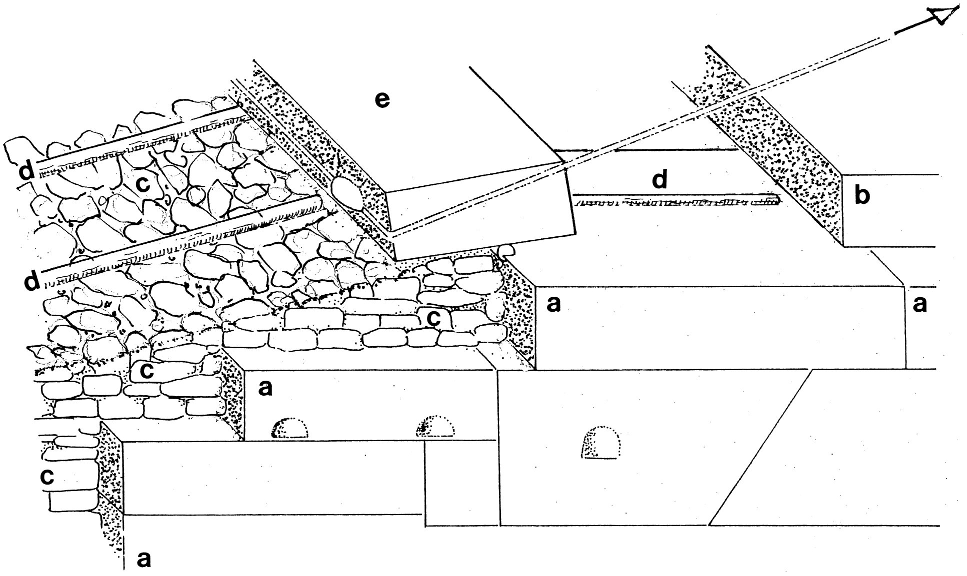
← 61. Karnak Temple of Amun Remains of Construction Embankments. Plan and Photograph. Thebes ca 370 BC. The first (outermost) Pylon at Karnak Temple (the work of Nectanebo I) was never completed, and very considerable remains of the construction ramps and embankments for the project survived into modern times. These remains have been progressively cleared away by the Antiquities Service in the interest of display; and now only a vestige of the embankment against the inner wall of the South Tower remains. 1) Remains of brick faced reinforced earthern construction embankment against inner wall of South Tower; 2) Remains of construction embankment against outer wall North Tower. The viewpoint of the photograph of 1 (*above*) is indicated by an arrow. After Arnold fig 3.50 (plan) & AAAE fig 49 (photograph).

↓ 62. Subsisting Remains of the Construction Embankment, unfinished Pylon I at Karnak. Thebes ca 370 BC. The final stage of construction work on a Pharaonic masonry structure was to clear the earth hillock raised about it for the delivery of the massive stone blocks onto the rising wall face. Thereafter the work of fine dressing and ornamenting the face of the masonry proceeded from scaffolding as is normal today. Sometimes, however, the work was interrupted and never finished, so that the earth mass subsisted in position to be gradually reduced in bulk over the ages. These photographs taken over 100 years ago show the situation as the site was being developed for display. The detail shows the grid of rubble stiffener walls, which consolidated the core of the earth fill. These photographs make it apparent that the construction method of Egyptian Pharaonic Masonry was identical with that of Western Megalithic monuments (Dolmens). An artificial earth hill was heaped up around and within the structure. However with Dolmens only the interior fill was removed, and the stone structure was left covered over by the external tumulus of earth; whereas with Egyptian Temples all the constructional earth works were scheduled for removal. After Clarke & Engelbach figs 87, 88.

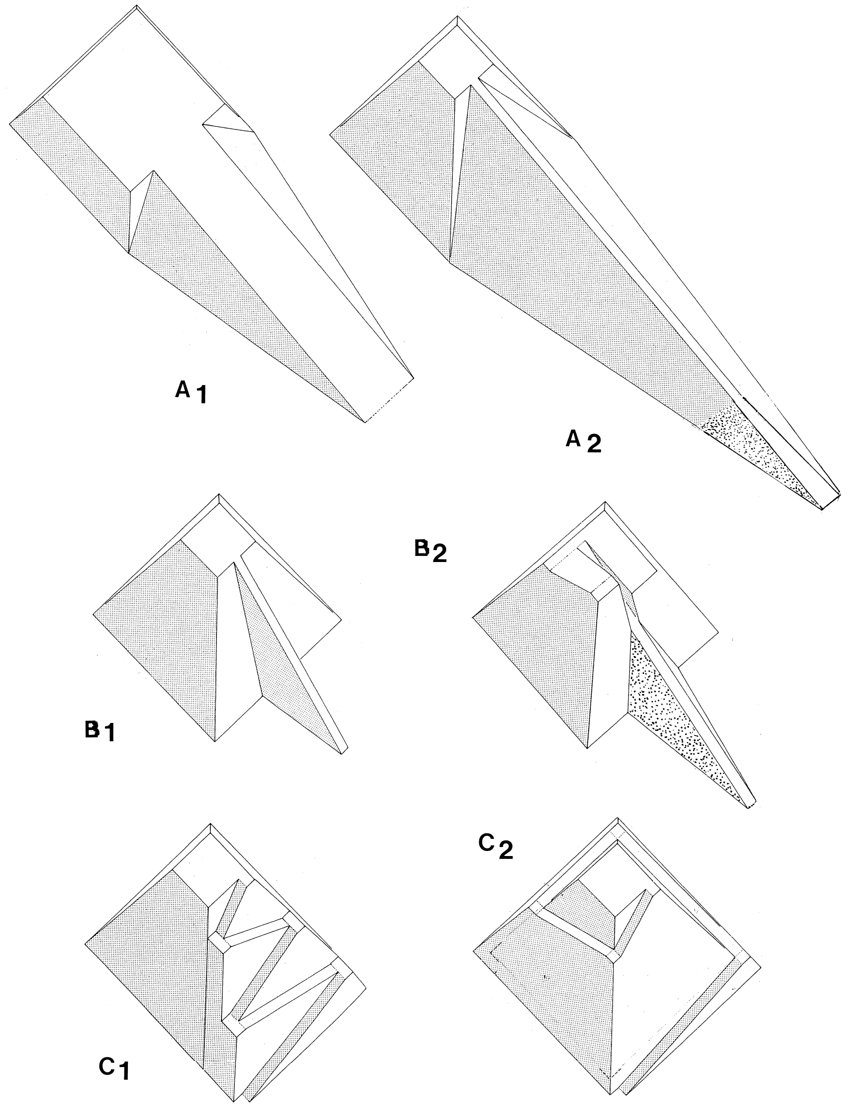




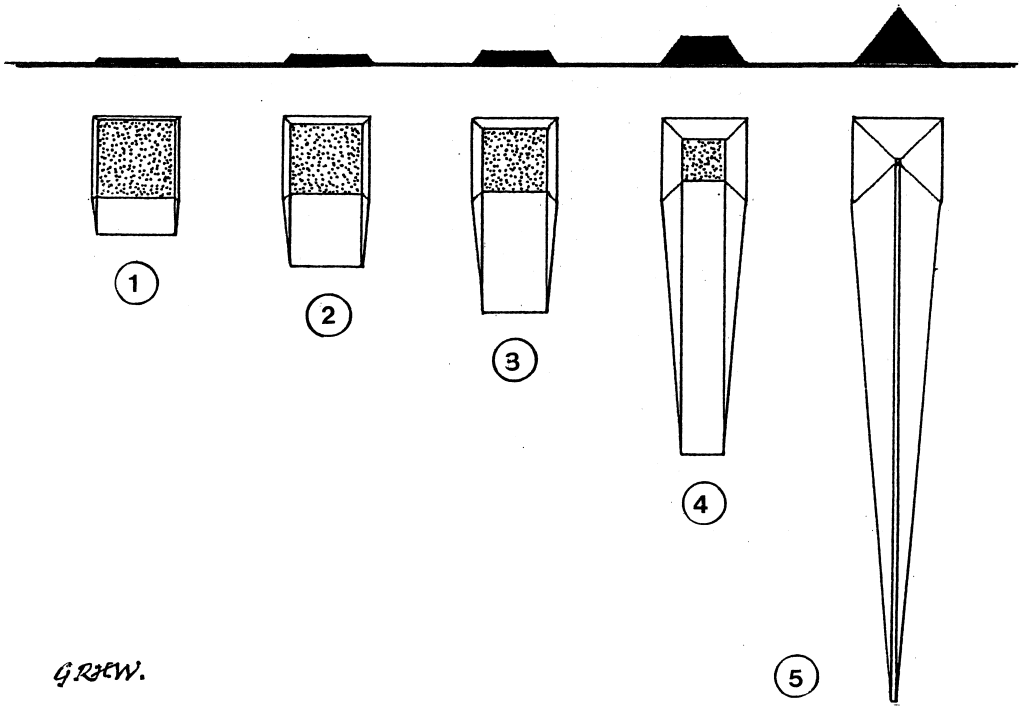
63. Pharaonic Building Construction Ramps and Embankments. The first (outermost) pylon at Karnak afforded striking evidence of construction earthwork by way of surviving remains. A reconstructed drawing (based on Holscher's original proposal) was presented by Arnold (fig 3.51). However the present diagram (following Arnold) may be regarded as of general significance. *Key*: A_1. Pylon South Wing – Standing Masonry; A_2. Pylon South Wing – Elevation as completed; B. Pylon North Wing Foundation; C. Pylon Entry Passage; D. Court, South Peristyle as completed; E. Enclosure Wall South – Standing Masonry; J. Construction Embankment for Pylon South Wing; K. Construction Ramp for Pylon South Wing Inner Face; L. Construction Ramp for Pylon South Wing Outer Face; M. Construction Ramp for Pylon North Wing Inner Face; N. Construction Ramp for Pylon North Wing Outer Face; 1. Original Direct Approach Rampway; 2, 3. Successive Modifications of Ramp to Gain Height.



64. Qasr el Sagha Temple. Ceiling beams hauled into position up stepped courses of wall face. Fayum, Old Kingdom. This illustration is of a particular instance of Old Kingdom masonry construction. It is, however, of general interest in view of the persisting suggestion that a general practice in Pharaonic masonry construction was to work blocks up the stepped wall masonry, thus obviating the necessity for extraneous construction ramps. Whether or not on occasion blocks were worked up wall masonry either by levering or by *ad hoc* ramping (as here) the general practice in Pharaonic masonry was to build up walls complete course by complete course not in stepped fashion. *Key*: a. Stepped courses of wall blocks *in situ*; b. Ceiling beam *in situ*; c. *Ad hoc* rubble ramp over stepped courses of wall blocks; d. Timber runners; e. Ceiling block being hauled up rubble ramp to seating on wall. After Arnold fig 3.45.



65. Construction Ramps in Pyramid Building. (A) The great height to be served by ramps in Pyramid building reveals very clearly the inherent drawbacks to the construction ramp, even though lack of space may not operate. The most obvious arrangement of ramps is the direct or frontal approach ramp. The requirements are that the ramp must attain the necessary height at a workable gradient and with a pathway broad enough to accommodate the heavy traffic of ascent and descent. Above all the structure of the ramp must be absolutely solid and secure; It is difficult to achieve these requirements with a direct approach ramp. A satisfactory ramp can be constructed to deliver blocks up to a limited height (A^1). The drawback is the great mass of construction required (more than the pyramid itself). However when the required height is much greater, then the direct approach ramp appears impractical (A^2). The mass of construction is enormous. To build up to such a height requires very strong construction and the pathway becomes ever more and more restricted. And an ever greater increase in the structure of the ramp is required to deliver ever less and less building material to the pyramid; (B) Modified direct approach ramp. The (part) internal ramp. B^1 illustrates the manifest impossibility of restricting a direct approach ramp to an economic construction. To mitigate this problem a (part) internal ramp has been suggested. The lower part of the pyramid construction is served by a reasonably economic direct approach ramp, which then continues into the interior of the pyramid (B^2) to serve the diminishing requirements of the upper part of the pyramid. In several pyramids infilled construction gaps have been reported which could represent the use of such internal ramp; (C) The Indirect (Angular) Approach Ramp. It is possible to avoid some drawbacks of the direct frontal approach ramp by angular changes in the direction of the approach. Such solutions not only have the advantage of spatial economy but they markedly diminish the mass of construction →



66. Pyramid Construction. The Direct Approach Service Ramp. Comparative Diagram based on the Dimensions of the Great Pyramid. Gizeh 4th Dyn. ca 2500 BC. The direct approach service ramp is contra-indicated for supplying building material to Pyramids except for the lowest part of the pyramid (a frustrum comprising ca the lowest ¼ of the total height). This results on the one hand from the geometrical form of the pyramid and, on the other, from the necessary construction of the ramp. The greater part of the volume of the pyramid is contained in the frustrum at the base so that as the pyramid grows in height, the added volume decreases sharply. On the other hand because a supply ramp must always maintain a gentle gradient (ca 1:10) to permit the hauling up of heavy blocks, as the ramp is raised to serve the construction of the higher levels of the pyramid, the volume of the ramp increases greatly. Thus a ramp above a certain height greatly exceeds in volume the part of the pyramid it serves. In this diagram showing the pyramid in elevation and a direct approach supply ramp with a gradient of ca 1:10 the relation between the volume of the pyramid frustra served and the volume of the ramp is of the following order: (1) The height of the frustrum is roughly 6% of the total height of the pyramid and the volume of the frustrum roughly 19% of the total volume of the pyramid. While the volume of the ramp is about 15%of the total volume of the pyramid – i.e. the volume of the ramp is less than the volume of the frustrum constructed; (2) The height of the frustrum is roughly 13% of the total height of the pyramid and the volume is roughly 36% of the total volume of the pyramid. While the volume of the ramp is about 30% of the total volume of the pyramid, i.e. the volume of the ramp remains less than the volume of the frustrum constructed; (3) The height of the frustrum is here ca 20% of the total height of the pyramid and the volume of the frustrum is ca 50% of the total volume of the pyramid; while the volume of the ramp is very little below that of the volume of the frustrum constructed; (4) The situation is now changed radically. The height of the frustrum is ca ¾ that of the total height of the pyramid, but the volume of the frustrum is now not much in excess of this figure, being ca 79% of the total volume of the pyramid. However the volume of the ramp is now 1 ½ times that of the volume of the pyramid. In short to build up the extra height of the pyramid has required an increase of ca 2 ½ million m^3 to the volume of the ramp to set in place, less than 1 million m^3 in the volume of the pyramid; (5) If the ramp is to serve for the total height of the pyramid then its volume will be well over 3 times that of the pyramid !. In short a direct approach service ramp is only economic for the lowest 20% or so of the total height of the pyramid.

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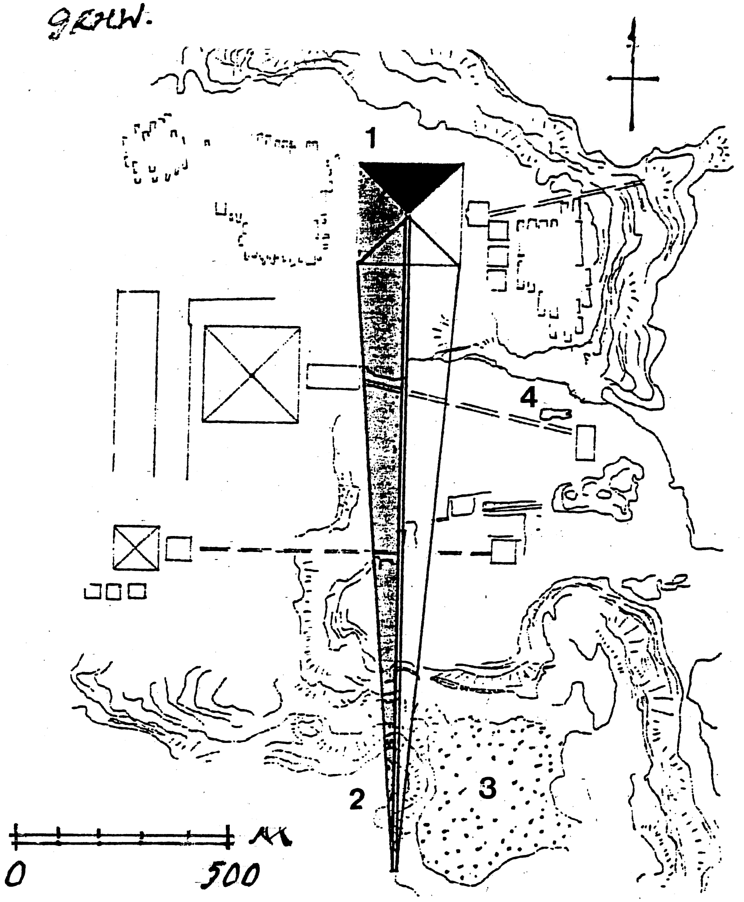
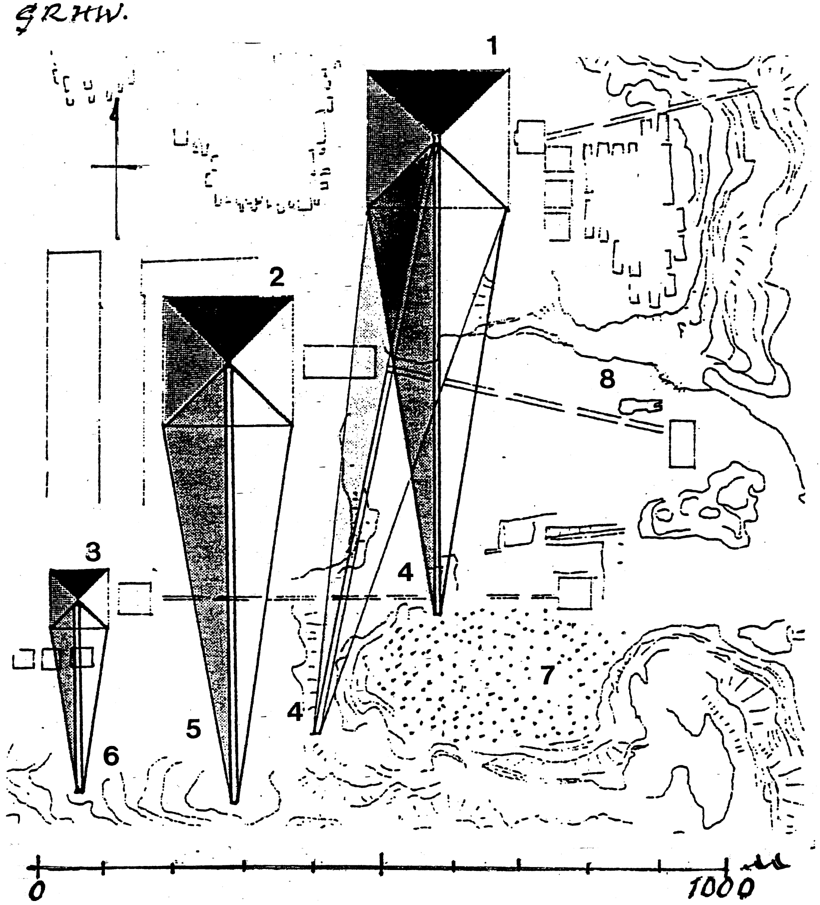
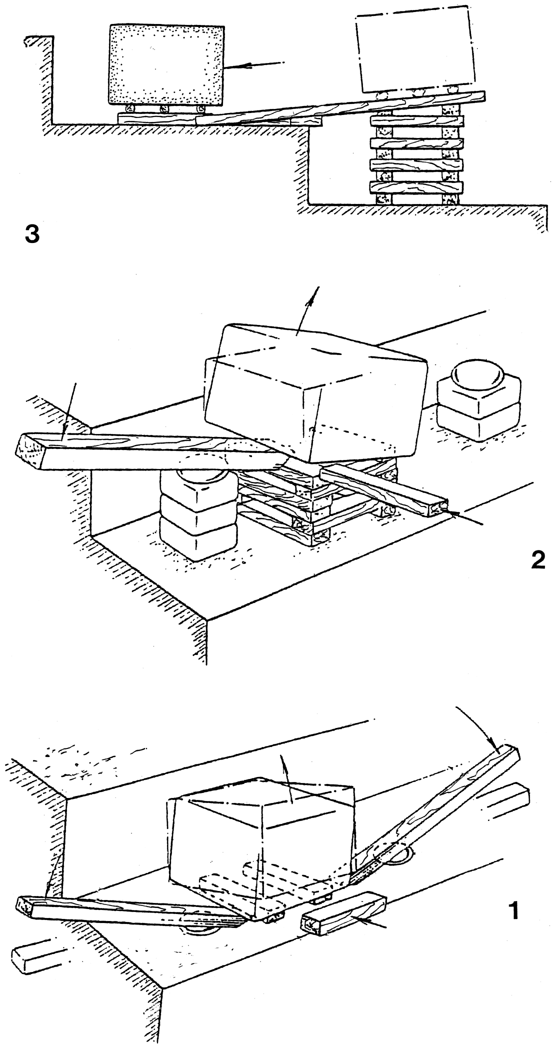
required for the ramp by "leaning" it against the solid pre-existing masonry of the pyramid under construction; C^1 The Reversing Ramp (cf Half Landing Stairs). This ramp grows by accretion against one face of the pyramid. It is preferable not to extend the run of the ramp to the extremities of the pyramid face so as to leave the arrises visible for checking the construction; C^2 The Winding Ramp (cf Quarter Landing Stairs). This is a practical construction using the pyramid as a newel. However this system has a very grave disadvantage. With the winding ramp the critical evidence of true geometric construction (i.e. the arrises) is hidden from view so that there is no visual control of the form during building. After Arnold fig 3.53.



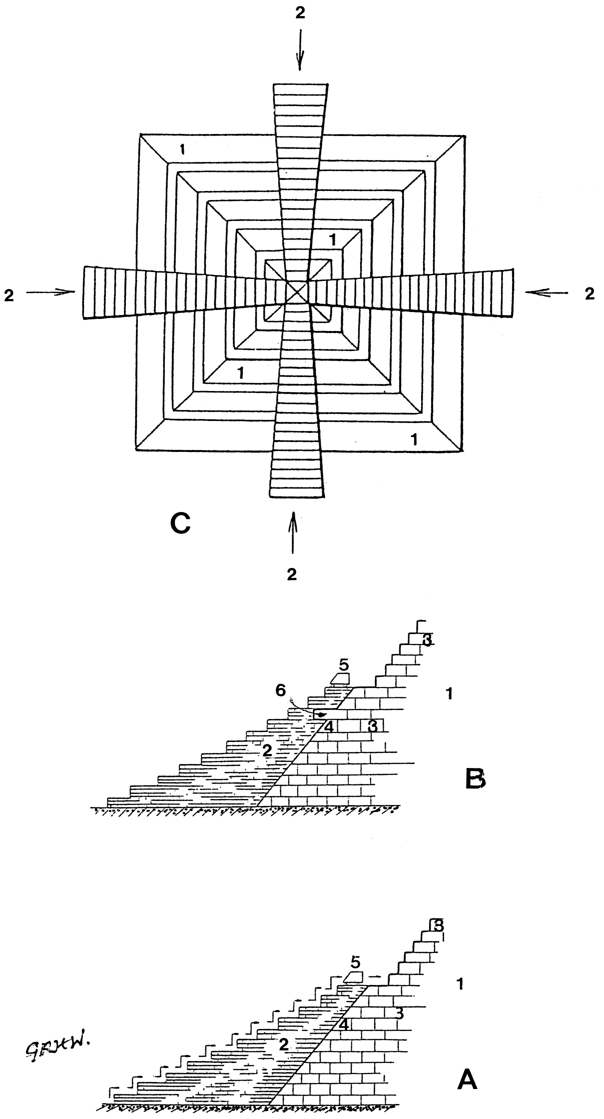
67. Gizeh Pyramid Area. Great Pyramid with proposed direct approach Construction Ramp. Ca 2550 BC. The proposed ramp is shown here with the functional gradient of 1:10, thus with a length of 1.5 kilometres. This carries its intake beyond the supply quarry, and makes its volume more than three times that of the Great Pyramid itself. However there is no indication in the area where this vast mass of material was disposed after the completion of the work. *Key*: (1) Great Pyramid; (2) Proposed direct approach construction ramp; (3) Quarry; (4) Sphinx. After P. Hodges p. 121, fig 108.



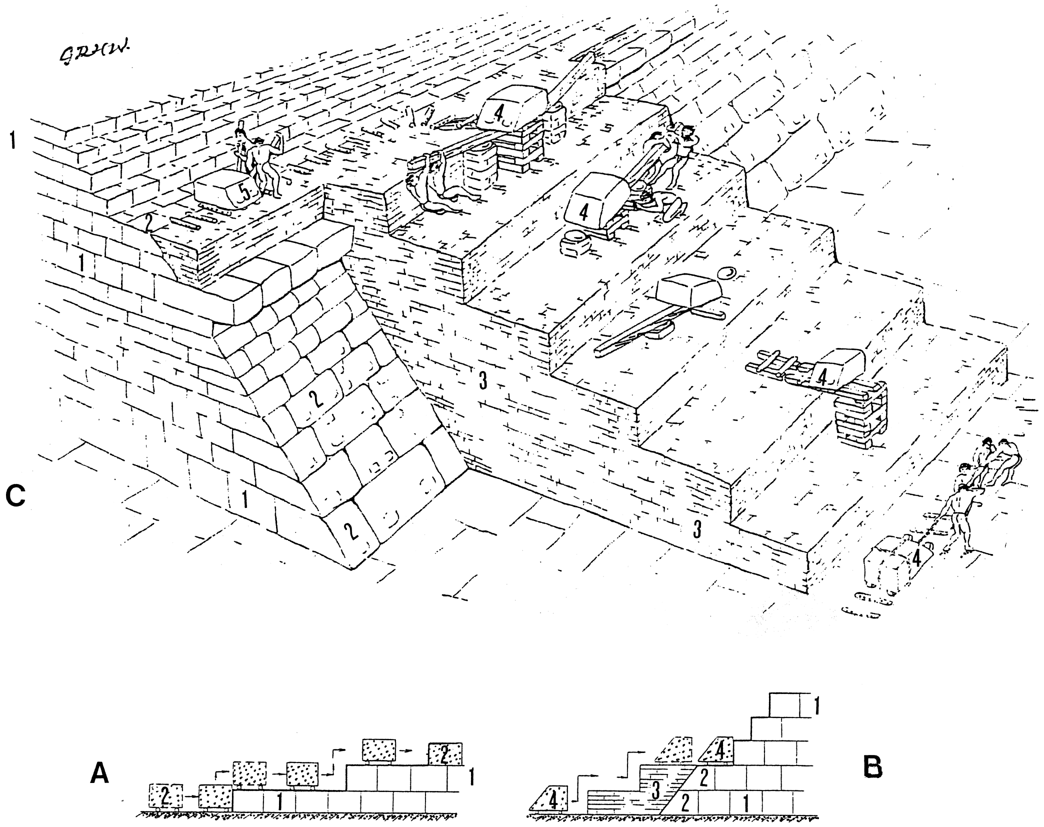
68. Gizeh Pyramid Area. The three pyramids with possible construction ramps as supplied from the quarry. Ca 2500 BC. To accommodate these ramps within any available area if served by the quarry, the ramps must have a steeper gradient (here 1:5 to 1:7) than is reckoned practical for haulage of large blocks. The mass of the construction ramps far exceeds that of the pyramids they serve and there is no trace in the area of the disposal of the great mass of material after completion of work. *Key*: 1, 2, 3 Pyramids; 4, 5, 6 Ramps; 7 Quarry; 8 Sphinx. After P. Hodges p. 121, fig 109.



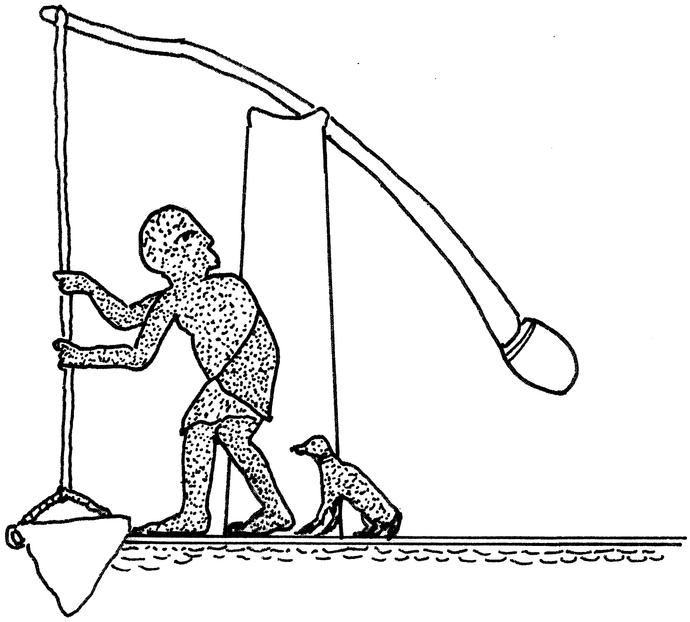
69. Levering stone block up stepped masonry. After each leverage wooden chocs are slipped underneath the stone block to prop it in position. These chocs eventually constitute a “cribbing” to support the block at a height in excess of the step. The fulcrum for the lever must be raised *pari passu* with the cribbing. According to experience the scale of this drawing indicates the limiting height that it is practical to lever up blocks – ca 50 cms.



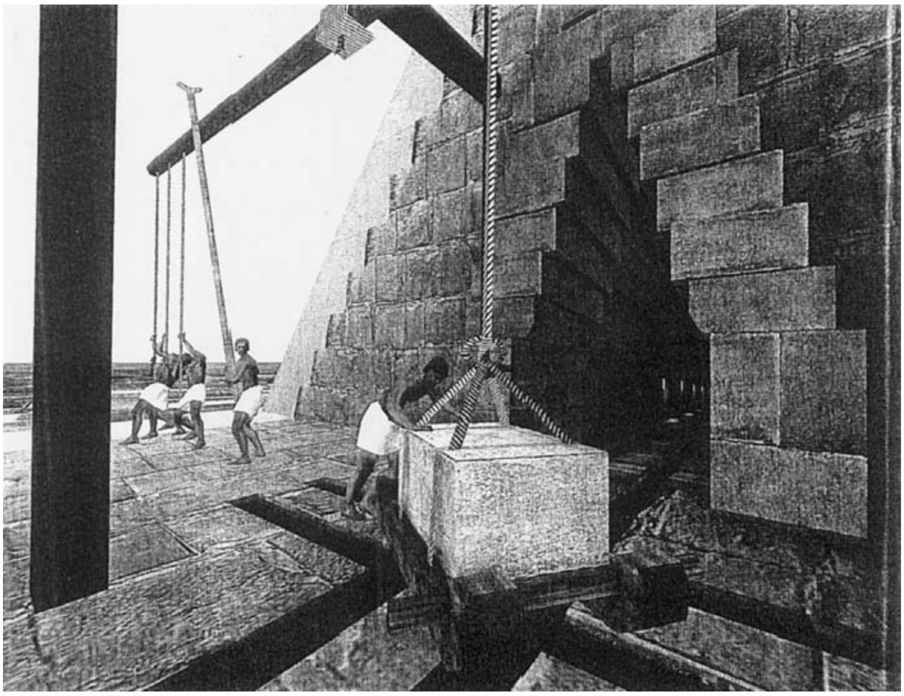
70. Pyramid Construction. “Supply Stairs” for setting bevelled facing blocks. Gizeh 4th Dyn. Such blocks cannot be levered up directly one course above the other. If they are to be raised up into position by levering, then a construction ‘stair’ must be installed. The surviving core masonry of the Great Pyramid appears to show that the outermost blocks of intermittent courses were made to project. These projecting courses could have served to advance the construction stair by way of keying. *Key*: A. Construction Stair abutted against core masonry; B. Construction Stair keyed into core masonry by intermittent projecting courses; C. Schematic plan of proposed construction stairs set one against each face of the Great Pyramid. 1. Pyramid masonry; 2. Construction stairs; 3. Core blocks of Pyramid; 4. Bevelled facing blocks of Pyramid set in place; 5. Bevelled facing block being set; 6. Projecting core blocks to key construction stair into pyramid masonry. NB. These drawings are diagrammatic only. After Isler figs 5, 6, 12.



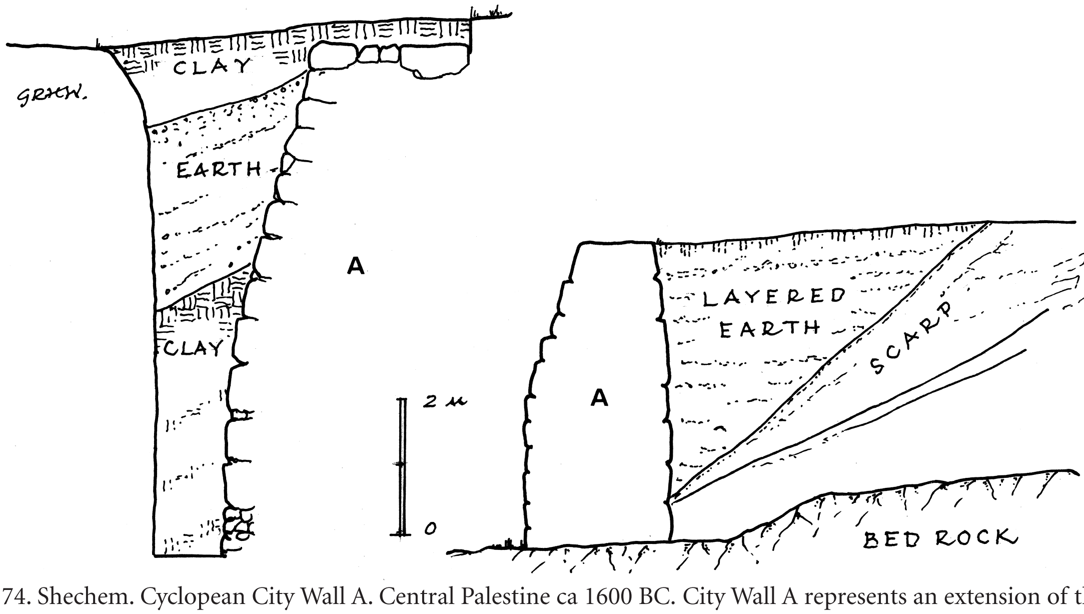
71. Pyramid Construction. Setting pre-formed bevelled casing blocks. Gizeh 4th Dynasty. A stepped construction is optimal for levering up blocks into position, but blocks cannot be levered up against an inclined wall face. It being generally accepted that the casing blocks of the Gizeh pyramid were pre-dressed to a face angle of ca 52°, then levering them up course by course required the installation of a supply stairway. *Key*: A. Blocks levered into position directly up a stepped structure; 1. Pre-set stepped structure; 2. Blocks being levered up into position; B. Blocks being levered up a structure with inclined face by means of a "supply stair" installation; 1. Pre-set core blocks; 2. Pre-set bevelled facing blocks; 3. Supply stair; 4. Passage of facing blocks being levered up; C. Sketch Reconstruction showing bevelled facing blocks being levered into position. 1. Pre-set core blocks; 2. Preset bevelled facing blocks; 3. Supply stair installation; 4. Passage of pre-dressed bevelled facing blocks levered up supply stairway; 5. Pre-dressed bevelled facing blocks levered into position. After Isler figs 3, 4, 20.



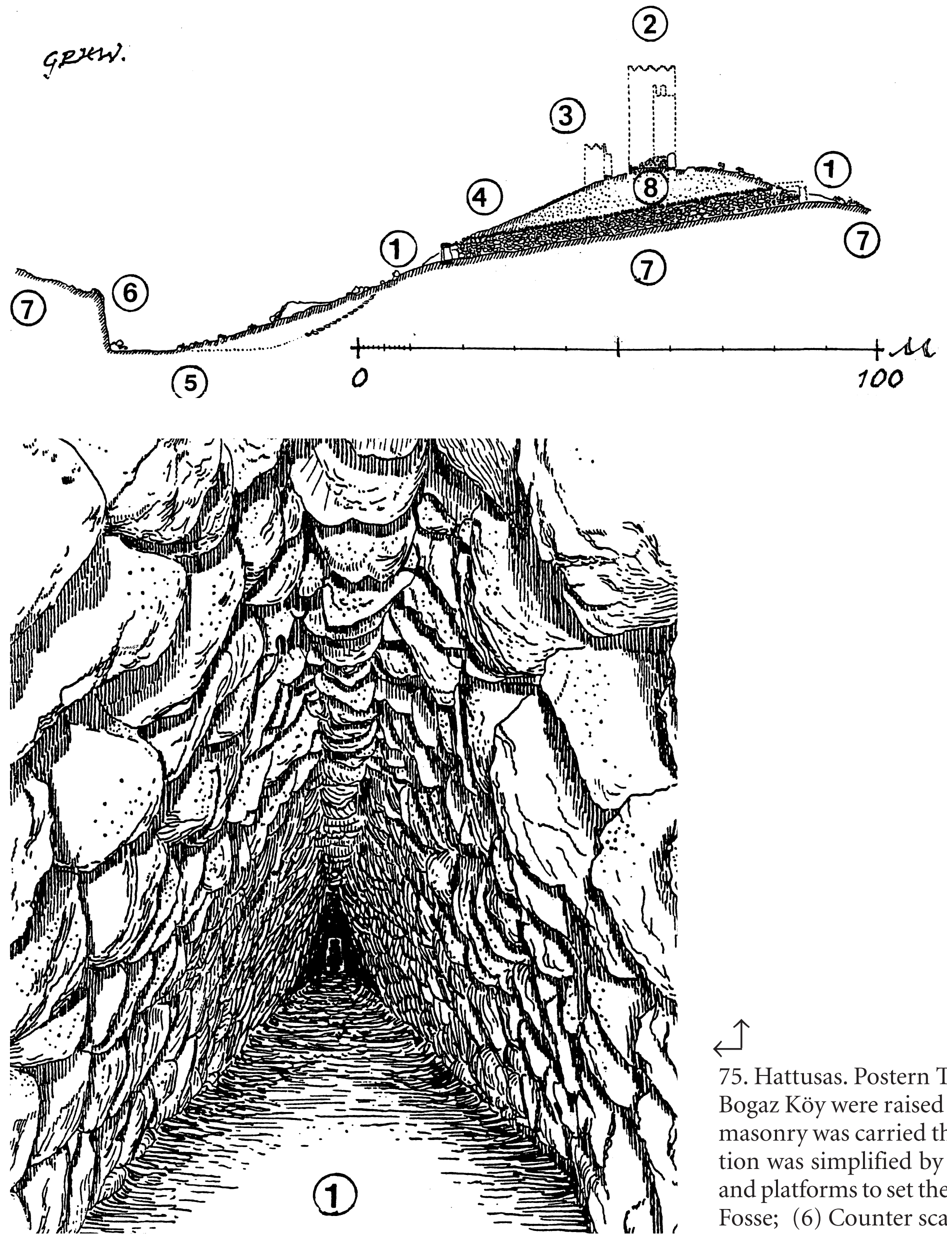
72. The Shadouf. Sketch from a tomb painting at Thebes, 19th Dynasty. This device, which can be easily operated by one man, has remained in use across the ages for raising water from pools and irrigation channels. It consists of a wooden arm pivoting on a support and suitably counterweighted at the far end. A bucket etc is suspended by rope from the near end and the arm balanced so it is easy for the man to draw the container down into the water, and when filled the counterweight will draw the filled container up to the required height.



73. The Overhead Lever. Imaginative Reconstruction. A raised beam pivoting on a support can be activated as a seesaw to raise up a load by hauling down on the other end. Although there is no surviving evidence that such a device was used in Ancient Egypt the device operates in a similar fashion to the Shaduf, so it is supposed that the overhead lever was also known and used. This fanciful drawing illustrates part of the procedure proposed for pyramid construction using an internal winding ramp. After Brier Archaeology May/June 2007 p.26.

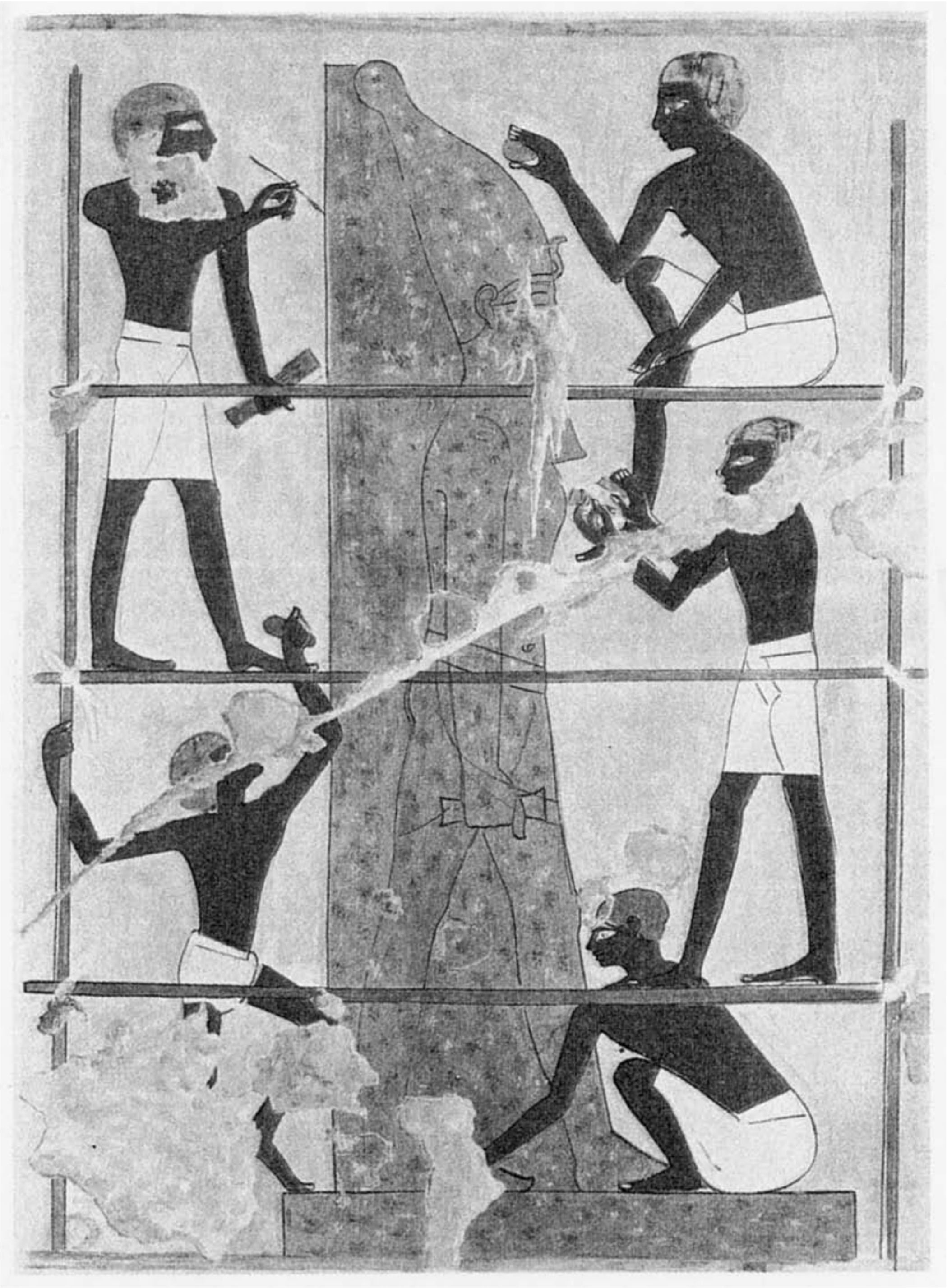


74. Shechem. Cyclopean City Wall A. Central Palestine ca 1600 BC. City Wall A represents an extension of the city to the NW and N in MB IIc times, ca 1600 BC. These drawings were made nearly a century ago, when more evidence in section survived. The drawing (*right*) shows the wall as part of the arrangements to extend the city. Here it fulfils the function of a retaining wall for the built up earth platform constituting the extension. The area immediately behind the wall is composed of successive horizontal layers of earth. These were obviously built up *pari passu* with the wall and would have provided the installation necessary for delivering the massive stones into their required position. The drawing (*left*) shows the disposition of the earth against the external face of the wall. The inclined layers are sterile and represent engineering of some sort, but their nature and purpose is not clear. After Shechem III, fig 99; Ill. 68.

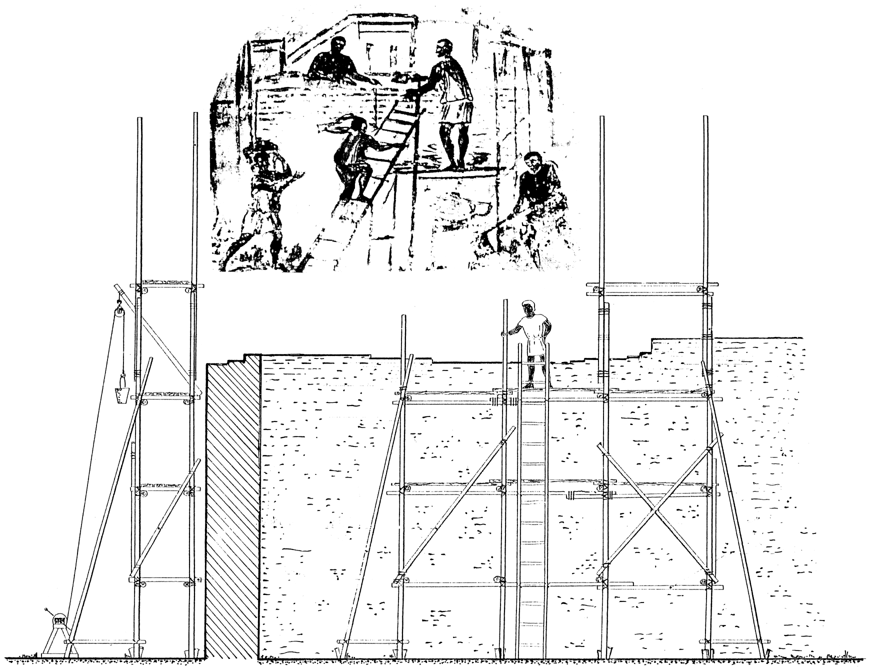


75. Hattusas. Postern Tunnel beneath Yerkapi Gate. Bogaz Köy. 14th Cent. BC. The Hittite defences at Bogaz Köy were raised on an earth embankment won from the fosse. The postern tunnel of Cyclopean masonry was carried through the earth embankment below the gate. The engineering of this construction was simplified by the presence of the earth embankment from which could be fashioned ramps and platforms to set the masonry. *Key*: (1) Postern Tunnel; (2) Yerkapi Gate; (3) Tower; (4) Scarp; (5) Fosse; (6) Counter scarp; (7) Natural soil; (8) Earth embankment. After Naumann figs 105, 106.

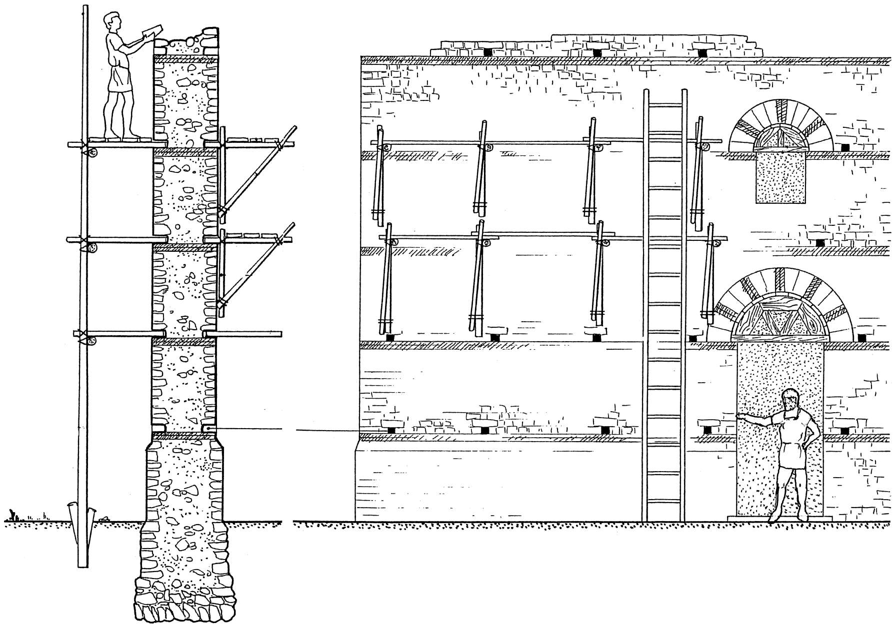
76. Hattusas. The Royal Gate. Bogaz Köy. ca 1400 BC. Typical Cyclopean masonry of modest dimension with special unit (here jamb of arched Gate) finely dressed. Although the wall blocks are not overly massive, they could not be set together by manhandling but require installations (e.g. earth, ramps) to raise them up several times head height. After AAAO Plate 125A.



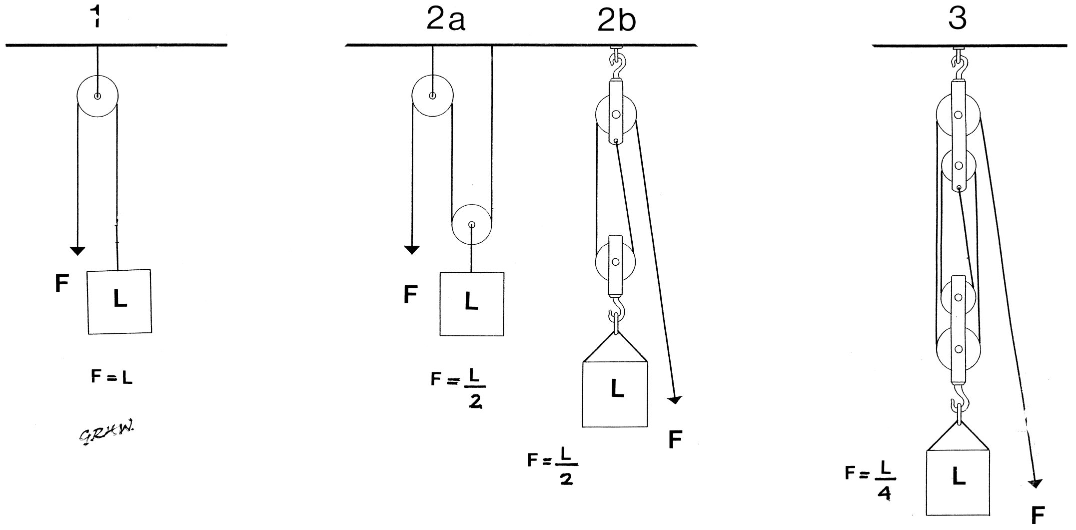
77. Egyptian Light Timber Scaffolding. Theban Tomb Painting ca 1500 BC. Because of the massive blocks used Egyptian building as a general rule made use of earthworks (ramps, embankments, fills). Thus according to outside (Greek) observation Egyptian builders did not employ scaffolding. However where the work did not involve handling heavy materials, Egyptians builders used light timber scaffolding. This was particularly evident in the last phase of a building programme, sculpture of relief ornament, which was often carried out as a separate programme after the end of the construction work – cf this ancient representation of sculptors finishing a colossus. After Arnold p. 231, fig 5.19.



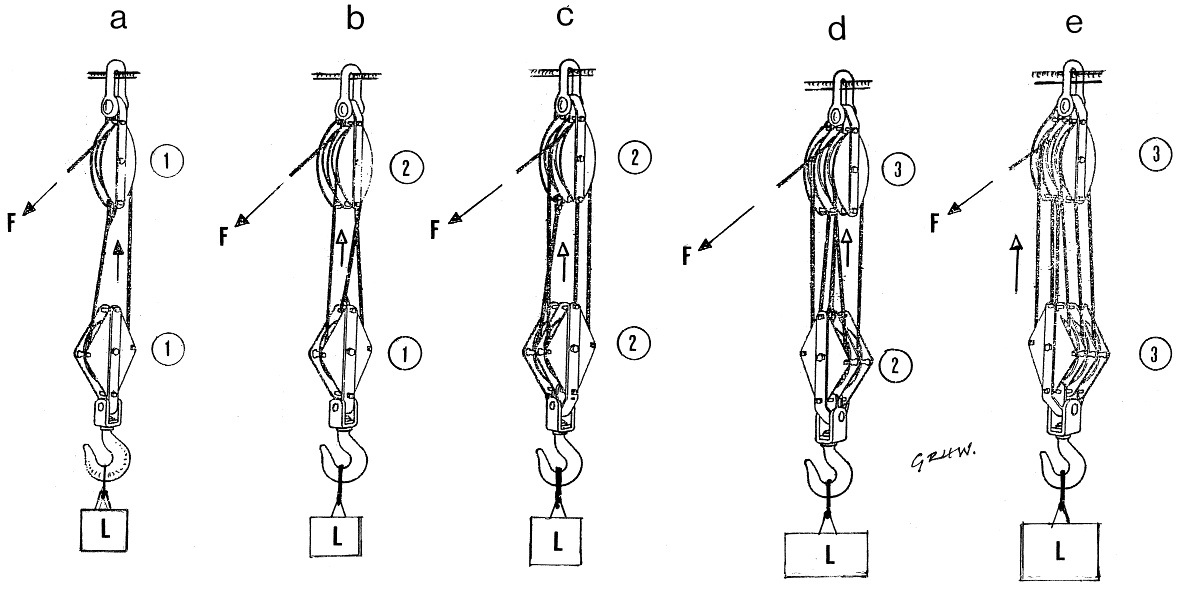
78. Roman Independent Scaffolding. Ancient representation (tomb on the Via Latina), together with a reconstruction drawing. The scaffolding provides access for workers only, it is not designed to facilitate the delivery into position of heavy building materials. It is independent scaffolding consisting of pole uprights (standards), pole horizontals (ledgers), solid cross pieces supporting plank for footing. The assembly is tied together by diagonal braces and further stabilised by raking stays. All joints are fixed together by rope lashing. Independent scaffolding does not deface the wall construction in any way, but is expensive because of the quantities of timber pieces required.. After Adam pp 86-87.



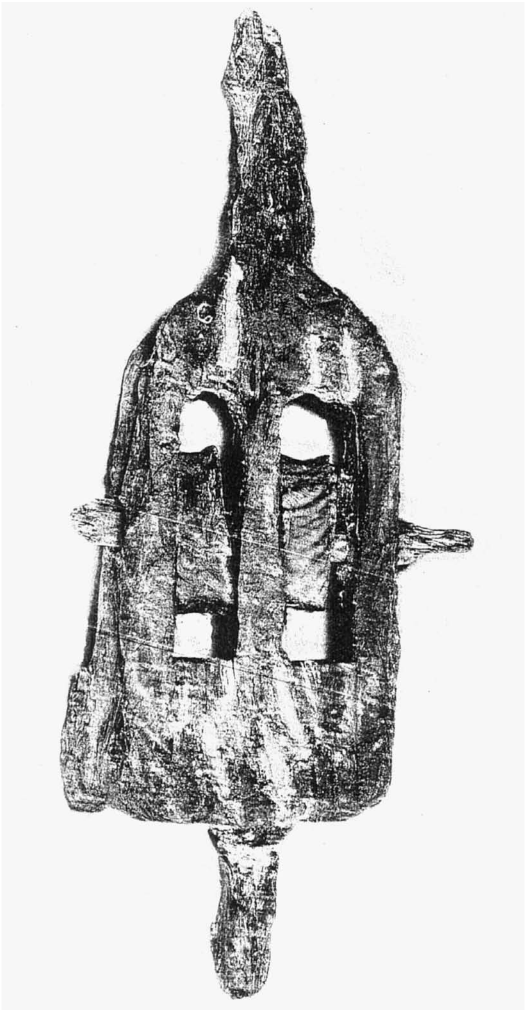
79. Roman Bricklayers (or 'Putlog') Scaffolding. Great economy in timbering is afforded by making the wall masonry a vertical support for the scaffolding. This involves recessing lodgements in the masonry of the wall face (which can be later blocked up and plastered over). Two schemes are possible. Either the outer vertical support is by poles (*left*); or this element is replaced by a series of triangular "trusses" set against the wall face (*right*). The transverse supports of the planking are let into the wall masonry. They are called 'putlogs' and the recesses contrived to lodge them are called 'putlog holes'. After Adam p. 87, fig 102.

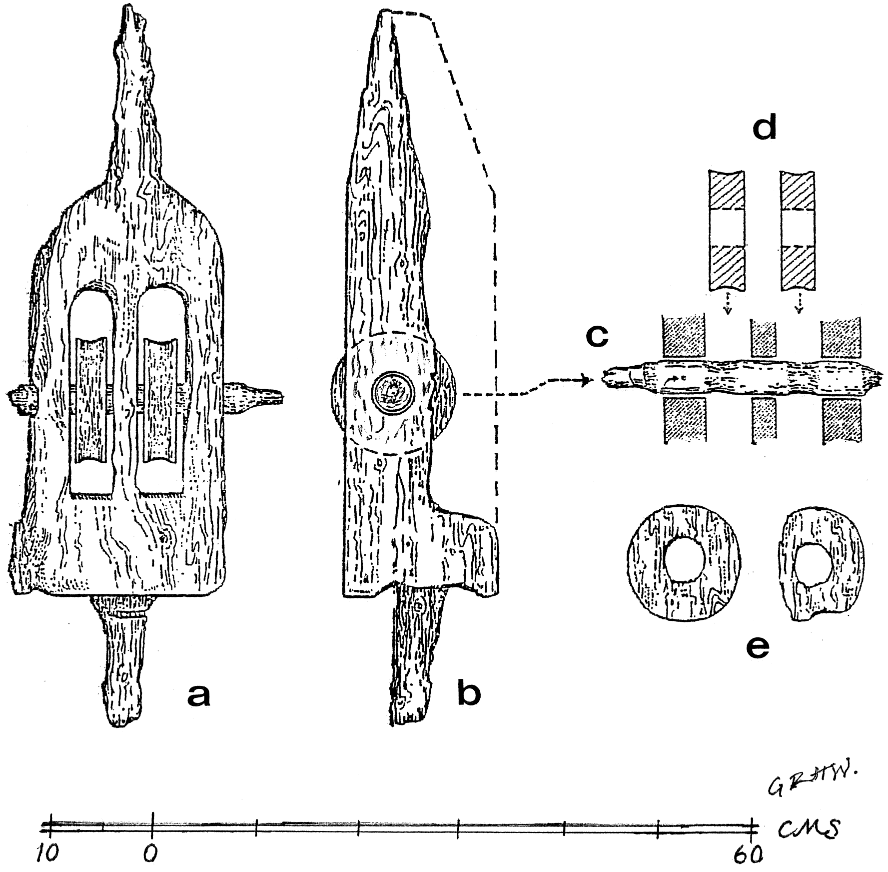


80. The Mechanics of the Pulley. The use of several pulley wheels in combination secures a mechanical advantage, i.e. it diminishes the forces required (F) to move a load (L), here shown working vertically against gravity. However so that the work input = the output, the force is required to move through a correspondingly greater distance than the load. 1. Single pulley wheel. This confers no mechanical advantage, (i.e. the force required to move the load must be equal to the load. However the wheel confers an advantage of convenience, since it is easier to haul downwards than upwards; 2. Theoretical diagram of 2 pulley wheels in combination. The force required to move the load is reduced to half the load, i.e. the combination gives a mechanical advantage of 2; 2b. 2 pulley wheels in combination as assembled in practice to give a mechanical advantage of 2; 3. 4 pulley wheels as assembled in practice to give a mechanical advantage of 4, i.e. the force required to move the load is reduced to a quarter of the load. NB. The force required in practice will always be something additional to the stated one, since the machine is not 100% efficient and work must be done to overcome the resistance of friction.



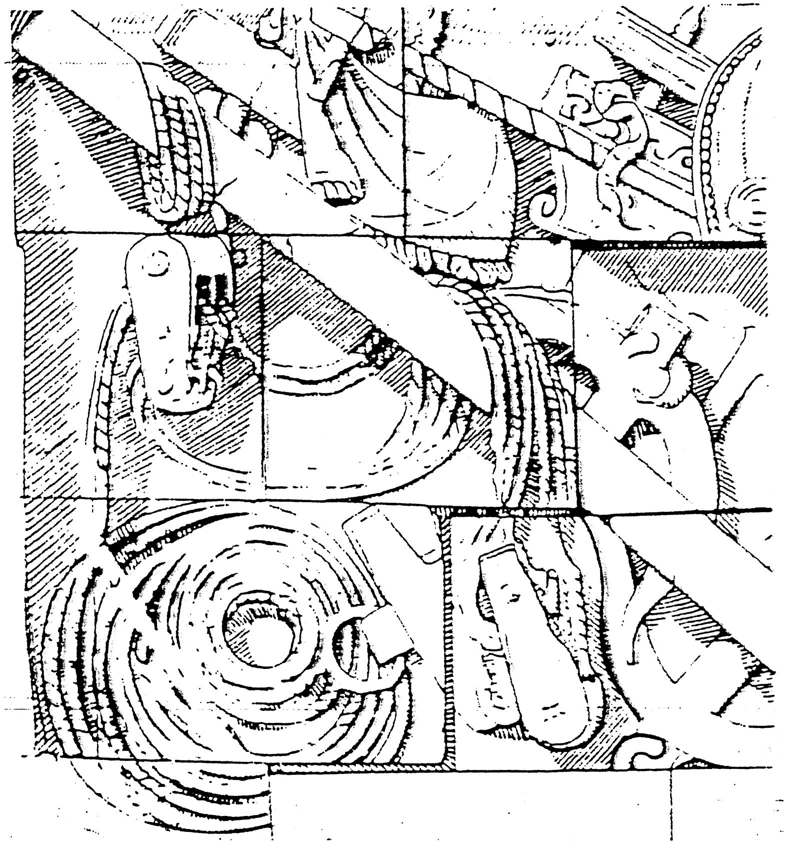
81. Traditional Modern Block and Tackle. The modern pulley block can have one or more (generally up to three) wheels, referred to as sheaves. Multiple wheels in one block are housed side by side. Two such blocks are assembled together, one above the other, so that the number of wheels at work is the combined total of the number of wheels in both blocks. *Key*: a, b, c, d, e Assemblages of pulley blocks; L Load to be lifted; F Force required to lift the load; ①②③ Number of wheels housed in the block. The total number of wheels (N) housed in assemblage a = 2; and the total number of wheels housed in assemblage e = 6. The general formula for the mechanical advantage of any assemblage is F=L /N (less the force required to overcome resistance due to friction). Thus in a, F=L/2; and in e, F=L/6.



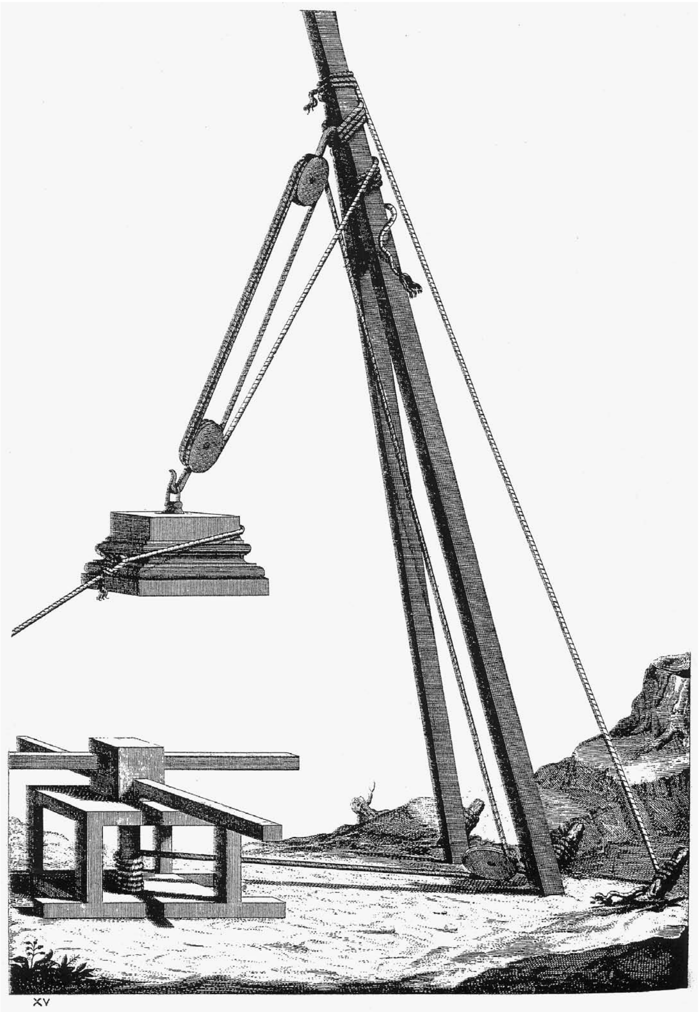


83. The Mechanism of the Kenchrai Pulley – Corinth Port, ca 400 BC. *Key*: (a) Face elevation of assembly; (b) Side elevation of assembly; (c) Axle in housing; (d) Wheels. After Shaw, Hesperia 38 1967, p. 390, fig 7.

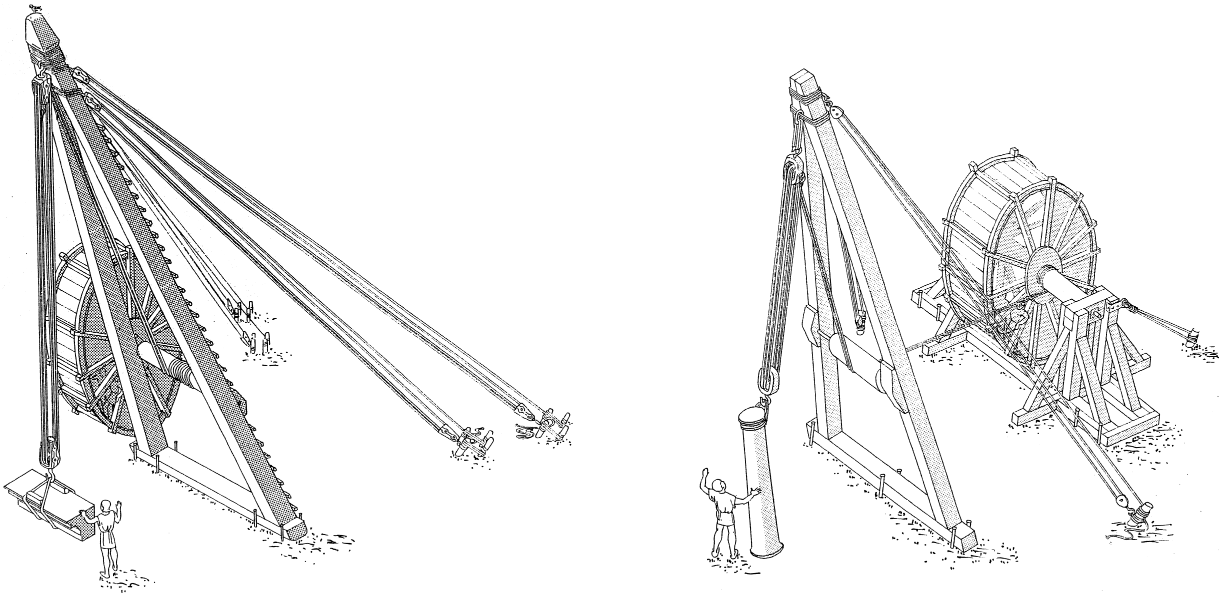
82. The Kenchrae Pulley Block. Corinth Port, ca 400 BC. The device is entirely of wood, now (after preservation) 71 cms long x 19 cms broad x 15 cms thick This represents a shrinkage of ca 10% from the original dimensions. It has 2 wheels, i.e. it is double sheaved. The wheels turn about a fixed wooden axle. There are traces of a thick solidified layer of material used to lubricate the wheels. The vertical projections infer that the block was housed within another component in a manner not as yet determined. The block was found in a building ("temple") and presumably was used for building construction work, where its functioning would require a companion block (which was not found). The wooden members and the ropes used would each withstand a working stress of something over 1 ton, and thus be adequate for lifting normal wall blocks of ashlar masonry. After Shaw Hesperia 38 1967 pl 76.



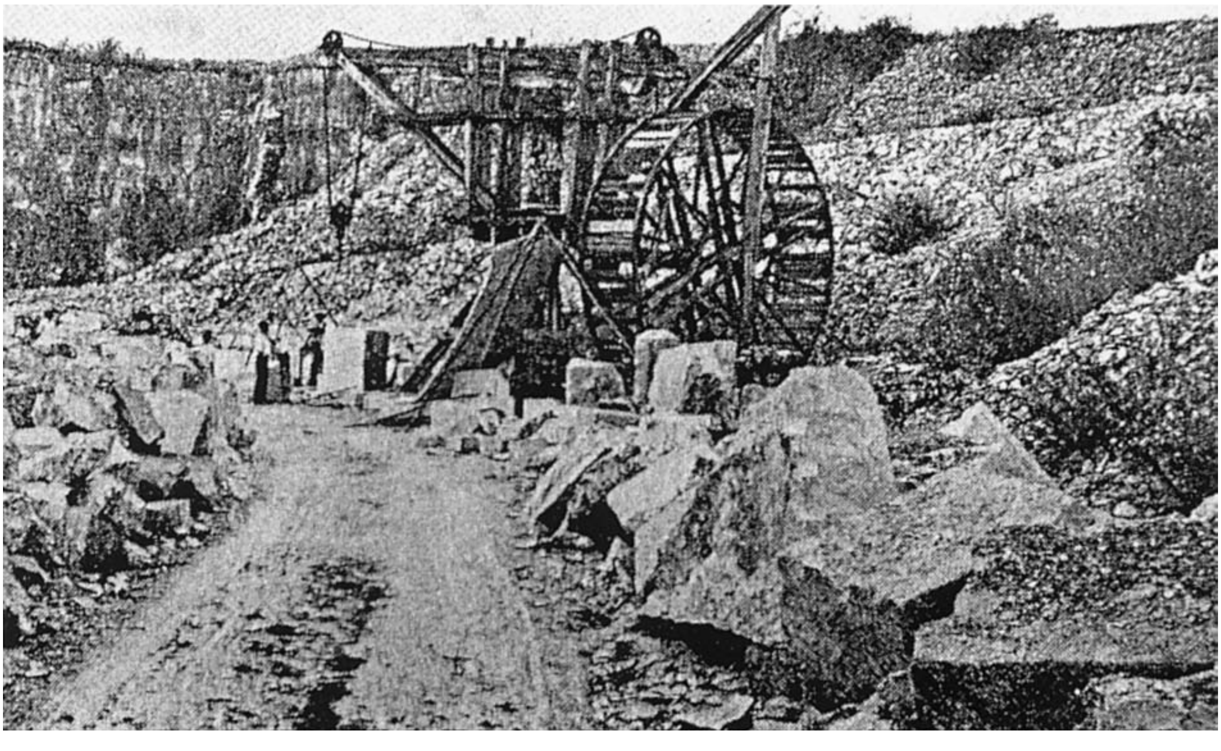
84. Orange Triumphal Arch Provence 1st Cent AD. Relief showing spoil from naval battle, including a double sheaved pulley block. Although all preserved remains of ancient pulley blocks are wooden, this realistic depiction gives the impression that it represents a metal original. After Hesperia 38 1967, pl 78d.



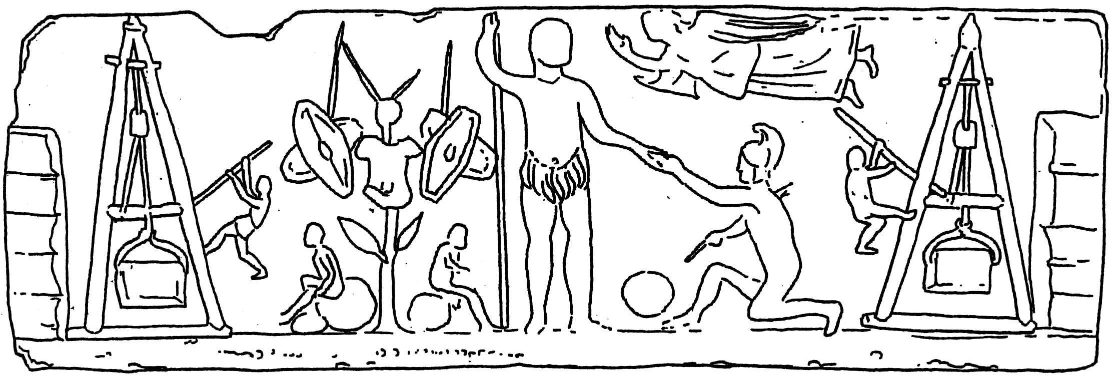
85. 18th Century illustration of a classical block and tackle lifting device (a dikōlos crane). This schematic representation of the dikōlos (two legger) crane shows a design which may have given sufficient control of delicate motion to permit of its safe use in setting blocks on the wall face. A massive capstan as shown here may have permitted an experienced crew of operators to have reacted to commands so immediately as to lower blocks into position virtually without impact shock.



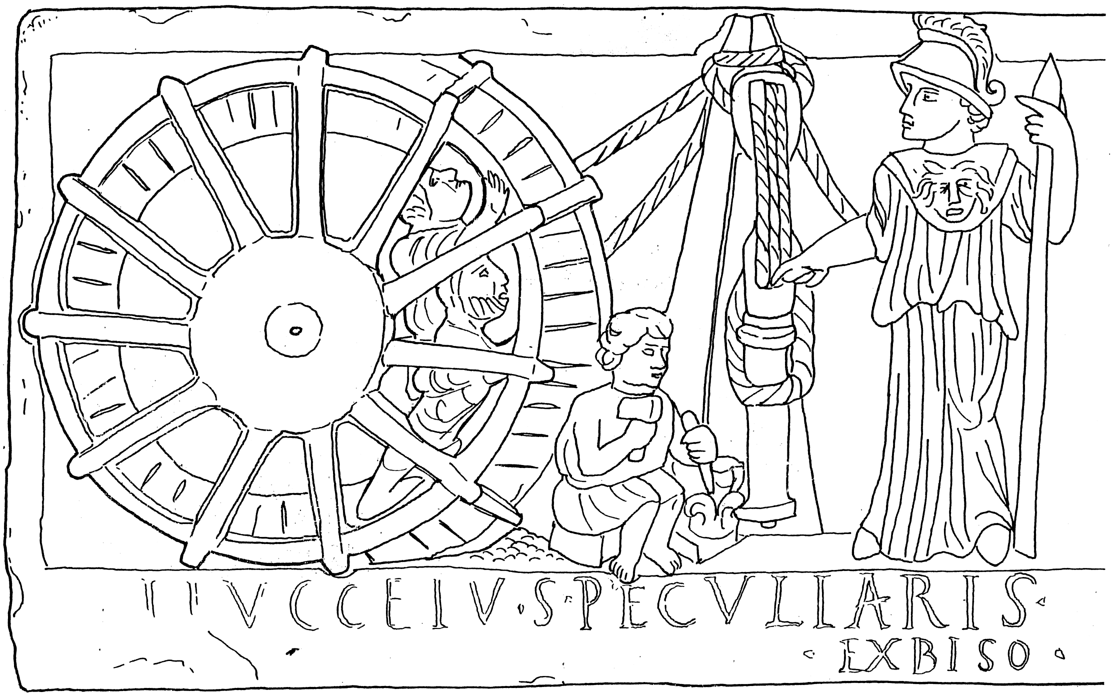
86. Adam's reconstruction of a Roman treadmill operated dikōlos crane, after evidence from ancient representations (e.g. the funerary relief of the Haterii). These representations give no indication of any device to provide for delicate motion or instant braking. After Adam, figs 93, 96.



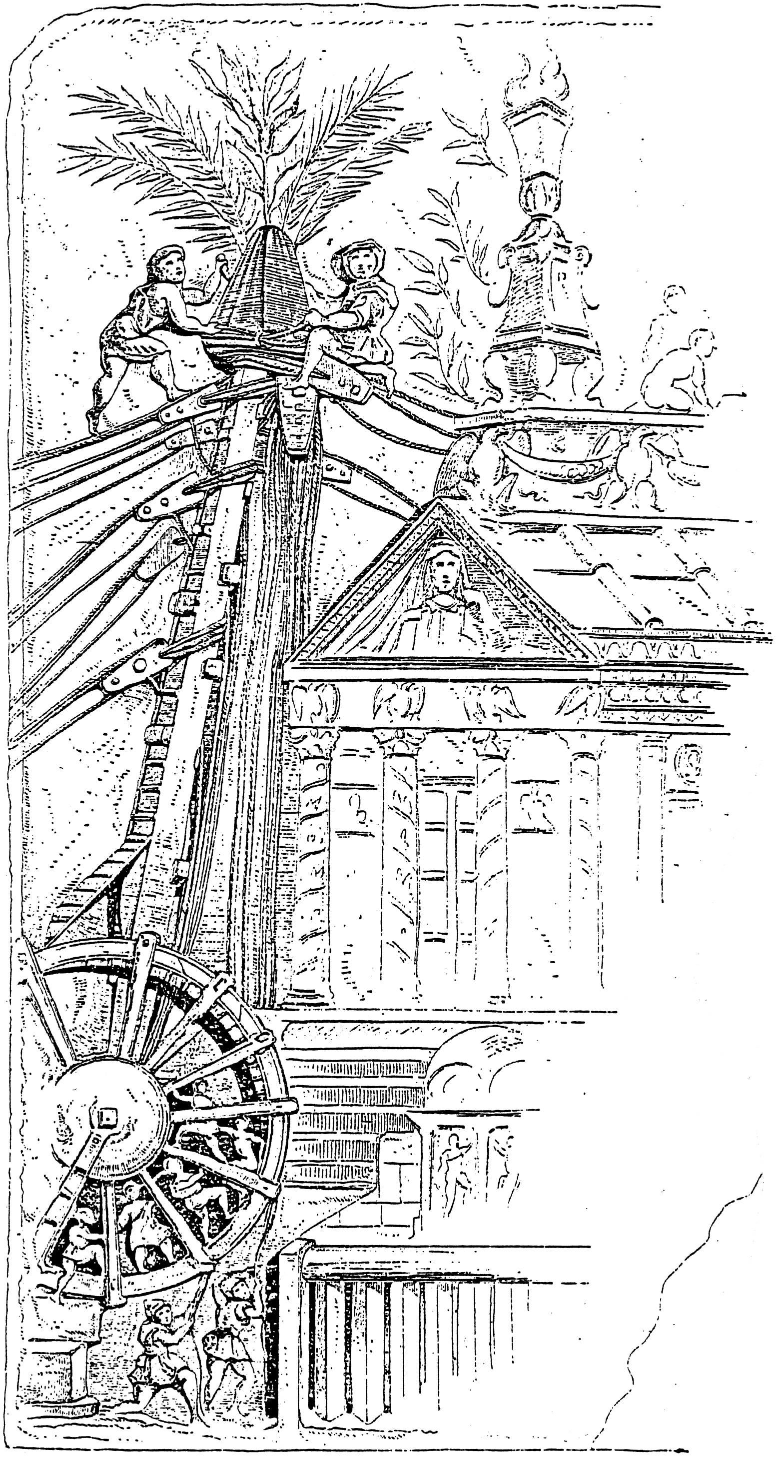
87. Traditional Modern Treadmill Crane. Old postcard (early 20th Century) photograph of a treadmill crane installed at a quarry in the south of France. The device was called a "Quarry Wheel". The treadmill drive is suitable for quarry work, i.e. handling rough quarry faced blocks, but unless some means of braking is possible, it is unsuitable for depositing dressed stone blocks into position on the wall face.



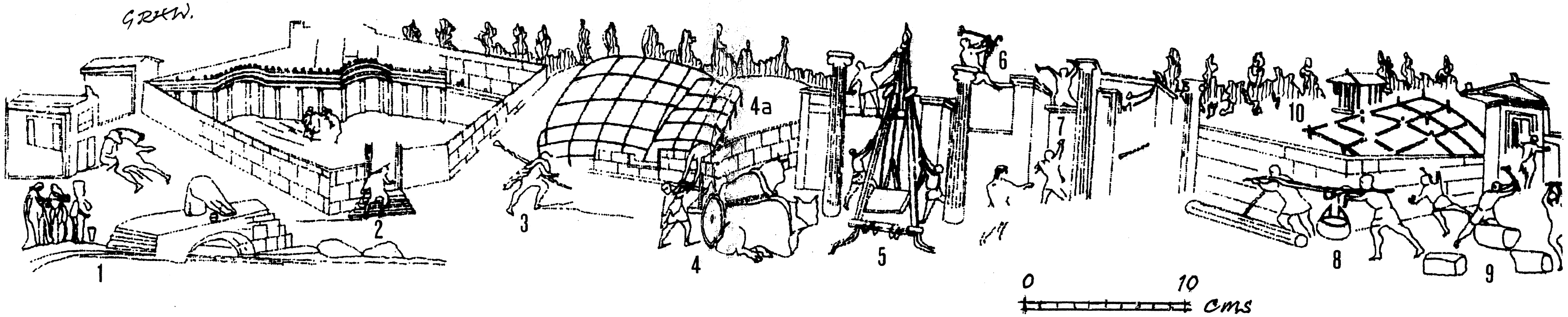
88. Terra Cotta Relief. Triumphal scene including two dikōlos cranes in operation lifting building blocks. Rome (National Museum). The operator is exerting great force on a handspike. It is assumed that he is using this to operate the crosspiece as a windlass; but it is possible it may be intended to represent a braking device (i.e. he is jamming a moving part). After Adam, fig 87.



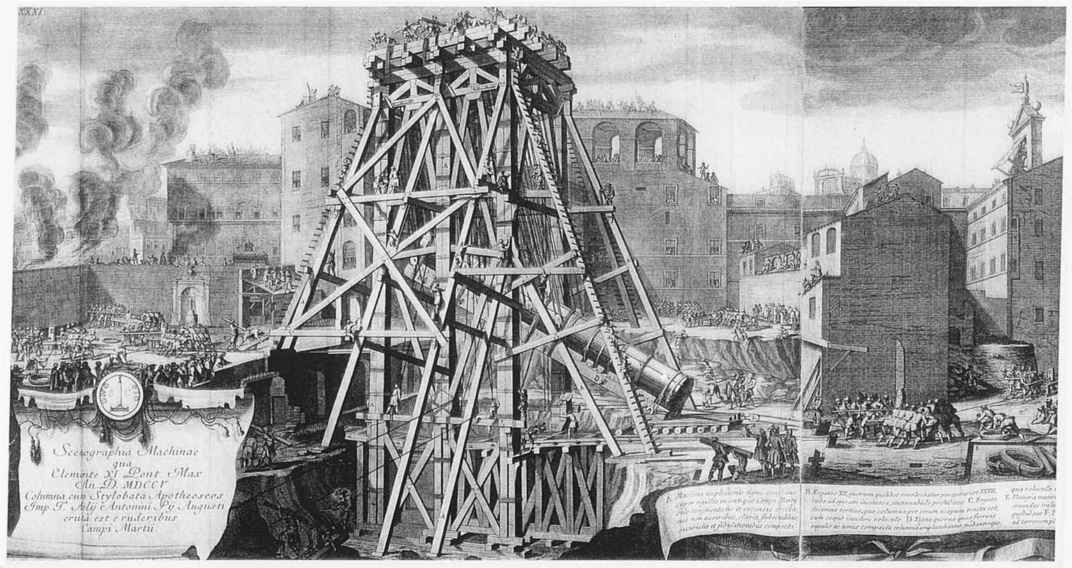
89. Stone relief showing Roman treadmill crane setting up a monolithic column. Capua. The depiction is entirely expressionist and shows no detail – indicating in principle only the treadmill, the pulley block and the attachment to the column. After Adam, fig 92.



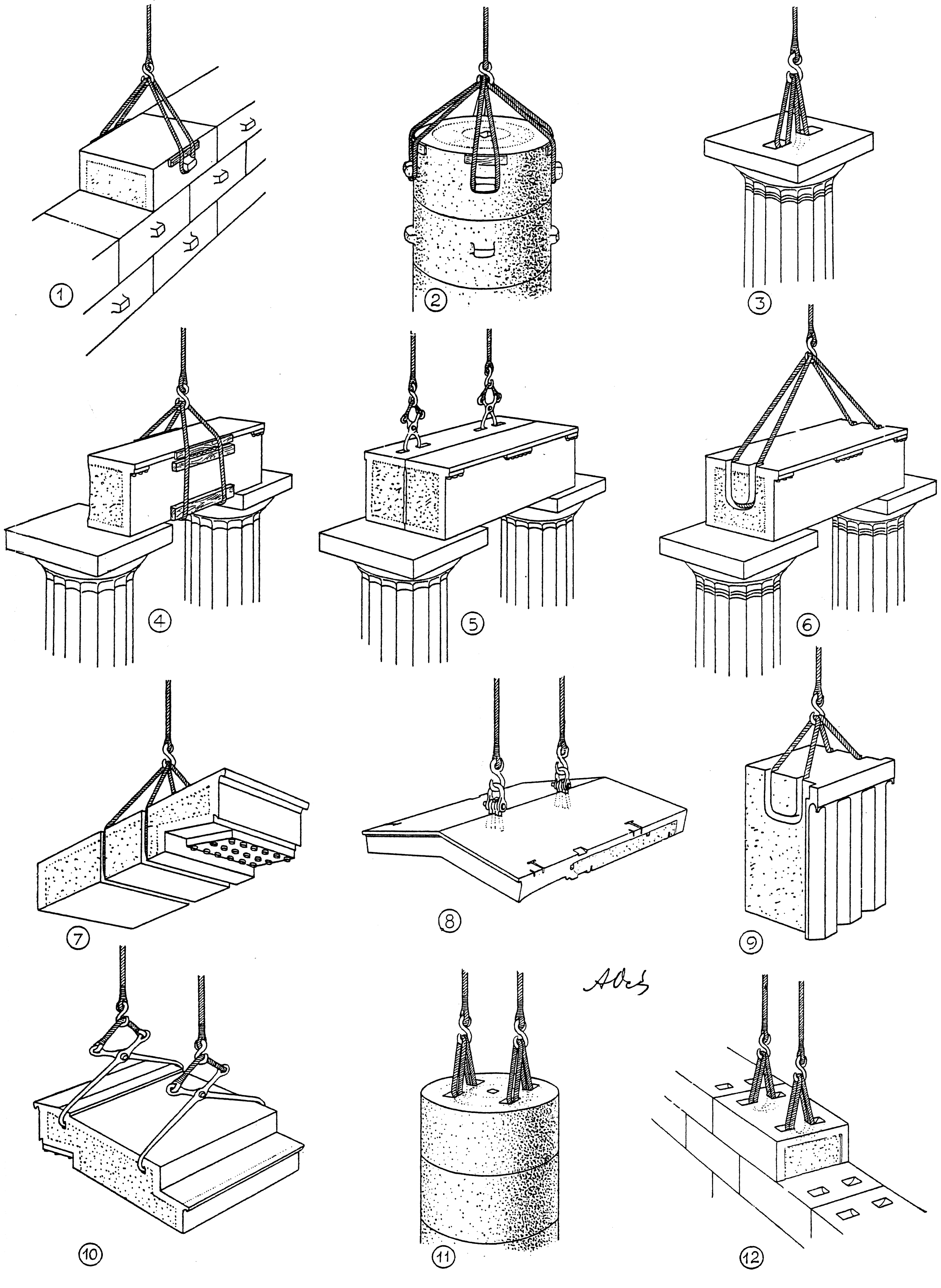
90. Funerary Monument of the Haterii. Relief depicting a treadmill crane in operation. Rome. Reign of Domitian. Similar treadmill cranes were still used at quarries in the South of France at the beginning of the 20th Cent AD. However for setting finely dressed blocks in position on the wall face some control of delicate motion is required. This control necessitates an instantaneous braking device. In this illustration the two men shown below the wheel holding the ropes may be operating a braking mechanism. However it is generally assumed that what is intended is a starting device to kick the wheel into motion. After Durm, B d R, fig 399.



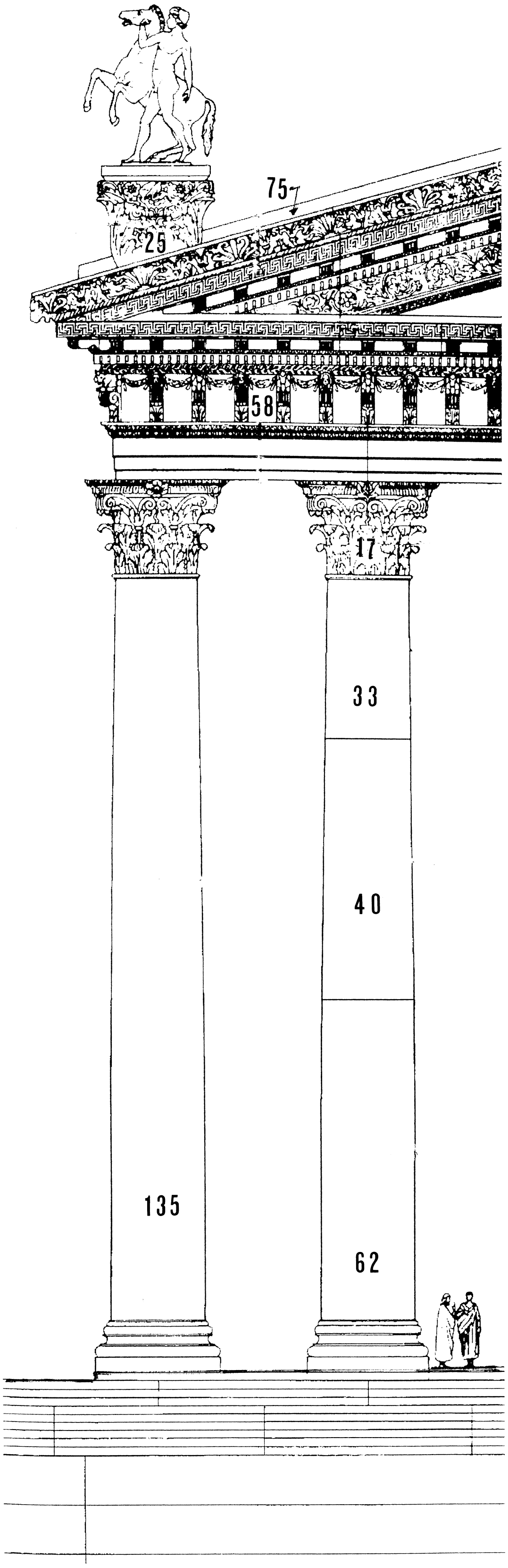
91. Villa S. Marco. Fresco showing building of a city. Stabiae 1st Cent AD. Unfortunately this fresco does not give details of site installations (e.g. scaffolding) but several characteristic operations are depicted. *Key*: (1) Water point ?; (2) Workman bringing water; (3) Architect or master builder with measuring rod (*regula*); (4) Delivery on site of portable items by bullock cart and their handing up to storeman; (4a) Probable storage sheds; (5) Clean lifting of masonry blocks by dikōlos crane. Operator adjusting position of jib head to bring it above required position for delivery; (6) Workman on wall apparently hauling up material directly by hand; (7) Mason completing fine dressing of capital *in situ*; (8) Workmen carrying mortar by means of yoke; (9) Masons dressing blocks “on the bench” prior to setting; (10) Plan of future building set out on the ground (with pegged cords). After R. Taylor, fig 52.



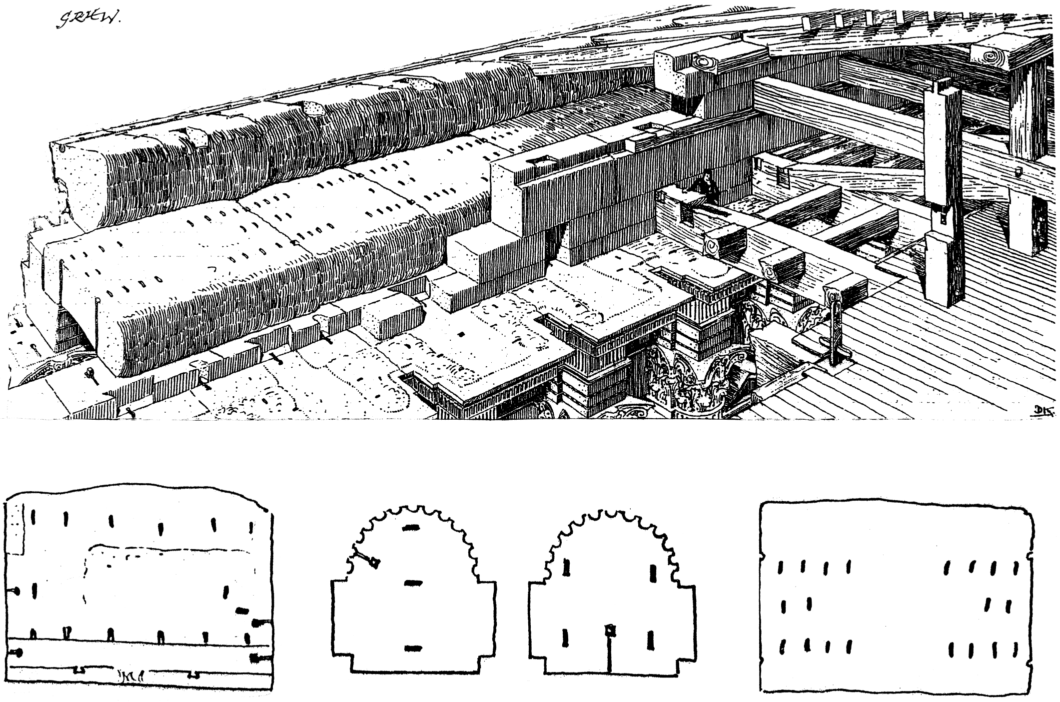
92. Lowering the Column of Antoninus Pius to the Ground. Rome, 1705 AD. The 15m column shaft was buried to two thirds of its height in the rising ground of 15 centuries, and had to be excavated. This engraving is of considerable interest since all the devices shown for lifting an excessive load were available in classical (Roman) antiquity. And it is not evident that in principle any other method could have been then employed. In particular is to be noted the massive timber scaffolding tower to mount on high the blocks and tackle (pulleys). Heavy baulks of timber cramped together to constitute the “pillars” are interconnected by trussing, and stabilised by raking shores. The traction on the ropes was effected by many capstans turned by a regiment of men (and horses). This force was highly drilled to answer immediately to signals (sounded on a bugle). It would be impossible to carry out this delicate and highly dangerous work with traction supplied by treadmills. After Bailey, p. 158, fig 3.



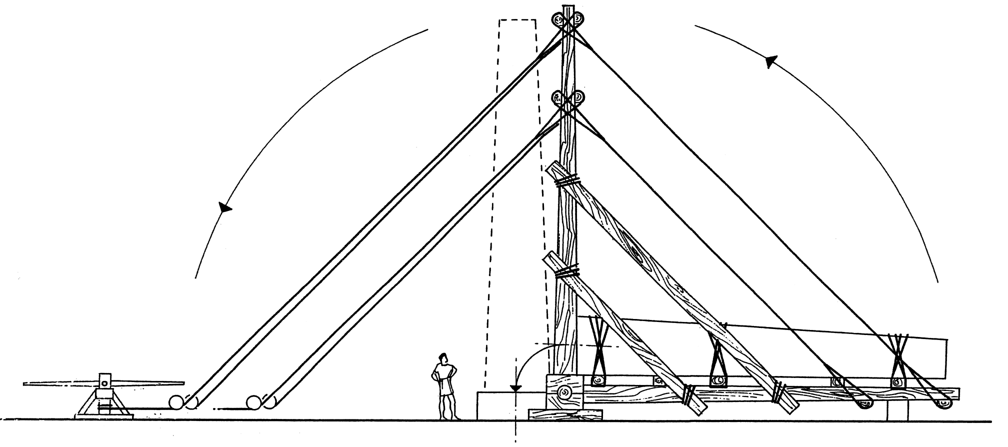
93. Synopsis of Attachments for hoisting blocks in Greek masonry. Including the following devices. Slings around blocks (4); slings and lugs (1 & 2); slings through channels (3, 6, 7, 9, 11, 12); tongs grasping blocks (10); tongs into cuttings (5); lewis (8). *Key*: 1. Propylaia Athens; 2. Parthenon; 3. Aphaia; 4. Sounion; 5. Sounion; 6. Aphaia; 7. Selinous; 8. Theseion; 9. Akragas; 10. Sounion; 11. Delphoi; 12. Olympia. After Martin, fig 97.



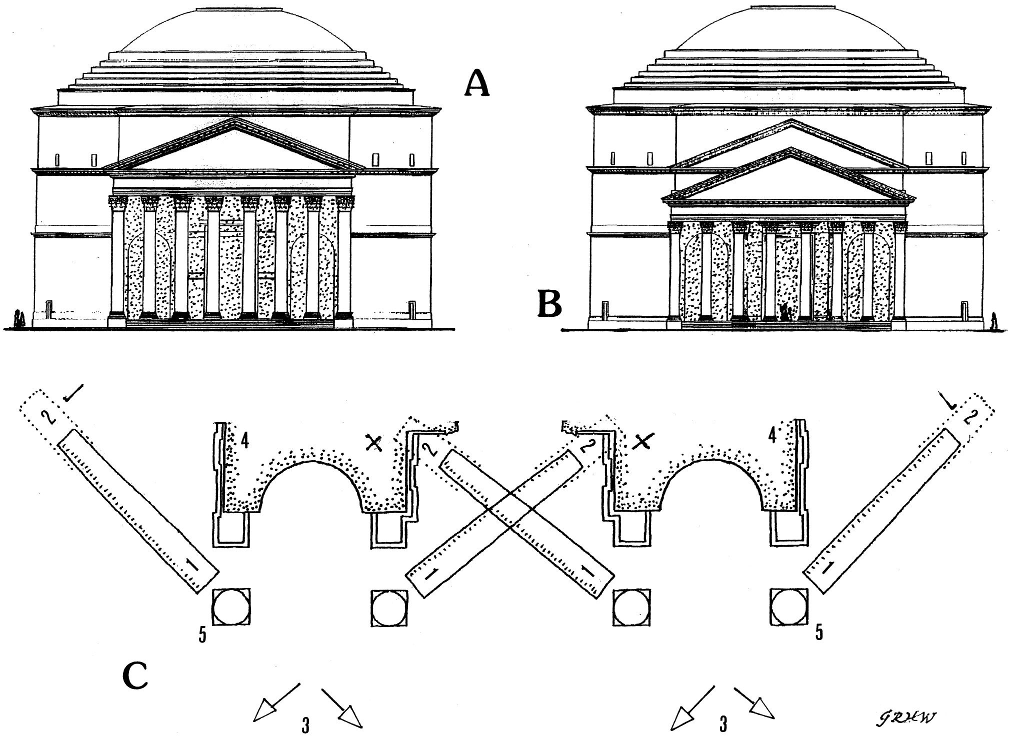
94. Baalbek. Temple of Jupiter Heliopolitanus. Excessive loads clean lifted by block and tackle. Lebanon 1st Cent AD. Angle of façade showing columns approaching 60 Roman feet in height together with part entablature and akroterion. The individual masonry blocks comprising this outsize construction are massive, averaging ca 50 tons burden (as indicated). If these items were clean lifted into position (which was undoubtedly the case) this could have been effected only by attachment of multiple block and tackle hoists mounted on the strongest possible wooden tower scaffolding; the system providing both for controlled lateral displacement and the most delicate motion when lowering the block exactly into position. After Ragette. Baalbek.



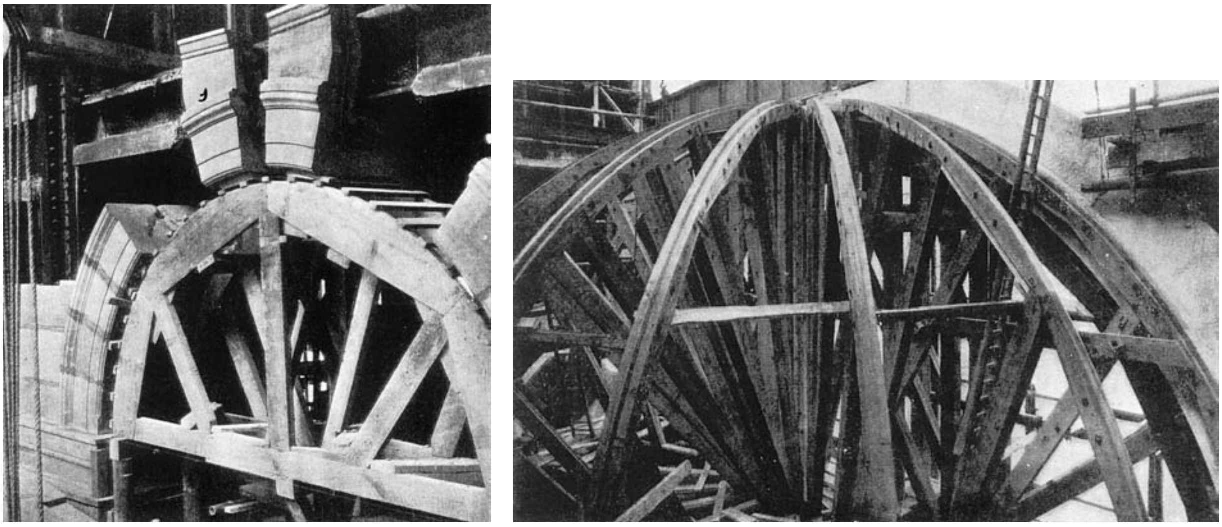
95. Baalbek. Temple of Bacchus. Lebanon 2nd Cent AD. Cut away view of roofing structure and details of upper bed joints of roofing slabs etc showing lewis holes for attaching lifting devices. The ashlar units at Baalbek are massive, in the main varying from several tons to many tons in burden. All were set in place by clean lifting as indicated by surviving lewis holes. The disposition of these lewis holes has been closely studied. The lewis holes testify to the number of attachments made. This was conditioned by the load and also by the quality of the stone. The concern was to limit the sheer stress induced in the stone about the lewis holes so that the attachment did not break away. H. Kalyan considered that, roughly speaking, one lewis hole was provided per each 5 tons weight of the block. This, of course, does not mean that each attachment indicated the use of an additional lifting device – e.g. the roofing slab on the right shows 20 lewis holes and so 20 separate pulleys were required to lift it. Obviously several attachments were made to the one lifting device to avoid excessive sheer stress at the lewis hole. However the presence of a number of lewis holes does indicate that more than one lifting device was used simultaneously to raise the block. This was necessary in view of the load which obviously exceeded the capacity of a single hoist. On the other hand, the conjoint use of several lifting devices was also necessary in order to provide for horizontal motion necessary to set the block down exactly in position. After Baalbek II, figs 92, 109, 110, 119.



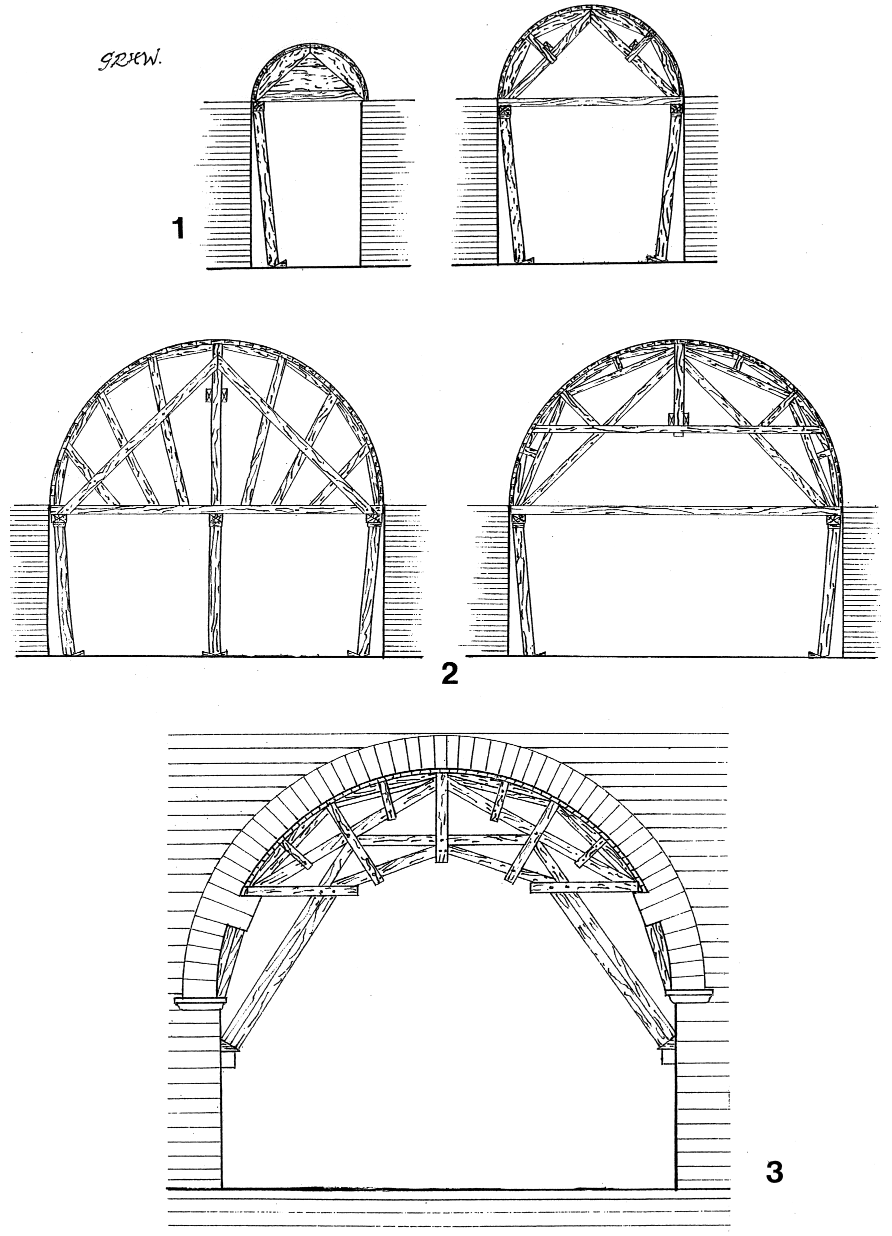
96. The Adam "Tilter". J-P Adam's proposed design for a machine to raise upright monolithic columns. Although an obvious device, no evidence for such a machine survives from antiquity. After Adam fig 98.



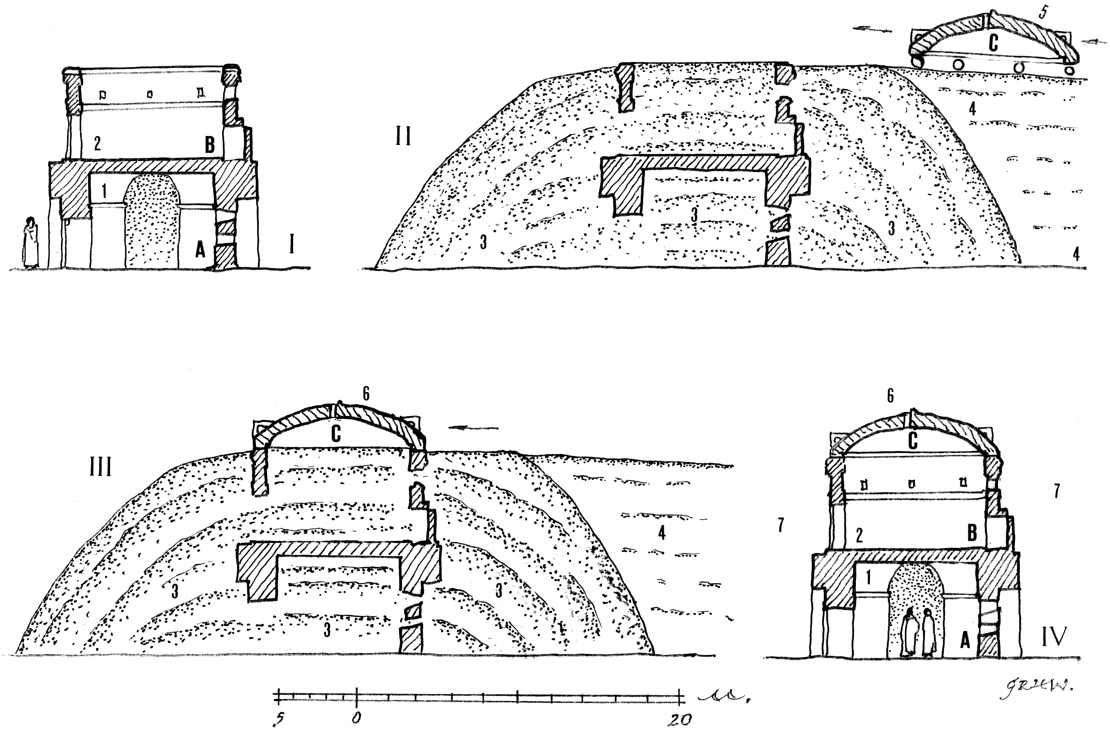
97. The Pantheon. Possible error in building schedule. Rome 125 AD. It is evident that the porch of the Pantheon was originally designed with column shafts of 50' (A) and then subsequently adapted for 40' column shafts (B). The reason for this was stated to be the difficulty in arranging for the supply of these outsize granite monoliths. This explanation has been controverted in favour of an error in operational planning (C). It postulates that the only device for erecting the oversize monolithic columns of the porch was "tilting" and avers that the porch structure (4) had already been built up before it was realised that there was not sufficient space to lay down the 50' porch columns (2) between the designed position of the inner bases (5) and the porch structure (4) as indicated here by crosses. Accordingly the 50 footers were replaced by 40 footers (1) giving sufficient room (indicated by ticks) to lay down the columns and also to draw the tilter upright (3). After R. Taylor figs 67, 68.



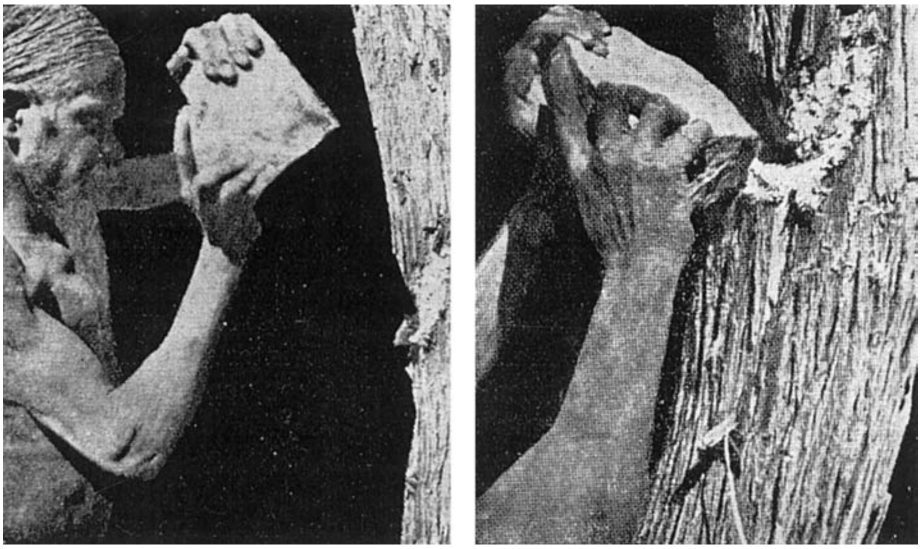
98. Centering in traditional modern building (20th Cent AD). Centering for a medium span arch of ashlar masonry (*left*); Centering for ashlar masonry of hemispherical dome of limited span (*right*). NB. This type of single truss unit centering can not be blown up in scale indefinitely. If larger spans are required the centering must be formed of compound truss units. After Warland Pls XXVI, XXVIII.



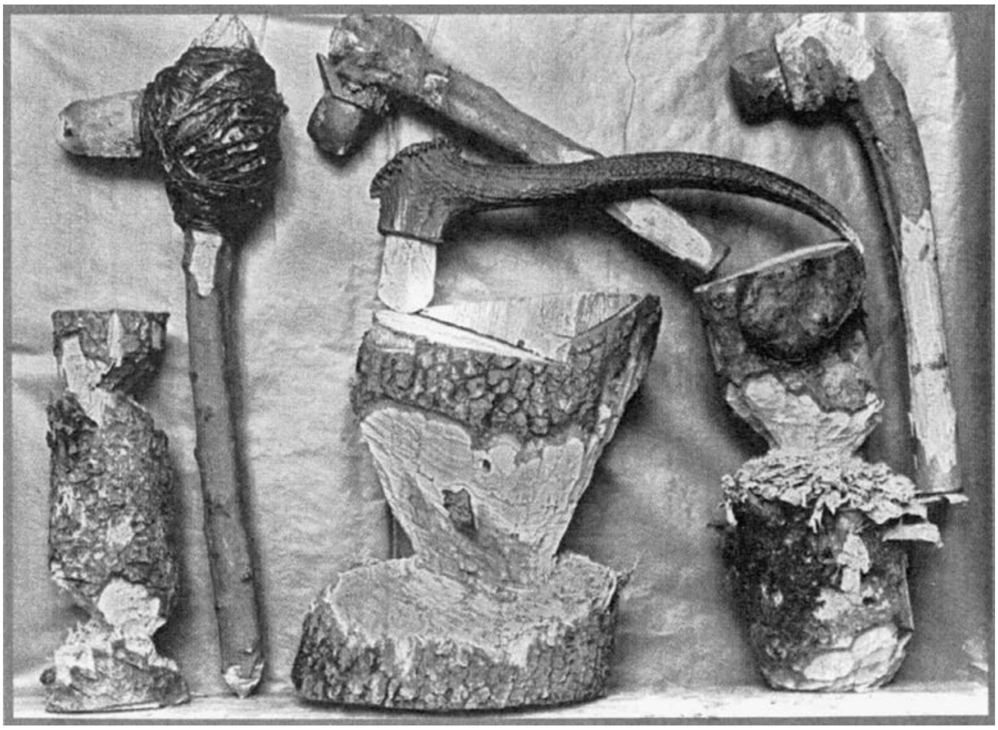
99. Diagram showing specimen centering schemes for arches of increasing span in Roman building. 1. span ca 1m – 2m; 2. span ca 5m – 6m; 3. span ca 10m – 12m. There is an inevitable increase in complexity of the centering construction as the span increases. For the smallest span, e.g. of a small arch headed window or door, the centering can be cut from a single piece of wood. When to save timber and reduce the burden the centering is built up of separate units, the principle is to build a truss and fir the "rafters" with curved units to give the required curvature (which, of course, is not limited to semi-circular). When the span becomes extended a simple basic truss is no longer sufficient, i.e. the required length of the horizontal unit (the chord) becomes impractical. Then a series of trusses articulated together are required. The installation of the centering can be arranged in two ways: as standing centering (here 1 & 2) or as flying centering (here 3). The former is propped in position by uprights rising from the ground; the latter, in some way, is supported at a higher level by abutment against the masonry under construction. This is, of course, economic when the arch is set at a considerable height above the ground. NB in all instances final adjustment of centering is by way of folding wedges. This also facilitates "decentering", i.e. easing and removing the centering from position after the arch has been built and is statically competent. After Adam figs 17, 18, 21.



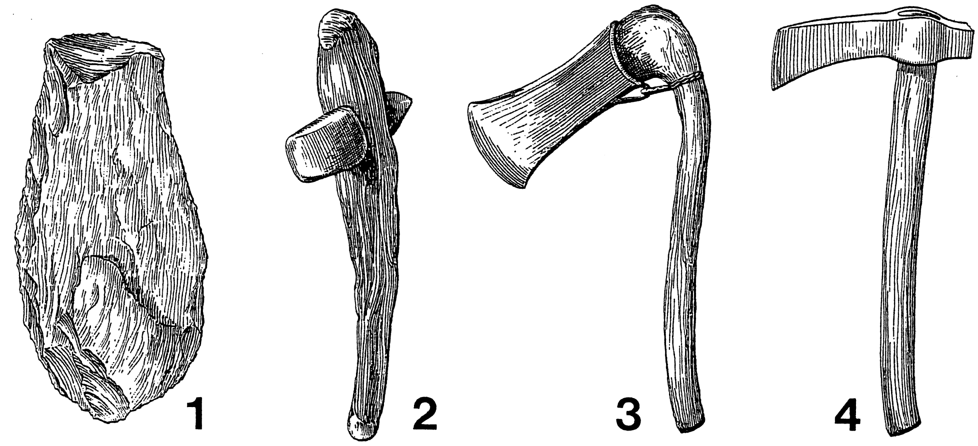
100. Ravenna. Mausoleum of Theodoric. North Italy, ca 520 AD. Sketch showing most likely procedure for seating monolithic dome by use of earth works (fills, embankments and ramps). (I) The ashlar masonry construction of the crypt (A) and the chapel (B) was set in place (1, 2). Then (II) this structure was filled and englobed in an earth mound (3) to render it proof against any displacement. An approach ramp (4) was heaped up against this earth mound and the monolithic dome (C) hauled up the ramp (5). Then (III) the monolith was set in place over the chapel drum (6) and (IV) the earthworks were removed (7). This procedure was used by megalithic builders 4,000 years earlier and by Egyptian builders 2,000 years earlier.



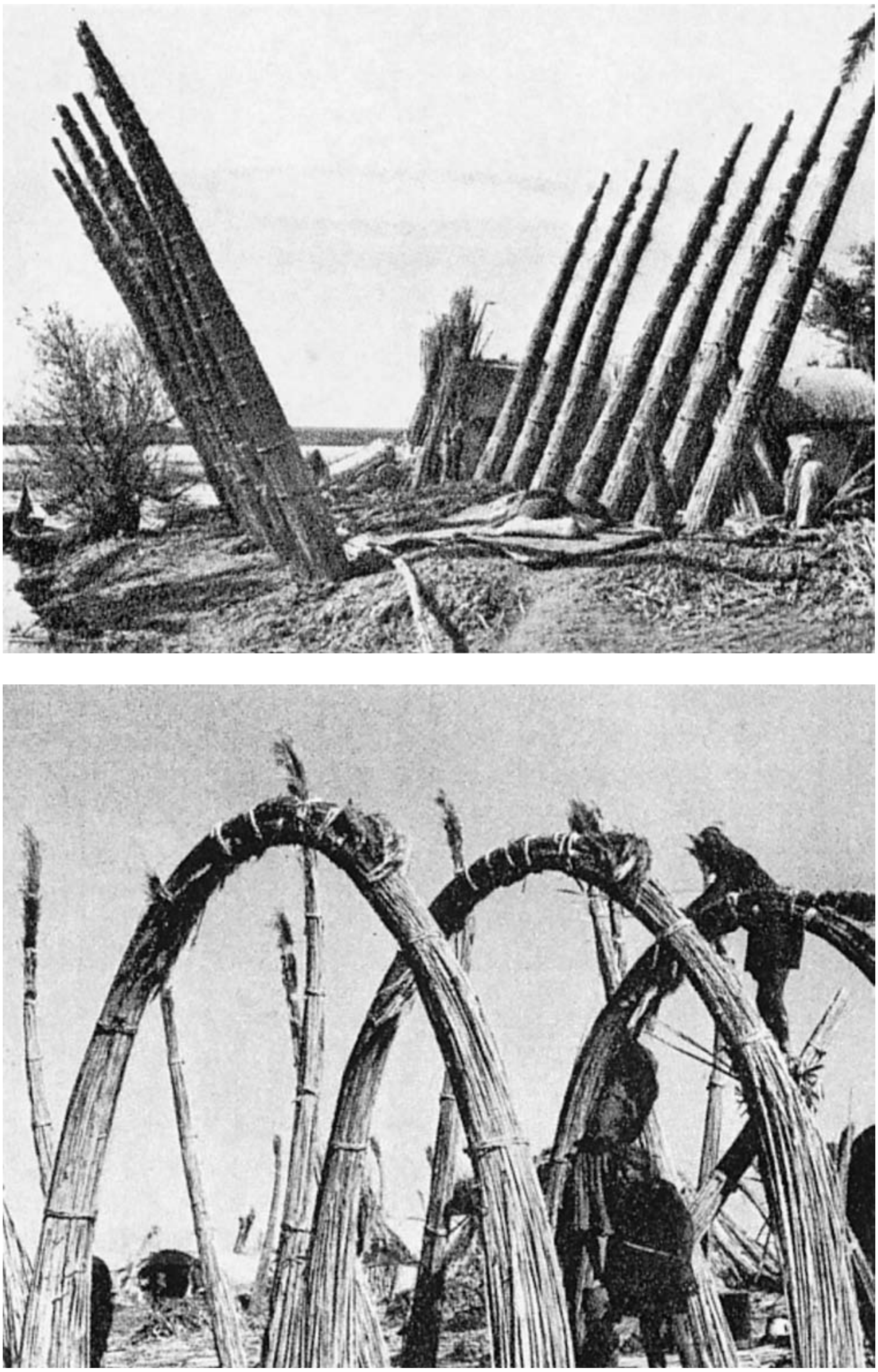
101. Australian aboriginal cutting into a small tree trunk using a field stone with a sharp edge. Such stones have been advanced as worked stones (eoliths). It seems unlikely that tools of this sort could fell substantial trees to provide heavy timber building members. After Oakley, fig 7.



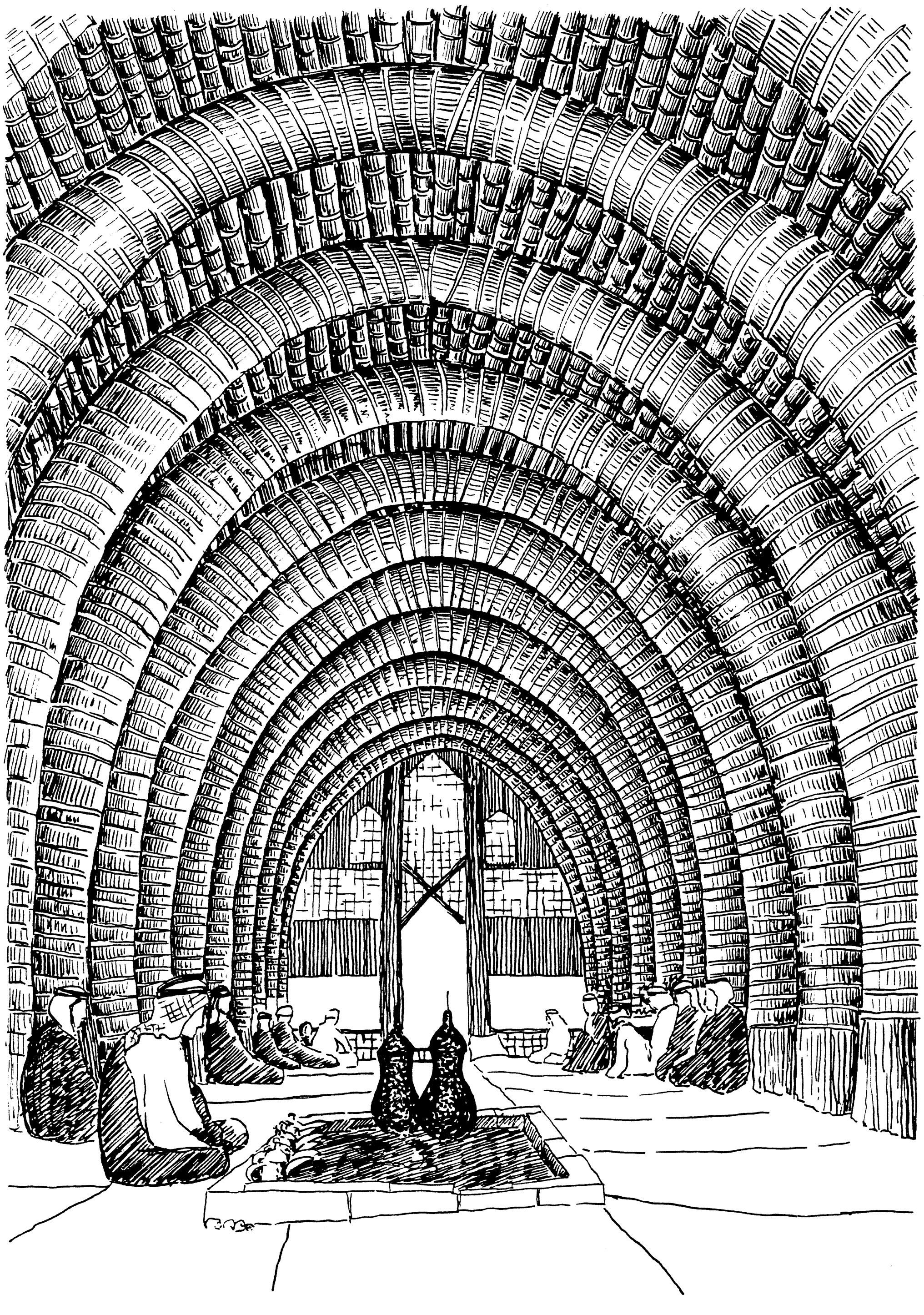
102. Ground and polished stone axe-heads hafted in modern times (ca 1910), together with evidence of experimental use in cutting through light timber. After Archaeologia April 2006, p. 69.



103. The Typological Development of the Axe. (1) Palaeolithic hand axe or cleaver (Kenya); (2) Neolithic ground and polished stone axehead (celt) hafted in wood; (3) Bronze Age axehead. Socketed (Austria); (4) Roman axe. Iron axehead with reconstructed wooden handle (Britain); It is difficult to imagine massive tree trunks cut through by axe types 1 & 2, however tree trunks from these periods are said to have been discovered almost completely chopped through by axes. With Late Bronze Age axes or iron axes of types 3 & 4, trees were felled in a manner comparable with modern times. After Oakley, fig 7.

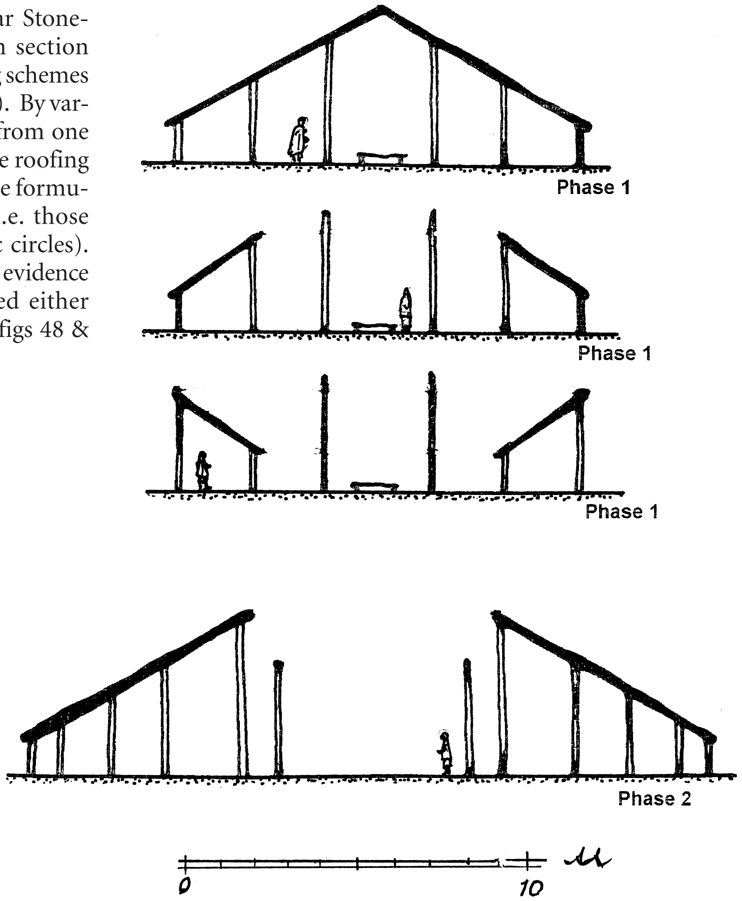


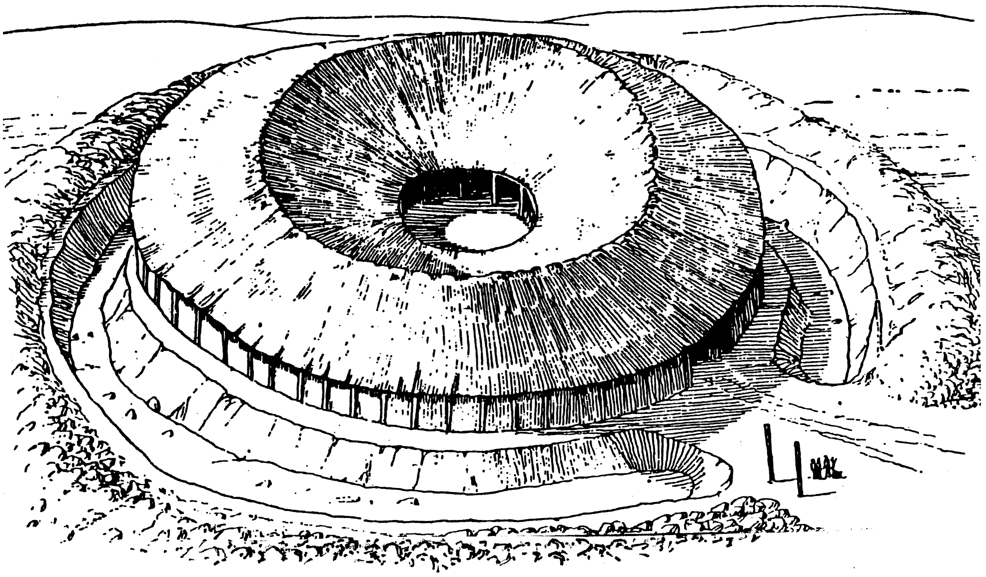
104. The Mudhif. Building Process. Framed construction in bundled reeds of the *mudhifs* ("guest houses") of the marsh arabs of Southern Iraq. The cladding is of horizontal "poles" formed from slighter reed bundles which act as ties between the hoop frame, and support sheets of matting. The characteristic (parabolic) curve of the pliant material identifies this type of construction. After Thesiger.



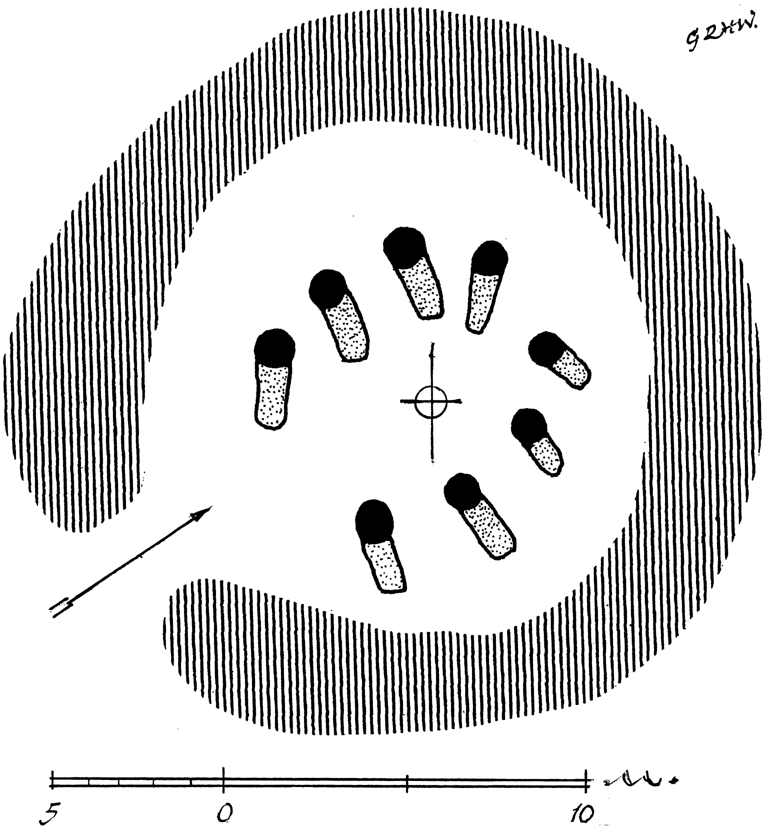
105. The Mudhif Interior. The communal Reception Halls of the Marsh Arabs of Southern Iraq are built almost entirely of light vegetal material; bundles of reeds lashed and tied by kilometres of palm fibre rope. The structural members are pairs of giant reed bundles, which are set into the ground and lashed together at the apex so that the natural flexion produces a parabolic arch. These ribs are then clad with slighter bundles of reeds and matting. The length of such *mudhifs* ranges up to 20 m. This technique was known in Mesopotamia during antiquity and there are ancient representations of reed construction. However the material decays completely and thus there are no upstanding remains of such building preserved. After Heinrich Tempel Vol III, Ill 15.

106. Durrington Walls (South). Near Stonehenge. 5th Millenium BC. Diagram section showing various hypothetical roofing schemes for a "timber circle" (a "wood henge"). By varying the height of the timber posts from one circle to another, numbers of possible roofing schemes (complete or annular) can be formulated for complex timber circles (i.e. those made up of a number of concentric circles). This possibility, however, in itself is no evidence that such timber circles were roofed either wholly or in part. Based on Gibson figs 48 & 99.

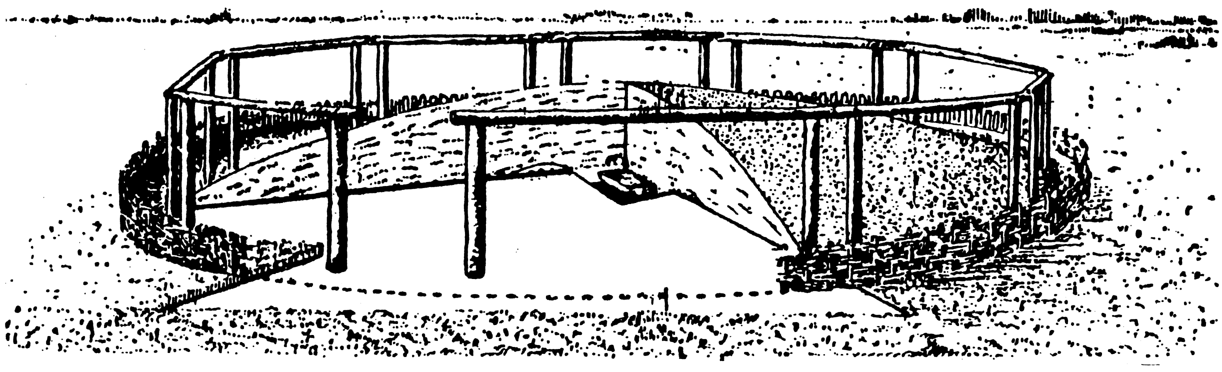




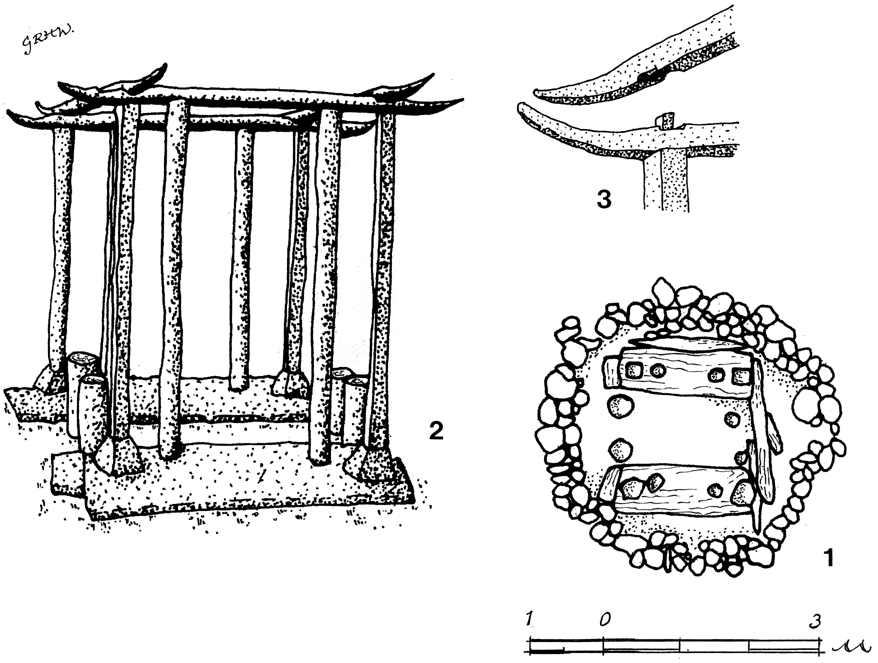
107. Woodhenge, near Avebury. Neolithic. Fanciful reconstruction of the Timber Circle as a roofed building. This reconstruction in view of its dramatic appearance found popular favour – but it is now generally accepted (on the analogy of Stonehenge) that these timber circles were of post and lintel construction, not roofed buildings. After Singer Vol 1, p. 315, fig 203.



108. Arminghall. Plan of Timber Circle. Norwich, Norfolk. ca 4,400 BC. The earth slides (stippled) for setting the timbers upright in their post holes (block) remain clearly distinguishable on the ground. Their disposition shows that the posts were set upright prior to the excavation of the enclosure ditch. After Gibson fig 50.

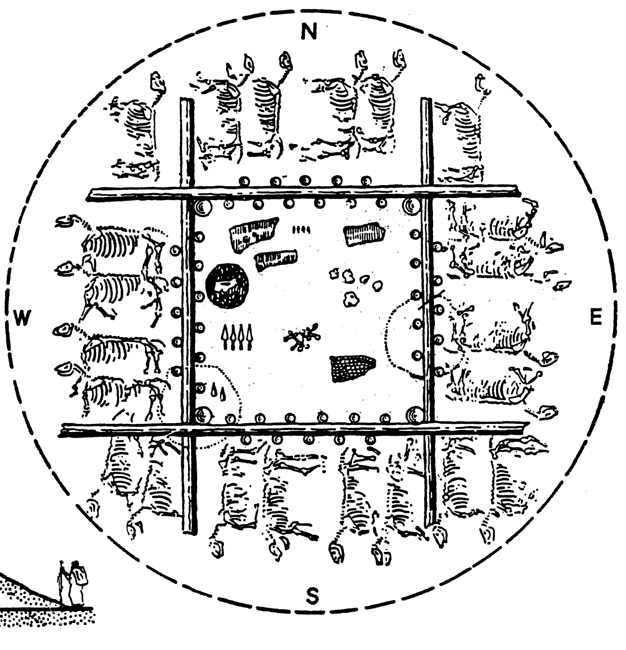


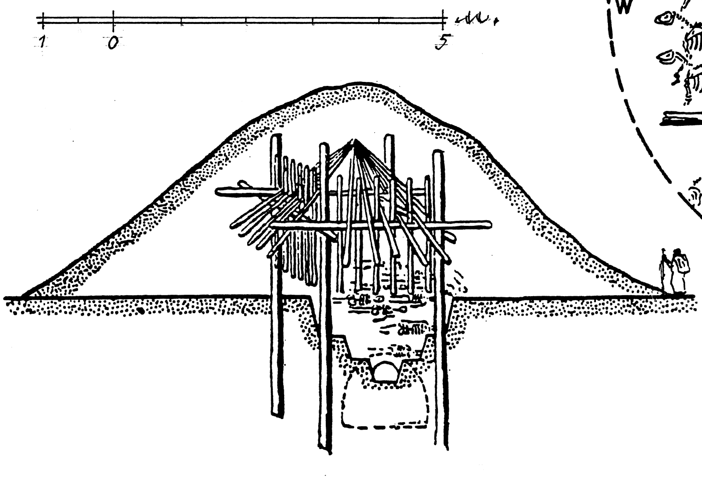
109. Hooge Mierde. Reconstruction of a Timber Circle, set about a round barrow. Near Groningen, Holland. Early Bronze Age. The relationship between the timber circle and the round barrow is not completely evident – but the upright timbers were standing above ground level about the barrow. The diameter of the timber circle is 12m, the height of the posts and also the lintels are conjectural. After Gibson, p. 130, fig 97.

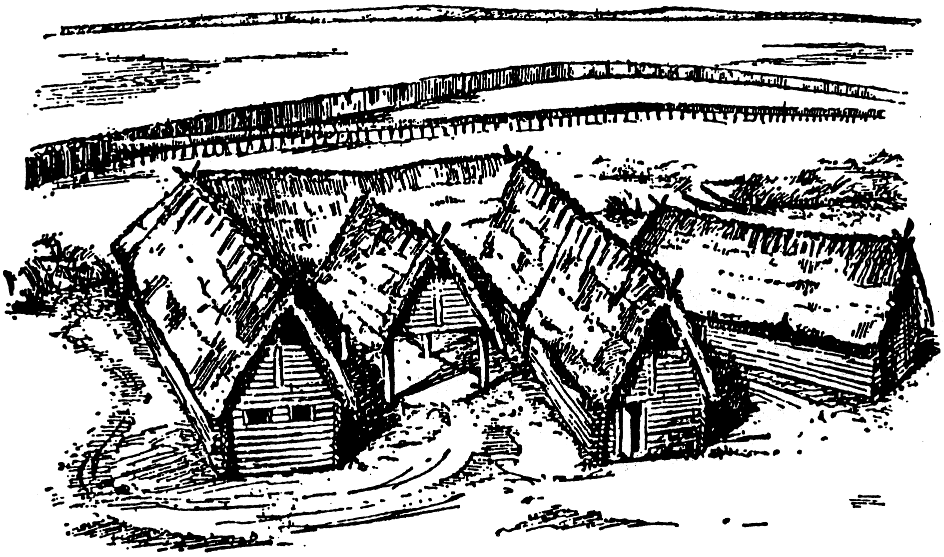


110. Drenthe. Plan and reconstruction of "skeleton" timber shrine. Holland. ca 1400 BC. The constituent timbers were found well preserved at a waterlogged site permitting their reconstruction as a skeleton of slender timber uprights pegged into two base boards thus constituting in plan a "square temple". The timber feature was surrounded by a ring of small boulders. *Key*: (1) Plan; (2) Reconstruction of "horned" shrine; (3) Detail of joinery. After Gibson, fig 74.

111. Kostormskaya Stonetra. The Burial Mound of a Skythian Chieftain. South Russia. 6th Century BC. The chieftain was interred in a deep pit which was refilled, then 22 sacrificed horses and rich burial goods were set out on the surface of the earth above the burial. Over this a commanding replica of a dwelling or shrine was set up – a centralised square structure with a pyramidal roof built of heavy timber posts. The feature was then covered by an earth mound. After Singer, Vol 1, fig 213.

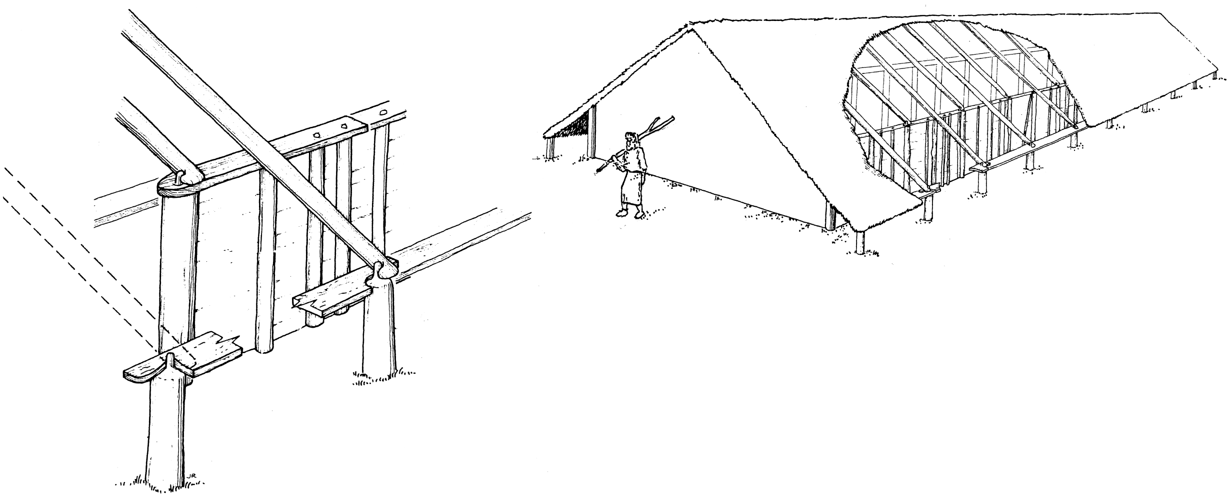




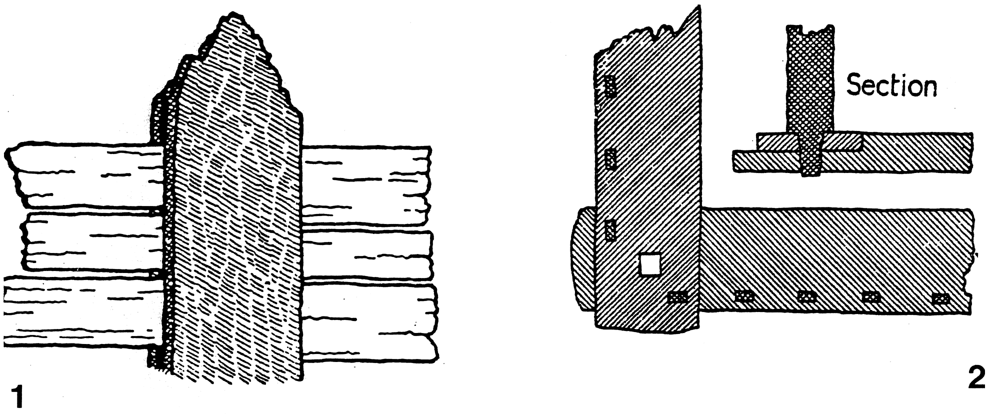


112. Wasserburg Buchau. Reconstructed log cabin farmstead on a waterlogged site. Former island in the Federsee, West Germany. ca 900 BC. After Singer, Vol 1. p. 236, fig 204.

113. Flag Fen. Building timbers used in all wooden houses. near Peterborough ca 1500 BC. Wood preserved by waterlogging in the marsh land includes unwrought timbers, squared up baulks and planks split by use of wooden wedges (v upper left) not by sawing.

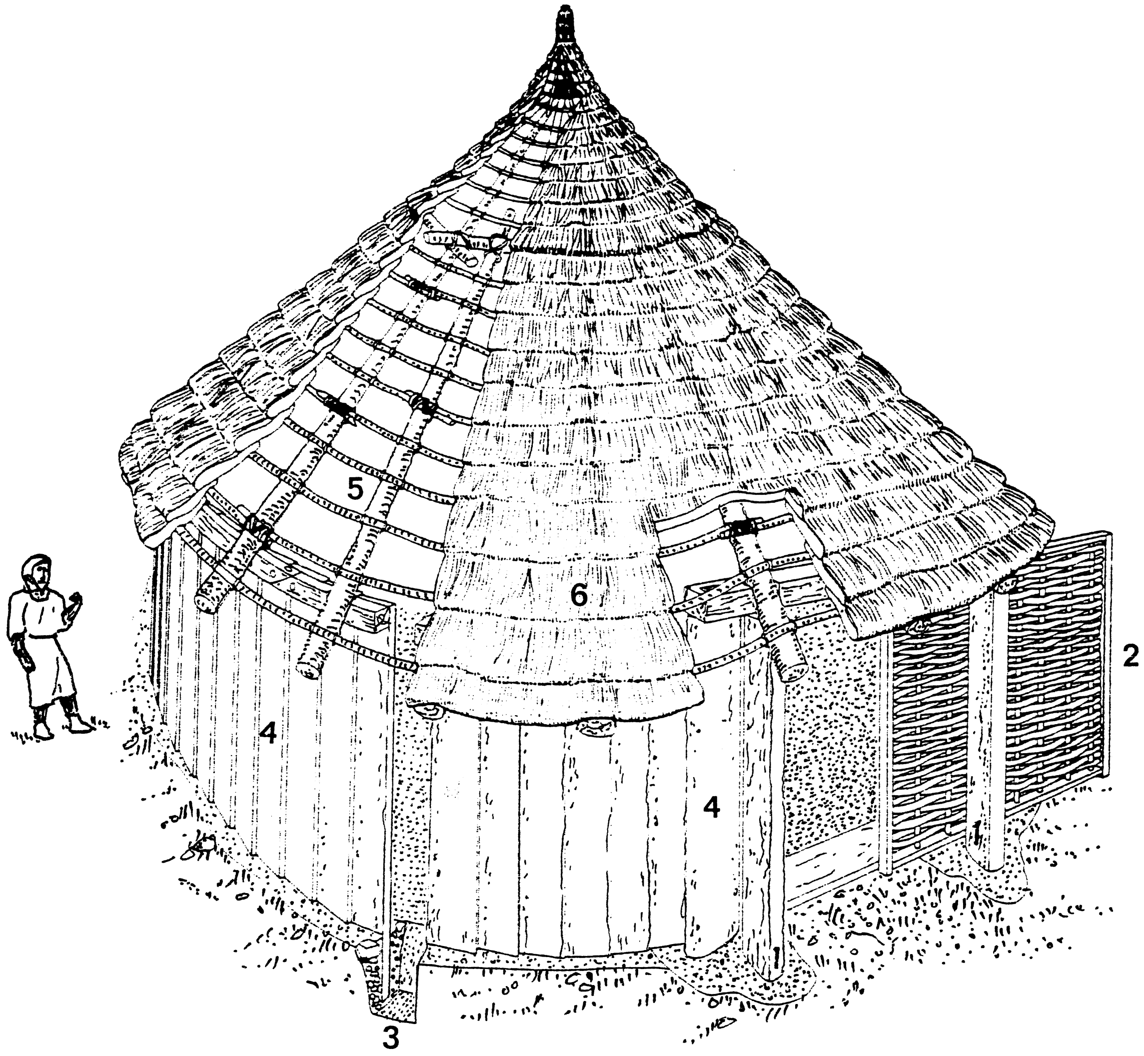


114. Flag Fen. Hypothetical reconstruction of long timber framed public building. Marshlands near Peterborough. ca 1500 BC. Posts, plates and rafters are finely hewn and fixed with effective joinery, e.g. rafters notched to tenons on posts. After WA 21 1989, p. 452, figs 3 & 4.

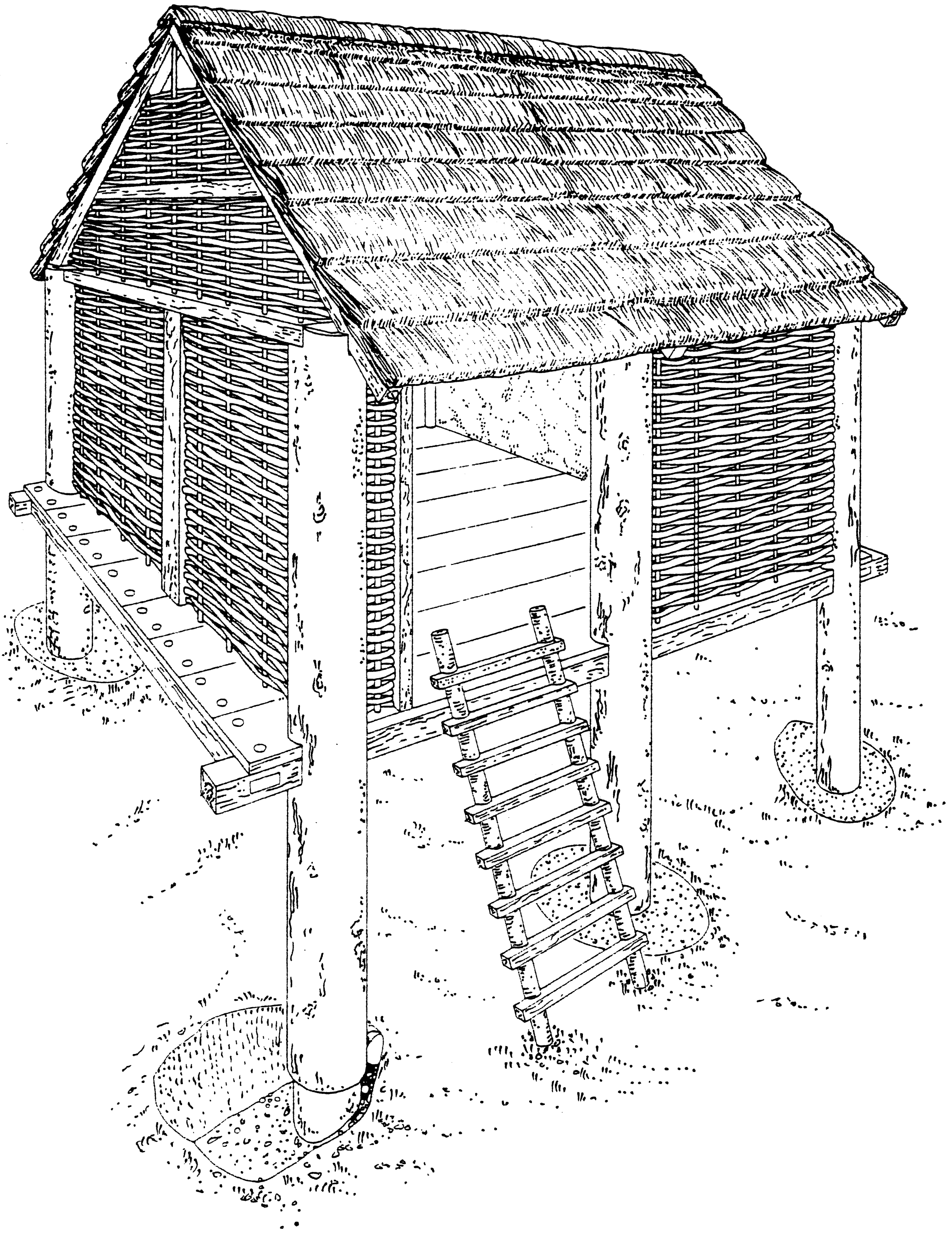


115. Glastonbury Lake Village. Wooden construction details. Southern England. Iron Age. Well preserved wooden remains from marshy ground indicate that most attachments of members was by joinery not carpentry. *Key*: 1. Planks grooved into an upright (not nailed to it); 2. Plan and section of framed wattle and daub construction. The horizontals at the bottom of the frame are jointed by halving, into which the angle post is dovetailed. While at the leading edge of the runners are the mortices for the vertical withies of the wattling. After Singer, Vol 1, p. 320, figs 207, 208.

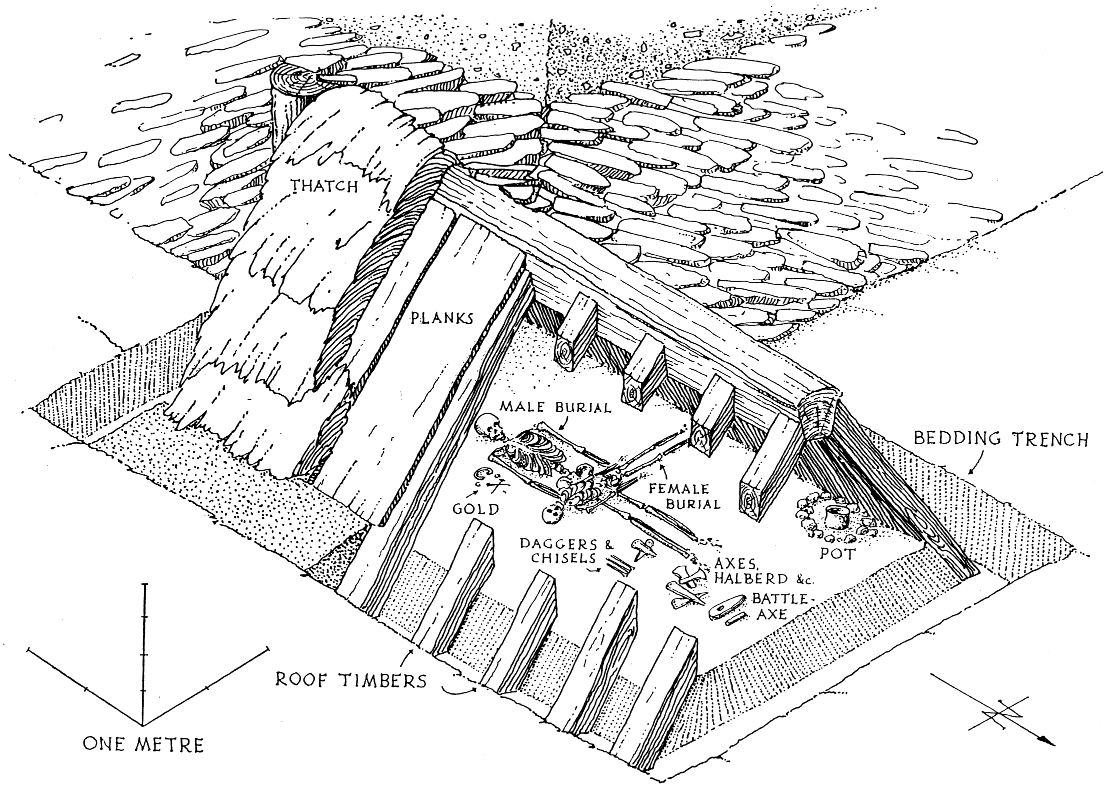
116. Danebury. Celtic Hill fort. Hampshire. Mid 1st Millenium BC. Panoramic view of part (south sector) of settlement showing rectangular storage buildings, granaries, lining street (in foreground), and (in background) three Round House dwellings. The granaries are raised well above ground level on a heavy wooden frame of (commonly) six posts with wattled panelling and thatched roofs. The round houses appear to have been constructed on either of two systems – either with pliant or with rigid members, the great majority of the former category. After Danebury p. 66, fig 50.



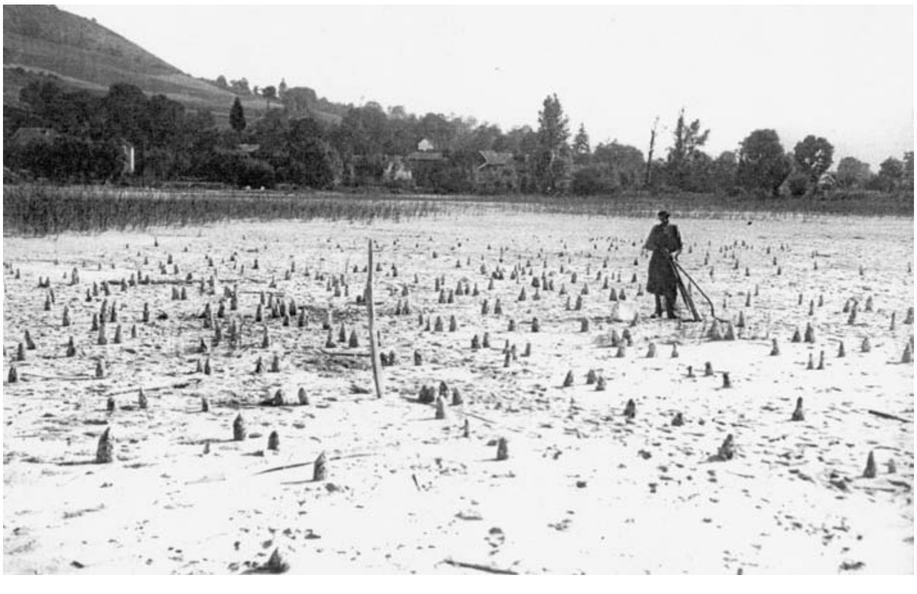
117. Danebury. Celtic Hill fort. Substantial Round house dwelling of all wood construction. Hampshire. Mid 1st Millenium BC. The reconstruction is conjectural. None of the building elements represented were found standing in place. The emplacement is recognisable in plan from the impression in the soil of the foundation trench and the nature of the wooden elements are evidence by random finds. The detail of the roofing is entirely conjectural. *Key*: (1) Posts of heavy external door frame constituting a porch; (2) Wattle door – either sliding or else completely removable (during day); (3) Perimeter trench (20cms – 30cms broad) for vertical boarding wall (shown sectioned); (4) Wall of vertical boarding – ca 30cms – 40cms broad; (5) Pole frame for conical thatched roof; (6) Thatching (of reeds from near the river bank). After Danebury, p. 59, fig 39.



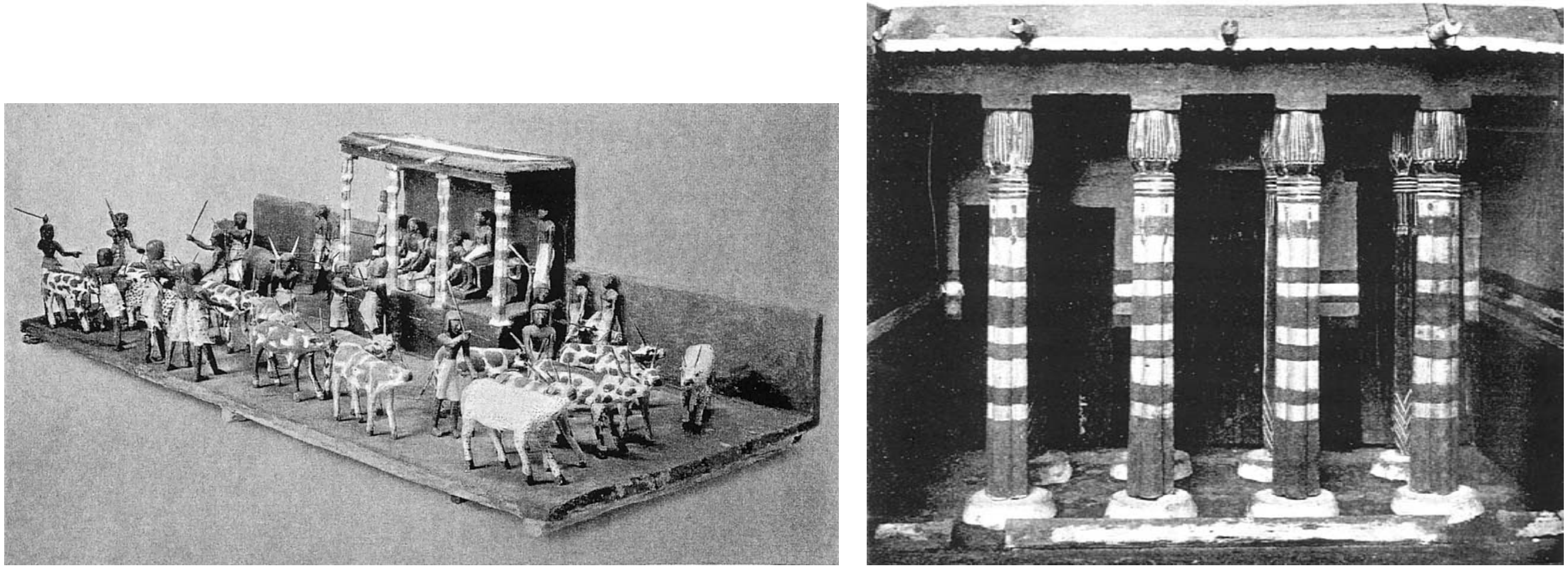
118. Danebury. Celtic Hill fort. Wooden granary raised above ground. Hampshire. Mid 1st Millenium BC. Reconstruction based on post hole evidence for plan and random finds of other wooden building elements. These buildings appear to have been a characteristic feature of the settlement. Exactly such raised wooden granaries survive across the ages in wooded parts of Europe (e.g. Finland and Rumania). After Danebury, p. 65, fig 48.



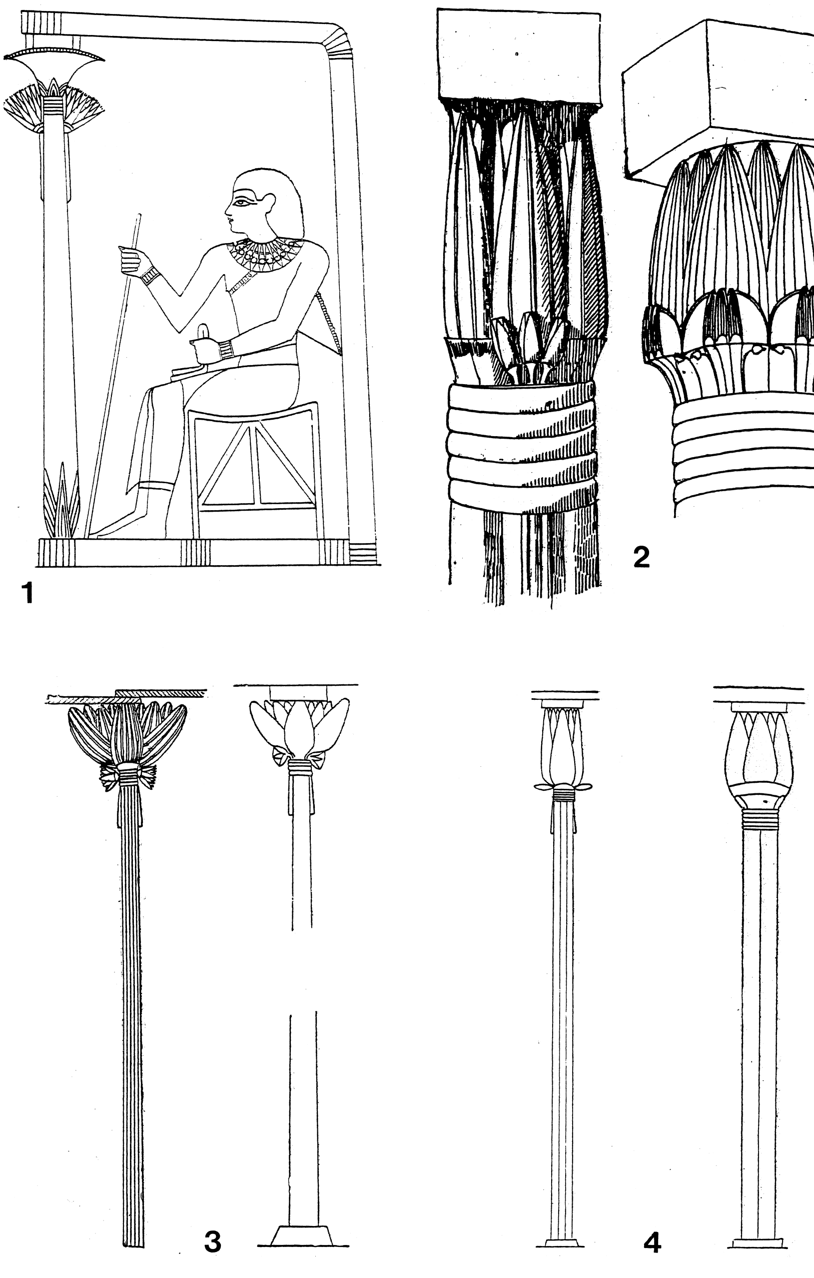
119. Leubingen. Wooden House Grave. East Germany. ca 1500 BC. If this reconstructed drawing is to be trusted in detail it shows a very solid construction of hewn timbers giving a gable roof with rafters and ridge beam. After Piggot.



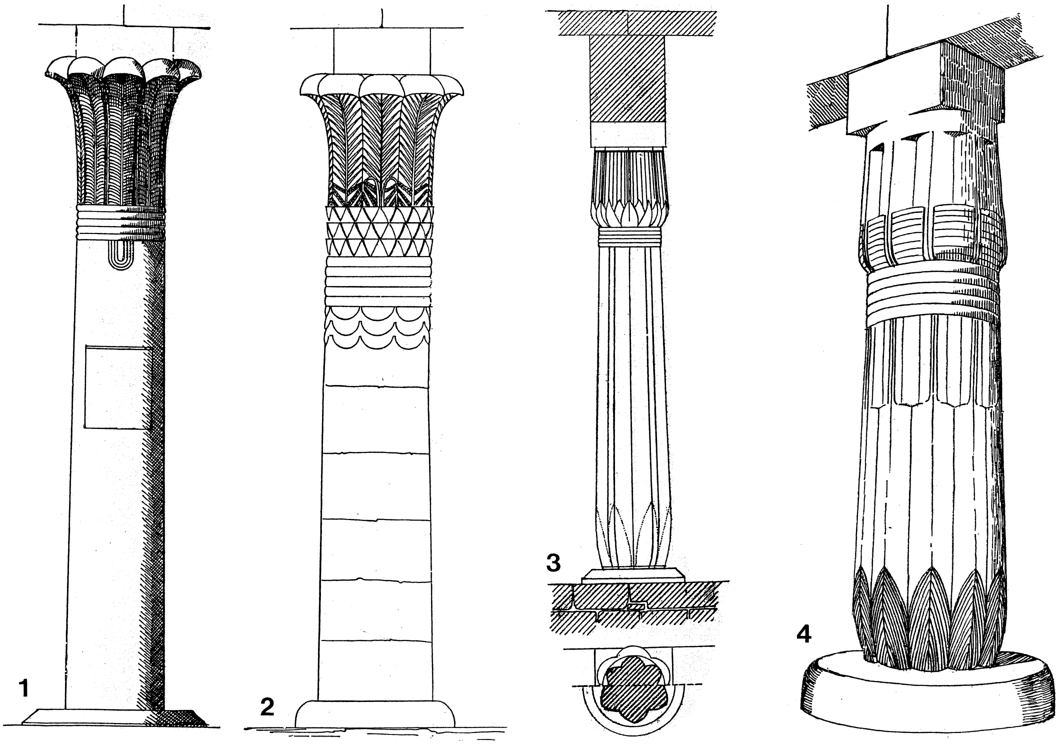
120. Lake Charavines. Neolithic Wooden piling driven into boggy ground. Near Grenoble ca 2700 BC. Typical appearance as revealed in modern time (1921) by an abnormal fall in the water level of the lake. The precise functioning of such piles is not patent and requires close investigation. It is now reckoned that they served to raise the floor of the buildings above the level of flood waters. They were not supports for a lacustrial settlement built out over the waters of a lake.



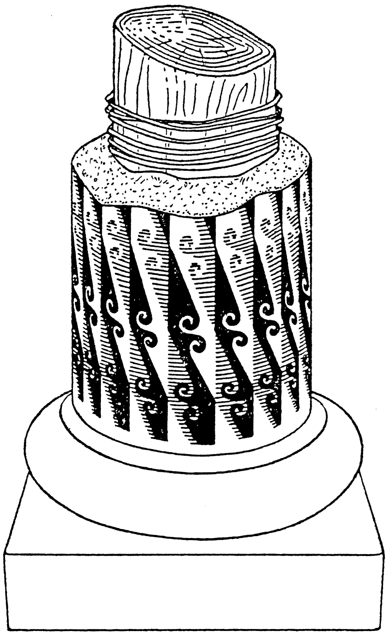
121. Theban Necropolis. Wooden columns in Egyptian domestic building. Thebes. Middle Kingdom. Whereas the columns in monumental stone building were always of stone, columns in domestic building were wooden. Material remains of such columns are very restricted but they can be readily identified in ancient representations – including the wooden models of scenes from daily life with which Egyptians furnished their tombs. These two models from the XI dynasty tomb of Meket-ra show (*left*) Meket-ra inspecting his cattle while sheltering under a pavilion rigged with wooden (lotiform) columns; and (*right*) the portico of his house with a 4 columned façade. In the latter instance the original columns are a material diversification in the mud brick built house. After Smith AAAE pl. 62.



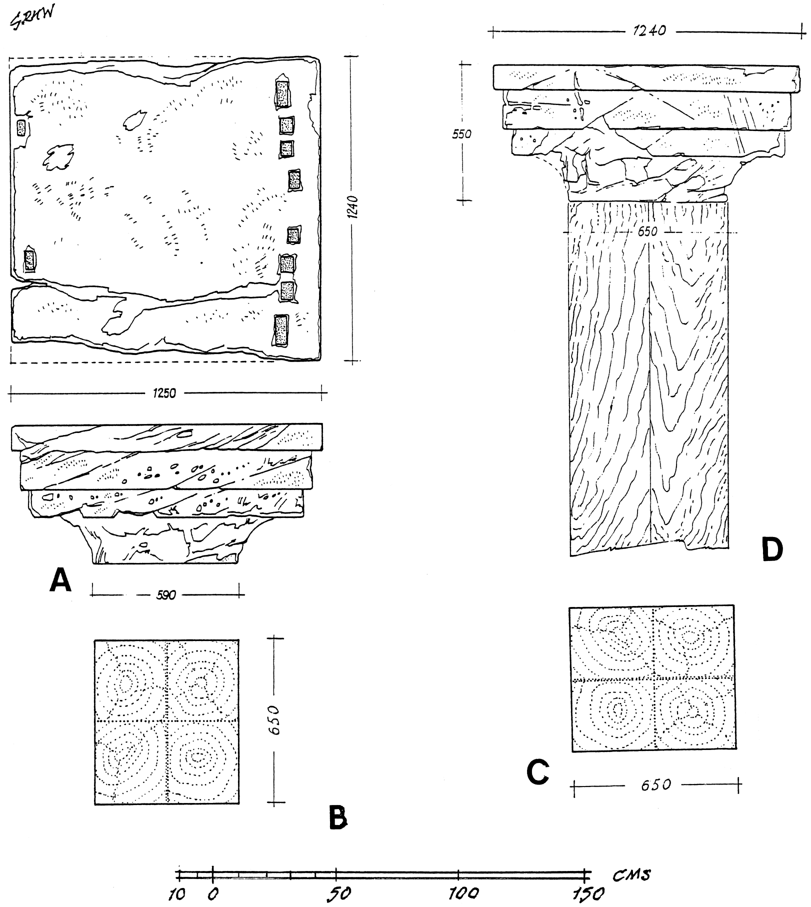
122. The Wooden (vegetal) Origin of the Egyptian Lotiform Column. Bundles of lotus stalks bound together crowned ornamentally by lotus flowers were used as supports in prehistoric shelters fashioned from pliant vegetal materials abundant on the banks of the Nile. This gave rise to the design of a stone column in later Egyptian monumental building – the Lotiform Column. Lotiform supports often appear in representations of light kiosks in historic times. Two stages of the lotus flower were represented as capitals: opening bud and full blossom. In the representation of the kiosk (1) the full blossom form is depicted (3). This form in later stone building often carried over into the simple bell shaped capital (the Campaniform Capital). However the opening bud form in the vegetal model (4) continued to be followed quite closely in stone (2). *Key*: (1) Mural painting in the New Kingdom Tomb of Nakht showing defunct seated in a kiosk fashioned from bundles of pliant materials; (2) Lotiform capitals of the opening bud type in stone building. Left, Old Kingdom; right, Ptolemaic; (3) Representations of colonnets in light pliant materials showing lotus flower in full bloom. Old Kingdom; (4) Representation of colonnets in light pliant material showing lotus flowers in opening bud. Old Kingdom. After Jequier, figs 126, 127, 131, 154, 145.



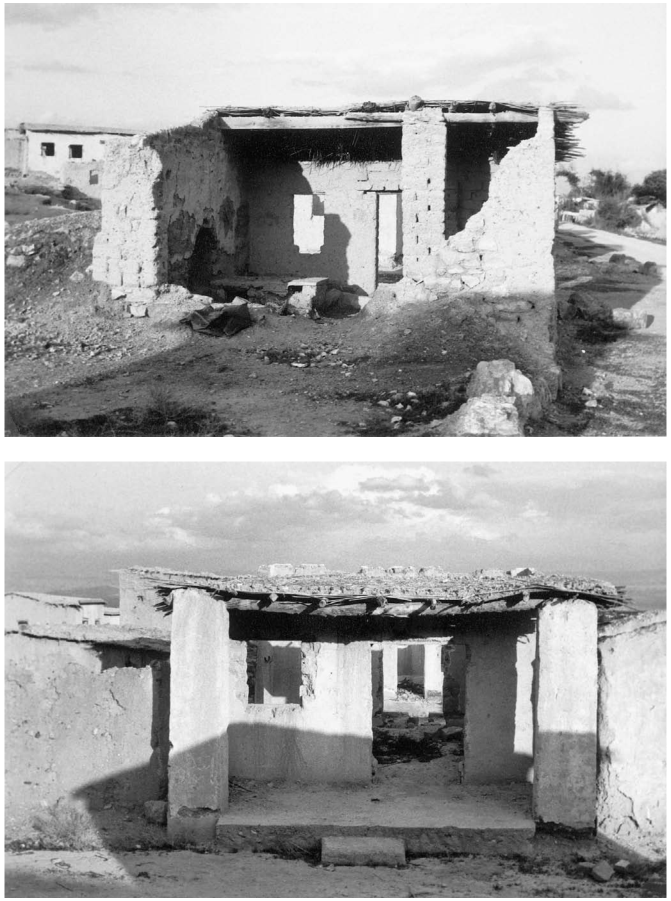
123. Conspectus of Egyptian Columns deriving from original supports of wood or woody (vegetal) materials. The design of 1 & 2 is based on the palm trees; and that of 3 & 4 on bundles of papyrus plants. *Key*: (1) Old Kingdom Palmiform Capital; (2) Ptolemaic Palmiform Capital; (3) Old Kingdom Papiriform Capital; (4) New Kingdom Papiriform Capital. After Jequier, figs 121, 125, 130, 142.



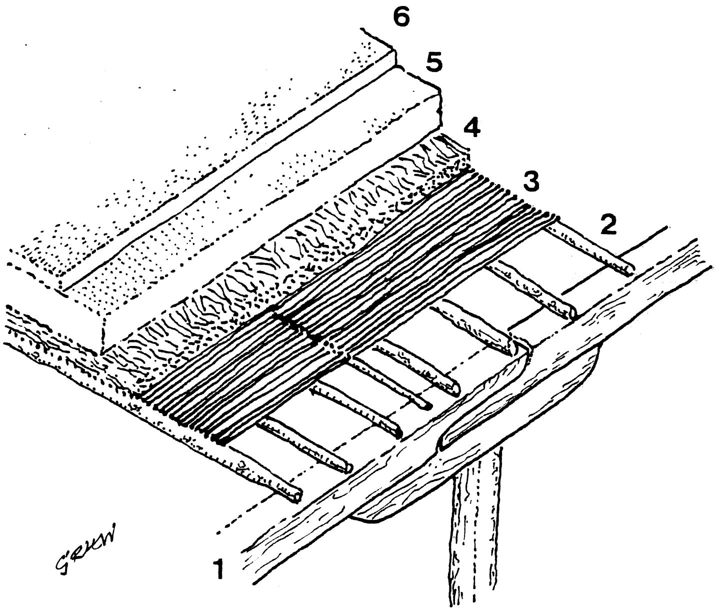
124. Persepolis. Wooden Post plastered to simulate monolithic Column. Persia ca 490 BC. The utilitarian nature of the storehouse/arsenal admitted plastered wood as substitute for the stone columns employed elsewhere in the monumental building at Persepolis. Keying of the plaster onto the wood was effected by rope wound around the post. After Frankfort AAAO, p.22, fig 111.



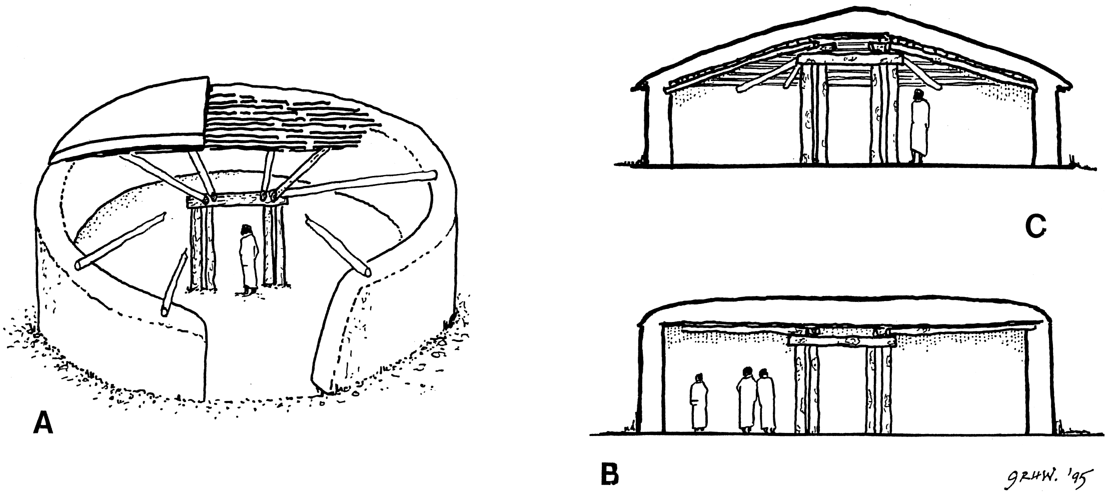
125. Kition. Late Bronze Age Mixed Order. Cyprus ca 1200 BC. Stepped stone capital and compound wooden pier. *Key*: (A) Abacus plan and elevation of 'Cypriote' stone capital; (B) Cross section of restored compound wooden pier; (C) Cross section of restored compound wooden pier; (D) Restored elevation showing stone capital crowning compound wooden pier.



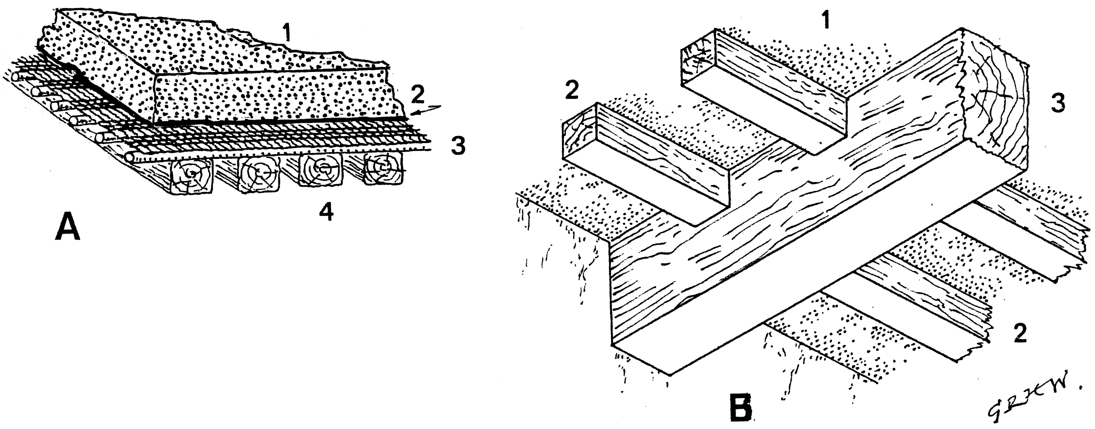
126. Jericho Refugee Village. Traditional Middle Eastern Flat Mud Terrace Roofing. Jordan ca 1950-1960 AD. This type of roofing on wooden bearers survived throughout antiquity into modern times for domestic construction. The wooden frame comprised substantial wooden beams (if required by the span), above which were laid closely set poles supporting contiguous reeds or matting. Over this was spread a layer of earth/clay with generally a surfacing of more water resistant earth (compressed by rolling). This construction was less than ideal. It was extremely heavy and thus the structure sagged and collapsed. Also it was not waterproof, and needed constant rolling and resurfacing between rainy seasons. The remains photographed here are from a deserted village built up in the early 1950's to house newly displaced refugees. It was deserted by the 1980's because of the changed political situation. In this way the substantial wooden beams, usually dismantled and carried off when a village is abandoned, remained in place.



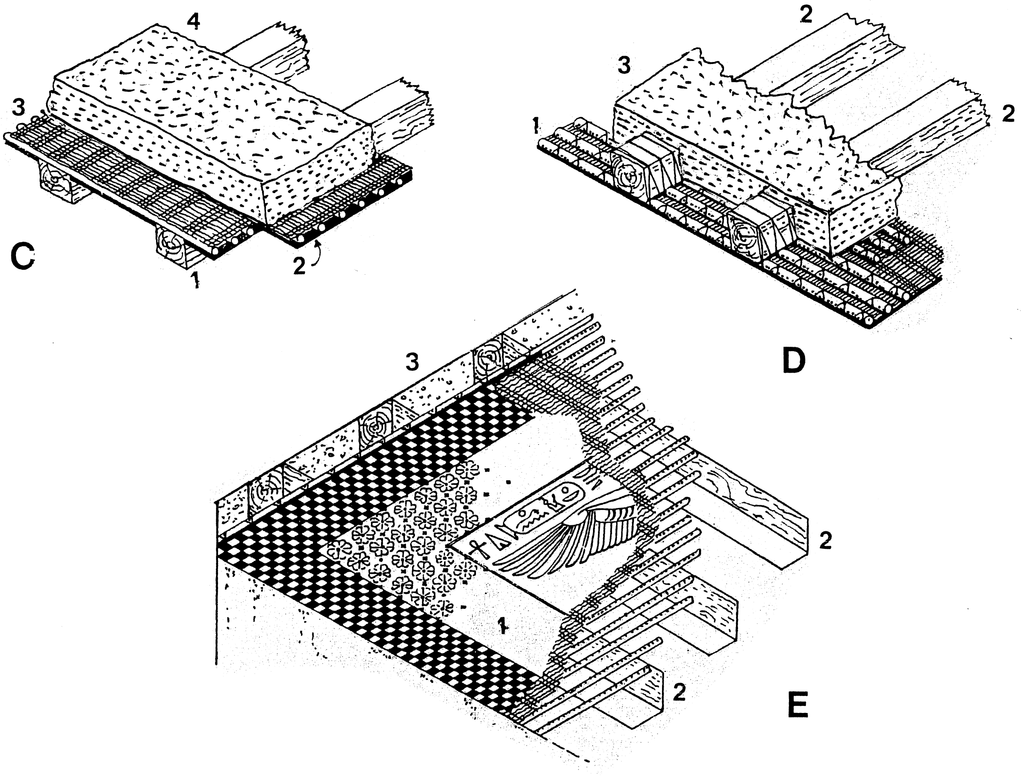
127. Cut away view of typical traditional modern flat mud terrace roofing. *Key*: 1. Halved timber beams; 2. Pole rafters; 3. Reed battens; 4. Rushes, matting etc; 5. Earth/mud; 6. White clay or lime plaster surfacing. After ABC II, fig 320.



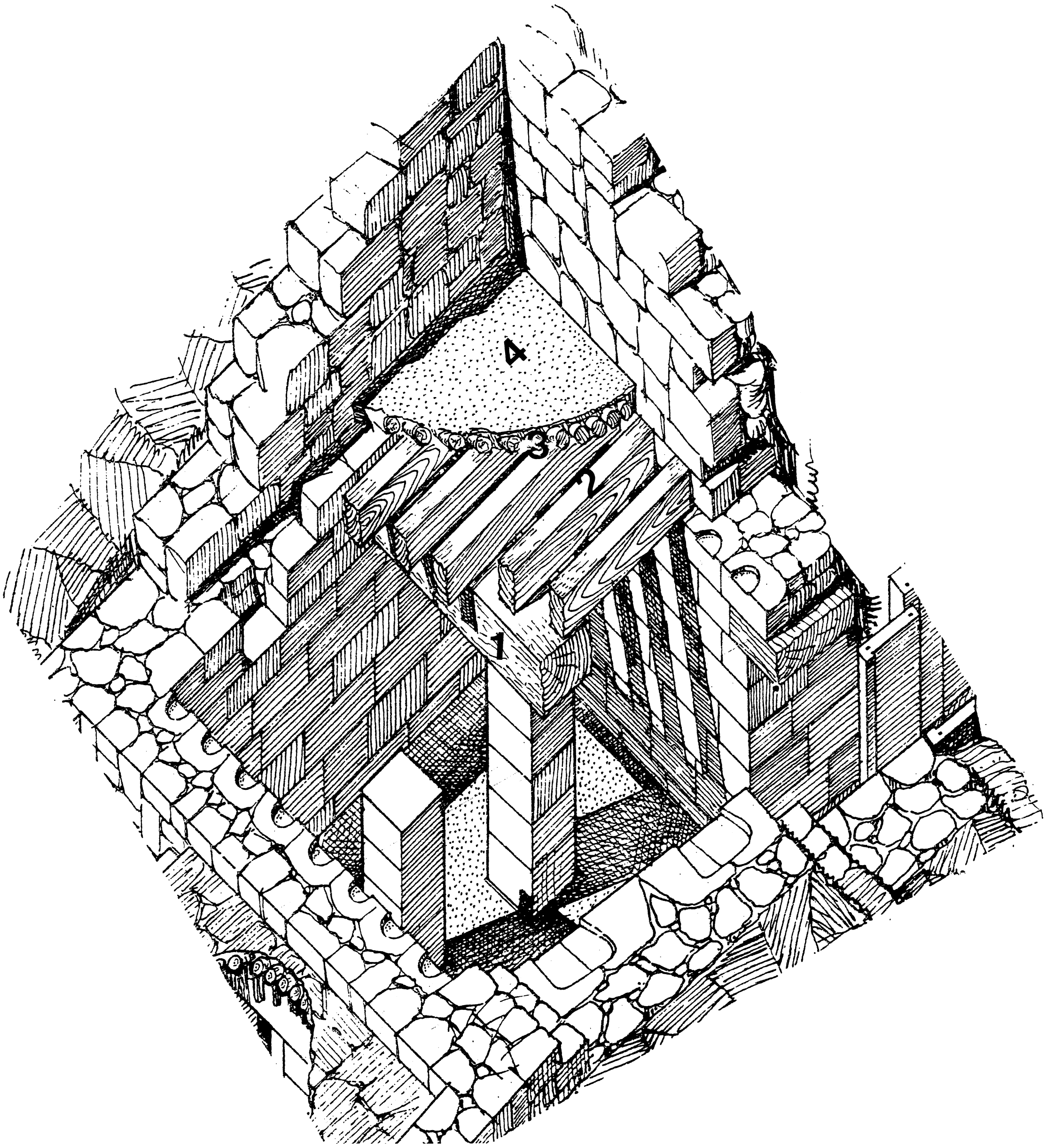
128. Mureybat. Roofing of Pre-pottery Neolithic Round House. North Syria. 8th Millenium BC. These early buildings of load bearing mud brick and rubble masonry were once assumed to be roofed in beehive form by corbelling inward the masonry. However recently evidence has been collected in the form of small fragments of clay roofing indicating that in some instances the mud roofing material was supported on wooden bearers, as is the case for later rectangular buildings. It was then asserted that the roofing was a flat (horizontal) mud roof as for rectangular buildings. However the evidence is equally consonant with a conical (or polygonal) roof. *Key*: A. Elevated perspective view with roofing partly cut away revealing general disposition of mud roof with bearing poles from wall to central timber support; B. Restored section showing flat mud terrace roof as proposed by some; C. Restored section showing conical (polygonal) mud roof more consonant with the design. After ABC II, fig 7.



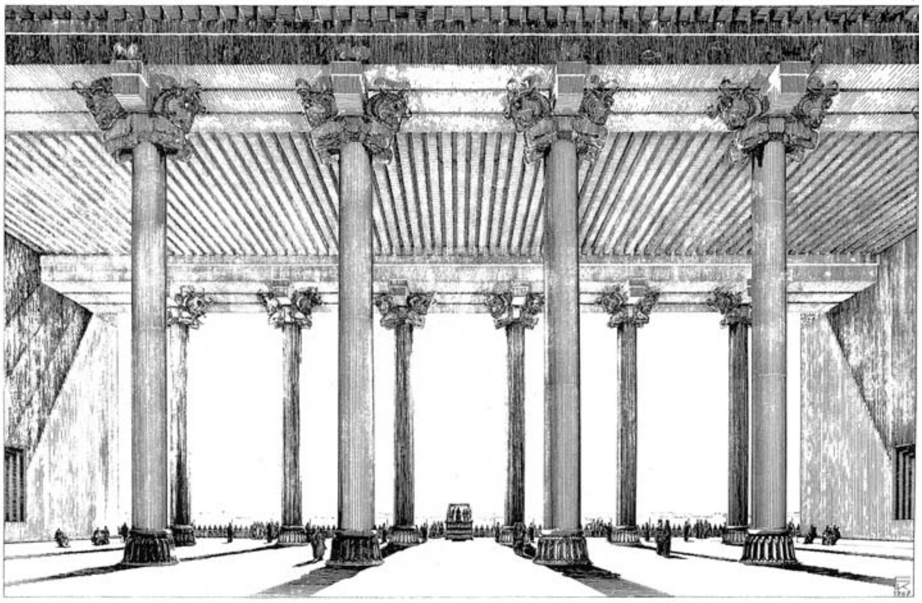
129. Amarna. Flat Mud Terrace Roofing. Egypt. New Kingdom. *Key*: A. Workmen's Village. The roofing here was that of normal village housing except that the wooden bearers were roughly squared. (1) Mud cladding; (2) Matting; (3) Withies and twigs etc; (4) Roughly squared bearers; B The Amarna House. Soffite View. The hewn timbering and the exposed ceiling were both plastered – the former decorated with patterns, the latter with a flat colour wash. 1. Plastered and coloured ceiling; 2. Hewn timber bearers plastered and decorated; 3. Principle beam plastered and decorated. After Smith AAAE, fig 60.



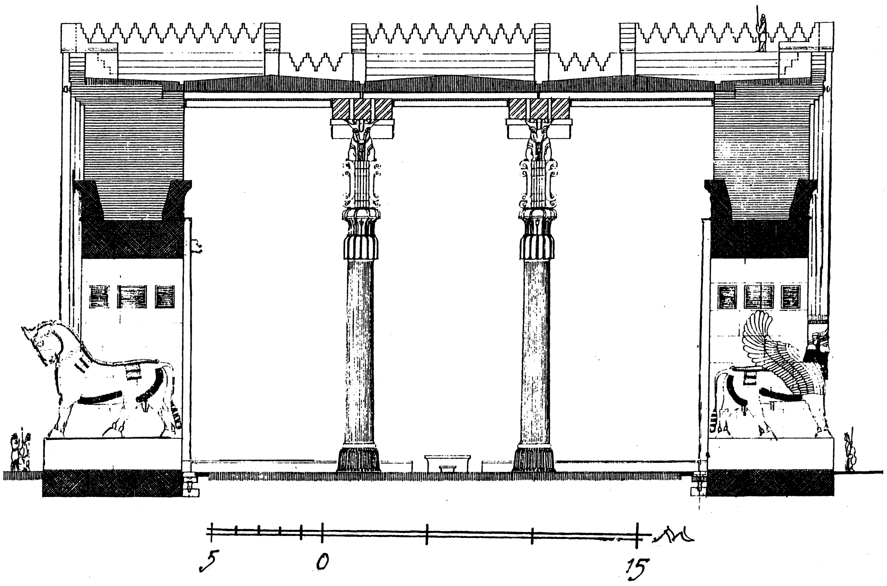
130. Malkata. The Flat Mud Terrace Roof of the Palace of Amenophis III. Thebes. New Kingdom. The mud terrace roofing was here afforded sophisticated presentation. In the corridors and less important rooms the hewn timbers were exposed; in the more important rooms the timber bearers were entirely concealed by a suspended ceiling so that the expansive soffite could be decorated with the traditional appropriate designs (evoking the heavens). *Key*: C. Minor Rooms. 1. Heavy wooden bearers; 2. Decorated plastered soffite; 3. Matting and reeds; 4. Mud; D. More Important Rooms with suspended ceiling; 1. Continuous soffite of matting fixed underneath reeds etc suspended by tying to the wooden bearers; 2. Concealed heavy wooden bearers; 3. Mud; E. Reconstruction of King's bedroom Ceiling; 1. Continuous soffite of plastered and decorated matting below reeds, suspended from wooden bearers; 2. Hewn timber bearers; 3. Mud roof cladding. After Smith AAAE, fig 60.



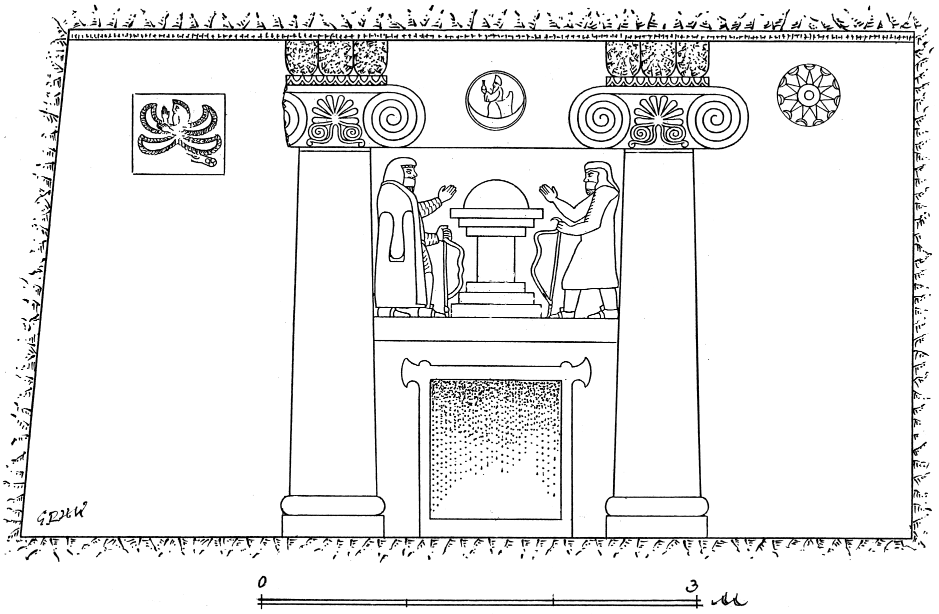
131. Knossos. Temple Tomb. Timber Framed Terrace Roofing. Crete. Late Bronze Age. Isometric Reconstruction by Piet de Jong. In traditional modern building this would be called a triple roof – i.e. with three successive spanning horizontals to progressively diminish the span and thus economise on the sections of timber required. *Key*: 1. Hewn wooden girder; 2. Hewn wooden beams; 3. Pole battens; 4. Plastered Earth. After Knossos IV Fig 932.



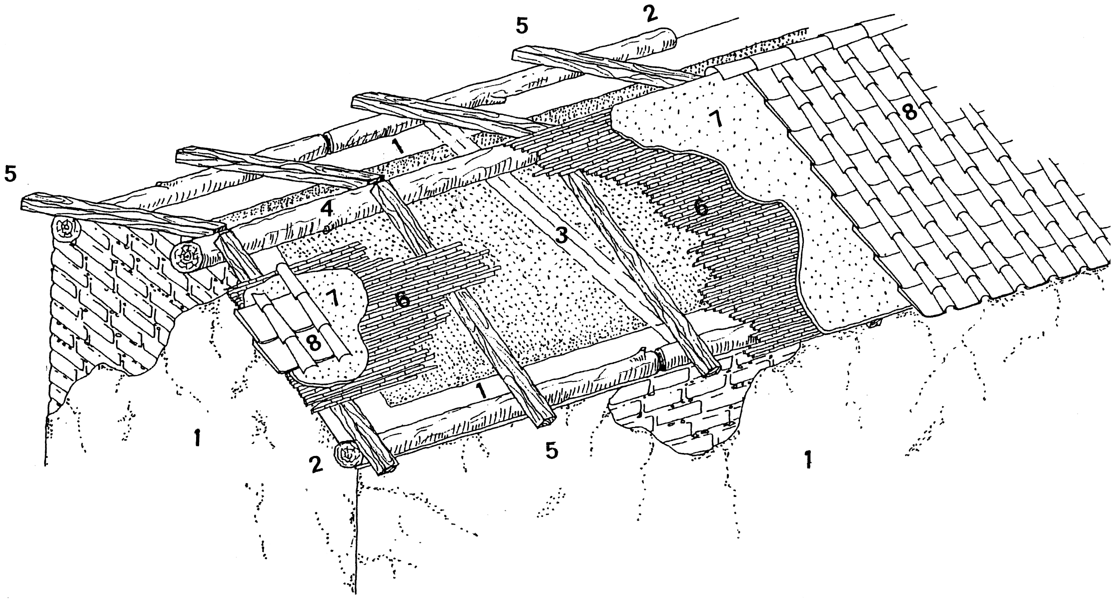
132. Persepolis. Throne Hall. Monumental Flat Terrace Roofing to Achaemenid Palace as reconstructed by Krefter. Persia ca 500 BC. The erection of these towering stone columns and then the timber frames for the acres of flat mud terrace roofing remains a wonder. The span for the primary roofing beams is ca 6m. Krefter's drawing shows a system of 3 beams in parallel (each hewn from a cedar of Lebanon). The timber bearers of extended span shown square in section are probably long poplar beams (boxed in). The waterproofing of the vast terraces must have been a constant headache. A more recent counterpart is the extended terrace roofing of South Indian temples. In spite of all contemporary damp proofing devices they can never be maintained completely waterproof. After Trumpelman Persepolis p. 75.



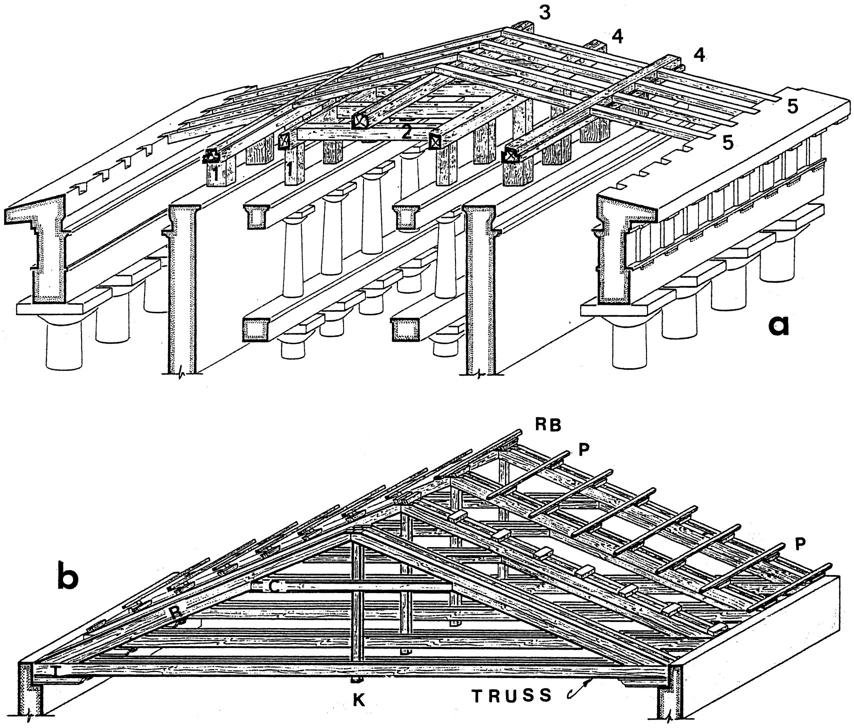
132a Persepolis. Gate of All Lands. Section showing mixed construction and details of roofing. Persia ca 500 BC. The monumental portals are of ashlar stone masonry together with the columns and their ornate bull protome capitals. The walls are of mud brick. The roof is a timber framed flat mud terrace roof. The principal beams are composite: three parallel cedar baulks. These support closely spaced roofing timbers, over which is spread the mud terrace. This drawing clearly shows the composite roofing beams as running parallel to the principal elevation of the capitals, i.e. that displaying the two bull protomes in profile. The roofing beams stand clear above the capitals, resting upon a wooden cross piece bearer bracket set on the saddle back of the capital between the bulls heads. In this way the capitals are properly seen to support the roofing beams and are not directly encumbered with the ceiling. After Trumpelman, p. 79, ill. 17.



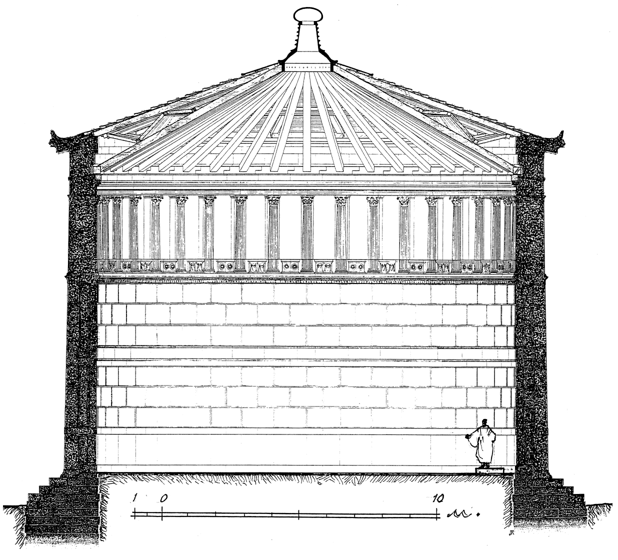
132b. Qizqapan. Rock Cut Tomb. Kurdistan. Achaemenid or later. Elevation of entrance to burial chamber showing engaged columns with representations of roofing to atrium. The two principal beams run at right angles to the faces of the Ionic capitals, i.e. out towards the mouth of the cave and support continuous poles bearing the flat roof. The principal beams are composite – 3 massive logs set side by side. Herzefeld noted this arrangement as representing the mode of roofing the great halls of Persepolis. In this connection it seems only to suggest that the principal beams there were also formed out of 3 cedar beams set side by side. However Krefter's reconstruction (Trumpelman fig 14) shows these beams set in the opposite manner to those of the Qizqapan relief – i.e. aligned with the face of the capitals (as is normal) and supported on a wooden bracket set in the saddle of the zoomorphic capitals. after Edmonds. Iraq 1, fig 2.



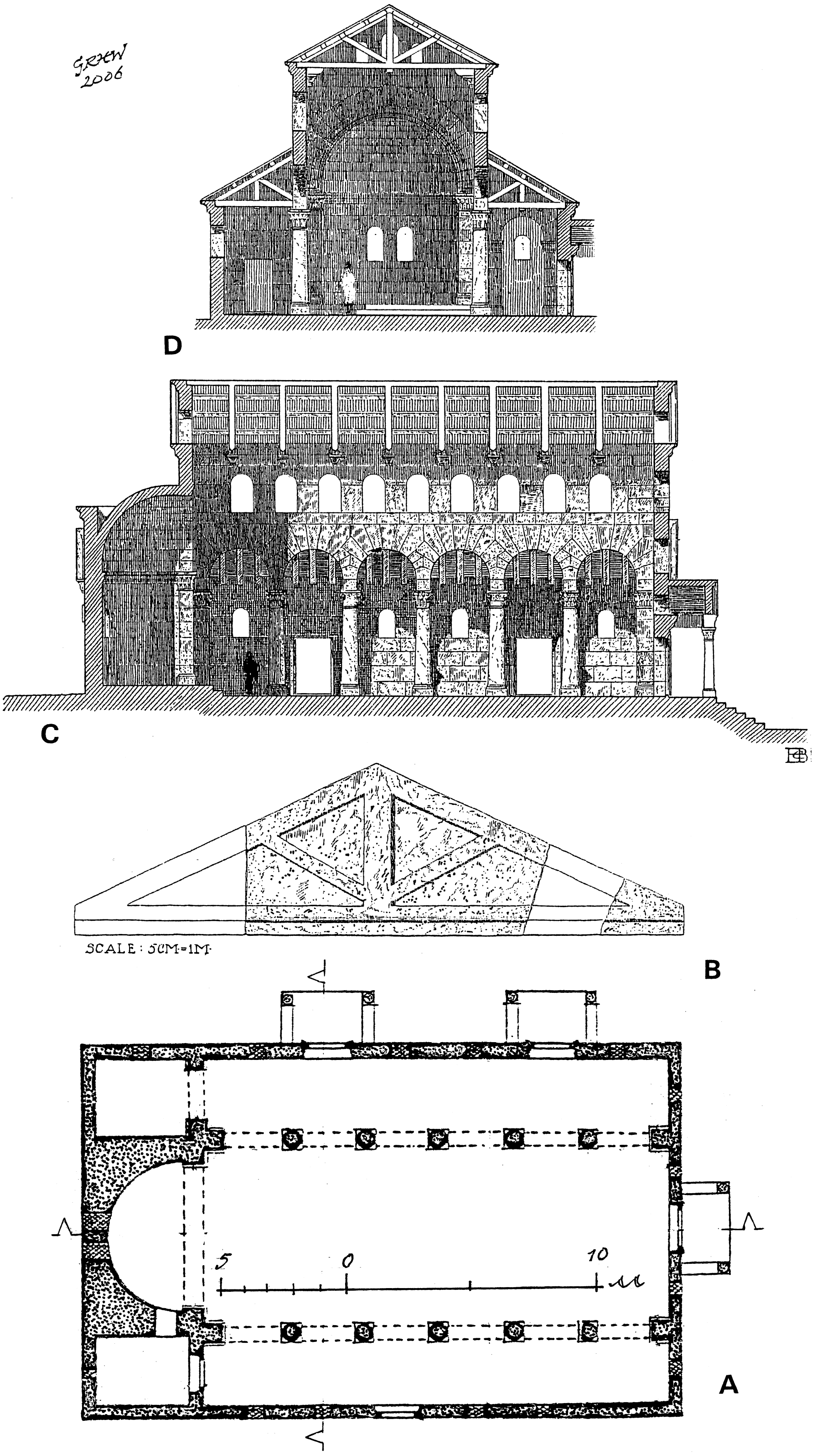
133. Timber framed Mud Roofing in Bronze Age Greece (Jakovides' reconstruction). It was previously accepted that Bronze Age Greek buildings were roofed in the flat mud terrace style of the ancient Middle East – i.e. that the Mycenaean megaron, unlike the Classical Greek Temple, did not have a gable roof. However more recently Bronze Age roofing tiles and tile fragments have been discovered and it is now generally agreed that the roofing tradition in Bronze Age Greece was the gentler pitched gable roof which is normal in modern Greek traditional building. *Key*: 1. Plastered mud brick wall; 2. Log as Wall Plate; 3. Possible tie beam (required to be well fixed into the walls); 4. Ridge Beam; 5. Common Rafters; 6. Reeds, canes, matting, etc; 7. Clay/earth grounds for roofing tiles; 8. Roofing tiles. After Jakovides in BCH Supp XIX, p. 159, fig 14.



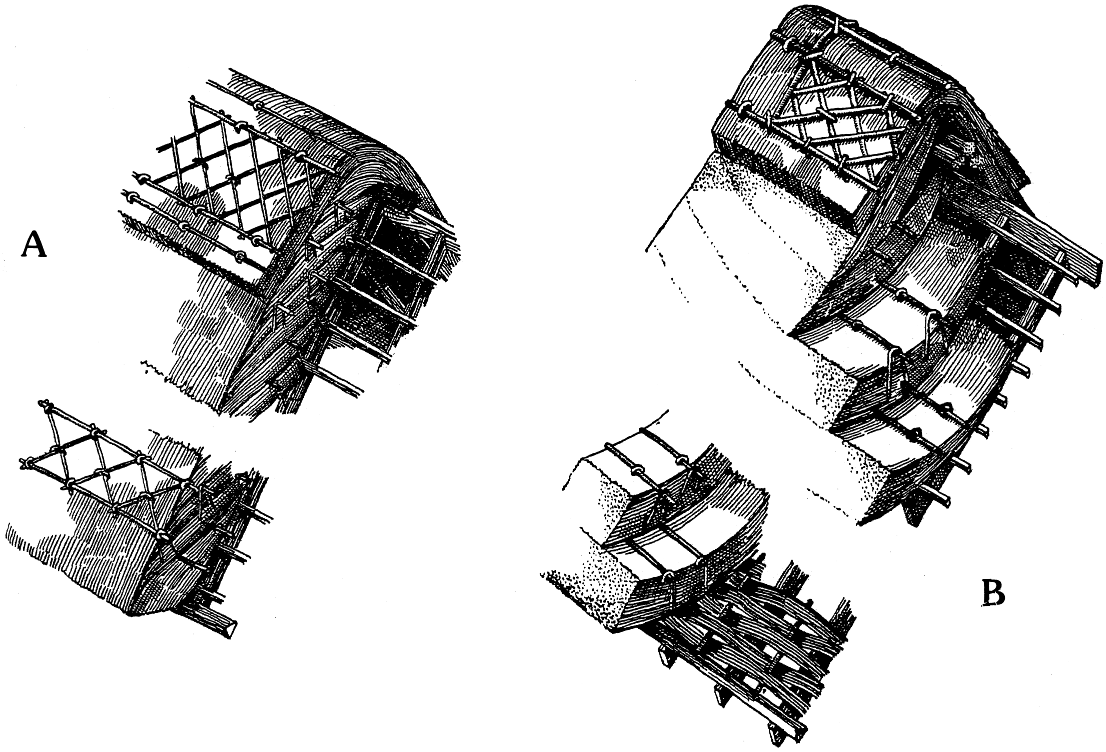
134. Heavy Timber Framed Gable Roofing of Monumental Building in Classical Antiquity. (a) Bearer Beam System. (Temple of Posiedon Paestum, ca 500 BC.); (b) King Post Truss. Basilica of St Paul fuori le mure, Rome, 4th Century AD (drawn to the same scale). The Bearer Beam system was the original tradition and prevailed for much of Classical Greek monumental building. The truss was certainly known and used in Roman times. It may also have been known and used in Hellenistic building in Southern Italy. In the Bearer Beam system the very heavy load of the pitched roof is ultimately taken by beams stressed in bending (tension), so imposing a limit to the clear span of the roofing. On the contrary so long as the jointing of timbers holds fast the several members of the truss act together as a single unit and can not deform separately. No member of the truss is stressed in bending. Thus roofing of a greatly increased clear span is possible (cf 25m). *Key*: (a) 1. Prop / Post; 2. Bearer Beam; 3. Ridge Beam; 4. Purlin; 5. Common Rafters; (b) T. Tie beam; R. Principal Rafter; K. King Post; C. Collar; RB. Ridge Beam; P. Purlin. After Varène.



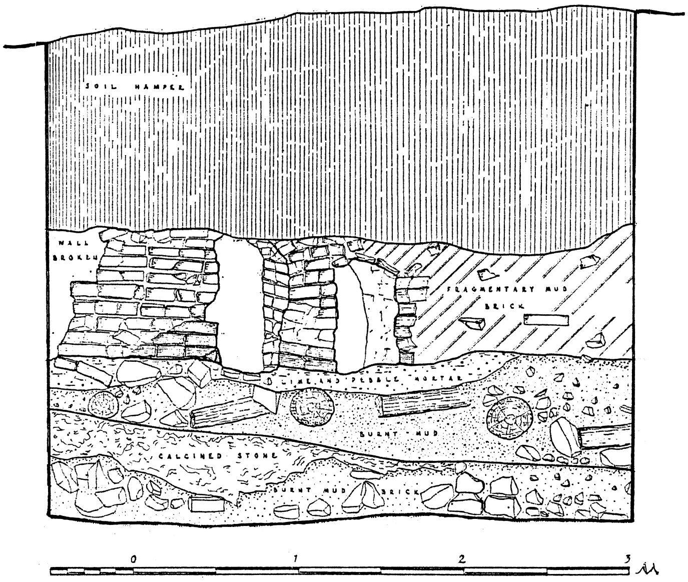
135. The Arsinoeion. Timber Framed Conical Roof to a Hellenistic Tholos. Samothrake, ca 270 BC. This manner of Timber Framed roofing was not long lived for centralised buildings. From the Imperial Age (the Christian Era) roofing centralised buildings of great span (cf the Pantheon) reverted to masonry domes, reviving the tradition of the Mycenaean Tholos; cf Lawrence, fig 103.



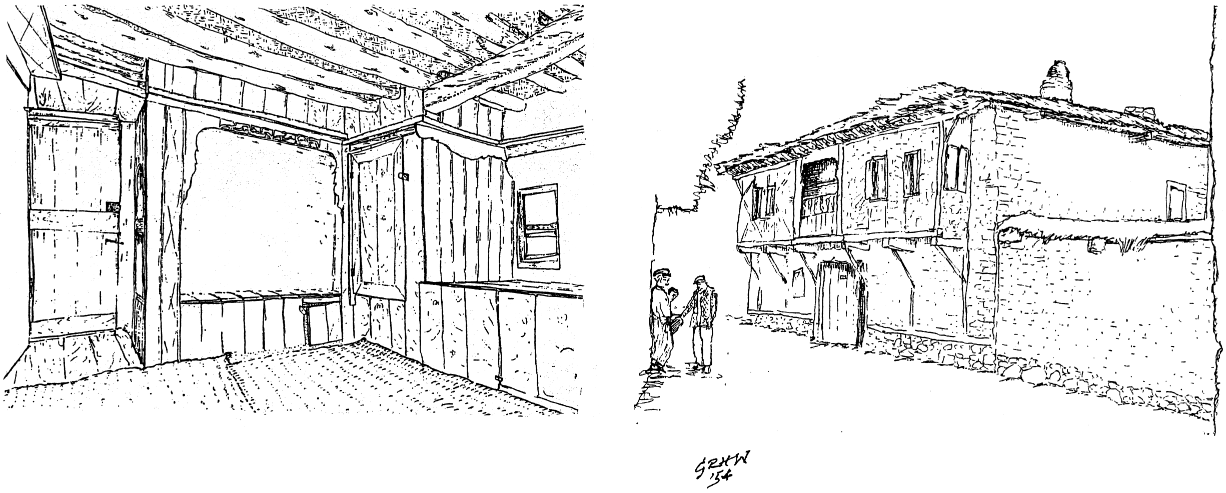
136. Mshabbik. Basilican Church Gable Roofed with King Post Trust. Syria. Early Christian. Restored drawings of church with timber King Post trusses as are depicted in relief decoration occurring on pediments to porticos of similar churches in the region. *Key*: A. Plan; B. Relief Decoration at Convent of Brad showing King Post truss; C. Long Section; D. Cross Section. After Butler. Ills 184, 201.



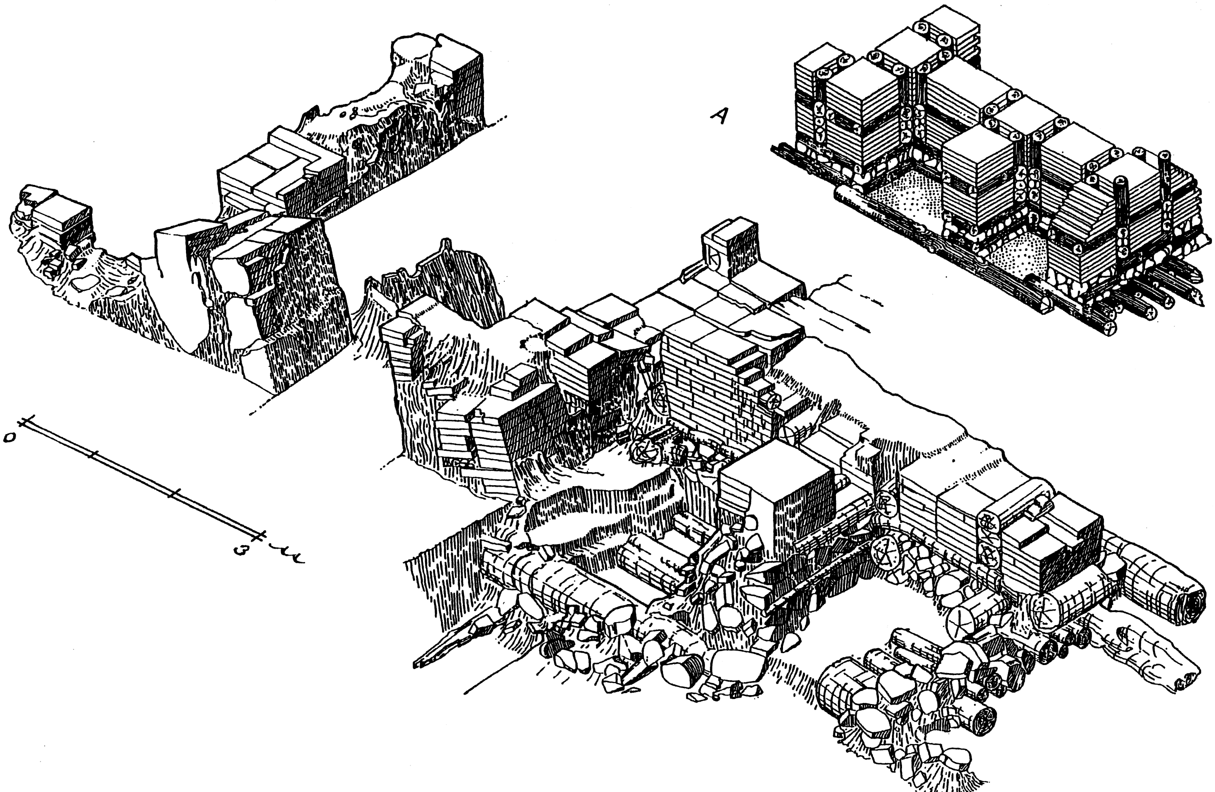
137. Traditional Modern Thatching. A. Long Straw Thatching. Yealms (bundles) are laid in horizontal registers, beginning at the eaves. The tops of the yealms are tied tightly to the battens and allowed to hang well over the eaves. The laying proceeds upwards in registers, the last register laid to straddle the ridge. The mass is further secured by horizontal sticks thrust through the yealms and tied to the battens. The whole work is finished by horizontal rods as runners pegged into the thatch; and all loose ends are trimmed off with a sharp knife; B. Reed Thatching. The yealms (bundles) are laid in vertical succession proceeding from eaves to the ridge and are secured by horizontal rods fixed to the rafters by iron hooks. At the ridge the terminal bundles are laid to project above it. They are then trimmed off and are capped by bundles laid across the ridge and fixed by horizontal runners pegged down into the thatch. Since no thatching endures in its integral condition for longer than a century, no recognisable passages of ancient thatching have survived. These typical examples of sophisticated modern thatching are illustrated to give some substance to the frequent reference to thatching in ancient building. Also they may provide some background better to identify surviving indications of ancient thatching. After Davey. Figs 41, 42.



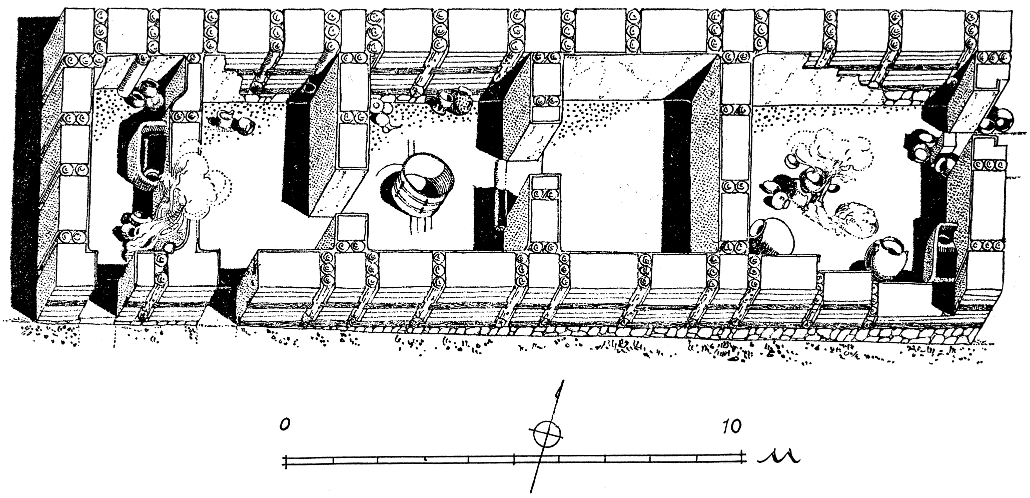
138. Beyce Sultan. Archaeological section indicating original mixed timber, mud brick and rubble construction. Western Anatolia ca 1500 BC. The palatial building had been destroyed by a violent conflagration. In this way passages of construction had collapsed maintaining their original conformation. The construction was mud brick on rubble foundations. However both by systematic gaps in the preserved mud brick walling and also by the presence of profuse remains in the debris of charred timber (e.g. logs ca 30 cms in diameter) it could be seen that the mud brick walling was systematically interlaced both horizontally and vertically with timber reinforcing. As the evidence accumulated the system of reinforcing was assessed in detail. However it was never conclusively shown whether this system amounted to a complete framed structure. after A St 1955 p. 195, fig 7.



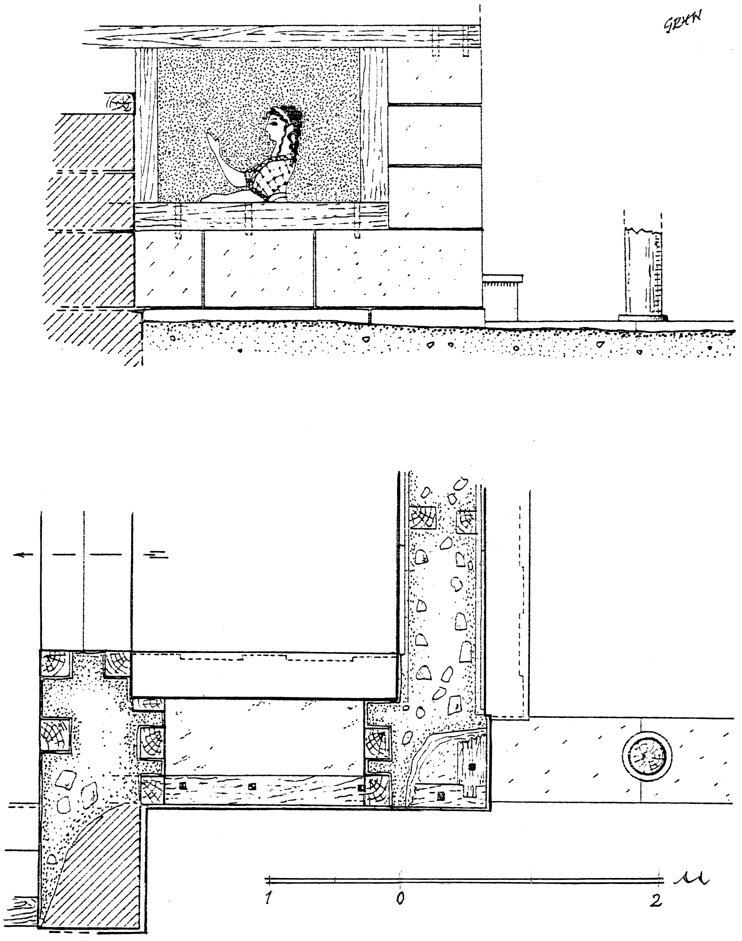
139. Beyce Sultan Excavation House. Mentesh Village 1954. This house is virtually a construction in tandem of wood and mud brick. It is wood framed, but the mud brick is also fully load bearing. It is interesting to compare it with the Bronze Age construction revealed by the excavations where much timbering was inset into the mud brick.



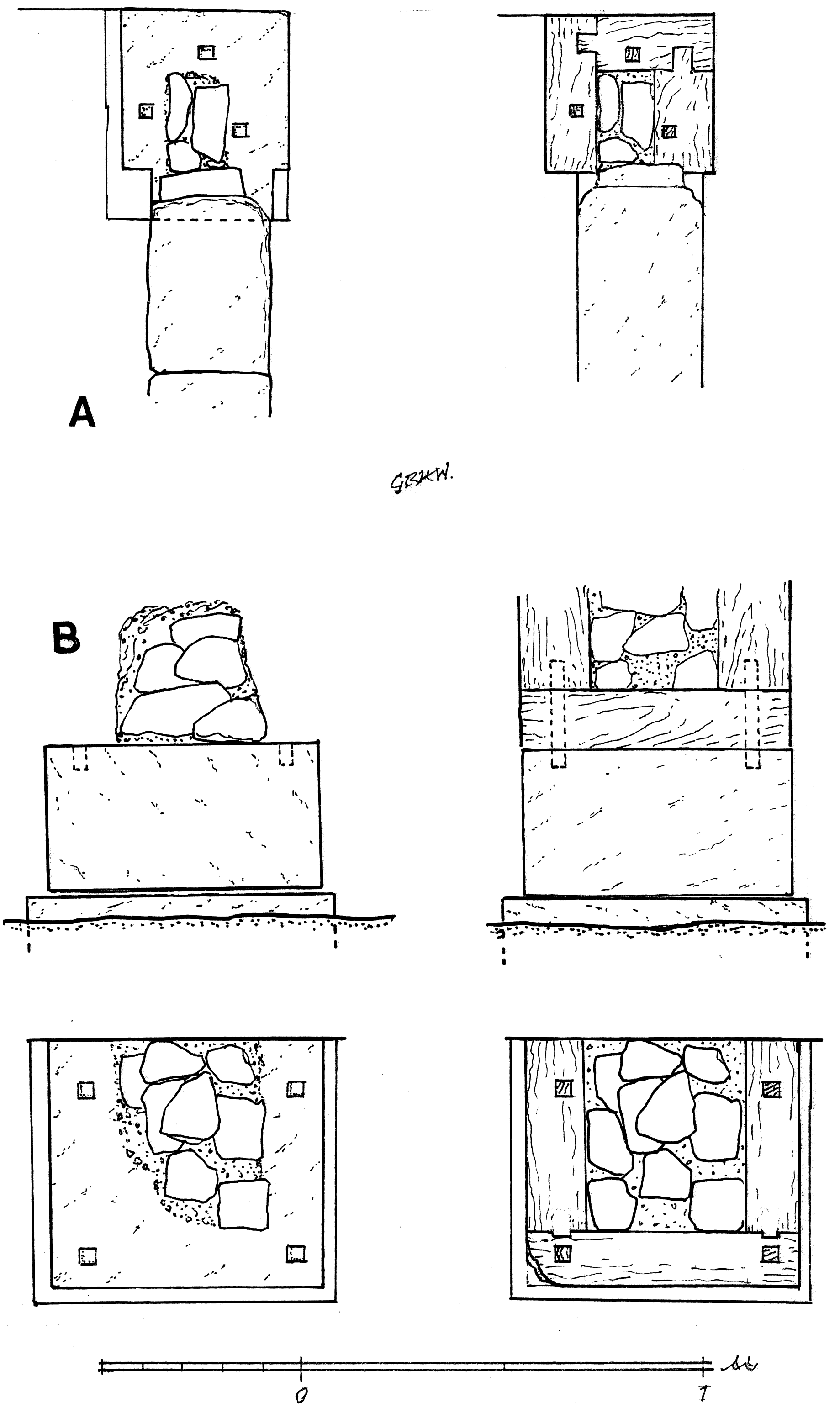
140. Beyce Sultan. Detail of wood inset into mud brick and rubble masonry. Archaeological remains and (A) reconstruction. Western Anatolia ca 1500 BC. This mixed construction is typical of the Levanto Aegaean area. However from the archaeological remains it is difficult to determine whether the insets constitute a framed structure. After S. Lloyd.



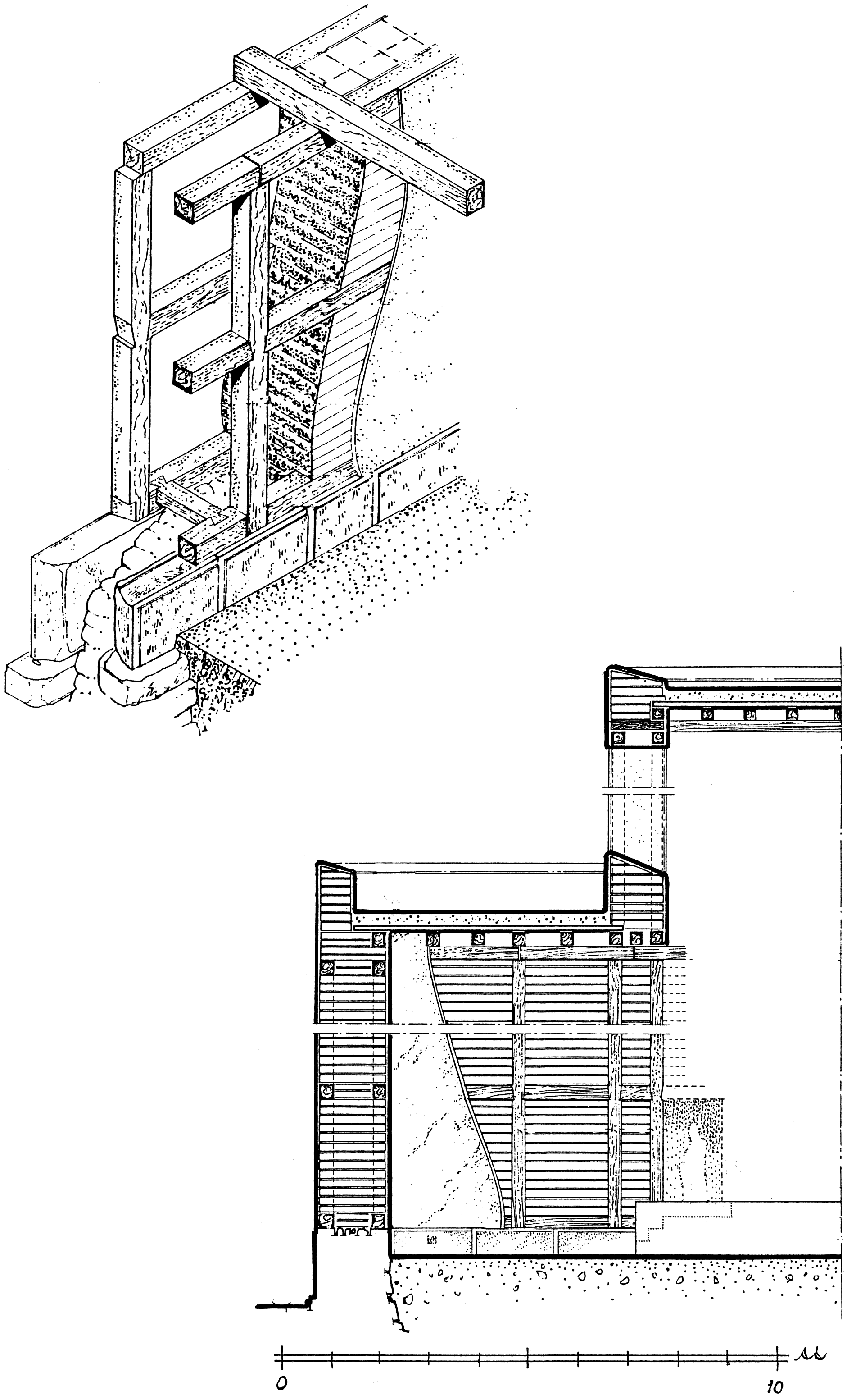
141. Beyce Sultan. Reconstructed drawing of mixed masonry of Temple in Trench R. Western Anatolia. ca 1500 BC. The wooden component is great – uprights at ca 1.50 m intervals and stringer beams every 3 courses of mud brick. Cf the construction of Solomon's Temple in Jerusalem (Kings 6.31: "And he built the inner court with three courses of hewn stones and a course of cedar beams"). After S. Lloyd.



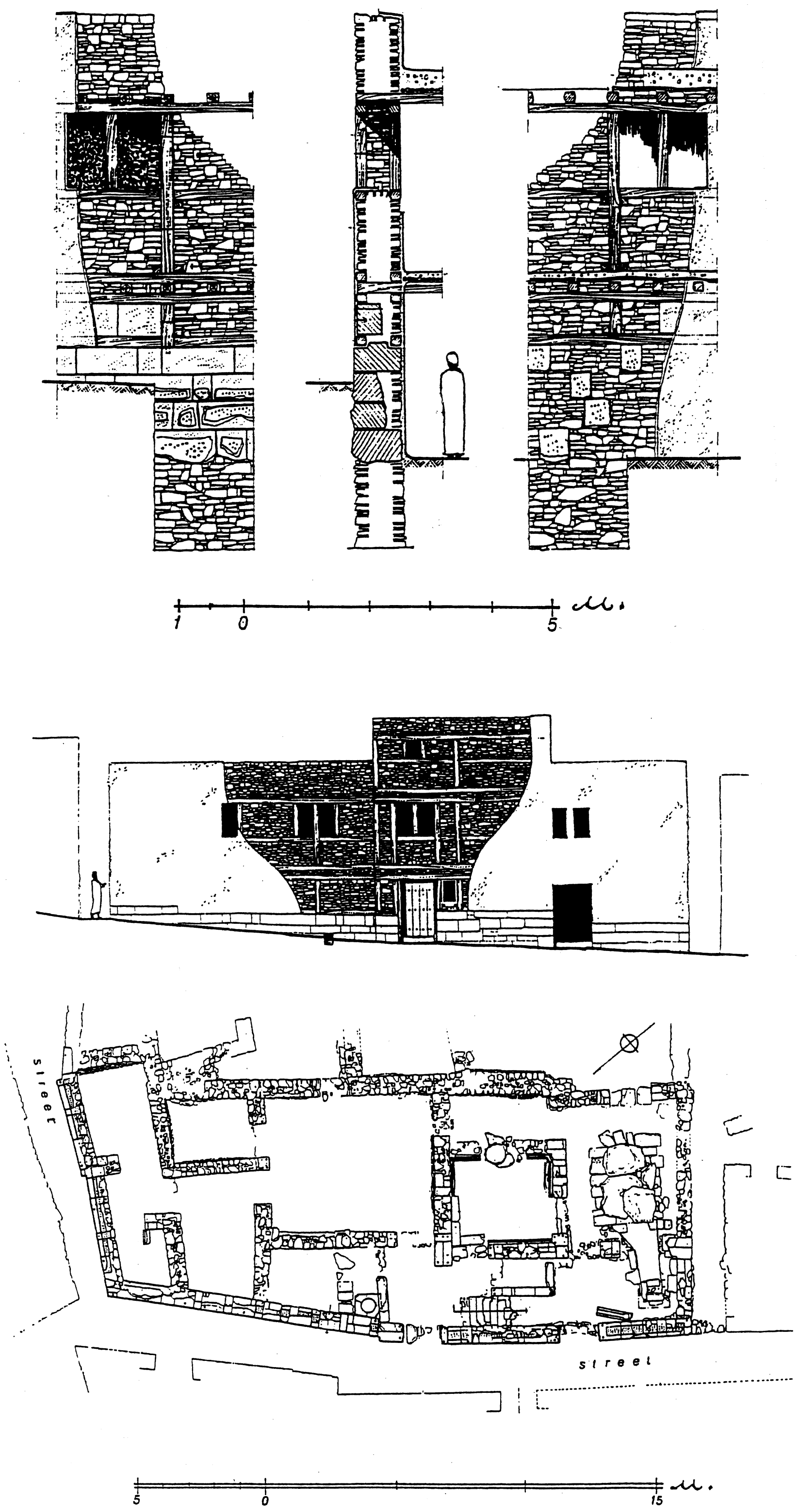
142. Ayia Triadha Palace. Wooden reinforcing to mixed rubble and dressed stone construction. Crete. Late Bronze Age. Squared timber reinforcing, both horizontal and uprights detailed to constitute wooden window frame. After Shaw p. 72, fig 203.



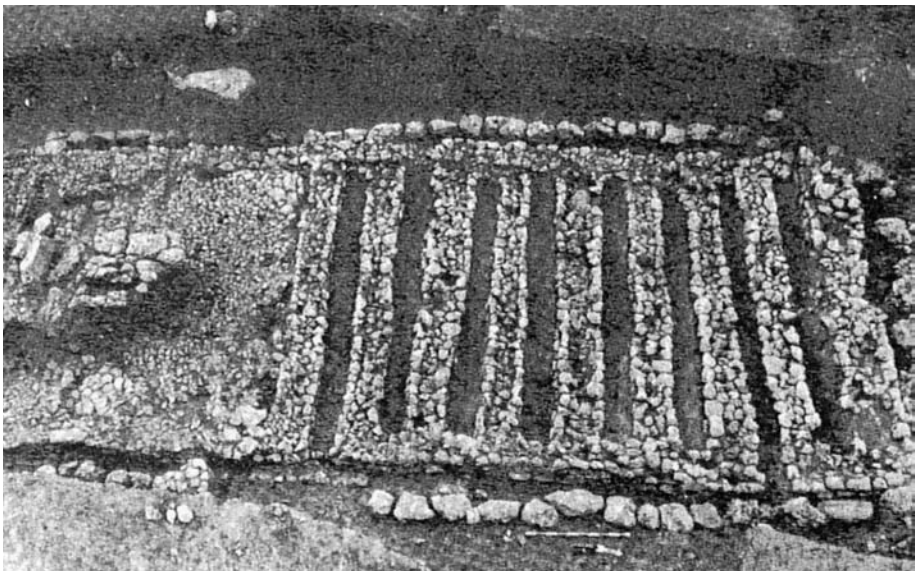
143. Phaistos Palace etc. Engaged Piers of mixed wood, rubble and dressed stone construction. Crete. Late Bronze Age. These piers are raised on a base of dressed stone into which is dowelled a squared timber framing confining a rubble core. *Key*: A. Plan of Pier at Kato Zakros Palace; B. Plan and Elevation of Pier at Phaestos Palace. Left: Surviving Remains; Right: Reconstructed Assemblage. After Shaw, figs 203, 204.



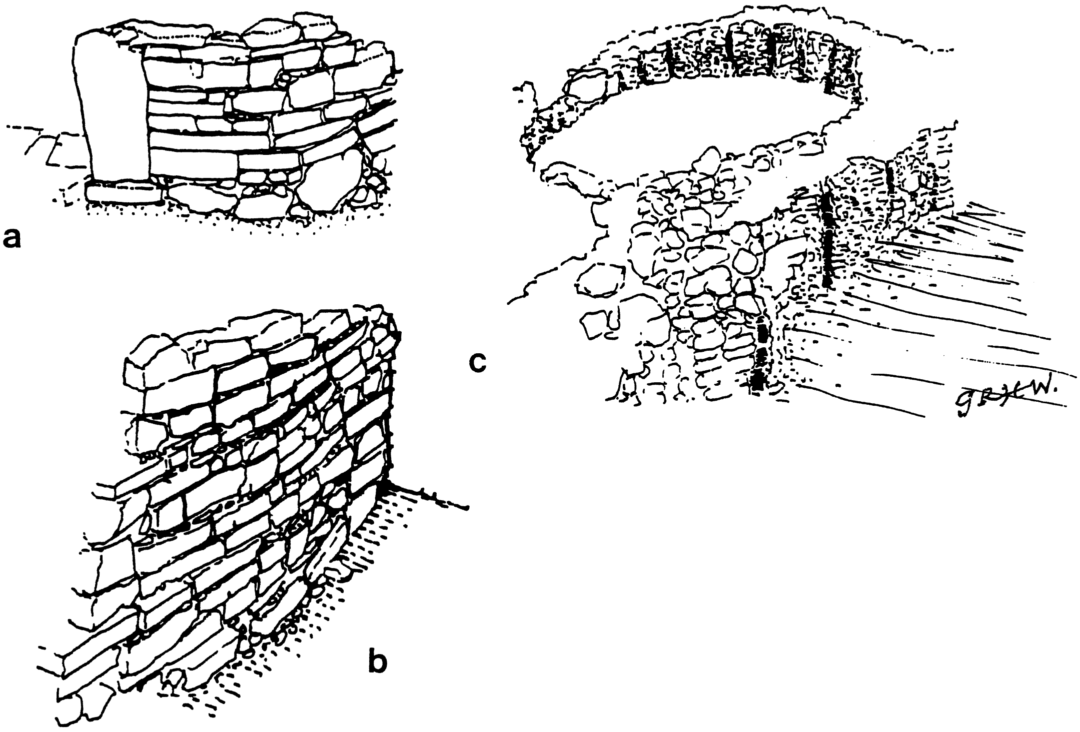
144. Kition Temple of mixed mud brick and squared timber construction. Cyprus ca 1200 BC. Sectional Elevation and Axometric Reconstruction showing complete heavy timber frame and massive mud brick walls set on a socle of ashlar faced masonry (Bastard Ashlar). Flat mud terrace roofing on square timber roofing beams. After Callot v ABC II, figs 248, 249.



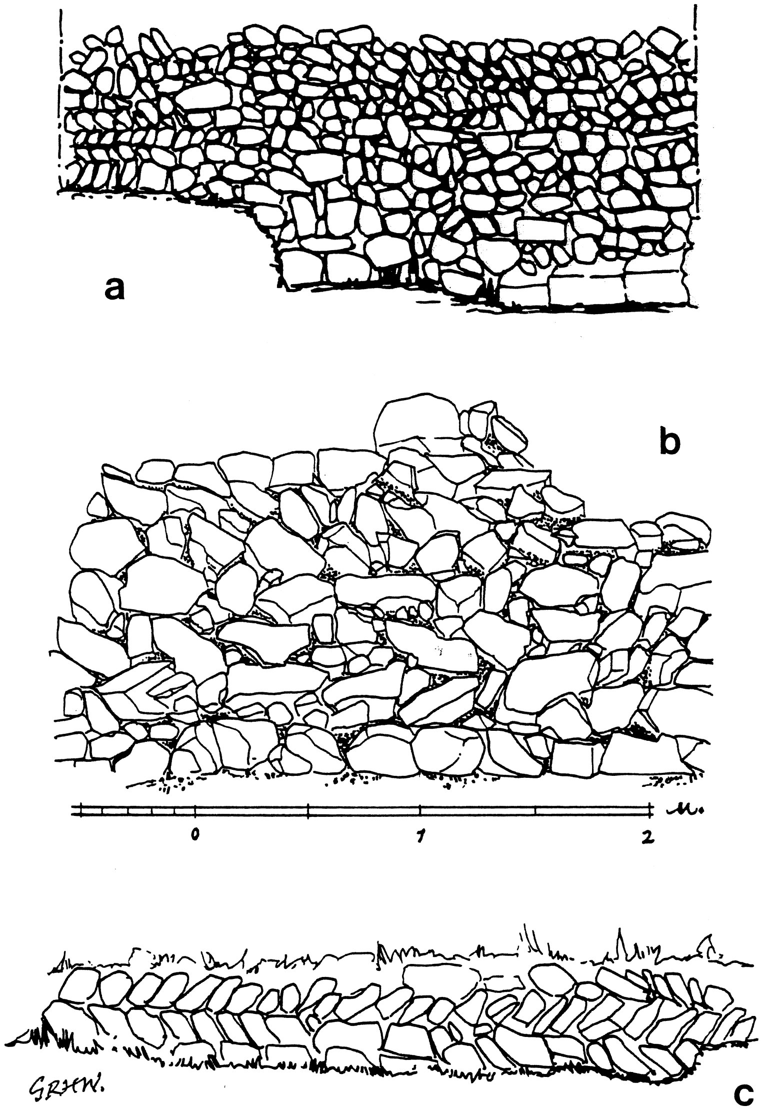
145. Ugarit. Houses of Mixed Wood and Stone Construction. North Syria ca 1250 BC. *Below*: Plan and Front Elevation of a house showing fine stone masonry for display walling with superstructure of rubble with timber framing; Above: Sectional Elevation details of 'half timber' type construction. After Callot v AfO XLIV-XLV, pp 573, 574.

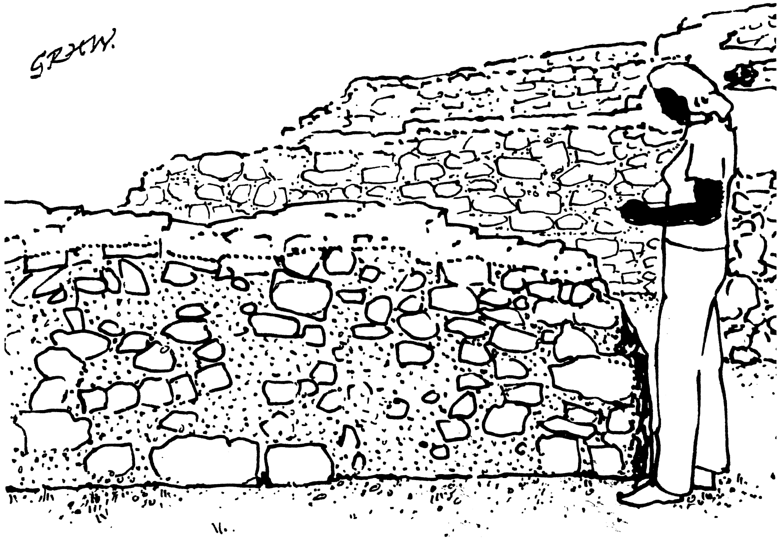


146. Cayönü. Neolithic “bifacial” Rubble Walling. Central Anatolia. ca 6000 BC. The enduring pattern of field stone rubble walling composed of two faces of larger and more regular stones with a core infill of smaller material was established very early. After Aurenche 2. pl 22.



147. Beidha. Neolithic Dry Stone Walling of Angular Flat Slabs. The Spoil of Insolation. Southern Jordan. 6th Millennium BC. This is a very early example of one enduring type of rubble walling. The regular plate form of these exfoliated fragments from the surface of sandstone exposed to the great diurnal range in temperature of the desert regions (near Petra), together with their extremely high “specific surface” makes them excellent dry stone building material. The high ratio of the area of bedding to the mass of the stone gives the masonry great stability. These views are of Pre pottery Neolithic Round House building. The construction is a local expression of an ecumenical building programme, familiar elsewhere almost entirely in mud construction. After ABSP II, fig 306.





149. Alambra. Random Rubble in thick masses of mud-mortar. Cyprus. ca 1700 BC. These stones were rounded water-borne outwash weathered from a basalt lava floor. The construction varies from stones bedded in thick mud mortar to stones drowned in a mud mortar matrix. Such walling is easy to build, but the continued integrity of the masonry depends entirely on the mortar retaining its adhesive property. After ABC II fig 225.

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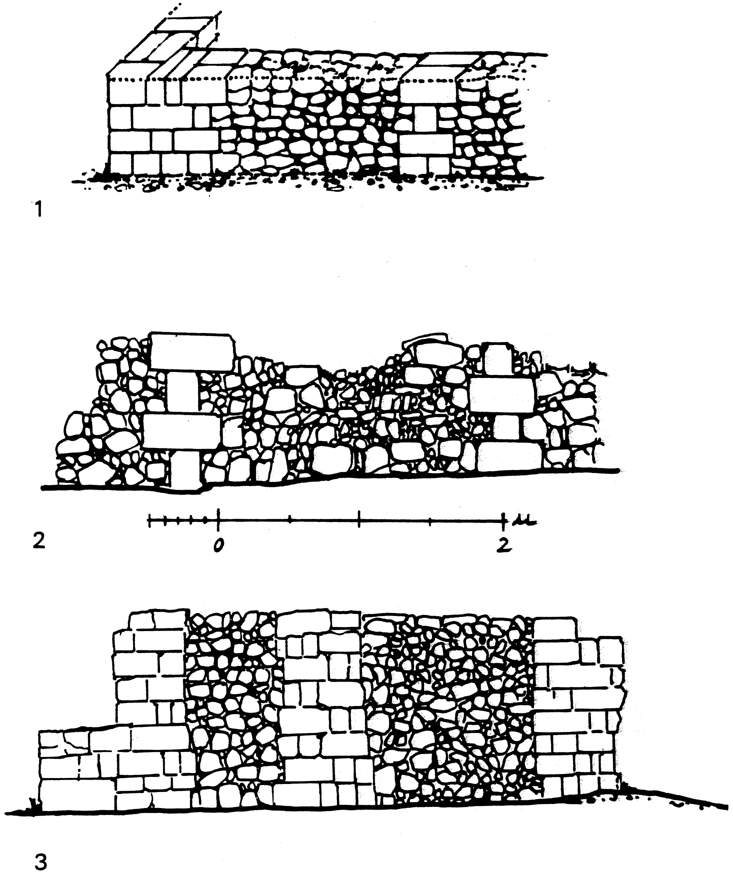
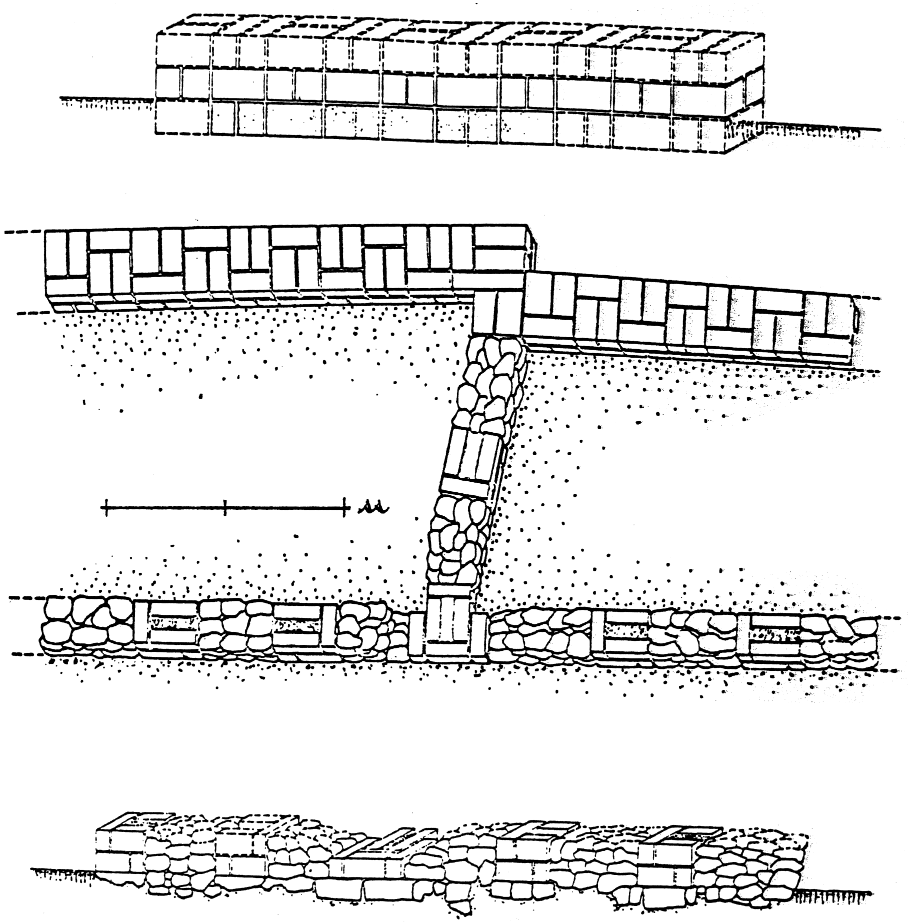
148. Rubble Walling in the Herringbone Tradition. Syria-Palestine. 4th – 1st Millennium BC. The diagonal setting of masonry units has many advantages, both in the convenience of setting and in strength and stability of the assemblage. It was originally and always remained proper to dry stone walling with flat slab-like units, however its use extended beyond these margins. The analogies with Mesopotamian plano-convex brick masonry are striking. *Key*: (a) Remains of Classic style herring bone masonry from Proto-Urban Byblos, contemporary with floruit of Plano-Convex bricks in Mesopotamia; (b) Late Iron Age City Wall at Megiddo. Angular stones set both horizontally and diagonally with some chocking and pebble fill; (c) Late Iron Age Dry Stone Walling in vicinity of the Bamah at Tell Dan. Here less angular stones are set in the herring bone manner. After ABSP II, fig 307.

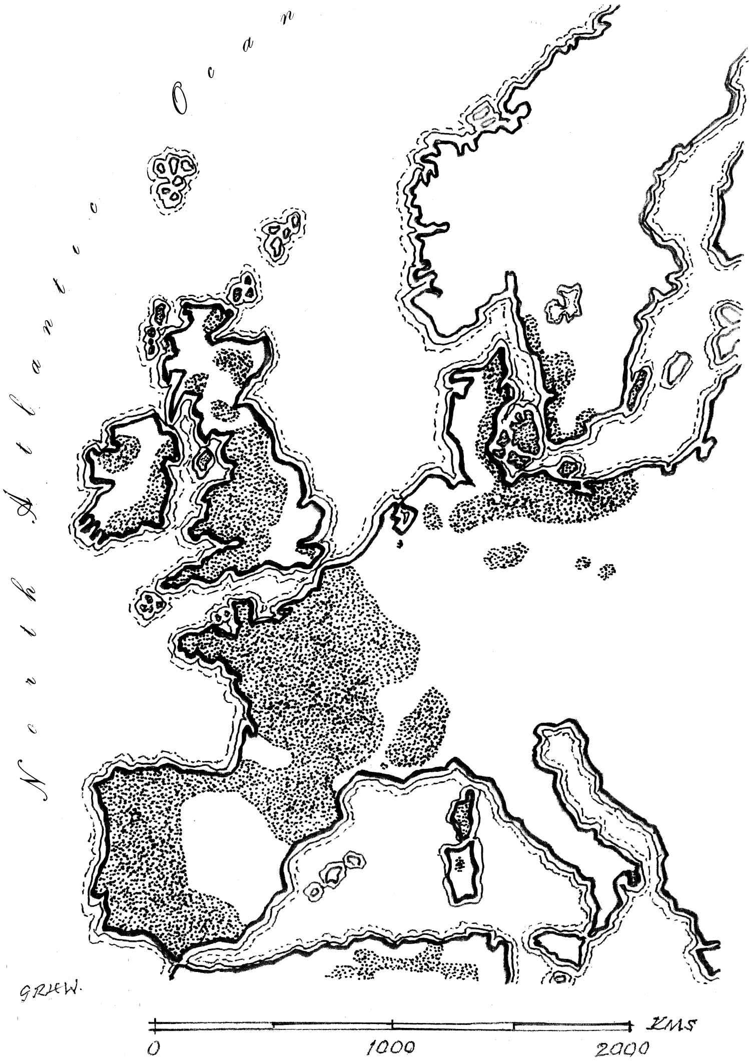


150. Random Rubble stiffened (reinforced) by elements of dressed stone. Palestine. 1st Millennium BC. This type of construction occurs in Phoenecia and provides the background to Roman *Opus Africanum* (derived from the Punic Colonies in North Africa). *Key*: (1) General type found at Iron Age Megiddo. Ashlar piers and coigning with rubble panelling; (2) Early example at Megiddo. Early 1st millennium BC; (3) Late Example at Jaffa. Here the piers are squared coursed rubble rather than ashlar and are correspondingly more massive; also they lack keying into the rubble panels. Persian Period, 450 BC – 320 BC. After ABSP, fig 322.

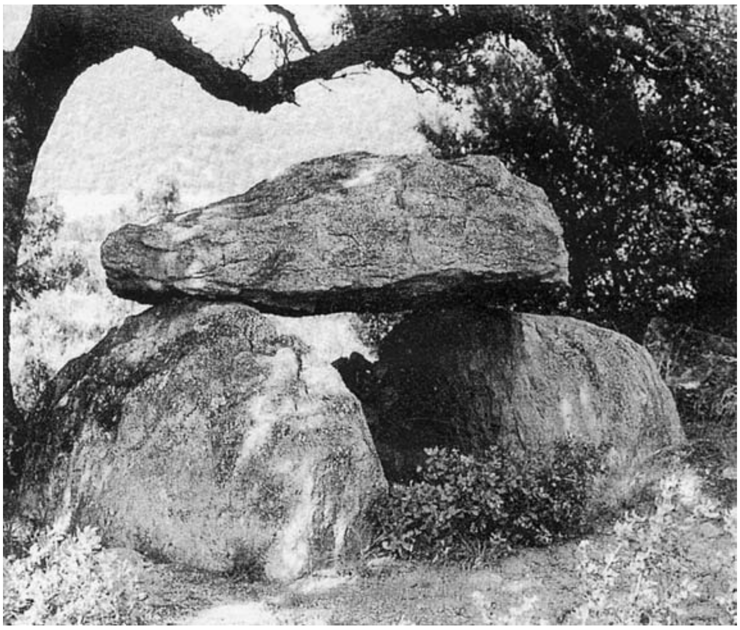


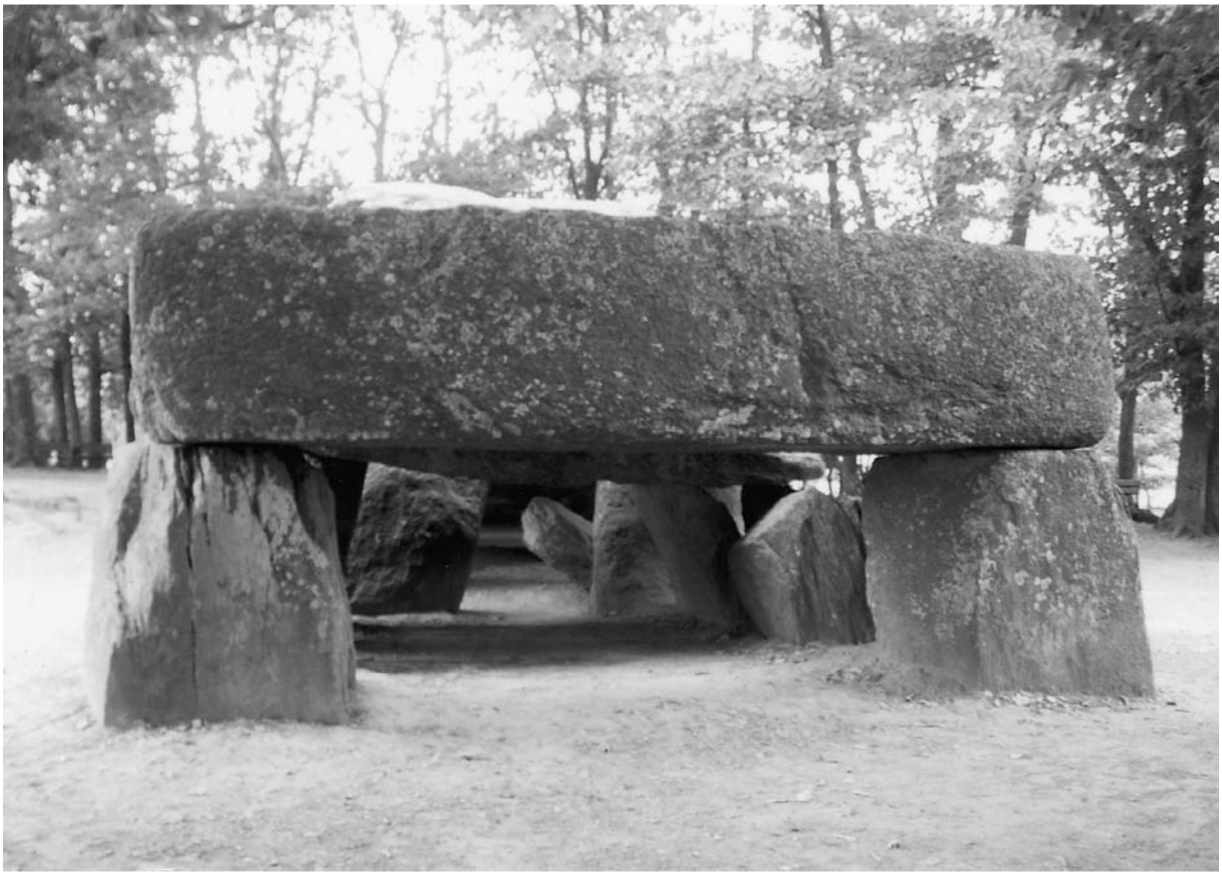
151. Tell Mavorakh. Finely dressed masonry Walling and rubble Walling used conjointly in the same building. Palestine. Persian Period. Casemate City Wall, the outer element of Ashlar and the inner element of ashlar stiffened rubble. After ABSP, fig 321.

152. Distribution Map of Areas of Megalithic Building in the Ancient World (shown stippled). Building with massive unhewn (roughly trimmed) stone in the Western Mediterranean and by the Atlantic shores of Europe constitutes a recognisable class (a style) of building. The strongly marked pattern of distribution of this type of building has given rise to various theories accounting for its origins and spread (by sea) to Western Europe during the Bronze Age. Dating by physical methods now shows that this type of building first occurs in Western Europe and the overall chronology is much earlier than previously reckoned. The manner is essentially Neolithic in origin and covers a period from the mid 5th millennium to the earlier 2nd millennium BC. After Nel Dolmens and Menhirs, fig 11.



153. Taupels. Typical Simple Dolmen. Eastern Pyrenees. France. ca 4th – 3rd Millennium BC. Basic megalithic construction consisting of 3 large unhewn slabs of rock, of which two act as lateral supports for a capstone (here ca 2m – 3m long). Although the megalithic tradition of masonry came to include finely dressed stone elements forming more complex constructions, the simple dolmen of unhewn slabs standing within an earth tumulus always remained characteristic.

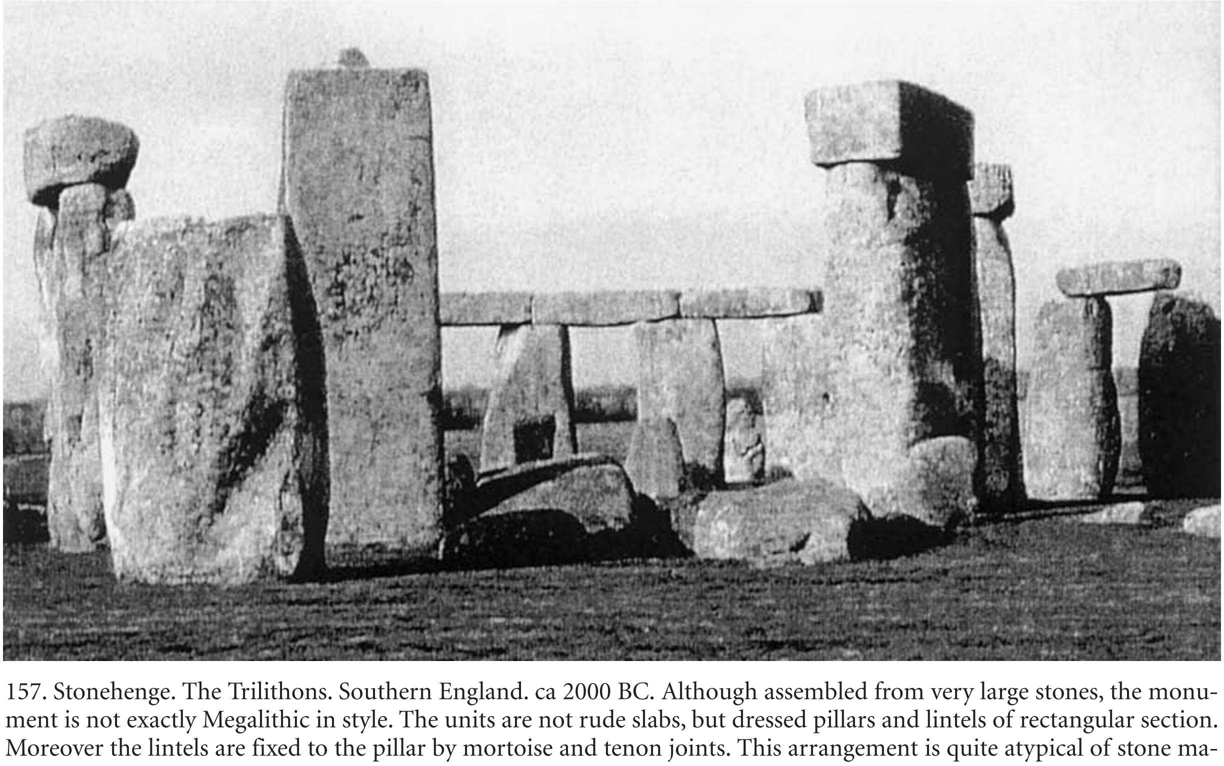




154. Essé. La Roche aux Fées Dolmen. The 'Trilithon' Entrance. Brittany 4th Millennium BC. The capstone 'lintel' is ca 5.5 m long, of square section ca 1.30m x 1.30m and thus well over 20 tons burden. The rock is purple schist and has been hammer dressed very truly into regular form. It is one of the most massive stone roofing beams to survive from antiquity, and one of the oldest (ca 1000 years older than massive roofing beams in Egyptian pyramids of the Old Kingdom). Photograph J-L Biscop.

155. Mnaidra. Flank View of Neolithic Temple. Malta ca 3500 BC. This view demonstrates that the Maltese Temples belong to the Megalithic Tradition (v the rude slabs in the foreground), yet incorporate considerable dressed masonry (v façade blocks to right).

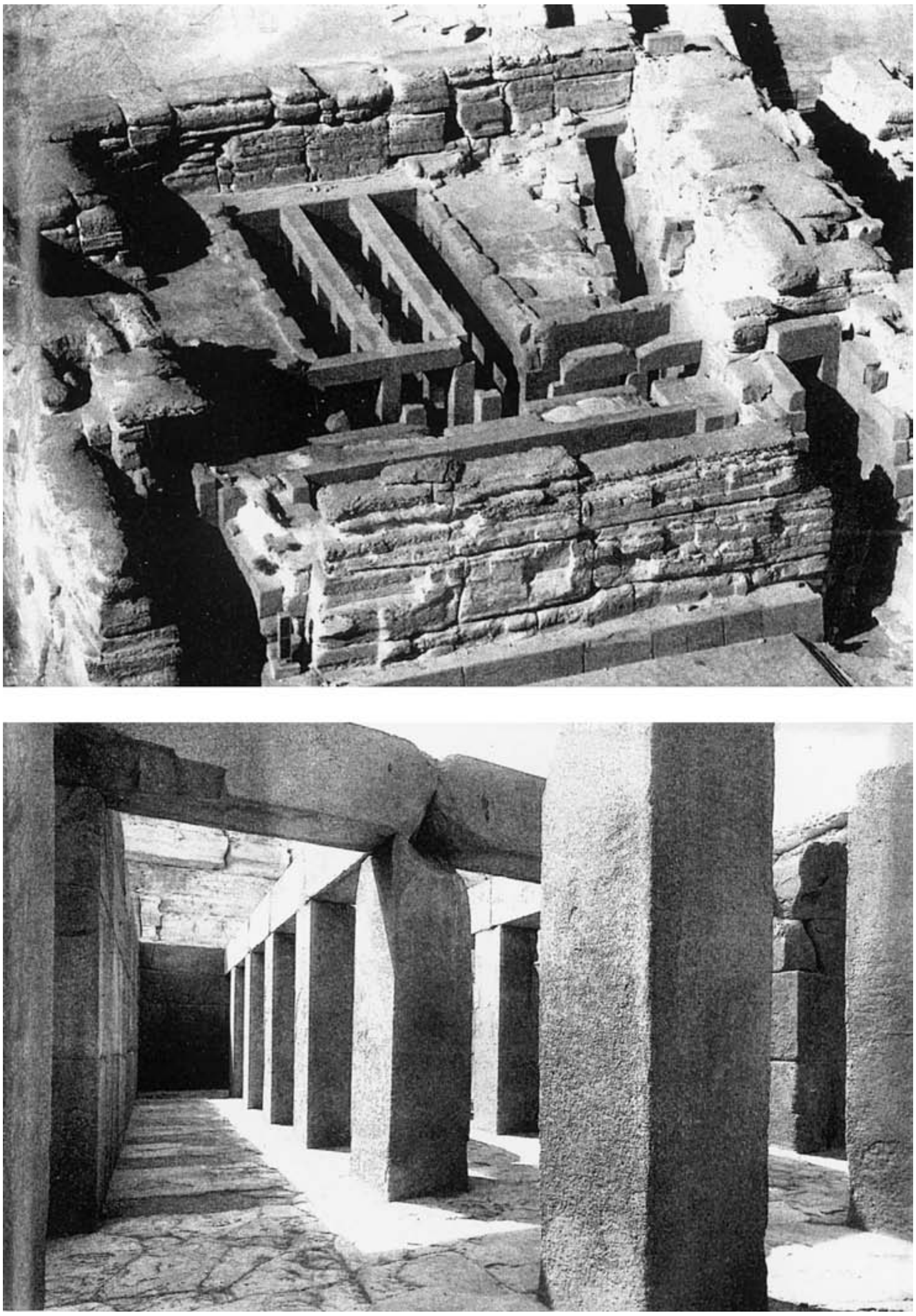
156. Hal Saflieni. The Hypogeum Rock cut Sanctuary Cemetery, The Holy of Holies. Malta ca 3300 BC. The forms of this rock cut complex are evidently modelled on the contemporary free standing megalithic "Temples". In this instance the entrance to a chamber with an altar is in the form of the cave like (*in antis*) entrance to a Megalithic Temple (e.g. Mnaidra). Of special interest is the projecting canopy-like ceiling which clearly simulates corbelled vaulting. Such vaulting occurred across the internal apses of the Temples.



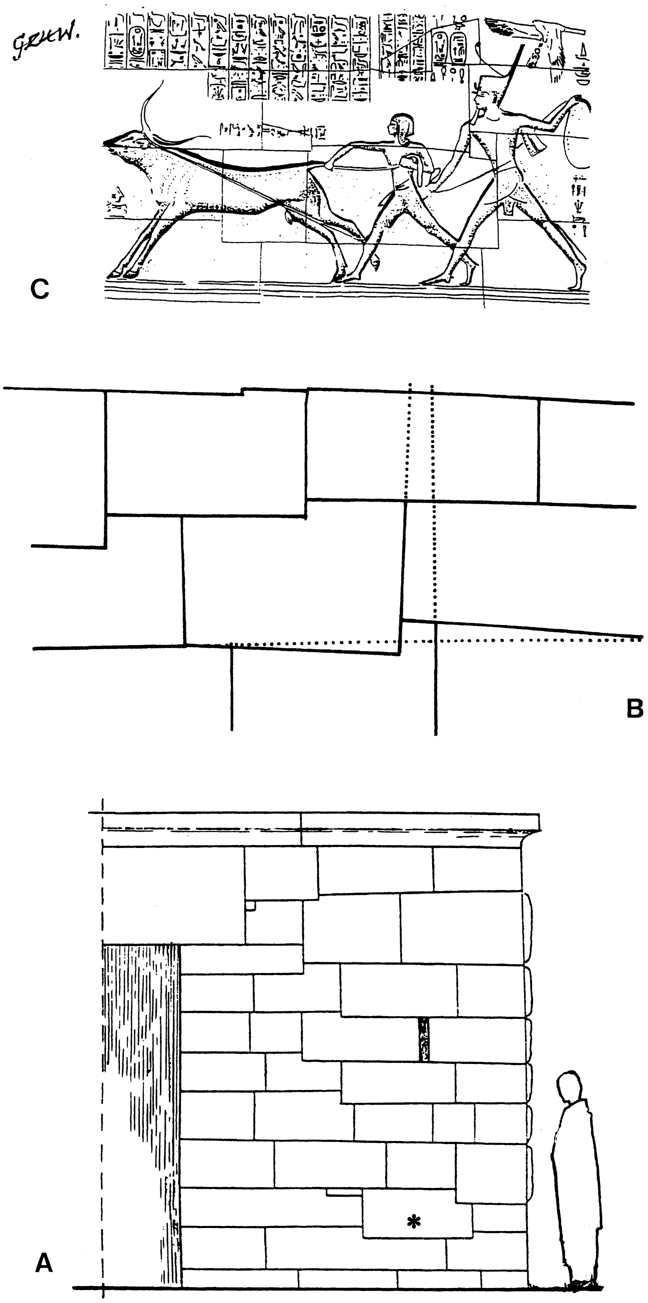
157. Stonehenge. The Trilithons. Southern England. ca 2000 BC. Although assembled from very large stones, the monument is not exactly Megalithic in style. The units are not rude slabs, but dressed pillars and lintels of rectangular section. Moreover the lintels are fixed to the pillar by mortoise and tenon joints. This arrangement is quite atypical of stone masonry involving wasteful dressing to obtain the projecting tenon; and incurring difficulties in setting since the lintel must be lowered into position. Also structurally the joint is redundant since the dead weight of the great blocks provides for the stability of the construction. These considerations suggest that Neolithic stone circles such as Stonehenge were derived from earlier Neolithic Timber Circles.

158. Small Dolmen in Tunisia. Uncertain date. Such structures are dolmens in form and geographically they are located within the Megalithic Building region (cf the Maltese Temples). However it is not at all certain that they fall within the chronological period of Megalithic building (i.e. later Neolithic times). They are more likely Graeco-Roman in date.

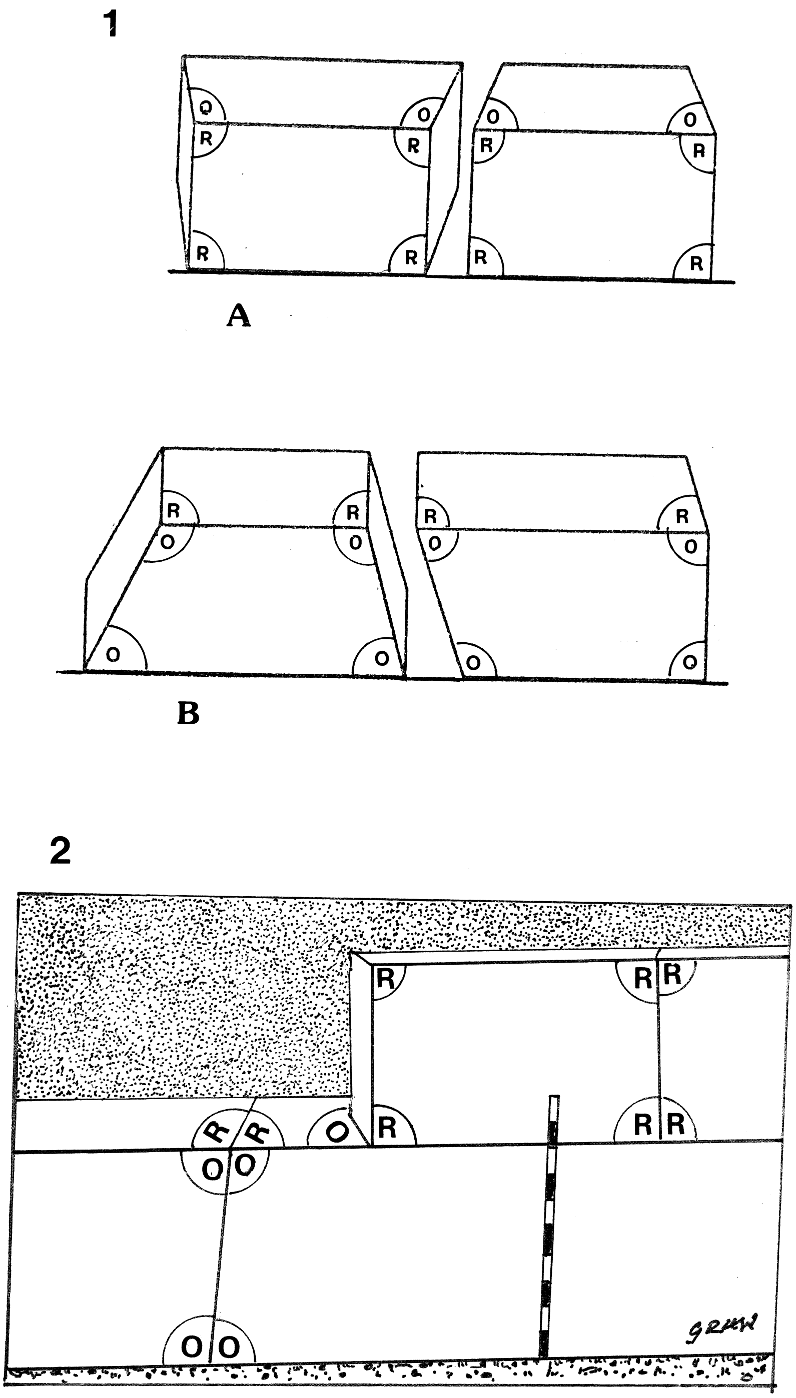
159. Saqqarah. The Stepped Pyramid Complex Masonry. Lower Egypt. 3rd Dynasty. ca 2650 BC. Typical "petit appareil" bastard ashlar masonry (Zoser Masonry). These relatively small blocks are finely dressed on the faces only (prior to setting) and roughly dressed joints splay apart to the interior. The masonry is a facing to a rubble core which is often only a false façade to a ground mass. The blocks are restricted in dimension (course height here ca 20 cms) and the weight ca 40 kilos or less – not of a different order from the large mud brick masonry which they replaced. They could be handled by two men (a mason and an assistant), thus requiring no different site arrangements from the monumental mud brick building which they succeeded. The fluting of the proto-Doric style engaged columns must have been worked *in situ* requiring the construction to be (lightly) scaffolded. After Lauer Saqqarah.



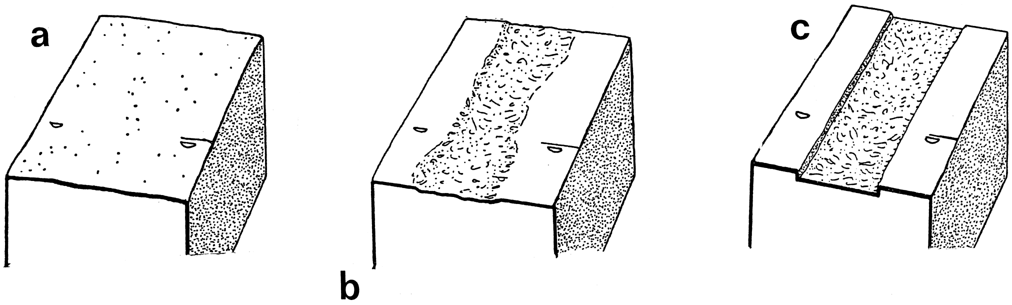
160. Gizeh. The Valley Temple of Khafra (Khephren). Lower Egypt. ca 2500 BC. Aerial view and masonry detail of pillared hall. The simplicity and majesty of this massive stone masonry produced an awesome effect. The pillars are ca 5 m high. The stone is Rose Red Granite and the Temple is sometimes known as the Granite Temple. The pillars and beams were dressed true with hand stone tools (dolerite pounders) and their faces polished. As opposed to coursed masonry blocks, the finished dressing of these items was carried out prior to setting – perhaps at the quarry. After Stadelman Pl 51.



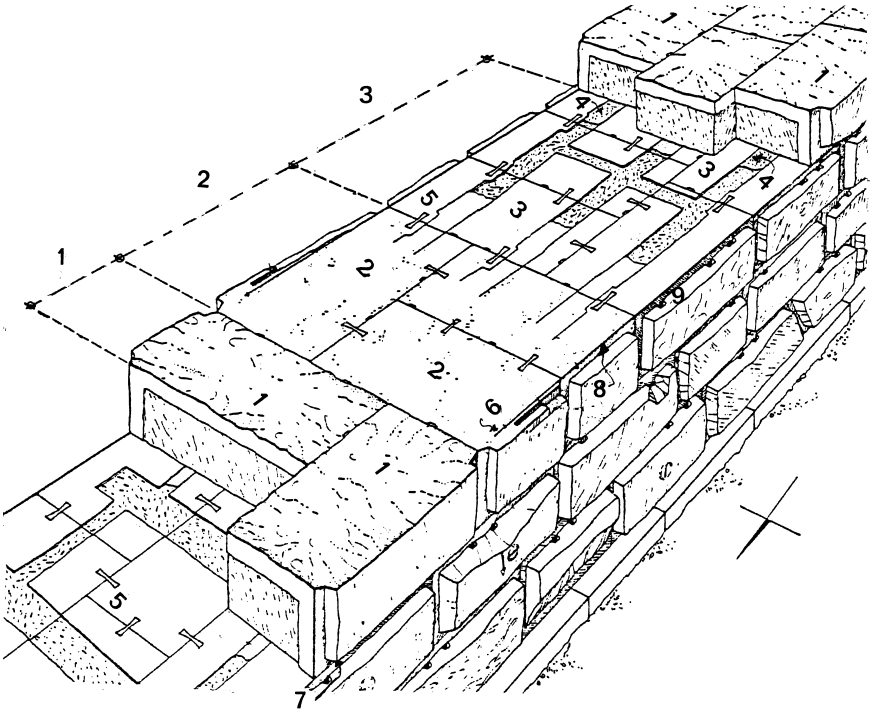
161. Pharaonic Masonry. Essential character shown in Elevation. Upper Egypt. New Kingdom. ca 1400 BC – 1200 BC. The essential character of Large block Pharaonic Masonry throughout most of its history is that: (1) Blocks were not uniformly orthogonal; (2) Bed joints were not necessarily continuous or horizontal. Each of these characteristics involved two considerations; (a) Dressing blocks into the required form; (b) Setting blocks so dressed. There has been much speculation (not all cogent) to explain Pharaonic Masonry practice taking these considerations into account. With respect to (2) irregular bed joints, there is no cogent account of masonry practice. Where blocks are not massive, i.e. can be manhandled into position, neither the dressing nor the setting of this type of masonry occasions great difficulties (cf Classical Greek polygonal masonry). However circumstances are entirely different for the massive blocks of Pharaonic masonry which cannot be manhandled into position. It is axiomatic that such blocks were not lifted but were hauled and levered into position. Nevertheless passages of Pharaonic masonry of this nature indicate that some blocks must have been lowered into position (e.g. block marked with an asterisk in A) – and no cogent accounting of the practice here has been advanced. *Key*: (A) Small Temple of Amenophis III at El Kab (ca 1400 BC) showing stepped coursing and sloping bed joints; (B) Temple of Ramses II at Abydos (ca 1250 BC). Detail of typical wall masonry showing bed joints and rising joints diverging considerably from horizontal and vertical; (C) Temple of Seti I at Abydos (ca 1300 BC). Detail of a typical wall masonry with overall relief ornament which was originally plastered and painted so that the imposing character of the fine masonry was rendered totally invisible. After Clarke & Engelbach *pass.*



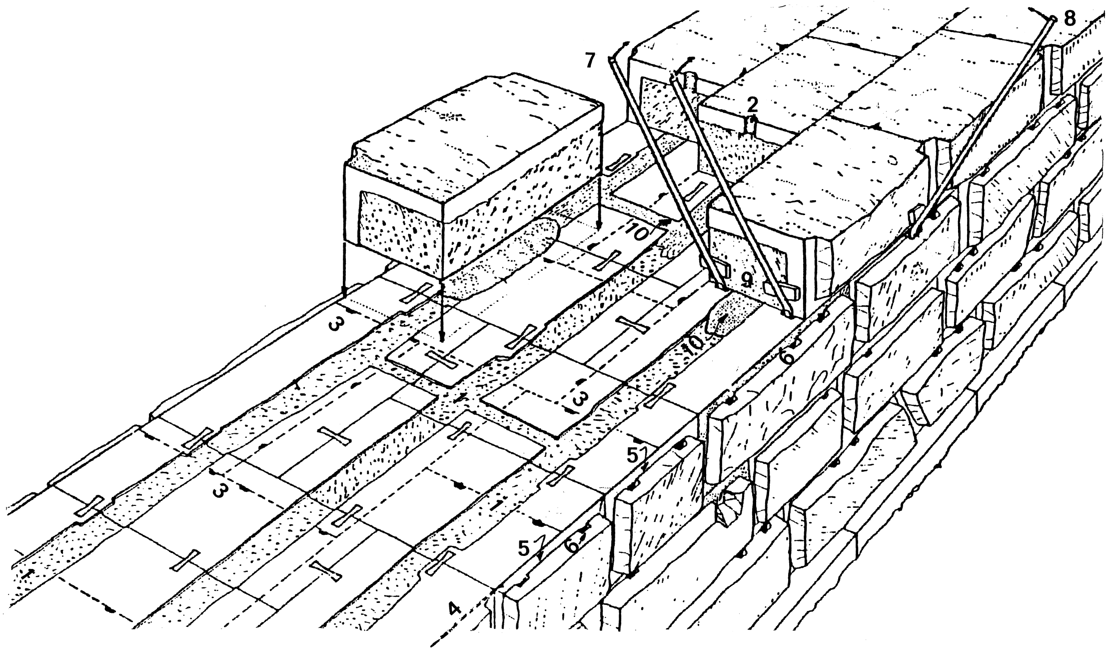
162. Use of Non Orthogonal Blocks in Pharaonic Masonry. NB No special problem arises in either the dressing or the setting of such masonry blocks. *Key*: 1. Diagram illustrating main categories of non-orthogonal blocks; (A) Plane of rising joints vertical – i.e. normal to the horizontal bed joints but oblique to the face of the wall; (B) Plane of rising joints normal to the face of the wall, but not vertical – i.e. not normal to the horizontal bed joints; 2. Elevation of Pharaonic masonry in the funerary temple of Unas at Saqqara, 5th Dynasty. Upper course blocks with plane of rising joints vertical; lower course blocks with plane of rising joints inclined to the bed joints, but normal to the face of the wall; R = right angle; O = oblique angle. After Clarke & Engelbach, figs 105, 106, 110.



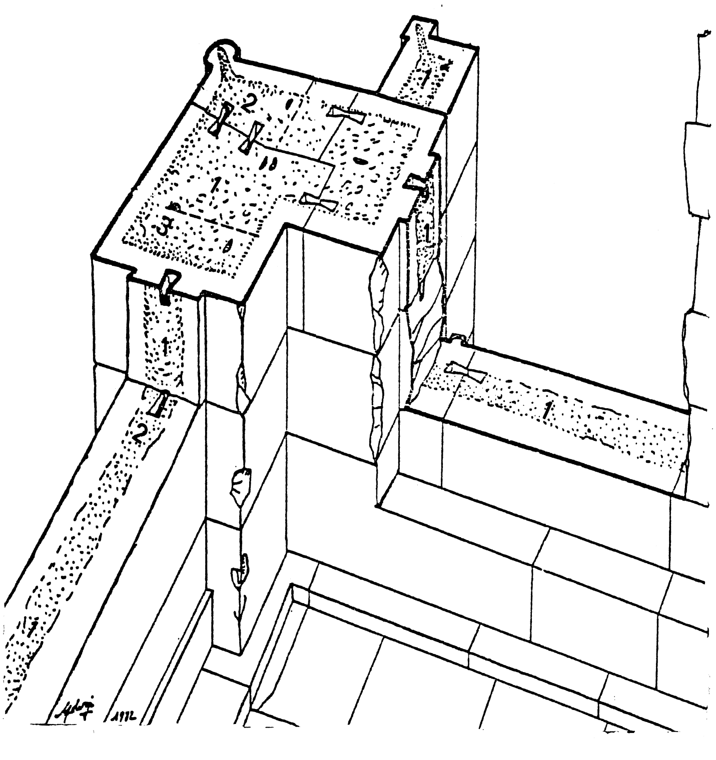
163. Diagram showing chronological development in typical dressing of upper bed jointing of Pharaonic masonry. Late Dynastic, Ptolemaic, Roman. ca 4th Cent BC–2nd Cent AD. *Key*: (a) 30th Dynasty; (b) Ptolemaic; (c) Roman. Over this range of time masonry coursing was, as a rule, continuous and horizontal. This final dressing was effected *in situ* after the complete course had been set. The position for setting the blocks of the succeeding courses was scribed on the bed and 'pry holes' were cut immediately behind these marks for final levering of the blocks into place. The abandonment of the earlier Pharaonic Masonry practice of '*ad hoc*' bedding (i.e. stepped and at times oblique coursing) for continuous horizontal coursing marks the influence of Classical Masonry. That the influence was cumulative can be seen in the development of the medial channel for distributing the lubricant mortar used to facilitate setting. After Golvin ASAE LXX 1984-85, p. 377, fig 3.



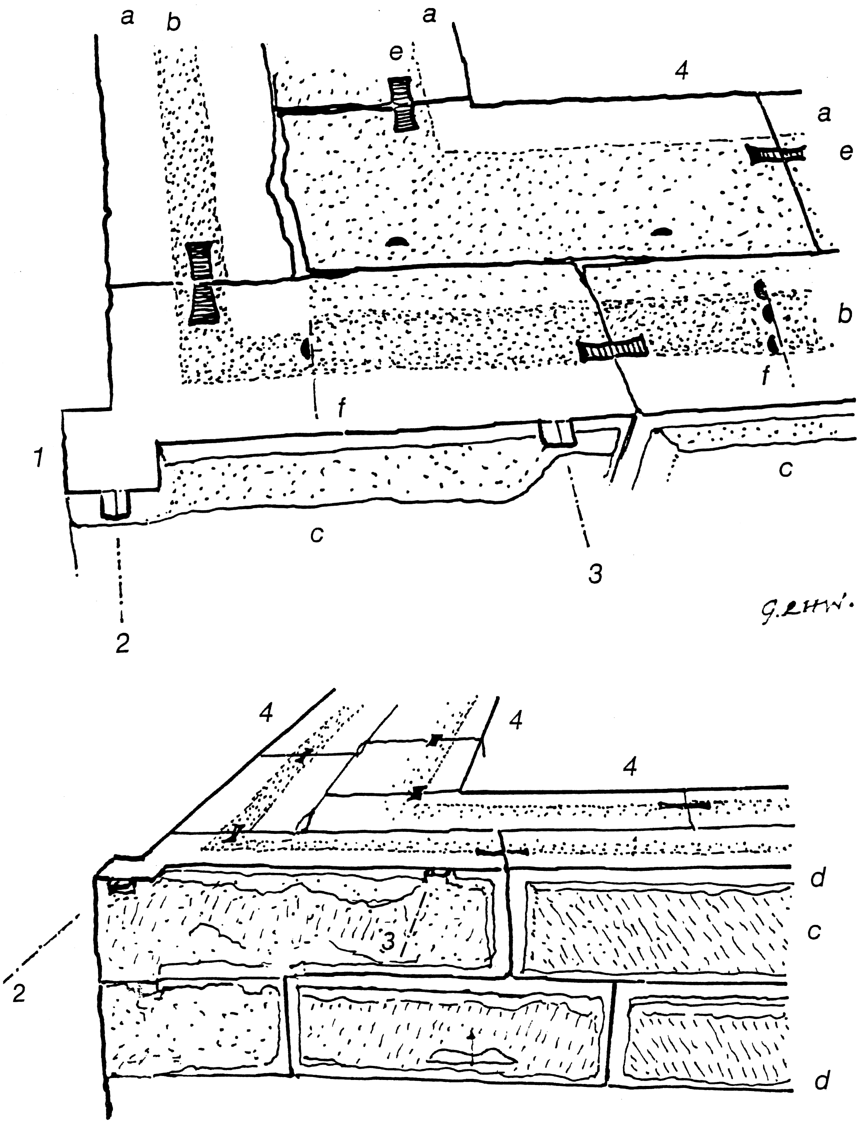
164. Setting of Regular coursed Pharaonic Masonry. Diagram illustrating *in situ* dressing of Upper Bed Joints and Faces of Masonry. Roman Period. The blocks were set with the upper bed joints slightly in excess of course height (1). These upper bed joints were then finely dressed *in situ* to course height when the complete passage of masonry had been set (2). Then the medial channels and areas were hollowed out to facilitate the distribution of mortar (3 & 4); and the emplacements for dove-tail wooden cramps were cut (5). The blocks were set with roughly draughted faces projecting beyond the line of the finished wall face which was inscribed in the upper bed joint of the lower course (6). Prior to setting a marginal draught along the lower arris was cut on the face of the block to be set, so that the block could be set to accord with the line scored out on the upper bed of the lower course (7). The marginal draught along the upper face arris of the blocks (8) could be cut theoretically at any time. Most frequently it was cut *in situ* before the super incumbent course was set, since the projecting boss afforded good purchase for levering (9). After Golvin ASAE 68 1982 p.180, fig 4.



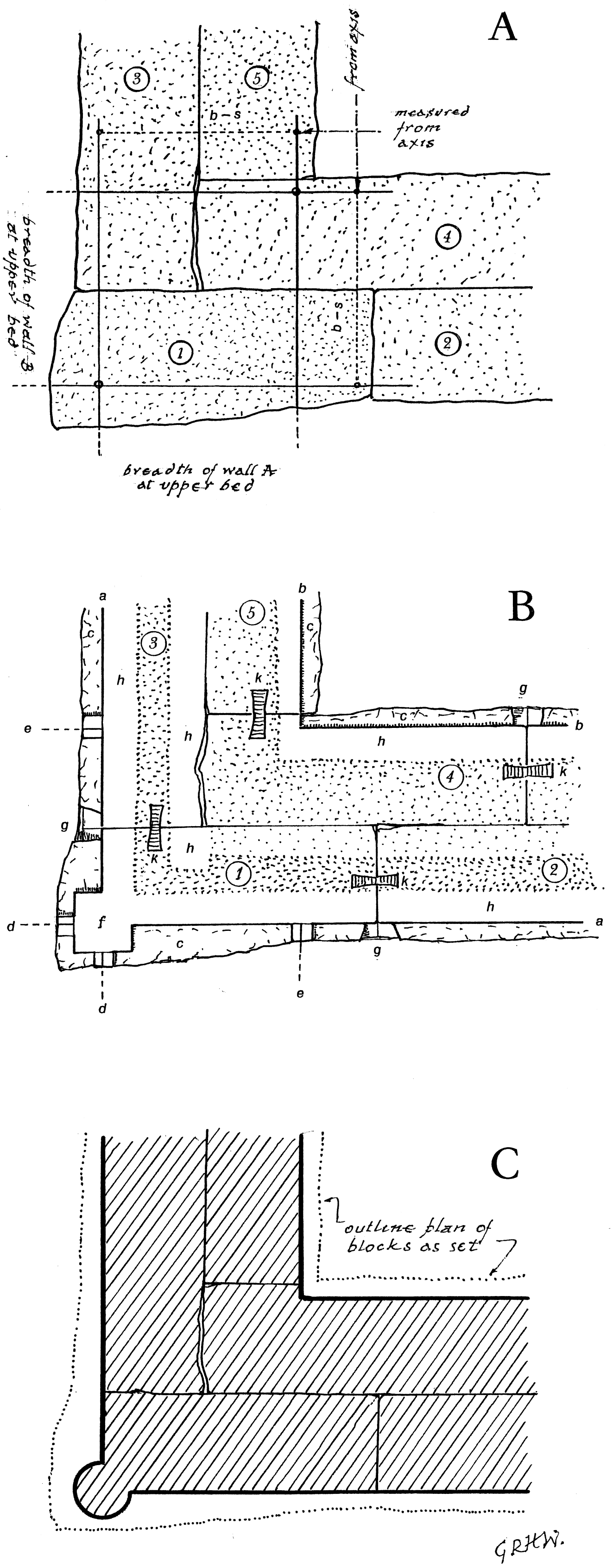
165. Setting of regular coursed Pharaonic Masonry – Diagram illustrating setting procedure. Preparation of the previously set course included cutting medial channels in the upper bed (1) to facilitate the distribution of the lubricant mortar. On occasion also “sink holes” may have been worked at the arrises of the rising joints (2) to promote the penetration of the mortar into these joints. The positions to be occupied by the blocks to be set were also marked out by an inscribed or painted line and pry holes were cut by them for the better purchase of levers (3). The faces of the wall were also marked out by an inscribed or painted line (4) and an upper marginal draught was cut in the block of this course (5) giving the arris to which the new course was to be set (NB This retreated with each successive course since all monumental masonry in Egypt was set with a “batter”). Into the bed of the bosses so created “pry holes” were cut as convenient (6) so that the fine lateral adjustment could be made to the blocks by levering. The blocks were then manoeuvred into their correct position by levering from behind (7) or from the outside (8). Wooden chocs were used between the levers and the blocks to prevent damage to the stone by the pressure exerted during levering (9). The mobility and manoeverability of the blocks during setting was promoted by spreading lubricant mortar over the channelled beds below. After Golvin ASAE 68 1982 p. 180, fig 4.



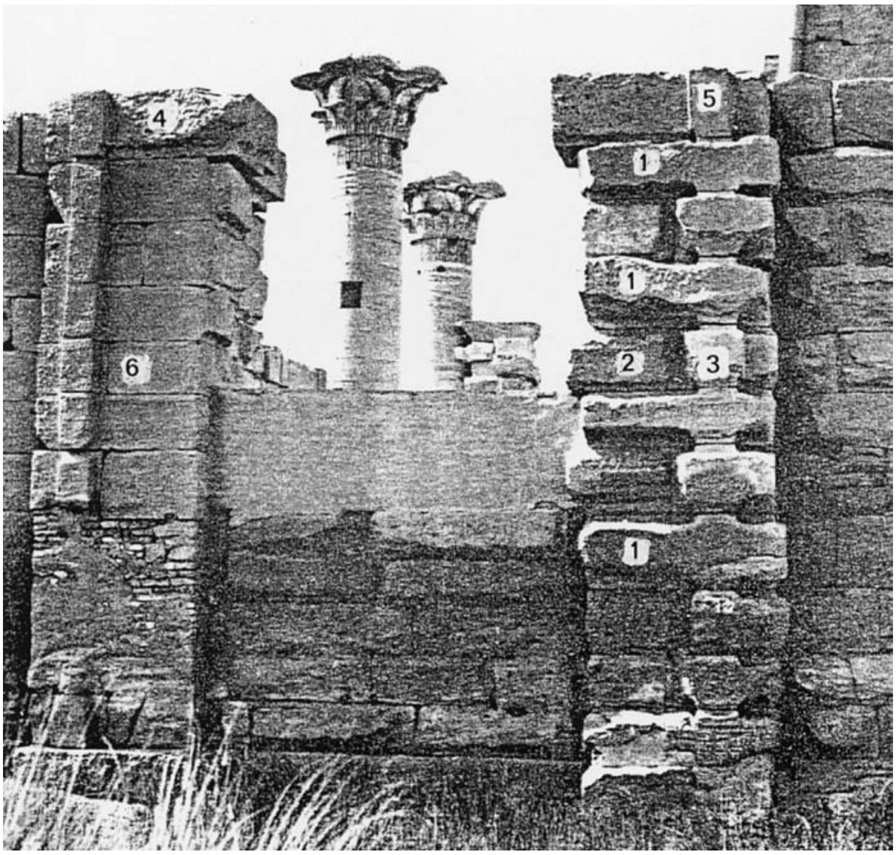
166. Mamisi, Edfu. Detail of Masonry Construction. Upper Egypt. Ptolemaic Period. Detail of wall and pier showing preparation of upper bed of blocks finely dressed to receive the super-incumbent course. The upper bed joints were finely dressed *in situ* when the complete course had been set. They were thus continuous and horizontal. The upper beds of walls of a single block thickness have been hollowed out slightly to effect a distribution channel for the lubricant mortar. Massifs of masonry as at the angle have been hollowed slightly over the complete area (1). The treatment of the upper bed has nothing to do with anathyrosis which is a feature proper to finely dressed dry stone masonry and is incorporated on rising joints only, which do not normally transmit compressive stresses. Cramp holes (2) were cut for dove tail cramps to secure the blocks one to the other (although when the circumstances can be investigated in undisturbed masonry, these cramp holes are very often empty). The position for setting blocks of the super incumbent course is indicated by inscribed lines and also by the ‘pry holes’ for engaging levers used in adjusting the blocks into exact position (3). After Golvin ASAE LXX 1984-85 p. 374, fig 1.



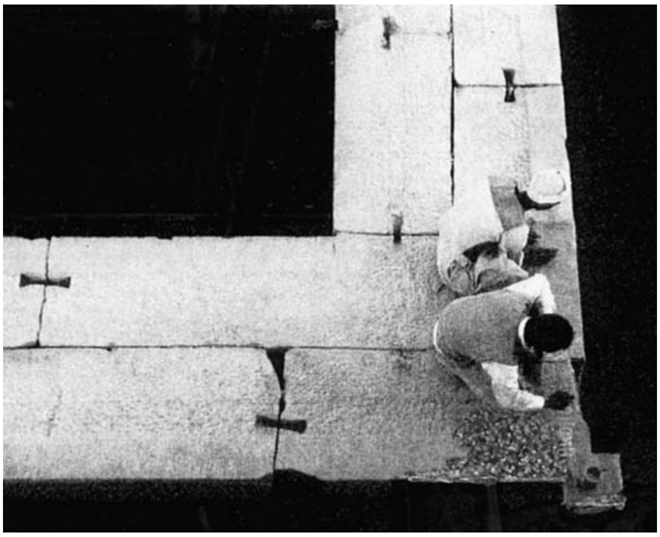
167. Kalabsha Temple. Pharaonic Masonry. Procedure at angles to give line of vertical inner faces and of line of "battered" outer faces of walls. Lower Nubia. 1st Century AD. Two tabulae with sighting lines on the outer face of one wall establish the outer and inner face of the return wall. They not only give the line of the wall in plan, but also establish the batter of the outer wall face. There is thus no need of controls from external perpendicular datums etc in order to obtain the correct batter. These tabulae must not be dressed away before the upper marginal draughts have been cut to delimit the faces of the wall. They are the references for the "face of operation". *Key*: (a) Smooth dressing of upper bed joint; (b) Lubricant mortar channel in upper bed joint; (c) Bosses remaining on faces of block; (d) Upper marginal draughts cut in faces of blocks to facilitate both setting and eventual facing of masonry; (e) Emplacements for cramps (for the greater part found empty); (f) Setting marks for blocks of super incumbent course, with "pry holes"; (1) Draught form of angle torus; (2) Tabulae with line of sight for battered outer face of wall; (3) Tabula with line of sight for vertical inner face of wall; (4) Wall face finely dressed *in situ.*



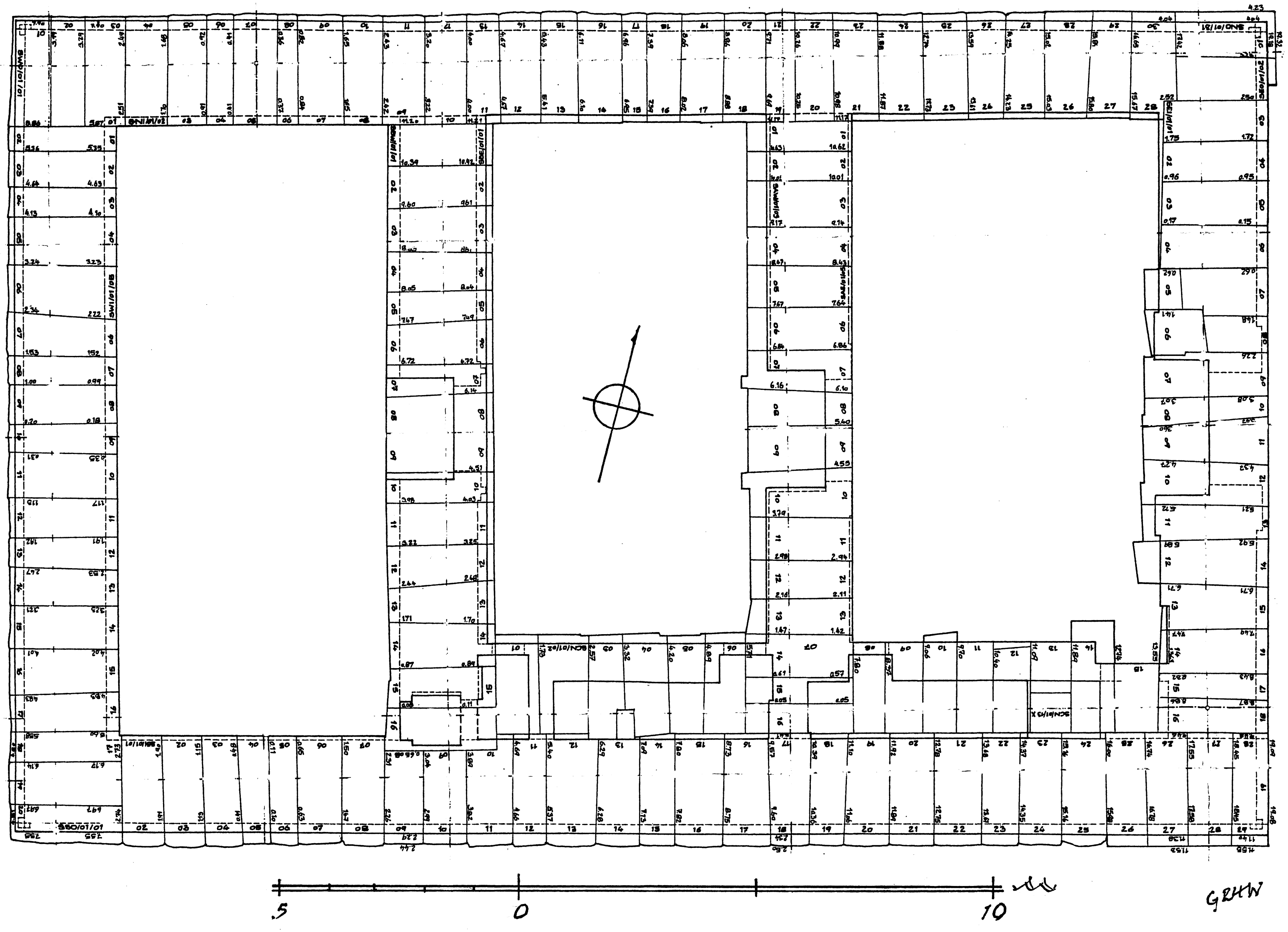
168. Pharaonic Masonry. Diagrams for procedure of setting and *in situ* dressing of angle. Based on construction of Temple of Kalabsha. Lower Nubia. 1st Century AD. *Key*: (A) Plan of upper bed of angle blocks set with only the lower bed joint finely dressed. NB This drawing does not discriminate whether marginal draughts on the face at the rising joints were cut prior to setting or not. The upper bed is roughly dressed and in this wall of two blocks thickness the blocs (1, 2, 3, 4) are set closely jointed back to back with the outer margin of the upper beds projecting well beyond the definitive course plan. The required lines of the outer and inner faces of the two walls are marked out at the angle by measurements outward from axes running through the entire temple which are carried up continuously course by course. The breadth of the wall at each successive upper bed is obtained by the formula b-s, i.e. the breadth at the upper bed joint of the preceeding course less the *s q d*, the inward retreat from the vertical proportional to the vertical height of the course. This was expressed in fingers/palms to the cubit (a common course height) and was roughly of the proportion of 1:7; (B) Plan of the same passage of masonry showing dressing carried out *in situ* to facilitate the succeeding course. *Key*: (a) Line of outer wall face; (b) Line of inner wall face; (c) Residual bosses on face of blocks; (d) Tabulae for sighting lines of outer wall faces; (e) Tabulae for sighting lines of inner wall faces; (f) Draughts for angle torus; (g) Marginal draughts on face at rising joints; (h) Finely dressed upper bed joints; (j) Channel in upper bed joints for distributing lubricant mortar; (k) Cramp emplacements; (C) Plan of same passage of masonry in finished construction when final *in situ* dressing has been carried out subsequent to complete setting of wall blocks. Original outline plan of masonry as set shown dotted.



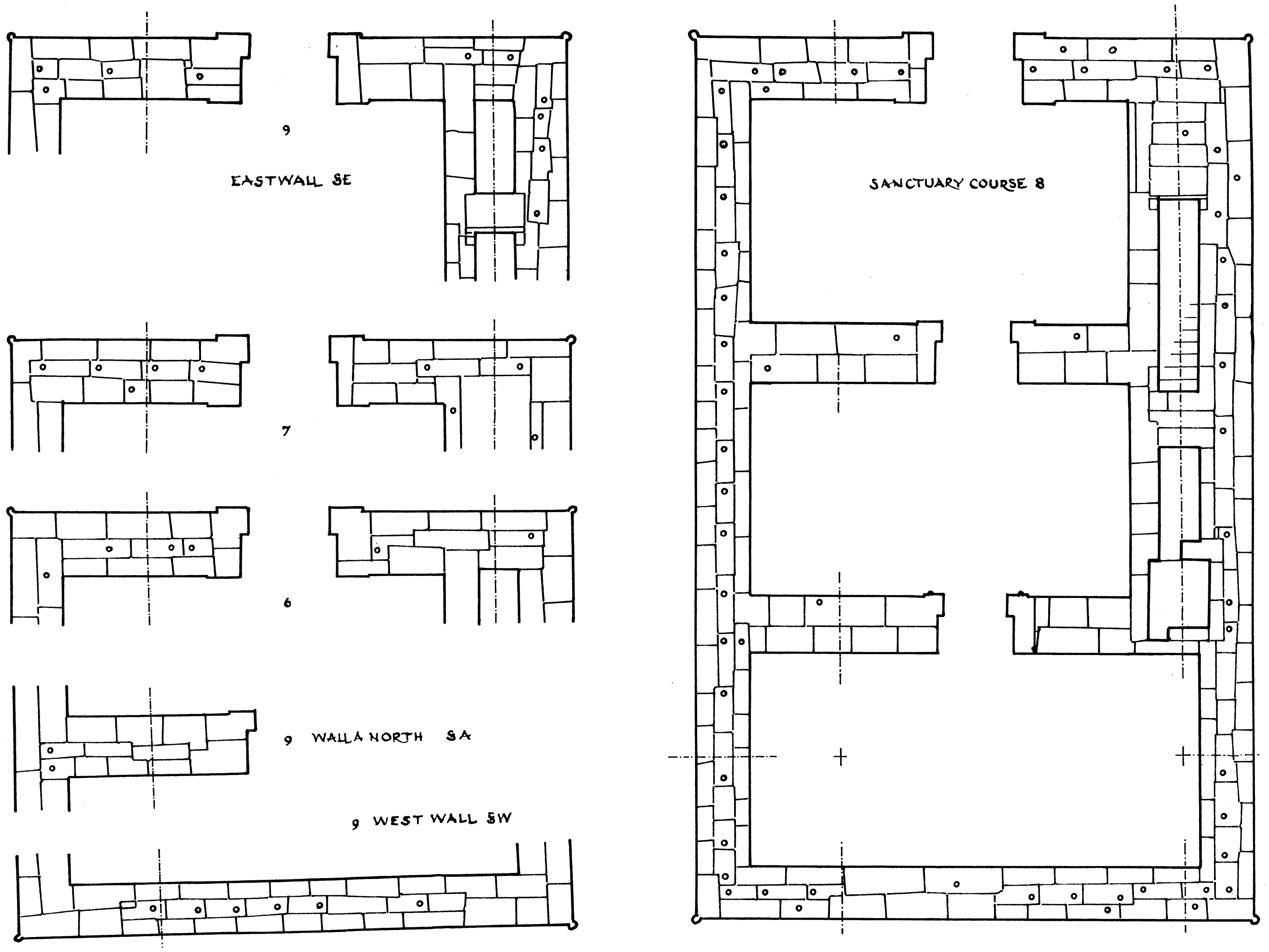
169. Medinet Habu. The Small Temple. View of Screen Wall featuring an Entrance with ornamental mouldings. Thebes. Roman Period. The unfinished state of the dressing indicates that the fine dressing of the masonry including the working of the mouldings was carried out *in situ* and proceeded directionally from left to right. The left jamb of the portal was finely dressed while the blocks comprising the right jamb were largely in bossed form, with only the initial stages of *in situ* dressing under way to work the vertical strip (torus) moulding. *Key*: (1) Blocks as set in bossed form with only marginal draughts worked prior to setting; (2) Face of blocks partly dressed back to delimit roughly the vertical strip moulding (torus / *Rundstab*); (3) Preparatory draught of vertical moulding; (4) Fine dressing of face of jamb in progress; (5) Finely dressed grounds for vertical strip moulding to be later worked into a torus (*Rundstab*); (6) Fair faced masonry of jambs. After Golvin & Larronde ASAE 68 1982 pp 165-194, Pl VII.



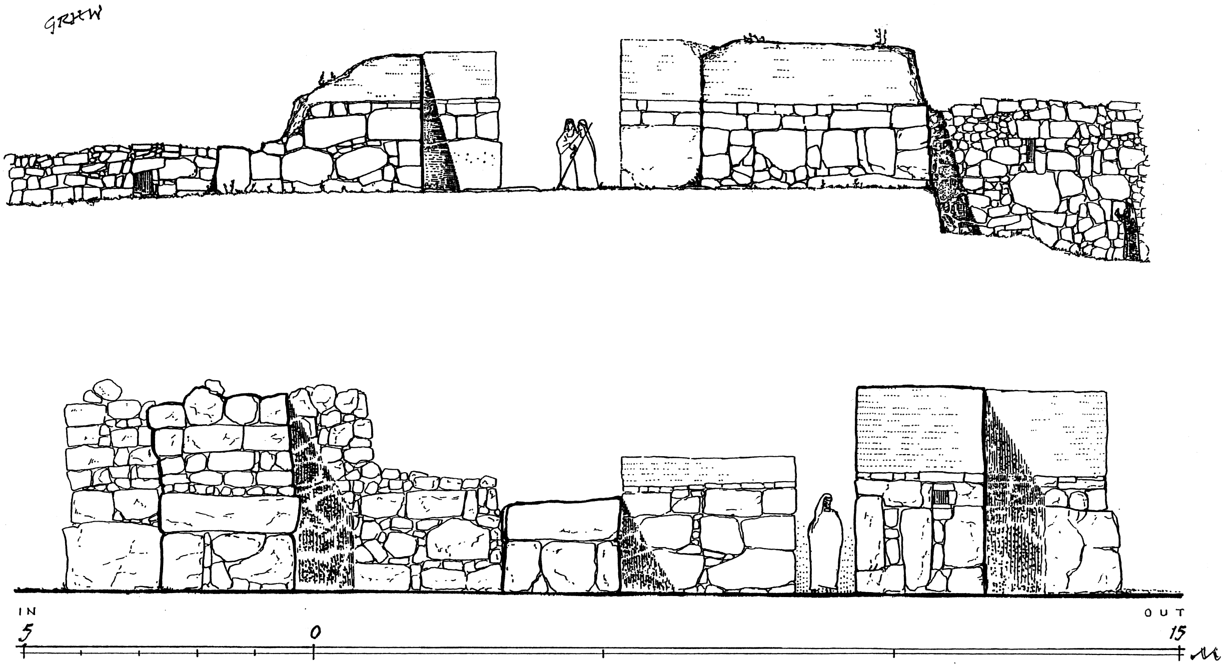
170. Kalabsha Temple. Pharaonic Masonry bonding of angle. Lower Nubia. 1st Century AD. Photograph made during work of dismantling the Temple at flood water Nile 1962. Shown here is the double stretcher bond universal throughout the temple for walls of double block thickness. The finely jointed massive blocks weighing several tons are rendered stable by their dead weight, thus no cross bonding of the two faces of the wall by way of headers is provided. After Kalabsha 2, pl 11.



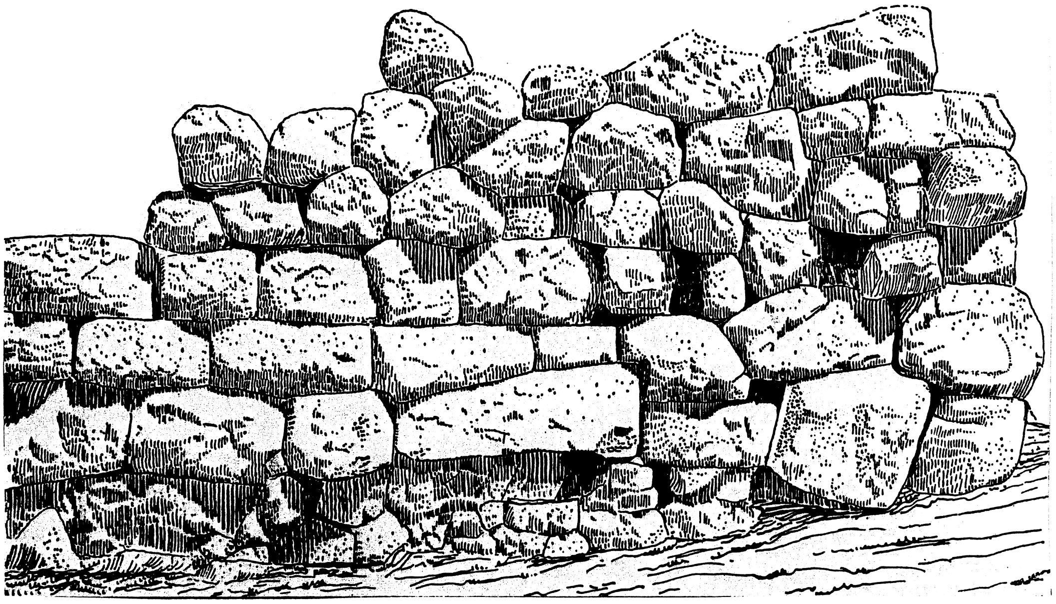
171. Kalabsha Temple. Pharaonic Masonry bonding of socle course. Lower Nubia. 1st Century AD. The finely jointed blocks (> 2m in length) comprising the Socle Course are set in header bond to provide against uneven settlement. After Kalabsha 2, Plan XII.



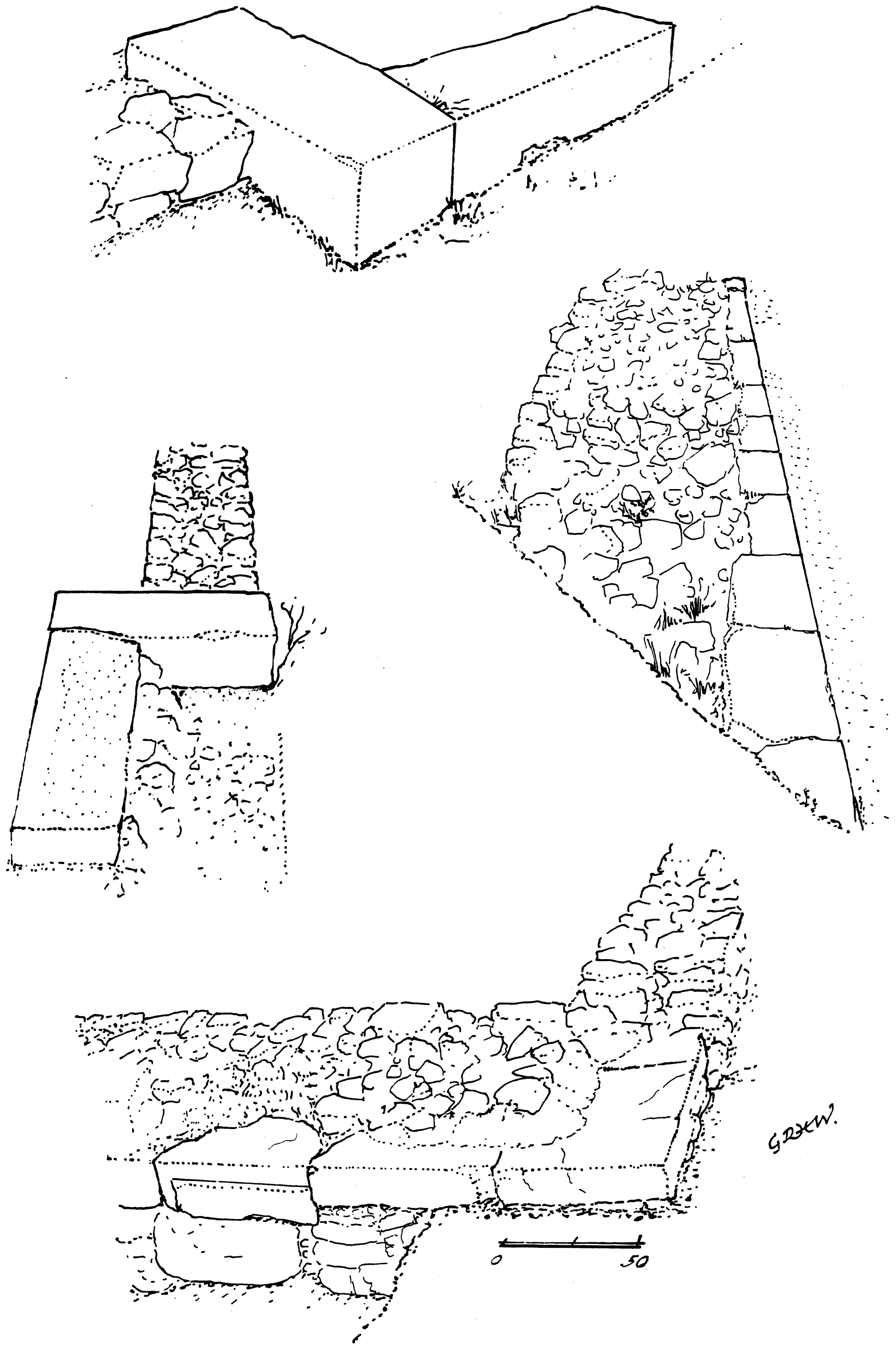
172. Kalabsha Temple. Pharaonic Masonry Bonding in Lower Courses of Sanctuary. Lower Nubia. 1st Century AD. Plans of courses 6-9 showing medial row of stretchers to make up thickness of walls. o = reused blocks. Because of the battered outer faces of external walls, the thickness of such a wall increases progressively towards the base. In this fashion two wall blocks of standard thickness which (when set closely jointed back to back) occupy the thickness of the wall in the upper courses may not comprehend the thickness of the wall in the lower courses. In this event the normal device was to provide a third row of (medial) stretchers closely jointed to the facing blocks. On occasions such blocks, being totally hidden from view, were blocks reused from an earlier monument. After Kalabsha III, p.86, plan 9.



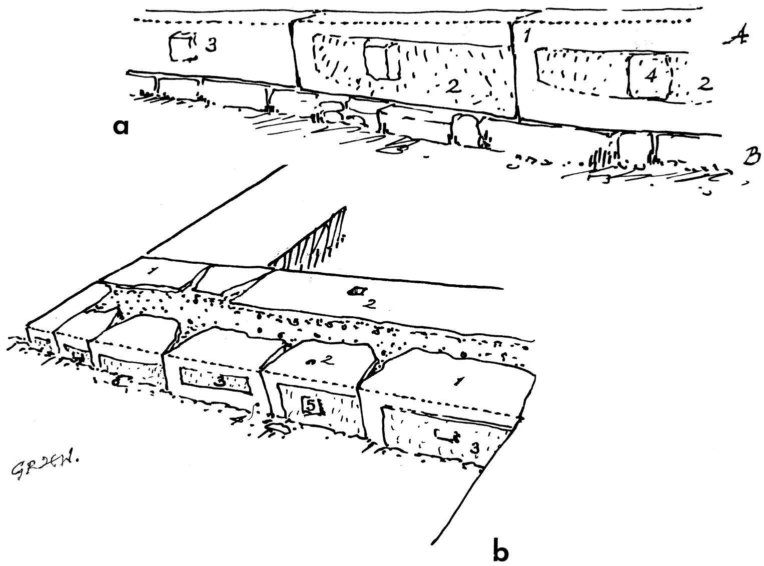
173. Shechem. North “Migdol” Gate in City Wall. Cyclopean Masonry. Central Palestine. Middle Bronze Age, ca 1650 BC. Mud brick superstructure on stone socle. The socle masonry of the Gate is of Cyclopean character but has been in a measure squared up by hammer dressing so that it is partly coursed; *above*: Elevation from outside city; *below*: Medial section through entrance passageway. After Shechem III, Vol 2. Ills 56, 57.



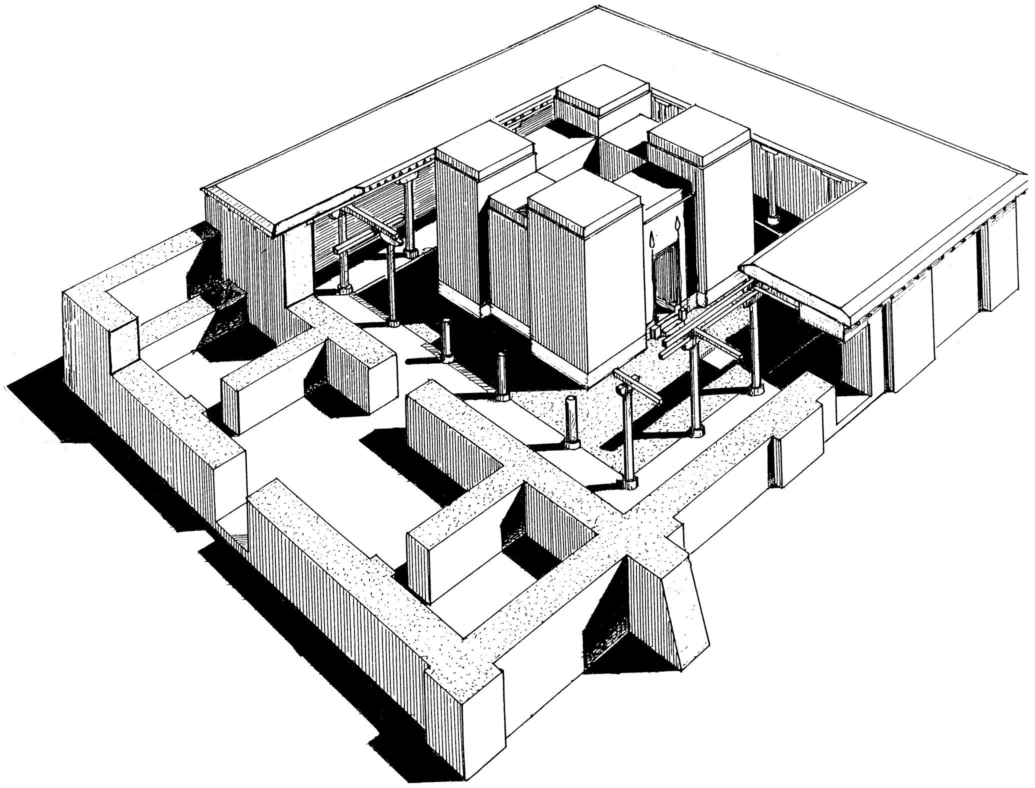
174. Hattusas. Hittite Cyclopean Masonry. The Lion Gate. Central Anatolia, Bogaz Köy. ca 1200 BC. These natural boulders are roughly shaped with a hammer when necessary, and are set to interlock. This assembly stands behind the dressed polygonal masonry of Archaic and Classical Greece. Some of the blocks are over 2m long and more than 1 ton in burden. Thus the construction can have proceeded only by way of earth ramps and embankments. After Naumann, fig 48.



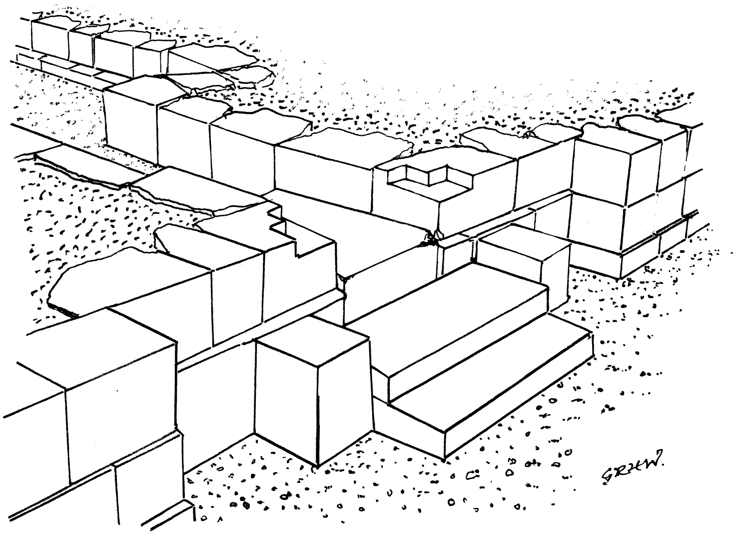
175. Middle East and Eastern Mediterranean. Bronze Age Bastard Ashlar Masonry. e.g. as in Maroni, Cyprus. ca 1250 BC. Bastard Ashlar, i.e. blocks finely dressed only at the face and face arrises, has two natures. It is finely dressed masonry only at the face but passes over into rubble behind the surface, i.e. it is finely dressed masonry in aspect but rubble masonry in structure. This type of masonry was common in the Middle East and East Mediterranean during later Bronze Age and Iron Age times. By nature it is associated with mixed construction as a facing. However in addition to its role as a facing, its occurrence in the Middle East and Eastern Mediterranean during Bronze Age and Iron Age times was always restricted to the socle of walls, where the superstructure was of another construction, e.g. rubble or mud brick. In this latter respect it differs from the original bastard ashlar of Old Kingdom Egypt (Zoser Masonry), which constitutes the entire wall face. Bastard ashlar long remained standard construction in Cyprus, continuing in use until Roman times. However it never developed autonomously into structures entirely of finely dressed masonry. After ABC II, fig 230.



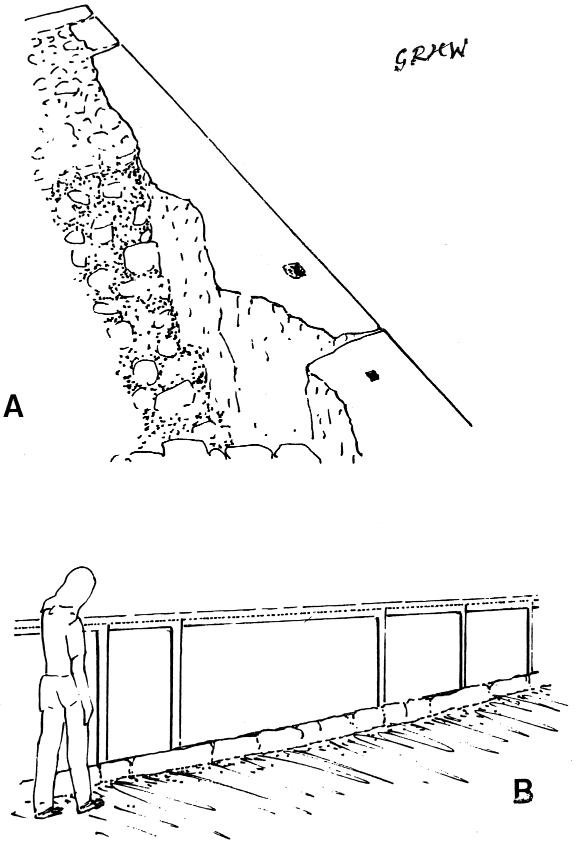
176. Kathari Sanctuary. Bronze Age Bastard Ashlar Masonry. Details of Socle Course to Mixed Construction with Mud Brick Superstructure. Kition, Cyprus, ca 1200 BC. *Key*: (a) Elevation of Socle Course (A) on squared rubble foundations (B); (1) Broad Marginal Draughts; (2) Partly Dressed away bosses; (3) Attachment lugs; (4) Vestigial dressed away attachment lug; (b) Plan of Socle Course. Bastard Ashlar facing to rubble core; (1) Finely dressed upper beds; (2) Dowel holes; (3) Face Panels; (4) Marginal Draughts; (5) Attachment Lugs. After ABC II, fig 245.



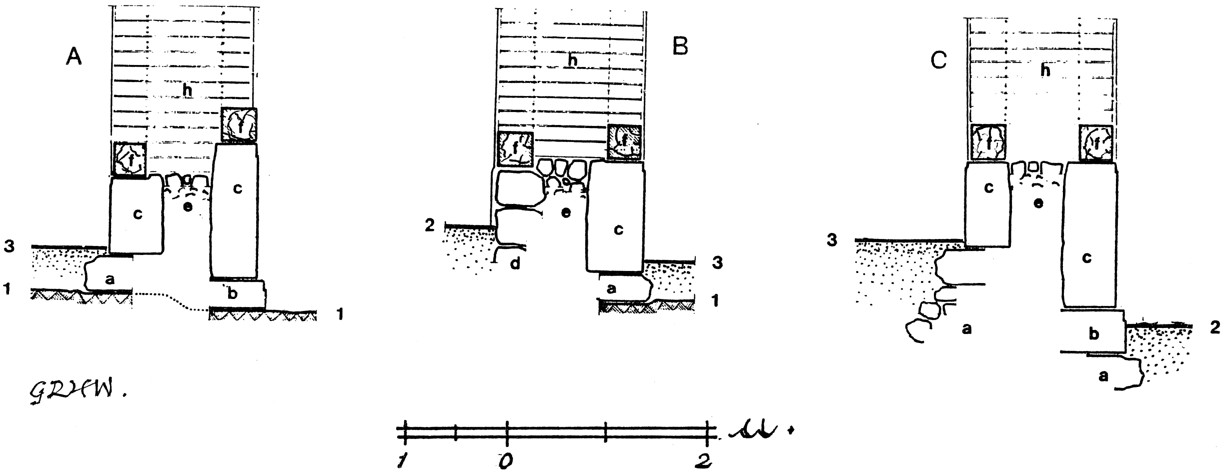
177. Altin Tepe. Reconstructed Perspective View of Urartian Tower Temple. Eastern Anatolia. 8th Century BC. This monumental building employs the mixed construction of the Middle East combining solid mud brick and timber superstructure raised on a socle with bastard ashlar masonry facing.



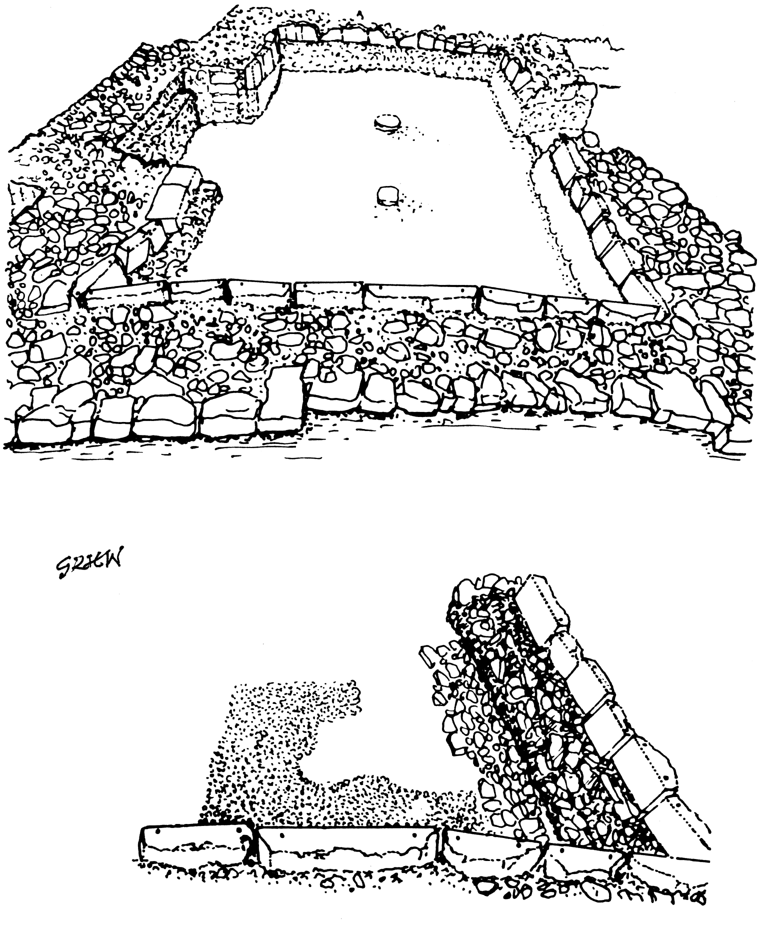
178. Altin Tepe. Urartian Tower Temple. Masonry Detail of Entrance to Cella. Eastern Anatolia. 8th Century BC. The socle is faced with finely faced stone masonry which constitutes one of the most expert developments of Bastard Ashlar comparing favourably with e.g. contemporary Israelite stone masonry



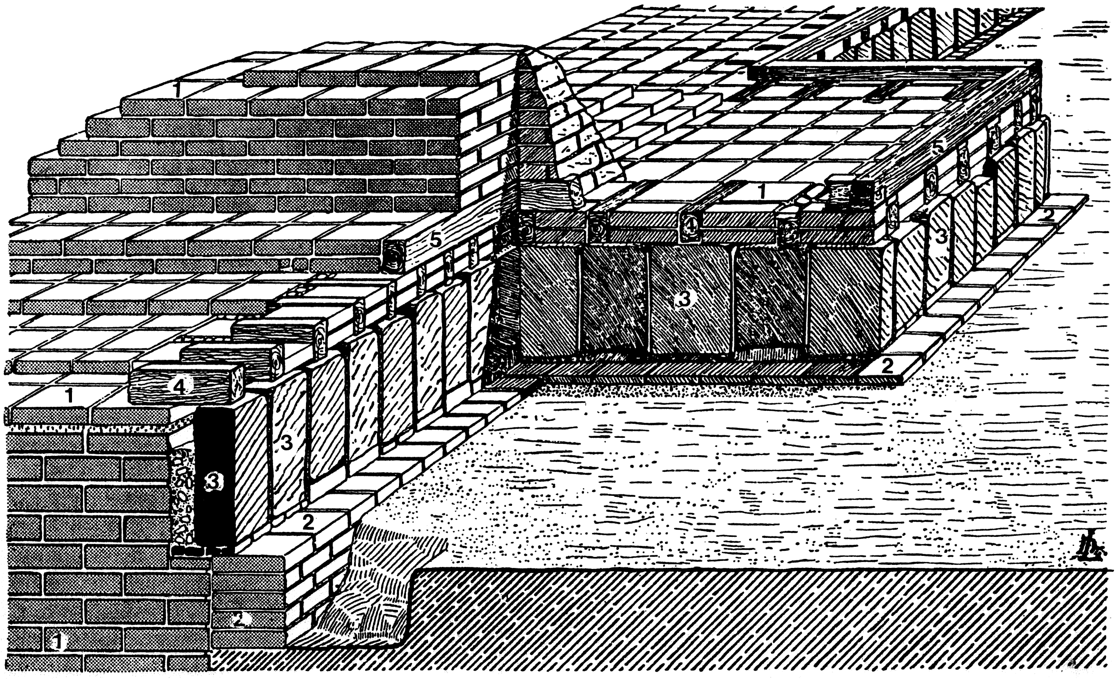
179. Kition. Kathari Sanctuary. The Socle of bastard ashlar masonry facing with orthostates. Cyprus ca 1200 BC. The bastard ashlar facing to the rubble core of the socle comprehends an ordonnance of imposing aspect with orthostates standing on a projecting plinth. Although the orthostates are expansive in aspect, they are slabs of no great thickness. In spite of the monumental aspect all these individual facing blocks can be moved about and set in place at ground level by a few men without requiring special site installations. *Key*: (A) Perspective view of socle showing fine dressing reserved to face, and splayed rising joints. The recesses in upper bed joints are for fixing the wooden reinforcing to the mud brick superstructure; (B) Perspective view of socle showing finely dressed orthostates with marginal draughting standing on plinth. After ABC II figs 244, 245.



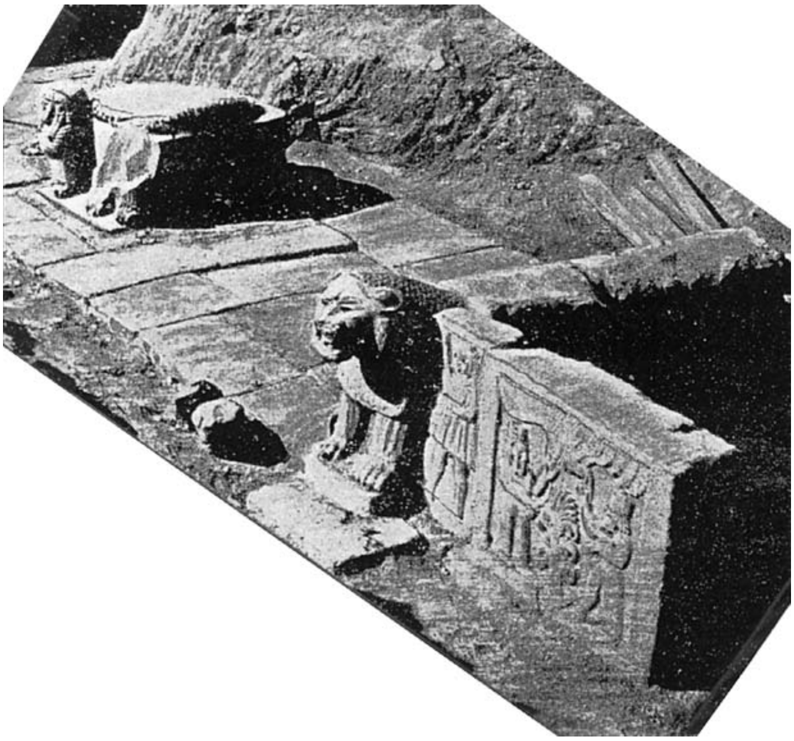
180. Kition. Kathari Sanctuary. Bastard Ashlar Masonry Substructure to Mud Brick Walls. Cyprus ca 1200 BC. Varied detailing of wall construction showing prime exhibition of orthostates on principal façade. *Key*: A, North Wall; B, East Wall; C, South Wall; (a) rubble foundations; (b) finely dressed plinth; (c) finely dressed orthostates; (d) facing blocks; (e) rubble core; (f) wood reinforcing stringers; (h) mud brick with plastered face; (1) bed rock; (2) external ground level; (3) internal floor. After ABC II, fig 246.



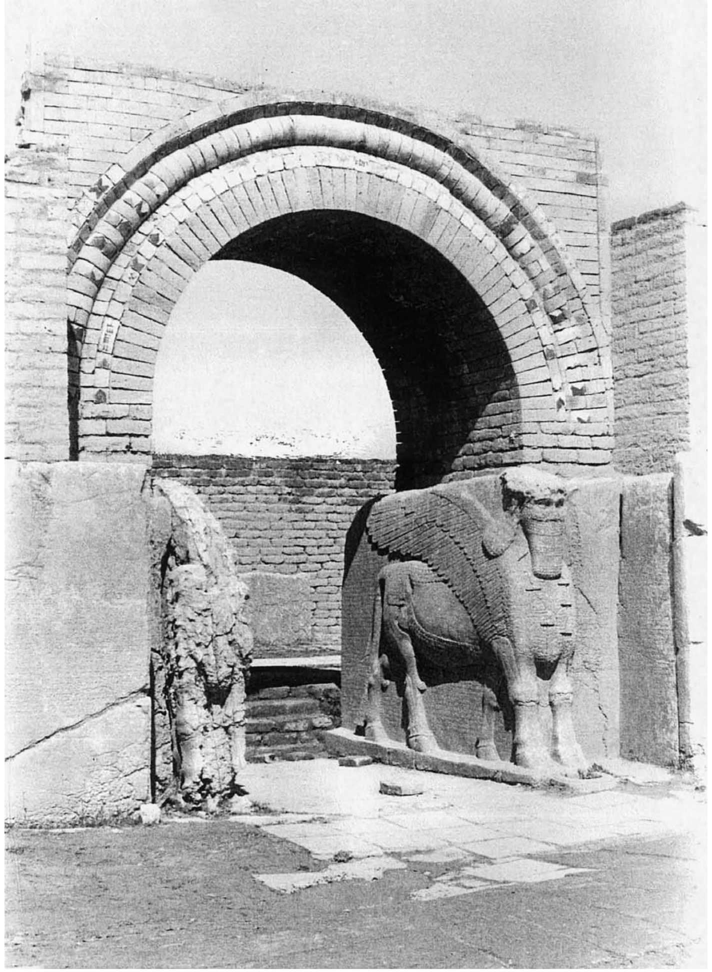
181. Hazor. Lower City Orthostates Temple. The Association of Orthostates and Bastard Ashlar Masonry. Northern Israel. ca 16th Century BC. Remains of stone substructure to walls of mud brick superstructure. Here excavations revealed two periods where the rubble substructure was faced with orthostates of bastard ashlar masonry. Evidently the orthostates were "lifted" for re-use in the latter period. The earlier period appears to show a rubble plinth on which the orthostates originally stood. Dowel holes in the upper bed joints show that the superstructure was provided with timber reinforcing secured to the masonry socle. The orthostate facing afforded a monumental aspect to the building, but these elements were not massive and could be moved about and set up by manhandling. After ABSP II, fig 313.



182. Tell Halaf Palace Temple. Detail of Orthostate Construction. North Syria. 9th Century BC. Orthostate facing to foot of mud brick walls anchored in place by wooden ties and stringer beams. *Key*: (1) Mud Brick Walls; (2) Mud Brick Plinth for orthostates; (3) Stone orthostates; (4) Wood anchor ties; (5) Wood stringer beams. NB The original drawing is defective in minor details. After Naumann, fig 75.



183. Sakjegözü. Syro-Hittite Palace Entrance. Jamb and Column Base. North Syria, ca 740 BC. These finely dressed orthostates applied at the foot of mud brick walls stand less than waist high and could be set directly in position at ground level by several men without the need of special installations.



184. Nineveh. Late Assyrian Bull Genii (*Lamassu*). These relief sculptures were in the process of being set up in a modern mud brick reconstruction of a palace building. They are a development from relief ornament carved in the bastard ashlar stone substructure to mud brick and rubble walls, a recognised mode of monumental building in the Levant during the Late Bronze Age.

185. Nineveh. Late Assyrian Orthostate Revetting to Mud Brick Palace Walls. Mosul. Late Assyrian. These orthostates were in the process of being set up in a modern mud brick reconstruction of a palace building. The figures are approximately life size. The orthostates are non-structural applied ornament and are an interesting demonstration of the development of structural feature into ornament, which is common in building history.

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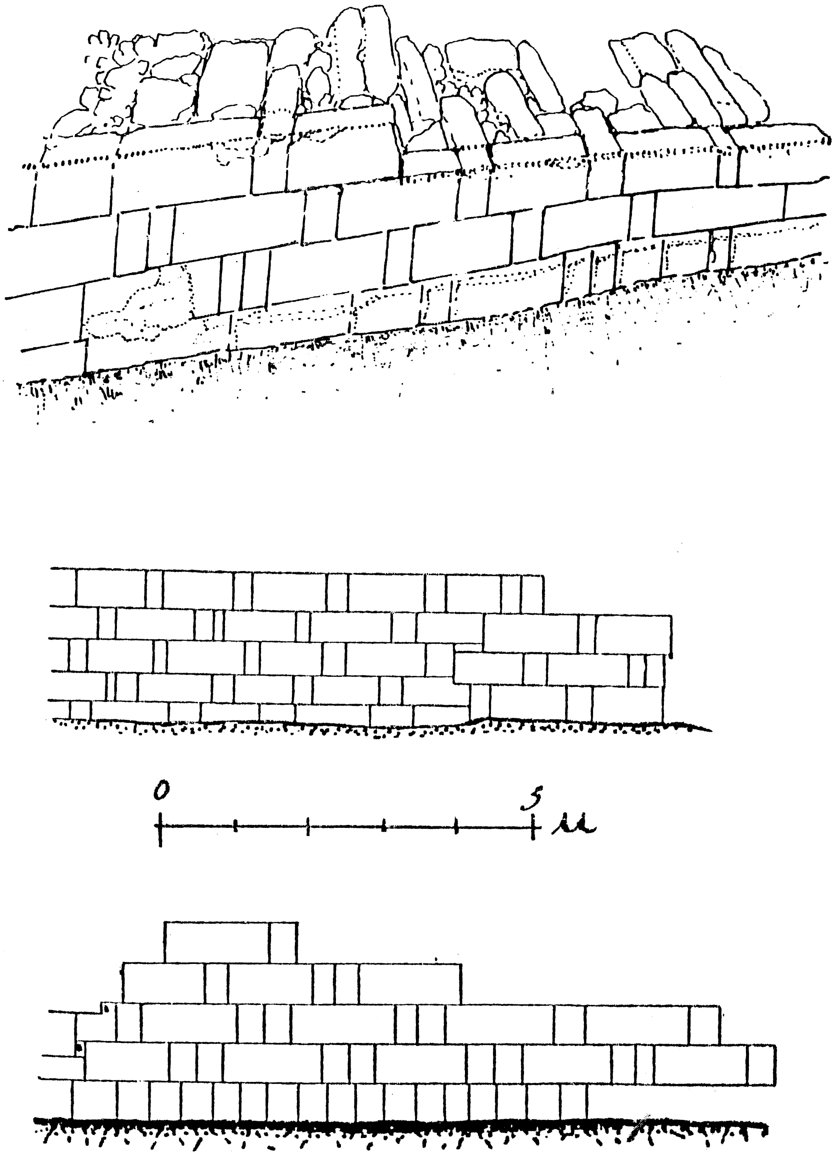

185A. Bonding in Israelite Masonry. 8th–7th Cent BC. The fine dressed stone masonry of the Israelite Kingdoms essentially followed on in the bastard ashlar tradition of the Palestinian Late Bronze Age – it was finely dressed at the visible faces only. Nevertheless the surviving evidence of fine Israelite masonry has been considered to be an exponent of the biblical term "the measure of hewn stones"(Kings 7.9-11). This proposal is based on the use of a standard block with proportions of 6 : 3 : 2, generally with length of ca 2 cubits (~ 1 metre). These proportions are those of a traditional modern 9″ brick, only the block is set on edge to give a slab with height half its length, and thickness 1/3 of its length. In this way the sum of the thicknesses of 3 contiguous blocks set in parallel is equal to the length of a single block. On this basis various bonds are possible in order to construct walls of 1, 1½ and 2 blocks thickness, where headers and stretchers alternate in the same course – i.e. the bonds are variations of Flemish Bond. These bonds proposed are largely theoretical constructs, but the significance of bonding in Israelite masonry as a precursor of Classical Greek ashlar remains an issue. *Key*: 1. Recorded passages of stone masonry from Samaria; 2. Ideal bonding systems suggested by the above which may represent →

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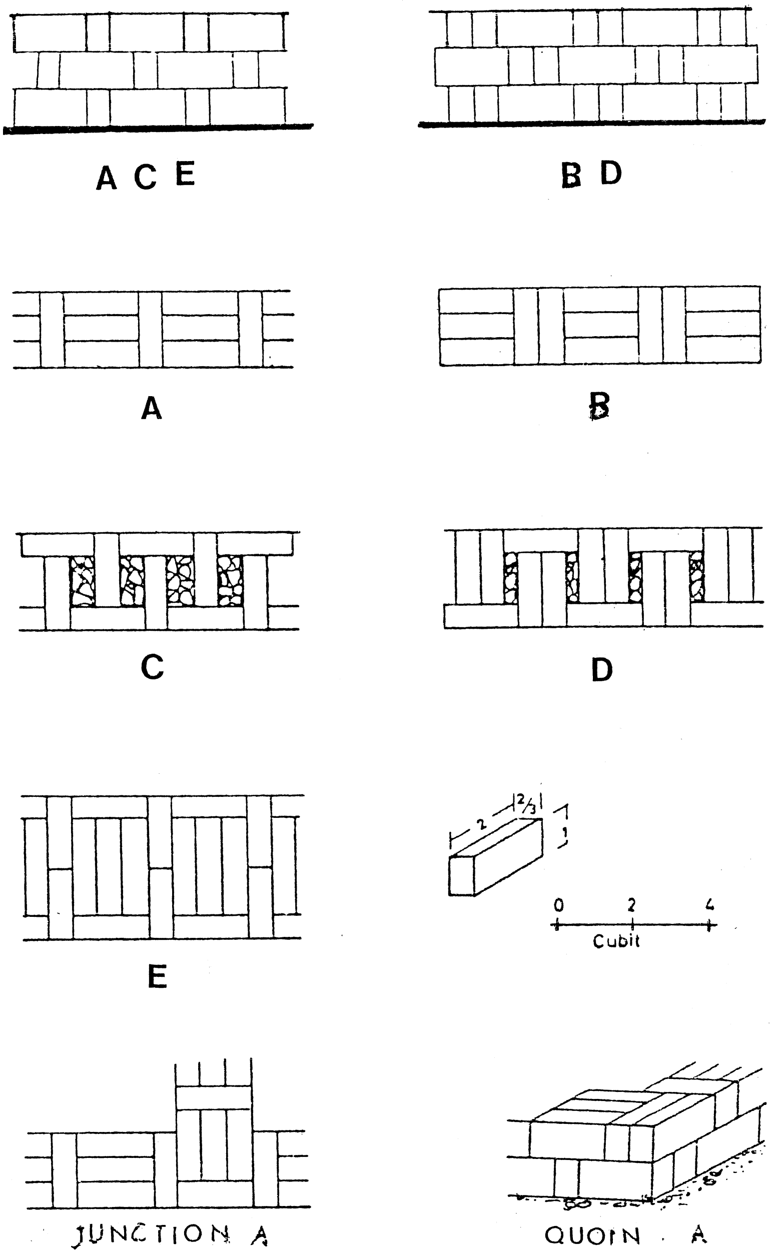
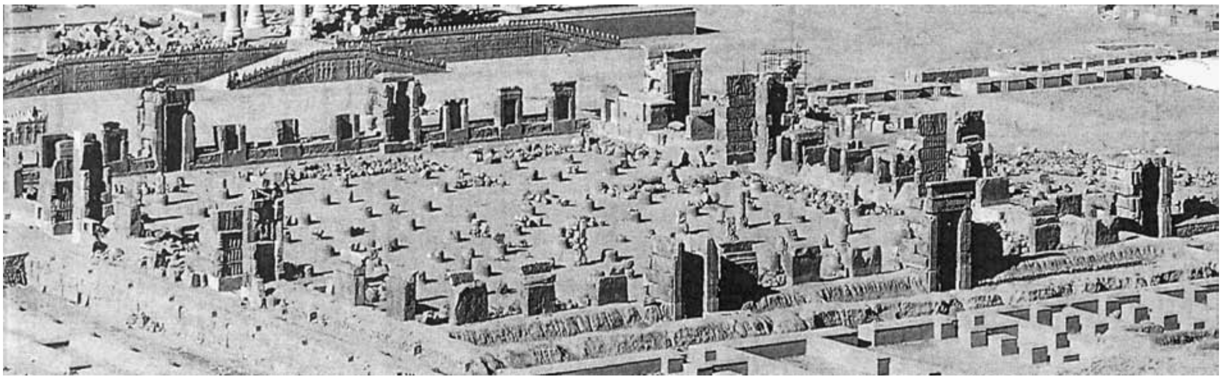
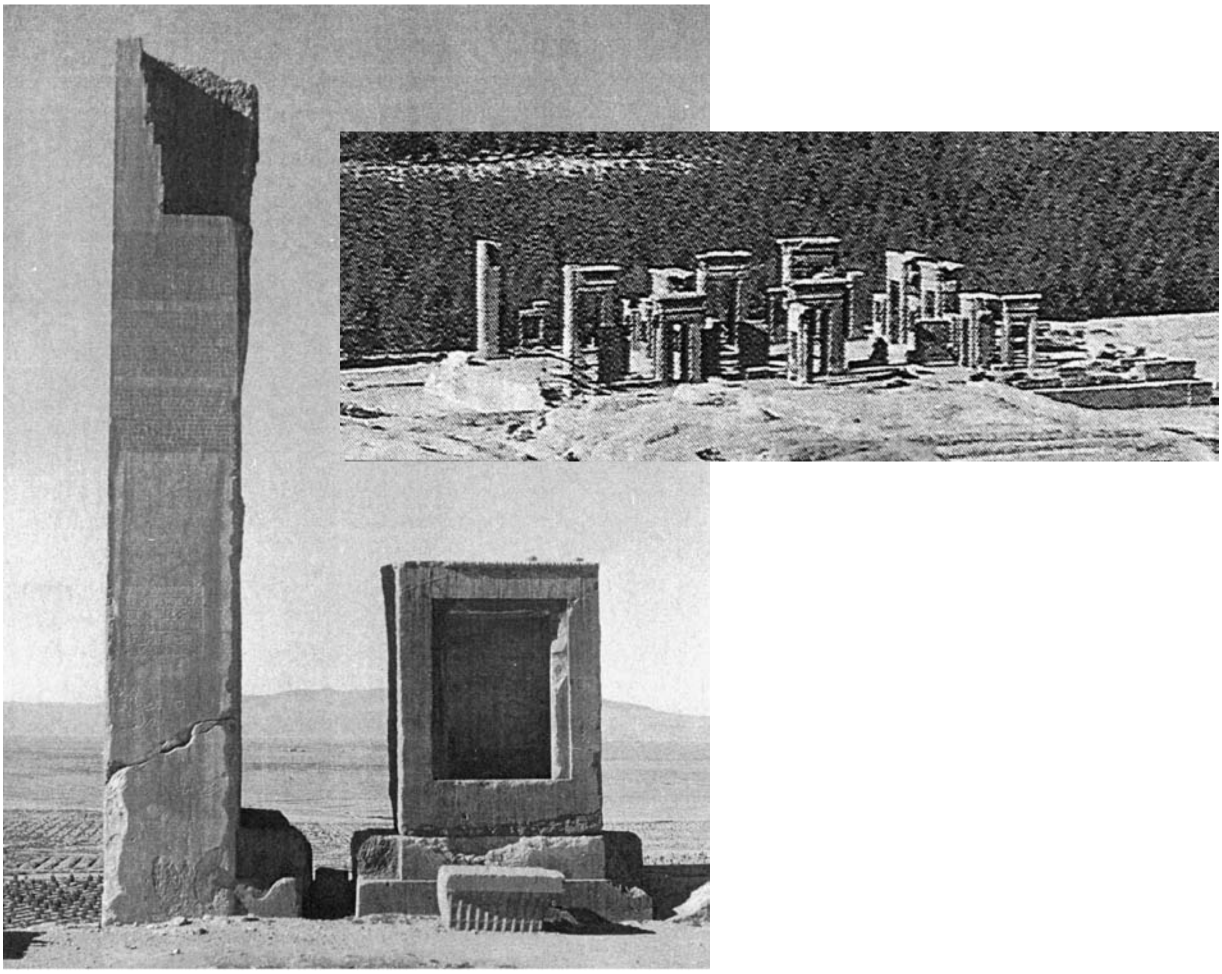


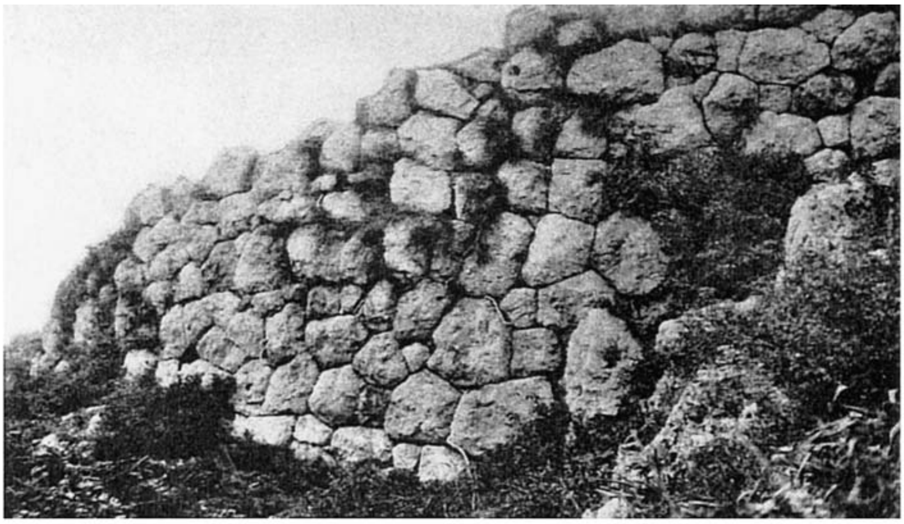
“the measure of hewn stones”; A. Wall of 1 block length thickness (2 cubits, ca 1m). Here if the blocks were set on their natural beds, the arrangement parallels a traditional modern 9″ Flemish bond brick wall; B. A bond incorporating more headers and thus giving a stronger construction. It is the inverse of Flemish Garden Wall Bond, where there are two stretchers to a header in the run of a course. C. Wall of 1½ block length thickness (3 cubits, ca 1.50m). This is economic as it reduces the labour of fine dressing and the cavities are filled with mason’s waste, cf the modern 13½ Quetta Bond, where the cavities are grouted and sometimes take reinforcing rods. (The English trade name for this type of bond is Rat trap Bond). D. A bond incorporating more headers and thus giving a stronger construction. It is the inverse of Flemish Garden Wall Bond, where there are two stretchers to a header in the run of a course. E. Wall of 2 block length thickness (4 cubits, ca 2m). Here if the blocks were set on their natural beds, the arrangement parallels a traditional modern 18″ Flemish Bond brick wall. (This drawing is defective in detail as the internal headers are shown longer than the standard block, which could be avoided by backing the face stretchers with another stretcher.) After ABSP II, ills. 317, 319, 320.

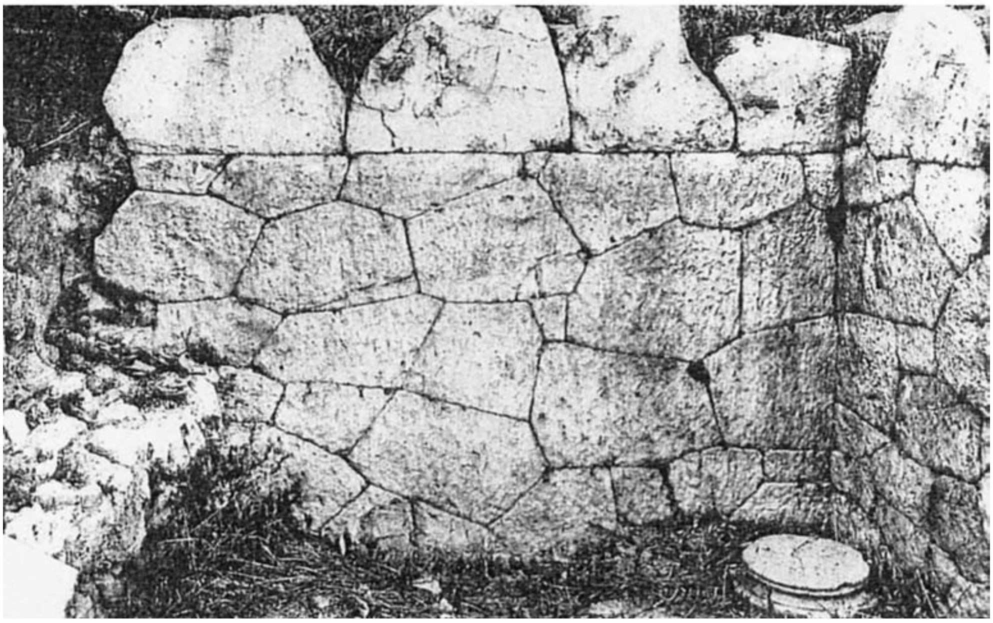


186. Persepolis. Hall of a Hundred Columns. Mixed Construction of Dressed Stone and Mud Brick. Southern Persia. Achaemenid, ca 500 BC. The walls and roofing of this magnificent building were of earth (mud brick), but the soaring columns and the frames of doors and embrasures were of finely dressed stone masonry serving to stiffen the earth construction of the wall. After Trumpelman Persepolis, fig 29.

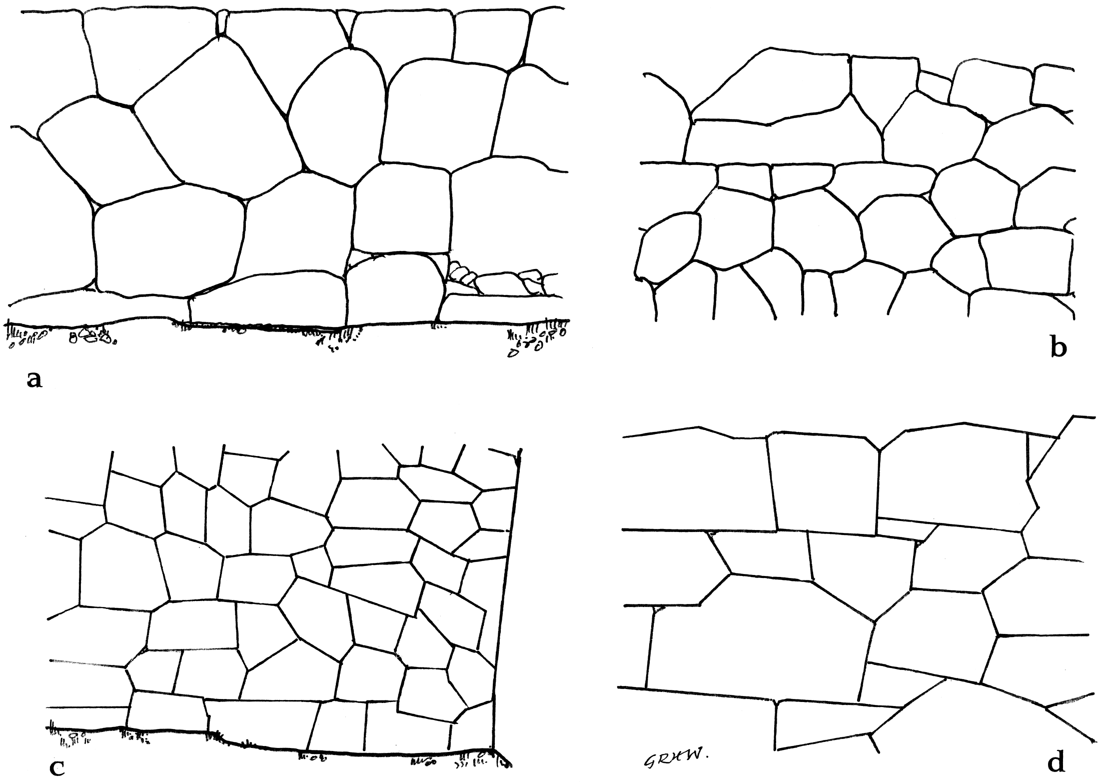


187. Persepolis. Palace of Darius. Detail of Mixed Fine Stone and Earth (Mud Brick) Construction. Southern Persia, Achaemenid ca 500 BC. *Right*: General View showing fine stone masonry of door frames and angle piers serving to stiffen the mud brick walls; *Left*: Detail showing fine stone masonry, angle pier and niche. NB Mud brick construction is always subject to angle collapse. After Trumpelman Persepolis, fig 27.

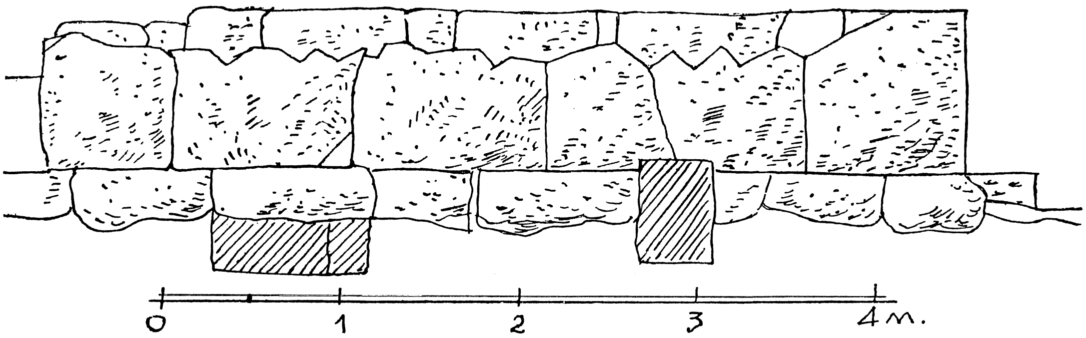




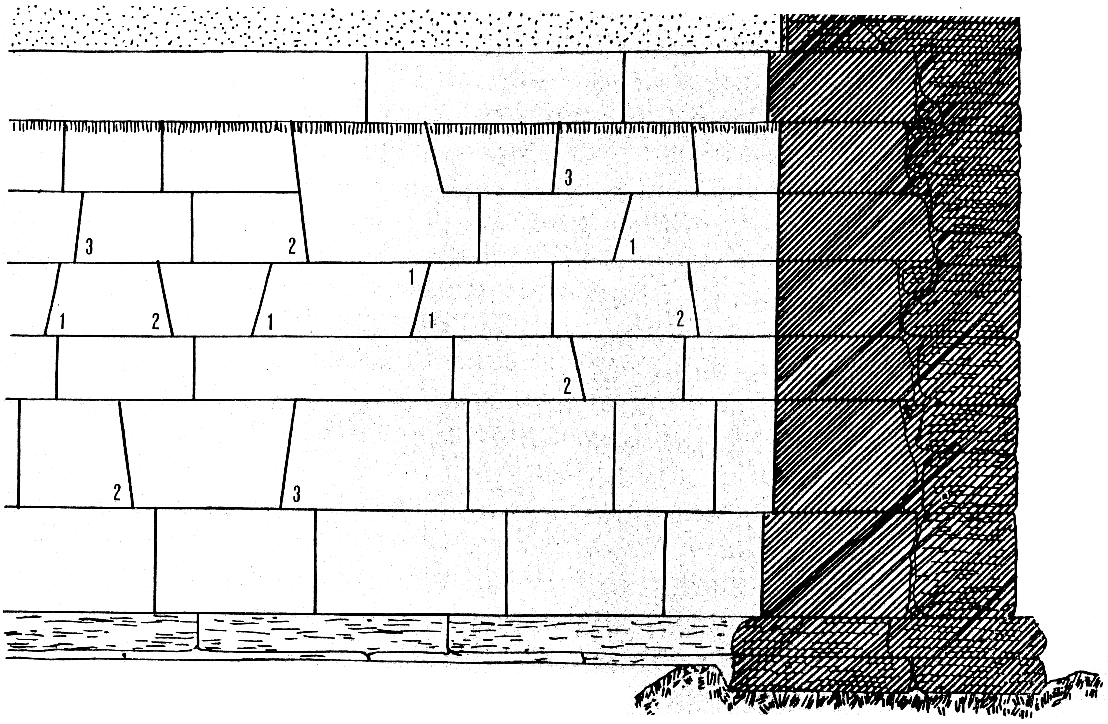
188. The Origin and Development of Greek Polygonal Masonry. The development of finely dressed, hair line jointed, polygonal masonry from carefully set angular rubble is clearly shown. The efficacity of such angular rubble against lateral thrust in retaining walls prompted its transformation into a genre of fine masonry construction for retaining walls. (*Above*) Dressed angular rubble, Pierian Seleucia; (*Below*) Finely dressed polygonal masonry, Athenian Acropolis Cistern. 6th Cent BC. After Martin Pls XXXVII^1, XXXIX$^{1.}$



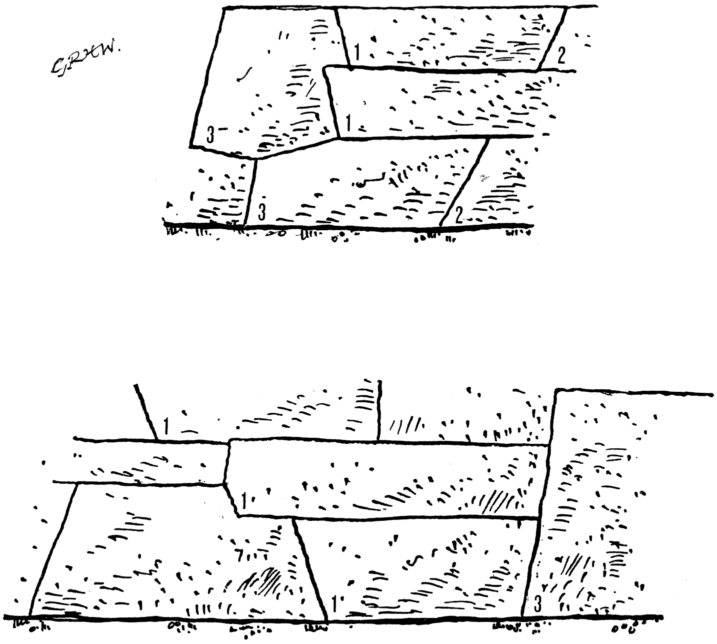
189. Classical Greek Lesbian and Polygonal Masonry. This type of masonry was once regarded as a development stage between rubble masonry and finely dressed ashlar masonry. This, however, is not at all its rationale. It is possible to associate its relative frequency with different places and periods, but its true distinction is functional. The angular interlocking of units gives great resistance to displacement by lateral forces, and so the proper occurrence of this masonry is in retaining walls, or defensive walls. It is not proper to the upstanding wall of buildings. Nonetheless its striking appearance came to be appreciated for its own sake, and in later (Hellenistic) times numbers of instances occur where this type of masonry was used out of place functionally. The difference between Lesbian (*above*) and Polygonal (*below)* masonry is rather one of degree and not kind. Lesbian masonry is the type where the sides exhibit a (more) pronounced curvature; polygonal where the sides are rectilinear. (Three dimensional viewing is necessary for a just appreciation of this question.). The dressing procedure provides some distinction between the two types. The curved sides of Lesbian masonry were obtained by the use of a lead strip template. The face angles of polygonal masonry were obtained by an adjustable bevel. As some mitigation of the great labour, the fine jointing was worked only for a narrow band at the face, the joints opened to the interior as with Bastard Ashlar. Whereas the dressing of this type of masonry has aroused lively interest, little concern has been accorded to its setting. Yet this is an equally demanding process. Such blocks must be lifted directly into position and with a massive polygonal block it is difficult to envisage how this was done. When the masonry constitutes a retaining wall, the operation is feasible. *Key*: (a) Lesbian Masonry surmounted by a brick wall. Pisistratid Wall at Eleusis, ca 500 BC; (b) Lesbian Masonry retaining wall of Temple of Apollo at Delphi, ca 500 BC; (c) Polygonal Masonry. Lower Terrace Wall of Sanctuary of Apollo at Delphi; (d) Polygonal Masonry of Ramparts of Sanctuary of Apollo at Delphi. After Orlandos, figs 149, 146, 141.



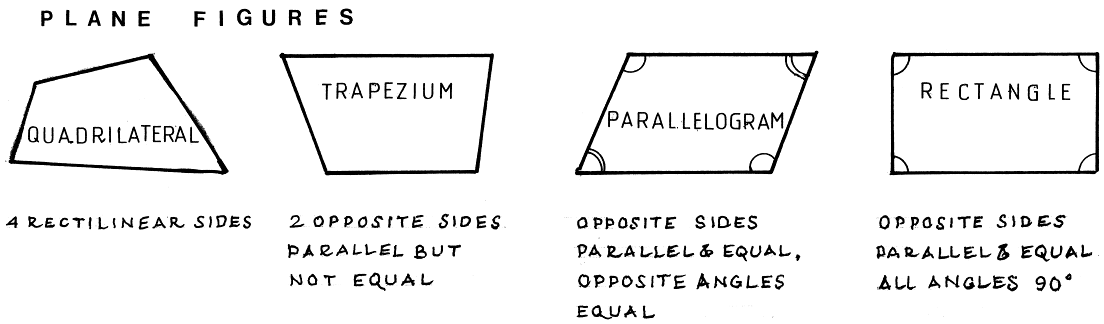
190. Eretria. Gate in City Wall. Polygonal Masonry with Saw Toothed Jointing. Greece 3rd Cent BC? This bizarre feature developed from levelling courses set on polygonal masonry but is a "*tour de force*". The device is functional in respect of fixation, but probably represents "archaising" for appearance. After Orlandos, fig 152.



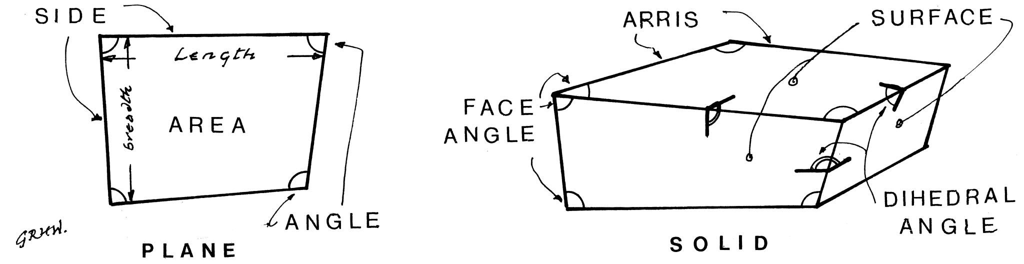
191. Delos. Hypostyle Hall. Trapezoidal Masonry. Insular Greece ca 210 BC. This masonry is regularly coursed ashlar but numbers of rising joints are cut oblique to the bed joints giving blocks of trapezoidal form (cf Egyptian Pharaonic masonry). In this connection the use of 3 distinct bevels (1, 2, 3) is manifested. After Orlandos, fig 158.



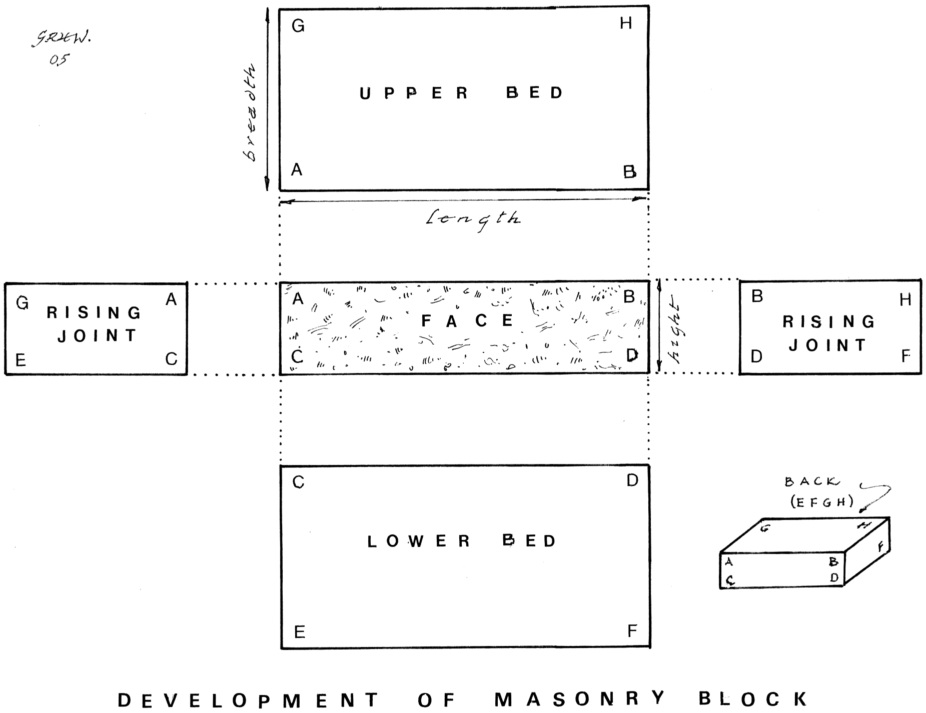
192. Egyptianising Masonry. Passages of irregular masonry with oblique and stepped bedding occur in basically regularly coursed construction. Individual blocks are trapezoidal or polygonal and the jointing indicates that the oblique rising joints were cut according to 3 different bevels (1, 2, 3). After Orlandos, fig 135 (cf Durm B d G, fig 36).



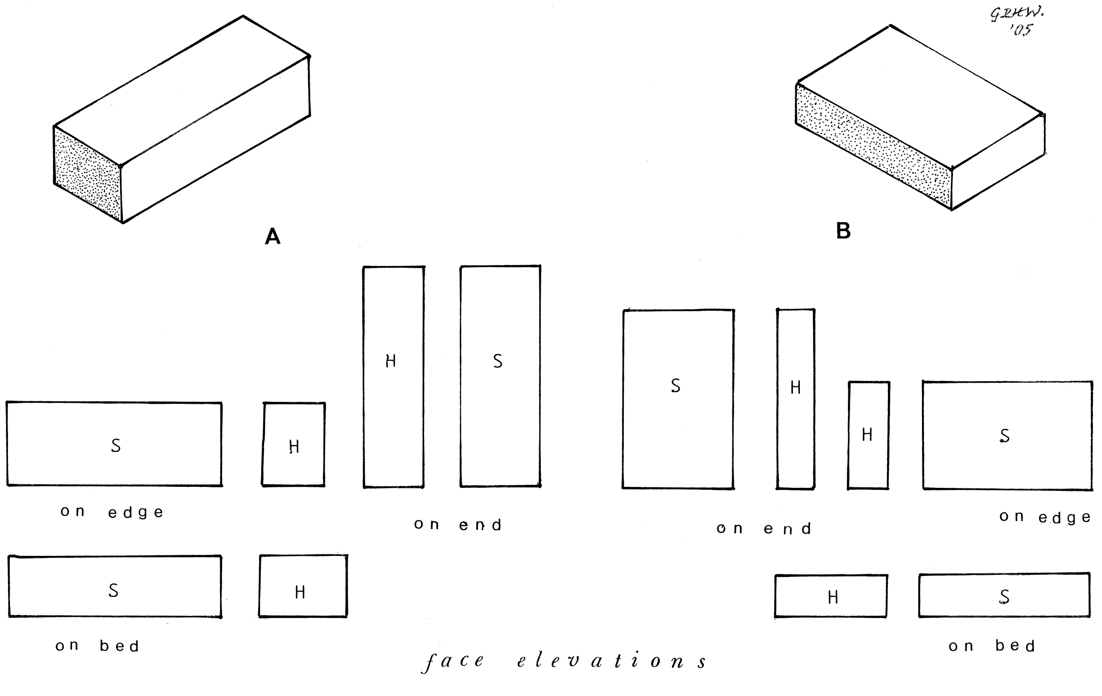
193. The Geometry of Fine Stone Dressing. Terminology of Plane Figures. Most finely dressed ancient stone masonry consists of blocks where the surfaces are plane figures with rectilinear margins. Blocks with surfaces of quadrilateral form are not normally set in courses; blocks of trapezium or parallelogram form are set regularly coursed, but the rising joints are oblique; rectangular blocks are set regularly coursed so that all the jointing is orthogonal.



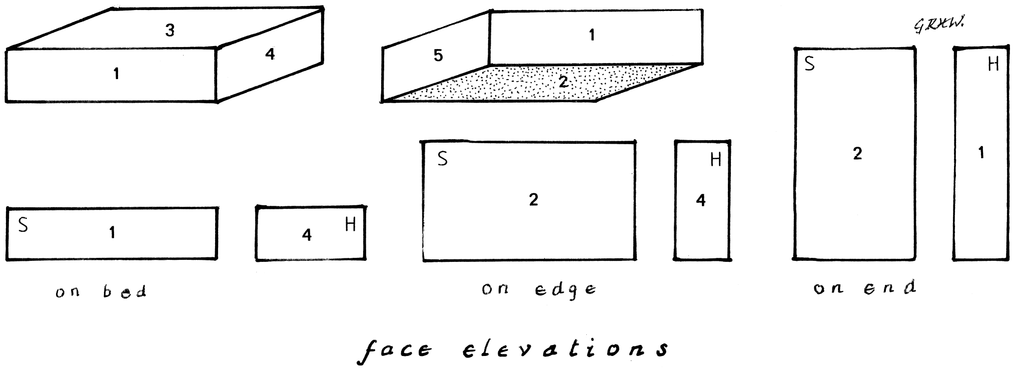
194. The Geometry of Fine Stone Dressing. Comparative Terminology of Plane and Solid Figures. A quadrilateral plane figure has 4 sides, 4 angles and a single surface. A solid figure bounded by 6 plane figures has 6 surfaces, 12 arrises, 24 face angles and 12 dihedral angles.



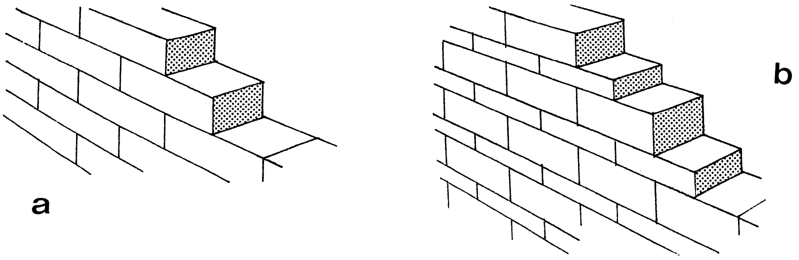
195. Terminology of the Masonry Block. A stone block bounded by 6 rectangular plane surfaces displays: one face; one back; one upper bed joint and one lower bed joint; 2 rising joints.



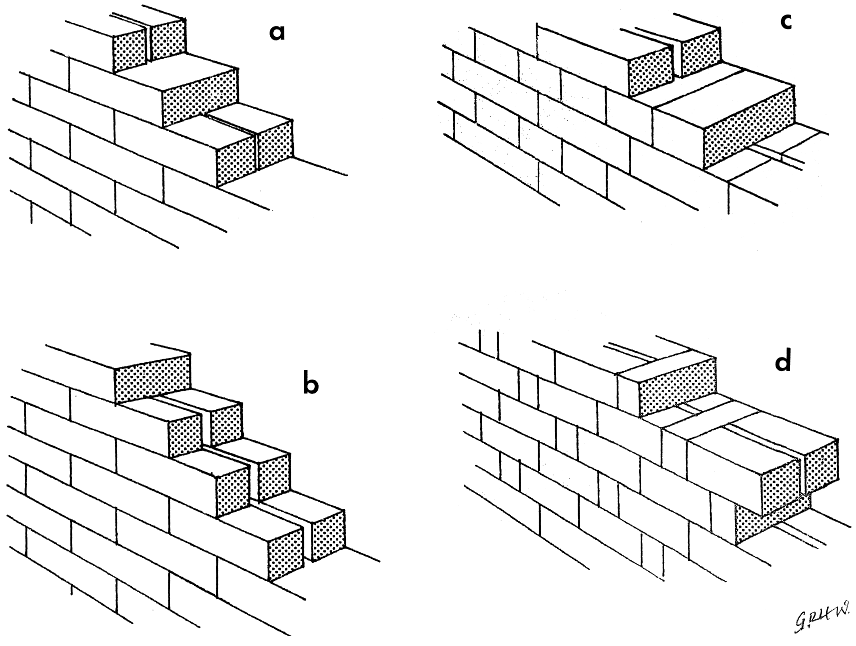
196. Setting of Masonry Blocks. Terminology. An orthogonal masonry block with 6 rectangular surfaces is termed a parallelopiped. It may be set on bed as a stretcher (S) or a header (H); on edge (i.e. on its face) as a stretcher (S) or header (H); on end (on a rising joint) as stretcher (S) or header (H).



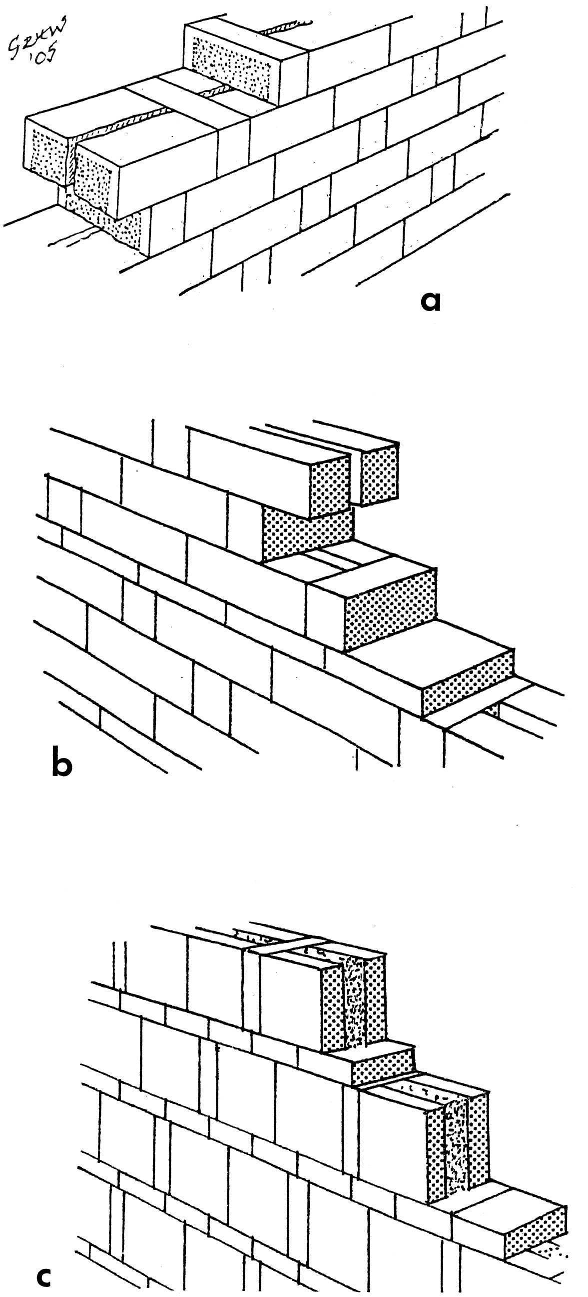
197. Setting of Masonry Blocks. Terminology (*bis*). As stretcher (S); as header (H).



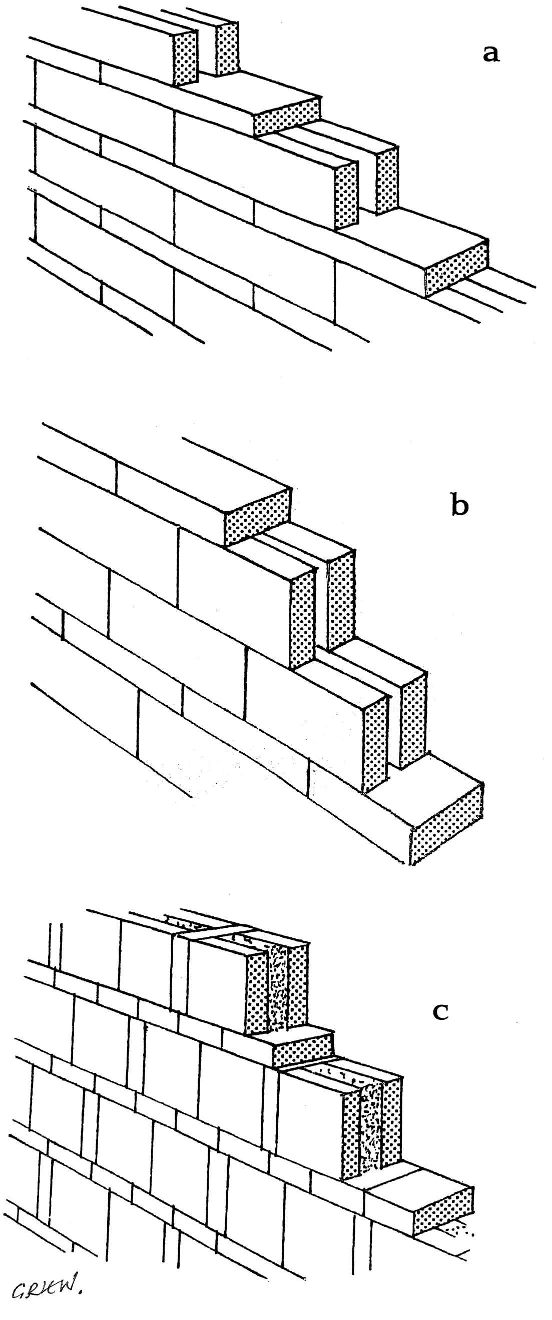
198. Typical Greek Ashlar Masonry Walling of Single Block Thickness. (a) Isodomic. Stretcher bond of standard rectangular blocks set on beds; (b) Pseudo-Isodomic. Alternating courses of standard rectangular blocks set on beds and slabs set on beds to give courses of two different heights.



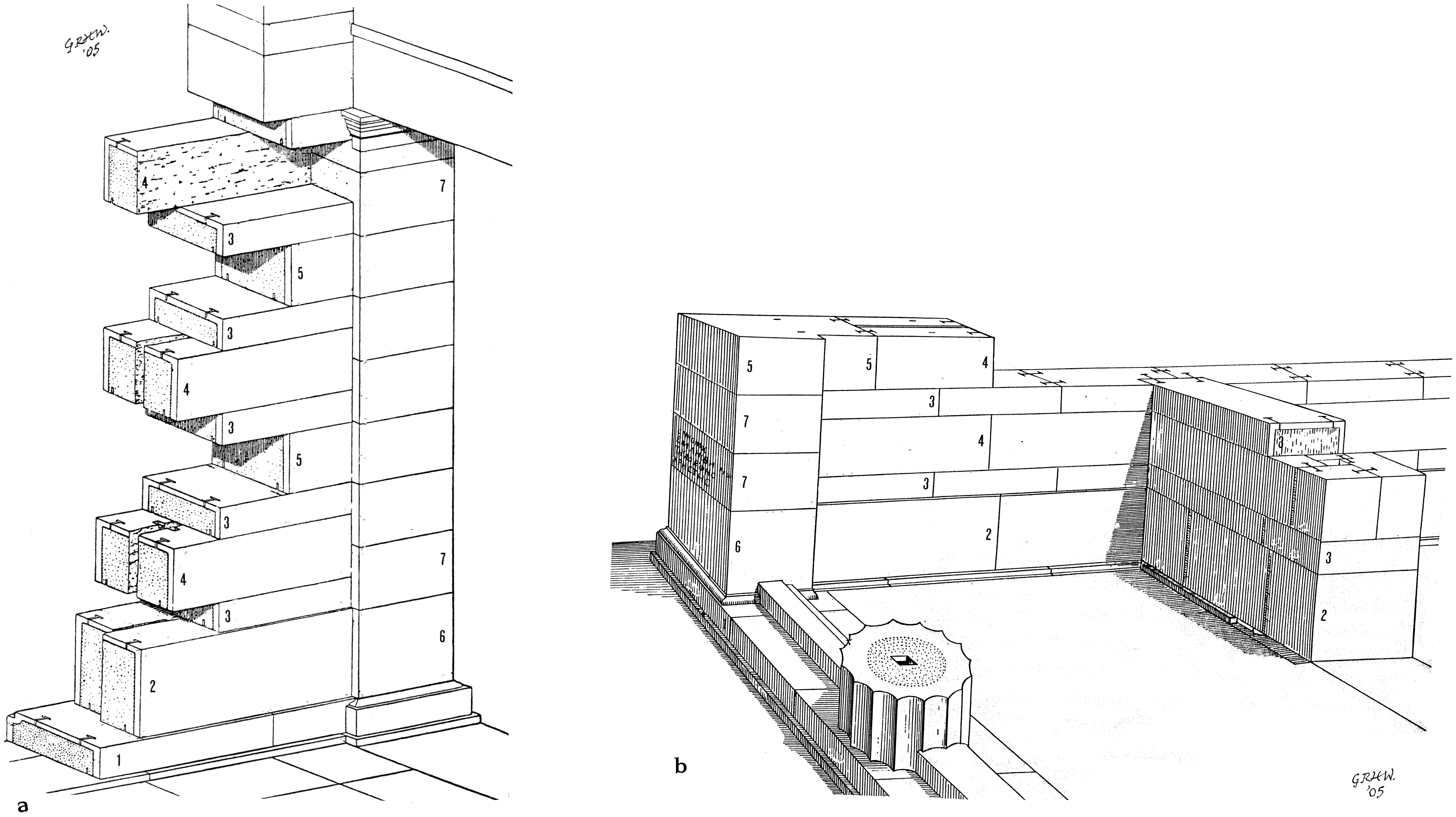
199. Typical Greek Ashlar Masonry Walling of two block thickness. (a) Isodomic Stretcher Bond; Courses of two blocks back to back alternating with courses of double breadth blocks; (b) Isodomic Stretcher Bond. Three successive courses of two blocks back to back alternating with one course of double breadth blocks; (c) Isodomic English Bond. Stretcher courses of two blocks back to back alternating with course of headers; (d) Isodomic Flemish Garden Wall Bond. Identical courses consisting of successive headers and stretchers (two blocks back to back) so that in a run two units of stretchers alternate with one header.



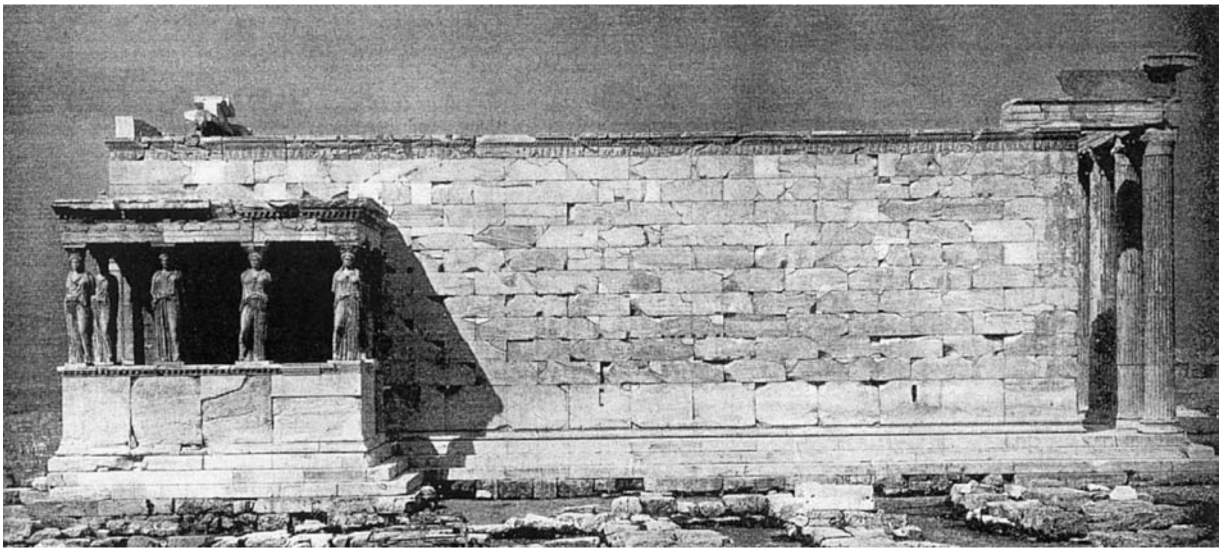
200. Typical Greek Ashlar Masonry Walling of two block thickness. (a) Isodomic Flemish Garden Wall Bond as 199 (d); (b) Pseudo Isodomic Flemish Garden Wall bond with a course of slab binders every 4th course; (c) Pseudo Isodomic Flemish Garden Wall Bond. Entirely slab construction with courses of recumbent slab binders alternating with courses of upright slabs set in Flemish Garden Wall bond i.e. a run of two stretcher units to a header – the stretcher units consisting of two upright slabs back to back with a rubble filled core.



201. Greek Pseudo Isodomic Ashlar Masonry Walling of two block thickness. (a) Stretcher courses of two blocks set back to back with a medial cavity alternate with courses of recumbent slabs; (b) Similar to (a) but with two courses upright stretcher slabs with a medial cavity to one course of recumbent through slabs; (c) Upright slabs set in Flemish Bond Garden Wall Style alternating with recumbent slabs.

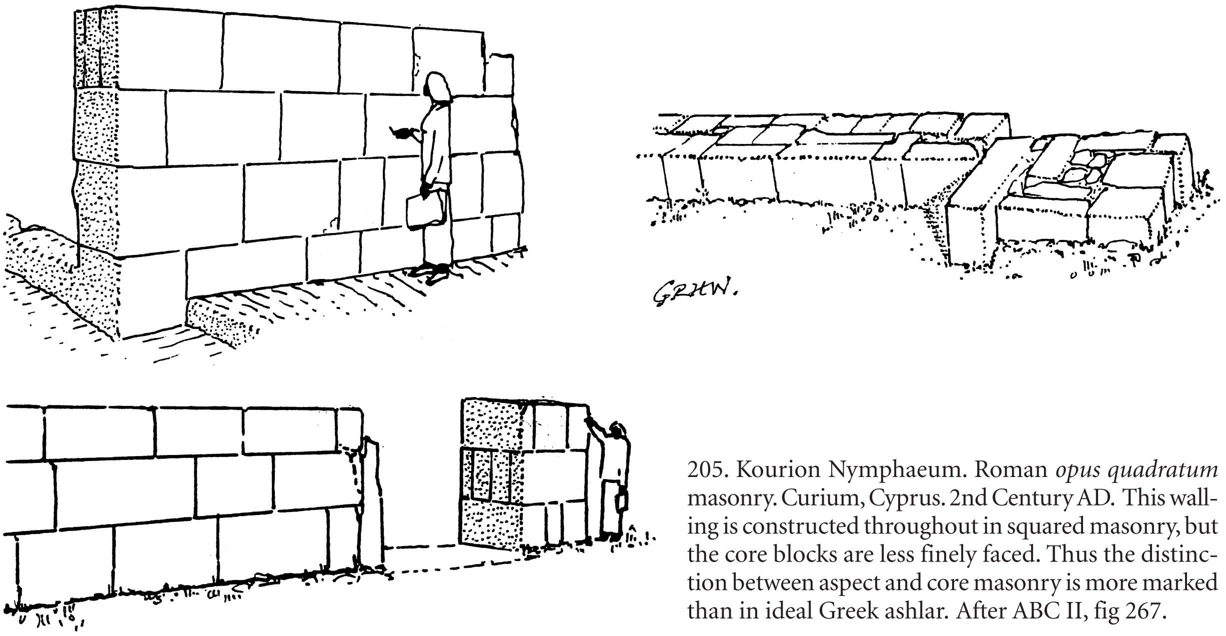


202. Sounion Temple of Poseidon. Varied Ordonance of Classical Ashlar Masonry Walling. Attica. 5th Century BC. a. Oblique view of Anta; b. Oblique view of Front Angle of Temple. Broadly speaking two types of block are employed in these passages of masonry – a normal rectangular block and a flat tabular slab. The block is set on edge as a stretcher and the slab is used both set on bed (as a plinth course or a bonding course) and also on edge as a pseudo orthostate course. *Key* (a) Oblique View of Anta in elevation; (b) Oblique View of Front Angle of Temple; 1. Large Slab set on bed as plinth; 2. Slab on edge as pseudo orthostate; 3. Slab on bed as bonding course; 4. Stretcher block set on edge. 5. Stone bonding with anta; 6. Anta orthostate; 7. Anta block. In principle the blocks are 60 cms high to give one course height and the slabs are 30 cms thick to give the other course height. The pseudo orthostate slabs as set on edge are ca 84 cms high. After Orlandos, fig 166. Martin, fig 177.



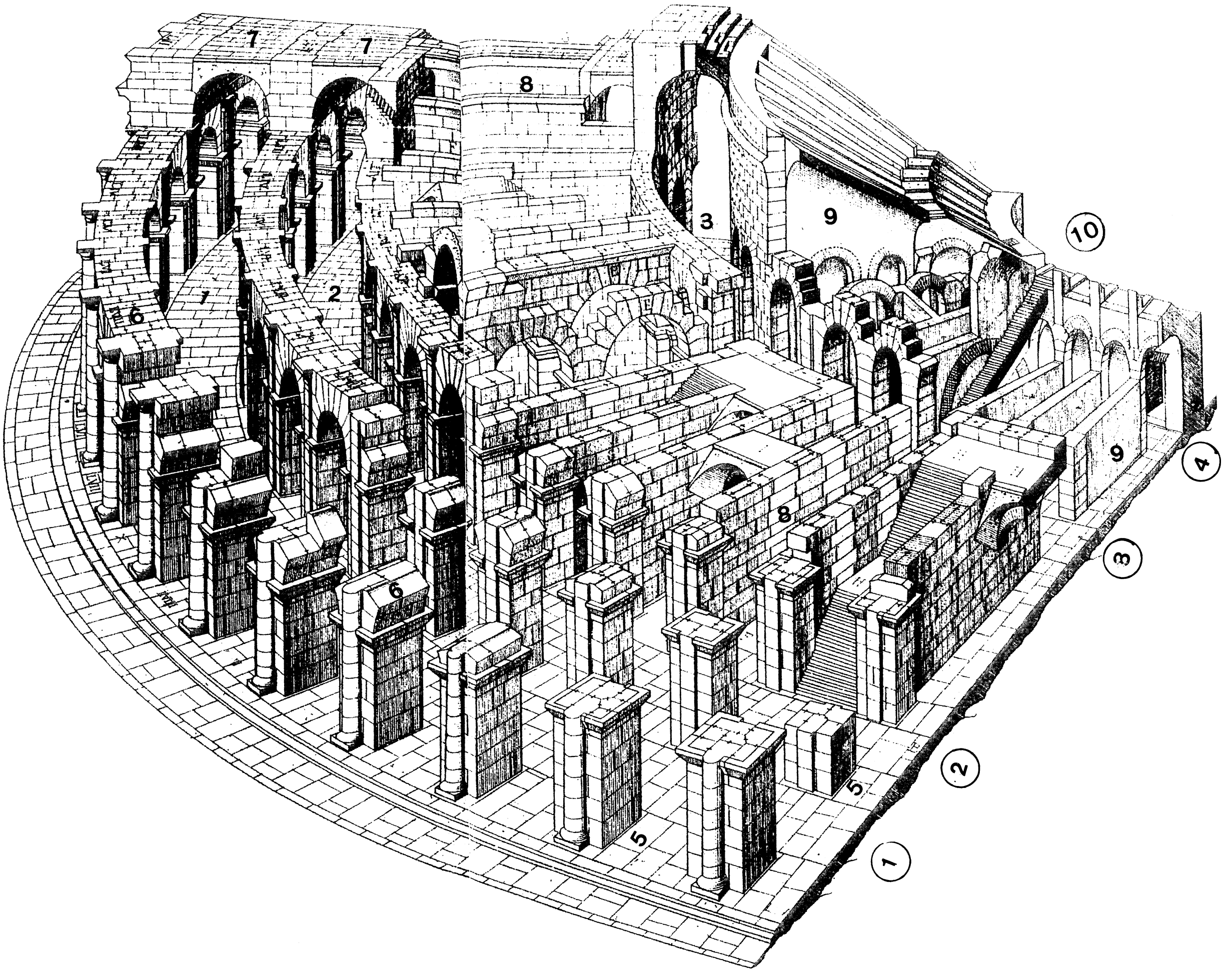
203. Athens Erechtheion. Masonry of South Wall with Caryatid Porch. Attica. Late 5th Century BC. Classical Greek hairline jointed dry stone ashlar-masonry with upstanding orthostates showing typical elongated wall blocks.

204. Sufetula. Temples of Capitoline Triad. Typical Roman *opus quadratum* masonry. Sbeitla, Southern Tunisia. 2nd Century AD. It is a characteristic of the aspect of Roman ashlar masonry (*opus quadratum*) that the blocks are of compact, squarish form rather than the elongated format of Greek ashlar blocks.

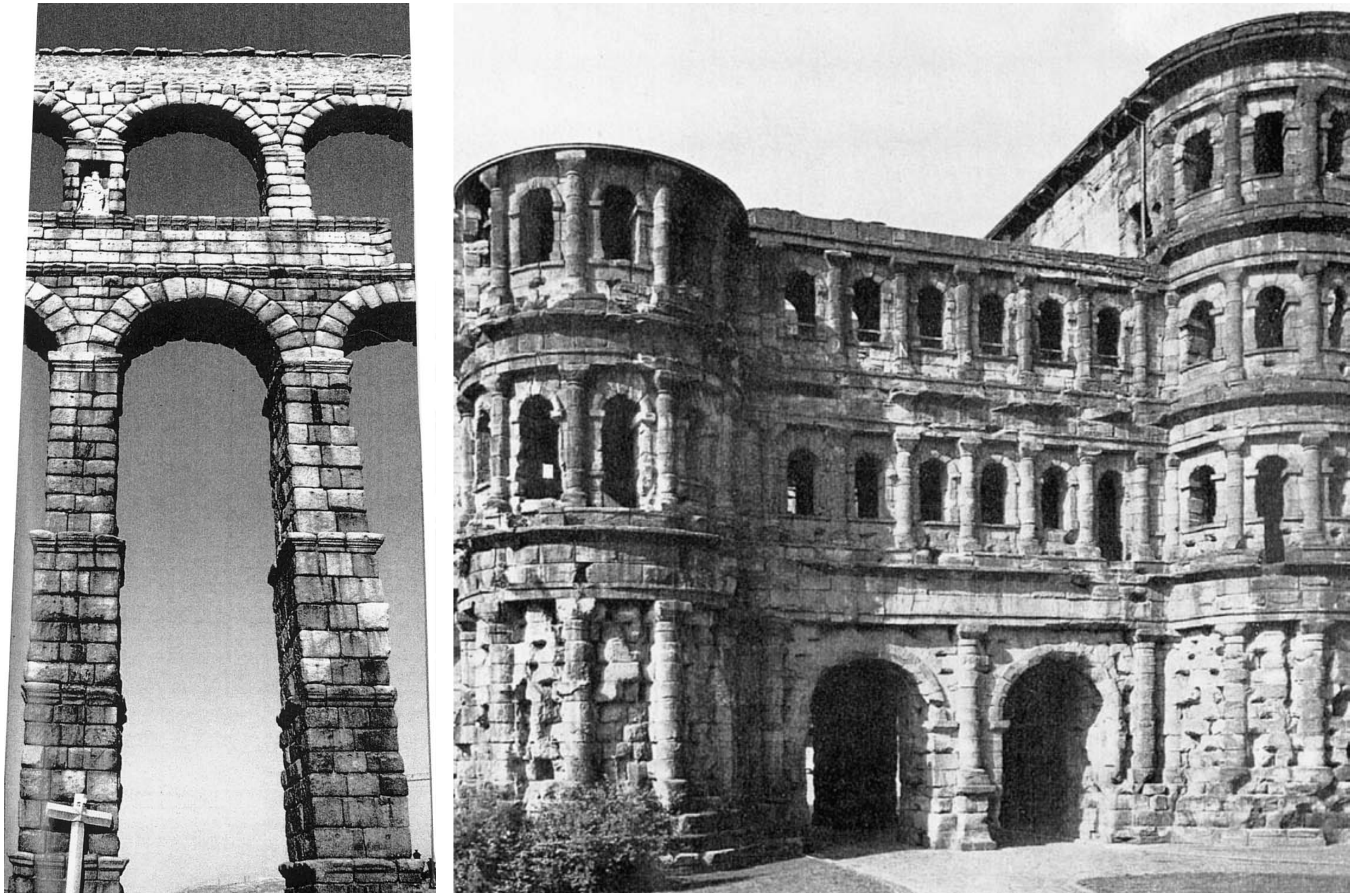


205. Kourion Nymphaeum. Roman *opus quadratum* masonry. Curium, Cyprus. 2nd Century AD. This walling is constructed throughout in squared masonry, but the core blocks are less finely faced. Thus the distinction between aspect and core masonry is more marked than in ideal Greek ashlar. After ABC II, fig 267.

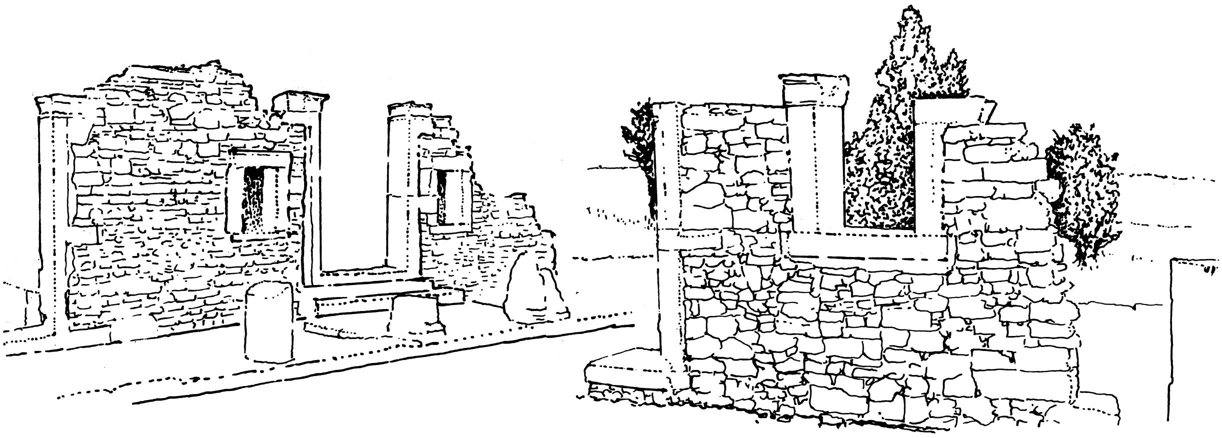
206. Nîmes. The Amphitheatre (Les Arènes). *Opus quadratum* Façade. Provence. Later 1st Century AD. The masonry is entirely of large ashlar blocks set dry stone.



207. Rome. Colosseum (Flavian Amphitheatre). Italy ca 80 AD. Cutaway Perspective View showing variegated masonry substructure of cavea. Here as was not uncommon *opus quadratum* stone masonry was used in conjunction with Roman Concrete. *Key*: (1) First Ambulatory; (2) Second Ambulatory; (3) Third Ambulatory; (4) Fourth Ambulatory; (5) Ashlar Outer Piers; (6) Ashlar Arches between Piers; (7) Concrete Vaulting of Ambulatories 1 & 2; (8) Ashlar Radial Walls supporting Cavea Seating; (9) Concrete Radial Walls supporting Cavea Seating; (10) Arena. After Gaudet (Les Moniteurs des Architectes 1875 pls 11-12).

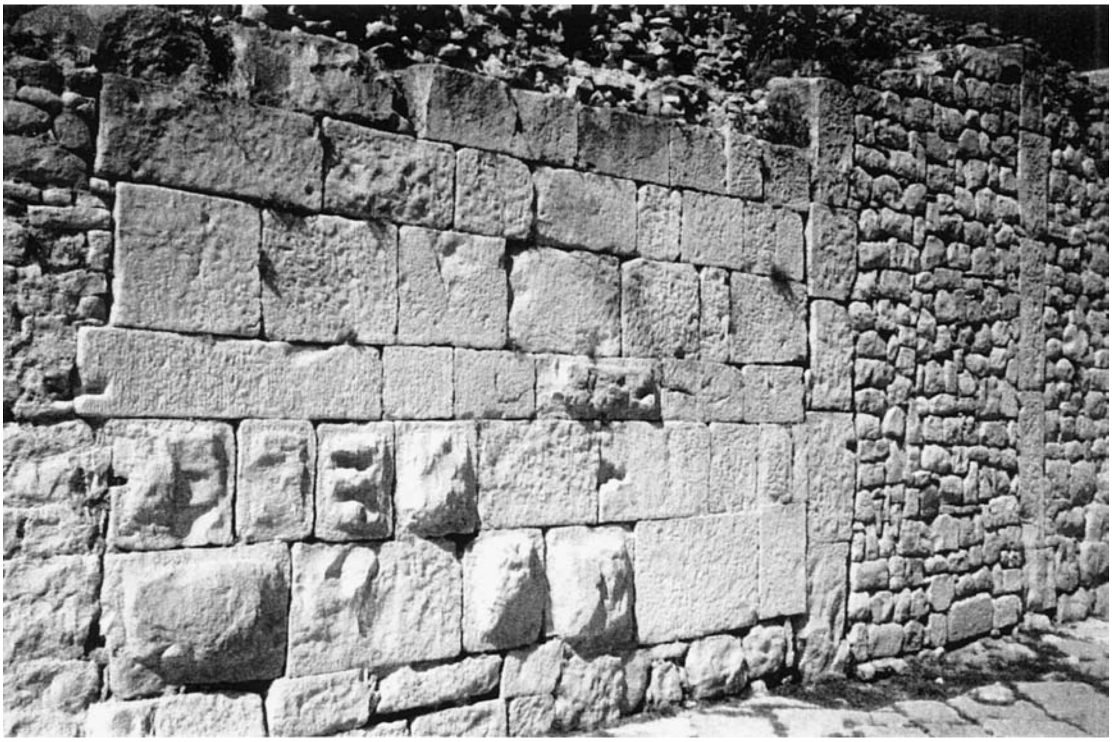


208. Roman Load Bearing Ashlar Masonry. Although solid load bearing ashlar masonry was not characteristic of Roman monumental construction as it was of Classical Greek and Hellenistic Monumental construction, it endured across the ages in Roman construction on a functional rationale. Solid, finely jointed, dry stone ashlar masonry was the strongest load bearing construction available in antiquity. In this way it remained in use for 'engineering' projects which required the utmost structural stability. These included equally civil engineering (*left*) and military engineering (*right*) projects. *Key*: (*left*) The Aqueduct of Segovia, Spain ca 100 AD. The slender, towering (30m high) piers are required to afford the utmost stability and strength in compression possible. This is produced by finely jointed dry stone ashlar masonry of large granite blocks; (*right*) Trier. The Porta Nigra City Gate. Rhineland, ca 300 AD. A tall city gate is the focus for hostile assault and battery, thus great strength and stability is demanded of its construction – here of large block finely jointed ashlar masonry.

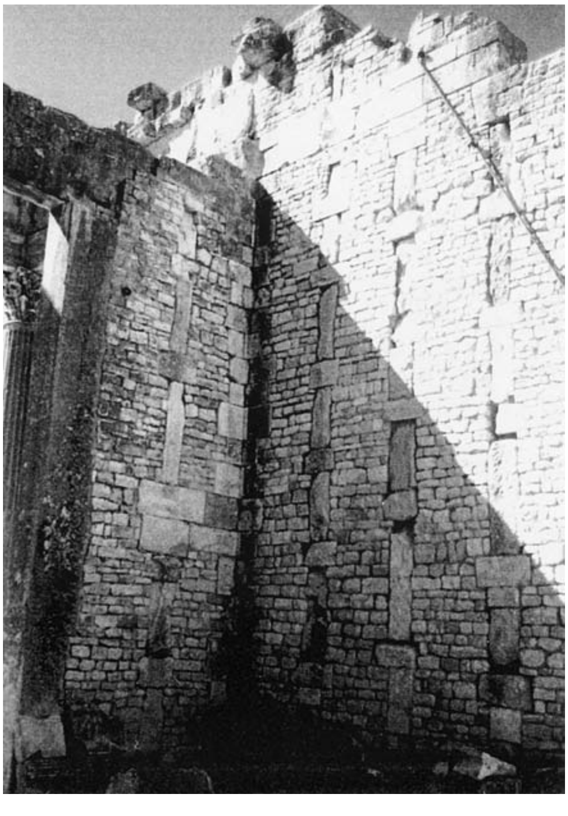


209. Kourion. Sanctuary of Apollo Hylates. Mixed Ashlar and Rubble Masonry. Cyprus. 1st Century AD. As opposed to Greek practice which was loathe to contaminate the perfection of ashlar by inferior association, Roman construction often employed ashlar elements to stiffen rubble walls in various fashions. One system (as shown here) was to stiffen rubble walls by ashlar coigning and framing to doors, windows. This very functional device recurred in numbers of contexts across the ages. After ABC II, fig 270.

210. Bulla Regia. Temple of Isis. Mixed Ashlar and Rubble Construction. Tunisia, Roman ca 200 AD. Masonry of coursed rubble stiffened by ashlar coigning and framing. This is a more solid and substantial expression of the mode than the previous example.

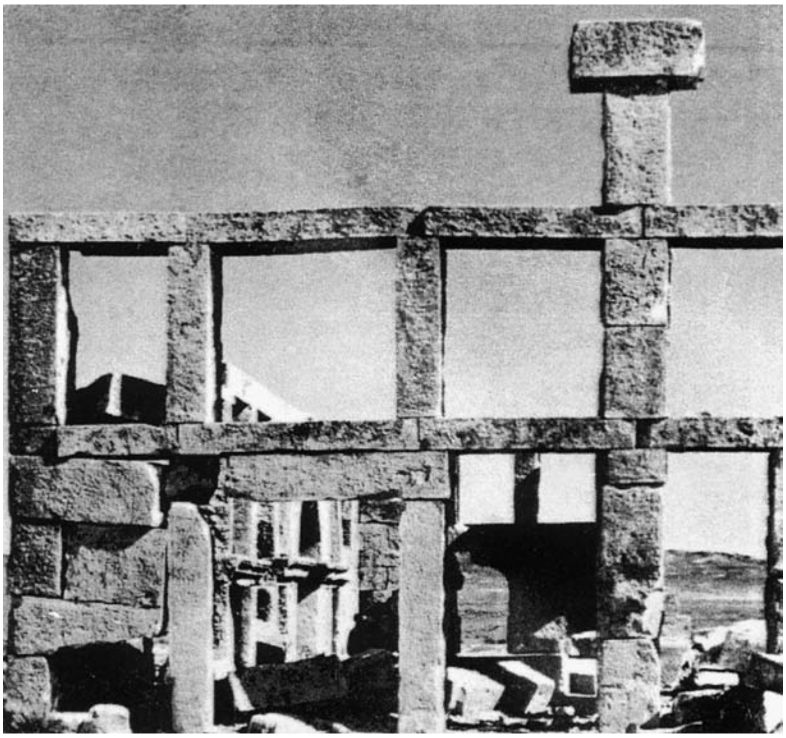


211. Ain Doura Baths. Mixed Ashlar and Rubble Masonry *(opus africanum)*. Tunisia, Roman. *Opus Africanum*, rubble stiffened by pillars of dressed stone was the masonry heritage of Punic North Africa from original Phoenecian antecedents. It survived in the North African provinces throughout Roman rule and into Byzantine times. Not infrequently it was used together with *opus quadratum.*

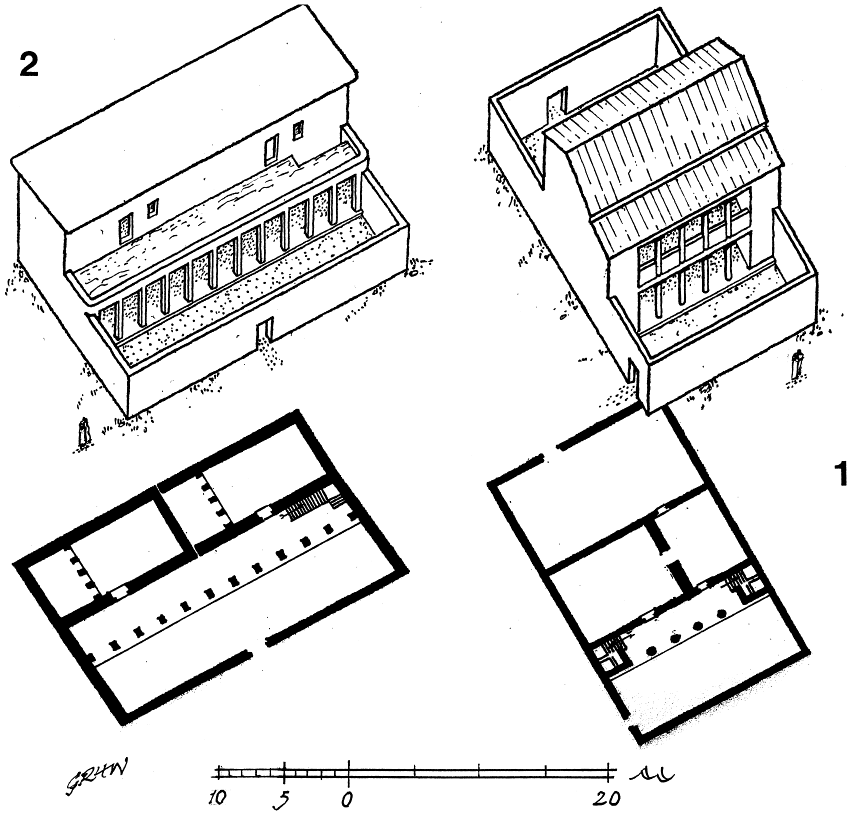


212. Thougga Capitoleum. *Opus Africanum* construction preserved to a considerable height. Dugga Tunisia. Roman, 166 AD. Since *opus africanum* construction is generally preserved only to a limited height, it remains an open question whether it functioned simply as reinforcement to wall masonry or whether it was carried up into a fully framed load bearing construction in itself. Here the latter case is suggested.

213. Cuicul. Market of Cosinius. *Opus Africanum*. Fully Framed Construction. Jemila, Algeria, ca 150 AD. This type of masonry appears the logical fulfilment of *opus africanum* and bestrides it and stone baulk framed construction familiar from Les Villes Mortes of Northern Syria. After Ward Perkins. Pl 241.

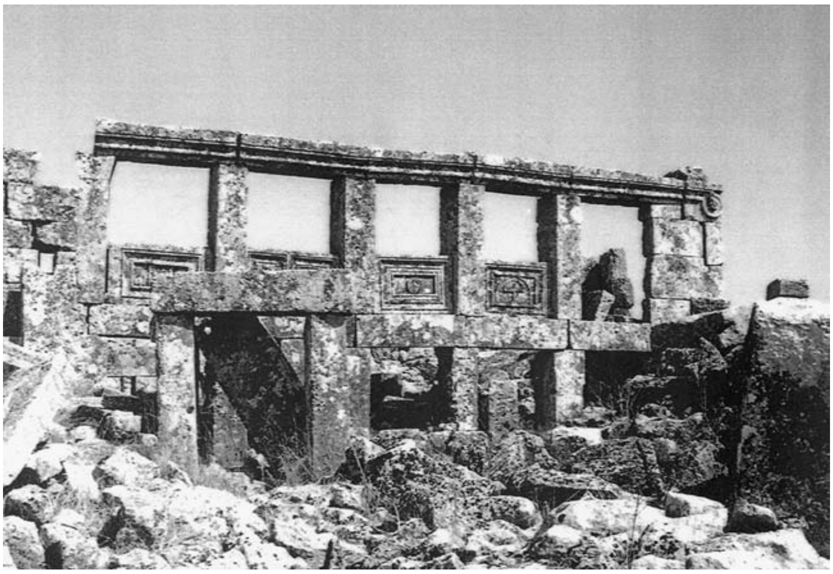


214. Brisganum. Ashlar baulk, stone framed Construction. Near Tebessa, Algeria, 2nd–3rd Century AD. The mode in this region clearly derives from *opus africanum* and is a fore-runner of stone framed construction of Late Antiquity. After Ginouves I, pl 26.4.



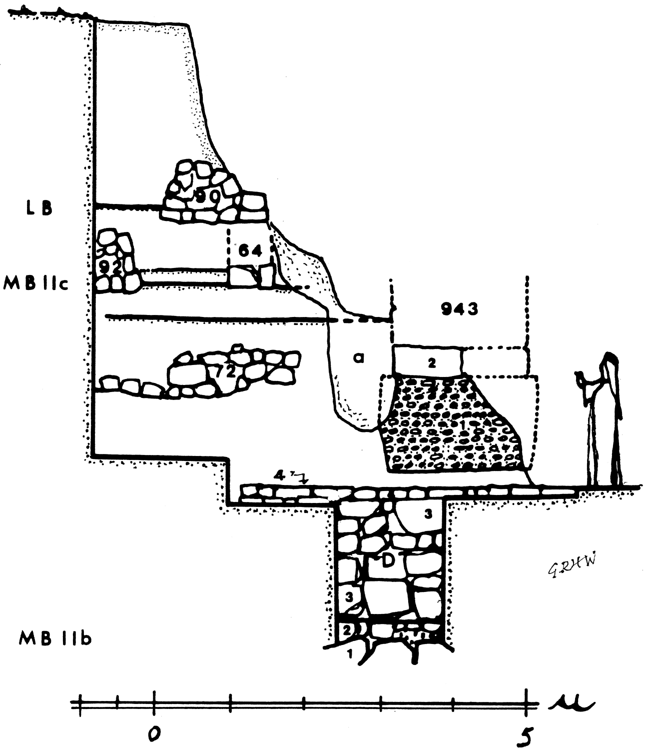
215. Syrian Portico Houses. Plans and axonometric views. The design and pillared construction is widespread in Central and Northern Syria from early Imperial times, and gives onto the striking framed masonry construction in the region during later antiquity. *Key*: 1. House at Banaqfur, 1st Century AD; 2. House at Taqle, 4th Century AD. After Ward Perkins. Fig 161.

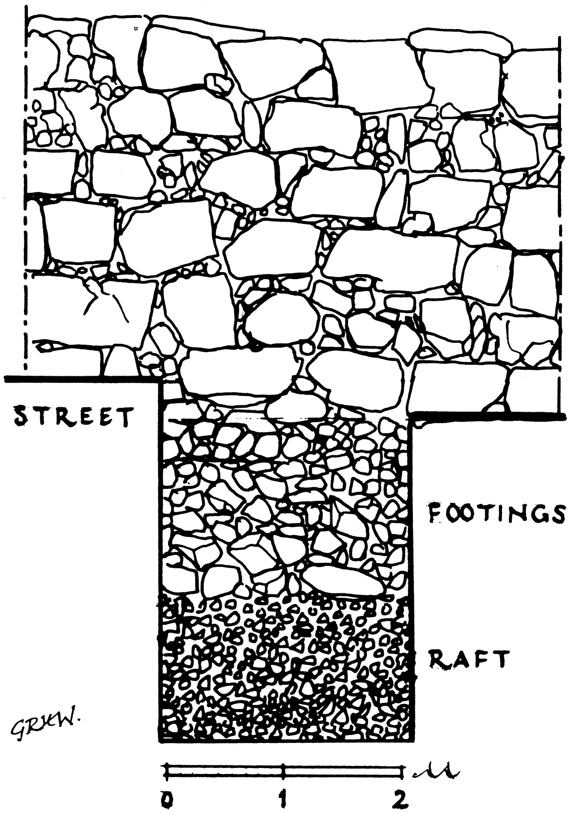
216. Dehès. Ashlar Stone Framed Wall Construction. North Syria. ca 500 AD. After 1500 years the massive blocks of the frame (ca 2m in length and of I ton burden) remain standing *in situ* on their rocky outcrop foundations, while the panelling of the ashlar blocks and slabs has collapsed and/or been robbed out. The surviving disposition of some buildings gave investigators the impression that these constructions were originally open porticos with at most a low balustrade between the piers. However, from examples like this, it is visually evident that the construction is the surviving skeleton of a stone framed wall – which is demonstrated by the traces remaining on the stone framing of the engagement of the panelling. Photo J-L Biscop.



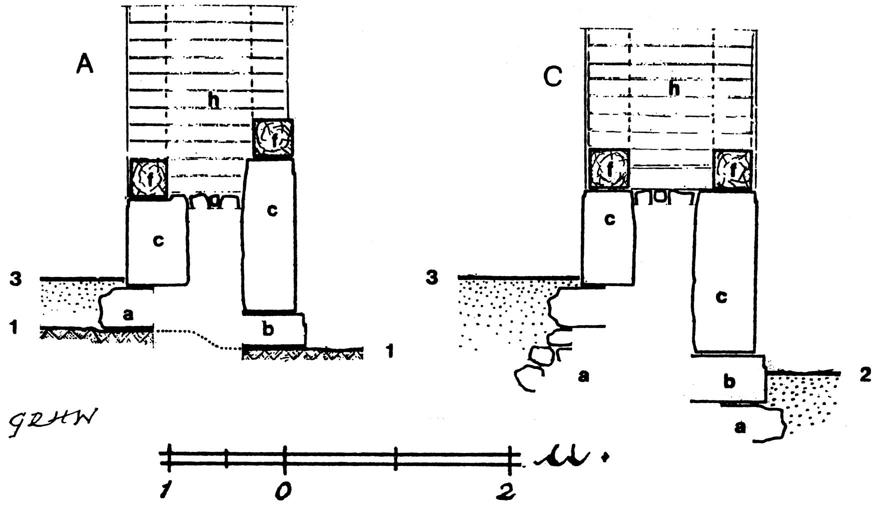
217. Dehès. Stone Framing Wall with closure slabs *in situ*. North Syria. ca 500 AD. On occasion the bays between the piers were not fully masoned up but the lower part only was enclosed by a balustrade in the form of a "closure slab" with characteristic decoration (cf the common use of such a member on the chancel screens of early Byzantine churches). Photo J-L Biscop

218. Shechem. Varied Stone Foundations. Tell Balatah, Central Palestine. ca 1800 BC – 1400 BC. Diagramatic Section showing differing foundations for walls of varied nature and function. This section is cut through the stratigraphic deposits of a "tell" (= a ruin heap). The natural foundations for the successive building periods are thus "made up ground" – in modern assessment the weakest type of natural foundations for buildings, and allowed in general no bearing strength at all. This section exposes three different classes of walls: common house walls (90, 92, 64, 72); an area enclosure wall (943); a city wall (D). In spite of the weakness in bearing capacity of the accumulated debris, the builders had no concern for the support of common house walls, since the loads of these mud brick structures were negligible. The stone footings for these walls were set only marginally below the earliest floor levels, and do not spread significantly beyond the wall faces in cross section. Their function is designed not in the structural interest, but as a provision against rising damp (i.e. a DPC) and for resistance to mechanical damage accruing at ground level. On the other hand the area (= acropolis) enclosure wall 943 (seen in section) has well constructed structural foundations which have been partly cut through by previous excavations (v trench a) and have partially collapsed due to exposure. The heavy coursed squared stone masonry of the wall (2) is founded on successive beds of cobbles, which stiffen layers of marl to form a raft of rigid conglomerate (1) packed into a trench 1.5m deep. The early City Wall (D) seen in elevation is founded with the concern demanded by military engineering. The foundations are of very heavy boulders closely interlocked (1), above which is a euthynteria (2) for the squared rubble socle of the wall (3). This is capped by a levelling course of smaller stones (4) on which stood the mud brick superstructure of the wall. The load of this massive wall nearly 3m broad is considerable but the foundations are designed equally in the military interest – i.e. to foil sapping etc. After ABSP II, fig 291.

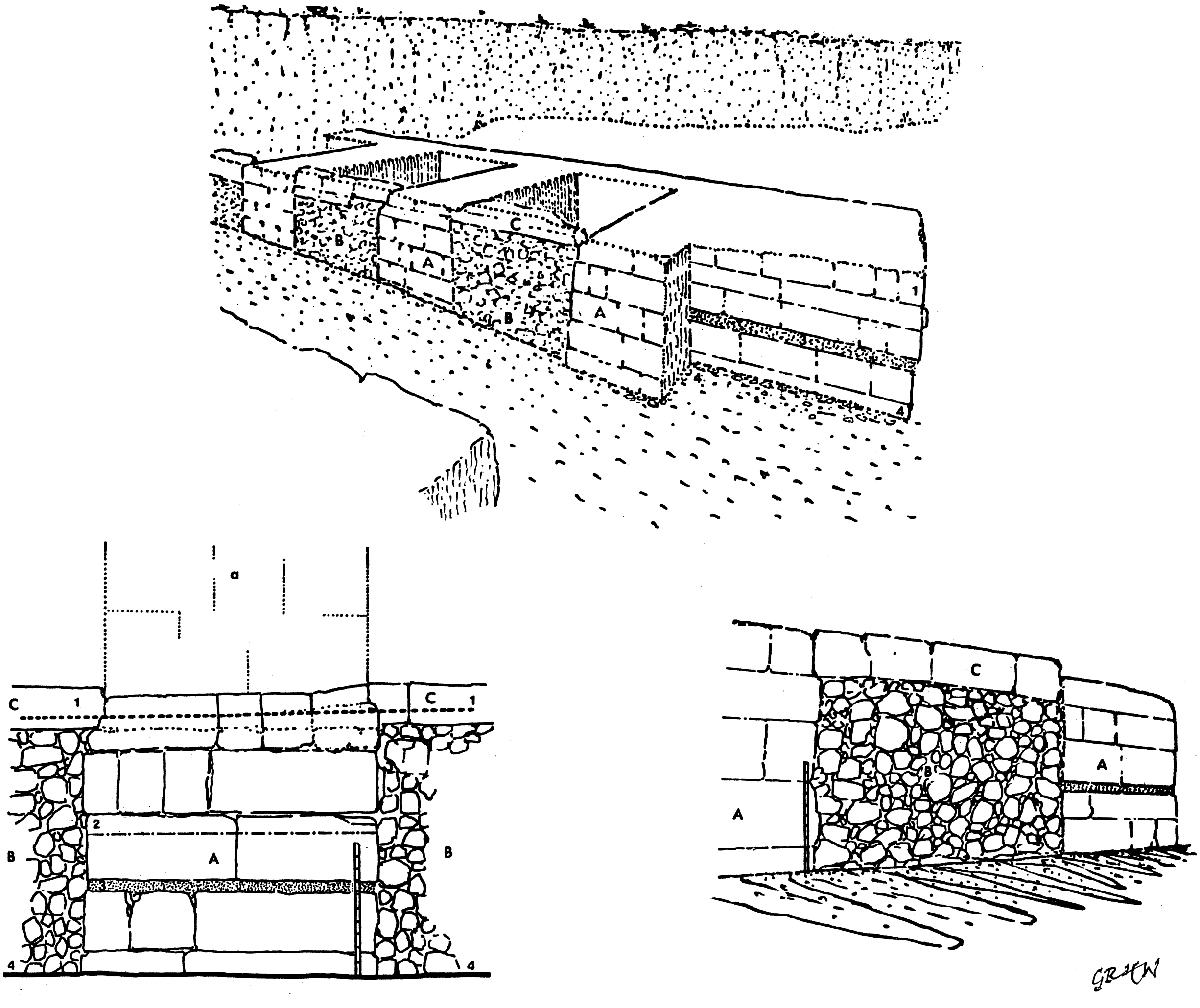




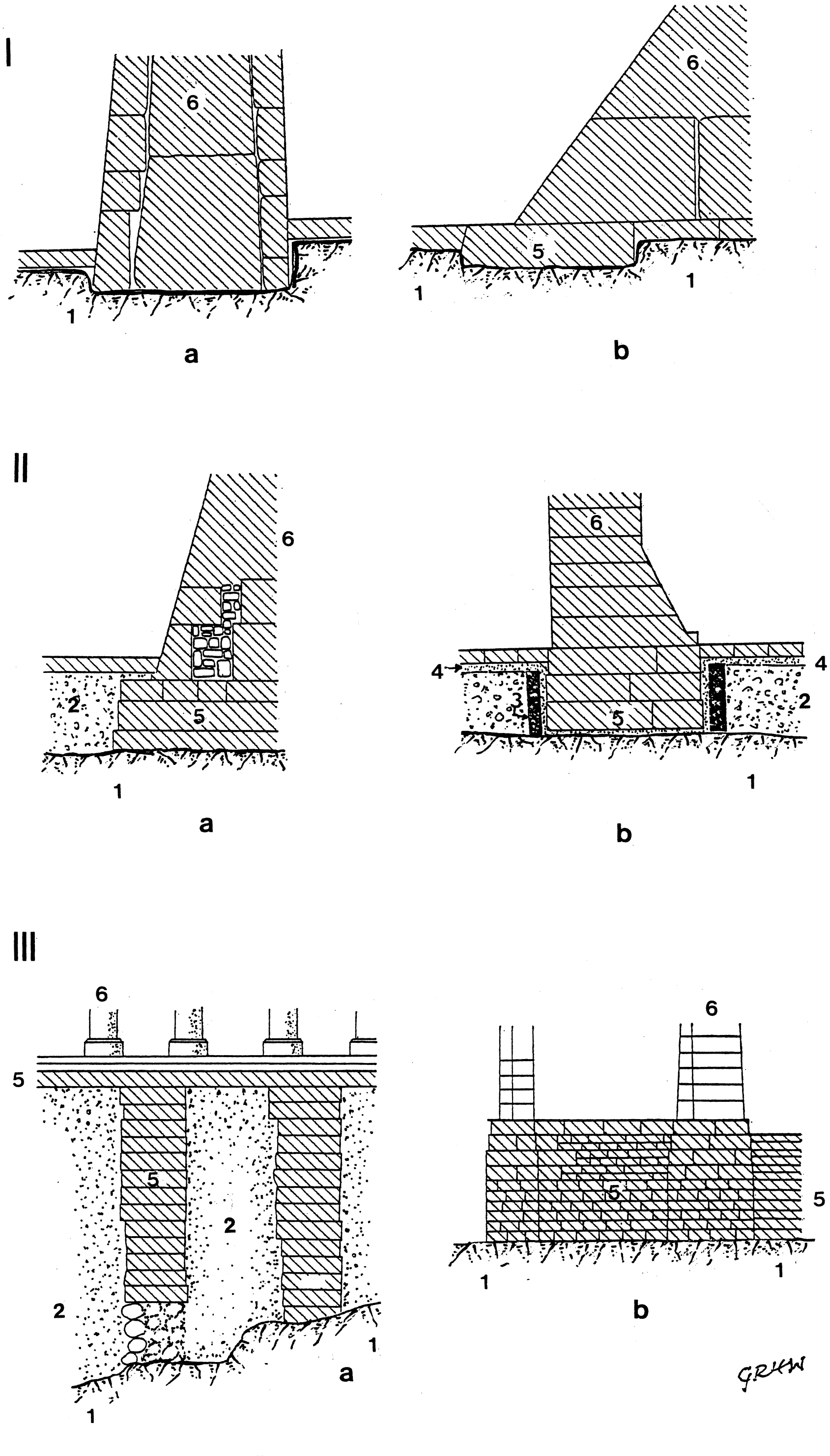
219. Shechem. Enclosure Wall of the Upper City (Acropolis) and its foundations. Tell Balatah, Central Palestine, ca 1800 BC. The massive 2m broad wall is built of coursed roughly squared boulders chinked with smaller stones. The foundations consisted of closely set angular stones nearly 2m deep set above a 'raft' of compacted small aggregate. In addition to other virtues this raft ensured that the masonry was well drained. After ABSP II, fig 290.



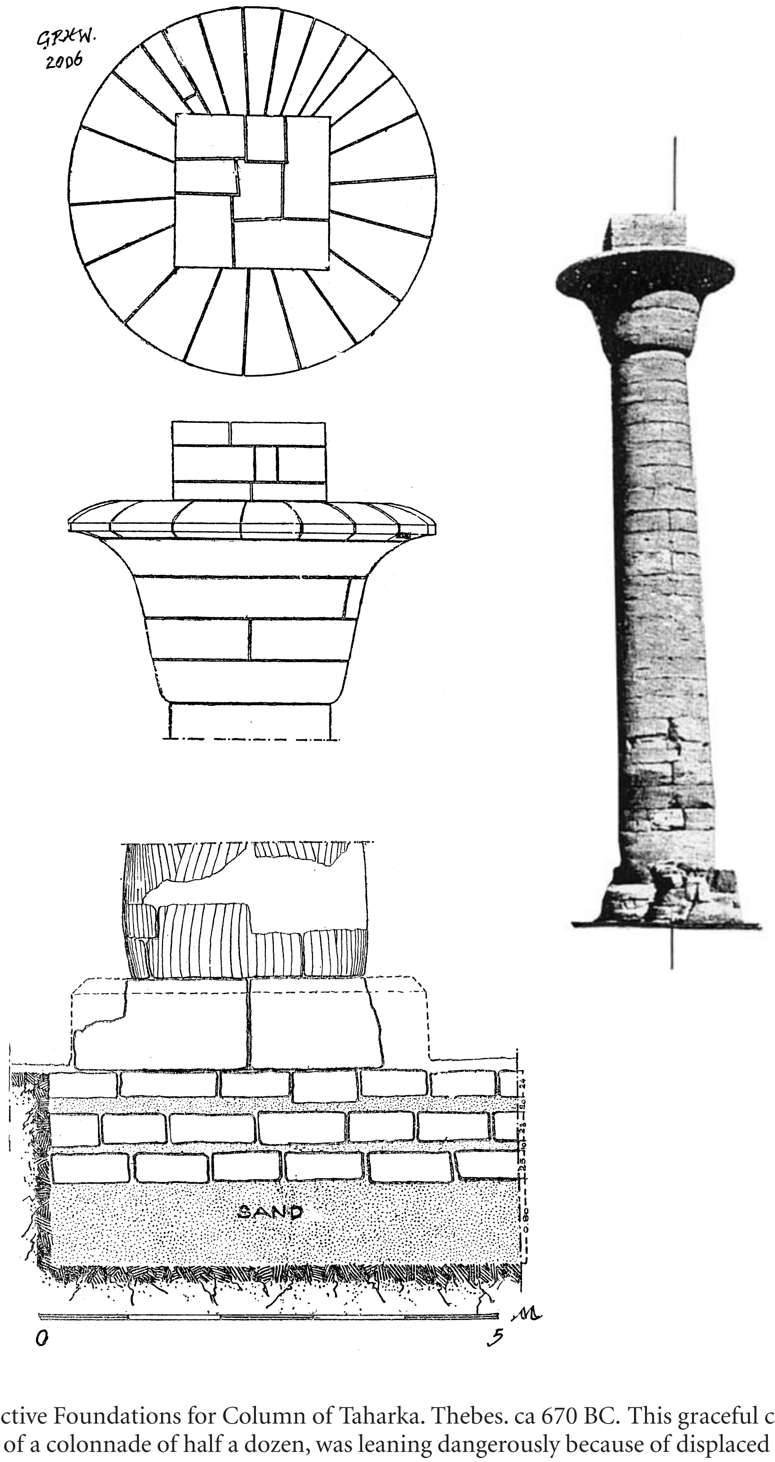
220. Kition. Kathari Sanctuary Temple 1. Foundations to mud brick walls with bastard ashlar masonry substructure. Larnaka, Cyprus. 13th Century BC. *Key* : (A) Bearer Foundations on bed rock; (C) Spreader Foundations in earth; (a) rubble foundations; (b) finely dressed plinth; (c) finely dressed orthostates; (f) stringers of timber framed mud brick superstructure; (h) plastered mud brick superstructure; (1) bed rock; (2) external ground level; (3) internal flooring. NB Elements of this ordonance carry over into Classical Greek ashlar masonry. After ABC II, fig 246.



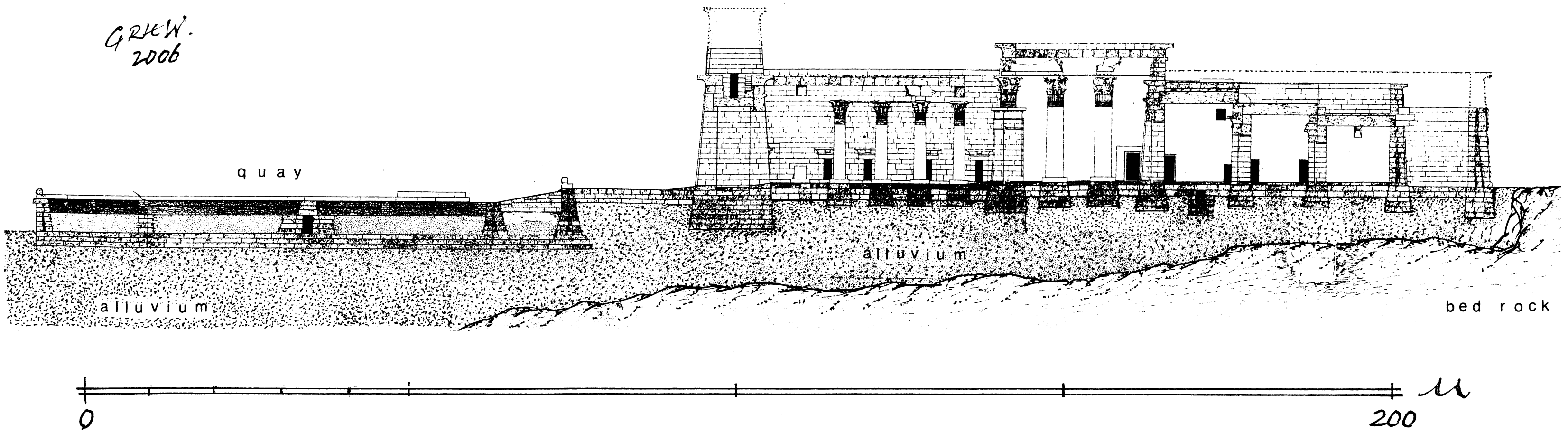
221. Megiddo. Stratum IV City Gate and its Foundations. Tell el Mutesellim, Palestine. ca 900 BC. General View of Surviving Masonry (above); and masonry details (below). There has been continued debate whether this masonry complex comprises the original foundation for an upstanding gate house now totally disappeared, or whether it is the upstanding masonry of an earlier gate house subsequently re-used as foundations for a later gate house now totally disappeared. If the latter B constitutes later blocking of original side chambers. If the former then B constitutes sleeper walls below the threshold of side chambers serving to compartmentalise the foundation fill. *Key*: (a) Upstanding masonry of side chamber wall no longer preserved. A. Subsisting ashlar masonry of walls (or foundations of walls) to side chambers; B. Rubble masonry below threshold to side chamber; C. Threshold of side chambers; 1. Pavement level of Gateway; 2. Masonry horizontal datum line; 3. Lodgement for inset wood tie beam; 4. Lime plaster surface. After ZA 74 1984, pp 279-80, fig 7.



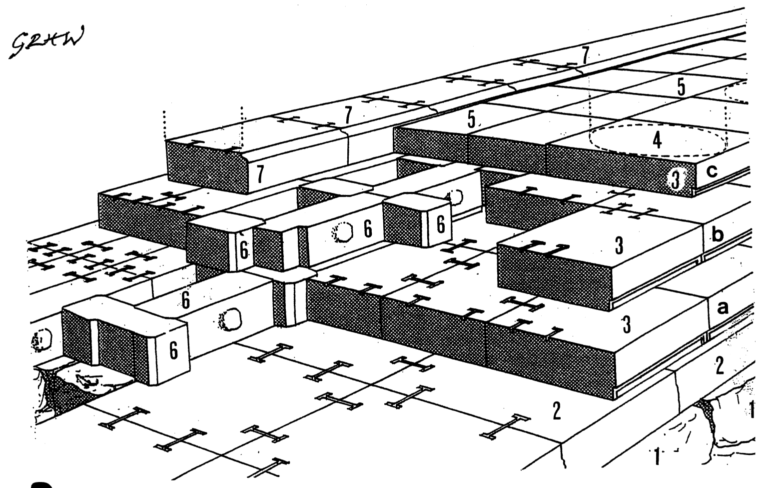
222. Conspectus of Effective Egyptian "Bearer" Foundations of Dressed Stone. *Key*: I. Old Kingdom Foundations directly set on outcropping bed rock (IVth Dynasty). (a) Khephren Pyramid Temple; (b) Kheops Great Pyramid; II. Old and Middle Kingdom Foundations carried down to bed rock; (a) Nussere Ra Sanctuary. Abu Sir 5th Dynasty; (b) Mentuhotep Temple. Deir el Bahari. XIth Dynasty; III Deep Foundations to bed rock (classical influence); (a) Philae Temple. Graeco-Roman; (b) Dakka Temple, Nubia, Roman; 1. Bed Rock; 2. Alluvium; 3. Brick barrier wall; 4. Sand bed; 5. Dressed stone foundations; 6. Upstanding masonry, walls and columns. After Arnold.



223. Karnak. Defective Foundations for Column of Taharka. Thebes. ca 670 BC. This graceful column, the last standing survivor of a colonnade of half a dozen, was leaning dangerously because of displaced foundations. It was taken down in 1927 by the Service of Antiquities and rebuilt on secure foundations. The pre-existing foundations in the alluvium were found to consist of a sand bed approaching 2m deep, which evidently ran continuously below the whole colonnade. In addition below the columns were three successive separated beds of limestone blocks set unjointed in the sand. It is difficult to see what effect these stone blocks could have (or be thought to have) on the bearing capacity of the sand. The sand bed (apart from its symbolic virtue) would have constituted a reasonable foundation if adequately retained by a surrounding barrier wall. Unfortunately no such barrier appeared to have been provided, and the sand had been infiltrated by ground water and had 'run'. After ASAE 27 1927, p. 40, fig 2.

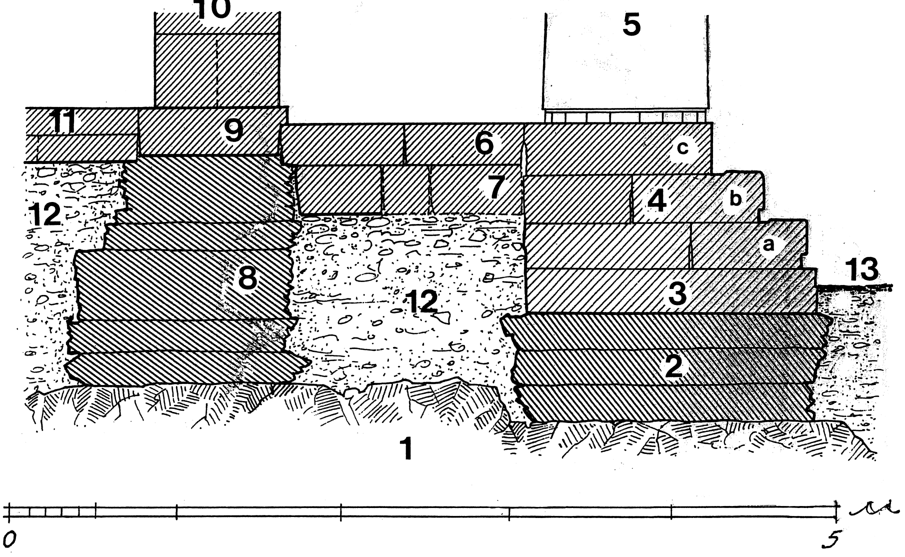


224. Kalabsha. Temple of Mandoulis by the Nile. Longitudinal Section showing Dressed Stone Foundations set down into the alluvium. Lower Nubia. 1st Century AD. This drawing was originally prepared under the direction of Barsanti during his work of consolidation at the Temple in 1911 to show the strengthening and additions he made to the original foundations because of the imminent submergence of the Temple at highwater Nile occasioned by the building of the first Aswan Dam. Whether all the additions shown were actually made is not clear. The present version of the drawing shows only the original foundations (according to Barsanti's investigations). The rear of the Temple abuts closely on the riverine cliffs of Nubian Sandstone, but no effort was made to carry the foundations uniformly down to bed rock (ca 15m below the Temple floor). However, according to Barsanti, very considerable engineering work was expended on the foundations. These consisted of ca 6 courses of large dressed stone blocks similar in nature to the upstanding wall masonry, and spreading somewhat beyond the breadth of the walls. Additionally to this the foundation of the quay rested on a continuous raft of dressed stone masonry 3 courses in depth. These works betoken the influence of Classical Greek tradition of foundation construction. After Barsanti, Les Temples Immergés.

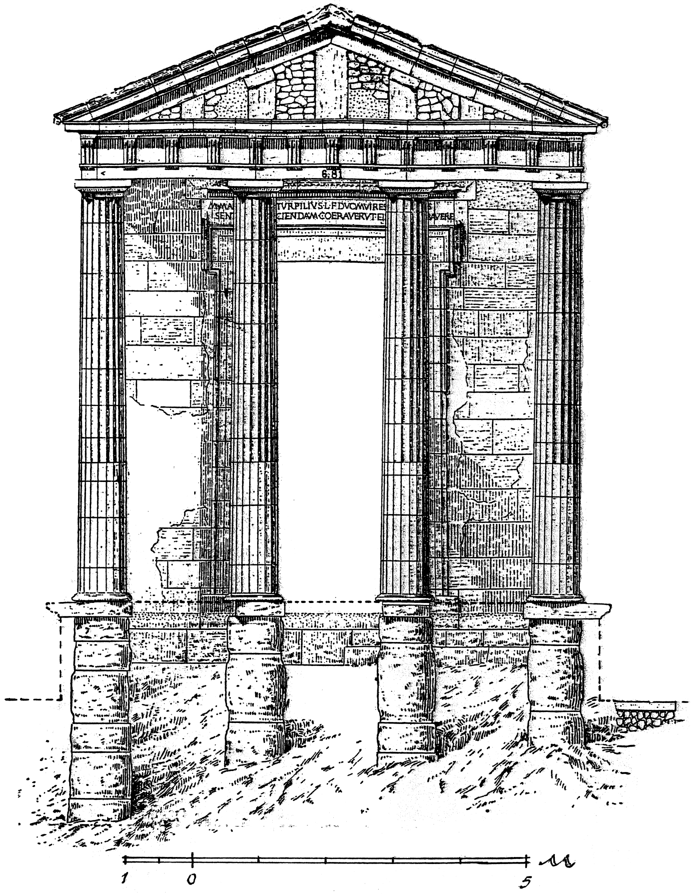


B

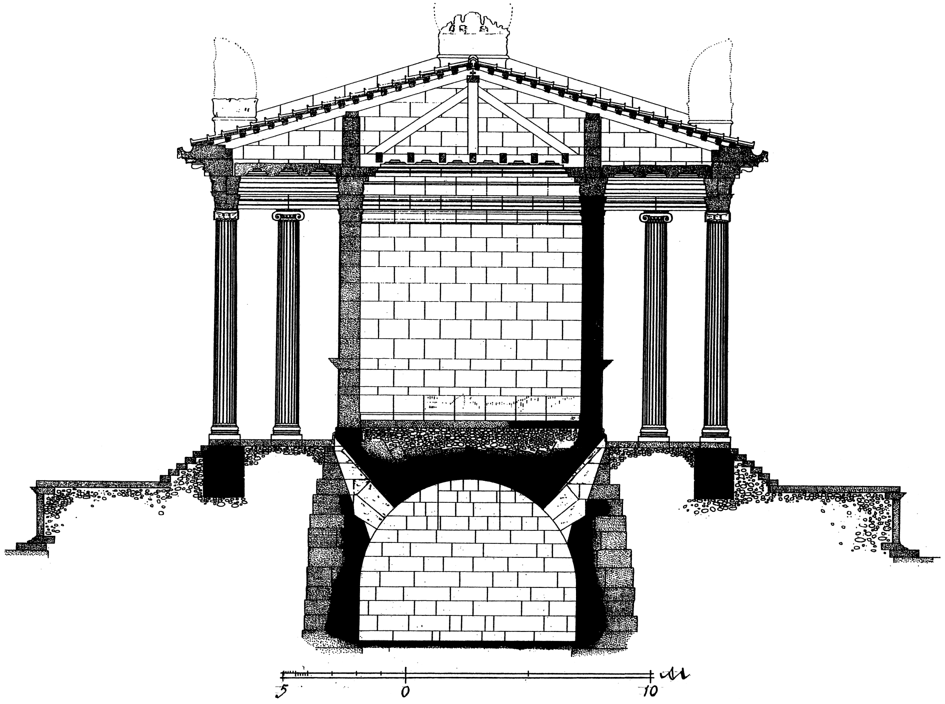
A



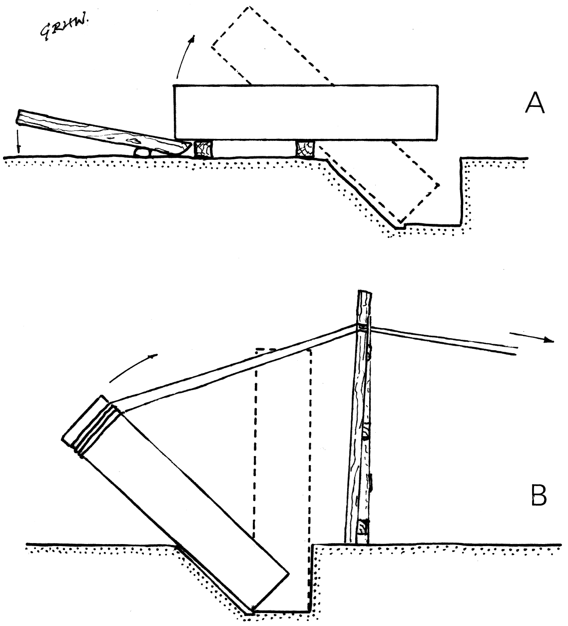
225. Conspectus of Masonry foundations of Classical Greek Temple on its Crepis. Greece, 5th Century BC. It is impossible to be meticulous in distinguishing between the crepis and the foundations of a Classical Greek Temple. The Crepis denotes the external aspect of the stepped platform on which the temple stands. However this feature does not have a homogenous internal structure. Enclosed within it are the separate masonry foundations below the load bearing elements of the temple (walls and columns), as also the masonry supports for the paving – the former descending where possible to bed rock, the latter much shallower. *Key*: A. Delos, Temple of Apollo. Section across peristyle showing columns and cella wall with paving and foundations coursed down to bed rock. 1. Bed rock dressed level to take masonry foundations; 2. Masonry foundations of crepis (and columns); 3. Levelling Course (Euthynteria); 4. (a, b, c) Crepis steps; 5. Upstanding peristyle column; 6. Peristyle paving; 7. Peristyle paving bearers; 8. Foundation masonry for cella wall; 9. Toichobate for cella wall; 10. Upstanding masonry of cella wall; 11. Paving of cella; 12. Foundation fill of earth and rubble; 13. External ground level. B. Delphi. Temple of Apollo. Perspective View of Crepis masonry extending across peristyle from columns to cella wall; 1. Foundation masonry blocks; 2. Euthynteria (levelling course); 3 (a, b, c) Crepis masonry; 4. Stylobate showing emplacement of column; 5. Peristyle paving; 6. Sleeper beams for peristyle paving; 7. Cella wall emplacement. After Ginouves II. Pls 2, 3[1].



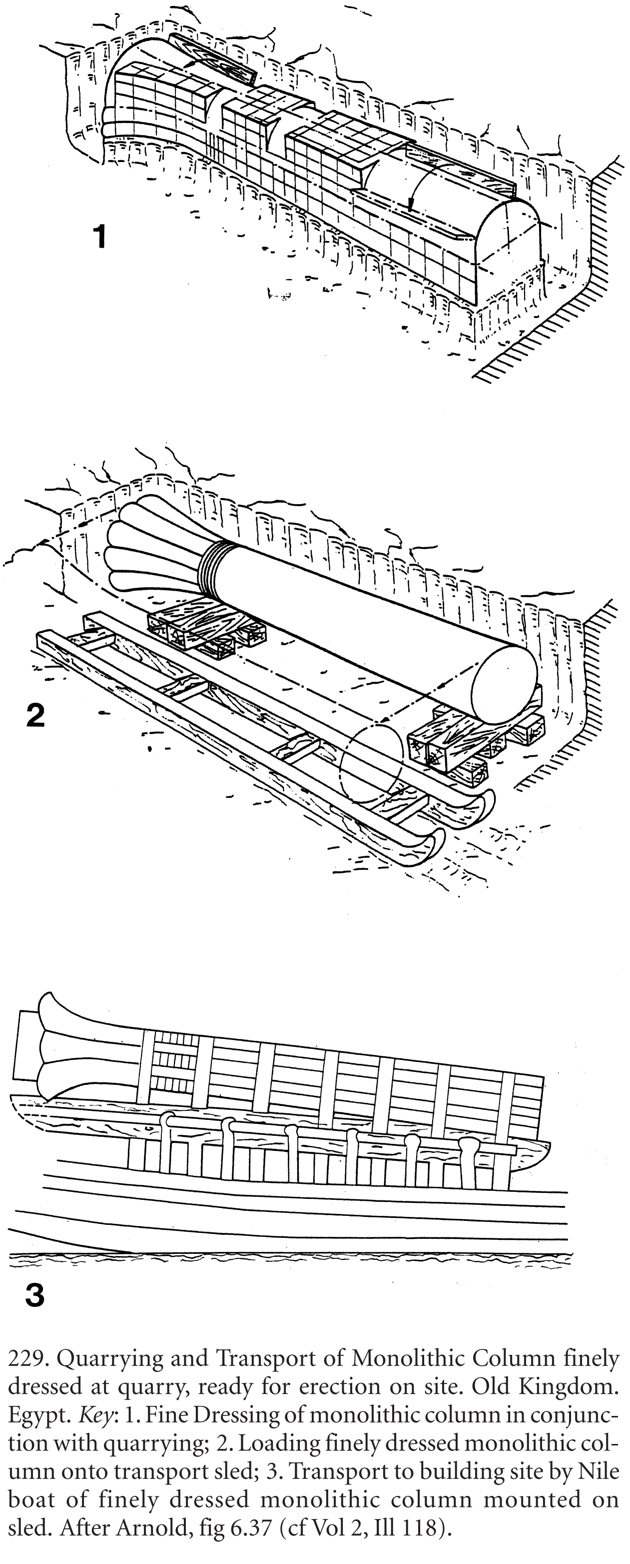
226. Cori. Doric Temple. Sectional Elevation of Façade showing Foundations. Cora, Italy. Early 1st Century BC. Roman podium temple – tetrastyle, prostyle, with porch foundations partly exposed. The confines of the destroyed podium walls indicated in broken line. This shows that the podium was primarily a design element not a principal foundation structure. The walls and columns of the Temple were each provided with their own dressed stone foundations independent of the construction of the podium. However the latter served in a measure to consolidate the foundation, by retaining a packed fill. Beneath the cella a practical device would have been a foundation vault (NB the *opus africanum* construction of the pediment). After Robertson, p. 208, fig 93.



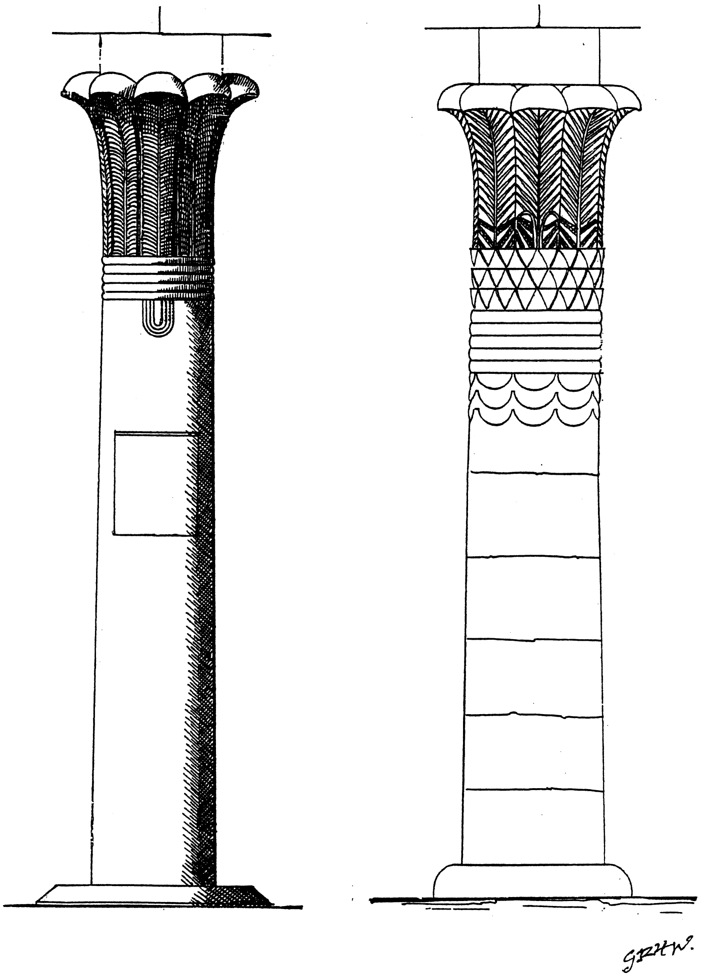
227. Aizanoi. Temple of Zeus. Restored Cross Section showing foundations (standing masonry blocked in). Phrygia. ca 125 AD. This temple was basically constructed in the Hellenistic tradition but incorporated Roman design elements in its siting. It was raised up on an artificial terrace to give a commanding axial view over the monumentally developed site. In this way it incorporated both a podium *and* a crepis. Below the cella is a large vault or crypt which may have been used for the worship of Cybele. However, although possibly not principally conceived as such, it serves the statical function of foundations for the massive temple. The load imposed by a building on the natural foundations (the ground) on which it stands can be demarcated as a bulb of pressure. This is the volume which is subjected to added stress. If part of that mass is dug away and replaced by empty spaces (a crypt/vault), then the load of the building imposed on the natural foundations can be reduced or entirely eliminated – i.e. the vault or crypt acts as artificial foundations (by way of removal) for the superincumbent building. After Ginouves III, Pl 21.5.



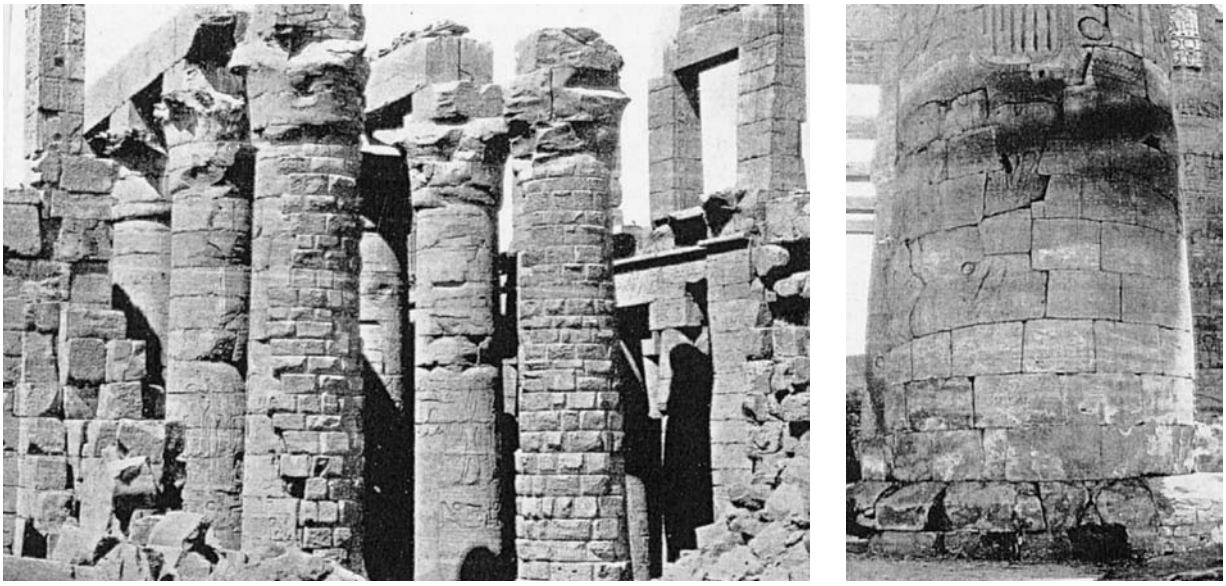
228. Gizeh. Pyramid Temple of Khephren. Possible Method of Erecting Granite Pillars. Lower Egypt. Old Kingdom. ca 2500 BC. These pillars in the megalithic tradition were not mounted on stones bases, but were set down into the earth to ensure stability. The sunken emplacement was prepared with one scarped margin; and the pillar was brought into position at this margin, base foremost overhanging the emplacement. The pillar was then levered up at the other end so that it slid down the scarp to rest in an inclined position (A). Ropes were then attached to the crown of the pillar so that it could be hauled vertically upright, most probably with the aid of sheer legs to vector the applied force to the best advantage (B). After Arnold, fig 3.9.



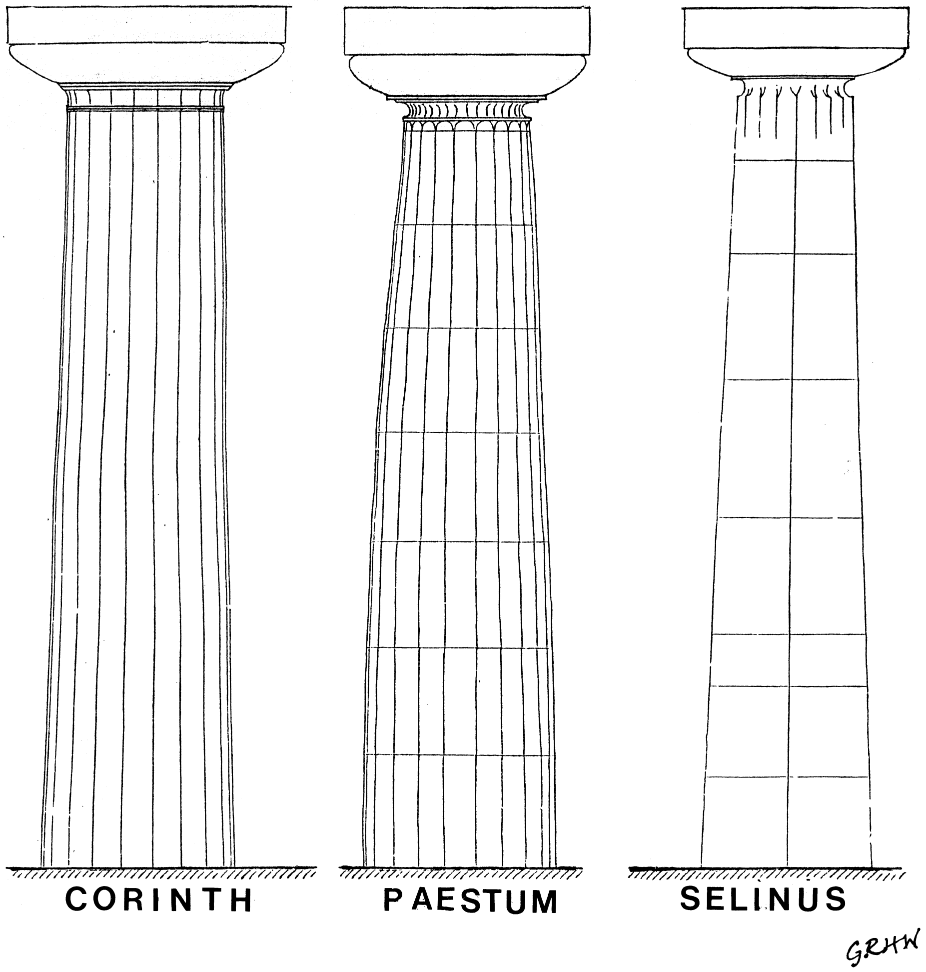
229. Quarrying and Transport of Monolithic Column finely dressed at quarry, ready for erection on site. Old Kingdom. Egypt. *Key*: 1. Fine Dressing of monolithic column in conjunction with quarrying; 2. Loading finely dressed monolithic column onto transport sled; 3. Transport to building site by Nile boat of finely dressed monolithic column mounted on sled. After Arnold, fig 6.37 (cf Vol 2, Ill 118).



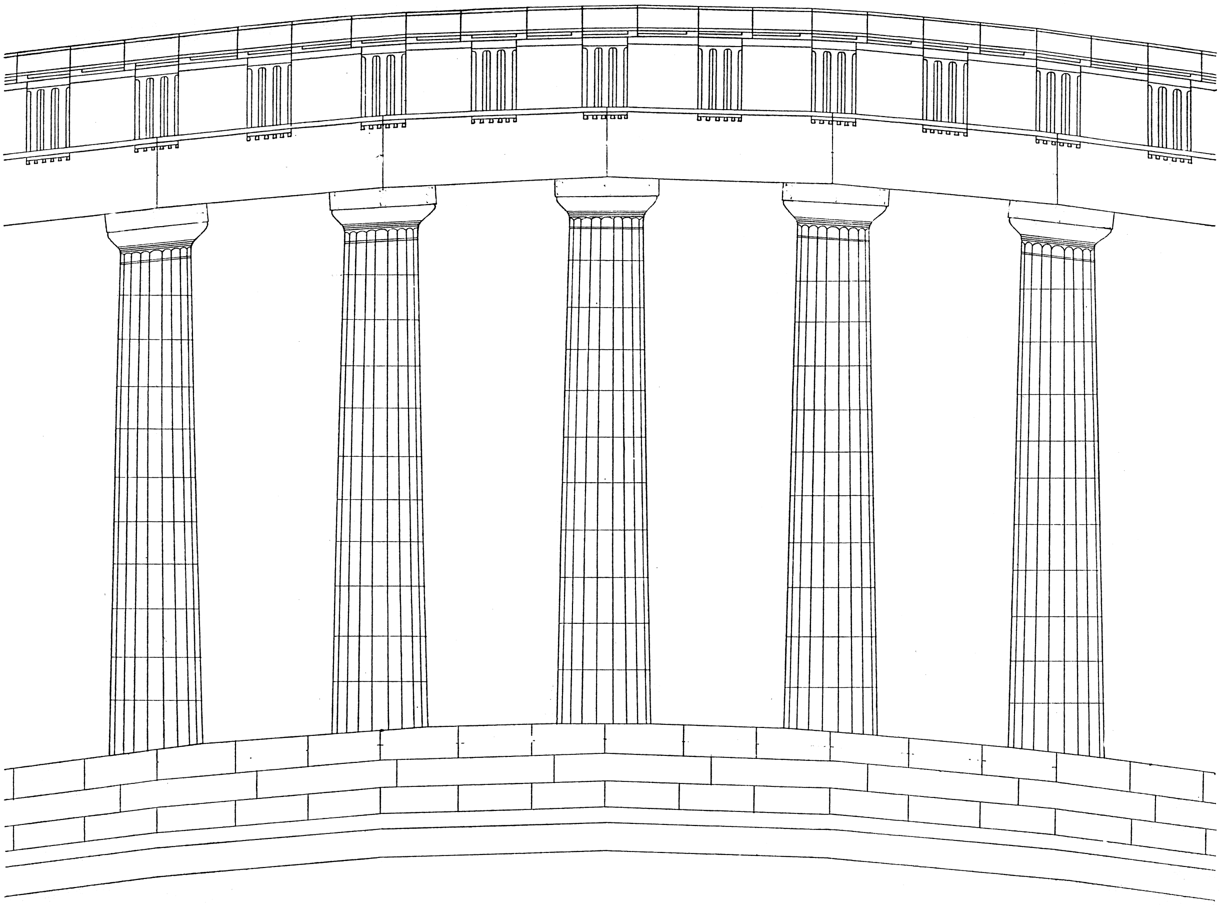
230. Typical Chronological Development from Monolithic Columns to Columns constructed from Drums. Old Kingdom to Ptolemaic. The Egyptian Palmiform Column. This type of column was one of the original plantform columns developed at the beginning of monumental stone building in Egypt (Old Kingdom, Pyramid Age); and it remained in vogue until the end of Egyptian Pharaonic building in the Christian Era. As can be seen, the overall design changed little, with only some minor variation in the ornament. However whereas the Old Kingdom columns of this nature (e.g. *left* from Funerary Monument of Sahu Re at Abu Sir, 5th Dynasty) were monoliths, from New Kingdom times onwards this type of column was as a matter of course constructed out of drums (*right* Ptolemaic Columns from Philae). This serves as an example for the same development with other plantform columns, e.g. Lotiform, Papyriform etc. After Jequier, figs 121, 125.



231. Karnak. Great Hall. Ancient Repairs to Columns effected in normal small block Masonry. Thebes New Kingdom or later. After Clarke and Engelbach, figs 166, 167.

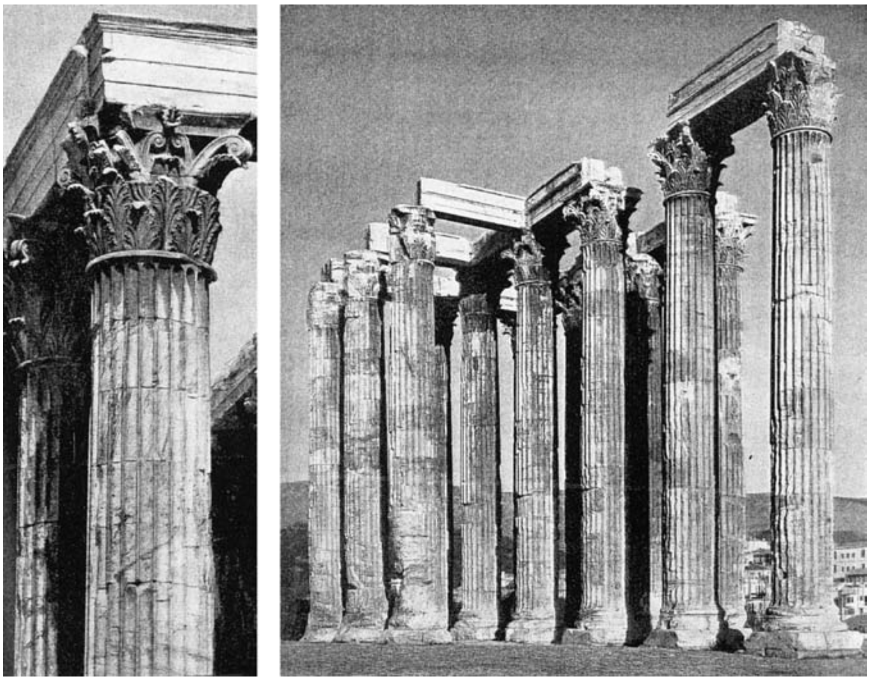


232. Early Doric Columns. Monolithic and out of Drums. West of Greece & Magna Graecia. Mid 6th Cent BC. Temple of Apollo, Corinth; Temple of Poseidon. (The Basilica) Paestum; Temple F, Selinus. The columns of the Temple of Apollo at Corinth are monoliths and without refinements of design. Their massive proportions probably derive from the quarrymen's distrust of the resistance of the elongated stone block to stresses in bending occasioned during handling. The columns at Paestum and Selinus are constructed out of (7 or 8) drums of standard form – and incorporate entasis. However they are not a later development than the Temple at Corinth. The total height of the column at Corinth is ca 7m and the proportion height to lower diameter was ca 1:4; the total height of the column at Selinus is ca 9m, and the proportion of height to lower diameter is ca 1:4.5. After Durm B d G, fig 65.

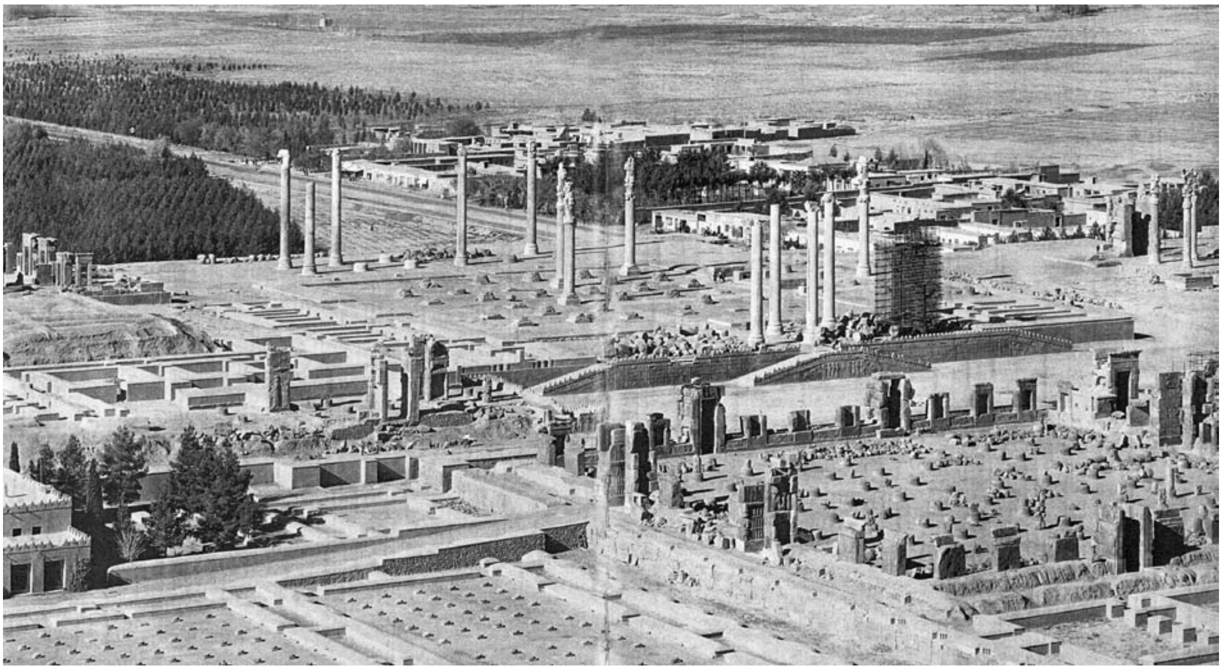


233. Athens. Parthenon. Diagram showing Classical Greek Column Construction out of Drums. Attica. Mid 5th Century BC. The columns are built up of drums (ca 1m or so in height), perhaps 8 to 12 to a column of medium height giving a proportion of height of shaft to lower diameter of ca 1:5.5. The drum is a squat cylinder, generally less in height than in diameter. The drums were fixed together by vertical dowels let into the upper and lower bed joints. The burden of a normal drum was in excess of a ton, and drums were set in place by clean lifting with block and tackle. The fluting of columns was carried out *in situ*. This diagram is intended to show by way of exaggeration the refinements in the design of the finest Greek temples. The departure from orthogonal is in the nature of millimetres, but is recognisable and measurable. After Lawrence, fig 98.

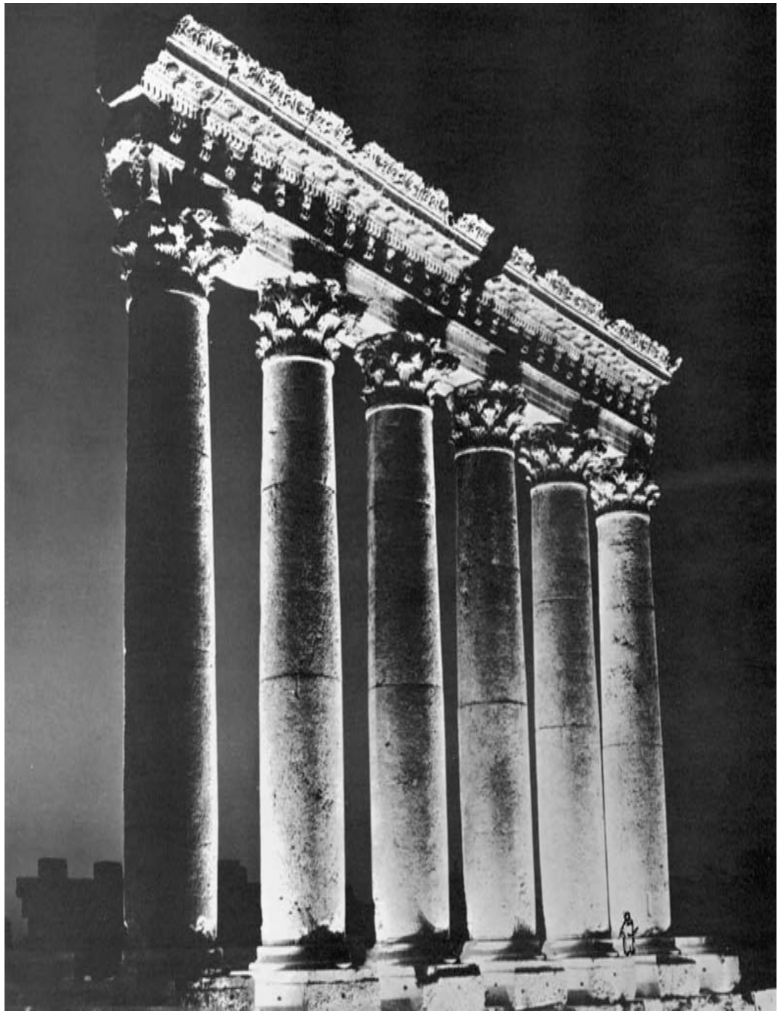
234. Temple of Segesta. Unfinished Column Construction showing unfluted Drums. Sicily. Late 5th Century BC. Work on this large temple was abandoned after the erection of the peristasis. This clearly demonstrates that the normal procedure for fluting columns was to carry out the work *in situ* after erection. These sizeable columns are each built up out of ca 12 drums, and narrow registers at the base of the lower drum and at the crown of the uppermost drum have been dressed back to the final dimension as a guide to the work of fluting. After Lawrence, pl 84.



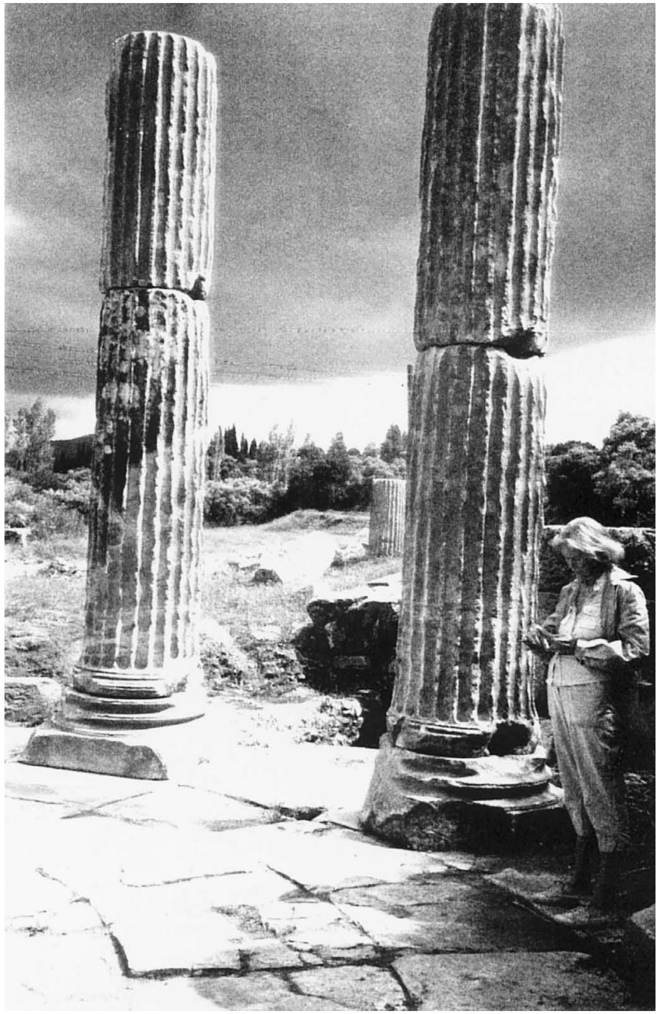
235. Athens. Temple of Zeus Olympios. Late Classical Greek Columns constructed with Drums. Attica ca 170 AD. These giant columns (height ca 18m) were built out of drums in the traditional Greek manner. They were among the last imposing columns so to be built. Within a century all monumental columns were prepared as monoliths at the quarry. After Lawrence, pls 106, 107.



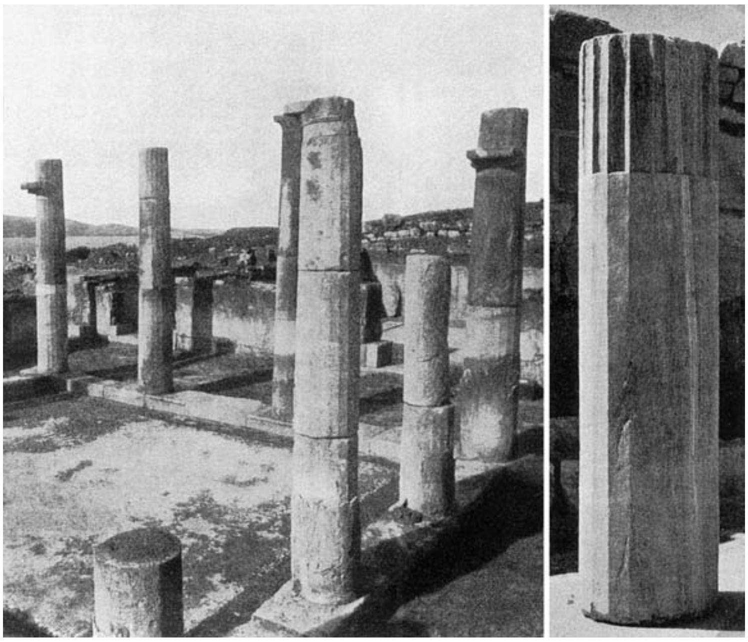
236. Persepolis. View with the Apadana in centre ground showing its towering columns (height of shaft ca 15m) which are not built of drums, but are either monoliths or of several frustra. Persia Achaemenid, ca 520 BC – 500 BC. Their mode of erection is a mystery. Historically speaking it would be possible for them to be lifted by block and tackle, but this would require a forest of the heaviest and highest wooden scaffolding imaginable, as also the disciplined force of a brigade of men working at capstans. On the other hand to erect so many giant columns in a confined space by hauling up ramps base foremost appears impossible. NB the closely packed tubular steel scaffolding required by modern restoration work.



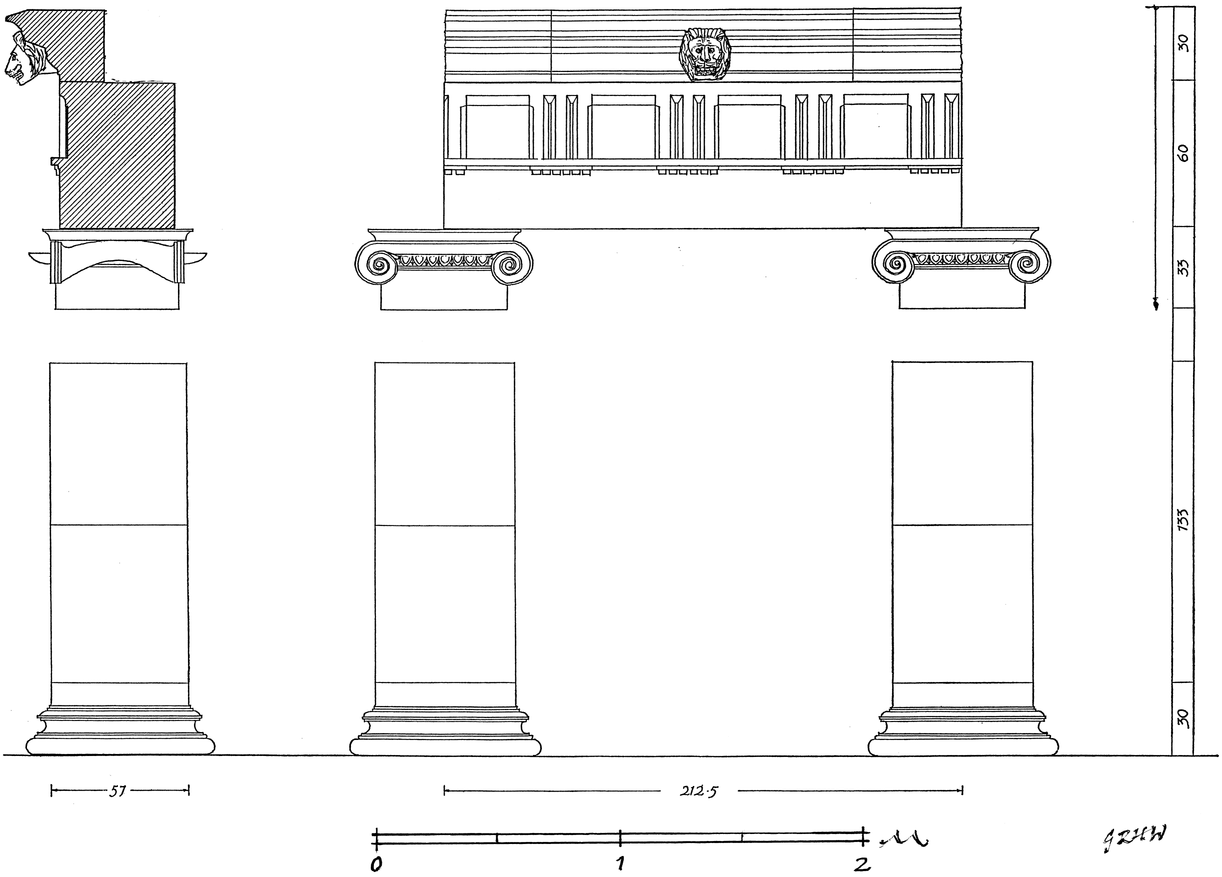
237. Baalbek. Temple of Jupiter Heliopolitanus. Peristyle Columns showing Frustra Construction. Bekaa Lebanon. 1st Century AD. This photograph of the 1960's made by night shows clearly that the giant Corinthian Columns (ca 20m high) were constructed not out of drums but from three frustra. Although each frustrum weighed ca 50 tons, it was set in place by clean lifting with block and tackle – obviously requiring a forest of heavy timber scaffolding.



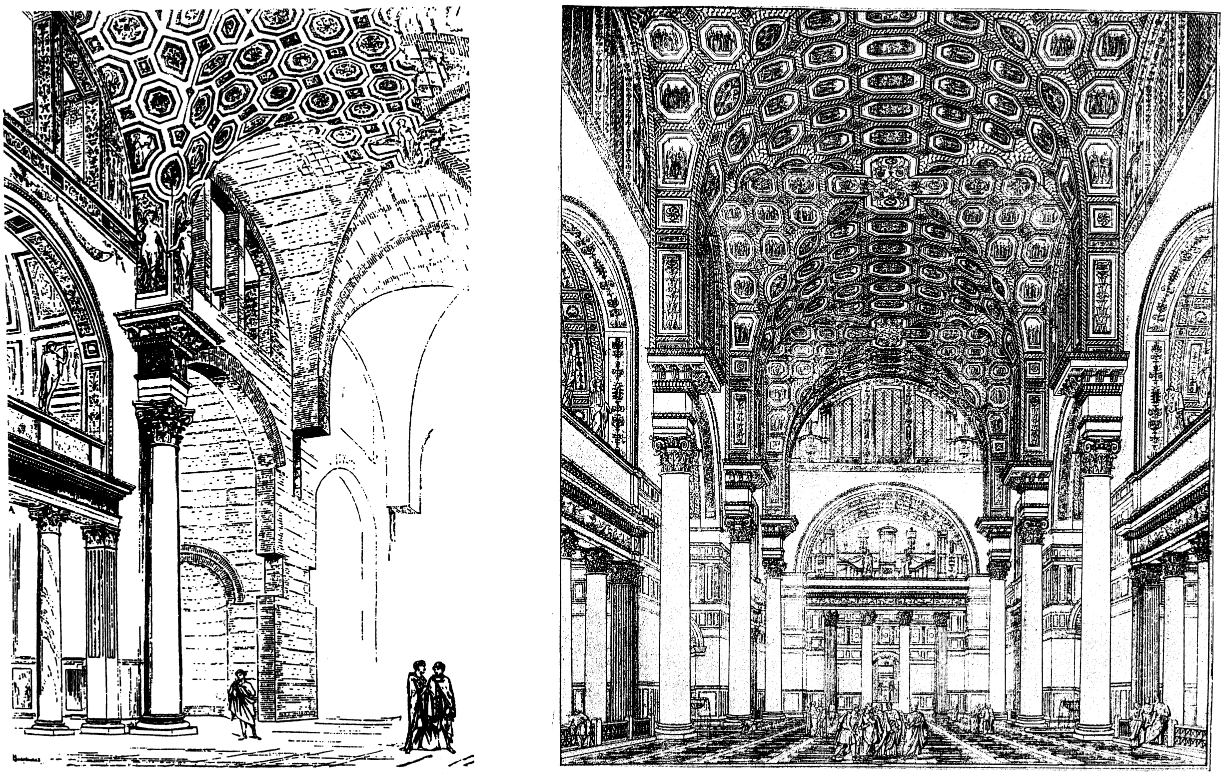
238. Lagina. Temple of Hecate. Monumental Corinthian Columns built from tall frustra. Southern Ionia. ca 100 BC. Although Ionic or Corinthian Columns built out of drums are normal in Asia Minor, it seems that an alternative tradition of building columns out of tall frustra also survived from Archaic times in the Islands and on the mainland of Asia Minor.



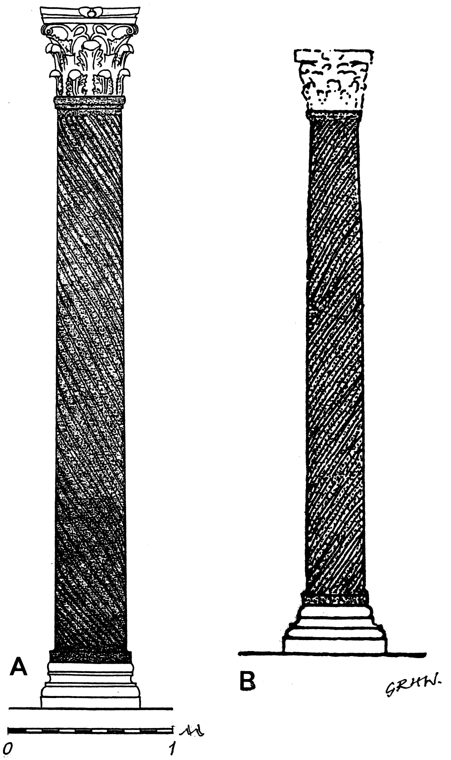
239. Delos. Rhodian Peristyle of Villa with Column Construction out of Frustra. Insular Greece. 2nd Century BC. With the increased wealth of the Hellenistic World ornamental dressed stone elements came to be used in private building (e.g. villas). This is sometimes called 'domestic doric'. The columns were relatively speaking slight, and for structural reasons were fashioned from several frustra only (e.g. 3 or 4), rather than from 8 to 10 (slight) drums. The frustra were not as a rule dowelled together as was standard practice with drums (v frustrum in left foreground). After Lawrence, pl 140.



240. Ptolemaic Villa. 'Domestic' order of Peristylar Court with columns built of Frustra. Tolmeita, Cyrenaica. ca 1st Century AD. Columns from several frustra with capitals and bases worked in same block as extremities of shaft. The lowest frustrum is a single block equivalent in height to 4 drums (of ca 33 cms), but scored to simulate 2 drums of 66 cms. These frustra were turned on a lathe. After Kraeling Ptolemais Fig 46.

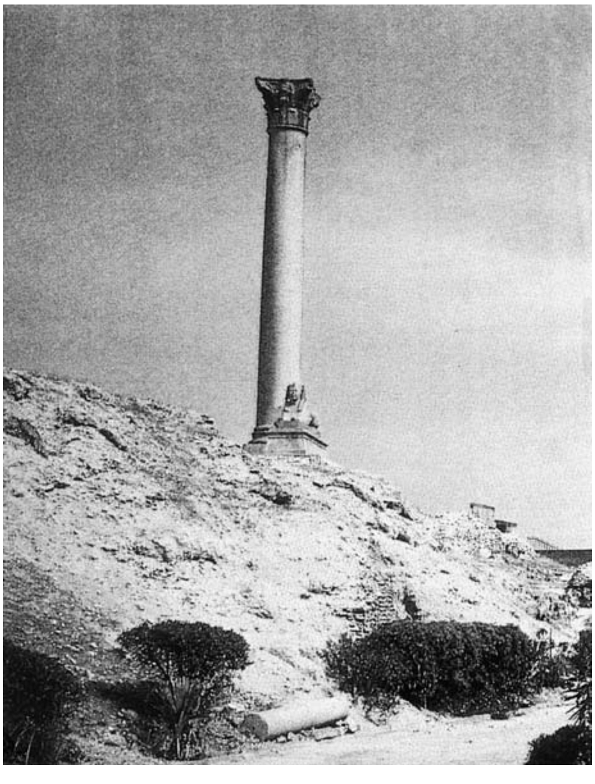


241. Baths of Caracalla. Grand monolithic marble columns employed as architectural ornament in Roman Concrete Construction. Rome. 2nd Century AD. *Right*: Reconstructed drawing of Great Hall; *Left*: Analytic diagram by Viollet Le Duc indicating the construction in Roman Concrete cross vaulting; with the stone columns and entablature applied ornament inserted after the concrete structure was completed and structurally functional. Thus the stone additions could be removed without threat to the stability of the structure. After Robertson, pl XVIII.



242. Monolithic Marble Columns. Spirally fluted shafts of dark blue grey marble, with white marble capitals and bases. Roman Empire. 3rd Century AD and later. This "Prefabricated Marble Style" took over during the later 2nd Century AD to become the standard form of monumental column construction throughout the Roman World in the 3rd Century AD and later. The elements were manufactured at the great imperial quarries and other centres and could be delivered almost anywhere because of the superior transport and communication facilities developed throughout the Empire. This obviated the necessity for employing highly skilled stone dressers at minor construction sites. *Key*: A. Ptolemais, Cyrenaica; B. Kourion, Cyprus.

243. Special Order Monolithic Columns abandoned at the quarry in present day wild setting. This scene gives eloquent testimony of the centralised economy during later antiquity and the international transport services of the time. A project to use these columns today at a distant building site would inevitably involve the construction of special heavy duty motor roads through difficult country.

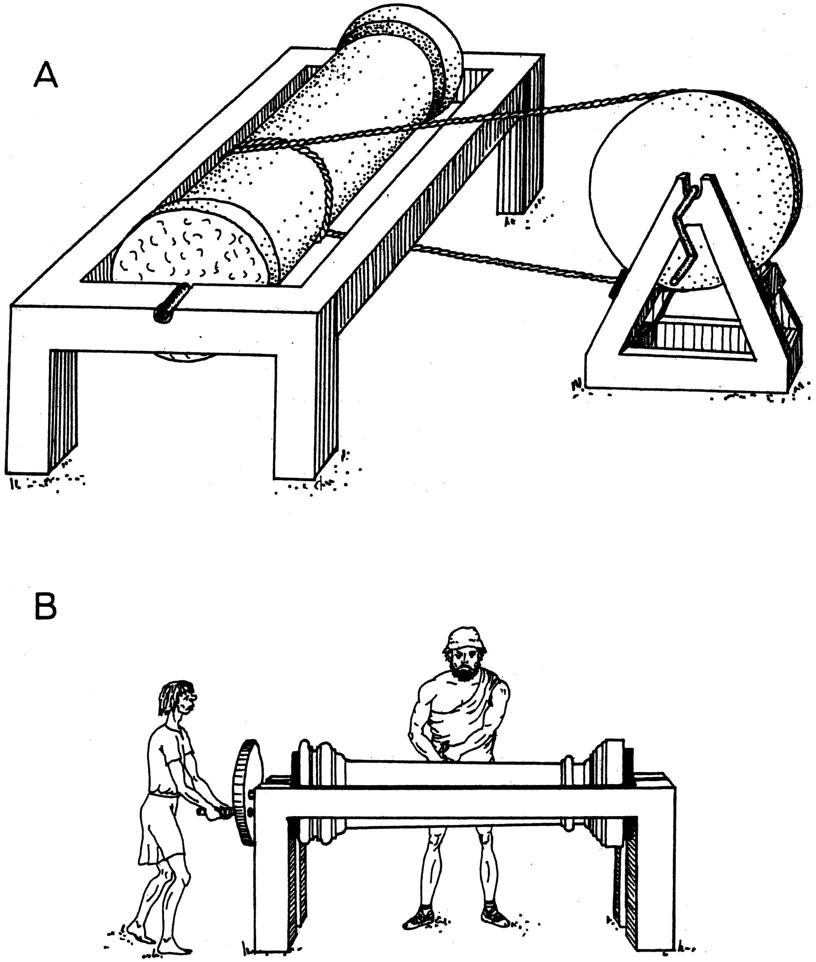


244. Alexandria. The Monolithic Victory Column of Diocletion *alias* Pompey's Pillar. Egypt 298 AD. It is interesting to note that once more after 2000 years massive monumental columns in Egypt were monoliths not built up in drums. This perhaps bespeaks the fact that the absolute rule of the Roman Emperor as Egyptian Pharaoh was comparable to the absolute status of the Old Kingdom Pharaohs. After G. Hölbl I, p. 39, abb 32.

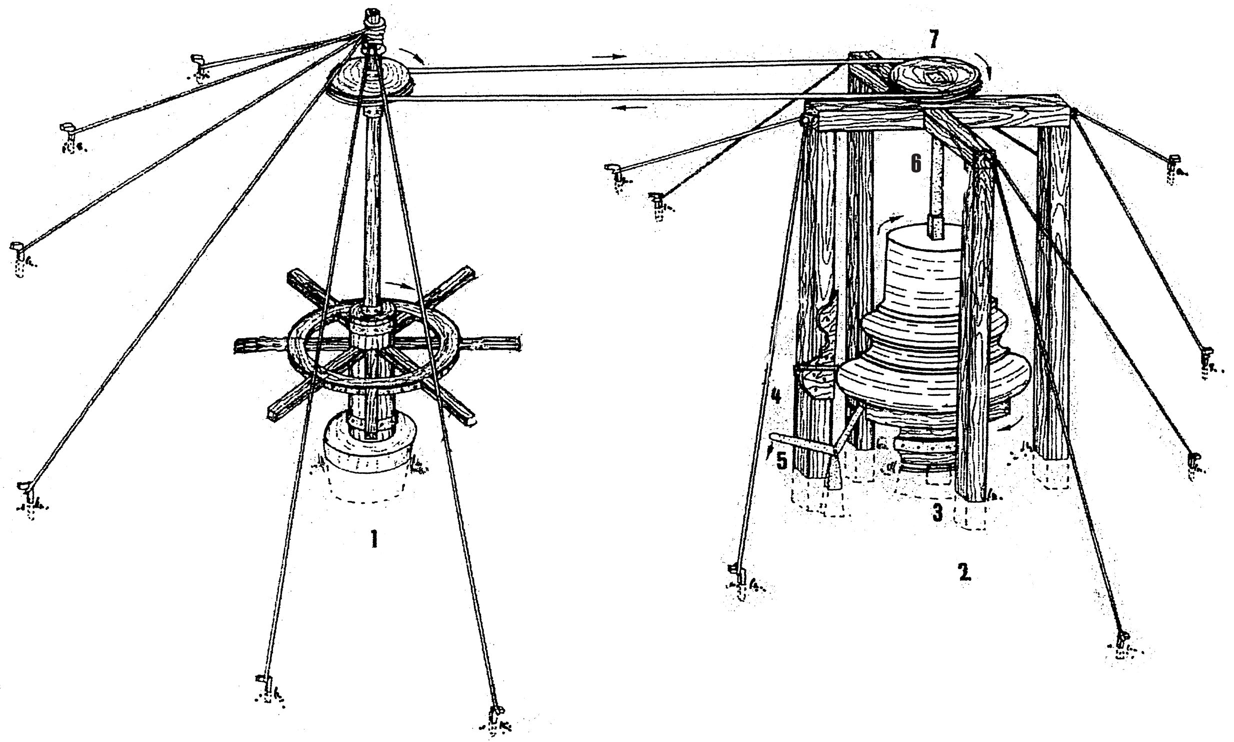
245. Apollonia East Church. View after anastylosis during the Italian Regime showing Monolithic Columns. Marsa Sousa. Cyrenaica. ca 450 AD. This church complex was constructed of (roughly) squared rubble masonry from local sandstone together with reused columns of Greek Island (Cipollino) Marble. The columns are all monoliths and demonstrate how monolithic marble columns ousted columns constructed of drums of local stone. This practice of importing pre-fabricated marble columns is particularly apparent in Cyrenaica, since most of the sites are on or near the coast, thus facilitating shipment and transport on site. Also the walling of rubble etc is abstracted for reuse over the ages, leaving broken column shafts as the residue of the building. After Christian Monuments of Cyrenaica, p.39, Ill 5.

246. Qalb Lozeh. The Basilica. View of nave and apse showing arcuated construction in heavy ashlar masonry. North Syria. 5th Century AD. Columns are not necessarily cognate with arcuated construction. In fact, structurally arches etc with their thrust are better supported on piers of masonry, as here. Builders in North Syria at this time gave a much greater span to arches supported on masonry piers than to those supported on columns. After Mango fig 107.

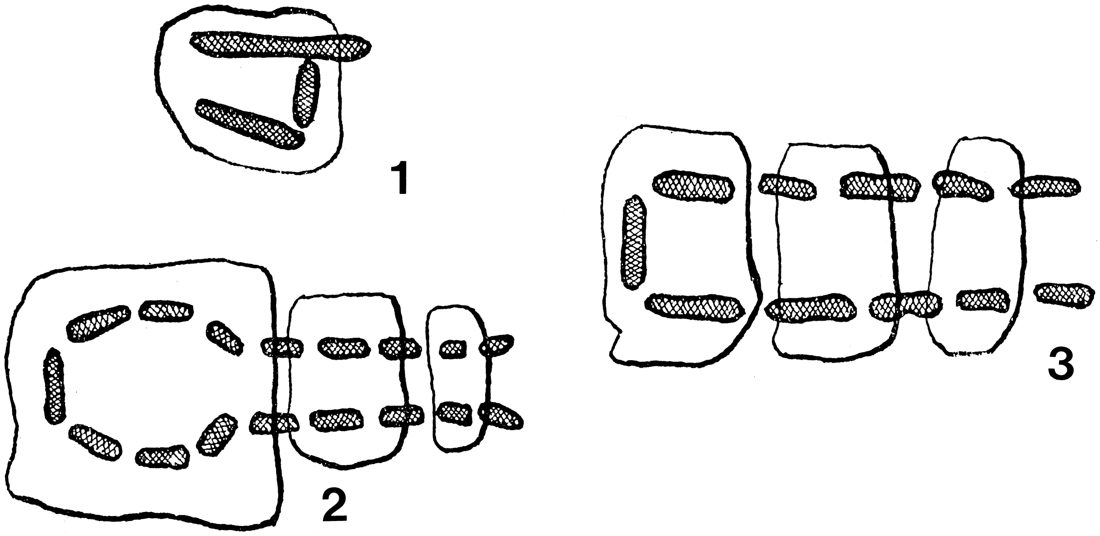
247. Constantinople Cistern of Philoxenus showing tall columns assembled from two columns set one above the other. Binbir Direk. Early 6th Century AD. This covered reservoir contributing to the city’s water supply built during the reign of Justinian was ca 65m x 26m. 448 monolithic columns were employed to sustain the vaulted roof. These columns were delivered from the quarry in two matching sets ready for erection. To maximise the depth of the cistern at each emplacement two columns were mounted one above the other. To increase the stability of this compound they were spliced together by a stone sleeve. After Mango, fig 93.



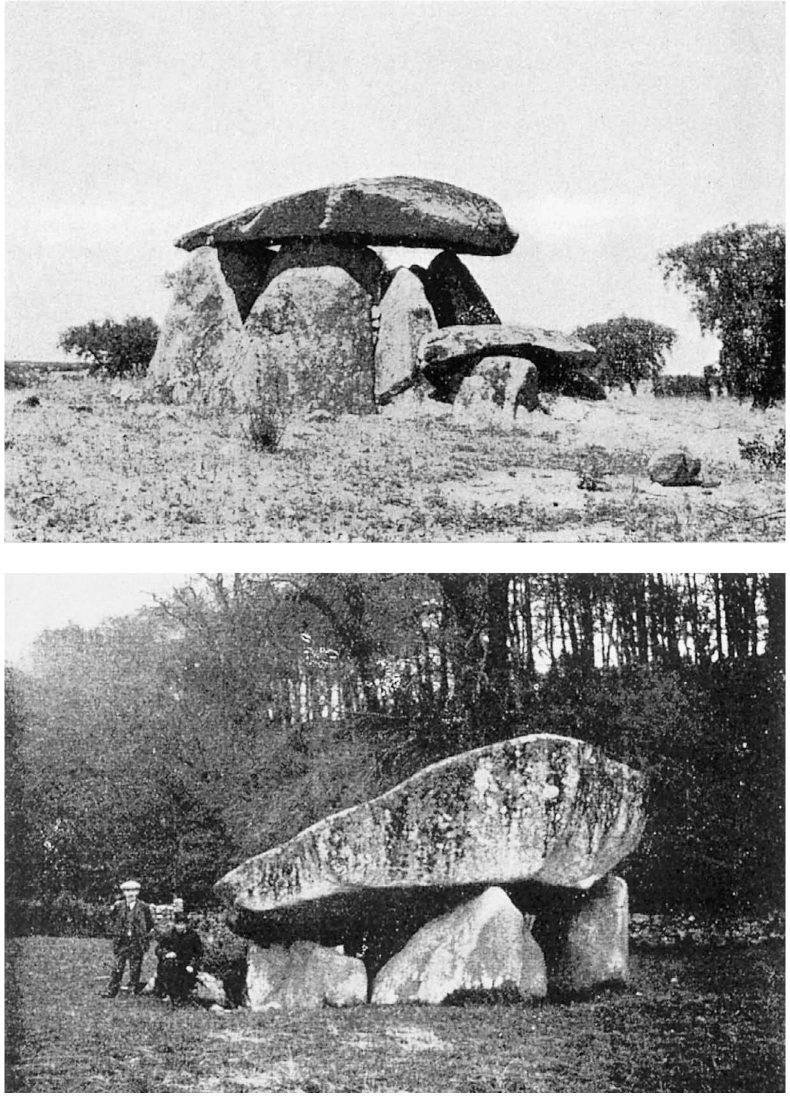
248. Projected Design for Horizontal Lathes used in antiquity for turning columns and column frustra. A. Lateral drive by windlass; B. End drive by windlass. After Blagg, fig 2.



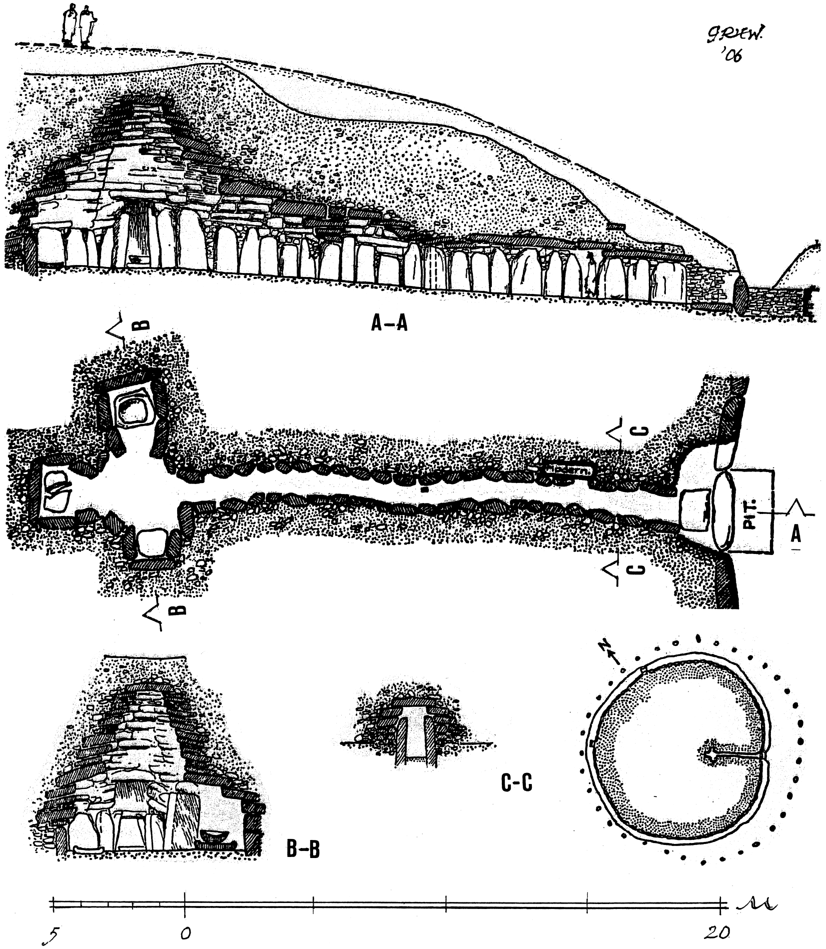
249. Projected Design for Vertical Lathe in antiquity turned by capstan. With such a machine once the rotation is established it would continue largely by centrifugal force, thus necessitating some braking device. *Key*: 1. Capstan; 2. Vertical lathe mounted on wooden frame; 3. Emplacement for turntable and axis of rotation; 4. Template mould; 5. Brake; 6. Upper axis drive shaft; 7. Horizontal pulley block. After J.C. Bessac Le Tournage, fig 8.



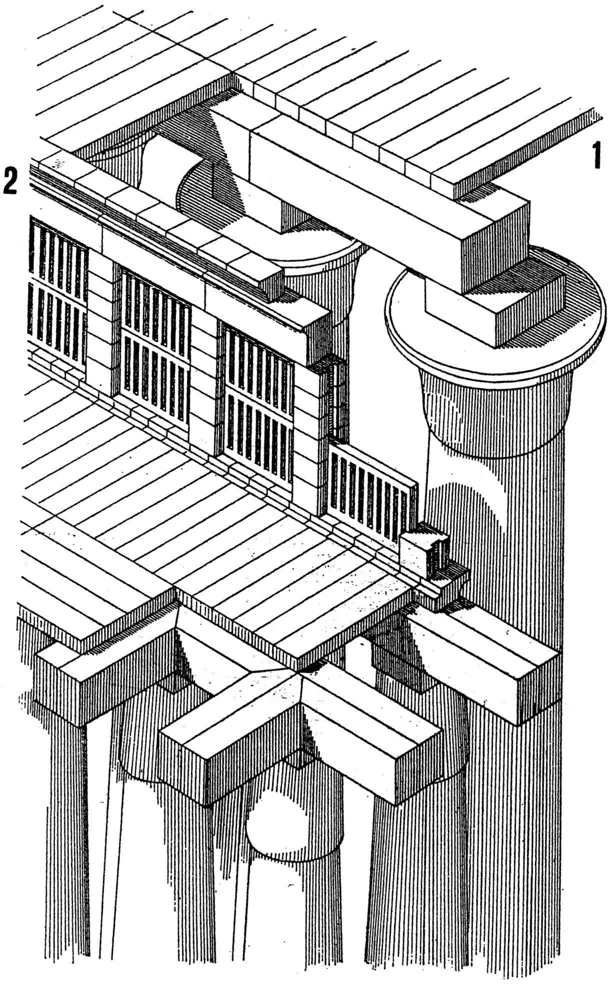
250. Diagram showing Slab Roofing of Basic Megalithic Building Types. Such slabs are massive, in general ca 4-5m long with spans of ca 3m. *Key*: 1. Simple Dolmen; 2. Passage Grave. 3. Gallery Grave. After Nel fig 3.



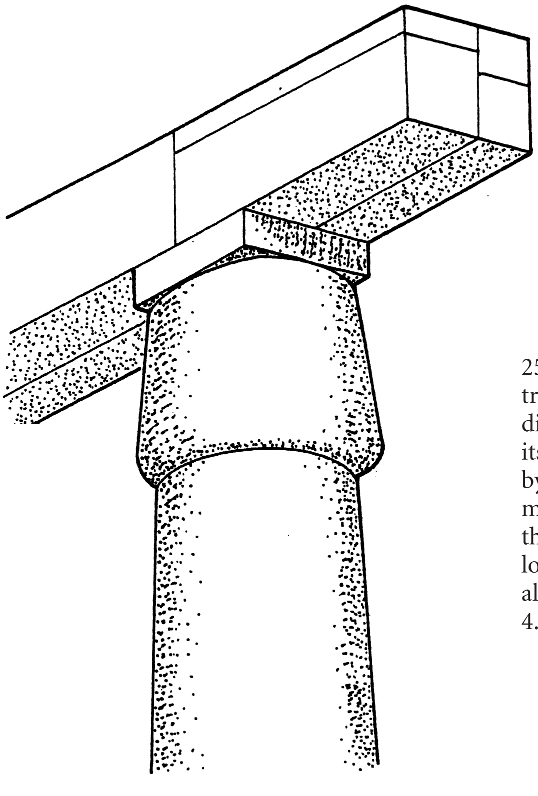
251. Typical Dolmens showing massive roofing of rude cap stones weighing many tons. ca 4th Millenium BC. Above: Portuguese “Anta”; below: Irish Megalithic Tomb at Bremarstown. After Megalith Builders, Pls I, II.



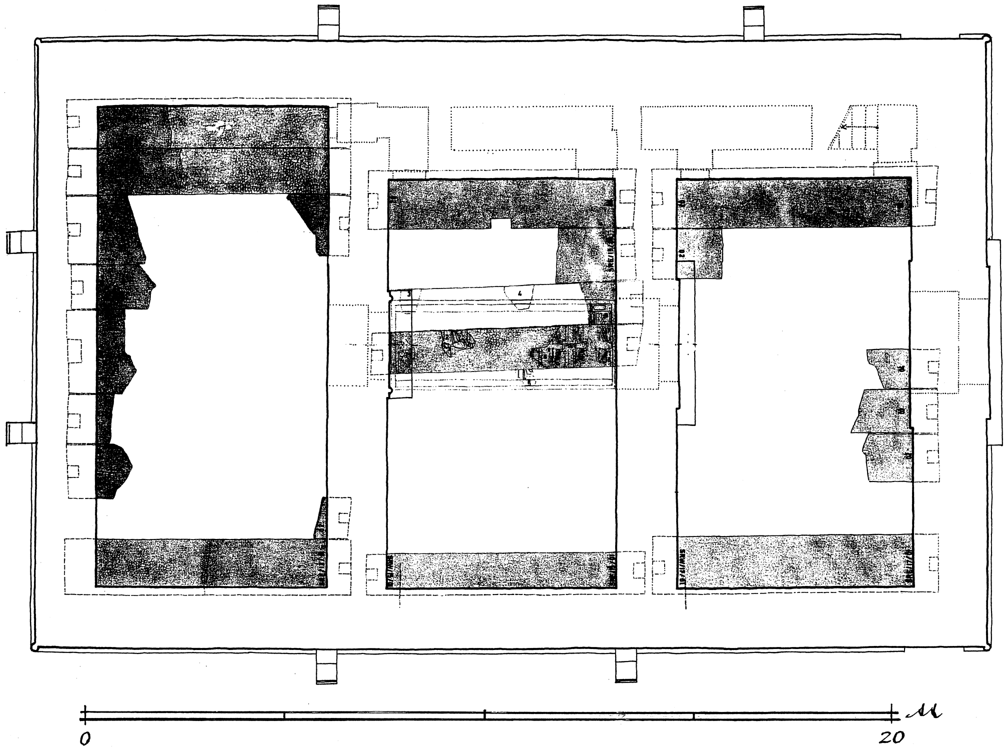
252. New Grange. Megalithic Passage Grave showing Corbelled Roofing. County Meath Ireland. ca 4,500 BC. Plan and Sections (AA, BB, CC) with (lower right) Key Plan of Burial Mound (Round Barrow) at reduced (ca 1/10th) scale. This early megalithic collective tomb reveals the varied resources of megalithic building. Several hundred slabs of approximately similar conformation were required and were set up as orthostates for the walling with slabbed roofing over the passages and a corbelled dome 7m high above the chamber. There are no known antecedents for such construction. Megalith Builders p. 106, fig 20.



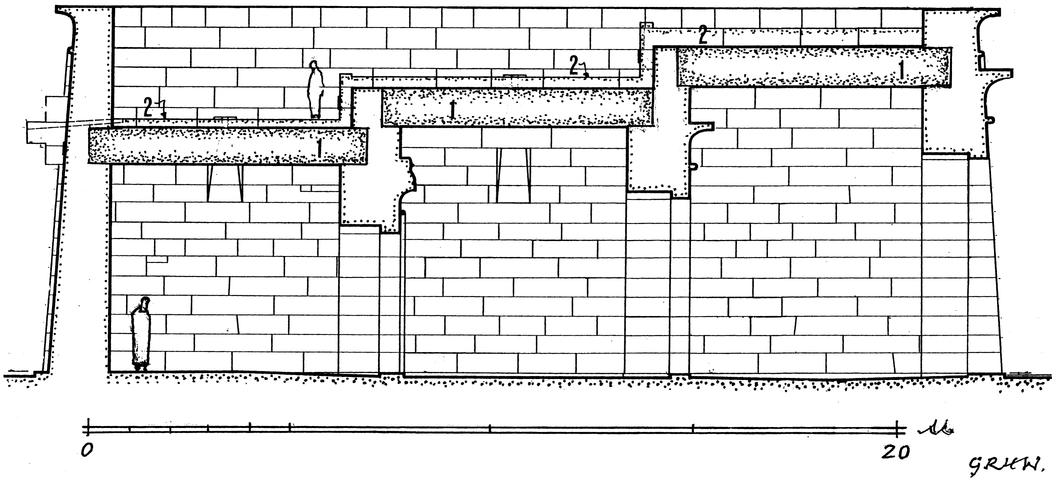
253. Karnak. Great Hall. Detail of Roofing Masonry. Thebes. New Kingdom. This old drawing of Perrot and Chippiez is of great interest as showing the unusual arrangement for clerestory lighting, and has been republished in all the manuals (Jecquier, Clarke and Engelbach, Arnold). However the details of the roofing are demonstrably incorrect. This is noted by Clarke and Engelbach; and Arnold's version attempts correction but runs into difficulties. Here, rather than attempting rectification without investigation *in situ*, attention is drawn to the anomalies. 1. The roofing slabs appear out of scale – they are too slight and should be both broader and deeper. They are shown less than $^{1}/_{3}$ the depth of the supporting beams, whereas the normal depth approaches ½ that of the beams (Arnold's version corrects this); 2. The entablature above the clerestory screen which should provide the marginal seating of the roofing slabs does not appear to afford sufficient seating to the slabs. While the cornice blocks should stand above the upper surface of the slabs to provide a parapet and should also oversail the slabs to weight them down. Equally it is unlikely that these cornice blocks should be small square blocks as shown, since thus they lack fixation in their exposed position – more likely they would be much longer to provide fixation by dead weight. Probably the drawing by Perrot and Chippiez was made from photographs which left details obscure. NB The lintels above the screen can be seen to be deeper so as to provide the requisite seating for the slabs in Clarke and Engelbach's accompanying photograph, fig 204. After Clarke and Engelbach, fig 203.



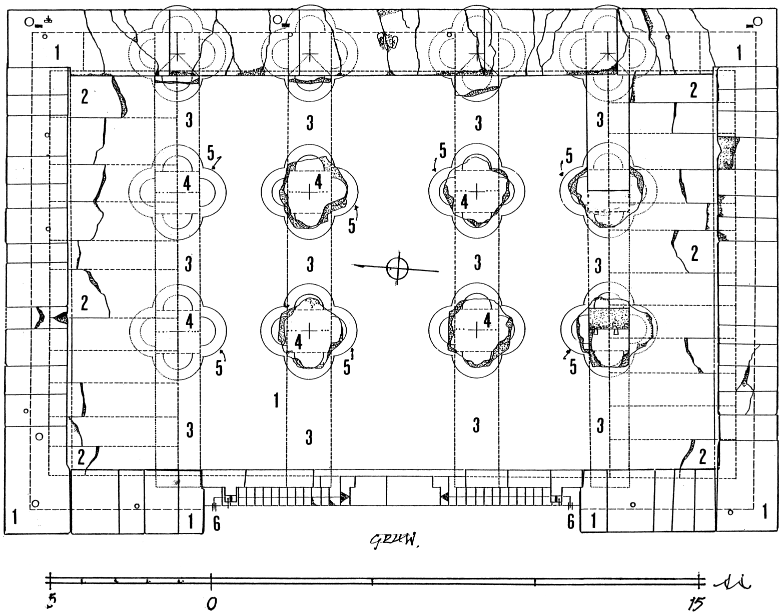
254. Karnak Temple. Hypostyle Hall. Composite Masonry Architrave / Roofing Beam. Thebes. New Kingdom. Egyptian builders did not seem over aware that the strength in bending of a beam is in its depth. Making up a composite beam by setting two beams side by side does not involve serious weakening of the structure, but making up a composite beam by setting two beams one on top of the other weakens the structure drastically. In this instance the shallow topping slabs operate only to even the seating, they add virtually no strength to the beam in bending. After Arnold, p. 186, fig 4.117.



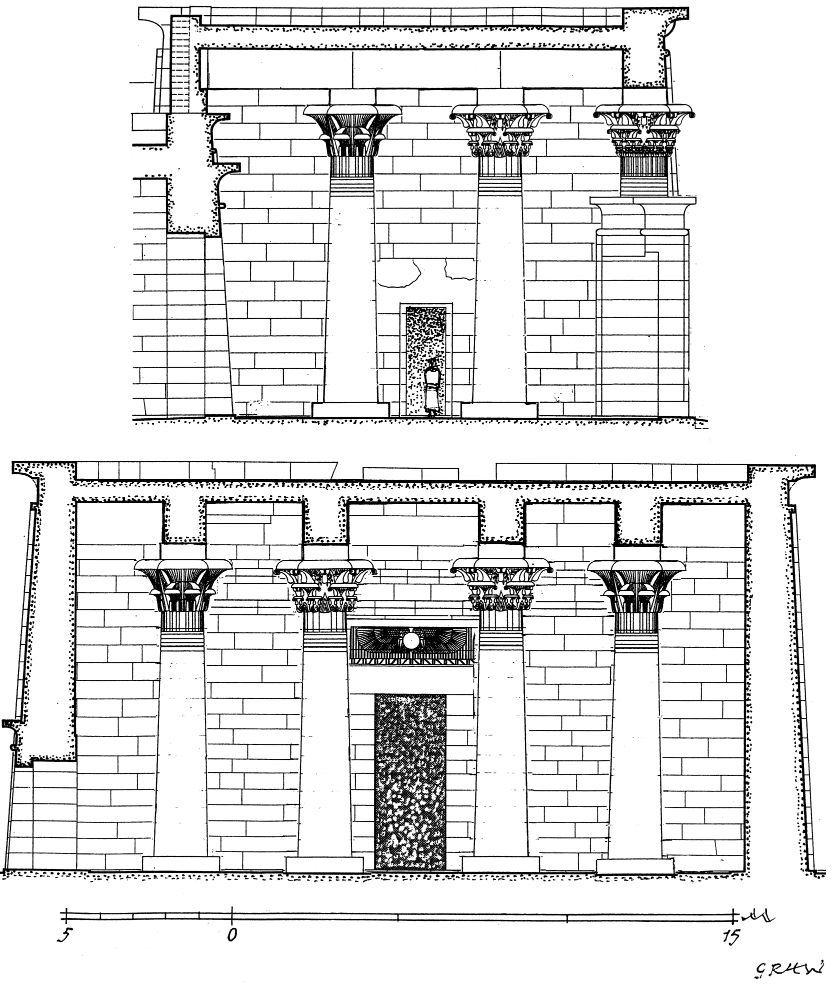
255. Kalabsha. Temple of Mandoulis. Soffite Plan (looking up) of Sanctuary Roofing. Lower Nubia. 1st Century AD. This plan shows all the evidence which could be collected of the fallen roofing slabs. Only one (with seating on 3 sides) survived in place into modern times. This contrasts remarkably with the upstanding wall masonry which has remained largely intact to cornice height. To roof an area ca 240 m^2 the load of the stone roofing slabs was in the nature of 600 tons or ca 2.5 tons per m^2. This demanded truly massive supports (walls and columns). The Temple of Kalabsha was built when Egypt was an Imperial province of the Roman Empire. Roman master builders must have been acquainted with this traditional masonry construction. Never did they attempt to roof sizeable spans elsewhere with stone slabs on the Egyptian model. After Kalabsha 2, plan XIV.



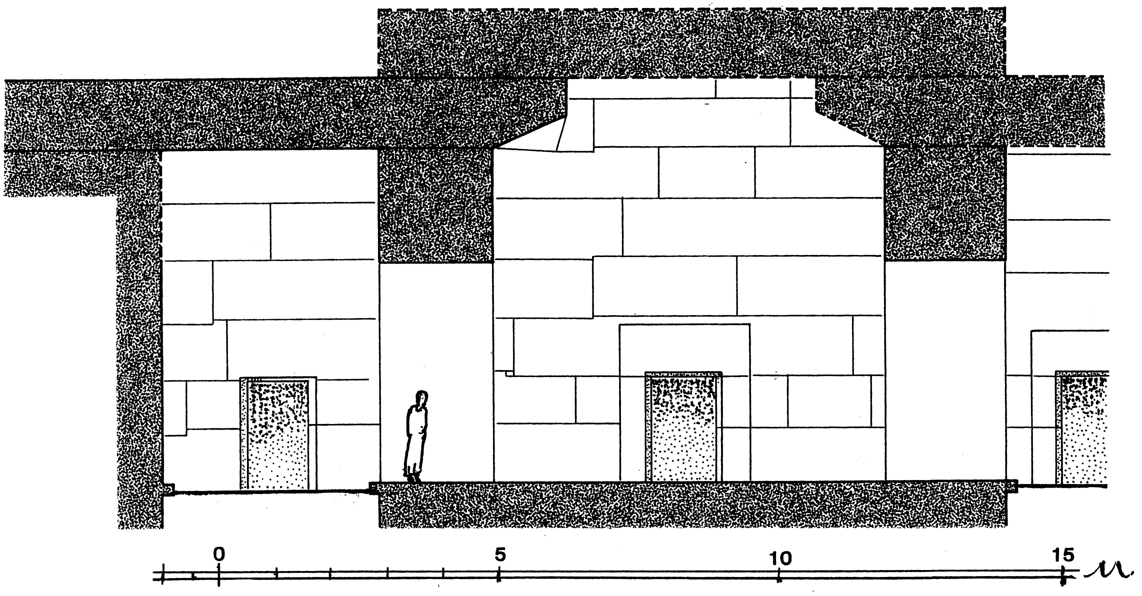
256. Kalabsha. Temple of Mandoulis. Longitudinal Section through Sanctuary showing Slab Roofing Construction. Lower Nubia. 1st Century AD. The three successive chambers were roofed each by 9 sandstone slabs with a clear span of nearly 6m. The 27 massive slabs were thus ca 7m long, ca 1.5m broad and approaching 1m deep – with an average weight of 25 tons. Additionally they supported sizeable stone paving blocks. This combined load stressed the slabs in bending beyond the safe limit; and across the ages all were fissured through and (with one exception) collapsed. *Key*: 1. Roofing Slabs; 2. Paving Stones. After Kalabsha 1, Taf 5.



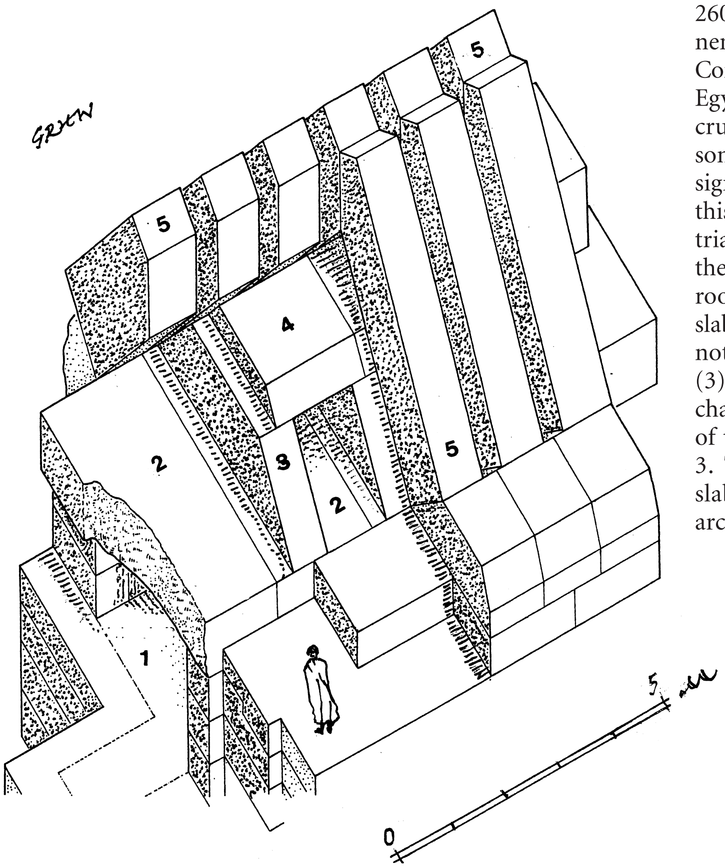
257. Kalabsha. Temple of Mandoulis. Hypostyle Hall Roof Plan. Lower Nubia. 1st Century AD. This plan is slightly restored better to show the traditional stone beam and slab construction. *Key*: 1. Cornice Blocks; 2. Roofing Slabs; 3. Architrave / Beams; 4. Abaci; 5. Capitals; 6. Steps up from Sanctuary Roof. After Kalabsha 1, Taf 15.



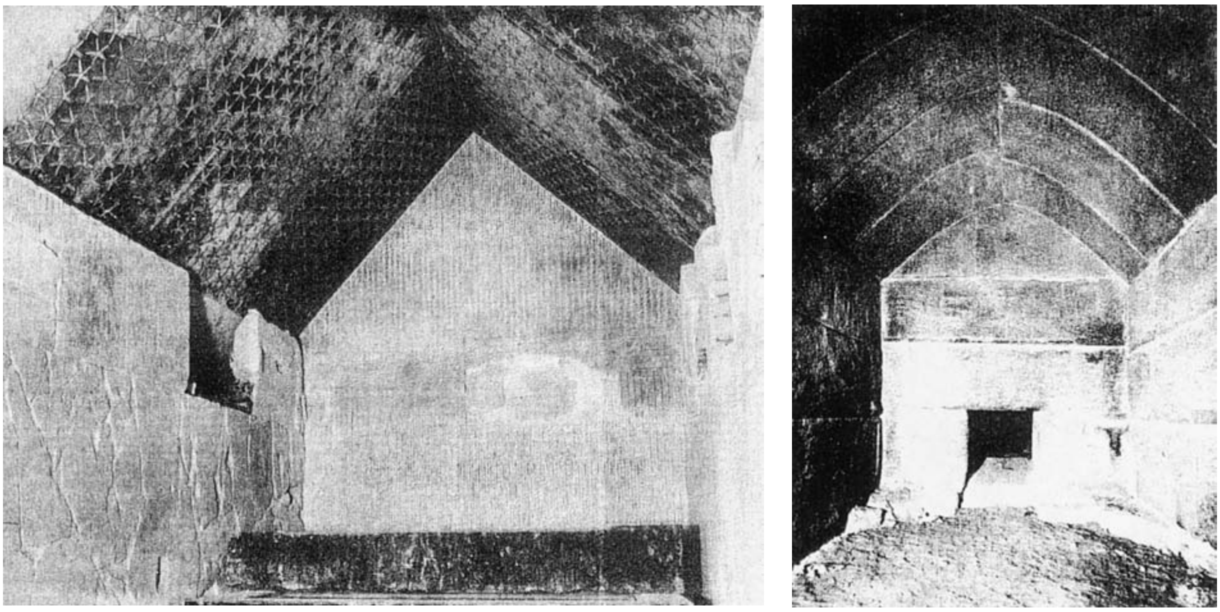
258. Kalabsha. Temple of Mandoulis. Restored Sections of Hypostyle Hall showing traditional stone Terrace Roofing. Lower Nubia. 1st Century AD. This construction was the only Egyptian solution to the roofing of monumental stone buildings involving considerable span. It involved massive stone beams (e.g. over 1 m^2 in section) supporting solid stone roofing slabs: and it remained in use from the Pyramid Age down to the end of Pharaonic Building early in the Christian Era. It was, however, less than ideal, stressing undersides of beams and slabs to the limit in tension so that they frequently collapsed. While much ancient Egyptian upstanding masonry has remained intact to the present day, very little roofing has survived intact *in situ*. After Kalabsha I, Taf 5, 6.



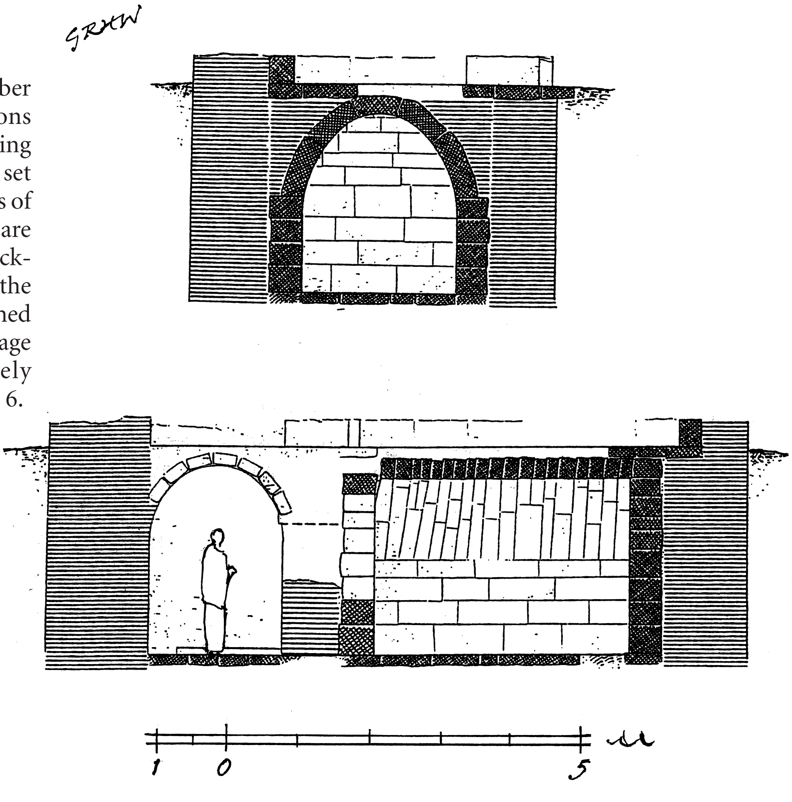
259. Abydos. The Oseirion of Seti I. Section showing Corbelled Roofing Construction. Egypt ca 1290 BC. The central crypt of this mystery cult place has a clear span of ca 7m – the longest possible for stone beams/slabs. By corbelling out the aisle roofing slabs the central span was reduced to the workable 5.50m. However to give an acceptable profile the soffites of the corbels were shamfered off; and instead of seating the crypt slabs entirely on the corbels, these slabs were made of sufficient length to carry back over the pillars. This drawing shows the length of these slabs to be thus over 10m – a prodigious length for a stone slab. After Arnold, p. 46, fig 4.116.



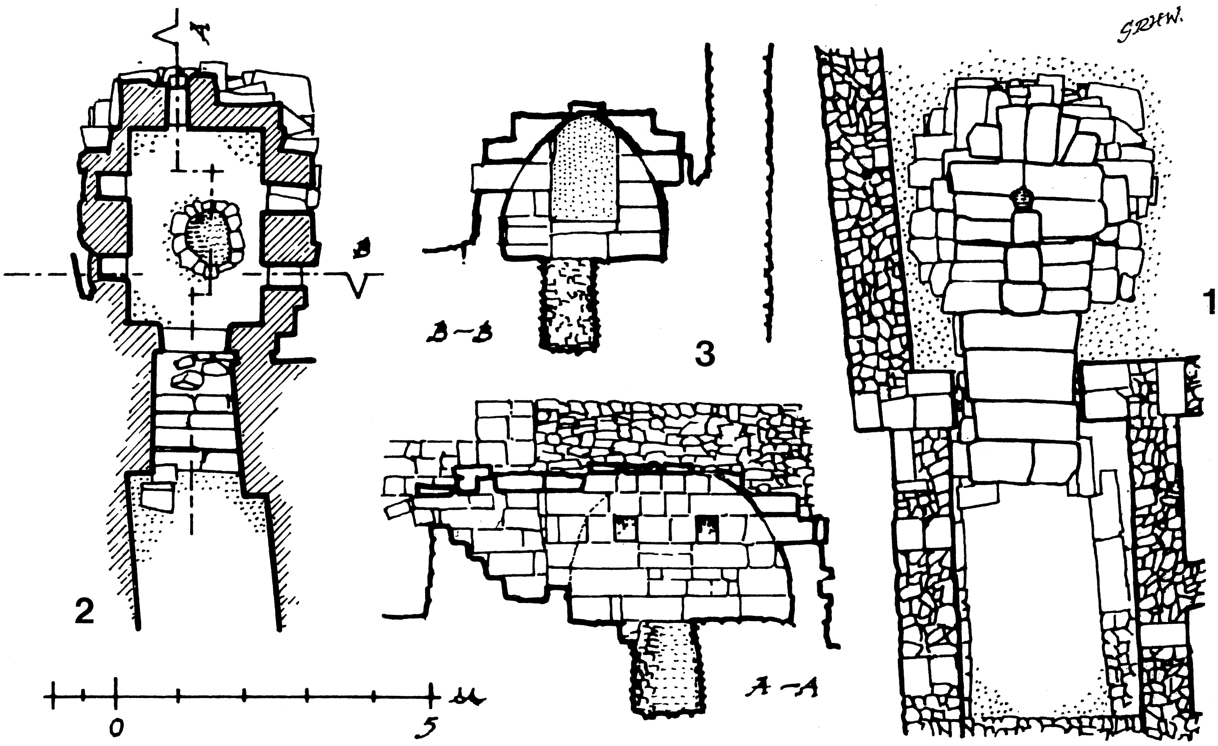
260. Dahshur. Burial Chamber of Pyramid of Amenemhat II. Axonometric Drawing showing Roofing Construction incorporating Relieving Devices. Lower Egypt. ca 1900 BC. Egyptian builders justly feared the crushing force of the superincumbent pyramid masonry on the roofing of chambers and sought to design ‘fail safe’ structures. Two were incorporated in this system. In the first instance a series of relieving triangular arches (5). If any of these arches gave way, then below there was another series of massive slab roofed vaults (3, 4). Only if these also failed was the slab roofing (2) affected. A defect in this design was not to hollow the soffites of the massive stone beams (3) so that they did not bear on the slabs (2) but discharged any load which fell on them onto the walls of the chamber. *Key*: 1. Chamber; 2. Roofing Slabs; 3. Tall Beams supporting; 4. Relieving roofing slabs; 5. Inclined beams for relieving “triangular arches”. After Arnold, p. 194, fig 4.132.



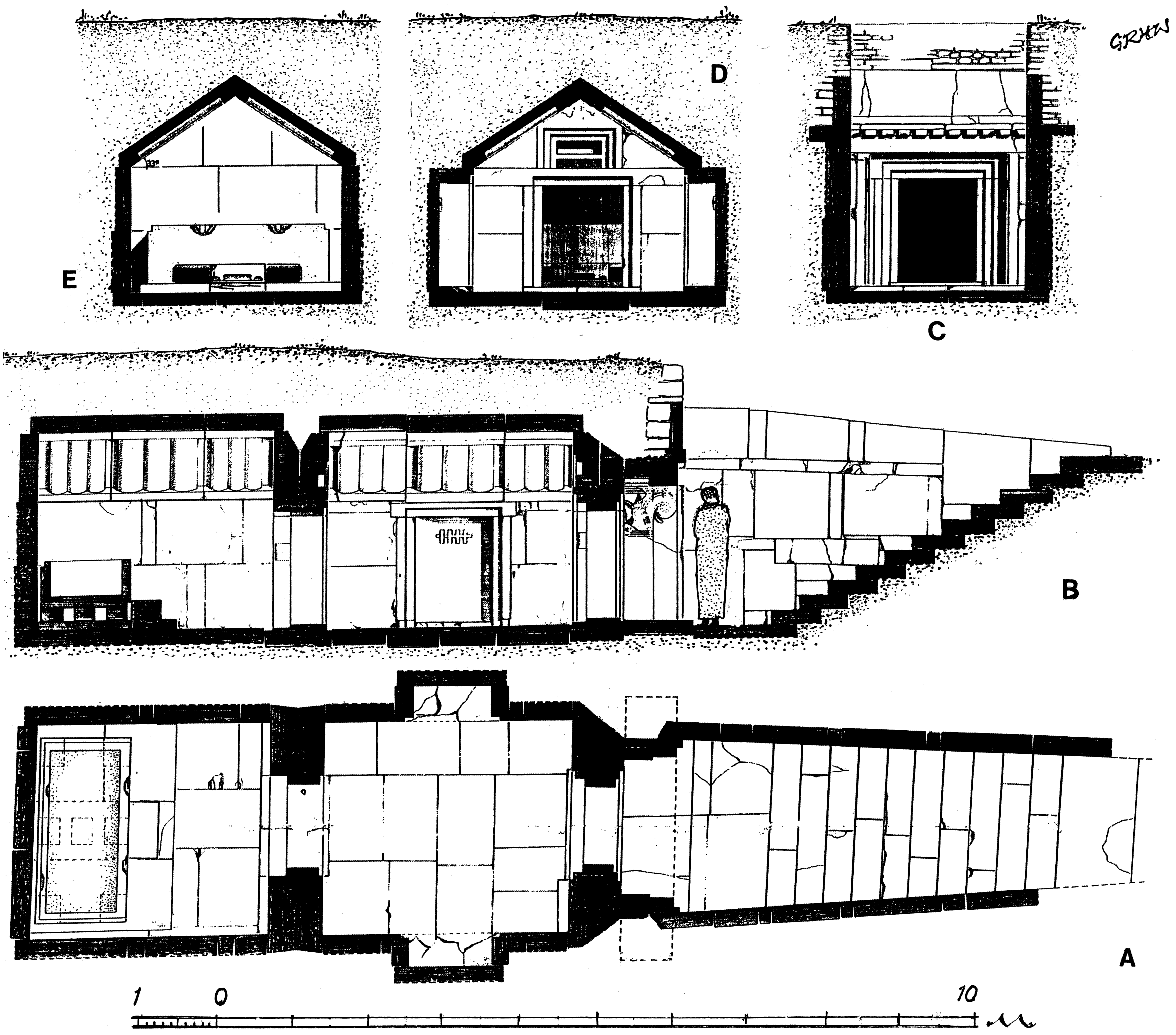
261. Sakkarah. The Triangular Vault in Old Kingdom Egypt. *Right*: Mastabat Fara'un in the Burial Chamber of Shepsekarf. ca 2500 BC. The chamber is roofed with heavy stone slabs inclined together to form a triangular vault, but the soffites have been hollowed out to simulate a pleasing (catenary) profile; *Left*: Pyramid of Pepi II. The Burial Chamber. ca 2190 BC. The chamber is roofed with very massive stone blocks inclined together to form a triangular vault. The soffite is meticulously decorated with stars to represent the canopy of heaven. NB Both forms were reproduced exactly among the underground built tombs of Late Archaic Cyprus two thousand years later – including the starry sky decoration (cf ABC II Ills 195, 197, 199). After Lauer Saqqarah, Pls 148, 150.



262. Medinet Habu. The Funerary Chamber of the God's Wife Shepenupets I. Sections showing Construction of (pitched) Vaulting Stone Roof. The roofing is out of flat slabs, set radially as voussoirs, constructed as a series of unbonded contiguous arches. These arches are erected not vertically, but slightly canted backwards to to rest against the rear wall of the chamber according to the technique of pitched mud brick vaulting. (The structural advantage of this device here is not immediately apparent). After Wesenberg pp 256-57, fig 6.

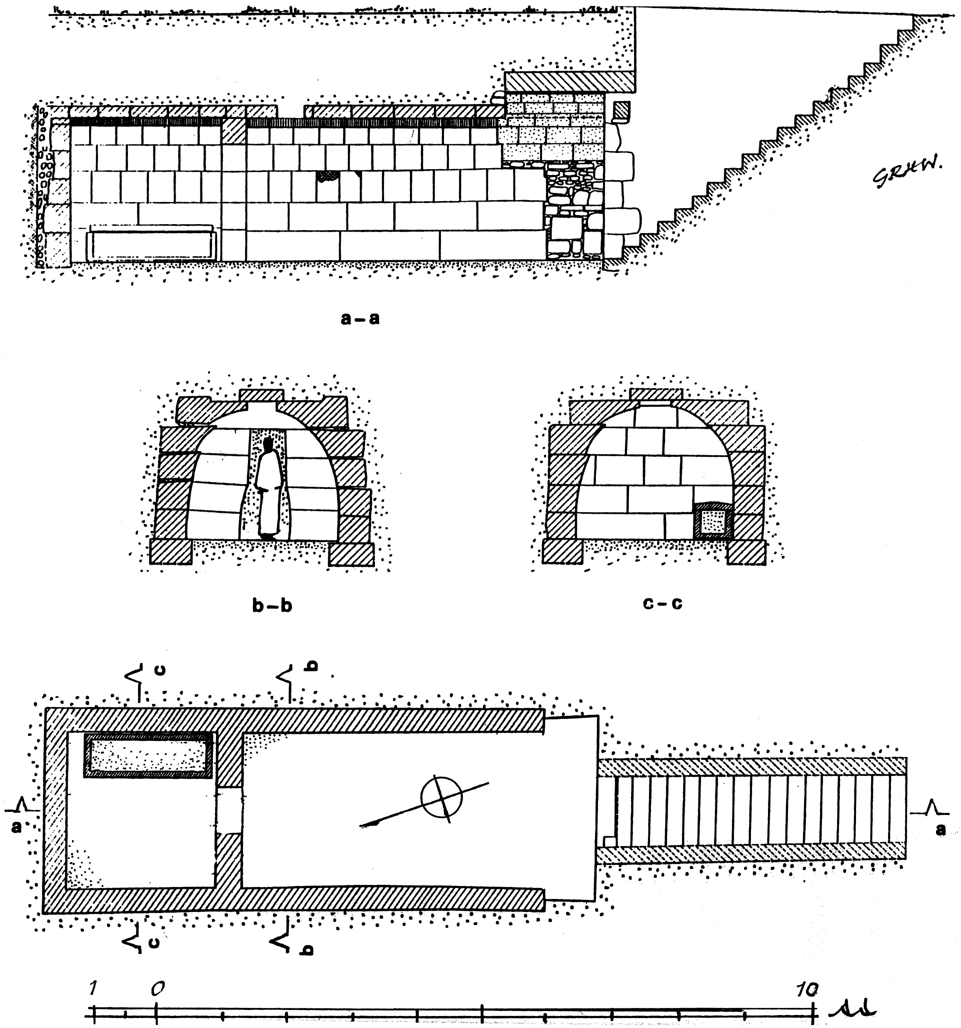


263. Ugarit. Corbel Vaulted Underground Tomb constructed in Bronze Age Bastard Ashlar Masonry. Ras Shamra, North Syria. ca 1300 BC. These family tombs were set down into the tell debris below the houses of wealthy merchants and entered by steps down from open courtyard areas. The vaulting was of corbelled construction – i.e. the blocks were corbelled out slabs not voussoirs; but the visible soffites were dressed to give a pointed two centred arch profile. *Key*: 1. Roof Plan; 2. Ground Plan; 3. Section B-B across vaulted chamber; Longitudinal Section A-A through chamber. After ABSP II, fig 273.

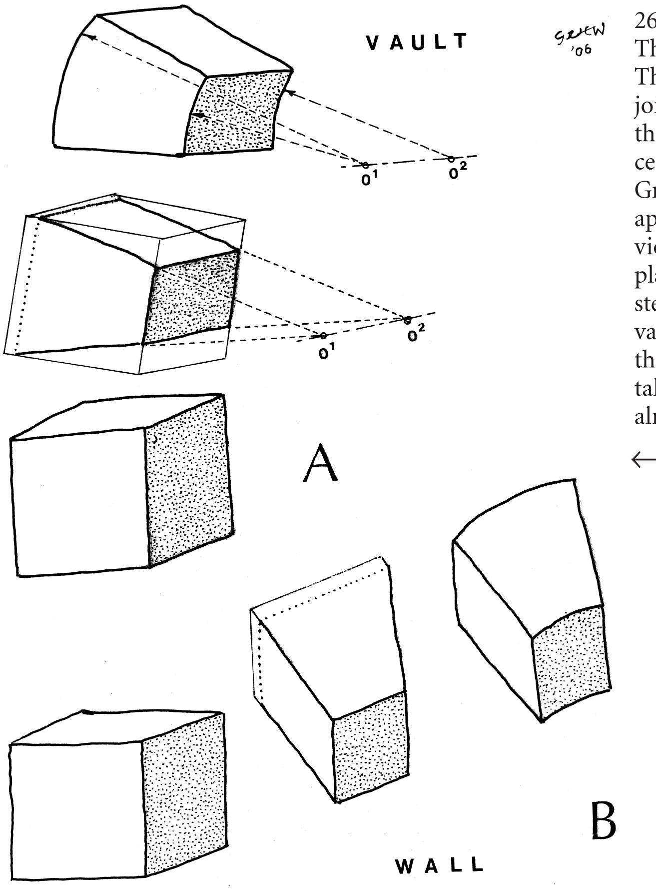


264. Tamassos. Royal Tomb. Plan and Sections. Underground Built tomb roofed with triangular vaulting. Cyprus 650 BC – 600 BC. The intact roofing is constructed of paired slabs inclined at 33° to the horizontal and abutting at the apex to form a triangular vault. The soffites of these inclined slabs are carved to represent a gabled roof of substantial logs. There are two possible analyses of the occurrence here of this form. That it is a skeuomorphic representation in stone of a wooden gabled roof current in Cyprus (or nearby regions) at the time. Or that it is a style of stone roofing for underground chambers and passageways developed elsewhere and introduced into Cyprus. Evidence can be adduced for both explanations. Tumulus tombs in Anatolia at this period contain wooden chambers gable roofed with logs in this fashion. On the other hand the stone slab triangular vault was a roofing device for underground passages and chambers in Pharaonic Egypt from the Pyramid Age onward. Since this style of roofing also occurs in Phoenecia it is easy to associate its appearance in Cyprus with Phoenecian influence via Larnaka (Buchholz Die Konigsgraber von Tamassos pp 22-27). *Key*: A. Plan; B. Longitudinal Section; C. Cross Section through Dromos; D. Cross Section through Antechamber; E. Cross Section through Burial Chamber. After ABC II fig 199.

265. Tamassos Royal Tomb. View from Antechamber into Burial Chamber. Cyprus 650 BC – 600 BC. This view shows the triangular vaulted stone roof with soffite carved to represent timber construction.



266. Kition. Evangelis Tomb. Plan and Sections of Monumental Underground Built Tomb with Corbel Vaulted Roofing. Larnaka Cyprus. ca 500 BC. The fine masonry corbelling is dressed so that the internal profile is a barrel vault. After ABC II, fig 210.



267. The Stereotomy of Ashlar Arcuated Construction. (A) The stereotomy for cutting a voussoir for a barrel vault. The upper and lower beds diverge radially but the rising joints are parallel. The face and the rear (the intrados and the extrados) are rectangular delimited areas of two concentric cylinders. The masonry techniques appeared in Greece during the latter half of the 4th Century BC, as an apparent innovation. However for 3 or 4 generations previously Greek Masons had built structures on curvilinear plans where the wall blocks embodied exactly the same stereotomy. Only the curvature in the voussoir of a barrel vault was disposed vertically, whereas in a wall block of a tholos or a semi-circular exedra it was disposed horizontally (B). The basic stereotomy of ashlar vaulting was thus already to hand.

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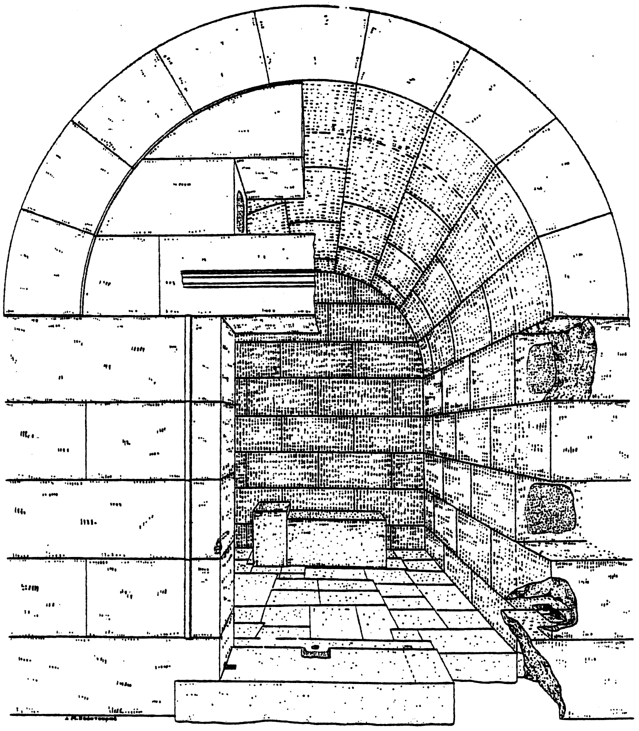

268. Vergina. Early Macedonian Underground Vaulted Chamber Tomb. Macedonia. Later 4th Century BC. The earliest examples are of simple basic design, without monumental façades which later became notable features. The chamber is roofed by a true barrel vault of ashlar masonry. There are several explanatory factors for this initial use of ashlar vaulting, both structural and aesthetic. The inward pressure of the earth tumulus provided an ample abutment for the lateral thrust of the vaulting. Also the fact that the vault masonry was out of sight under the earth meant that it did not offend traditional taste by lack of dignity in aspect. On the other hand internally its contours are that of a natural cavern with all its symbols. After B d A, p. 257, fig 9.

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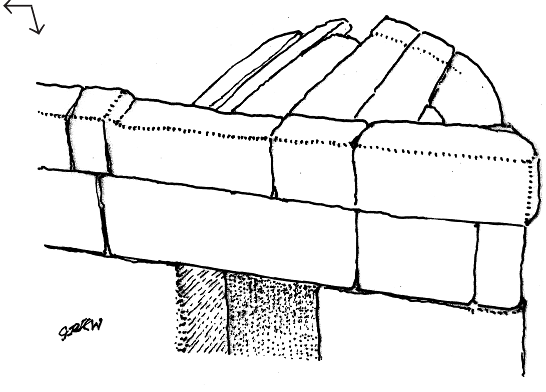
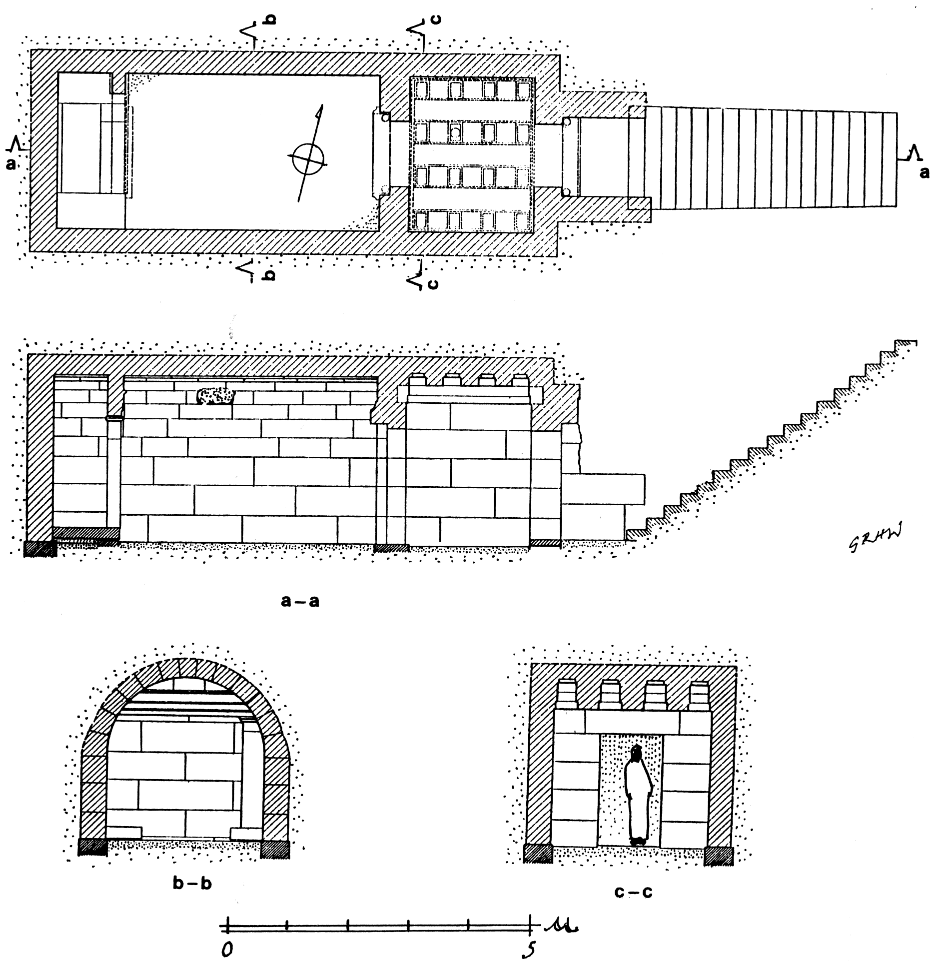
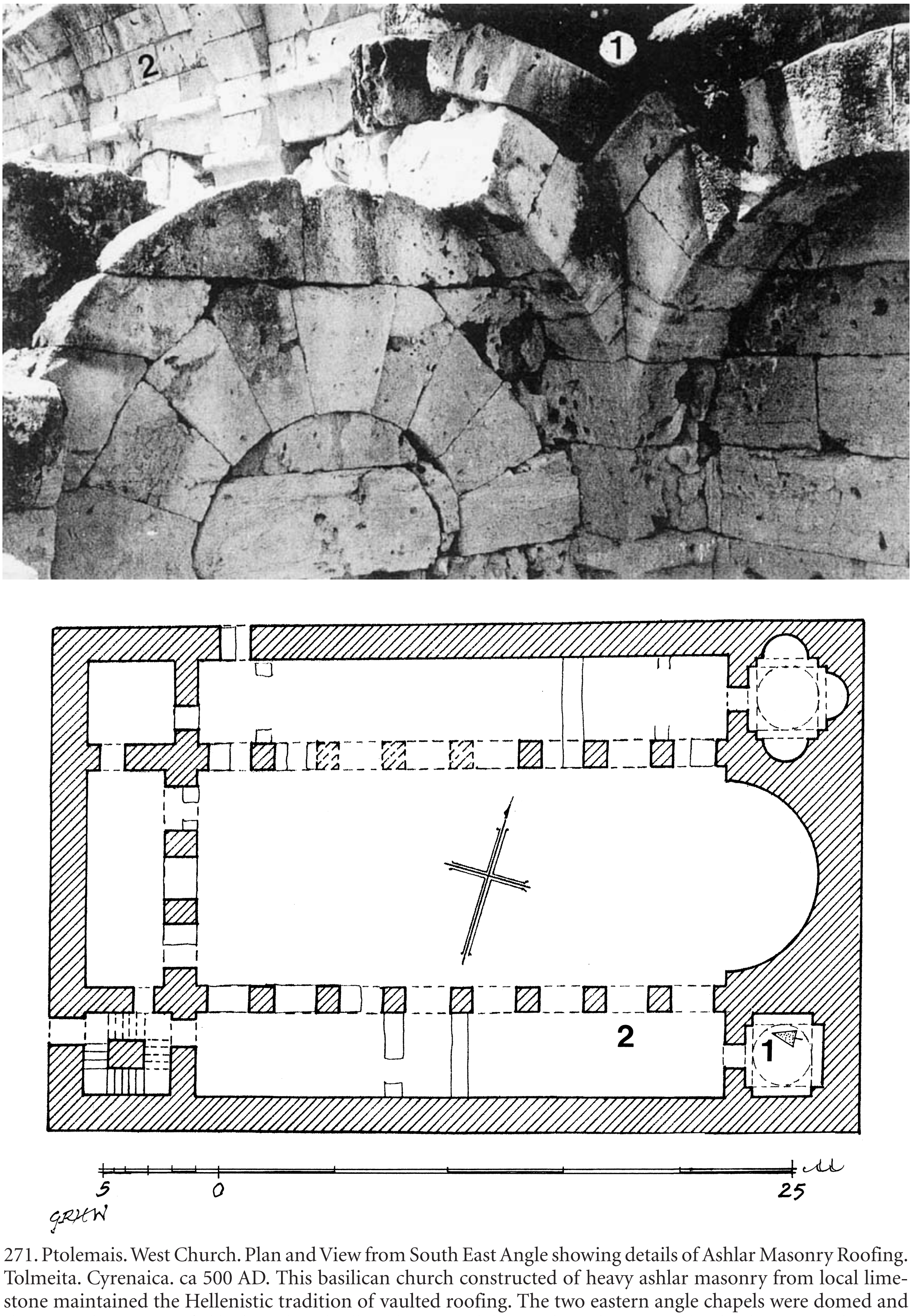




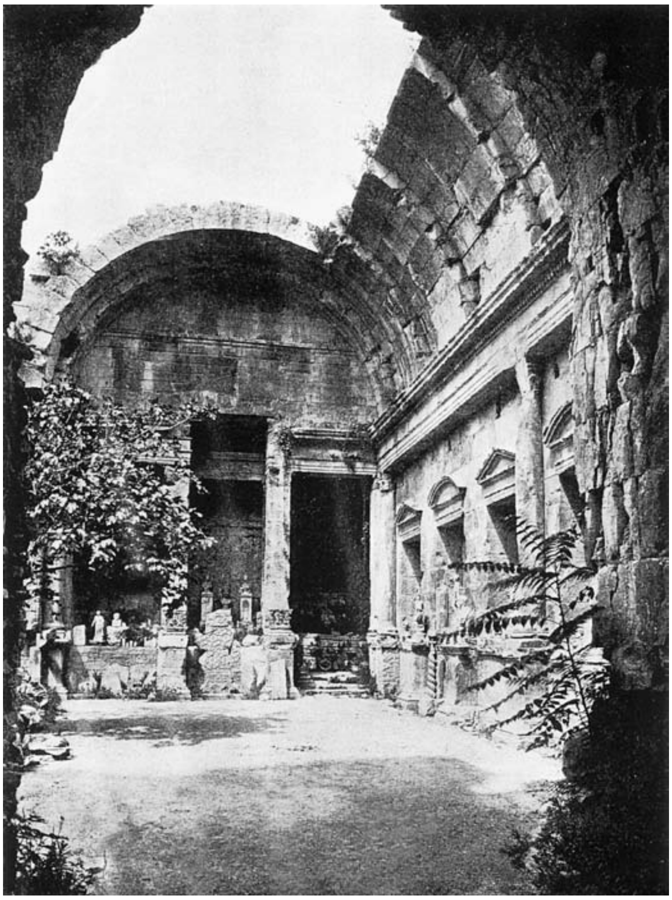
269. Kition. Cobham's Tomb. Plan and Section of Monumental Underground Built Tomb with true Ashlar Vaulted roof. Larnaka, Cyprus. Roman. The roofing of the antechamber is trabeated with an ornamental coffered ceiling in the classical tradition. The roofing of the chamber is a true barrel vault with radially set voussoirs. After ABC II, fig 211.

270. Ain Thunga. Ruins of Small Triumphal Arch exposing Ashlar Vaulting of Passageway. Tunisia. ca 2nd Century AD. The construction of ashlar barrel vaulting in the classical world remained unchanged from its first appearance during the later 4th Century BC in the Macedonian Vaulted Tombs. It was highly functional for roofing passageways, corridors, etc; but it was virtually never exposed to external view – cf the unusual appearance of the ruins of this small Triumphal Arch where the structure of the ashlar vaulting is now exposed.

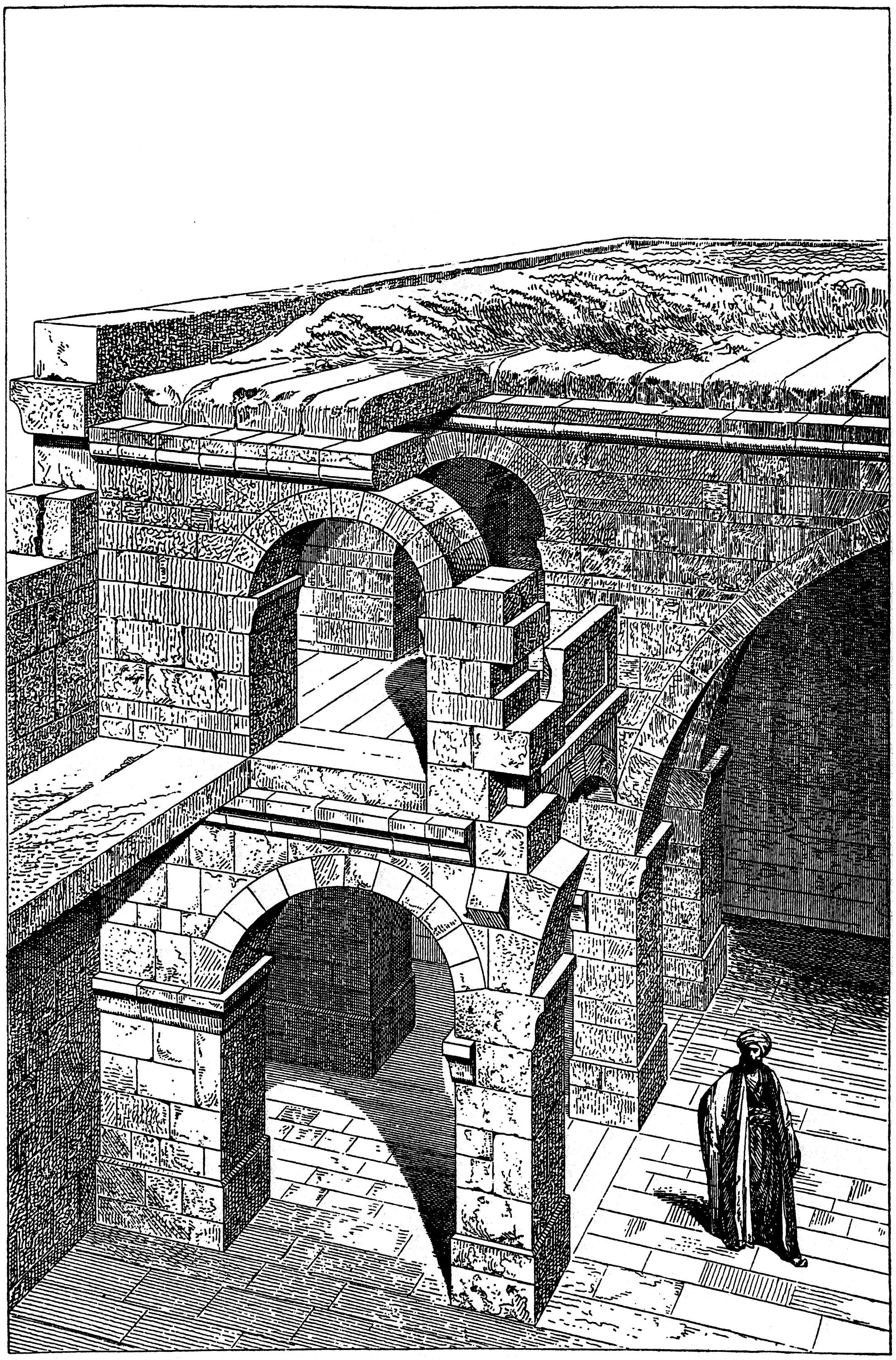


271. Ptolemais. West Church. Plan and View from South East Angle showing details of Ashlar Masonry Roofing. Tolmeita. Cyrenaica. ca 500 AD. This basilican church constructed of heavy ashlar masonry from local limestone maintained the Hellenistic tradition of vaulted roofing. The two eastern angle chapels were domed and the two aisles were roofed by barrel vaults (largely restored during the Italian regime). The dome over the angle chamber was carried on pendentives (1); and the barrel vaulting over the South Aisle was stiffened by transverse rib arches (2).

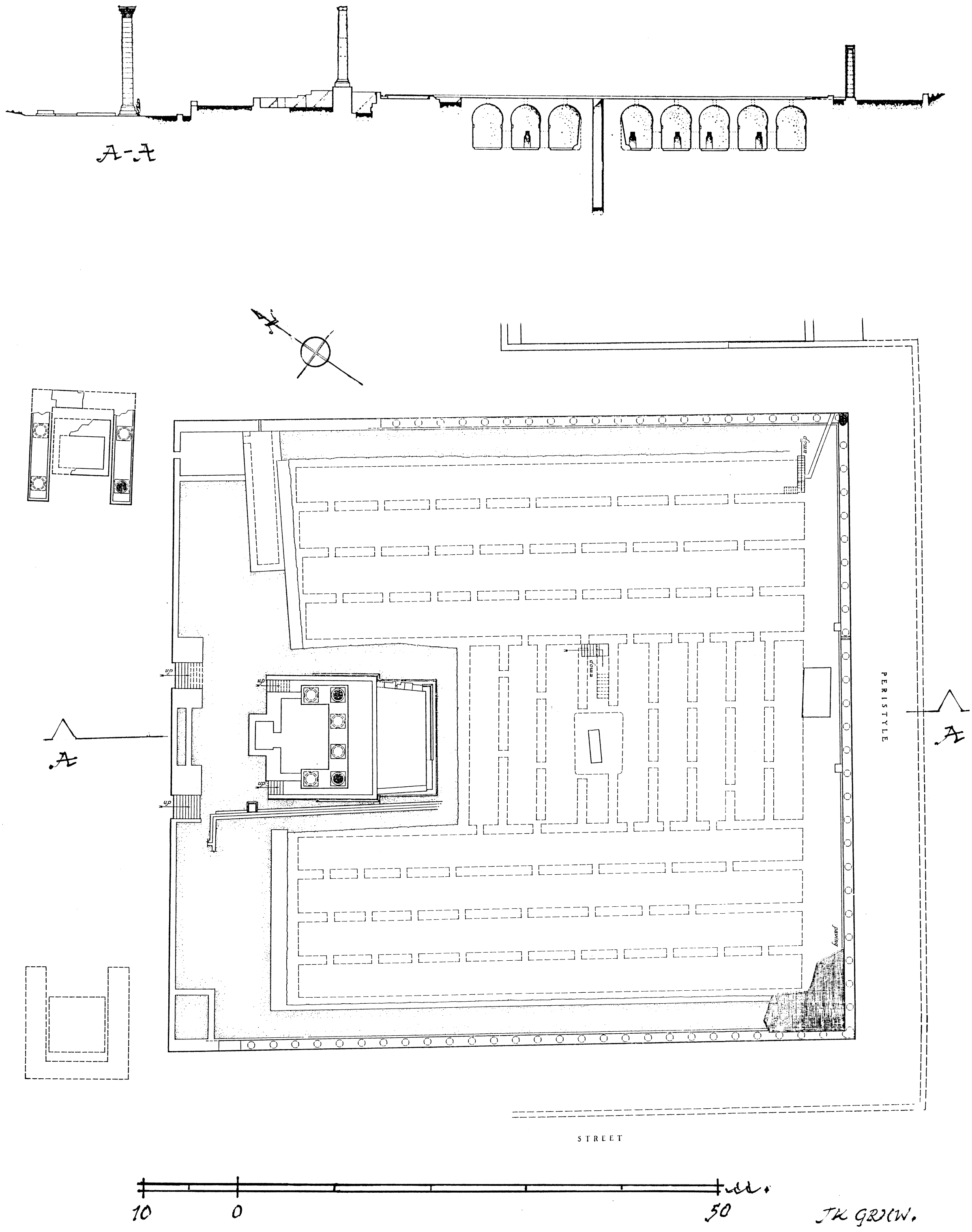
272. Thysdrus. Amphitheâtre. Aerial Photograph of large scale Vaulted Construction. El Jem, Tunisia. ca 240 AD. This large amphitheatre modelled on the Colosseum was unfinished, which together with its present state of ruin exposes to view the pervasive incidence of barrel vaulting in its structure. The circulation both horizontal and vertical was effected by barrel vaulted passages. This vaulting could be constructed in ashlar masonry, rubble masonry or Roman Concrete.



273. Nemausus. The Temple of Diana (Fountain House). Hybrid Barrel Vaulting. Nîmes. ca 120 AD. Ashlar arcuated construction inter bred with stone slab roofing. The present roofing construction may be thought of as ribbed barrel vaulting with the load bearing elements, the rib arches and the slabs spanning between the cladding. However this is not a valid analysis. The slabs are structural members which at the crown of the vault are stressed in bending. This construction is a true hybrid and would be difficult to analyse mathematically. After Robertson, Pl XV.

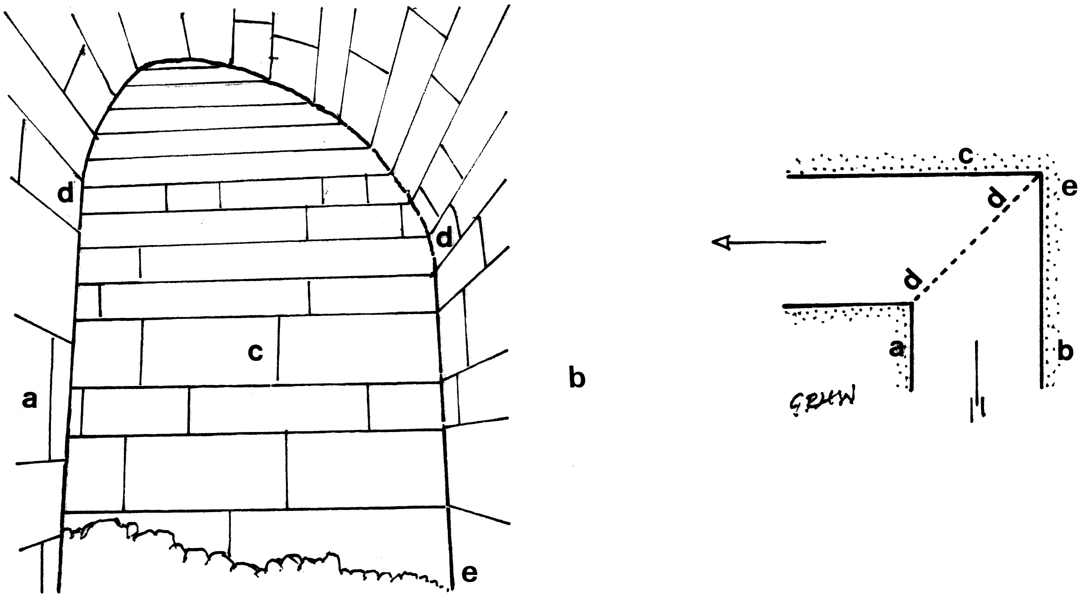


274. Shaqqa. Basilica. Stone Slab roofing carried on Arches. The Hauran, Central Syria. ca 200 AD. The interior of Central Syria is a vast stony landscape formed by ancient basalt lava flows. Wood is unavailable and stone omnipresent. Thus building construction was generally entirely of stone, including the roof – but the preference was for a flat stone slabbed roof. The hybridisation here consisted in that the supports for these roofing slabs were not pillars/columns and beams, but arches (or rather cross walls pierced by arches). After Robertson, p. 239, fig 99.

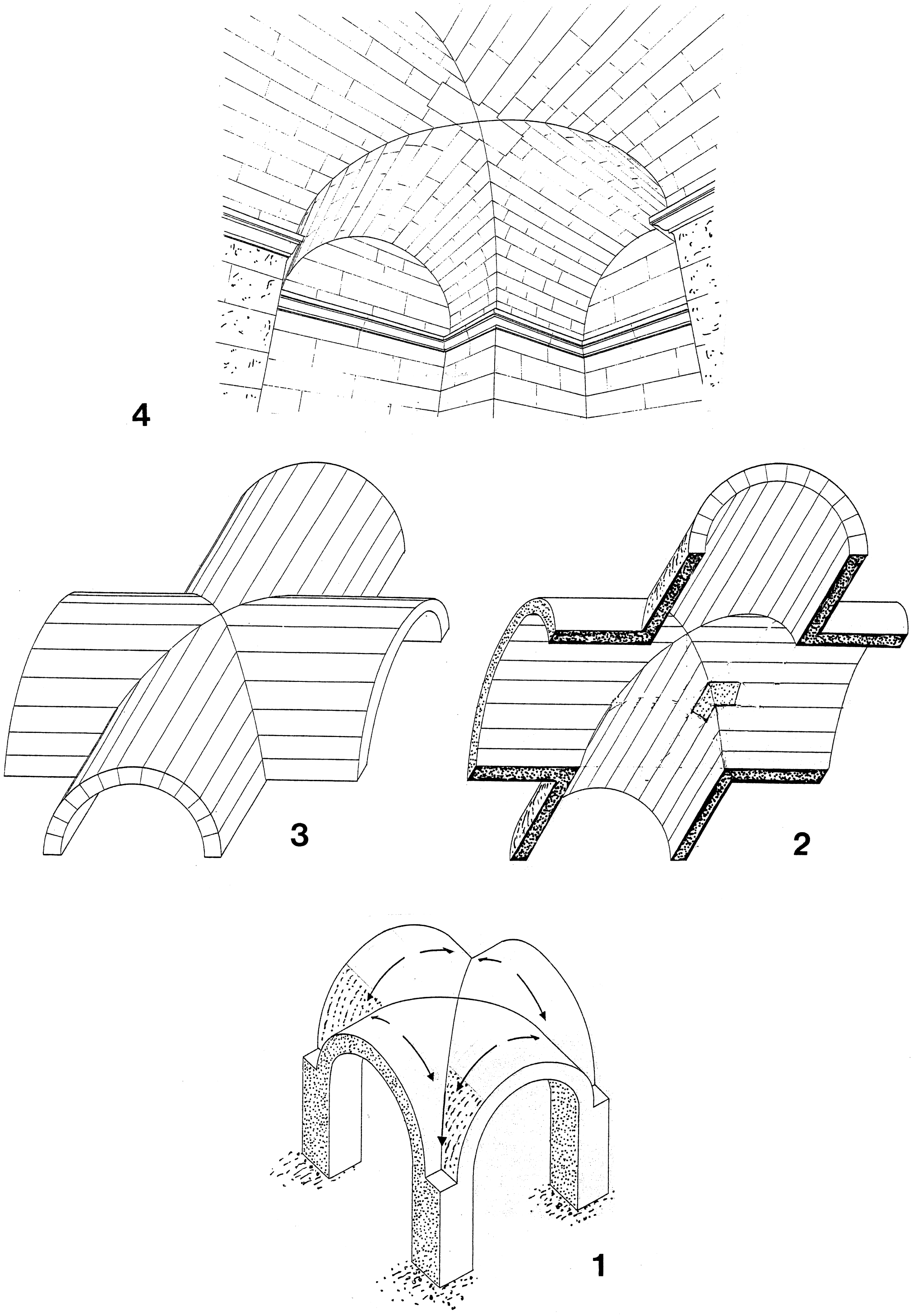


275. Ptolemais. The Square of the Cisterns Long Barrel Vaulted Reservoir entirely of Rubble Construction. Tolmeita, Cyrenaica. ca 2nd Century AD. A monumental columnar plaza built in the uppermost reaches of the city affords an extensive cachement area and the run off is stored in a vaulted substructure of many compartments. The construction is of rubble masonry with waterproof plastering, not of Roman Concrete. (The region adheres to the Oriental Hellenistic masonry tradition). After Ptolemais. Plans V & VI.

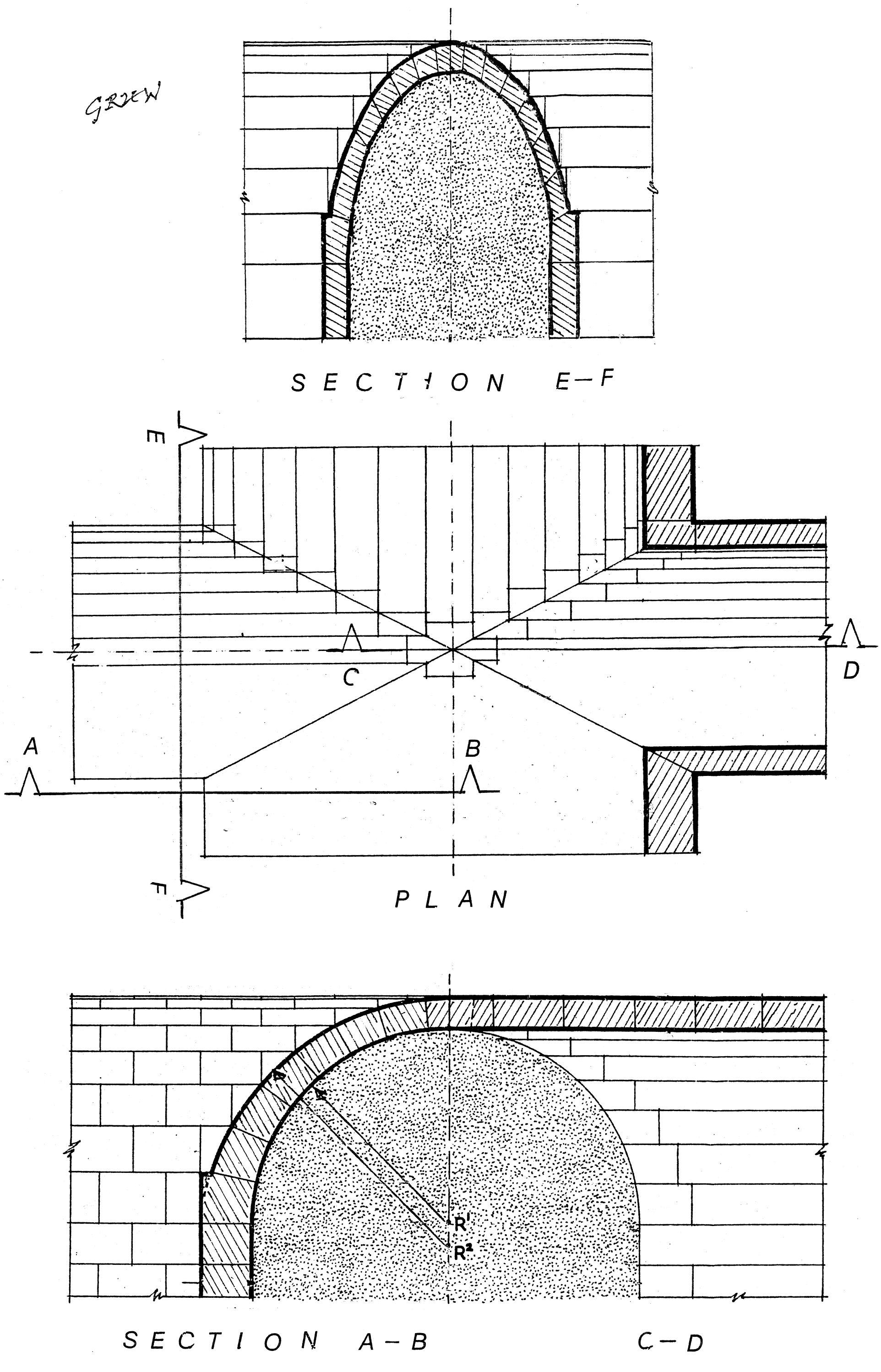
276. Siret el Reheim. Barrel Vaulted Cisterns of Rubble Masonry Construction. Cyrenaica. ca Early 6th Century AD. A pair of vaulted cisterns set against the enclosure wall of a church, probably from the time of Justinian are of utilitarian construction. The barrel vaulting of depressed parabolic contour is constructed of long flat field stones set radially in strong mortar. Cisterns of similar construction occur elsewhere in the region. After Christian Monuments of Cyrenaica, p. 359, ill 303.



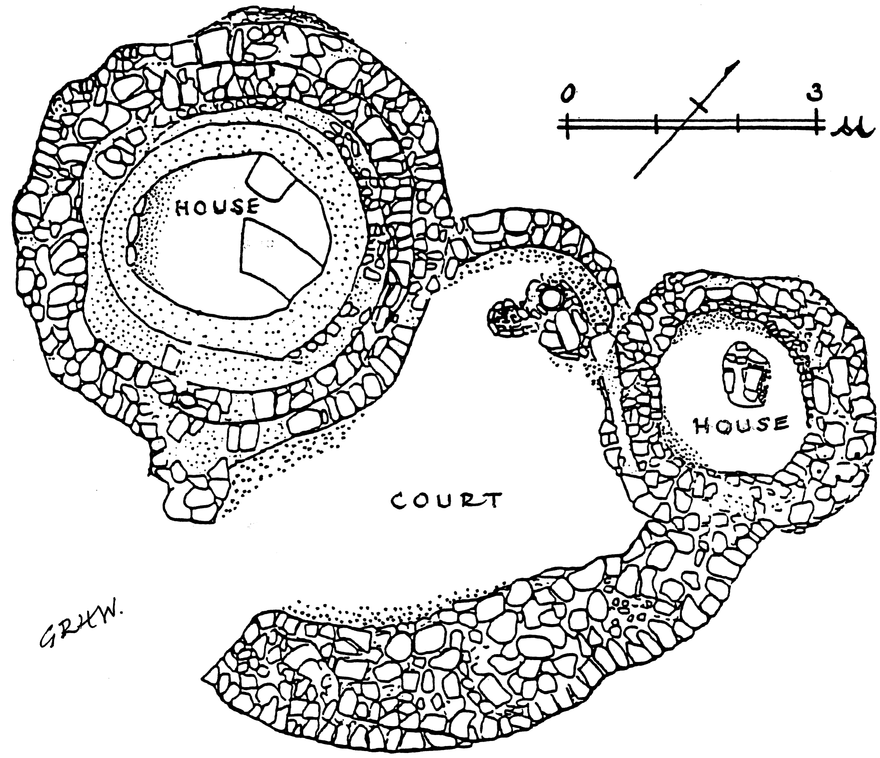
277. Alinda Theatre. Groined Ashlar Masonry Barrel Vault over Angled Passageway at rear of Cavea. S.W. Anatolia. ca 2nd Century BC. *Right*: Plan – diagram of passageway. *Left*: One point perspective view showing groin. After AJA 82 1978, p. 96, fig 12.



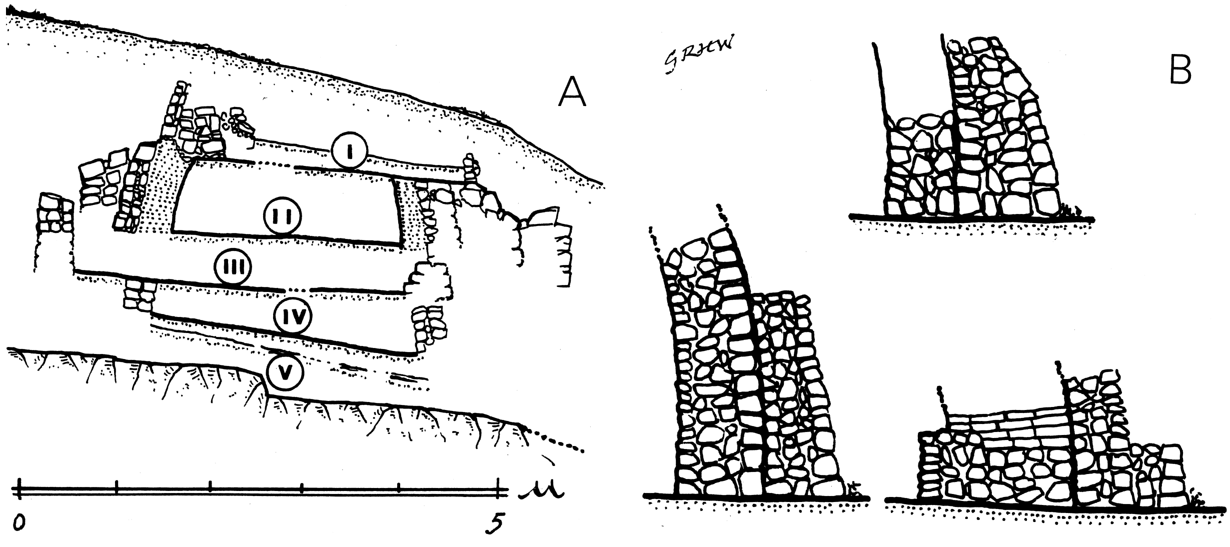
278. Diagram Illustrating Groined Ashlar Cross Vaulting. The simplest form is that generated by the intersection at right angles of two similar hemispherical barrel vaults. This ideal solution to the vaulting of a square bay was applicable whether or not the overall plan was cruciform. It could be used to roof a square chamber (4) or an open pavilion formed by 4 arches on piers (1). Here the distribution of the load is shown by arrows indicating the transmission to piers. The axometric views (2 & 3) show the interpenetration of the vaulted arms of a cruciform plan from above (3) and from below with a groin stone stippled (2). View (4) shows an actual view from below of a cross vault in the Mausoleum of Theodoric the Ostrogoth at Ravenna (ca 520 AD).



279. Diagram, Plan and Section illustrating the Roofing of the Crossing of two Intersecting Ashlar Masonry Vaults of the same Height but not of the same Breadth. This was very unusual in Roman masonry practice, which by various devices generally avoided the intersection of vaults of different spans. To bring the narrower vault up to the same height as the broader meant giving the former vault a different (steeper) profile, i.e. non-hemispherical, if the broader vault was hemispherical. This device became a fundamental of Gothic architecture with its pointed arches where the contour of the arches could be readily varied.

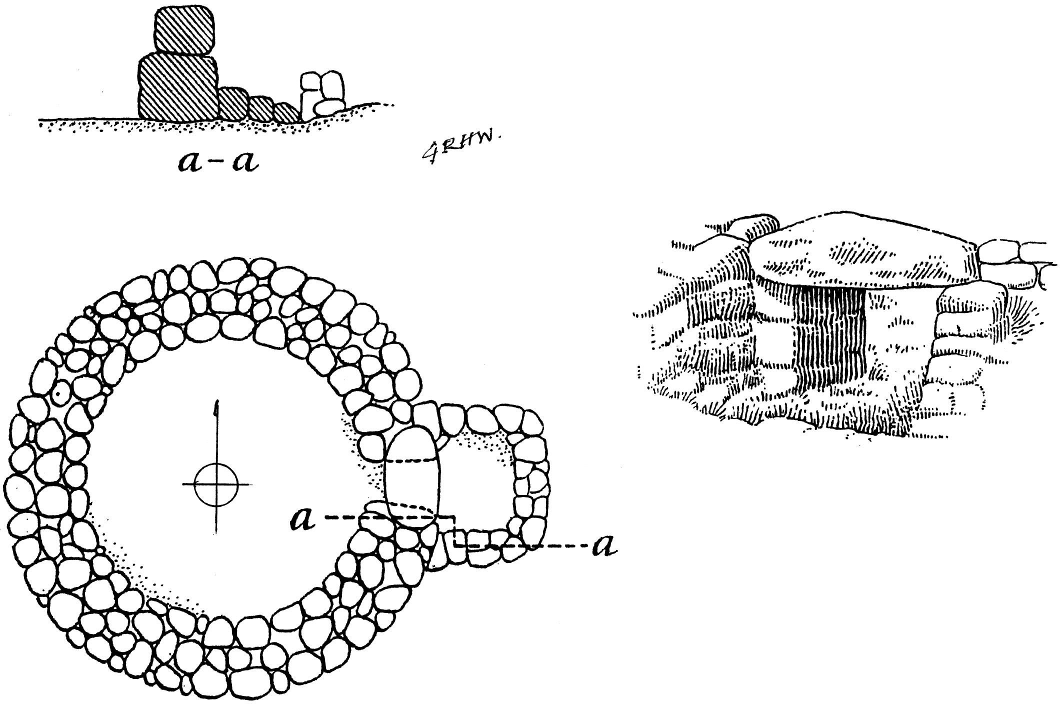


280. Khirokitia. Pre-pottery Neolithic Round House Complex. Southern Cyprus. 8th – 7th Millenium BC. The exclusively curvilinear lines of the plan betoken a mentality entirely conditioned by this form – which is that of natural growth. It is thus unlikely that the form expressed in elevation should differ – i.e comprise curvilinear walls and horizontal roof. After Beehive House p.9, fig 2.

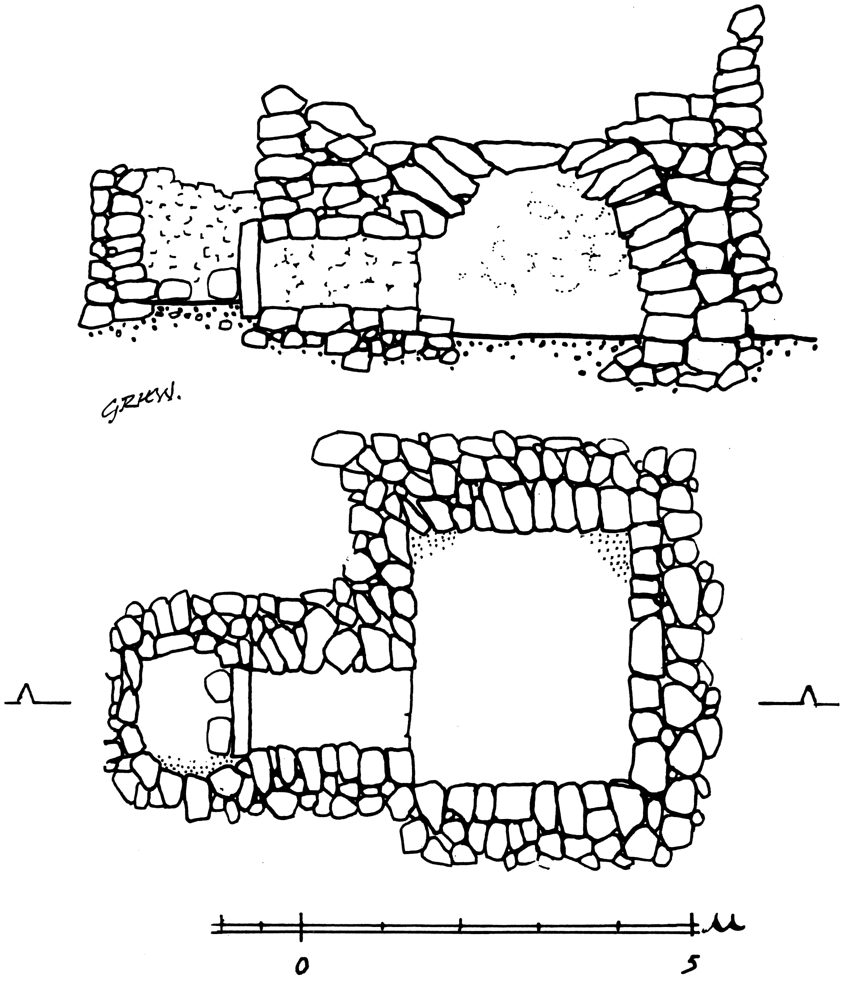


281. Khirokitia. Pre-pottery Round Houses. Sections showing Form in Elevation. Southern Cyprus 8th – 7th Millennium BC. *Key*: A. Section across a succession of 5 Round Houses (I – V) on the same emplacement. This shows a variation in the building material from the earliest (V) light wooden framed structure just above bed rock, through 4 later houses constructed out of rubble and/or mud (brick). The form was constant – a beehive vault; B. Details of Walling. Not only the profile of the walls indicate that the form of the round houses was arcuated in elevation, but the heavy buttresses of the lower part of the walls denote that the builders were aware of the lateral thrust exerted by the domical structure and provided against it. After ABC II, figs 152, 339.

282. The Messara. Typical Vaulted Tomb Artist's Reconstructed View. Southern Crete, ca 2000 BC. This imaginative drawing shows these impressive free standing masonry tombs in their impressive setting. It indicates some form of domed construction for the chamber, but leaves the precise material of construction undetermined. After Beehive House, p. 19, fig 9.



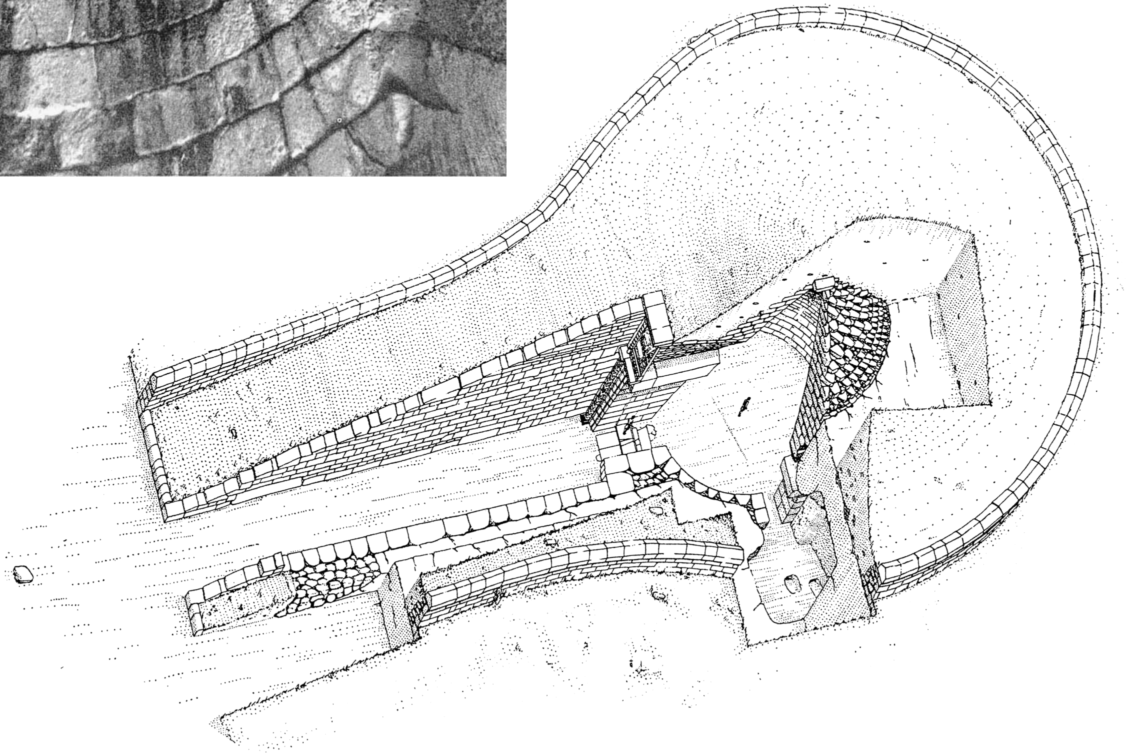
283. The Messara Type of Vaulted Tomb (Ossuary). Plan, Part Section and View of Door. Southern Crete. ca 2000 BC. These free standing monuments are numerous on the Messara Plain, and vary considerably in size (internal diameter ca 4m – 13m, and rising to perhaps 12m high). The walls are built of substantial rubble (boulders), with the door in megalithic style (cf the lintel and its resemblance to the lintel of Mycenaean tholoi). It is generally agreed that the roofing, although nowhere preserved, was arcuated – whether or not of stone construction. The walls incline inwards but are not preserved to more than 3 or 4 m. Their date falls between the latest round houses of Chalcolithic Western Cyprus and the earliest Mycenaean tholoi. Accordingly they have been seen as providing a link between the Neolithic Round House tradition and the circular tombs of the later Bronze Age. After Lawrence, p. 20, fig 16.



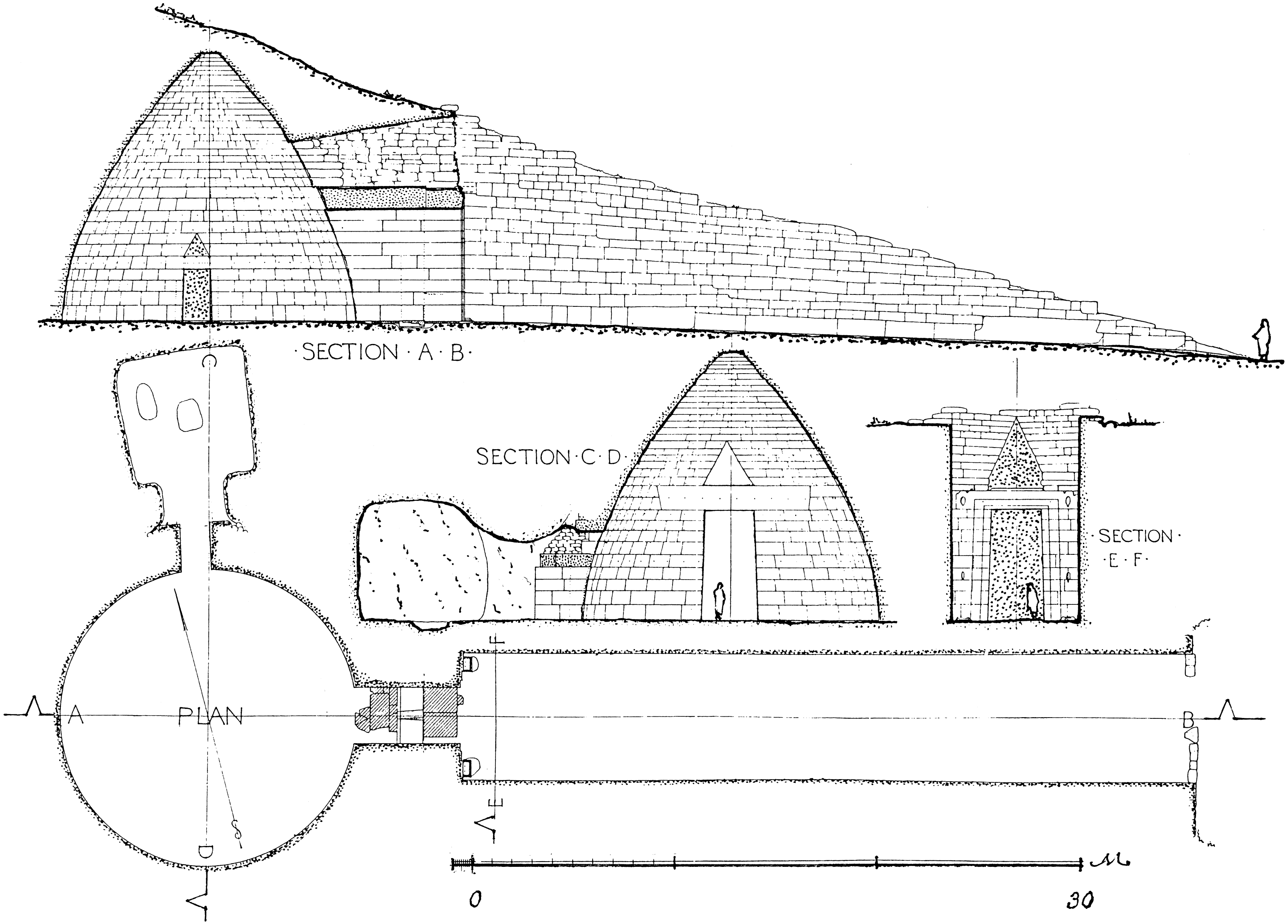
284. Megiddo. Middle Bronze Age Underground Built Tomb of Domical Construction. Tell el Mutesellim, Palestine. ca 17th Century BC. The tomb is built of heavy rubble set more or less dry stone. The construction appears to have been a continuous dome on pendentives with the voussoirs set radially (the original drawing is not fully explicit). After ABSP II, fig 274.

285. Phournos. Mycenaean Vaulted (Tholos) Tombs of Rubble Masonry. By Mycenae, Greece. 15th Century BC. *Above*: Epano Phournos, early 15th Century; *below*: Kato Phournos, late 15th Century. NB. The development during a century from random rubble to coursed, squared rubble. After Lawrence, Pls 8b, 9b.

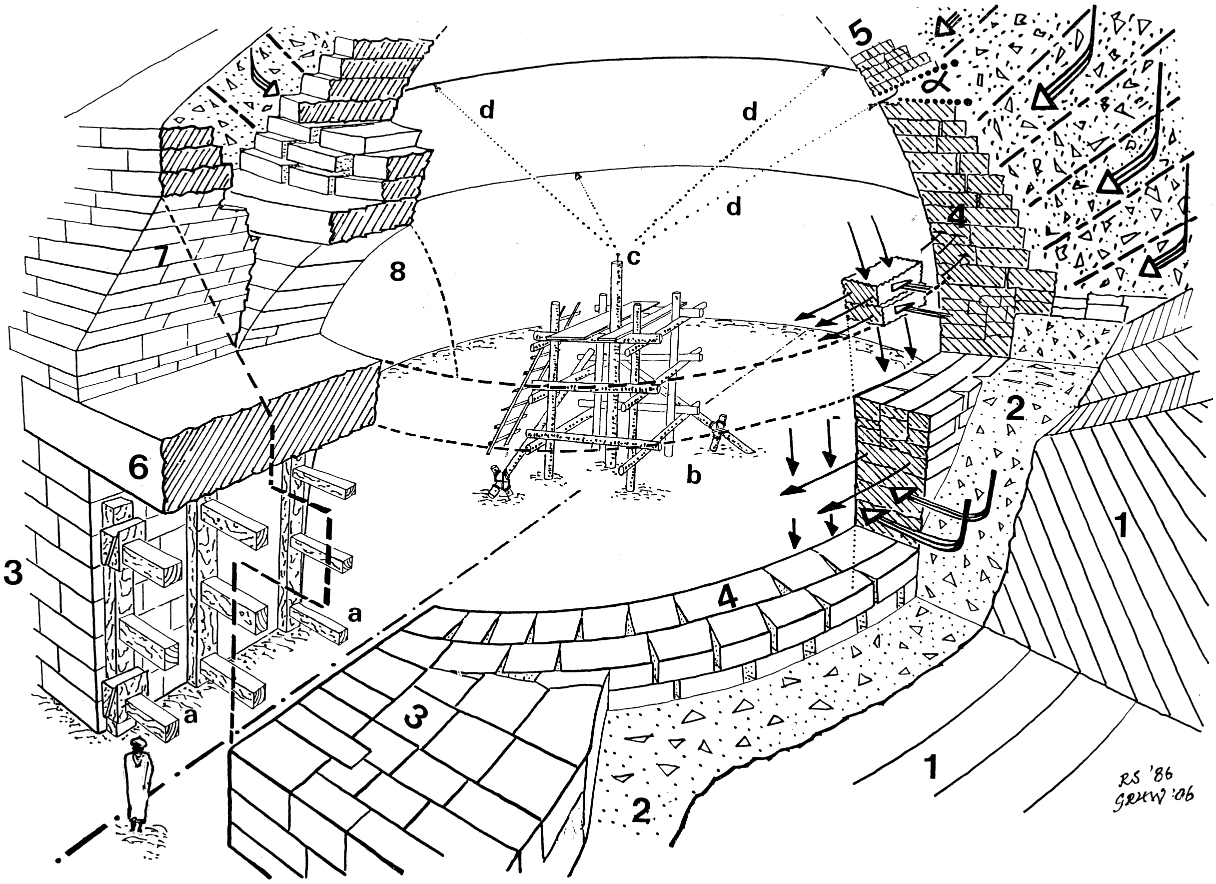
286. Mycenae. Treasury of Atreus. Tholos Tomb. Interior View showing finely dressed masonry of Bastard Ashlar type. Greece. ca 1300 BC. This masonry is interior facing to earth matrix, and the jointing is less exact behind the exposed face. The development in finely dressed monumental masonry over ca 150 years from the tholos tombs at Epano and Kato Phournos is striking. After Lawrence, pl 11.



287. Mycenae. Treasury of Atreus. Tholos Tomb. Reconstructed Analytic Drawing showing Tomb set within a tumulus. Greece. ca 1300 BC. The finely dressed stone masonry represents a later development in the chambered earthen mound tomb characteristic of Western (Atlantic) Europe up to 3 millenia earlier – the Megalithic round and long barrows. Since there is to all intents no free standing stone masonry, the masonry is Bastard Ashlar in type. After Sinclair Hood.

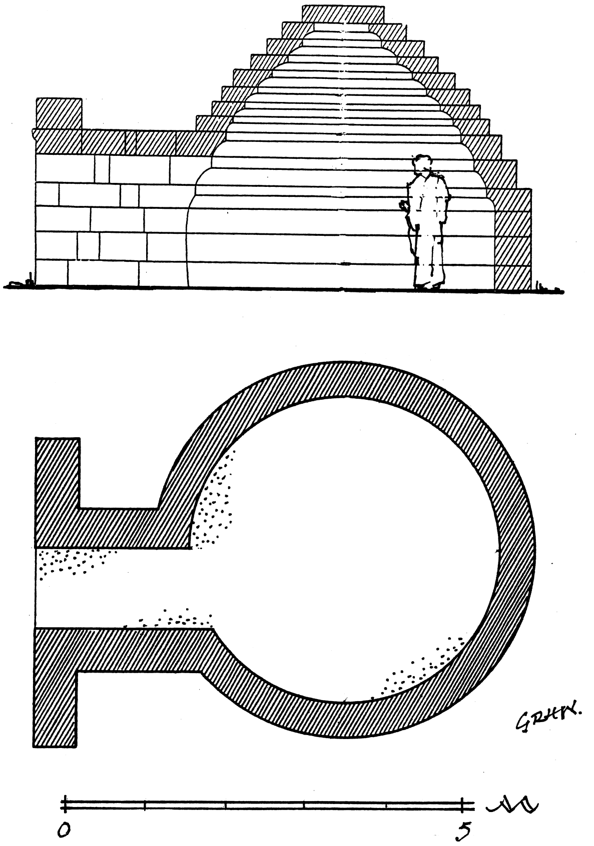


288. Mycenae. The Treasury of Atreus. Tholos Tomb. Plan and Sections. Greece. ca 1300 BC. Finely dressed large block corbelled Masonry Construction giving Beehive Vaulted burial chamber ca 15m in diameter and 13m high. After drawing by Piet de Jong.

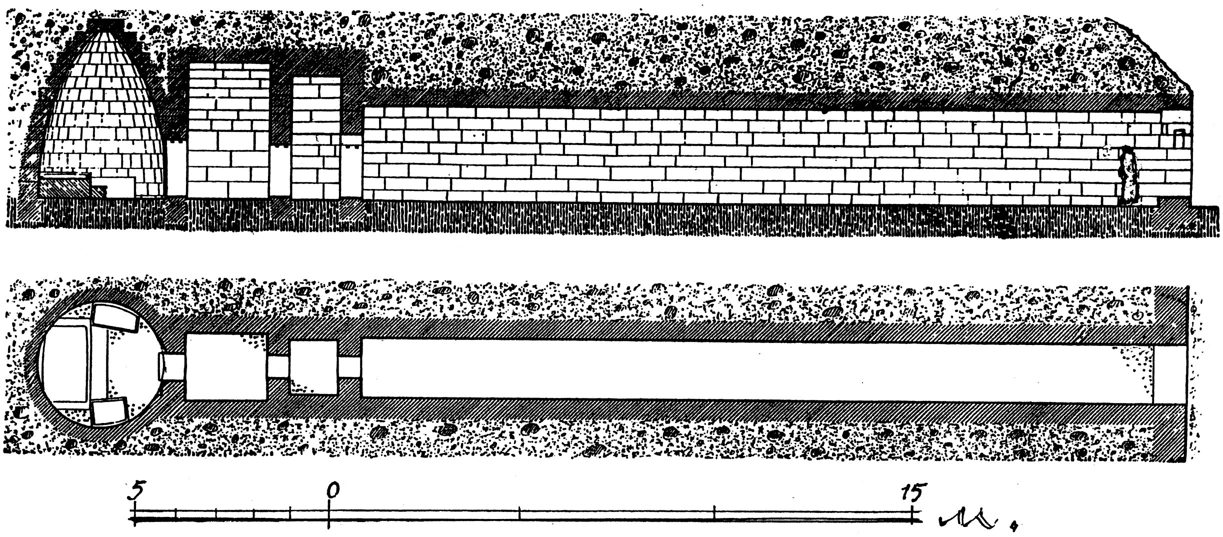


289. Mycenae. Treasury of Atreus. Santillo's Analysis of Mycenaean Tholos Construction. The heavy arrowing indicates the proposed static analysis of the structure. The gist of it is to avoid the stigma of a corbelled dome construction being any less a true dome than one with voussoirs set radially in the vertical sense. The limiting case is taken that each course of dome masonry, because of the lateral compression, behaves as a rigid unit resisting all tensile stresses, and transmitting all compressive stress from the superincumbent masonry vertically downwards – i.e. the construction is to be imagined as a succession of annular elements (e.g. metal rings) of decreasing radius placed one above the other (obviously a stable assemblage). *Key*: 1. Excavated Terrain; 2. Earth debris and fill; 3. Finely dressed closely jointed ashlar masonry; 4. Bastard ashlar facing to earth fill with splayed rising joints; 5. Masonry at crown of tholos set as radial voussoirs; 6. Megalithic lintel; 7. Relieving triangle; 8. Relieving arch; (a) Wooden strutting. Flying shoring across entrance gap to maintain tholos masonry in lateral compression. (Further secured against displacement by dead weight of Megalithic lintel.); (b) Wooden Scaffold device to give centre of 'Beehive' tholos masonry; (c) Nail for attaching cord to give radii of successive courses; (d) Cords to control positioning of masonry. After Op Ath XV 1984, p. 47, fig 1.

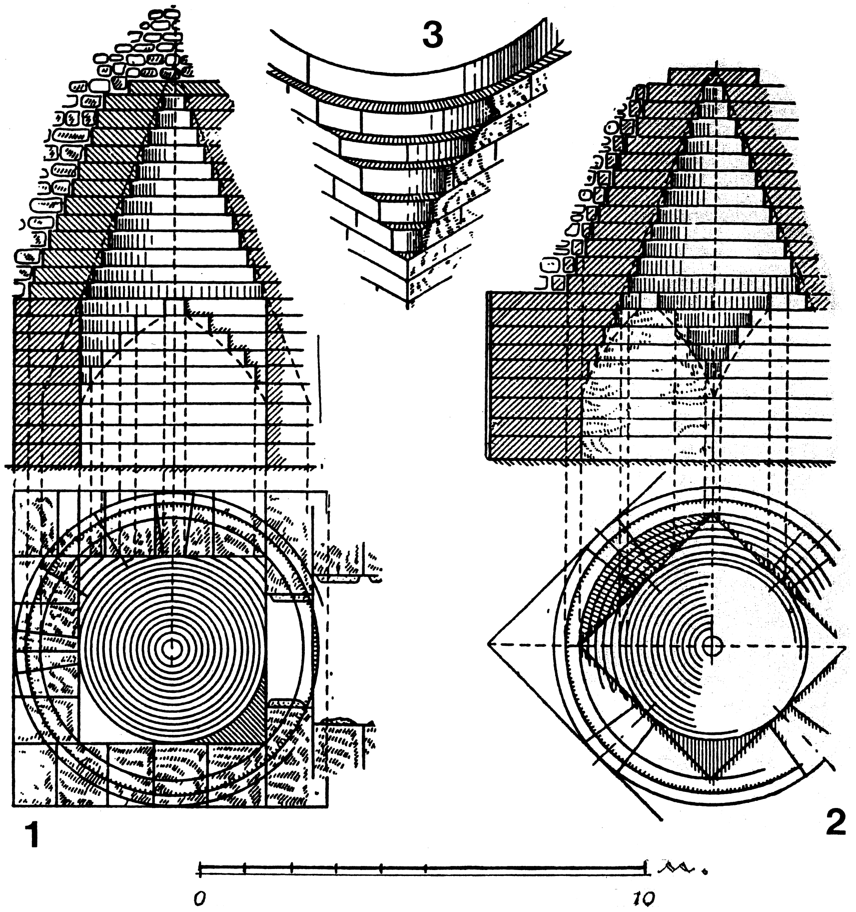
290. Vetulonia. Tomba della Pietrera. View of Angle of Etruscan Tomb Chamber showing rudimentary pendentive construction. Etruria. 7th Century BC. Transformation of square chamber into circular plan for base of domical roofing by way of corbelled courses. After Plommer, pl 16.



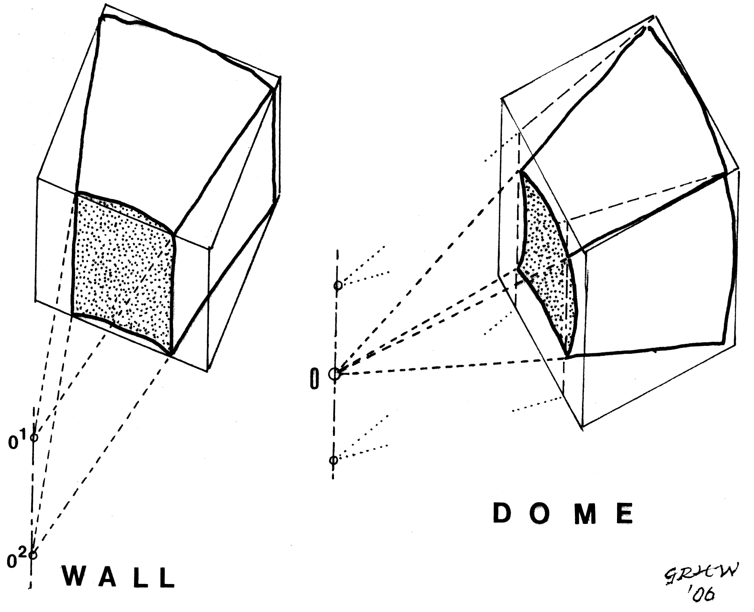
291. Kirk Kilisse. Thracian Prince's Tumulus Tomb of Beehive Vaulted construction. Plan and Section. Thrace. 5th Century BC. The circular chamber entered by a short passageway is roofed with a corbelled conical vault. The intrados of each course is carved into a cavetto moulding which gives an oriental aspect. After Orlandos 2. fig 259.



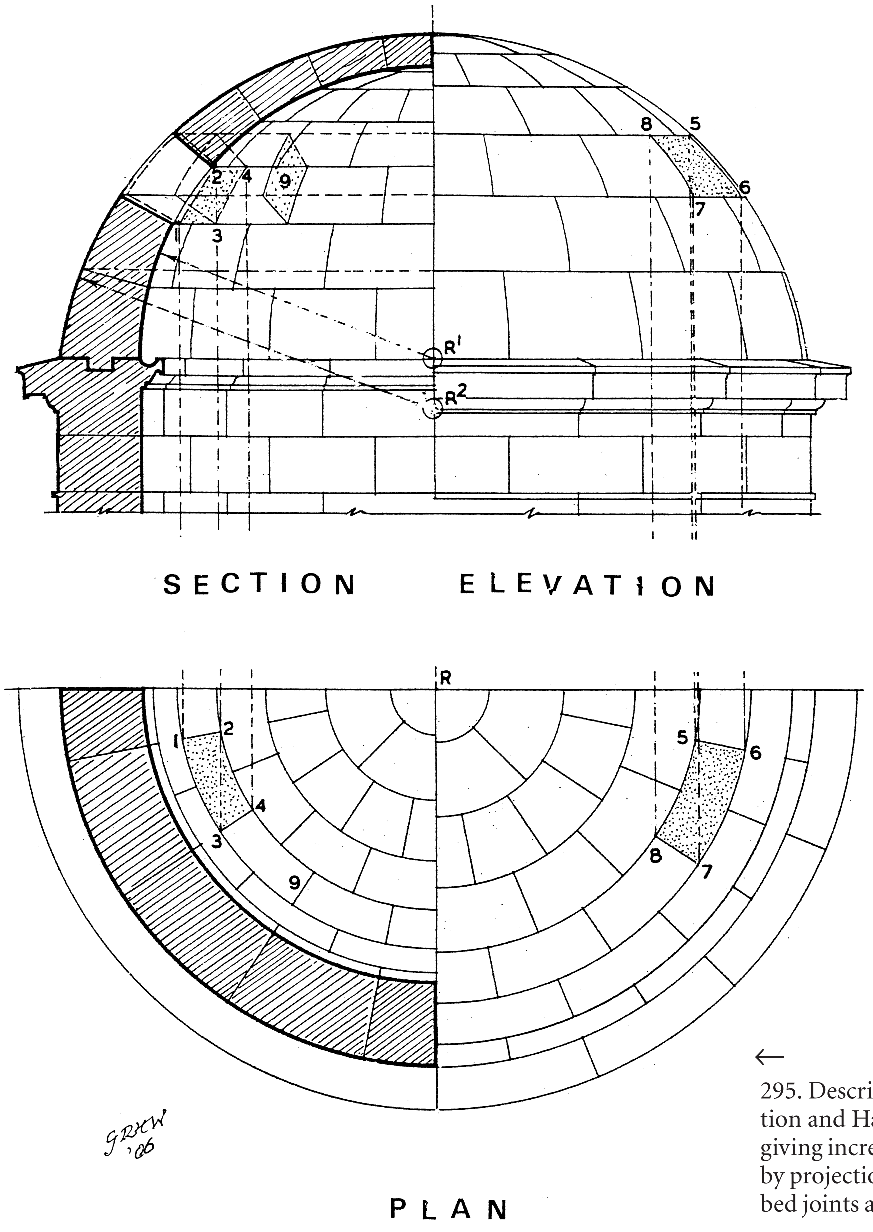
292. Mal Tepe. Corbel Vaulted tumulus Tomb. Plan and Section of Dromos and Burial chamber. Thrace. Early 4th Century BC. The plan of this tomb is exceptionally elaborate with 3 successive "thalamoi". The long dromos and the rectangular thalamos are roofed with triangular vaulting; the circular chamber with a conical beehive dome reminiscent of the Mycenaean tholoi. All roofing is corbelled. After Orlandos 2. fig 260.

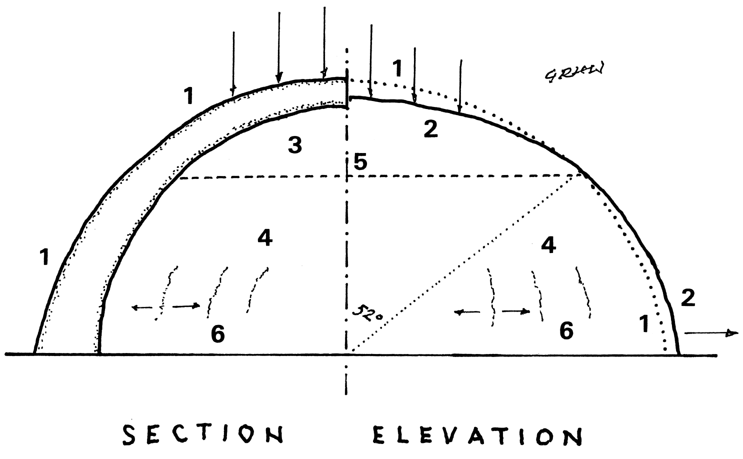


293. Panticapaea. King's Tomb. Plans, Sections and Detail of Corbelled Pendentives. Crimea. 4th Century BC. Tumulus tomb with dromos and square burial chamber. The chamber is roofed by a tall conical vault based on corbelled pendentives. *Key*: 1. Plan and Section of Tomb Chamber taken on the square; 2. Plan and Section of Tomb Chamber taken on the diagonal; 3. Perspective View of corbelled pendentive. After Orlandos 2. fig 270.



294. Comparitive Stereotomy of Dome Voussoir. Whereas the stereotomy of a barrel vault voussoir equates with that of a block in a circular wall, the stereotomy of a hemispheral dome voussoir is more complicated. The rising joints of the wall block diverge radially, but the bed joints are parallel horizontals. However with the voussoir of a dome, the bed joints also diverge radially, so that all the plane surfaces of a dome voussoir have a single point of origin. The circular wall block and the voussoir of a vault are alike part of the envelope of a cylinder, the dome voussoir is part of the envelope of a sphere. Thus the dressing of the dome voussoir involves cutting much more stone to waste. After Adam, p. 184, figs 403, 404.





296. Diagram showing Statical Behaviour of Dome. Section and Elevation of Hemispherical Dome under self load. The upper parallels of voussoirs in a dome are stressed horizontally in compression and the lower parallels of voussoirs are stressed horizontally in tension. Accordingly the statical behaviour of the dome structure is for the crown to drop (increasing the compression in the upper parallels) and for the base to spread outwards (inducing vertical cracking in the lower parallels). This can be mitigated by binding the voussoirs together by an encircling iron chain inset into the masonry at base level. *Key*: 1. Contour as constructed; 2. Exaggerated Deformation of Contour under self load; 3. Compression Zone; 4. Tension Zone; 5. Neutral Parallel; 6. Vertical Cracking (the effect of hoop tension).

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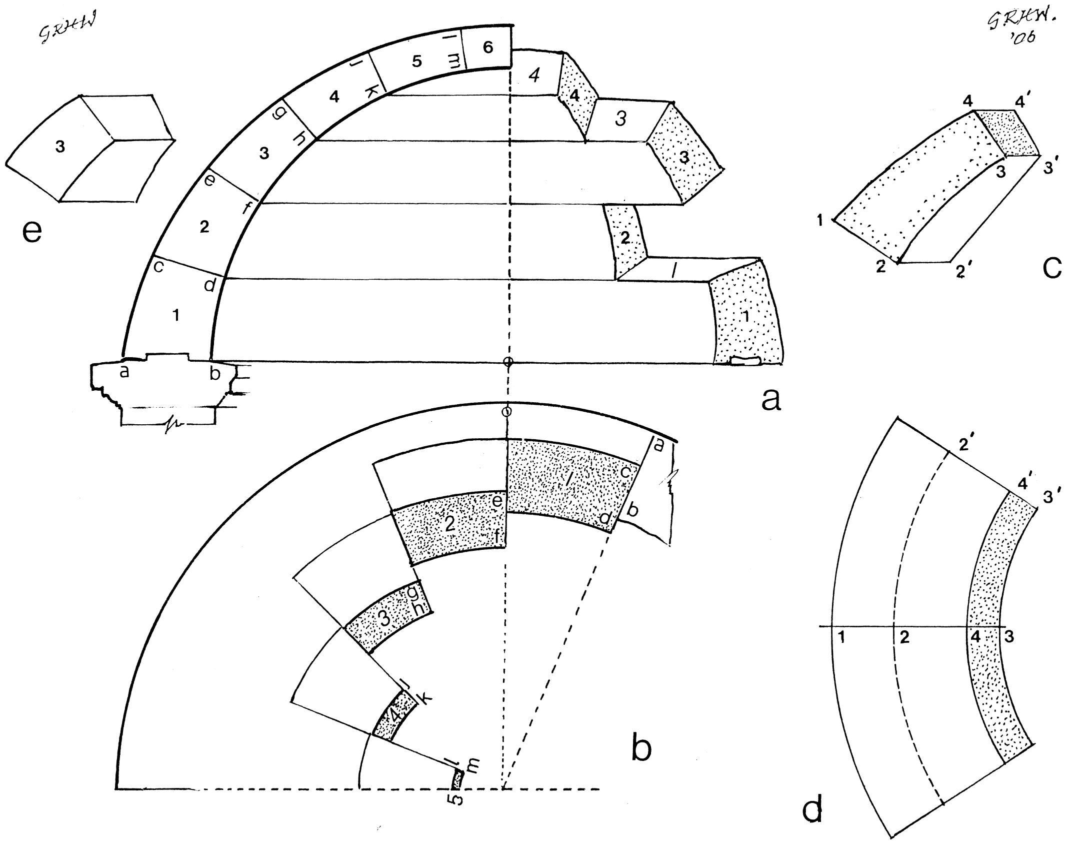
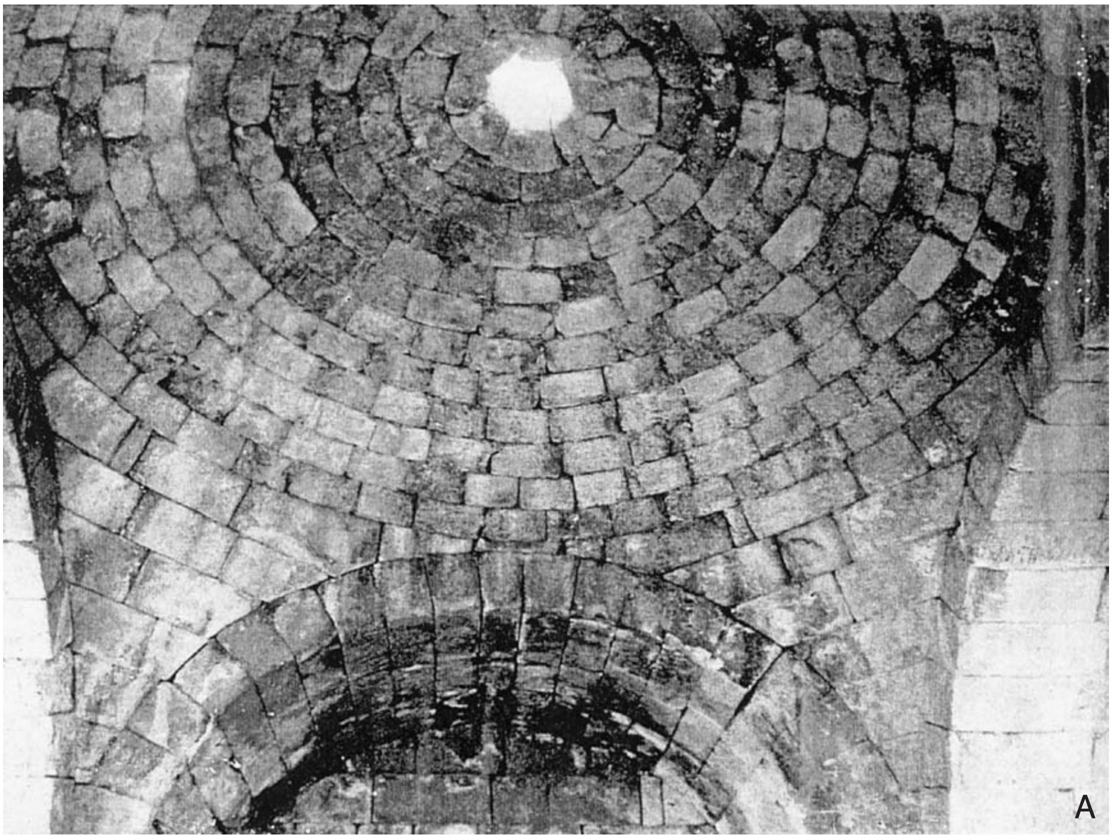
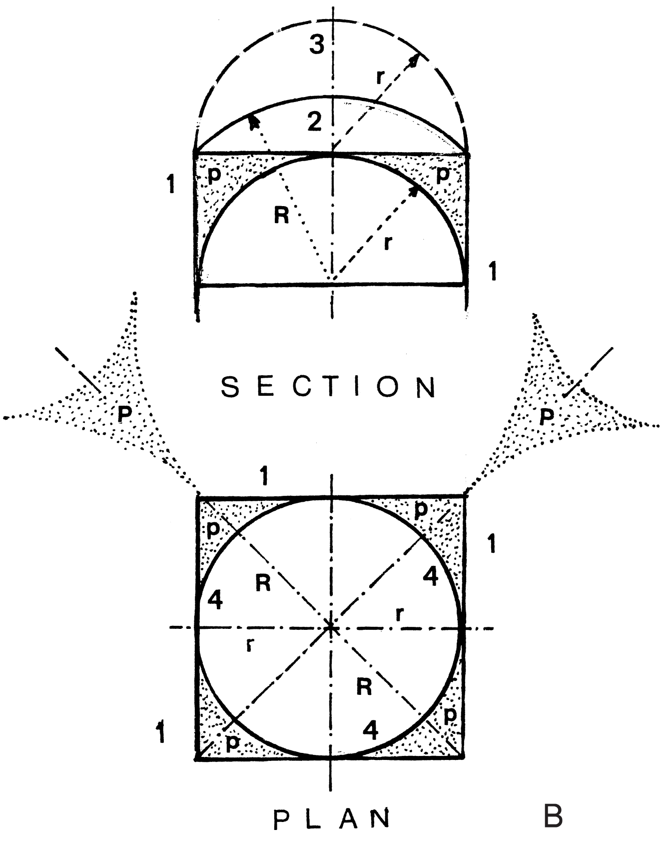
295. Descriptive Drawing of Typical Hemispherical Ashlar Dome on Drum. Plan, Half Section and Half Elevation showing intrados and extrados struck from two centres (R^1 and R^2) giving increasingly solid section at base. Two voussoirs (1, 2, 3, 4) and (5, 6, 7, 8) are identified by projection in plan, section and elevation showing arcuated surfaces of face and back, with bed joints and rising joints plane surfaces. One rising joint (9) identified in plan and section.

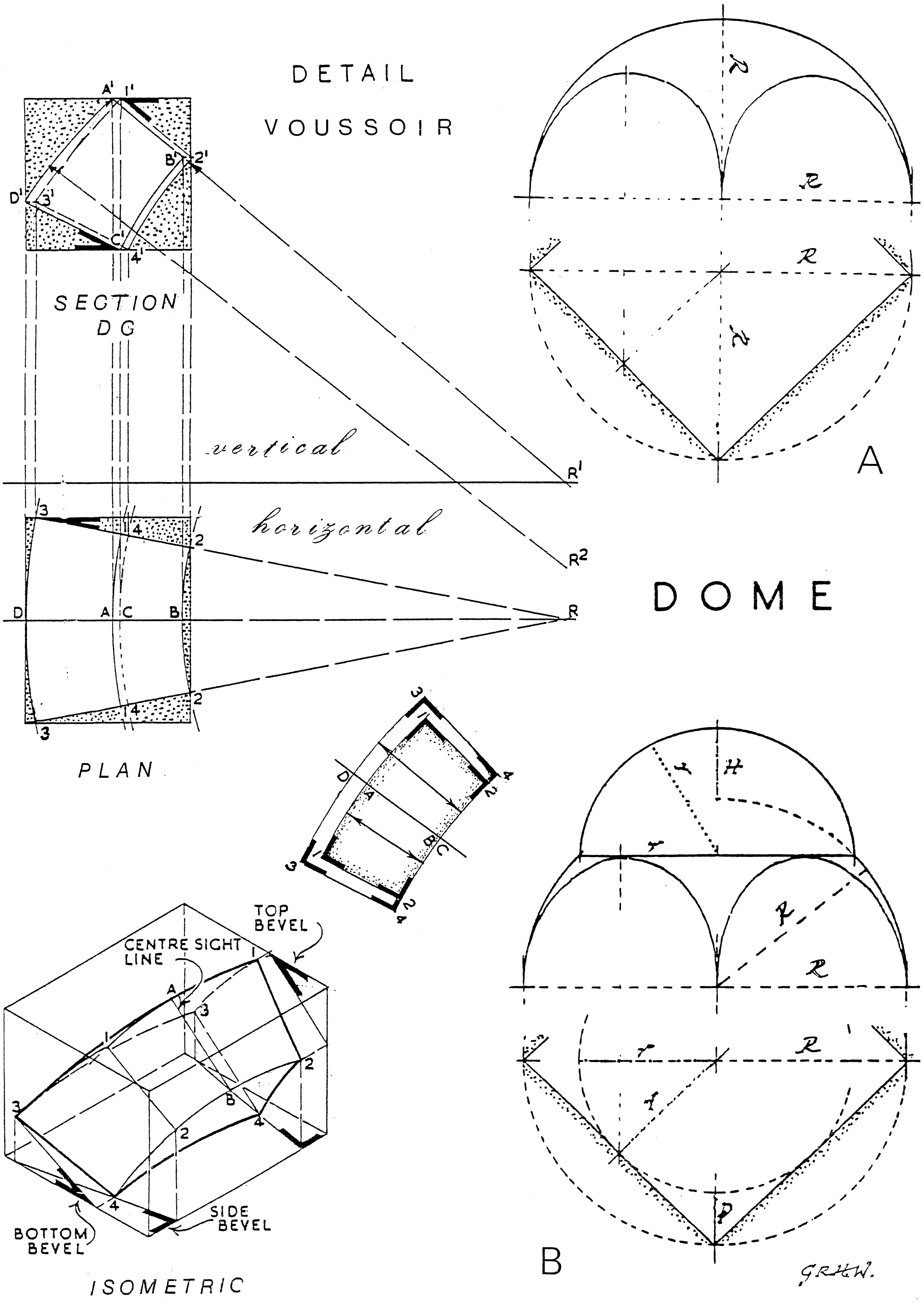


297. Mason's Setting Out Drawing of Ashlar Dome. For clarity all construction lines have been removed and developments omitted. The mason's setting out is directed to obtaining the "moulds" – i.e. the templates to be applied to a block of stone in order to obtain the surfaces of a voussoir (in as routine and error free way possible). The drawings as here presented show how little normal orthogonal projection describes the solid form of a voussoir. In place of construction lines indicating correspondences in plan and elevation, individual elements have been numbered and lettered similarly on plan and elevation. *Key*: a. Sectional Elevation of Dome with courses numbered and upper bed joints identified by letter (c-d, e-f, etc); b. Half Plan of Dome as seen from above showing sectors from successive courses, upper beds stippled and elements numbered and lettered similar to section; c. True Section of Voussoir (to larger scale); d. Corresponding True Plan of Voussoir (to larger scale) showing upper bed stippled; e. Projected three dimensional view of Voussoir from course 3.

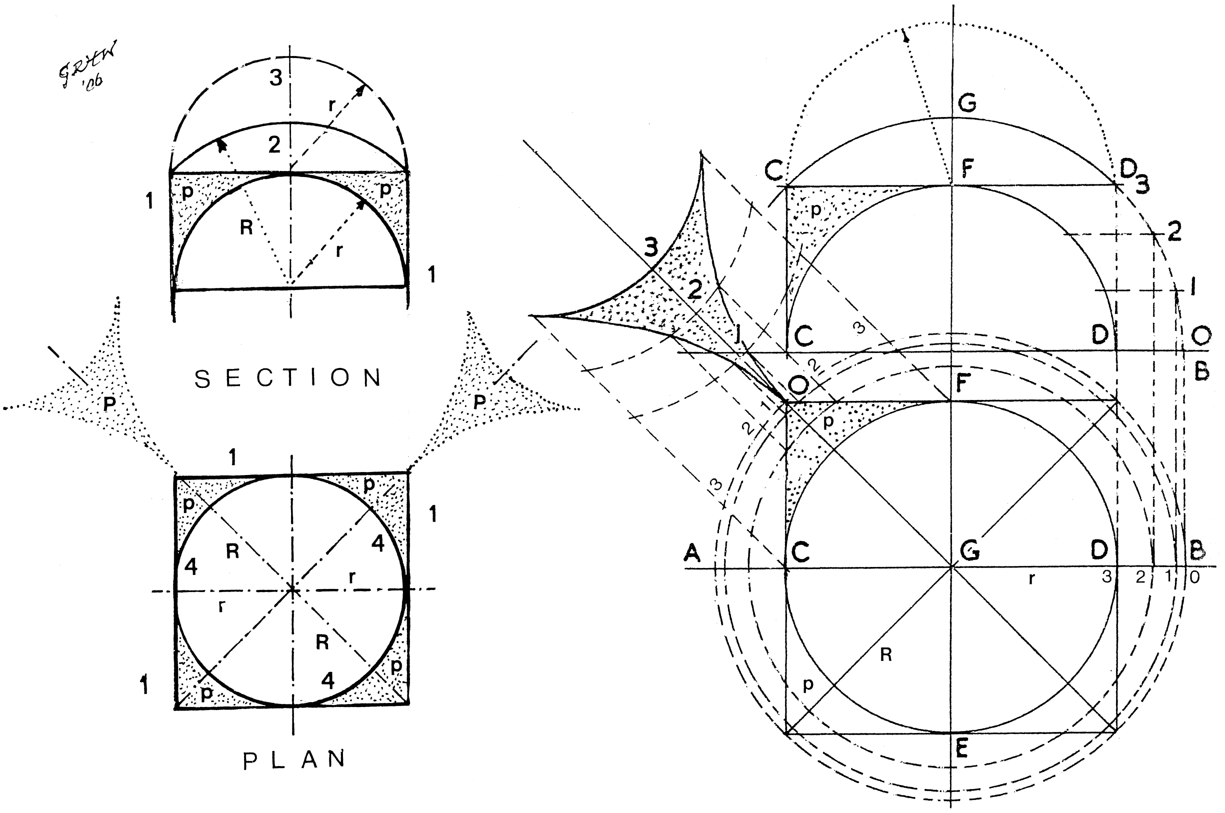




298. Hemispherical Masonry Dome on Pendentives over a Square Chamber. *Key*: A. View from below of ashlar masonry of very early hemispherical dome at Jerash. ca 1st Century AD; B. Explanatory Diagram (Plan and Section) of Geometry of dome on pendentives; 1. Inner face of walls to square chamber; 2. Soffite of continuous dome on pendentives (saucer dome); 3. Soffite of independent dome on pendentives; 4. Trace of springing of independent dome; p. Pendentive area; P. True geometric development of face of pendentives; R. Radius of pendentives and continuous (saucer) dome; r. radius of independent dome.



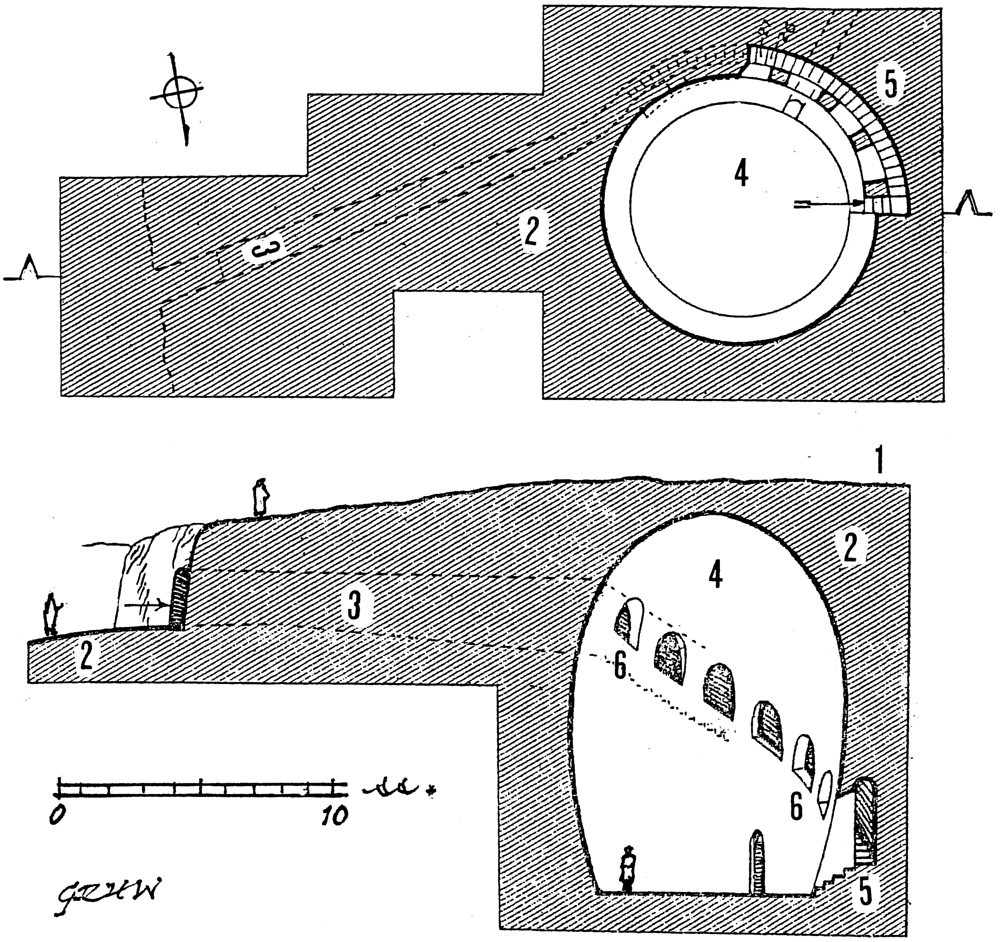
299. Geometrical Construction for Hemispherical Ashlar Dome on Pendentives. Right: Geometrical Setting Out of Dome. A. Dome on Continuous Pendentives (Saucer Dome); B. Dome on Independent Pendentives. *Key*: R. Radius of Curvature for pendentives and continuous dome; r Radius of Curvature for independent dome; P Pendentive; H Additional Height with independent dome set above Pendentives. Left: Voussoir Details Plan, Section, Isometric Mason's setting out to cut a voussoir for hemispherical dome. NB the large quantity of stone cut to waste (shown stippled in plan and elevation). Classical Greek knowledge of solid geometry was quite adequate to these demands and from the Christian era onward this setting out fine dressing was routine stone masonry.



300. The Geometry of the Hemispherical Dome on Pendentives giving (right, to larger scale) the construction for obtaining the face development of a pendentive. *Key* (*left*): 1. Inner face of wall to square chamber below; 2. Soffite of continuous dome on pendentives (saucer dome); 3. Soffite of independent dome on pendentives; 4. Springing line of independent dome on pendentives; p Pendentive area; P True development of face of pendentives (cf to larger scale right); R Radius of pendentives and continuous (saucer dome) = ½ diagonal of square chamber; r radius of independent dome = ½ side of square chamber; *Right;* Geometrical Construction for Development of Pendentive: divide the rise of the pendentive as shown on section into any number of equal parts (here three) = 1, 2, 3; Project these divisions in elevation down onto the plan to devide the oversailing of the pendentive at the angles of the square (= B – D = R – r) into the same number of parts (= 3). These dimensions are carried around to intersect the sides of the square (OF, OC), and the diagonal GO is extended to form the medial line (axis) of the required development. On this medial line the distances O-1, O-2, O-3 are marked off and lines are drawn parallel to the medial line (axis) from the intersection of the diameters 3, 2, 1 with the sides of the square OF, OC to give the ordinates. Coordinates are then obtained by drawing through points 1, 2, 3 as marked on the medial line (axis) arcs with radii equal to the corresponding circles on plan. The points obtained by the intersection of the corresponding ordinates and coordinates lie on the periphery of the development of the pendentive and can be joined up to give the required developed form of the pendentive; NB The master mason building such a hemispherical dome on pendentives must be able to draw out this construction to obtain the required form of the pendentive blocks in finely dressed masonry.

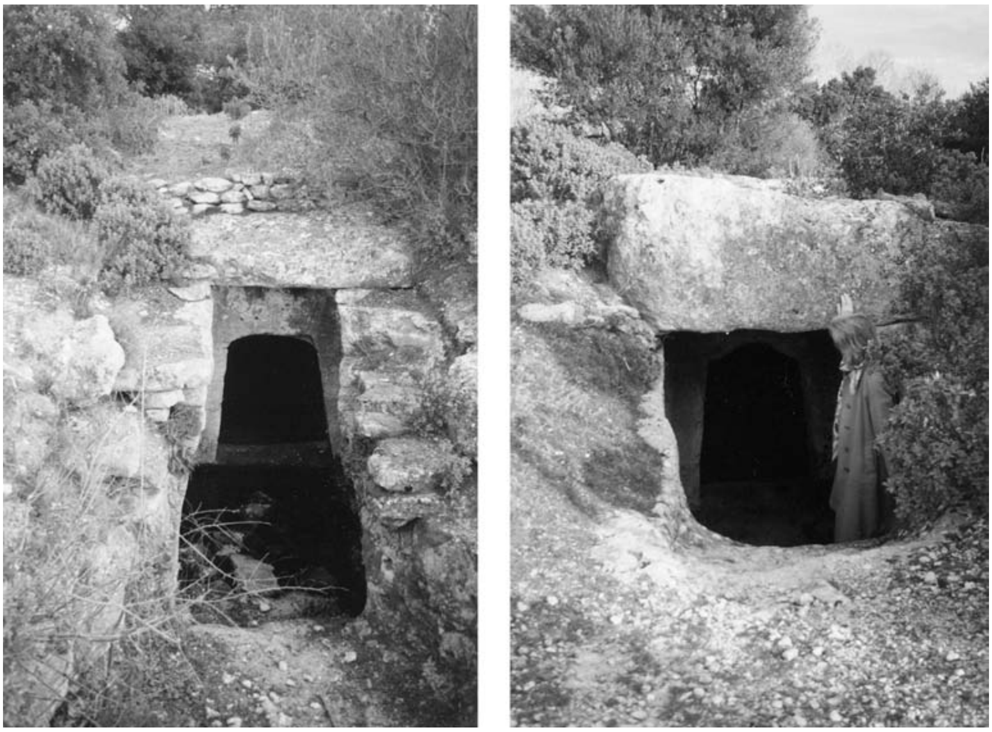
301. The Mausoleum of Theodoric the Ostrogoth with a Monolithic Capstone Roofing. Ravenna ca 520 AD. The domed roof is a monolith ca 11m in diameter, with a rise of ca 3m, weighing 300 tons and more, fashioned to simulate the form of a (saucer) dome. It was perhaps levered up to the required height and propped in position so that the underlying masonry structure could be built up beneath it.

302. Hal Saflieni. Hypogeum. Entrance to Holy of Holies. Malta. Late 4th Millennium BC. The portal in the foreground is (low) head height. Both the scale and the architectural ‘order’ make this astounding Neolithic work one of the most impressive of rock cut monuments. These apartments constitute a shrine, which is closely parallel to the Neolithic temples of the Island. The caverns in three descending tiers were hewn out of the solid rock by hard stone pounders and hand axes etc. The design is completely in accordance with Neolithic ‘round house’ mentality. There can have been no way of setting out this design in advance of the cutting, which must have proceeded by virtue of ‘participation mystique’ in growth patterns of nature.



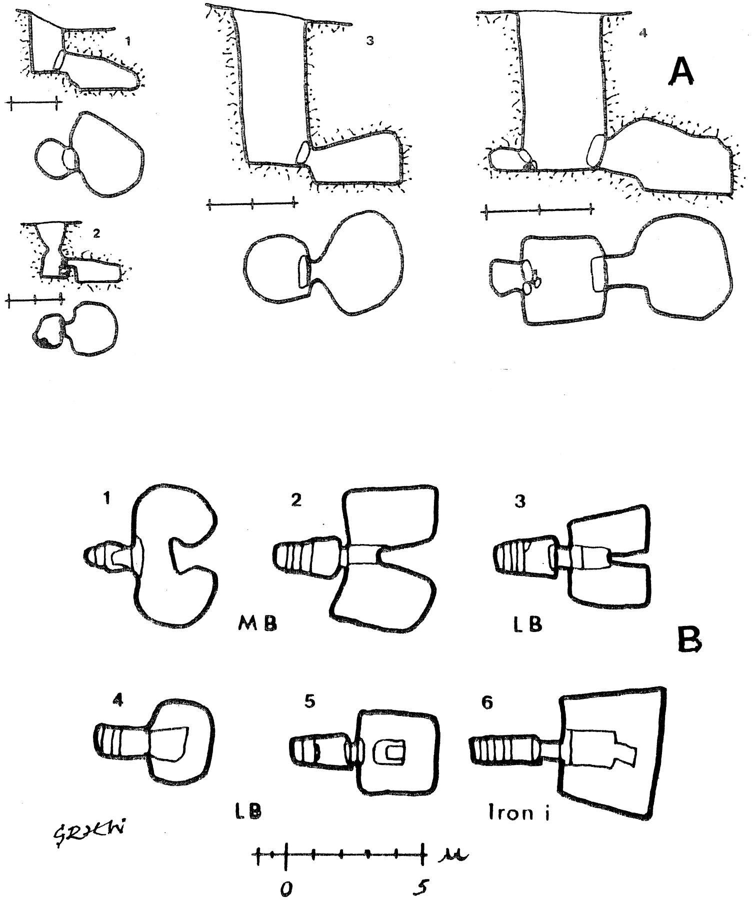
302a. Knossos. The Pre Palatial Hypogeum. Crete. 3rd Millennium BC. This drawing does not purport to be a representation of the rock cut Hypogeum. It is a redrawing of Evans original publication drawing designed to make its essential components as clear as possible. As shown the drawing portrays circumstances which may be characterised as amazing to downright impossible. Cutting the large vaulted chamber (4) out of bed rock can only have proceeded from above downwards, i.e. the original access to the projected area of the chamber can only have been gained through the dromos (3) and the highest of the entry points (6) from the stepped descent (5) – and this means of access must have sufficed to remove the rock spoil yielded. Each successively lower port must then have provided the same facilities for the hollowing out of the chamber as the work proceeded downwards. If this can be imagined to have been the case, it must then be remarked that to control the rock cutting of this complex, consisting of a large vaulted chamber of perfectly regular geometrical form with a descending passage way wrapped about its periphery but separated from it, would tax all the resources now available to a mining surveyor. The only ancient feature comparable with this arrangement is the Hal Saflieni Hypogeum in Malta, but there is no other evidence of community between Neolithic Malta and Crete. As a first suggestion of common sense, it would appear that the chamber was not entirely rock cut as shown here, but that access for its cutting was gained directly from ground level above, and the crown of the vault was subsequently made good in masonry. *Key*: 1. Ancient surface; 2. Bed Rock; 3. Dromos giving access from rock face to the winding stepped descent (5); 4. Rock cut vaulted chamber; 5. Winding stepped descent passage way down to floor of chamber; 6. Port holes cut through rock wall separating the stepped descent (5) from the chamber (4). After Evans Palace of Minos I.

303. Grotte de la Source. Rock Cut Gallery Grave. Interior view looking out and in. Near Arles. ca 3000 BC. The gallery is cut down into bed rock with smoothly dressed walls splaying apart below. The roofing is constructed of deep and massive slabs spanning the excavation.

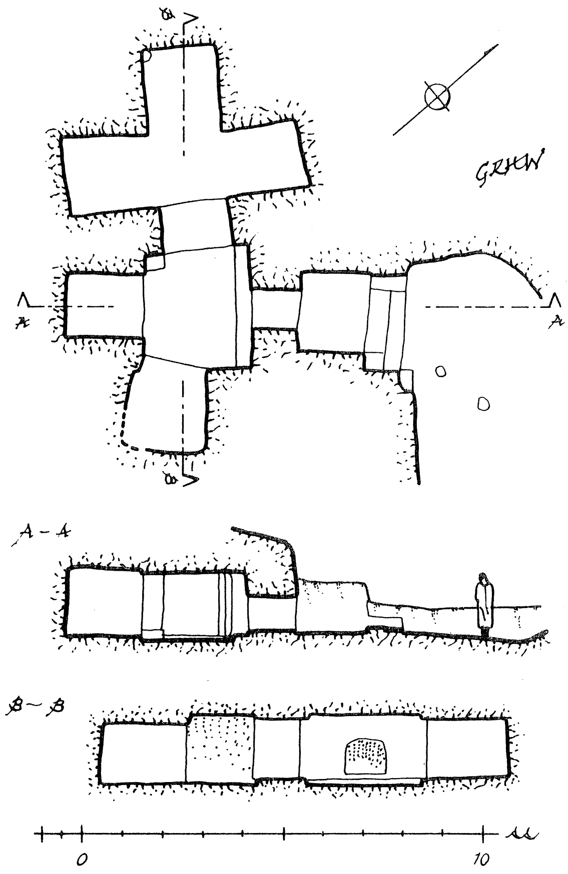


304. Grotte de la Source. Rock Cut Gallery Graves. View of entrances showing massive roofing slabs. Near Arles. ca 3000 BC. The juxtaposition of these squared up roofing slabs over the rock cut gallery raises the bare possibility that the gallery may have been quarried out to yield the slabs.

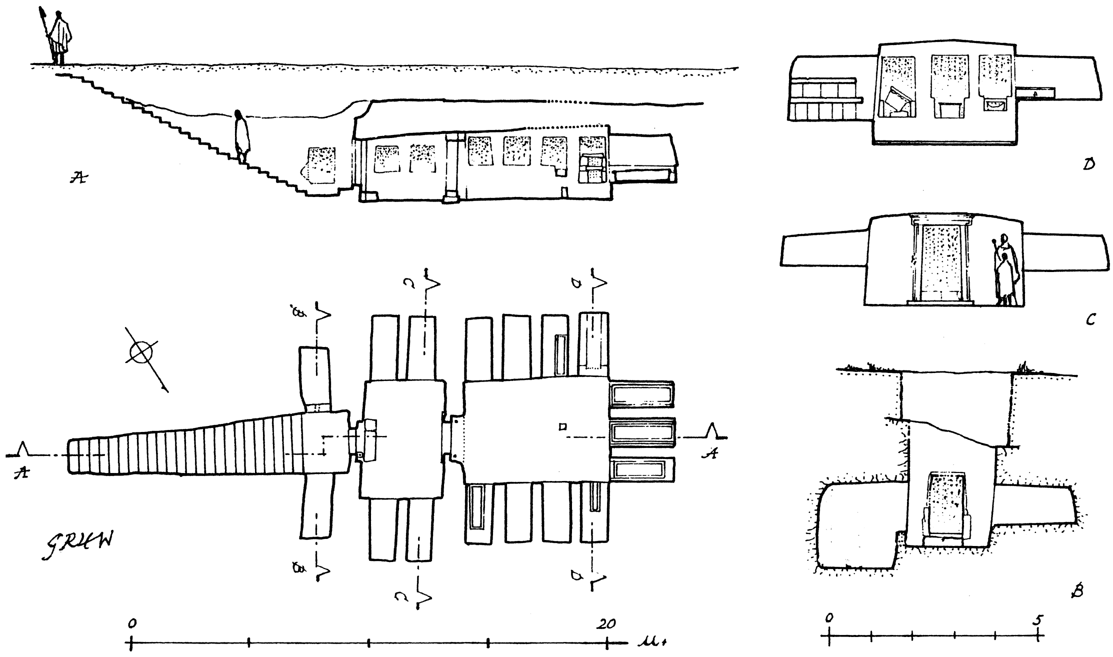
305. Essé. Interior view of large gallery grave. Brittainy. Late 4th Millennium BC. The form of this famous built gallery grave and that of the rock cut gallery graves near Arles are identical.



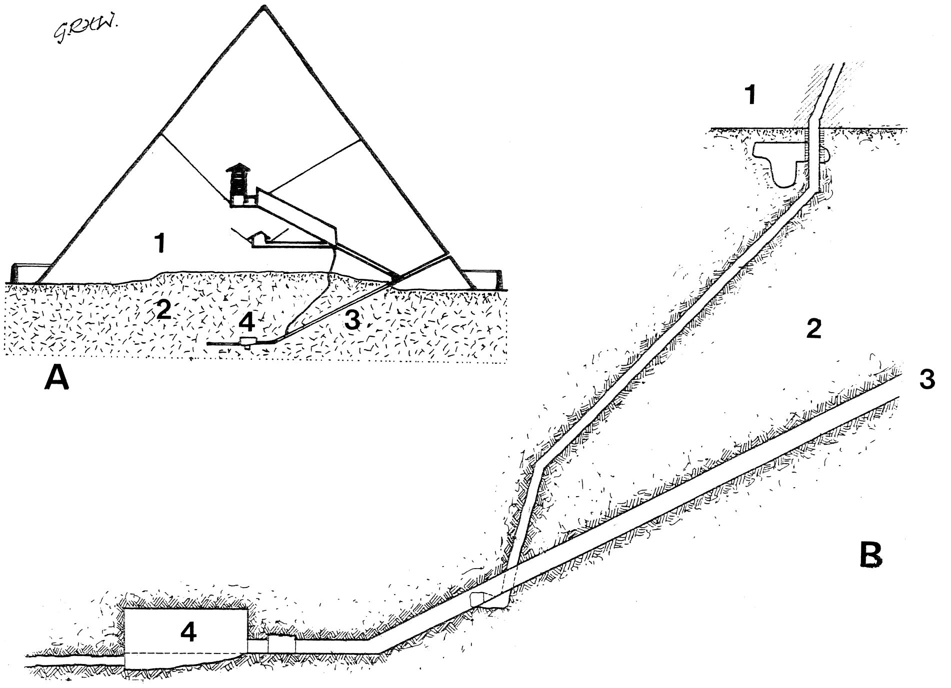
306. Specimen formal development of simple rock cut chamber tombs. Palestine. 3rd - 1st Millennium BC. A. Early (E B). Small chamber tombs of basically curvilinear form. These tombs were hollowed out, often in the soft secondary limestone (*huwwar*), virtually by digging out. Neither quarrying nor building construction in finely dressed stone was then current in the region. NB Entrance to the chamber kept high up, just underneath the roof. *Key*: (1) Jericho (single burial); (2) Bab eh Dhraa; (3) Jericho; (4) Jericho (rectangular shaft dromos); B. Later (MB – Iron Age) Chamber tombs at Sharuhen (Southern Palestine) showing progressive development of rectangular form in both single and bilobate chamber tombs; It is theoretically possible that some quarrying out may have been employed in hollowing out the later angular tombs, since quarrying and building construction in finely dressed stone became increasingly common during LB and Iron Age times in Palestine. However this possibility also depends on the quality of the rock in which the tombs were cut. *Key*: (1) MB rounded bilobate tomb; (2) MB semi angular bilobate tomb; (3) LB rectangular tomb; (4) LB rounded central cist tomb; (5) LB semi angular central cist tomb; (6) Iron I (Palestine) angular central cist tomb. After ABSP II, figs 266, 270.



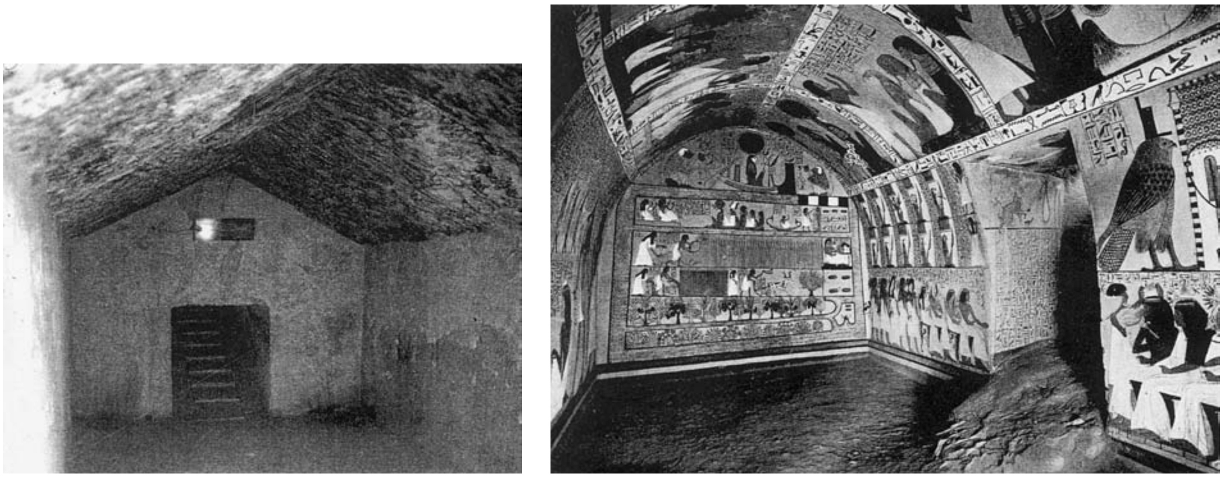
307. Megiddo. Developed chamber tomb complex. Central Palestine. Later Bronze Age. This tomb is not accurately set out. Although it is possible that such a tomb might be partly quarried out, this is unlikely. Quarrying and building construction in dressed stone masonry were in use at the time. After ABSP II, fig 268.



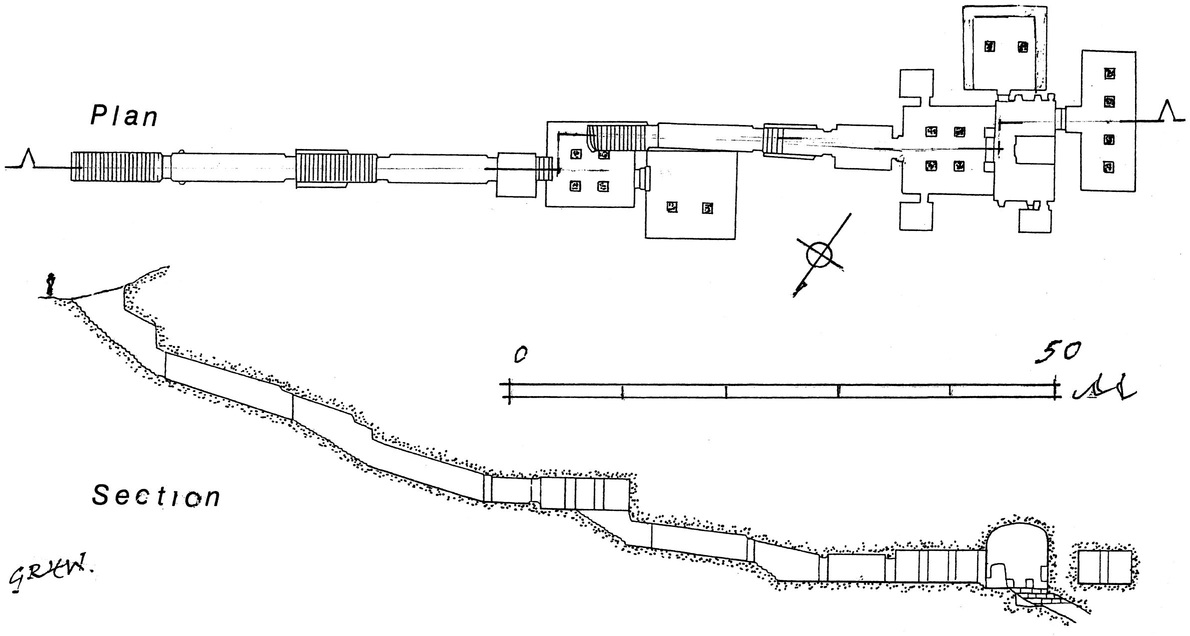
308. Salamis. Ayios Sergios. Tomb 1. Cyprus. Roman Period. This developed multiple loculi tomb of the kokhim type is utilitarian not monumental in nature. However in its place and time both quarrying and fine stone masonry building construction were every day matters and it is possible that such tombs were partly cut out by quarrying. After ABC II, fig 194.



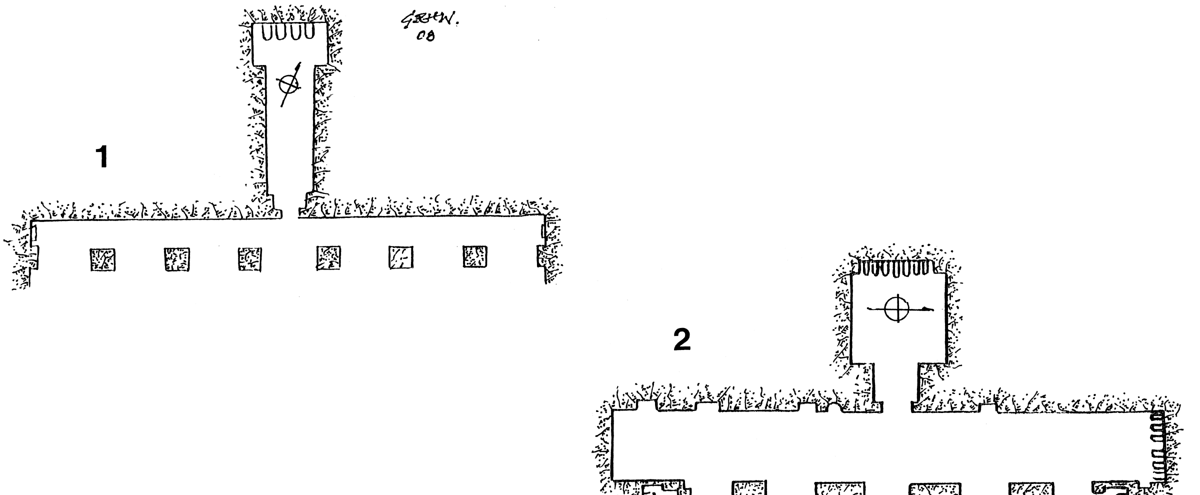
309. Gizeh. The Great Pyramid. Rock cut passages and chambers. Lower Egypt. ca 2550 BC. From the beginning of Old Kingdom pyramid construction the design included accurately cut chambers in the bed rock. These are the earliest instances of monumental rock cutting on rectilinear lines, and correspond to the contemporary development of large scale quarrying. It is not convenient to quarry out steeply inclined passages, and presumably these were cut to waste (cf mining adits and galleries). However it is likely that large chambers were quarried out, and the masonry blocks yielded were hauled up and out. *Key*: A. Section of pyramid showing disposition of rock cut features. B. Detail section of rock cut feature; 1. Stone masonry of pyramid; 2. Bed rock; 3. Descending passage cut in bed rock; 4. Rock cut chamber (provisional burial chamber ?). After Stadelmann Pyramiden fig 30.



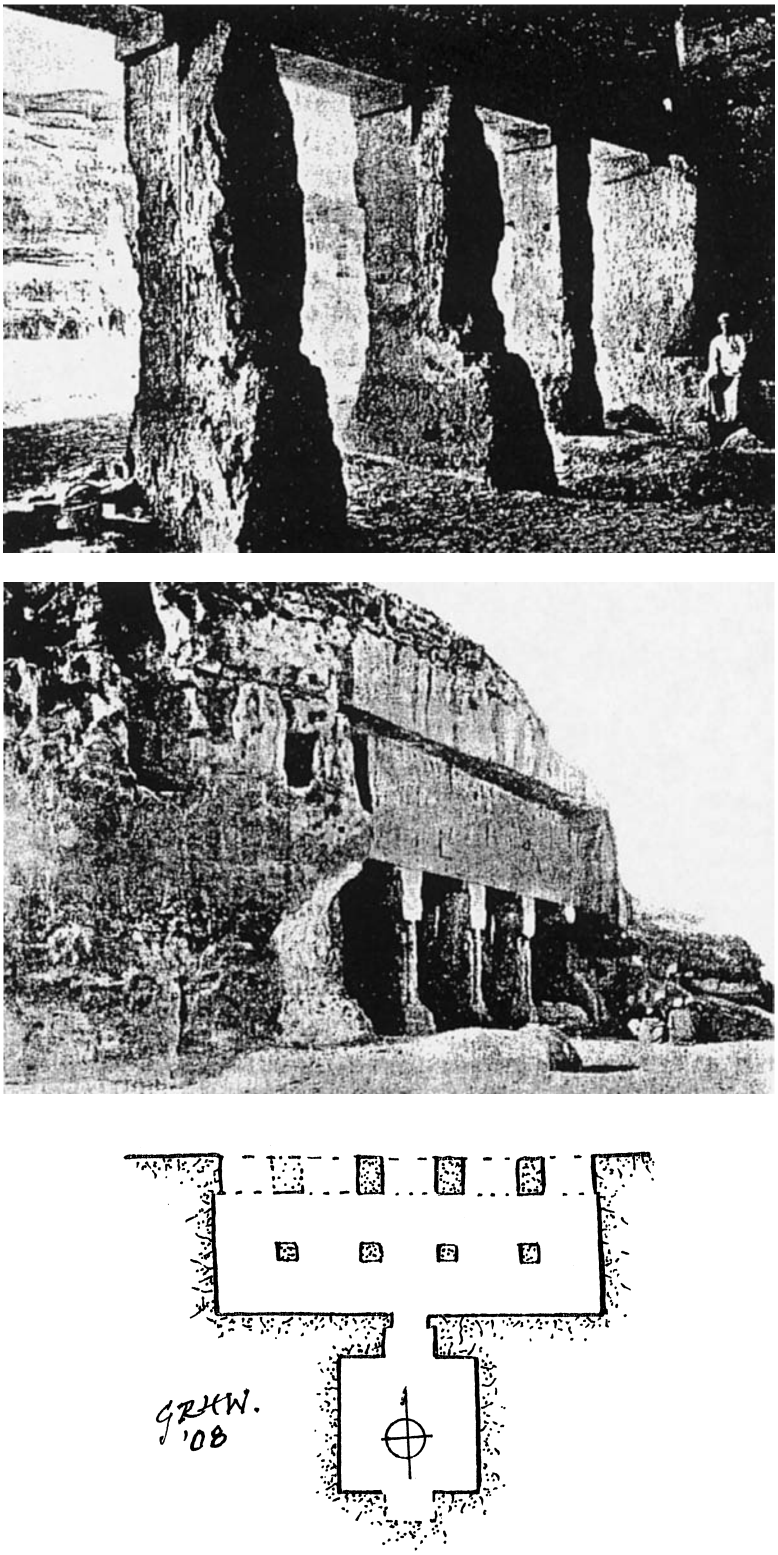
310. Gizeh and Thebes. Vaulted Ceilings to Rock Cut Funerary Apartments. 4th Dynasty & 19th Dynasty. A vaulted ceiling adds to the technical complications of rock cutting, but it seems to have been preferred for funerary apartments of the hypogeum type. *Left*: the Pyramid of Khephren at Gizeh, ante chamber to the burial chamber with saddle vault (triangular vault). A built masonry example of such a chamber exists at Saqqarah in the Pyramid of Pepi II ca 2190 BC (v Ill 261A). This type of vault was standard during the Old Kingdom. *Right*: Tomb of Sennedjem. Hypogeum rock cut tomb with barrel vaulted ceiling. Deir el Medinah. The barrel vault is not as common in earlier (Old Kingdom) times, but becomes standard in the New Kingdom and Late Period. For a built masonry example at Medinet Habu, ca 800 BC, v Ill 262. After Stadelman Pyramiden pl 50, AAAE pl 164.



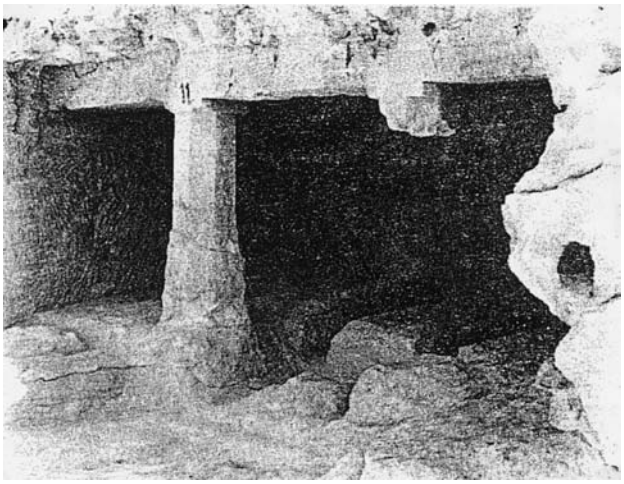
311. Valley of the Tombs of the Kings. Rock Cut Tomb of Seti 1st. Thebes. ca 1300 BC. There are more developments of the cutting at different levels than are shown on this simple drawing. However it is sufficient to indicate that the monumentality of the hypogeum type tomb is entirely in its interior apartments (all richly decorated with painted plaster). The exterior was generally (until the 20th dynasty) made as inconspicuous as possible for reasons of security. This tomb is notable since it is the most extended of the Kings' Tombs, penetrating the rock to 100m overall. There has been little detailed study of the fashioning of these hypogeum tombs. The inclined passages were not propitious for quarrying operations, but the halls and horizontal passages were most likely quarried out. The quarried blocks were then hauled up the inclines with ropes before the steps were cut.



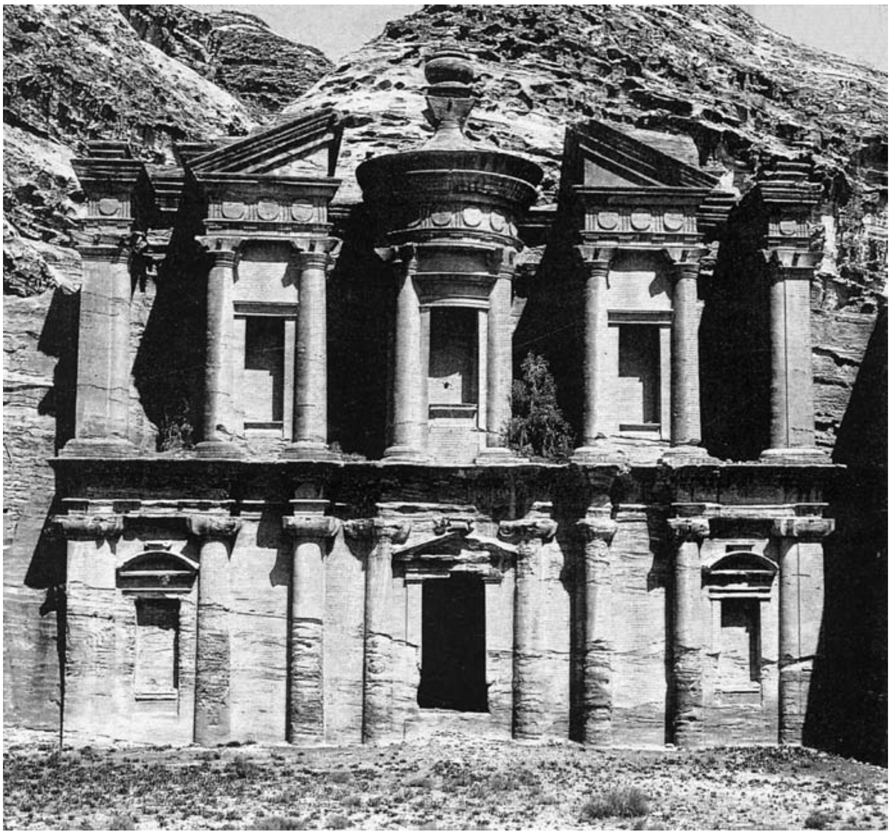
312. Specimen Rock Cut Monuments of Speos type. Upper Egypt. Middle and New Kingdom. During the Egyptian Middle Kingdom monuments cut into cliff faces so as to display an imposing colonnaded façade became very profuse, serving both as tombs and as sanctuaries. Here the monumental aspect resides in the façade, and the chamber(s) behind the façade may be little developed in aspect. The type survived into the New Kingdom, but then the hypogeum became predominant. *Key*: 1. Tomb of Ineni at Thebes (with statues at rear of chamber); 2. Sanctuary at Jebel Silsileh. (NB Small lateral sanctuaries cut into the antae of the colonnade). After Vandier Manual II, figs 259, 441.



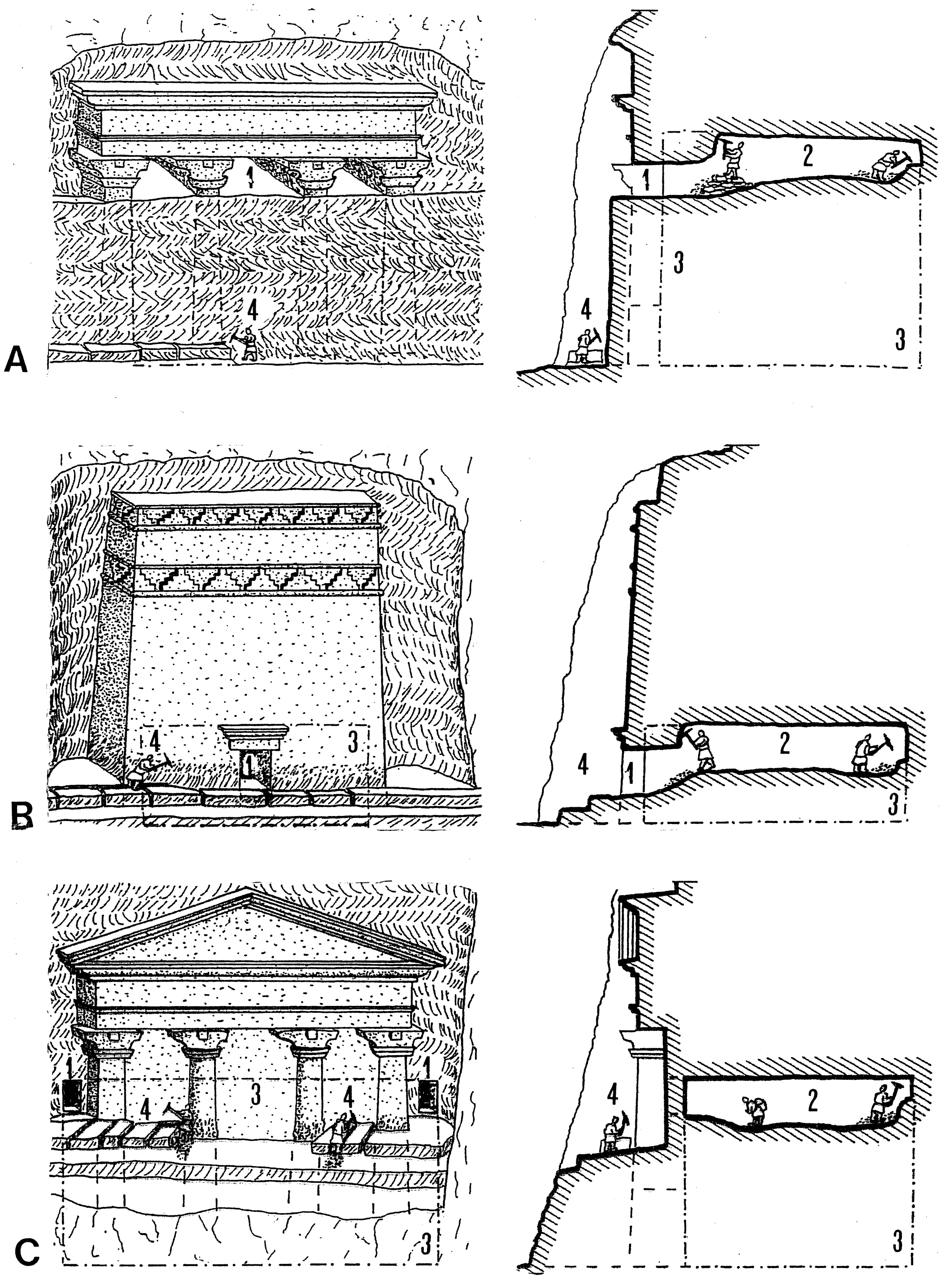
313. Beni Hassan, Speos Artimedos Sanctuary, probably of Middle Kingdom origin, dedicated to Hatshepsut by Thothmes III. Middle Egypt. 18th Dynasty. The spacious colonnade of the façade facilitates the rock cutting of the chamber which was effected by quarrying. The monument stands in a region of quarries. After Vandier Manual II, figs 441, 442.



314. Beni Hassan. Unfinished rock cut chamber tomb. Middle Egypt. Middle Kingdom. This casual photograph records evidence of channelling for quarrying out masonry blocks. It thus indicates that these Middle Kingdom rock cut chamber tombs were fashioned by quarrying not by cutting to waste. The quarrying procedure was greatly facilitated by their open colonnade façades. After A. Dodson. Egyptian Rock Cut Tombs, fig 59.

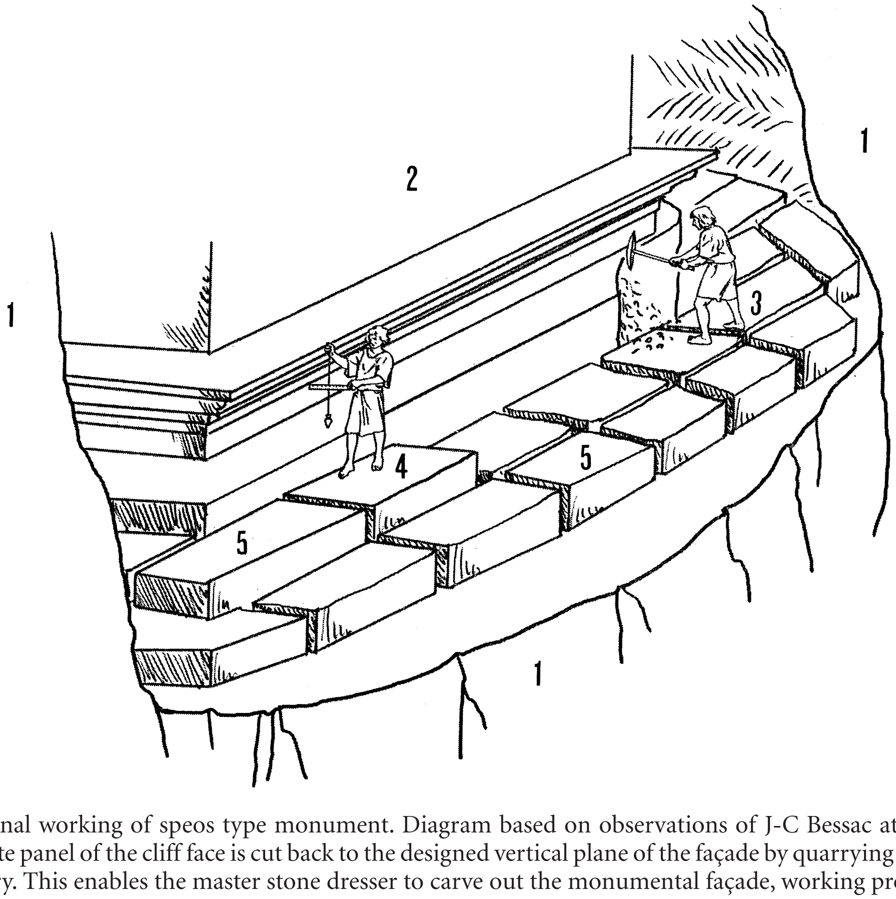


315. Petra. The Deir. An imposing monument cut in the cliff face. Jordan. 1st–2nd Century AD. Although the interior apartments of this monument are relatively large, its monumentality subsists in the façade. The concept of a three dimensional representation of the external façade of a palatial building has been greatly disputed. However little enquiry has been directed to the manner of the rock cutting. The relatively high relief in which this façade has been freed from the rock matrix means that a great amount of rock needed to be cut away, and this was effected by quarrying. Even so a calculation of the comparative labour units involved would show that to carve this façade out of the cliff was more economic than to build it up in ashlar stone masonry.

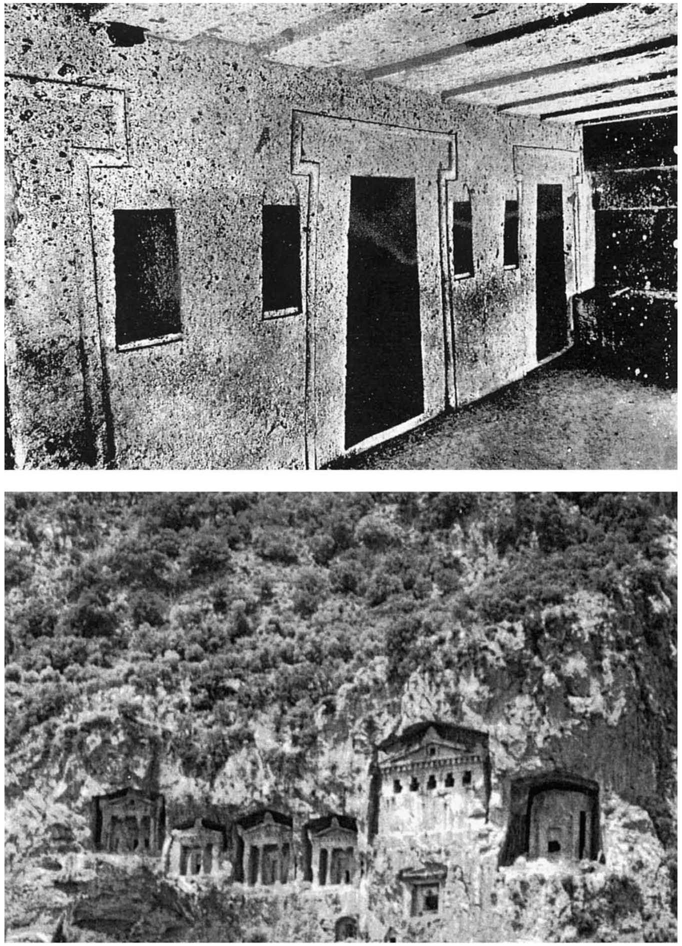


316. Diagram illustrating rock cutting procedures based on observation of J-C Bessac at Petra. These diagrams illustrate the non-viability of cutting rock upwards. This is practical only to a very limited extent to give sufficient head room for working. This entails that entry must be gained to the projected confines of the chamber as close as is possible to required ceiling level. In turn this means that often in the speos type monument there is little relation between a possibly towering façade and the ceiling height of the chamber behind it, since entry is often gained through the door (or a fanlight above the door). *Key*: A. Access gained directly below the entablature of colonnade façade. B. Access gained below the lintel of door. C. Access gained by two lateral apertures cut in cliff face, one on each side of the ornamental façade; 1. Entry port (access) for cuniculus (pilot gallery); 2. Cutting cuniculus (to waste); 3. Projected confines of the chamber; 4. Quarrying down cliff face in front of façade. After Bessac Petra, fig 104.

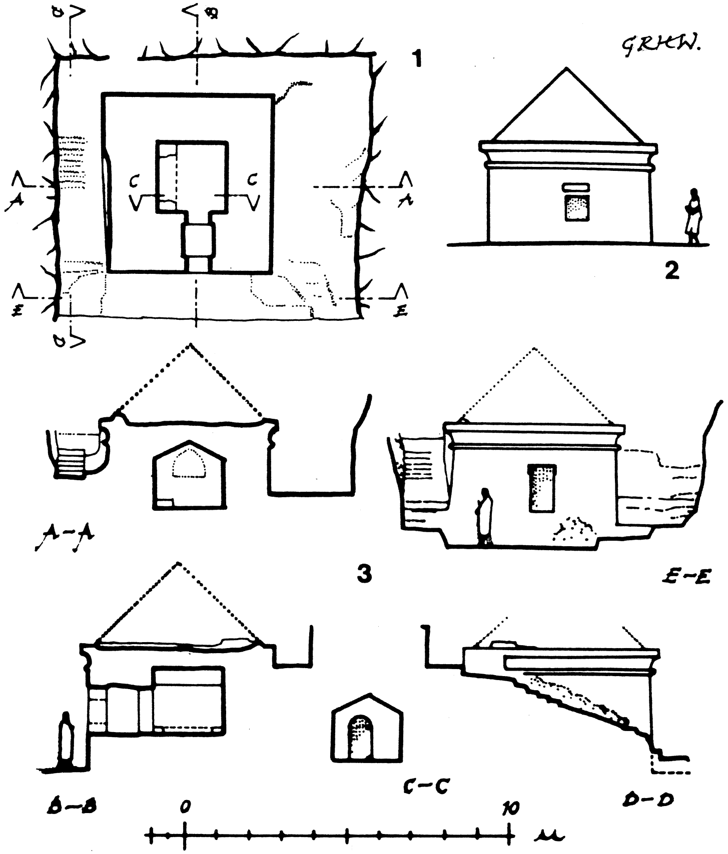
317. Petra. The Storied Tomb. Unfinished rock cutting of alcove. Jordan. ca 1st Cent AD. This is one of the rare examples of *in situ* evidence establishing that where practical monumental rock cut apartments were fashioned by way of quarrying out the rock to yield masonry blocks, not by cutting the rock to waste. After Bessac Petra, fig 120.



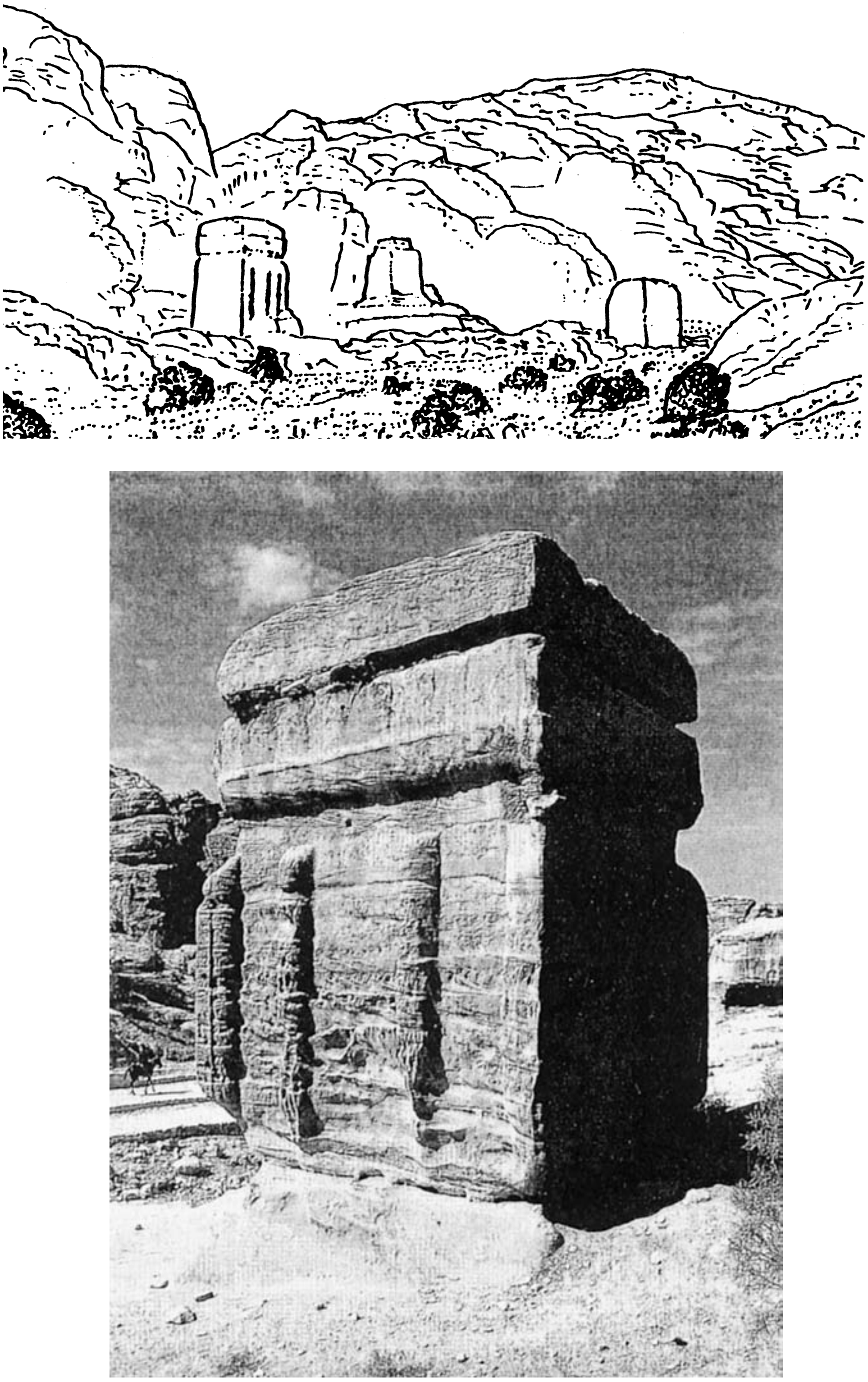
318. External working of speos type monument. Diagram based on observations of J-C Bessac at Petra. An appropriate panel of the cliff face is cut back to the designed vertical plane of the façade by quarrying out blocks of masonry. This enables the master stone dresser to carve out the monumental façade, working progressively downwards. Thus the wall is a combined programme of quarrying and ornamental stone dressing. *Key*: 1. Original cliff face; 2. Plane of façade of monument; 3. Quarryman cutting the cliff face back to the plane of the façade; 4. Freemason carving details of façade ornament; 5. Separated blocks prepared for detachment to carry the work downwards. The progressive lowering of the surface of the rock thus provides the scaffolding to carry out the work. After Bessac Petra, fig 146.



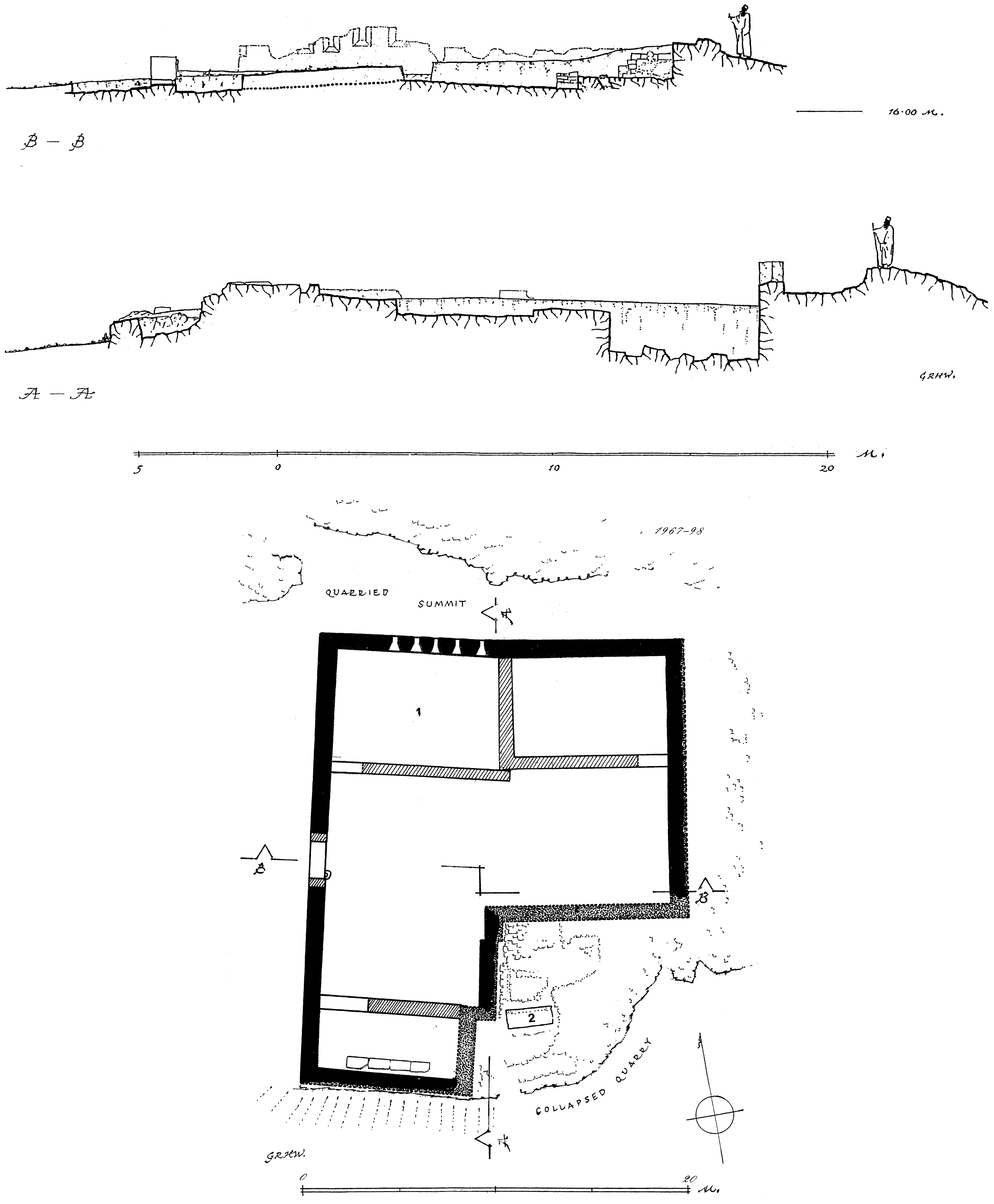
319. Cerveteri. Caunus. Rock Cut Monuments as evidence of building construction details both internal and external. Etruria (ca 500 BC). Caria (ca 300 BC). In none of its manifestations, neither as façades nor as interiors, did rock cutting develop specific styles of its own. Always it represented as closely as practicable contemporary building construction. Since rock cut features are more resilient than built ones, thereby they can convey valuable information regarding details off construction not well preserved in ancient buildings. *Key*: above: Interior shown in Early Etruscan rock cut tomb chambers at Cerveteri, ca 500 BC. Below: Temple façades forming the external aspect of rock cut tombs at Caunus in Caria, ca 300 BC. After Ward Perkins, pl 36.



320. Silwan Tomb of Pharaoh’s Daughter. Jerusalem. Later Israelite Period. This monumental rock cut tomb is cut in the rocky terrain across the Kidron Valley from “The City of David”, in a long enduring cemetery area. The pyramidal form of the monument is modelled on small Egyptian tombs at Thebes, and the crowning pyramid was a masonry addition – now disappeared, but recognisable from cuttings for its seating. The external confines of the monument were detached from the surrounding rock by quarrying on all sides except the rear where they remained semi-engaged. The small burial chamber may have been hollowed out by quarrying. It comprehends the added complication for rock cutting of a gabled roof, which also occurs in other rock cut tombs in the vicinity – and is another Egyptian feature. *Key*: 1. Plan; 2. Restored front elevation; 3. Sections AA – EE. After ABSP II, ill 277.



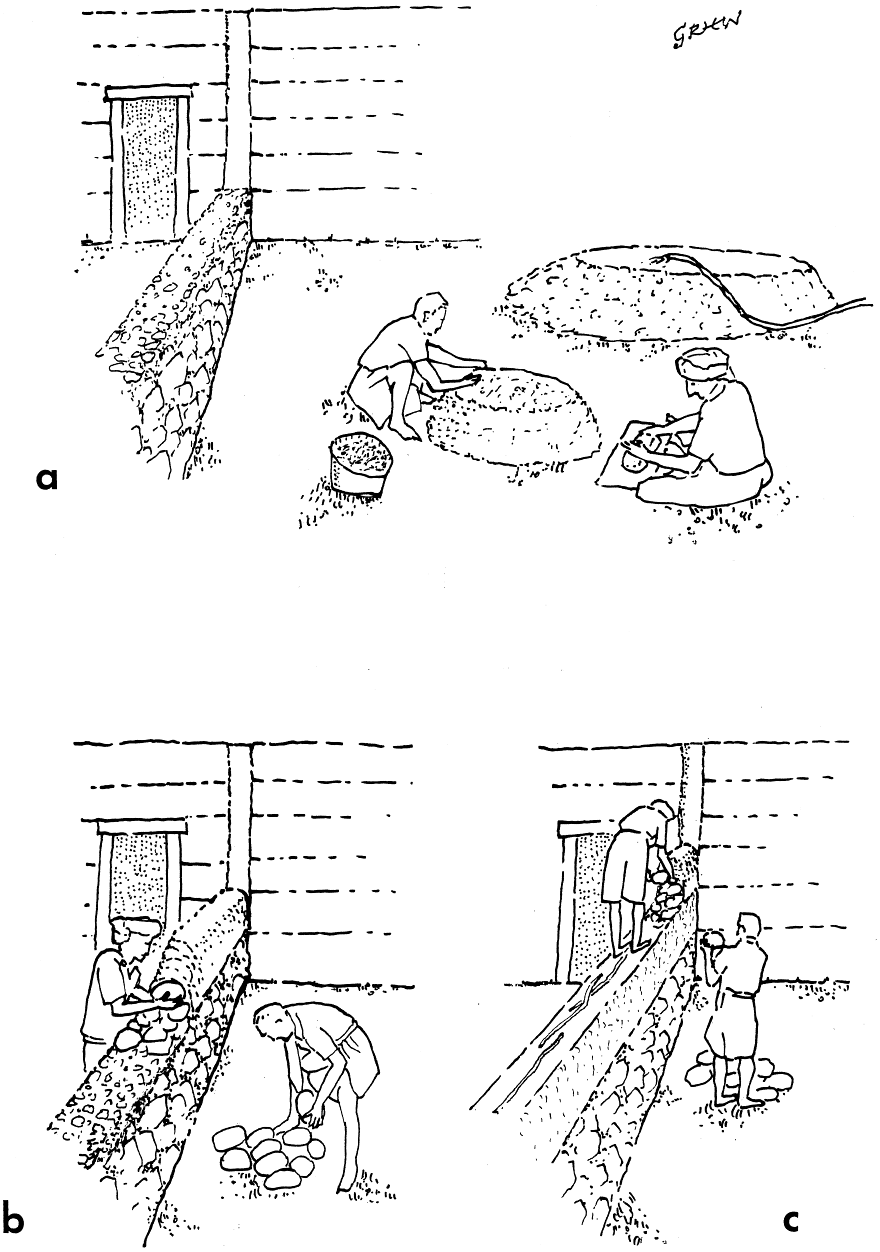
321. Petra. Jin Blocks at Mouth of Siq. Jordan. ca 3rd Cent BC (?). Free standing rock cut tombs. Above: View of a group of 3 similar tombs; below: Photograph of central tomb in upper view. These massive (ca 10m high) Hellenistic type tower tombs are carved out of the rocky flanks of the mouth of the Siq (the gorge entrance to Petra). They contain small burial chambers or lodgements and were originally ornamented by inset and crowning masonry additions of classical entablature. Although the matter has never been investigated, a very great amount of rock most have been removed by quarrying the surround in order to create them (cf the restricted work required for the Iron Age tomb at Silwan, ill 320). After East and West 47, 1997, p. 146, fig 4.



322. Apollonia East Fort. Restored plan with sections. Cyrenaica. ca 3rd Cent BC. The fort was established on a rocky headland 1km east of Apollonia previously exploited as a quarry. The summit of the outcrop had been quarried down, and there had also been underground quarrying. When the fort was established, it was partly constituted by further quarrying so that the external walls were partly formed out of solid rock, while a deep cellar or cistern had been quarried down inside the northern wall. *Key*: Restored rock cut walls stippled; Restored masonry walls hatched; 1. Quarried cellar below; 2. Cist grave. After L St 29, pp 9, 14.

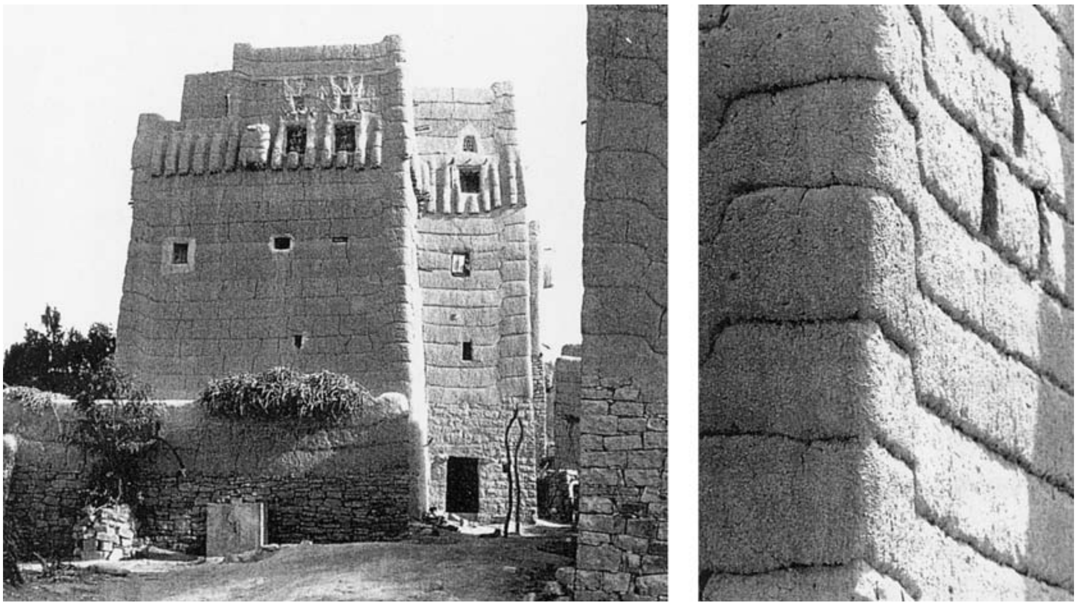
323. Ellora. Kailasa (Shiva's Paradise). Free Standing rock cut temple precinct. Western India. 8th Century AD. This virtuoso rock cut monument covers an area ca 100 m x 50 m (i.e. half a hectare). NB Standing human figure lower left by elephant, for scale. It stands towards the end of a 1000 year long development in the genre of rock cut premises and monuments. It is a culmination of the façade style of rock cut premises, i.e. with an ornamental façade cut into the cliff face. Only whereas in the Western World such monuments are of rudimentary internal working, in India the interior is worked as elaborately as the façade. As is apparent from the elevated view point, the difference between the free standing Kailasa and a normal rock cut façade type monument is that instead of the face of the cliff being cut back a few metres to provide a tableau for working the façade, here an expansive area has been cut down from above into the hill side sufficient to house a 'monolithic' version of a temple precinct. Nothing approaching this free standing rock cutting exists in the Western World. After P. Brown. pl XX VIII.

324. Mahabalipuram / Mammallapuram. The Rathas (= carriages) or "The Seven Pagodas". Free standing rock cut shrines near the shore. South of Madras. Mid 7th Century AD. These early Hindu shrines fashioned at the apogee of the Pallava (cf Pahlavi) Dynasty are the quintessential developments of rock cut free standing monuments, since their siting is entirely natural in appearance, undifferentiated from that of buildings. Great ingenuity and labour was required in eradicating the 'false note' of a rock matrix. For siting and effect they may be compared with the Jin Blocks at the mouth of the Siq at Petra, 6 or 7 hundred years older. Photograph R. Nagaswamy.

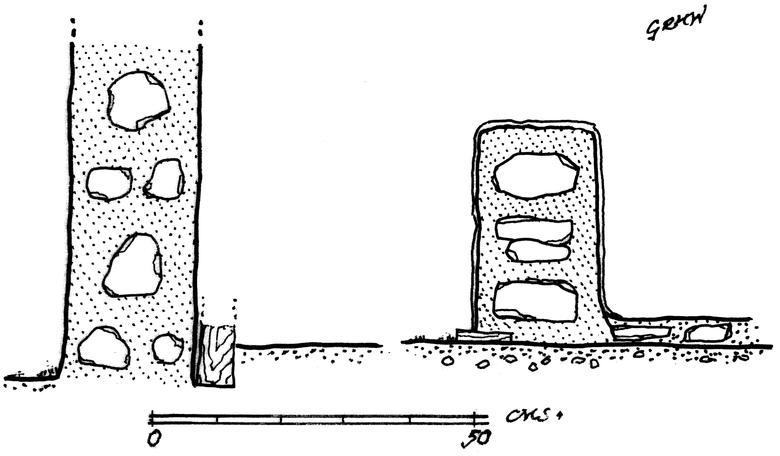


325. Tauf (Zubur) Construction. The primordial system of building with plastic earth, illustrated by the repair of a garden wall at Rawdah, North Yemen in 1982. The identical process serves to construct without any tools skyscraper residences 30m high. *Key*: a. The waller and his assistant using as materials a supply of earth, water, sand and binders such as dry leaves, mix the materials into mud balls which are rolled in sand to provide surface tension; b. These balls are handed or thrown up to the walling mason by the assistant. The mason places, or rather drives them into position using the balls as both brick and mortar (breaking them up if necessary) to form a 'course' of ca 50 cms in height which is left a day or so to consolidate; c. The waller then mounts on this construction to build another course of the same height, and so on. Binding branches can be placed between courses as tensile reinforcing if desired.

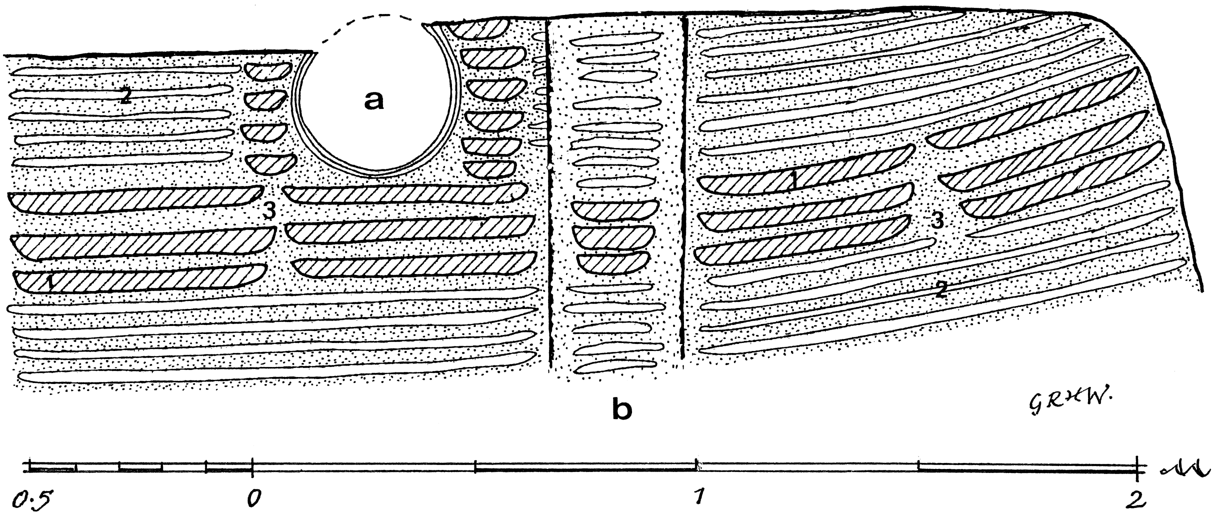
326. Saada. Traditional Modern Puddled Mud (tauf) Construction. North Yemen. 20th Century AD. This typical building in the desert regions of Northern Yemen shows a strong tower house of 4-5 floors entirely of plastic mud construction identical with that of garden walls and sheds in the lower foreground. The building procedure requires no installations or equipment of any description. After G.R.H. Wright ABADY 4 1988 pl. 44a.



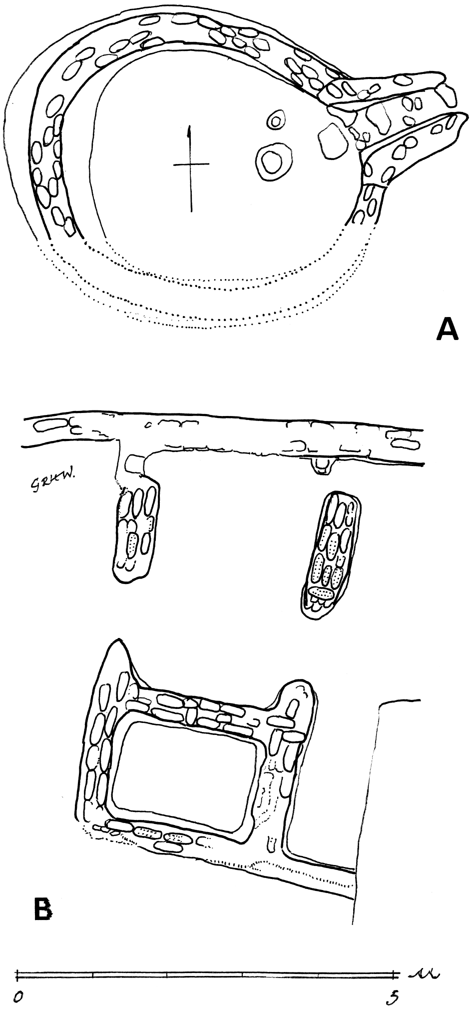
327. Typical Puddled Mud (Zubur) Construction. North Yemen. 20th Century AD. These traditional tower houses (left) in the desertic region of North Yemen are massive and strongly built for reasons both of security and of heat insulation. The average height is ca 10-12 m fashioned in horizontal registers of plastic earth of ca 50 cms height. These horizontal layers are built up at the angles in the semblance of decorative horns (right). This is a functional device to put the layers of earth in compression so as to counteract the tendency of such material to fissure and collapse at the angles. The entire construction is carried out by hand with lumps of plastic earth and requires no installations or tradesman's tools. After G.R.H. Wright ABADY 4 1988 pl. 42.



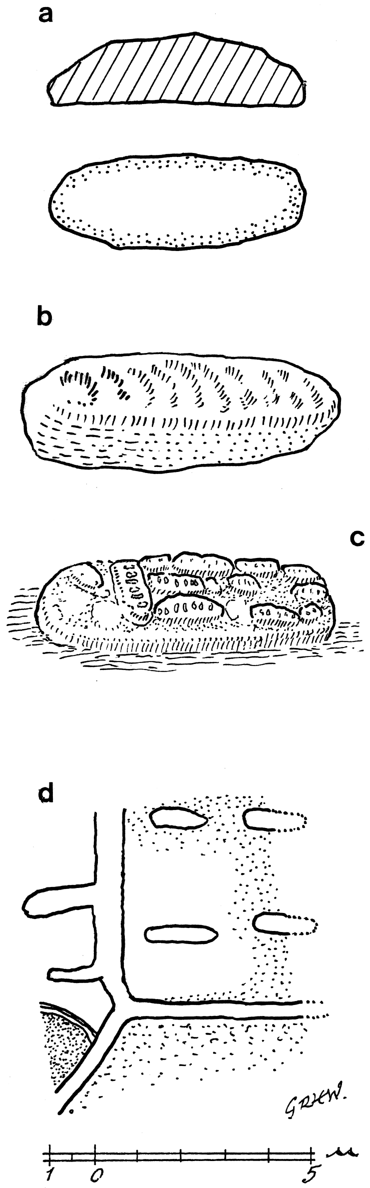
328. Mureybit. Rubble drowned in Mud. North Syria. Ca 7000 BC. Small internal partition walls of plastic mud, stiffened by random inset field stones. After Aurenche I fig 5.



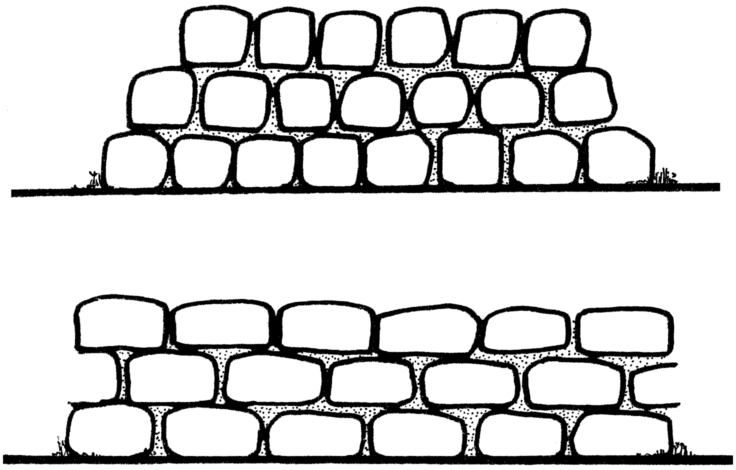
329. Ganj Dereh. Mud Wall of mixed Construction. Western Iran. Ca 7000 BC. Some walls are of mixed construction which includes hand modelled mud brick of slightly convex form, at times very long and 'low' (1). These units must have been formed on a board and then transported to the building site to be set upside down – i.e. convex surface below. Such bricks were set in tauf/zubur/chineh, i.e. plastic mud (3), as a stiffener. Also this mud was interlayered with very long strips of mixed mud and vegetable matter of light colour (2). These walls were of slight thickness (30 cms – 40 cms) and were buttressed at intervals (b). Also the walls were pierced at intervals by circular port holes (a) of yet undetermined function, not necessarily utilitarian. After D.E.L. Smith WA 21 1990 p.329, fig 2.



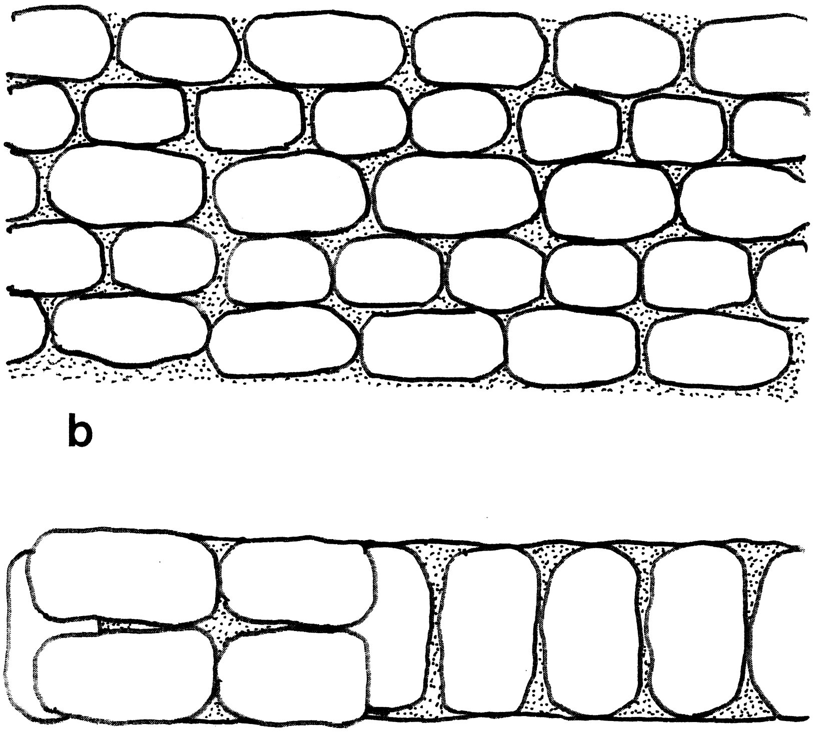
330. Jericho. Early Pre-pottery Hand Modelled Brickwork. Cigar Shaped Bricks. Jordan. 8th Millennium BC. *Key*: A. Round House Building PPNA; B. Rectangular Building PPNB. The originals of these drawings have limitations, however they show that hand modelled mud bricks of "cigar shaped form" were used at the time of the earliest substantial Neolithic building at Jericho in the Round House Tradition (PPNA) and survived in use into the succeeding rectangular building tradition (PPNB). They also indicate that in the earliest stage (cigar shaped) mud bricks were not set closely together to form bonded brickwork but rather bricks were set separately into plastic mud as a stiffener – i.e. drowned in mortar. Unfortunately the graphic record of brick construction in the Jericho plans in less than explicit, and it may be that the vestiges of individual bricks were not clearly distinguished in the excavations and not clearly rendered in the drawings. However according to the drawings it seems that hand modelled mud bricks developed out of a background of "tauf" (i.e. plastic mud) construction. On the other hand it appears that with the rectangular building tradition, mud bricks were set regularly and close together – i.e. the tradition of bonded brick work was being developed. Also to be noted is the striking fact that the "cigar shaped" form of the individual mud bricks was echoed in the overall plan of the building units they composed. Thus in rectangular building junctions and stopped ends were rounded, minimising angle collapse and frangible arrises. After Jericho III pl 300c, pl 263c.



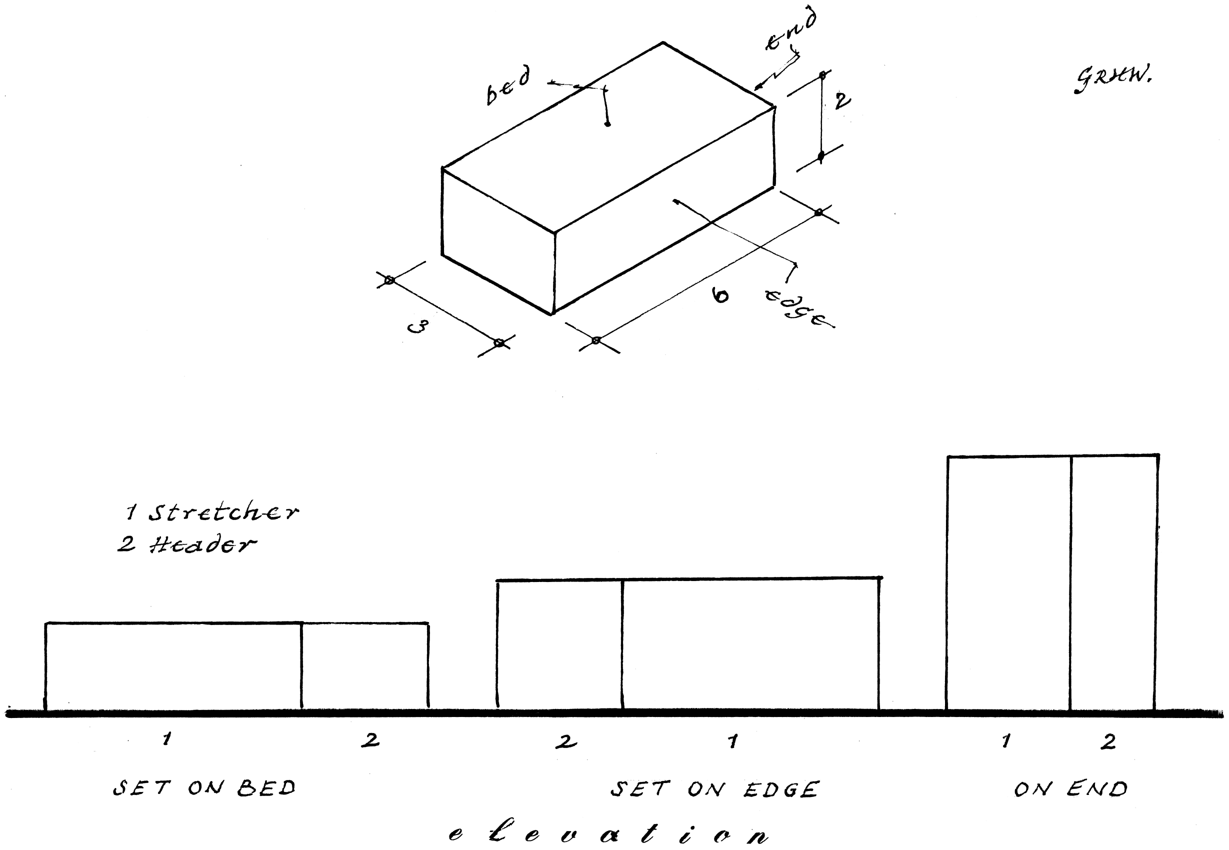
331. Jericho. Elements of Pre-pottery Neolithic Hand Modelled Mud Brick Construction. Jordan. 8th Millennium BC. The use of hand modelled mud bricks developed out of earlier experience with plastic earth (puddled mud) construction, cf rounded ends and slightly ovoid forms. *Key*: a. Plan and Section of 'hog backed' mud bricks (length 39 cms); b. Cigar shaped mud brick with thumb impressions as "frogging" (length 46 cms); c. Wall or pier of cigar shaped mud bricks with overall form that of individual mud bricks (length ca 1.20 m); d. Part plan of house incorporating above elements (c) built of cigar shaped bricks. After ABSP II fig 298.



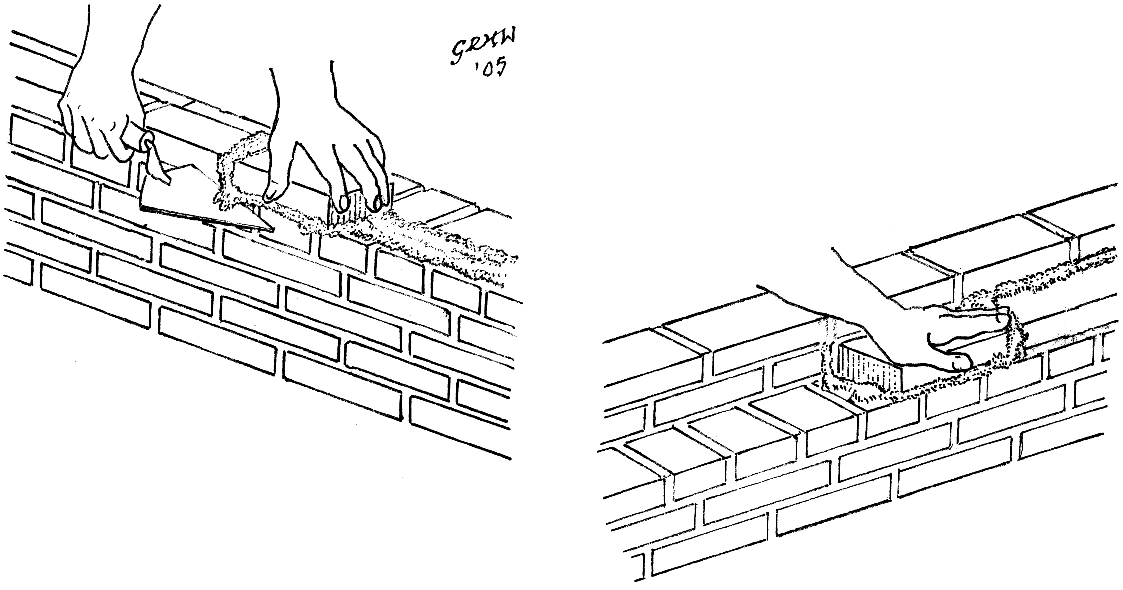
332. Tuleilat el Ghassul. Hand Modelled Mud Bricks. Palestine. Chalcolithic. 4th Millennium BC. The very regular (quasi rectangular) bricks are from a region (Palestine) where there was a very great time lag in the introduction into general use of form moulded bricks. The standardised regular contours of these bricks together with their setting close together, uniformly coursed and keeping bond (above header bond, below stretcher bond) illustrates the overall evolution in the development of brick masonry – and even the influence of form moulded bricks long established as standard in adjacent lands. After Tuleilat el Ghassul I, figs 13, 14.



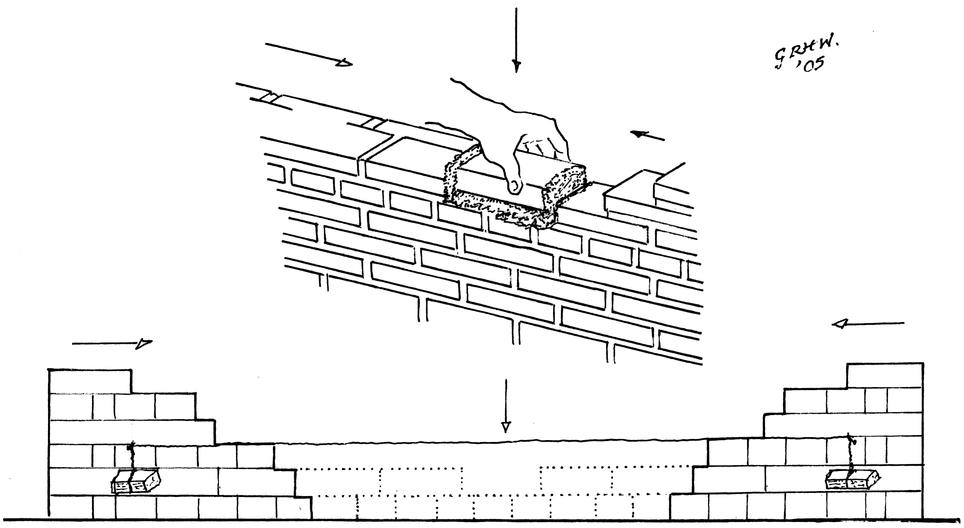
333. Tepe Sialk. Hand Modelled Mud Brick Wall. Iran 5th Millennium BC. *Key*: (a) Plan; (b) Elevation. These late hand modelled mud bricks are verging towards the rectangular disposition of form moulded bricks, thereby to acquire the advantages of regularity and close setting. Here they are purposefully laid in an approximation of English Bond. After Aurenche I, fig 81.



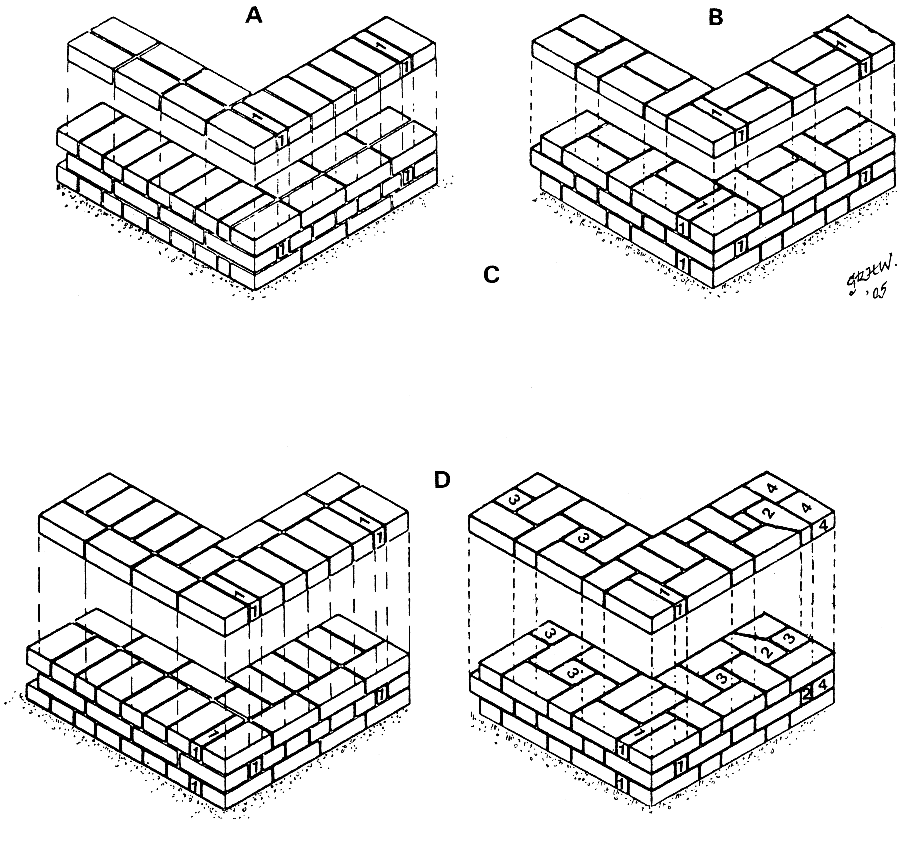
334. Form Moulded Brick – Basic Terminology. Diagram showing surfaces of bricks respectively designated bed, edge and end in a frequently occurring set of proportions; together with the several aspects in elevation consequent on setting as header or stretcher on bed, on edge or on end.



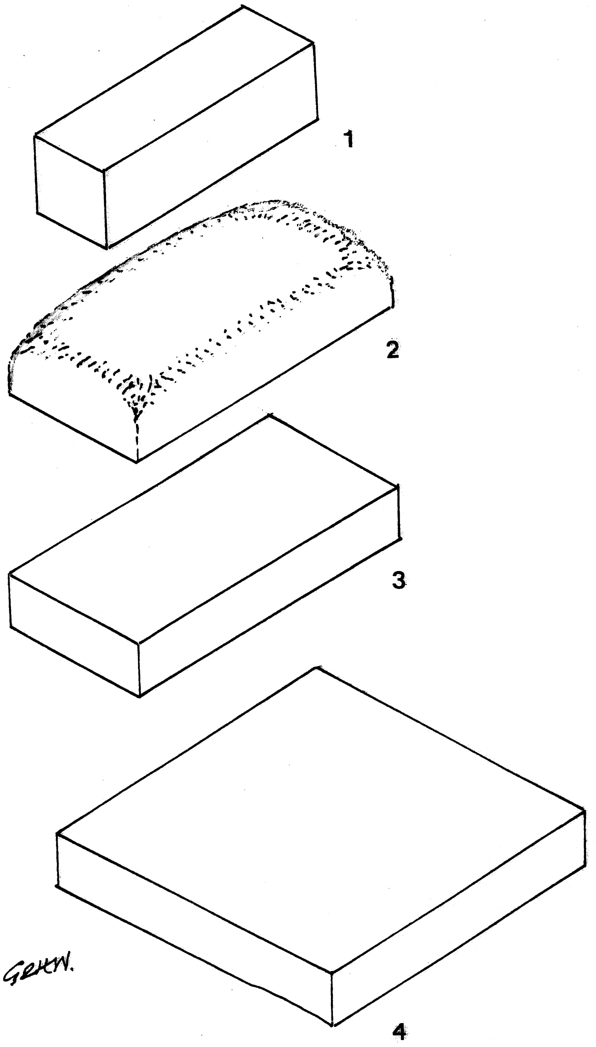
335. Diagram Showing Basic Procedure of Bricklaying. Mortar spread by trowel on bed and rising joint of existing masonry, then brick placed into position by hand and finally surplus mortar cleaned off by trowel.



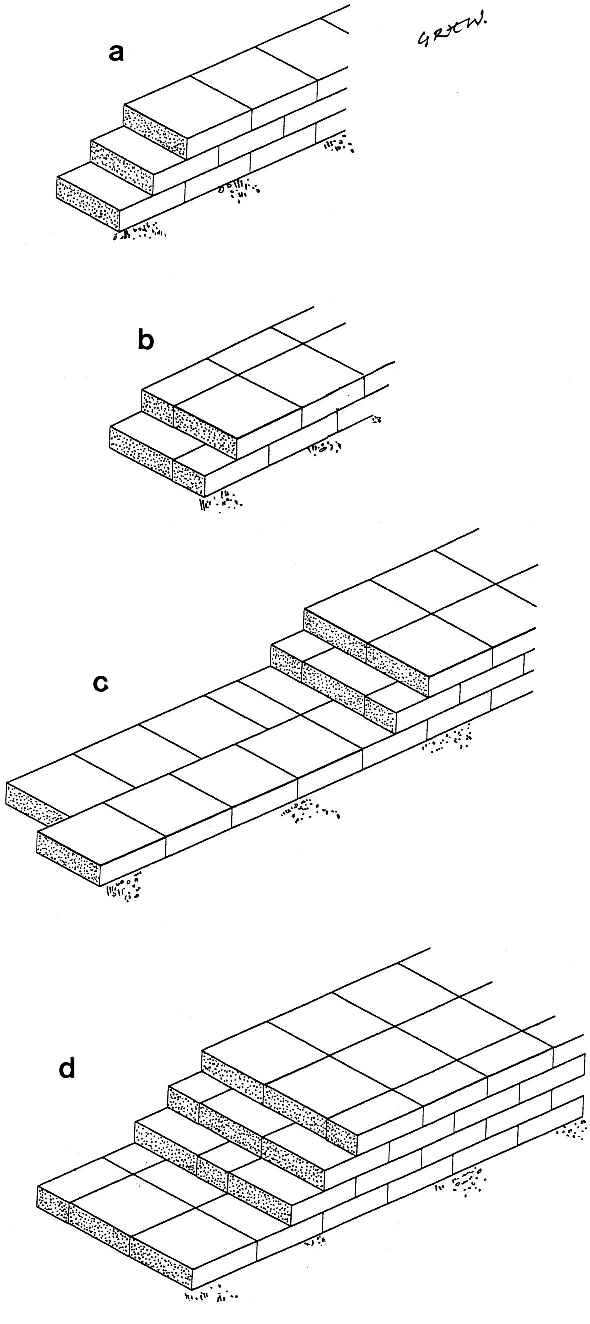
336. Diagram Showing Order of Laying Bricks to Build a Wall. The bricks are laid true to the face of the wall in plan by fixing a line to run from one end of the wall to another, and are laid true to horizontal coursing by testing with a level. Stepped angle piers are first built up at each end of the wall, and intervening run completed by working inwards from each end with a final closer inserted at the middle. Care is taken to keep the intermittent succession of rising joints (the perpends) in line vertically.



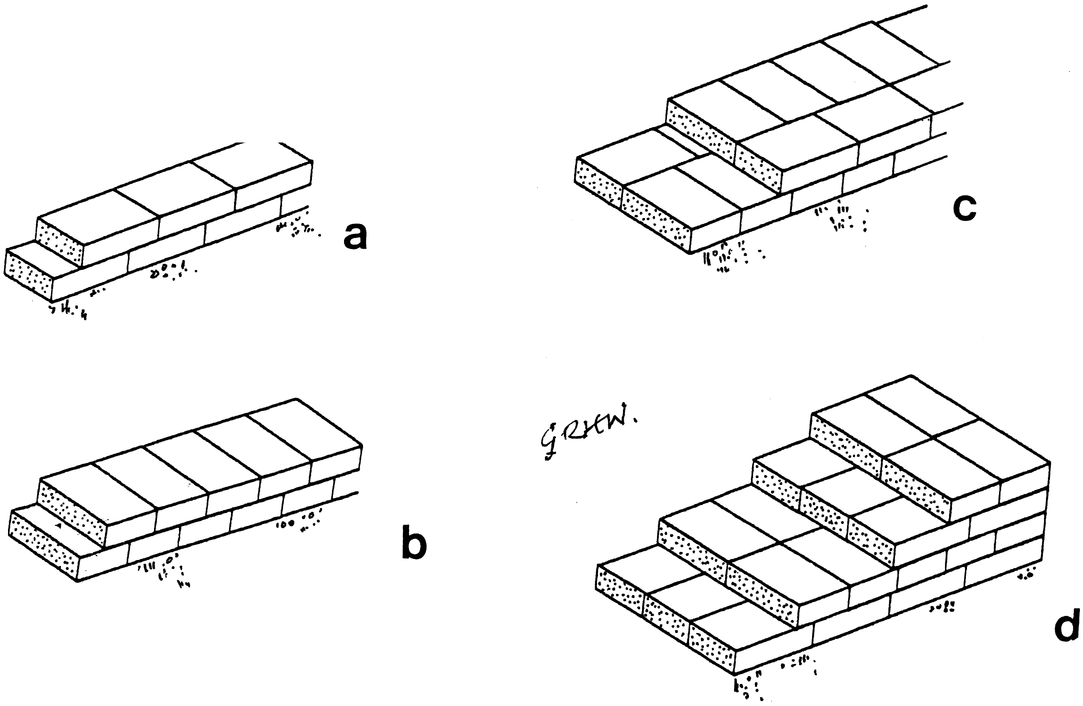
337. Common Bonds in Traditional Modern Brick Masonry. *Key*: A. (left) English Bond = alternate courses of headers and stretchers; B. (right) Flemish Bond = bricks in each course set alternately as headers and stretchers; C. (above) One brick wall = wall of the thickness of 1 brick length; B. (below) One and a half brick wall = wall of the thickness of $1^{1/2}$ bricks in length. 1, 2, 3, 4 indicate part bricks of various forms which are set at stopped ends, angles and junctions to provide for correct bonding. According to available evidence such devices were not used in ancient brick masonry.



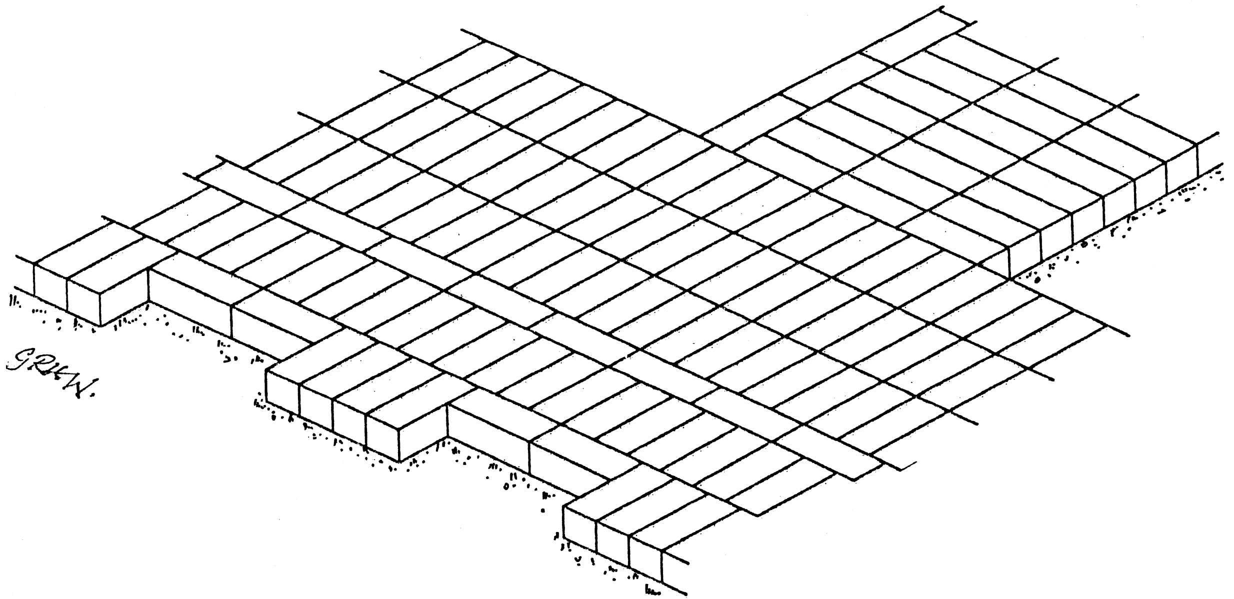
338. Basic Forms of Bricks used in Mesopotamia. *Key*: 1. Riemchen (= little belt); 2. Plano-convex; 3. Rectangular; 4. Square.



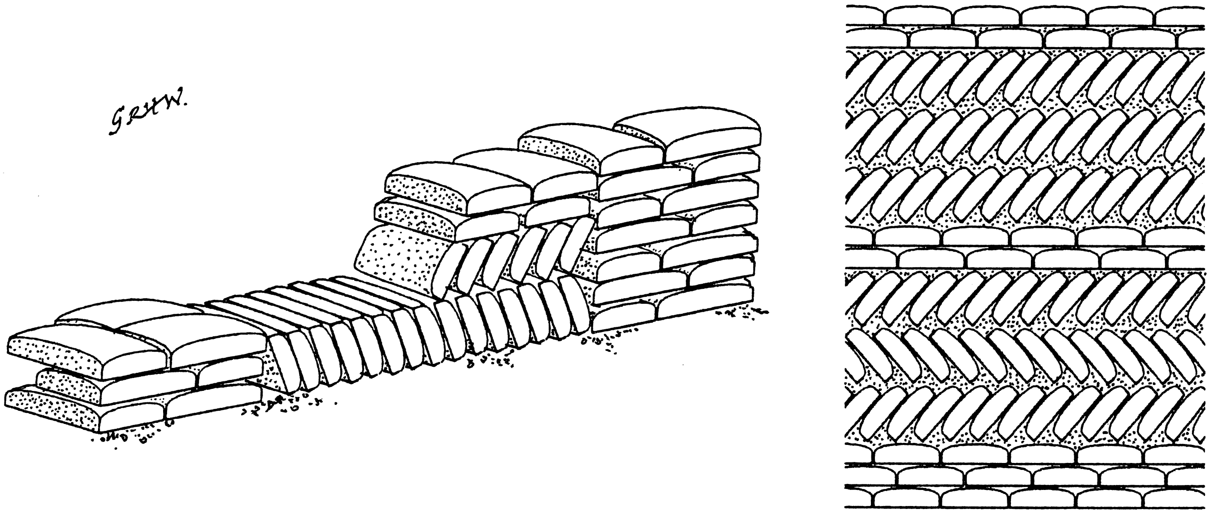
339. Mesopotamia. Bonding of Square Bricks. This is the type of brickwork handed on to Classical Greece and Rome and is referred to by Vitruvius. Apart from what is shown here, if the thickness of the bricks bears some integral proportion to the length of the sides, then the bonding scheme can be varied by setting some bricks on edge. Other than this the use of half bricks is always necessary somewhere to break the vertical joints and is the only contrivance required and necessary. It generally appears at the faces of alternate courses when the thickness of the wall is more than that of a single brick. *Key*: (a) Wall of 1 ½ brick thickness; (b) Wall of 1 ½ bricks thickness; (c) Wall of 2 bricks thickness; (d) Wall of 2 ½ bricks thickness. These examples are from Isin. After Sauvage pl 45.



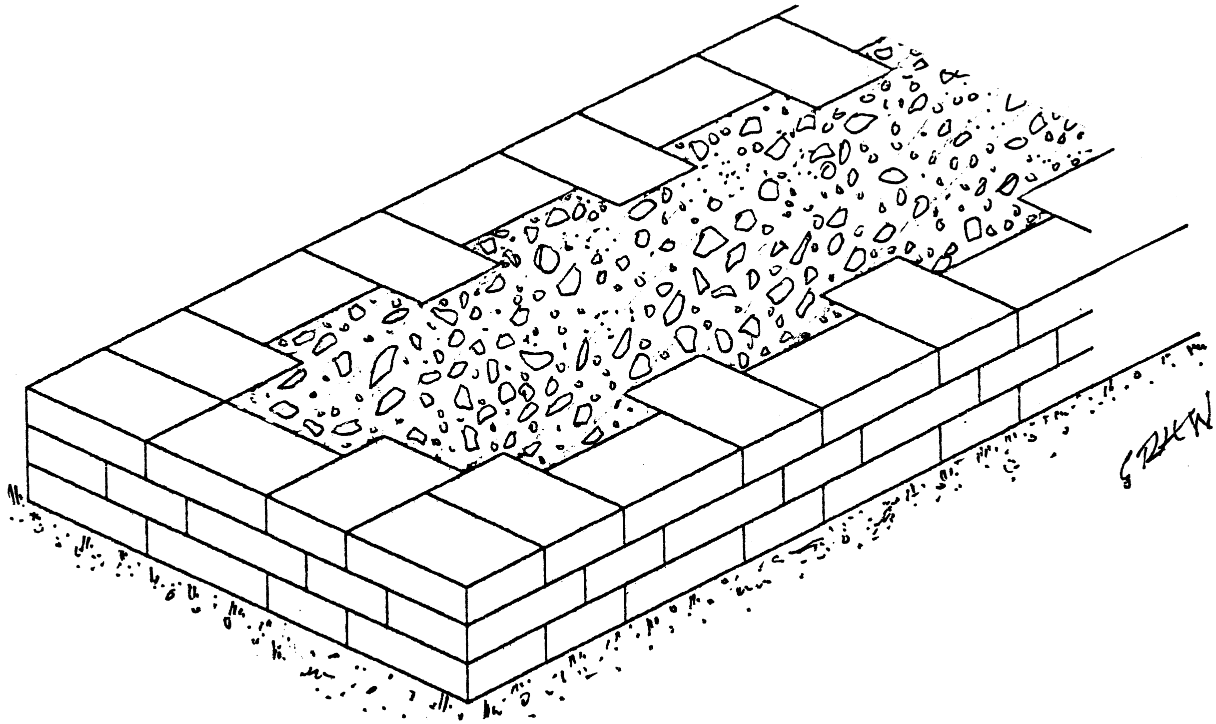
340. Mesopotamia. Basic Bonds employing header and stretcher rectangular bricks. *Key*: (a) Stretcher bond, i.e. ½ brick wall; (b) Header bond, i.e. 1 brick wall; (c) English type bond, 1½ brick wall; (d) English type bond, 2 brick wall. NB The proportion length: breadth of these bricks is not 2:1, but for convenience the modern terms 1, 1½, 2 brick walls etc are maintained. After Sauvage *pass.*



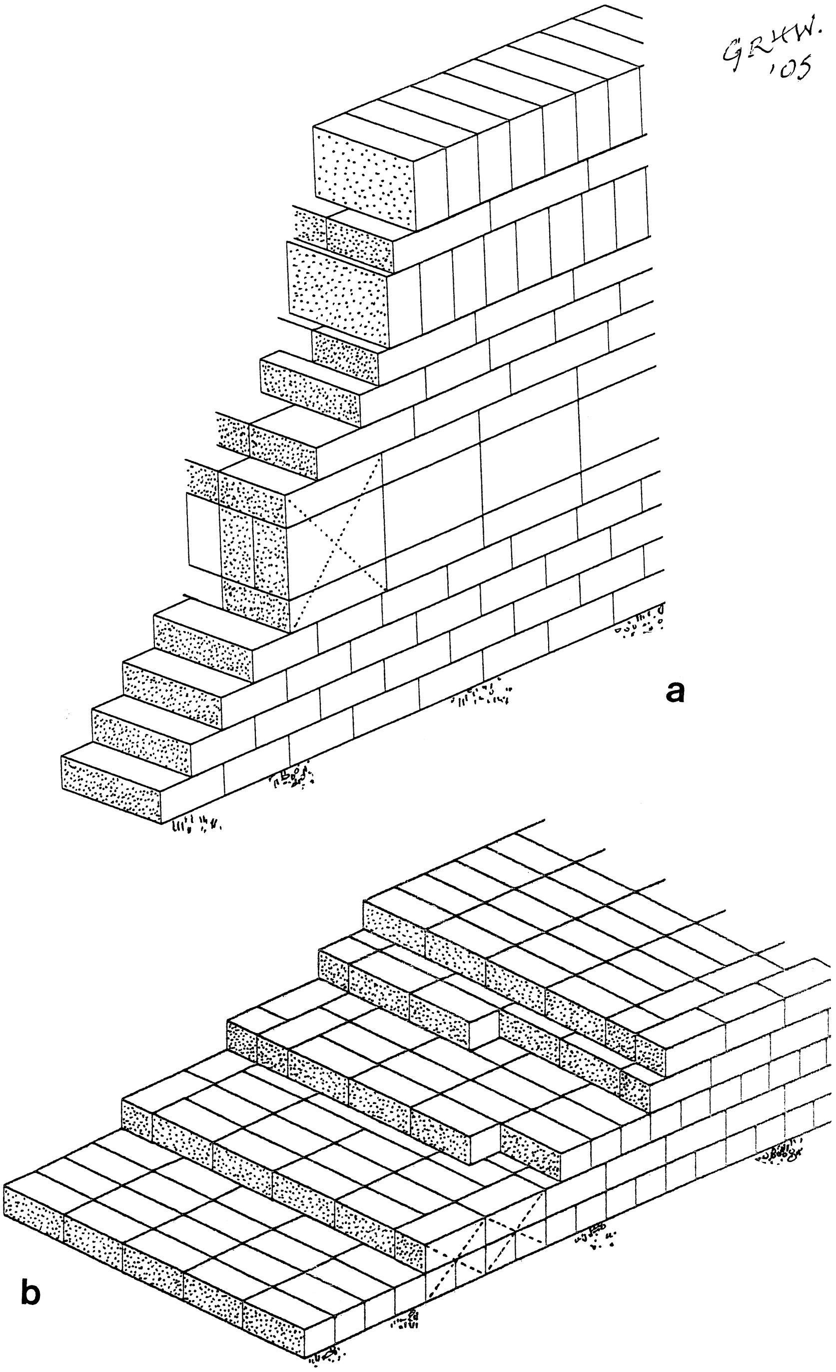
341. Mesopotamia. Riemchen Bricks laid in typical Bonding Pattern (*Riemchen Verband*). Uruk level IV. These idiosyncratic bricks of constricted square section are characteristic of Uruk, Jemdet Nasr and early Dynastic times, i.e. at a period of rapid urban development. In the overall they are set as headers, notably when in massive walls. Generally they are held together in the mass by a facing row of stretchers which is sometimes repeated (as here) within the core of a massive wall. The proportion of length to breadth is often 2 ½: 1, which makes for a convenient bond between headers and stretchers. The virtue of these bricks is ease of handling and speed of setting. The form devolves from hand modelled 'long' bricks of early Neolithic times. After Sauvage, p. 402, pl 12e.



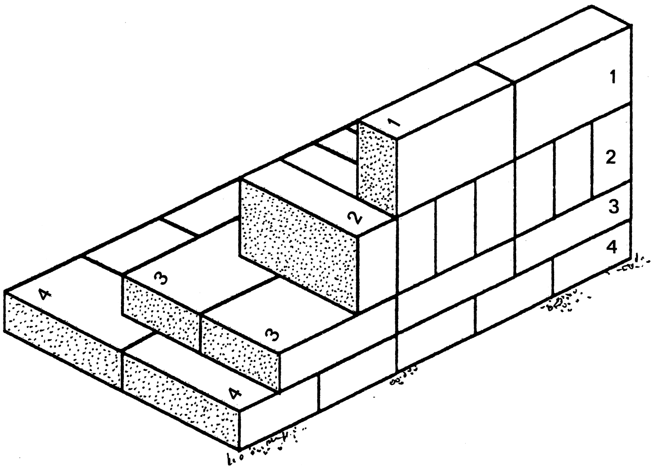
342. Typical Plano Convex Brick Masonry. Herring bone bond formed by courses set on the diagonal vertically, and framed by horizontally laid levelling courses and stopped ends. After Sauvage, *pass.*



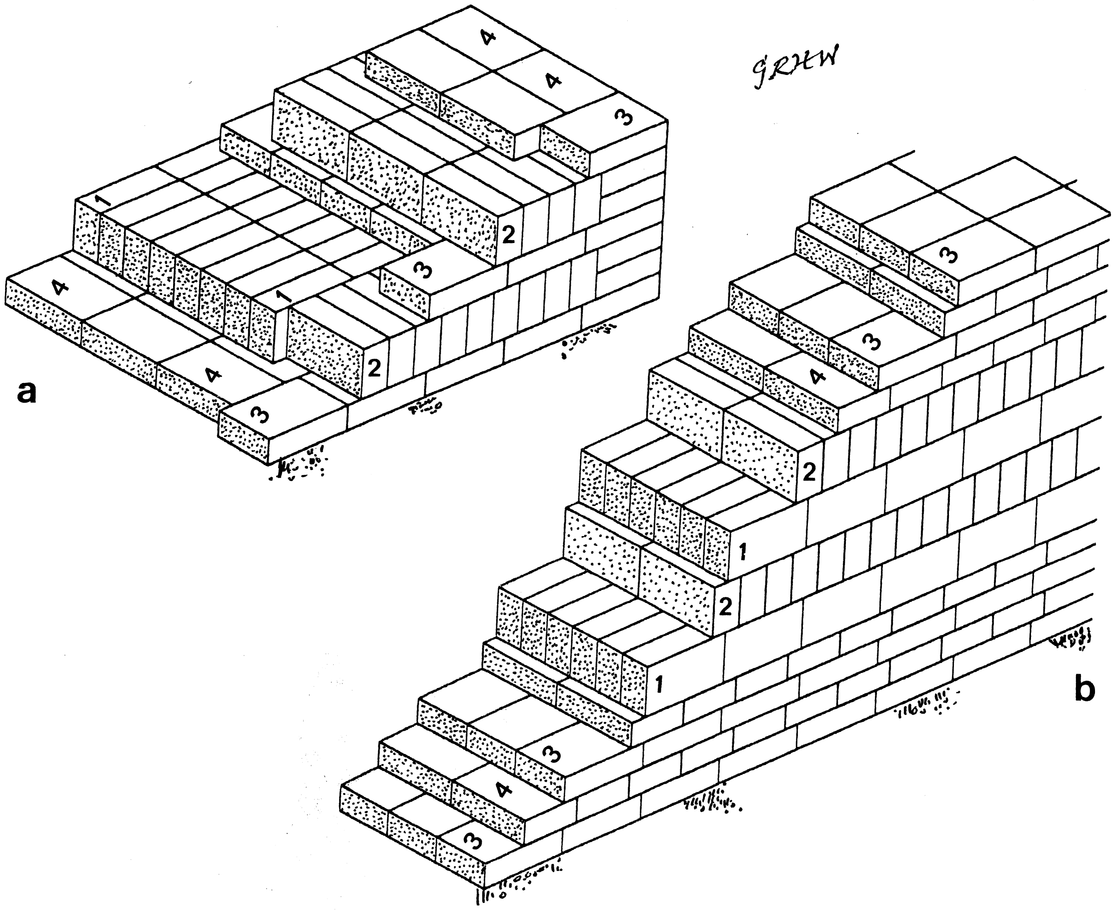
343. Mesopotamia. Rectangular Bricks set with Headers and Stretchers in Flemish Bond. This is one of the rare occurrences of Flemish Bond in antiquity. In fact it is not a bond at all, as the bricks are only facing to a core of other material. It is the Mesopotamian equivalent of Roman Opus Testaceum. After Sauvage, p. 427, pl 37b.



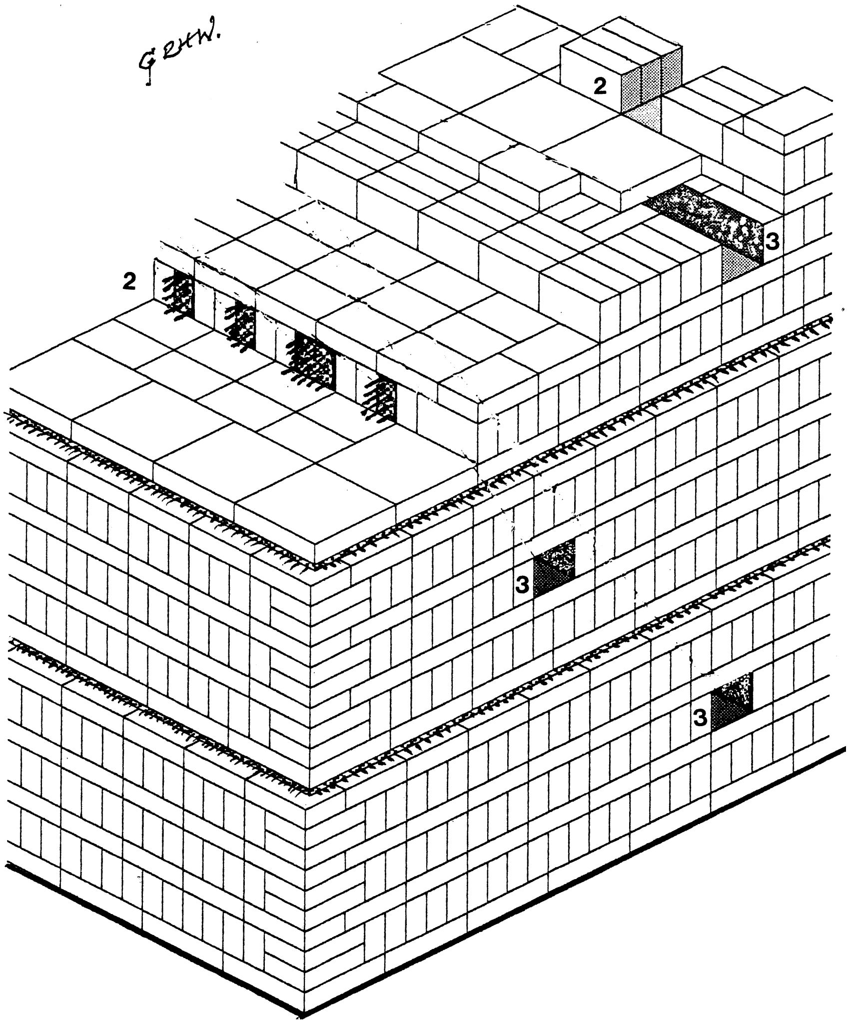
344. Mesopotamia. Bonding Composite Units of Bricks rather than Individual Bricks. A widely recognised practice in ancient masonry (both brick masonry and fine stone masonry) was to take as the unit to be bonded a small block of masonry forming a dwarf pillar or the like. Continuous vertical joints (straight joints) ran up the margin of these units for the several courses of the assemblage, but above and below these, joints were broken by a differently set course. There is nothing structurally defective about this practice. Here such bonding units are shown crossed for their better identification. *Key*: a. Bonding Unit assembled from bricks of normal format; b. Bonding Unit assembled from "Riemchen". Here a thick wall is built of a special type of small brick of prism form (i.e. square in section). Here the bricks are as a double cube, i.e. the length = 2 x the breadth/height. Bricks of this form were termed *Riemchen* by the D.O.G. excavators a century ago and this unhelpful term has remained current. As befits a thick wall bricks are laid almost entirely as headers. After Sauvage *pass.*



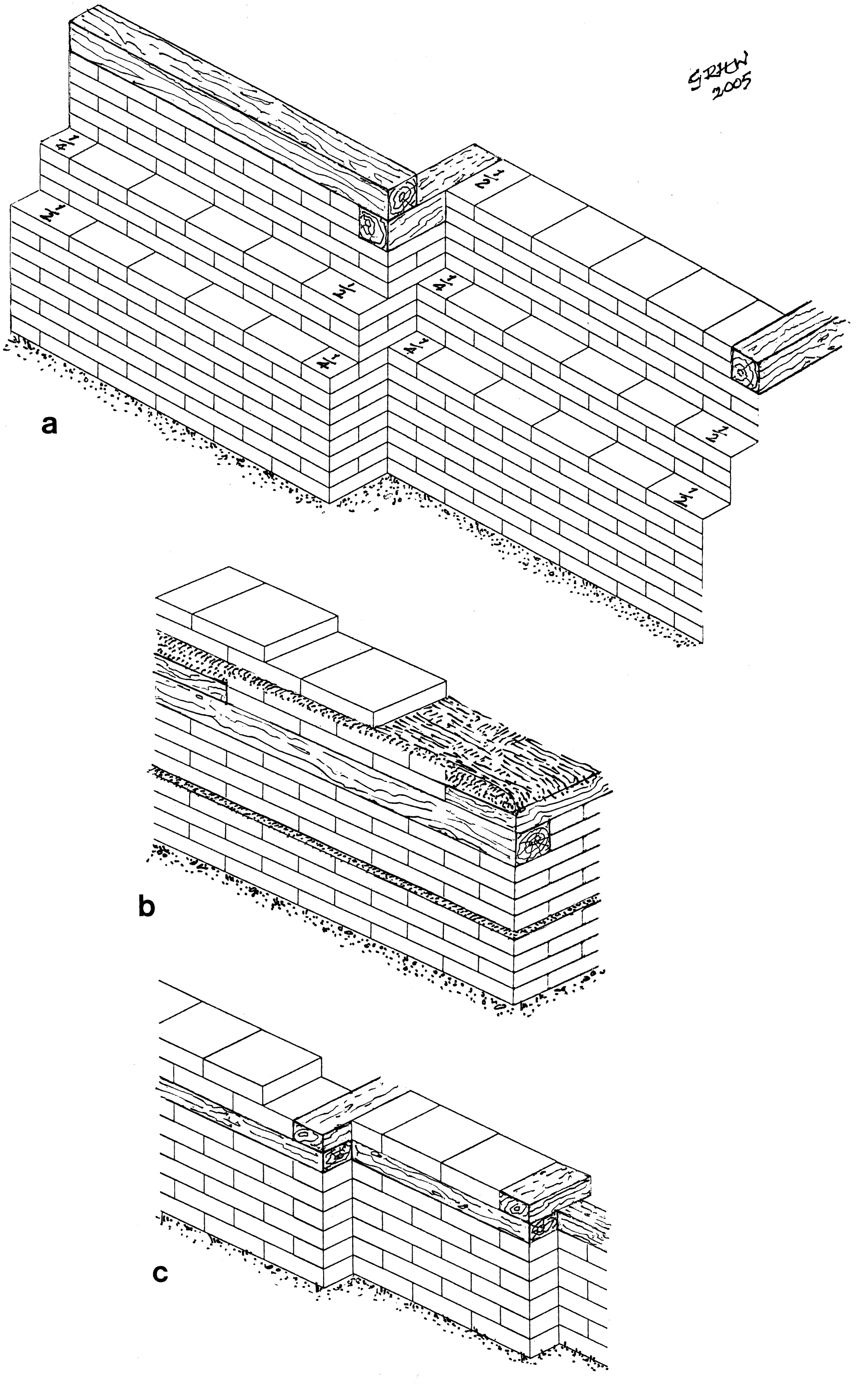
345. Mesopotamia. Bonding by alternation of courses set on Bed and on Edge. Extensive use of this device was in part promoted by bricks dimensioned in the proportion of 3: 2: 1 so that one header on edge backed by one stretcher on edge gave the same wall breadth as two stretchers set normally on their beds. The alternation of courses on bed and on edge could be in blocks of different numbers. *Key*: 1. Stretchers on Edge; 2. Headers on Edge; 3. Stretchers on bed; 4. Headers on bed. After Sauvage, fig 38.



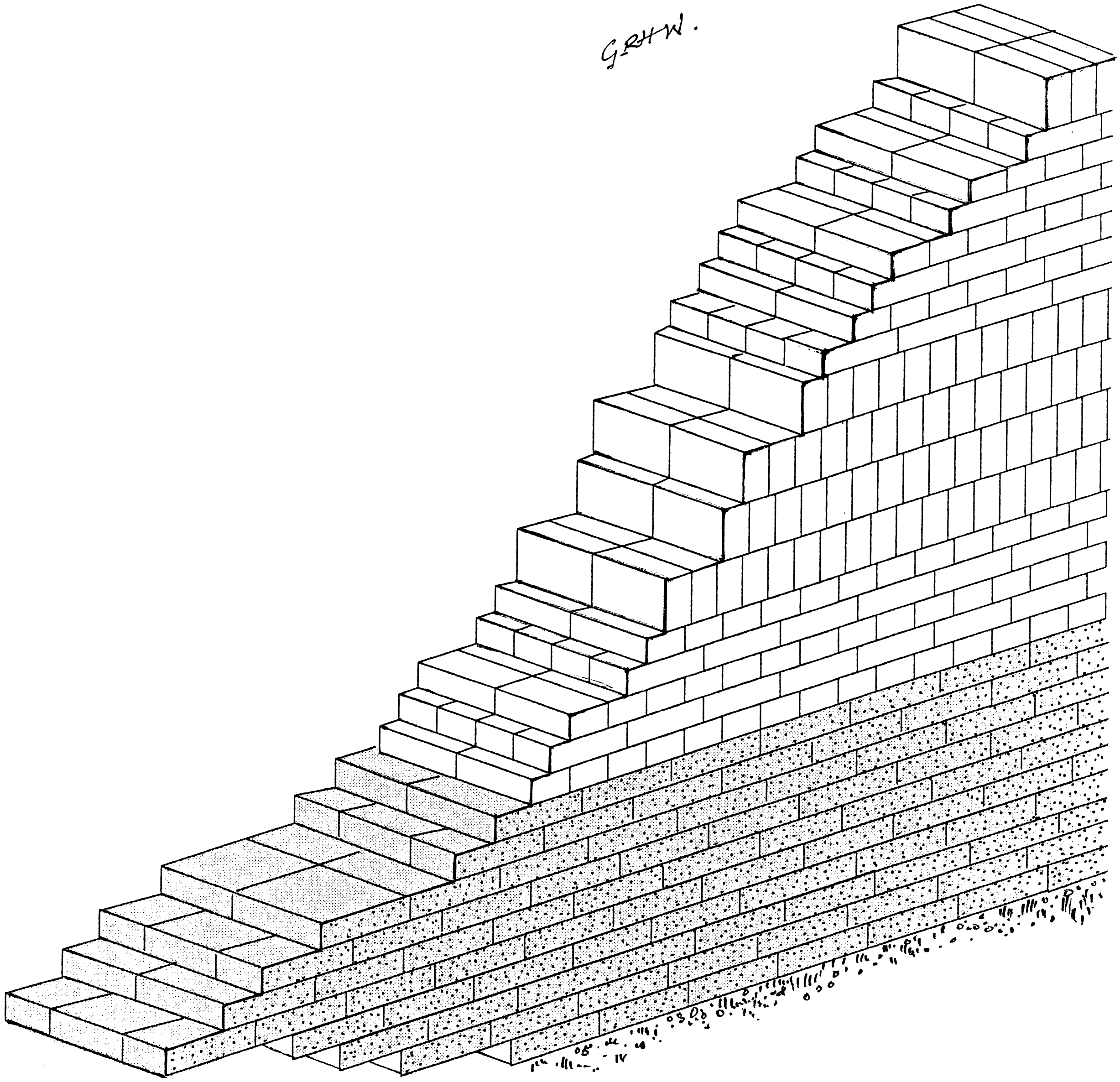
346. Mesopotamia. Typical Bonding Patterns of Brick laid variously on Bed and on Edge. *Key*: a. Courses laid alternately on bed and on edge; b. 4 successive courses laid on bed alternating with 4 successive courses on edge. 1. Stretcher on edge; 2. Header on edge; 3. Normal stretcher on bed; 4. Normal header on bed. After Sauvage, figs 48, 49.



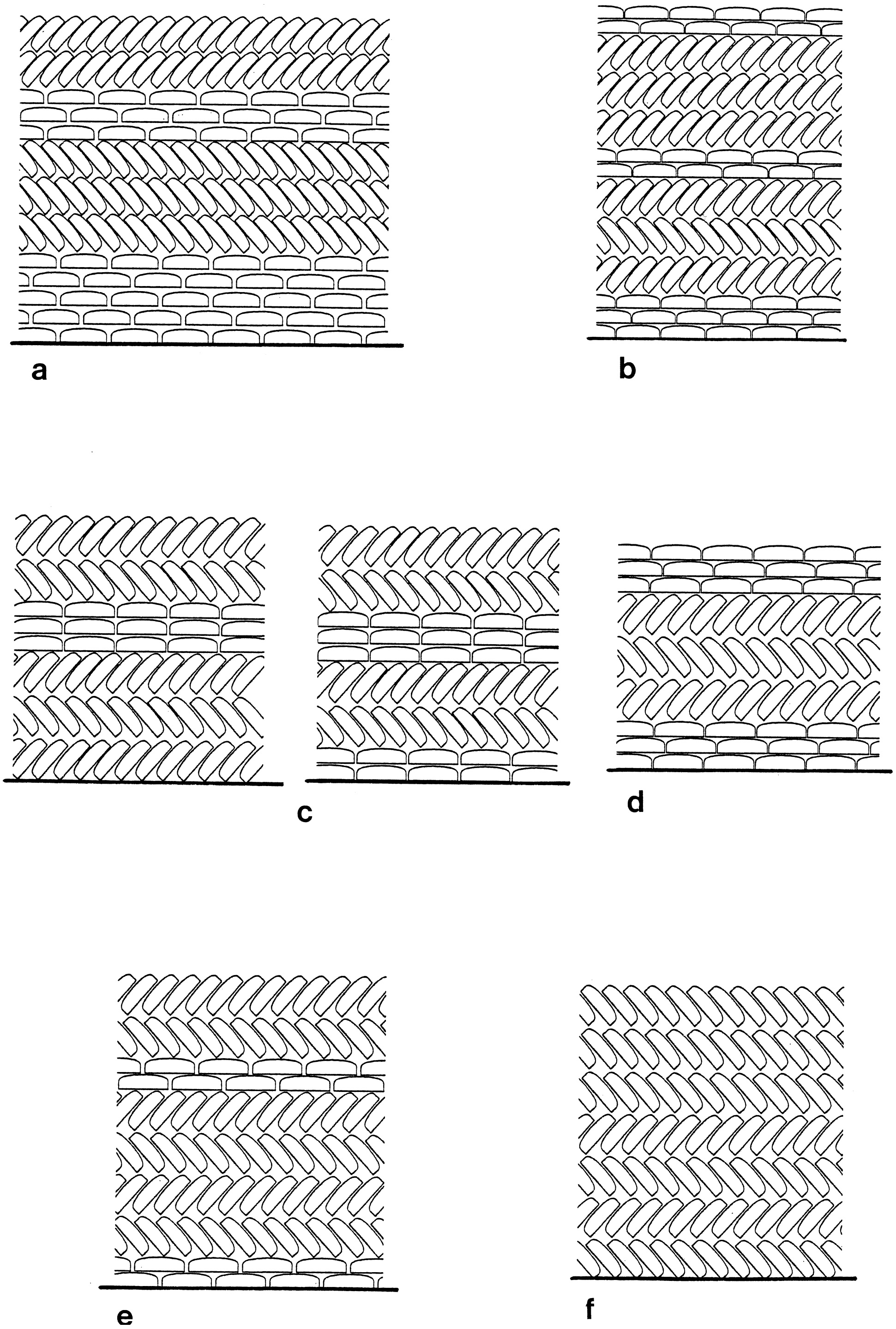
347. Mesopotamia. Core Masonry of Massive Brickwork as in Ziggurats. The bonding as is ever a rule in massifs shows an overwhelming predominance of headers. Also special measures are provided against uneven settlement and lateral spreading, both of which result in serious fissuring. Further steps are taken to promote drying out of mud brick removed from the atmosphere, deep in the core. *Key*: 1. Carpets of reed matting spread in every 9 courses to cushion and equalise settlement; 2. Stringer reed bundles (and/or wooden beams) thread the masonry lengthwise to tie it together laterally; 3. Drainage/drying in the masonry appears at the faces to act as "weep holes". After Sauvage, pl 49.



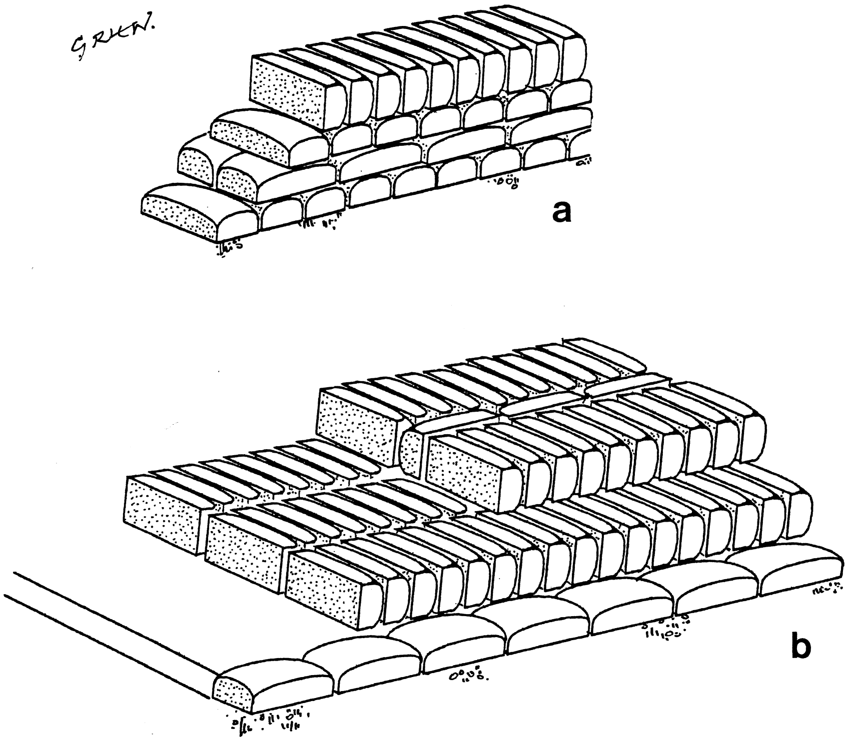
348. Mesopotamia. Neo-Babylonian Square Brick Construction. Babylon. 6th Century BC. This construction incorporates wooden tensile re-enforcing, both stringer beams and cross pieces. Perhaps these wooden insets were not always so accurately squared up as here shown, the interstices could always be made up with mortar. Another feature was the use of matting and rushes at intervals between courses. This served two purposes. It promoted drainage of internal moisture, and cushioned settlement. Bonding arrangements were elementary. For the square bricks regular perpends were kept by the simple device of using ½ bricks on the faces and ¼ bricks at the angles (unacceptable practice in modern bonding). Also it appears that only stopped ends and angles were attended to; intersecting walls were not bonded together but simply butted against one another. *Key*: (a) Babylon. Old Palace, South Tower; (b) Babylon. Merkes, Temple of Ishtar; (c) Babylon. Merkes, House III. After Sauvage, pl 54.



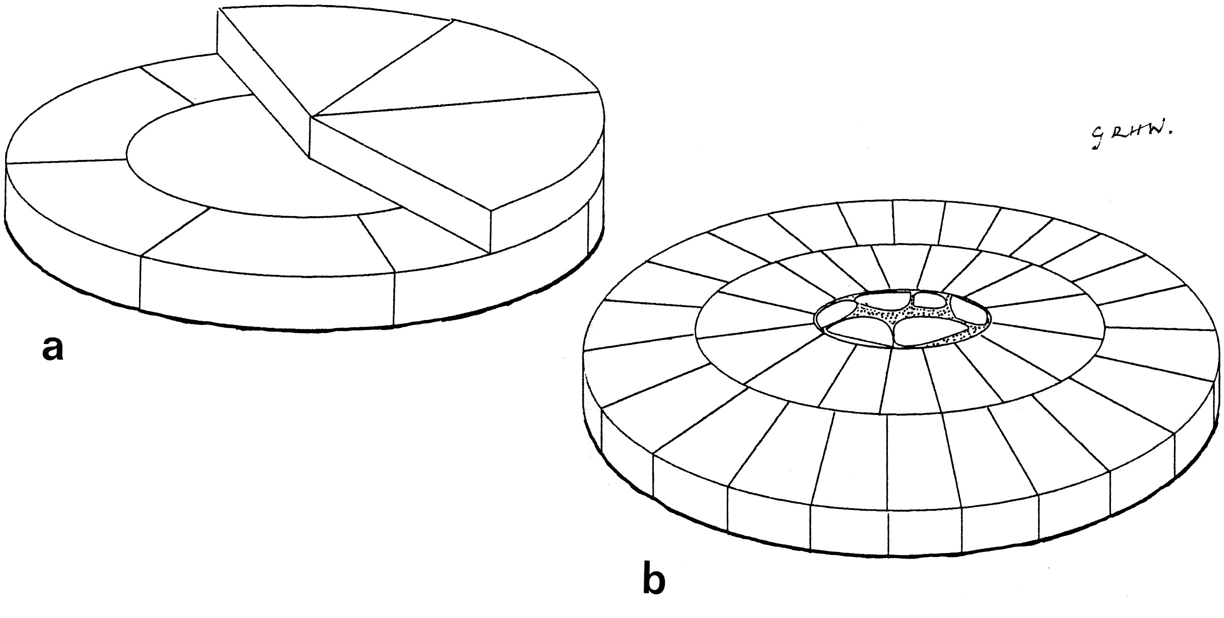
349. Mesopotamia. Mixed Mud Brick and Burnt Brick Construction. Larsa. Burnt brick as a superior building material came into use conforming to a recognised development pattern. At first used in very limited special circumstances where its extra strength and durability were required, it then passed to use for passages of construction in conjunction with the use of mud brick for the remainder. Finally it became an all purpose material used for a complete building (cf, e.g. the development in use of marble). Here the substantial mud brick wall has a substructure of 10 courses of burnt brick. This drawing demonstrates that the process of brick laying was the same for burnt brick as for mud brick. Bond was kept between the two types of bricks. The square burnt brick construction was set in the simplest square brick bonding. The mud bricks were half brick format set in alternate courses of headers and stretchers (English Bond) interspaced with registers of headers set on edge. After Sauvage, p. 436.



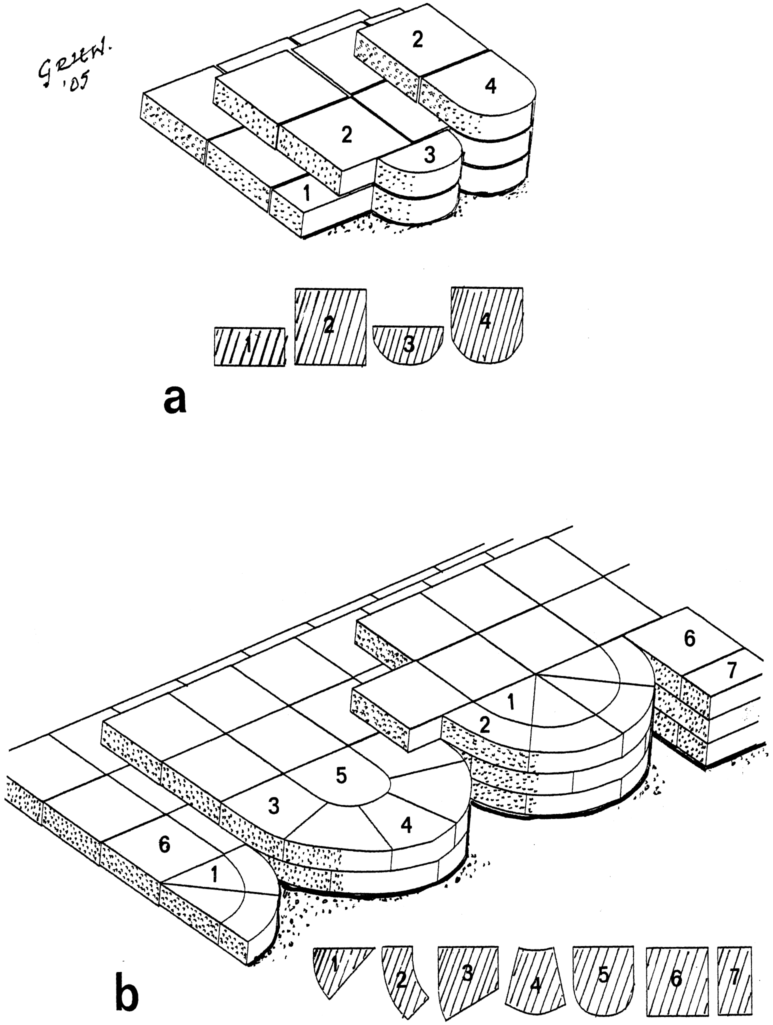
350. Mesopotamia. Specimen Conspectus of Plano-Convex Brick Bonding. Southern Mesopotamia. 3rd Millennium BC. This highly characteristic type of moulded mud brick evolved out of flatish field stones eminently suitable for dry stone walling. Such field stones were conspicuously absent in the alluvial country of Southern Mesopotamia – hence the development of *ersatz* mud brick versions. Equally these were layed in identical herring bone formation found in the dry stone walling with flat stones. Many other variant formations are known and recorded. *Key*: (a) from Ur; (b) from Ur; (c) from Fara; (d) from Tell Hiba; (e) from Ur; (f) from Ur. After Sauvage, Pl 22.



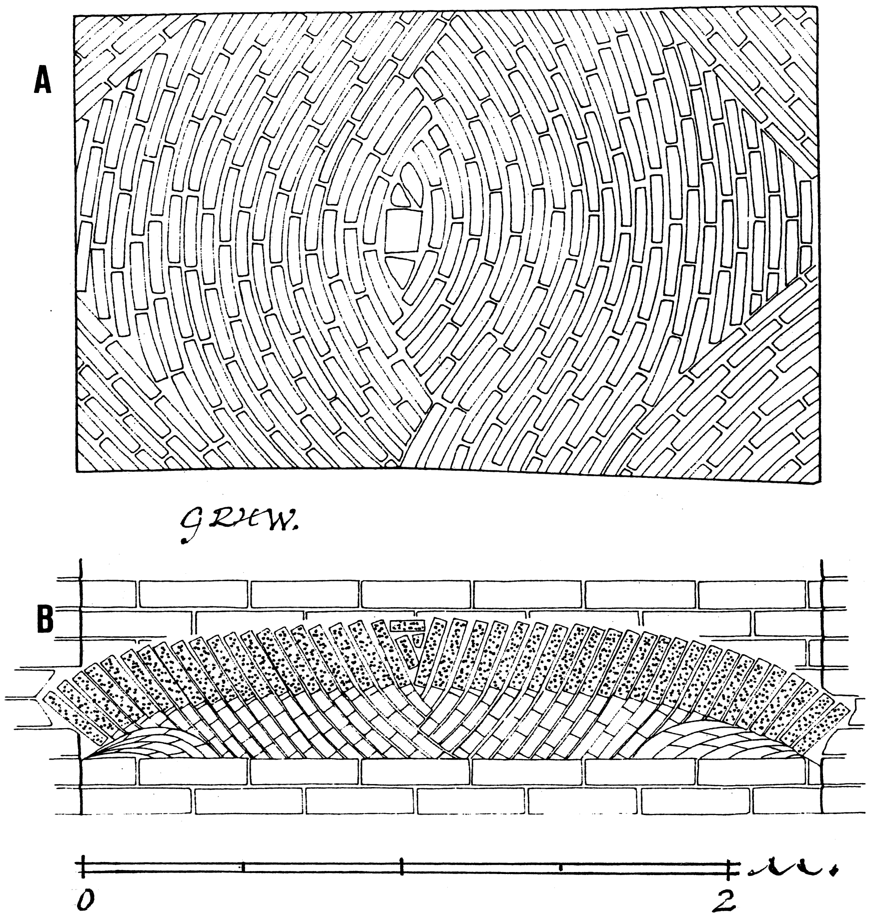
351. Mesopotamia. Plano-convex Brick. Orthogonal Bonding. Plano-convex bricks were not always used herring bone fashion (i.e. set diagonally). Sometimes they were set orthogonally in the fashion of normal bricks both on bed and on edge as stretchers and headers. *Key*: (a) from Fara; (b) from Tell Asmar (Eshnuna). After Sauvage, pls 20, 21.



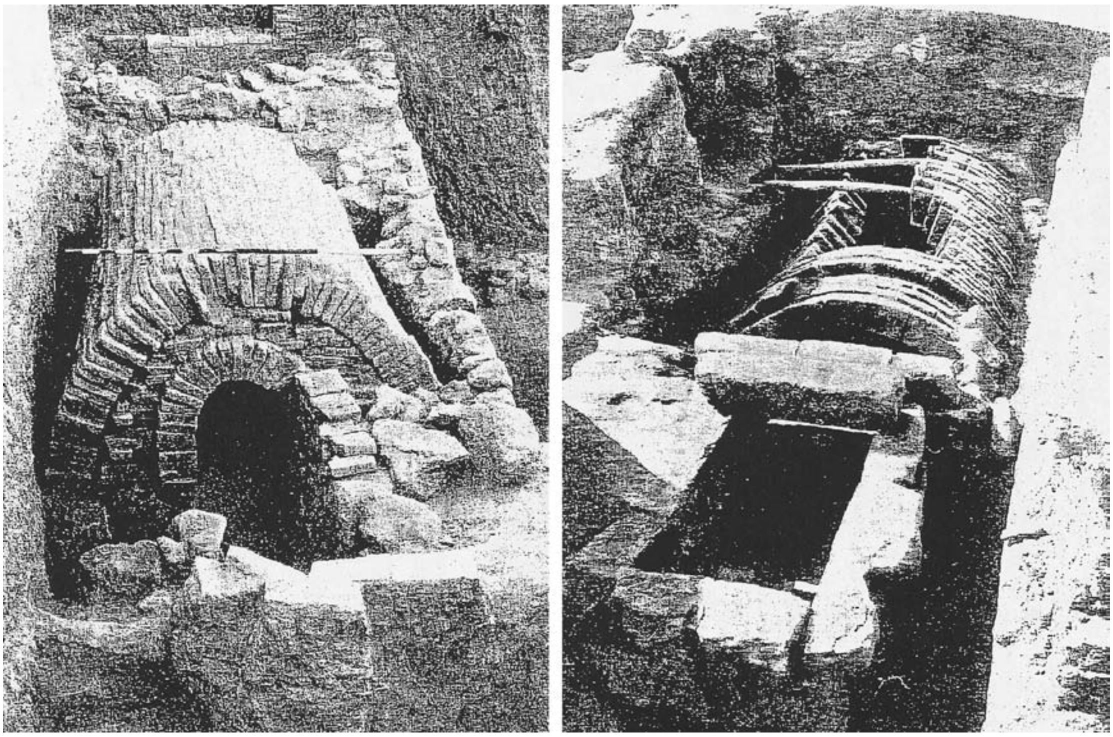
352. Mesopotamia. Brick Masonry Columns. Southern Mesopotamia. ca 3rd Millennium BC. Although massive columns in brick masonry were known during Early Mesopotamian times, columns became very rare features in later building. However the technique of their construction in brickwork remained known throughout the history of Mesopotamian building; and it was probably from Seleucid practice in Mesopotamia that the identical technique reached Hellenistic Greece and Italy to become a common feature of Roman building (cf Vol 2.2, Ills 181, 208). *Key*: (a) from Ur (Temple of Nin-giz-zida); (b) from Uruk. After Sauvage, pl 56, 57.



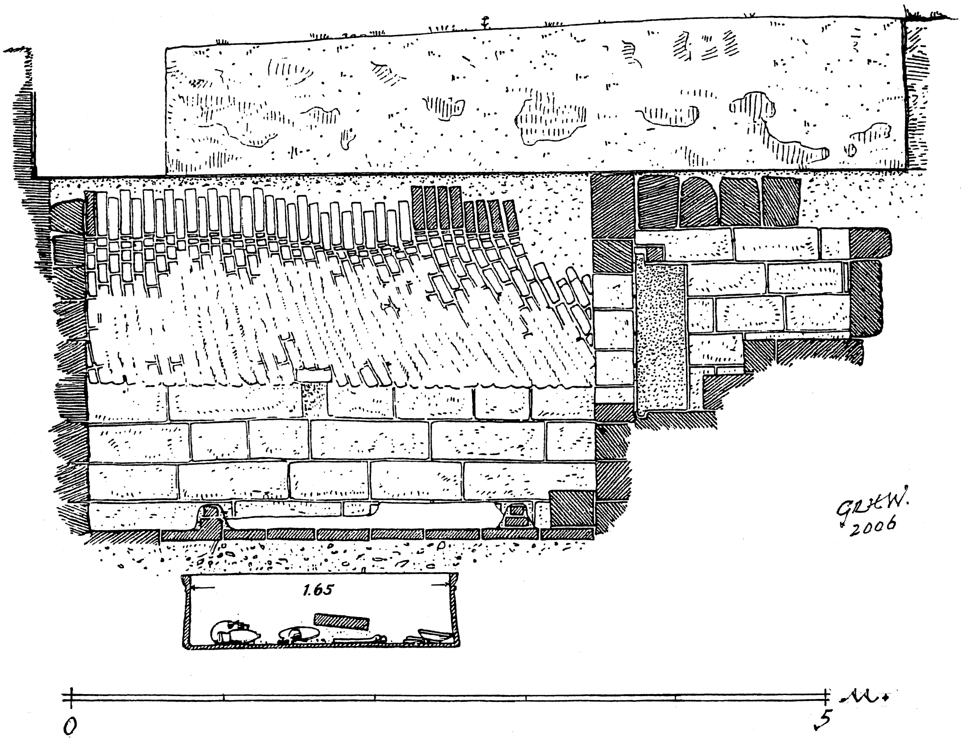
353. Mesopotamia. Brick Masonry Engaged Semi-Columns. Engaged semi-columns occurred in Mesopotamian brick building from the Uruk Period onward; and in later times often bore relief ornament (e.g. spiral cabling). *Key*: (a) from Larsa (The Ekabbar, Court 1). 1 – 4 Moulded Brick forms; (b) from Assur (Temple of Assur). 1 – 7 Moulded Brick forms. After Sauvage, pl 39.

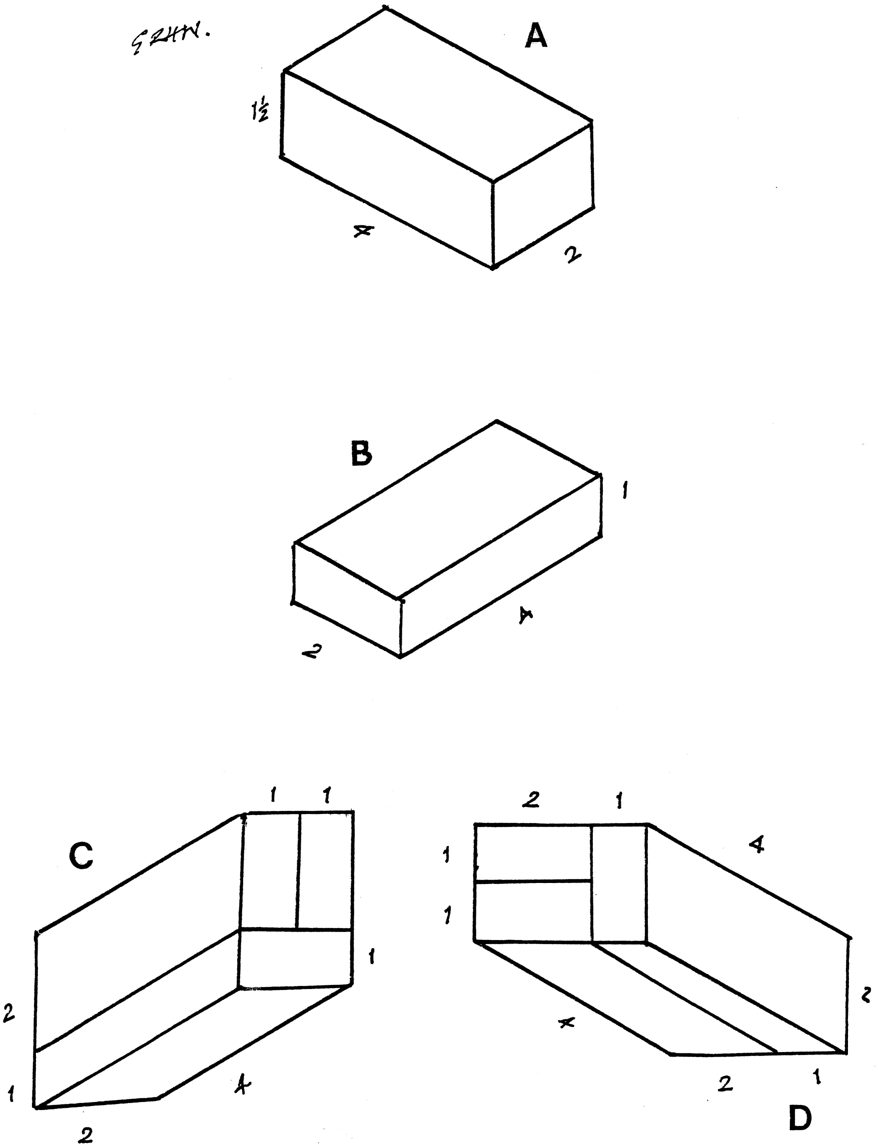


354. Tell al Rimah. Great Temple. Small Domical Vault (Saucer Dome). Northern Iraq. ca 2100 BC. This shallow ogival saucer dome (or more exactly 'sail vault') is constructed in pitched brick masonry – i.e. the flat bricks are inclined backwards to rest on one another. The large surface contact together with the use of quick setting mortar fixes them together during construction without the need of installing centering. This complicated example of pitched brick construction is started by squinch arches in the angles; but these elements while facilitating the construction are not essential to it. Much later vaulting of this ogival form, but of simpler construction without squinches occurs in Roman Egypt at the Fayyum (v Spencer, p. 106, fig 65). *Key*: A. Soffite Plan; B. Section. After D. Oates, WA 21 1990, p. 402, fig 7.

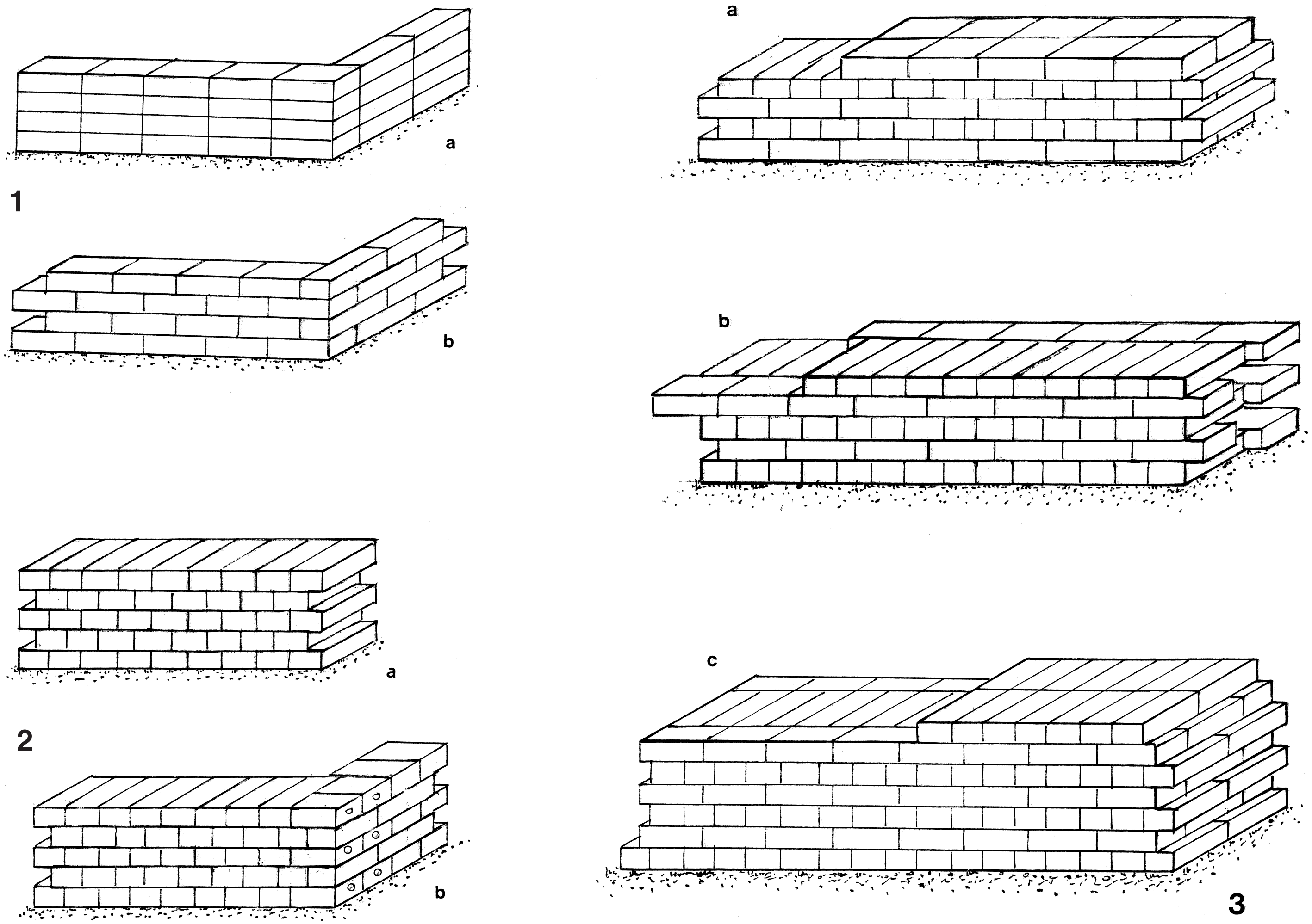


355. Assur. Mud Brick Barrel Vaulting to Burial Crypt. North Iraq. Late Assyrian Period. The existence of burial crypts below houses is common in the Late Assyrian Empire, and many were excavated at Assur. The walls are of stone and the vaulting is of brick on edge, often (as below) pitched – i.e. inclined backwards so that no centering is required since the quick setting mortar and the large surface area in contact will hold the bricks in place during construction. After Wesenberg, B d A, pp 252 ff, figs 1, 2, 3.

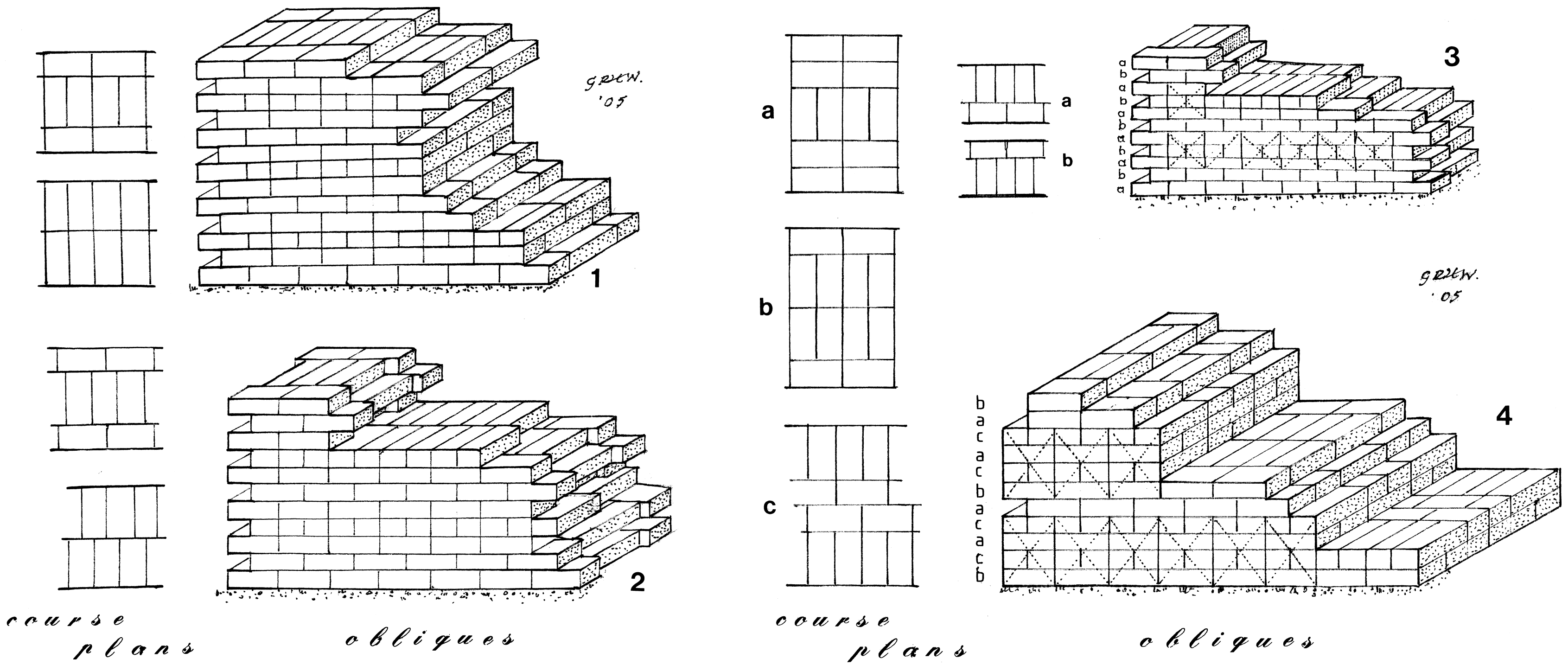




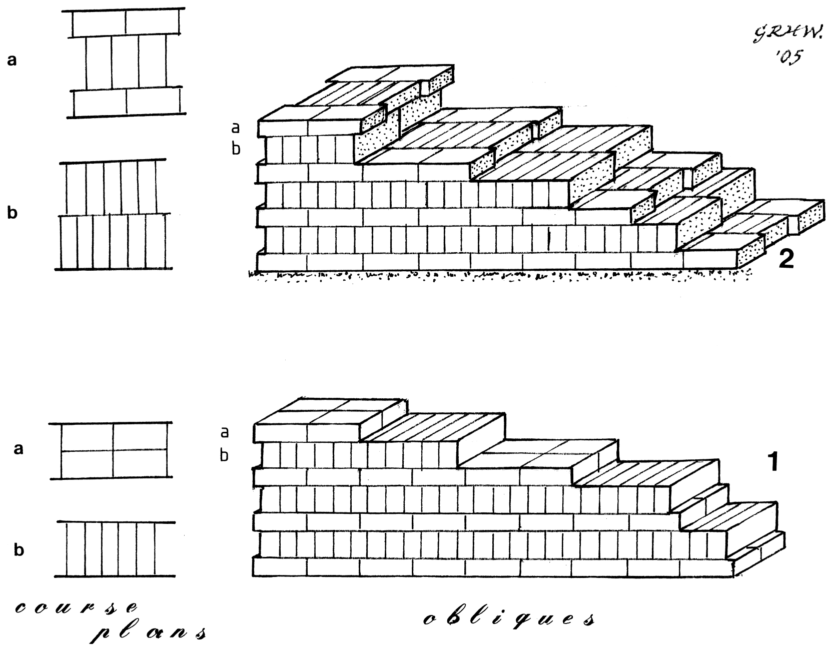
356. Standard Egyptian Brick Form. The one standard Egyptian form of brick for building walls is a rectangular brick generally something like twice as long as it is broad. The proportion of breadth to height is something like 1 ½: 1. This gives a brick very like the traditional modern 9″ brick (9″ x 4 ½″ x 3″) (A). In theory the proper relation of length to breadth is not 2: 1, rather the length should be twice the breadth plus the width of a mortar joint. And in fact when the proportions of Egyptian bricks are plotted graphically, they generally cluster slightly above the 45° normal line. There is a recognisable variant in the proportion of breadth to height, to align with the common practice of sometimes setting bricks not on their beds, but on their side (on edge). If the proportion of breadth to height is not 1 ½: 1, but 2: 1 (B), then bonding is facilitated between bricks set on bed and bricks set on edge. This operates in two senses: when bricks set on edge are kept to one course to give something like English bond (C); and when bricks set on edge are laid in the same course as bricks set on bed to give something like Flemish bond (D). In the first instance the run of two bricks set on edge = the breadth of a brick set on bed; and in the second, the height of a brick set on edge = the combined height of 2 courses of bricks set on bed. As a rule square bricks are not used for walling, they are reserved for use in arcuated constructions (arches, vaults, etc) or for paving. Bricks where the breadth = the height (as with Mesopotamian Reimchen) occur sporadically, but not so as to constitute a basic category as in Mesopotamia. Nothing approaching Mesopotamian plano-convex bricks was used in Egyptian brick construction.



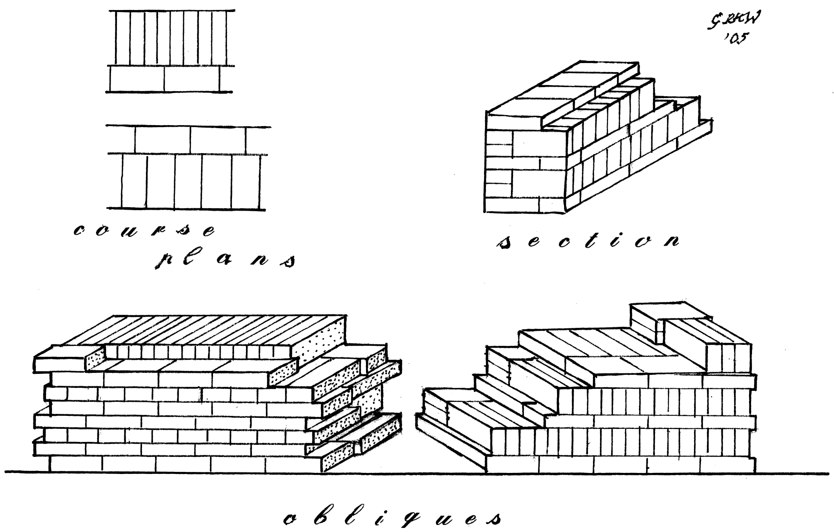
357. Simple Egyptian Stretcher Bond and Header Bond. *Key*: 1. Stretcher Bond; (a) Egyptian style stretcher bond with (defective) straight vertical joints; (b) Modern stretcher bond breaking joint vertically. This occurs but is uncommon in Ancient Egypt; 2. Header Bond; (a) Header bond with broken vertical jointing as in traditional modern practice is common in Ancient Egypt; (b) There is little published evidence of header bond coigning. Modern practice is to set two ¾ bats at the angle on alternate faces; 3. English bond, i.e. alternate courses of headers and stretchers. This occurs in Ancient Egyptian walls and is overall the most common bonding during all periods of brick building; (a) Wall of 1 brick (length) thickness; (b) Wall of 1 ½ brick (length) thickness; (c) Wall of 2 brick (length) thickness.



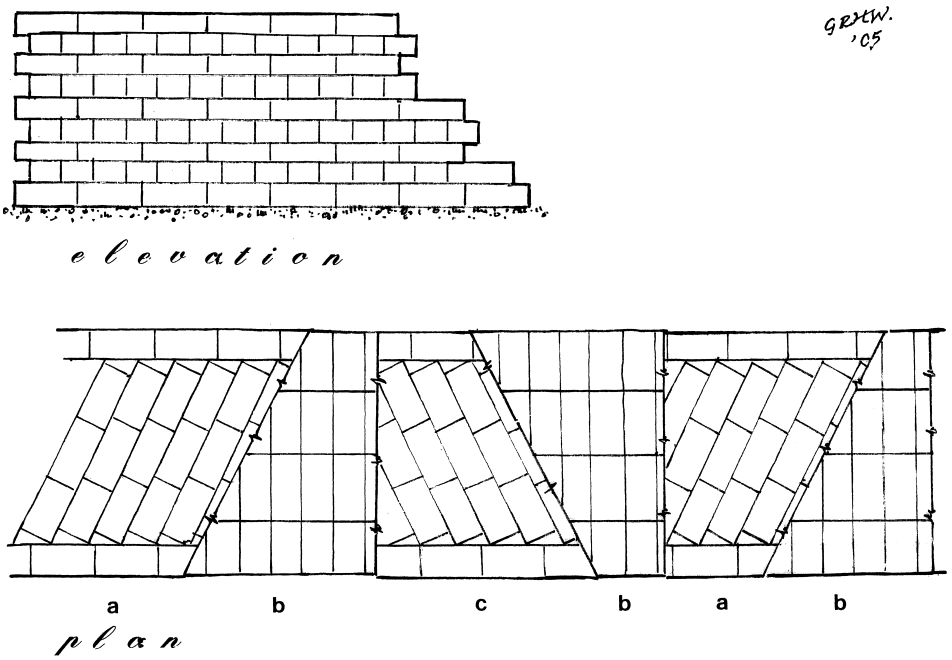
358. Apparent Composite Unit (Dwarf Pier) Bonding. In the Ancient World in both brick masonry and stone masonry a type of bonding was recognised where the unit bonded was not the single brick or ashlar stone block, but a composite unit of several bricks etc forming a dwarf pier, 3 or 4 courses high. These dwarf piers were set contiguously so that the vertical joints between them were straight joints However this straight joint did not extend the height of the wall, but was broken every third or fourth course by a course of a different format. A very common brick bond in Ancient Egypt was to use 2 or more different course settings and to arrange the superposition of these courses so that the face bonding gave the appearance of dwarf piers. However this was superficial only, as the apparent dwarf piers did not subsist as entities running through the thickness of the wall. Indeed, as opposed to modern bonding, a prime concern of Egyptian bonding was to break the horizontal jointing. The rationale of these intricate bonds is not obvious, and it seems some extraneous motive was at work here. *Key*: 1. Two brick thickness wall, two different course plans, straight horizontal jointing; 2. Two brick thickness wall, two different course plans, broken horizontal jointing; 3. One and a half brick thickness wall, two different course plans, broken horizontal jointing; 4. Massive three brick thickness wall, three different course plans, mainly straight horizontal jointing. After Spencer pls 2, 3, 6.



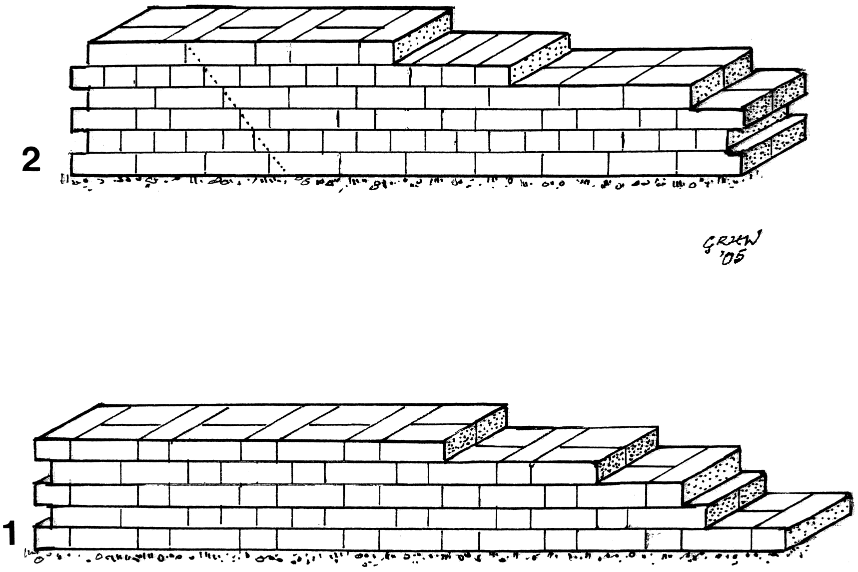
359. English type Bond with Headers on Edge. Egyptians made much use of bricks set on edge; often (as here) set as complete alternate courses, in which instance there was no requirement for bricks of special format. Here apart from the fact that the headers are set on edge, the bond is exactly English bond. This bond was rare in dynastic building, but increasingly popular in Roman and Coptic times, when it was more common than standard English bond for single brick thickness walls. *Key*: 1. One brick thickness wall; 2. Two brick thickness wall. After Spencer pl 17.



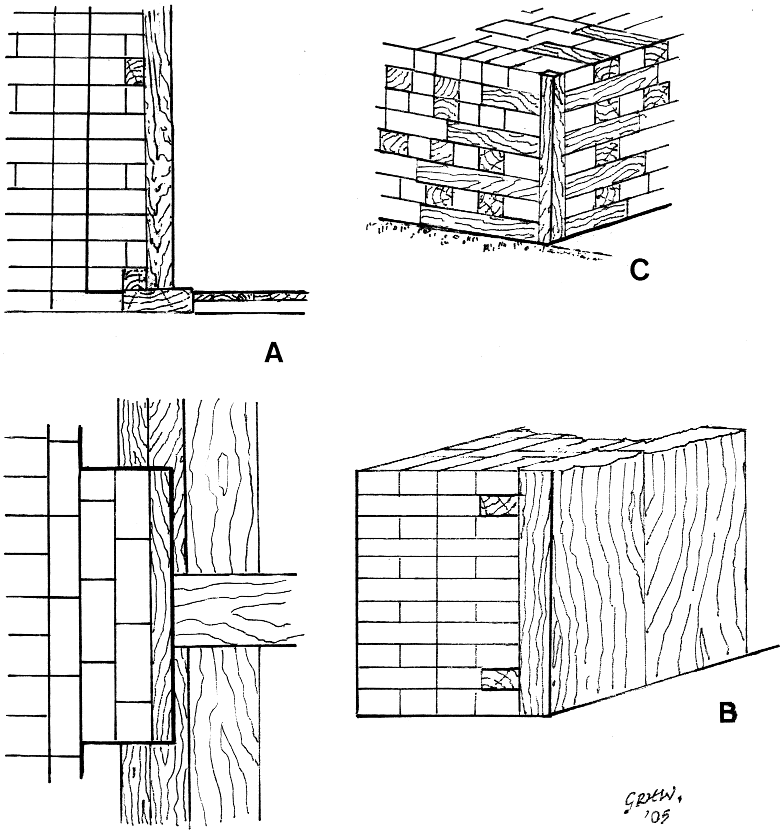
360. English type Bond with bricks on bed and bricks on edge set in the same course (as alternate courses) of 1 ½ brick thickness wall. This bond requires bricks of a format where the breadth is twice the height so that two rows of stretchers on bed can be set one above the other to equate with the height of a header set on edge. This type of brick work occurs in Late Roman time. After Spencer pl 15.



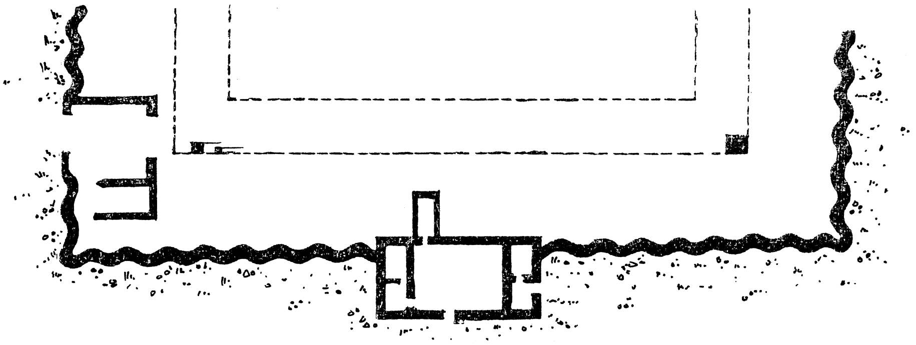
361. English Bond Facing with Diagonal Brick Bond in Core of Massive Walls. Alternate courses of headers set to rake diagonally across the run of the wall contained within a row of stretchers on each face are set alternately with courses of headers to give an English bond facing. This is functionally a very superior bond for a massive wall (here of 4 bricks thickness) as making maximum use of headers, and also breaking joint in the most thorough fashion possible. It was used in Egypt during Graeco-Roman times. NB This bond is used in modern India where it is known as Diagonal Raking Bond (v Sharma and Kaul pp 89 ff). Also from time to time it has been proposed to revolutionise modern European brickwork by the wholesale adoption of raking bond. After Spencer pl 9.



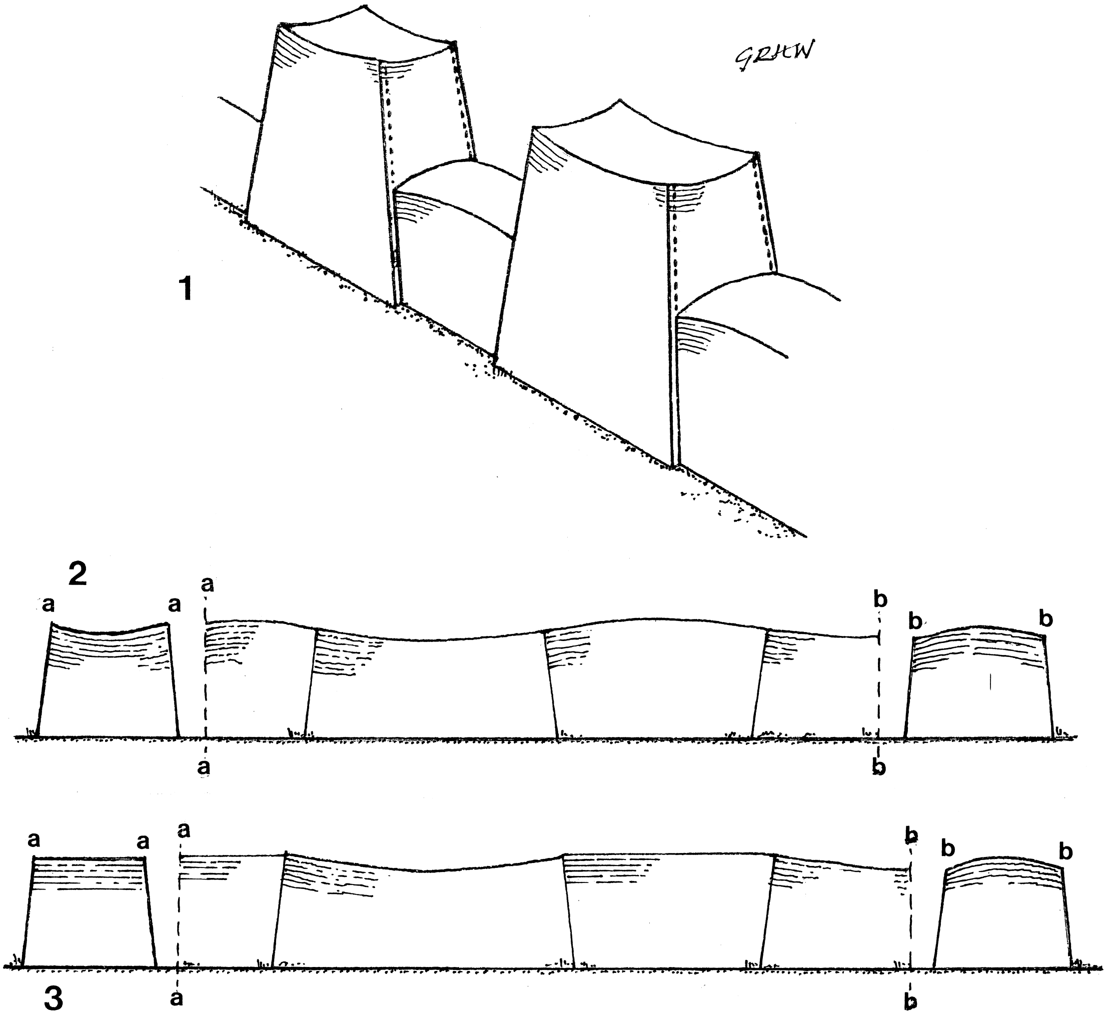
362. Flemish Type Bond. Flemish type bond was not used in Dynastic Egyptian brick masonry, but occurs in Roman Period building. *Key*: 1. Wall of 1 Brick Thickness Flemish Bond; 2. Wall of 1 Block Thickness. Successive courses of Flemish Bond, Headers, Stretchers giving the aspect of traditional modern Dutch Bond where the line of the perpends (indicated by a broken line) runs diagonally across the wall. After Spencer pl 10.



363. Wood Insets and Adjuncts to Mud Brick. This usage occurred during all periods. Originally in monumental building but later the practice became very common in domestic building during Graeco-Roman and Coptic times – when there are well preserved remains at, e.g. Karanis. A. Facing to pilasters in burial chamber of Mastaba at Saqqarah (1st Dynasty); B. Veneer to jamb, i.e. wooden door frame, Mortuary Temple of Neferirb at Abu Sir (5th Dynasty, ca 2400 BC); C. Angle protection and reinforcing to house at Karanis (Graeco-Roman). After Spencer, figs 10, 36, 62.

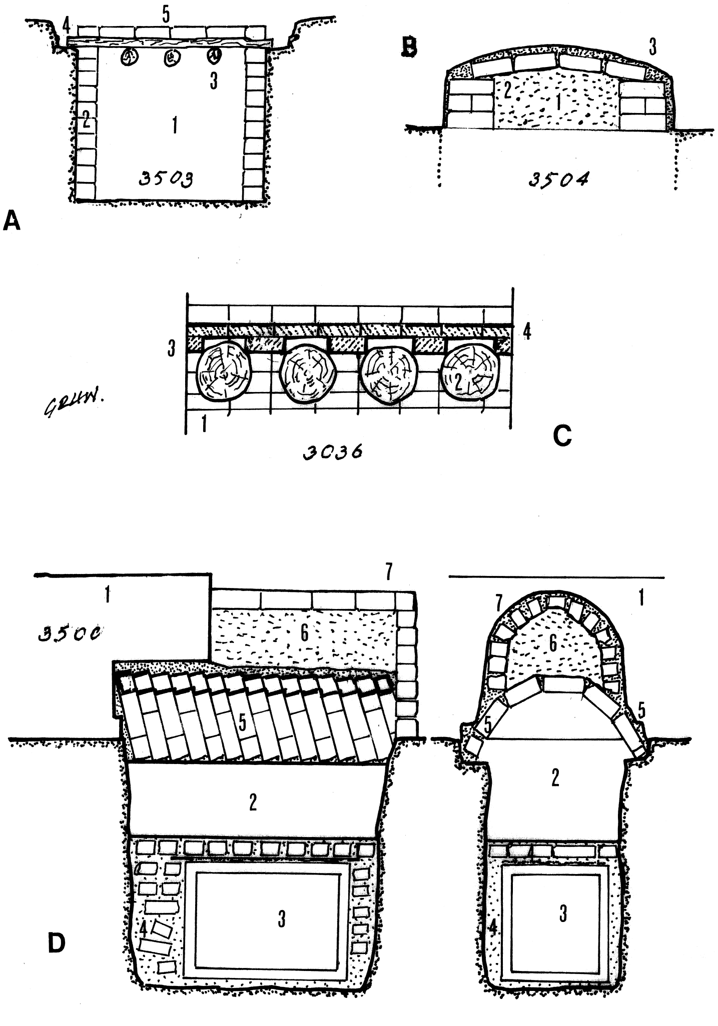


364. The Undulating Plan of Unstayed Boundary Walling. An extended wall which is unstayed has little rigidity or stability. This deficiency is abated either by abutting walls or buttresses or else by massive breadth. Where buttresses were not appropriate as with the enceinte wall of a precinct, Egyptians builders adopted the device of "corrugation" to avoid the necessity of uneconomically massive construction. Brick construction lends itself to this device which is familiar in the once ubiquitous corrugated roofing iron or asbestos sheets. The corrugation radically increases the rigidity of the sheet and of its resistance to deformation. Egyptologists have suggested that the origin of this device for stabilising unstayed brick walls was to be seen in prehistoric enclosure walls of vegetal nature with interlacing pole uprights. There may be some chronological succession involved, but the structural principle is sufficiently obvious to account for the device. After Jequier fig 33.

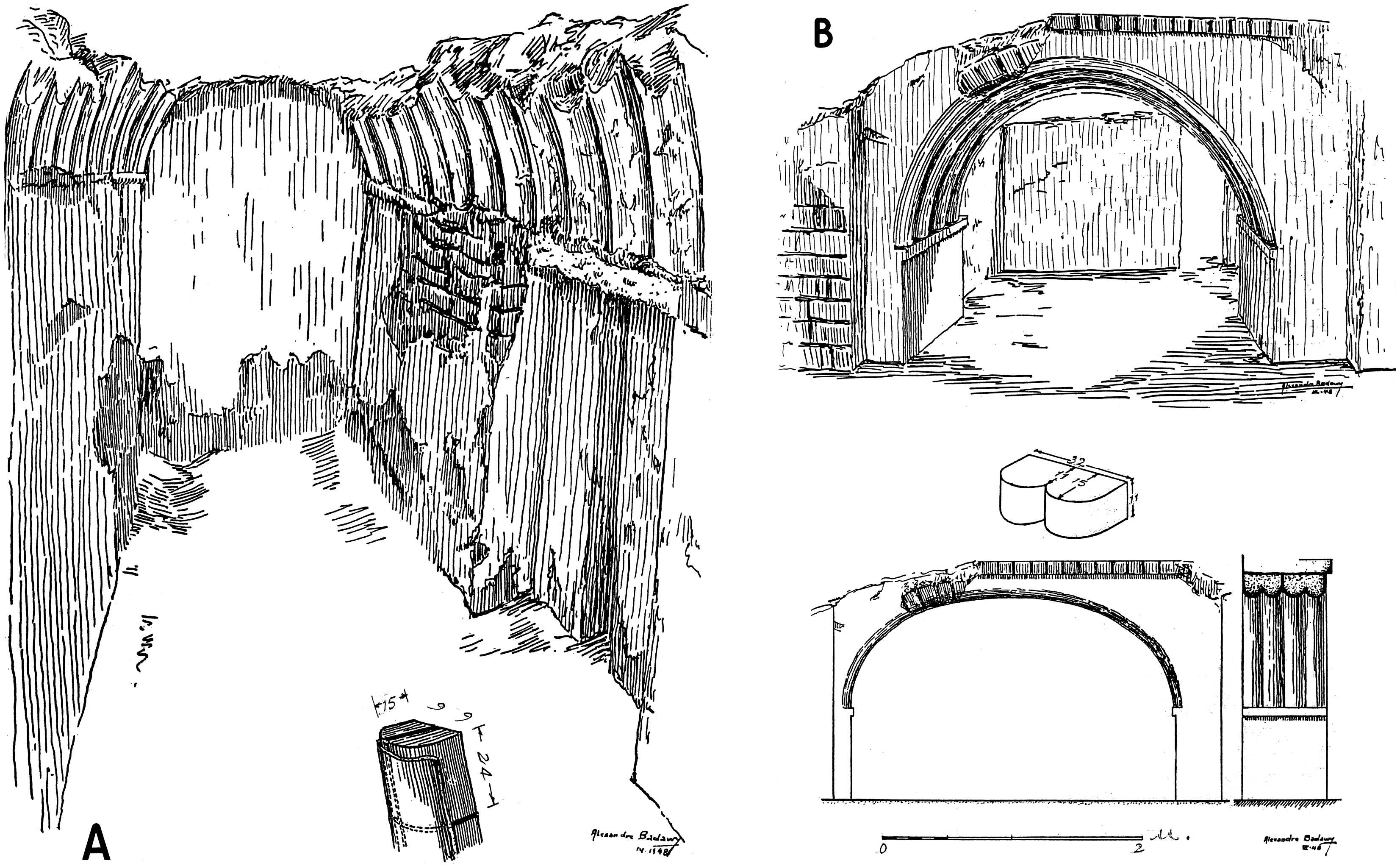


365. Functional Analysis of the 'Wavy' Enclosure Wall. In addition to enclosure walls with an undulating trace in plan, another class of enclosure walls incorporates curved bedding, i.e. they undulate vertically. Here although the longitudinal undulation of these brick walls is evident, it is not generally realised that in many instances the masonry is also curved in cross section, i.e. with curvilinear bedding. In this fashion there is an interrelation between the disposition of the bricks both longitudinally and transversally, thus incorporating a double curvature of construction. This is in fact a very sophisticated device, matched only by the optical refinements of Classical Greek stone masonry. The separate runs of walling manifest both convex and concave bedding in both the longitudinal and transverse sense. In the transverse sense two antithetic interests obtain: the rounded "hog backed" coping represents the most stable "stopped end' of any masonry; on the other hand, the concave bedding puts the masonry in compression transversally so as to militate against scaling away at the faces. The several possible rationales to the undulating brickwork in the longitudinal sense have all been advanced. Not least is the advantage of constructing a long unstayed boundary wall in discrete runs (ancient city walls were traditionally built in this manner). There is an attestation to the recognition in antiquity of the virtue of concave bedding as avoiding fissuring or spreading by putting the stretch of masonry in compression. All significant tauf (puddled mud) walling in Yemen incorporates this feature by way of raising up the angles in the form of horns (cf Ills 326, 327). It should be noted that the correlation between the longitudinal curvature of the brickwork and the transverse curvature is double in nature. The sense of the curvature may be similar longitudinally and transversally, e.g. concave in both senses (1); or on the other hand opposite, i.e. convex in cross section, when concave longitudinally (2 & 3). Obviously much thought was given by ancient Egyptians to the device of undulating enclosure walls. *Key*: (1) Type of Wavy Wall brick masonry at Medinet Habu (19th Dynasty); (2) Type of Wavy Wall brick masonry at Karnak (New Kingdom); (3) Type of Wavy Wall brick masonry at Karnak (XXVth Dynasty). After Jequier fig 28; Spencer figs 75, 78.

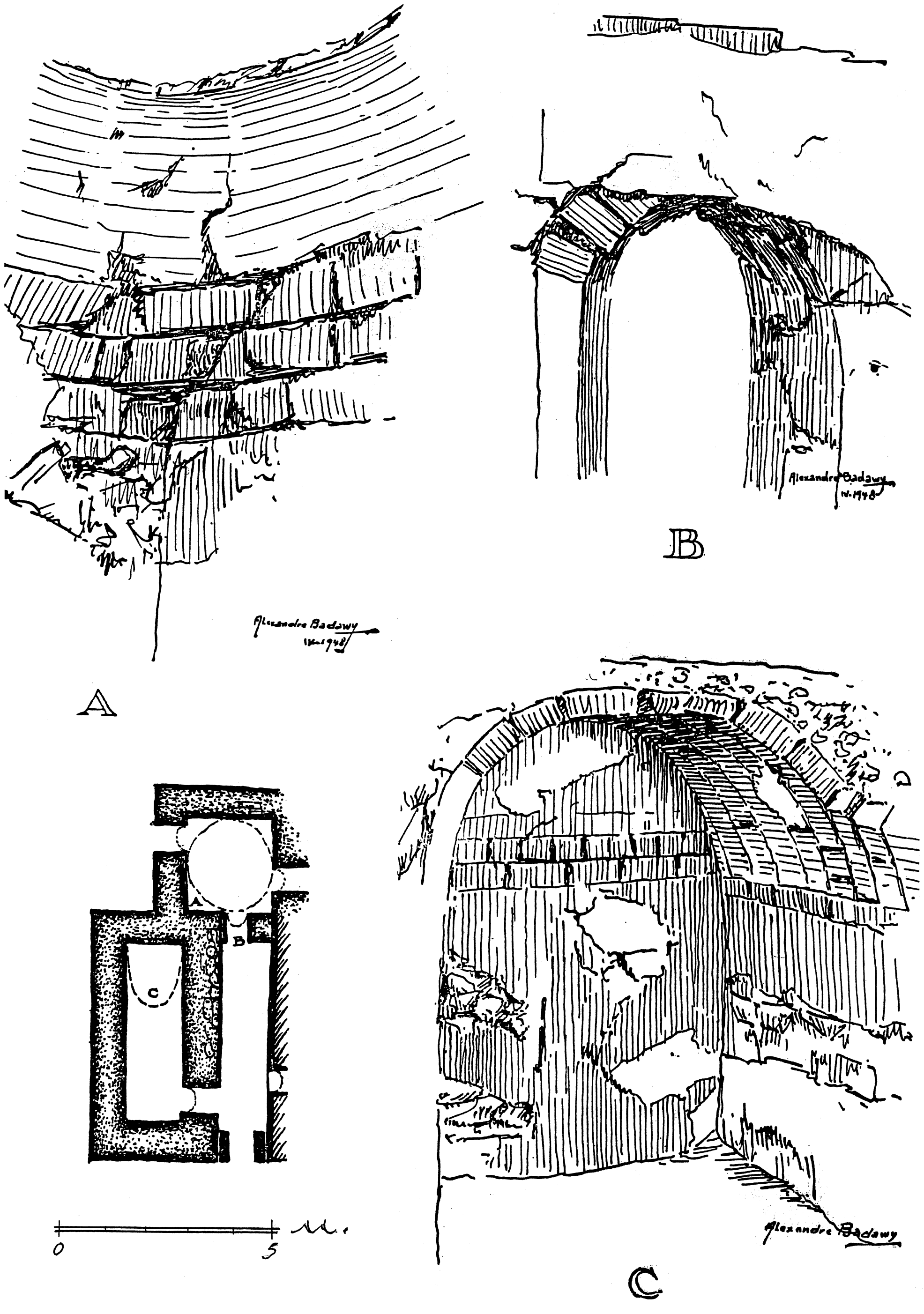
366. Abydos. Mud Brick Enclosure Wall Kom es Sultan, Middle Kingdom. Typical construction for extended enclosure walls unstayed by abutments was to build the wall in discrete runs of ca 20m with the bedding of the bricks alternately concave, convex and/or horizontal. The functional explanation of this device has been controverted – and additionally some Egyptologists have suggested a symbolic significance. It is, of course, possible that both a functional and a symbolic rationale could co-exist. Certainly an obvious symbolism was to be seen in a wavy elevation to the brickwork – i.e. it represents the primaeval waters (*nun*) out of which the primaeval mound/island of creation arose. So far as the functioning of the device is concerned it is evident that *grosso modo* it is designed to counteract fissuring and collapse but there are diverse explanations of the mechanics of this process, or rather how ancient Egyptians may have apprehended it. After Clarke & Engelbach.



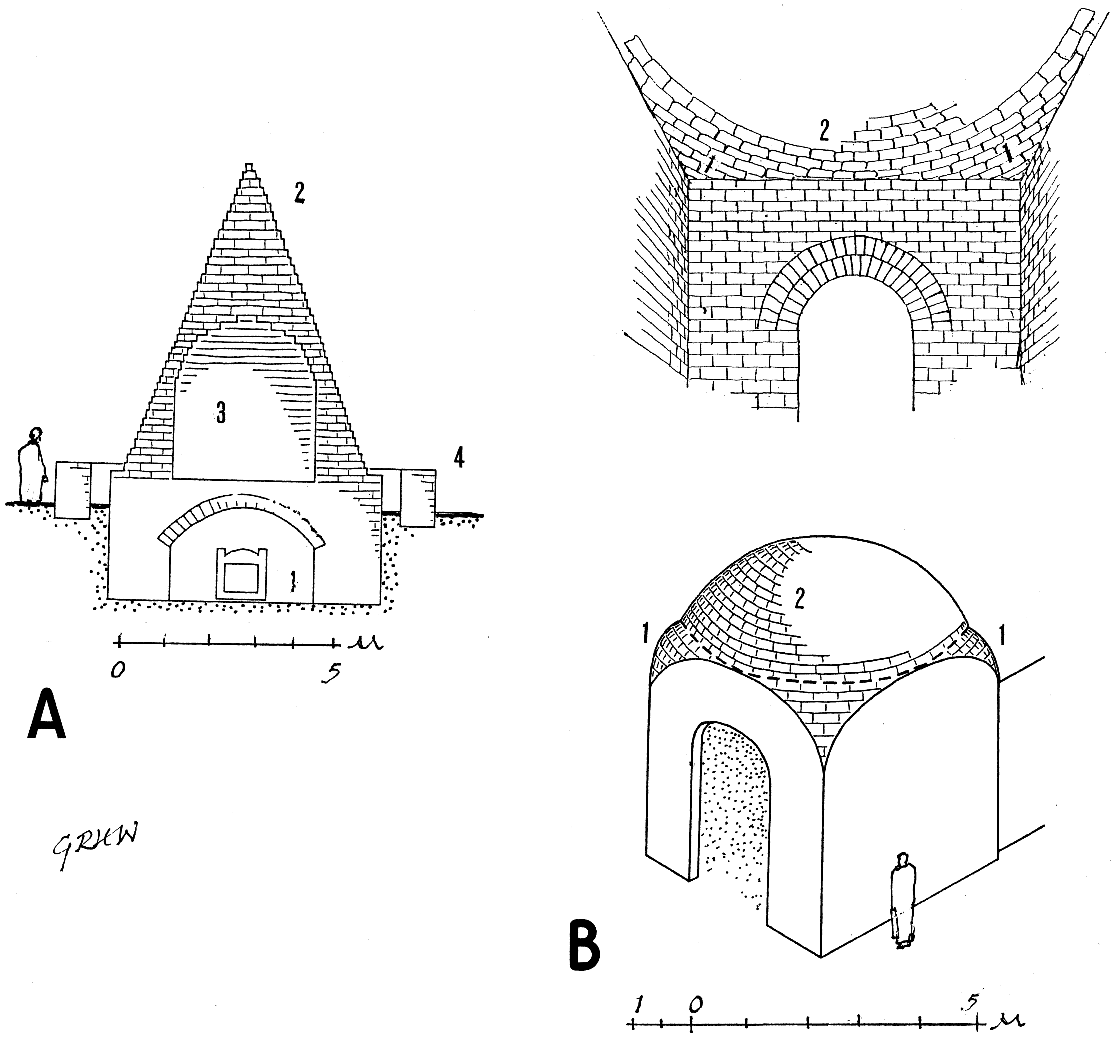
367. Saqqarah Cemetery. Underground Origin of Mud Brick Vaulting in Egypt. Lower Egypt. Archaic – 1st Dynasty. Stages in the association of mud brick with wooden roofing of Archaic pit graves lead to replacement of the Wooden Roofing by mud brick vaulting. A. Non structural layer of mud bricks set above boarding of wooden roof; B. Earthen mound marking pit retained by plastered mud brick in the form of a vault; C. Wooden boarding over log bearers replaced by mud fillers between logs capped by layer of bricks; D. Structural pitched brick vaulted roof of subsidiary grave set against mud brickwork of main grave as "back stop" for inclined bricks. *Key*: A. Cross Section of Grave 3503; 1. Pit; 2. Mud Brick internal lining; 3. Bearer logs; 4. Wooden Plank roofing; 5. Layer of mud brick; B. Cross Section of Surface Marker of Grave 3504; 1. Earth fill of grave marker; 2. Mud brick retaining walls and capping; 3. Surface plastering; C. Cross Section of Mud Brick Roofing on Wooden Bearer Logs of Grave 3036; 1. Mud brick wall of pit; 2. Bearer logs for roofing; 3. Mud bricks set as fillers between logs; 4. Surface layer of mud bricks; D. Long and Cross Section of Pitched Brick Vaulting; 1. Massif brickwork of main grave 3500; 2. Pit; 3. Burial; 4. Earth and brick filling; 5. Pitched brick roofing vault; 6. Earth fill of surface marker; 7. Plastered mud brick vault retaining earth fill. NB These diagrams illustrate the development of mud brick vaults for roofing pit graves. In the originals details are now insufficient and inconsistent and cannot logically be rectified. After Spencer figs 1, 2, 11, 3.



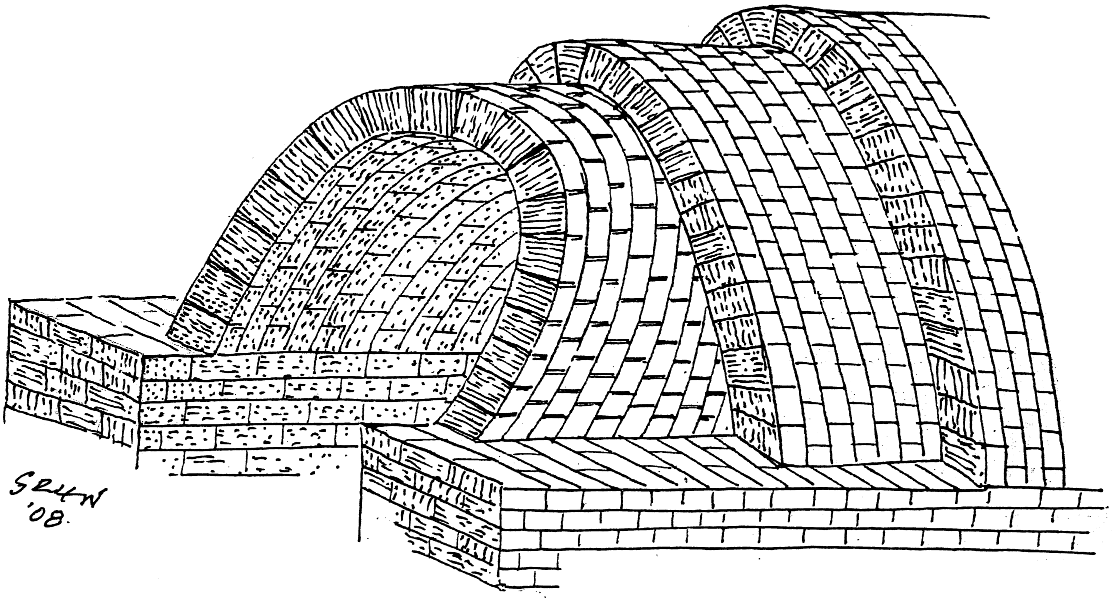
368. Gizeh Mud Brick Vaulting with Reeded Soffite. Lower Egypt. Old Kingdom. A. Tall catenary vault. The reeding is contrived out of two specially moulded quadruntal bricks set bed to bed. This simulates the ancestral reed bundle form. After Bedawy Giza Vaults fig 110; B. Nfri's Chapel. Flat Vaulting with reeded Soffite. The soffite bricks are specially moulded in the form of two bull nosed bricks set side by side, giving a ribbed profile which resembles the appearance of ancestral reed bundles. The flat arch curve (approximately a 3 centred arch) follows the curvature of bent reeds. The span (ca 2.50m) required support (centering) during construction. After Bedawy Giza Vaults figs 104, 106.



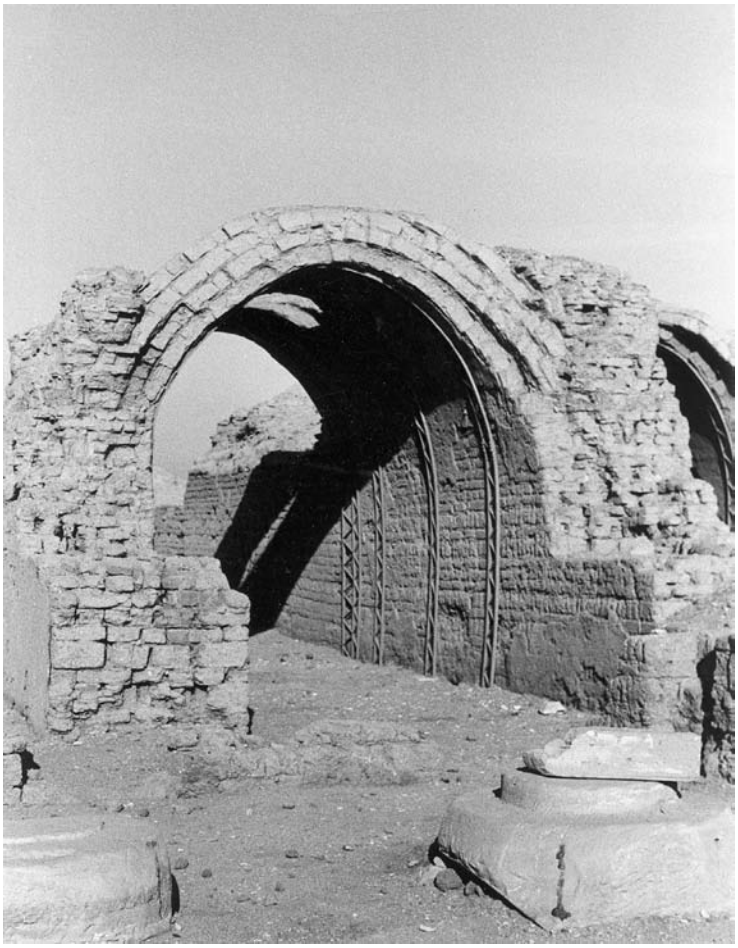
369. Gizeh Seneb's Chapel. Varied mud brick arcuated construction. The construction evidences variously: A. a dome on something like pendentives; B. an arched lintel; C. a flat (3 centred) vault. After Bedawy Giza Vaults figs 113, 114.

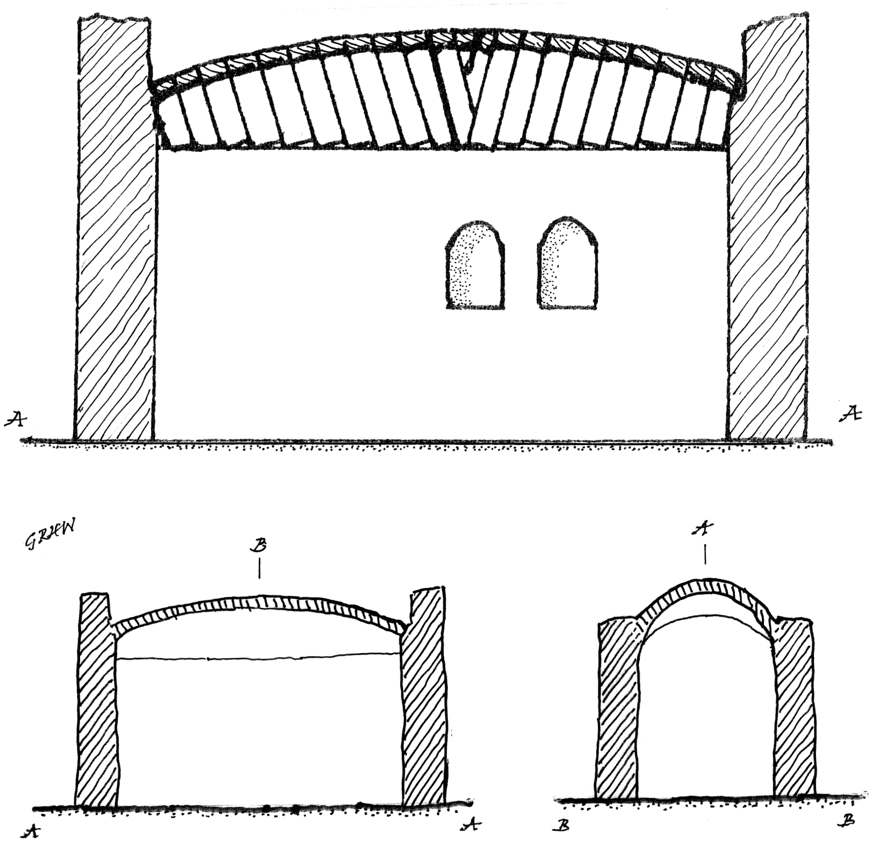


370. The Corbelled Brick Dome. Upper Egypt. New Kingdom. A. Corbelled Dome over Circular plan. Abydos, private grave surmounted by brick pyramid with core brickwork hollowed out by domed chamber. This chamber is a device to relieve the load on the brick barrel vault over the funerary chamber below. *Key* (1) Barrel vaulted burial chamber; (2) Mock pyramid; (3) Round chamber with corbelled dome; (4) Precinct Wall. After Jequier, fig 207. B. Corbelled Dome over Square Plan. This tomb excavated 100 years ago at Dra Abu el Naga has kept its place in the manuals. An interior view (*above*) of the remains was republished by Jequier, fig 208; and a reconstructed exterior view (*below*) was published by Brinks (Lexikon der Aegyptologie II, cols 882 – 884). These drawings have little cogency: the internal view is graphically incorrect; while the external view is simply a "type" drawing of an independent hemispherical dome on pendentives. It is a drawing of an interpretation, not a reconstruction of the actual remains. It is possible that this brick tomb at Dra Abu ʿel Naga was constructed with brickwork in the angles in the nature of pendentives, but the published drawings do not represent adequately the surviving remains. *Key*: (1) Corbelled "pendentives"; (2) Corbelled independent hemispherical dome set on pendentives. After Jequier and Brinks.



371. The Ramasseum. Pitched Mud Brick Barrel Vaulting for Long Gallery Store Rooms. Thebes. 19th Dynasty. *Above* Diagram showing construction system. The flat (square) bricks are set on edge in discrete single brick arches. These arches are not built vertically but canted backwards. The first inclined arch leans against the upstanding rear wall and the subsequent arches are held in place immediately on setting by the large surface exposure of the bed joints and the very adhesive mortar, together with the increased friction due to the non-vertical bedding. In this way no centering is required for their setting. Frequently this roofing is composed of several superposed vaults. In which event only the initial vault need be built pitched. When required it then acts as lost centering for the superposed vaults which may then be set vertically in the normal manner. *Below* Remains of pitched vaulted roofing to the store rooms behind the funerary temple of Rameses II (The Ramasseum) at Western Thebes.





372. Dimai. Domical Vault in Pitched Brick Construction. Faiyum 1st–3rd Century AD. The mud brick village houses frequently incorporate cellars with pitched brick vaulting. In this instance the pitched brick construction is of developed form. The bricks are laid in two moieties inclined in opposite directions to rest against both end walls, and are connected by packing in the middle. This is a common development, but here the successive brick arches are made to rise longitudinally in a segmental curve. The construction is thus curved in two planes and is properly a dome – it is a flat saucer dome or domical vault. This construction sometimes referred to as a "sail vault" or "dish vault" is a practical method for roofing a rectangular chamber, and is a structural advance on a barrel vault, since the units are put into compression on two axes not one. After Spencer p. 100, fig 65.

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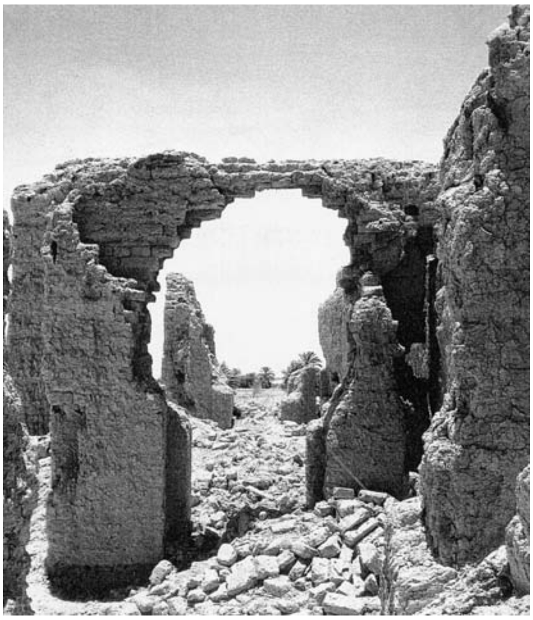
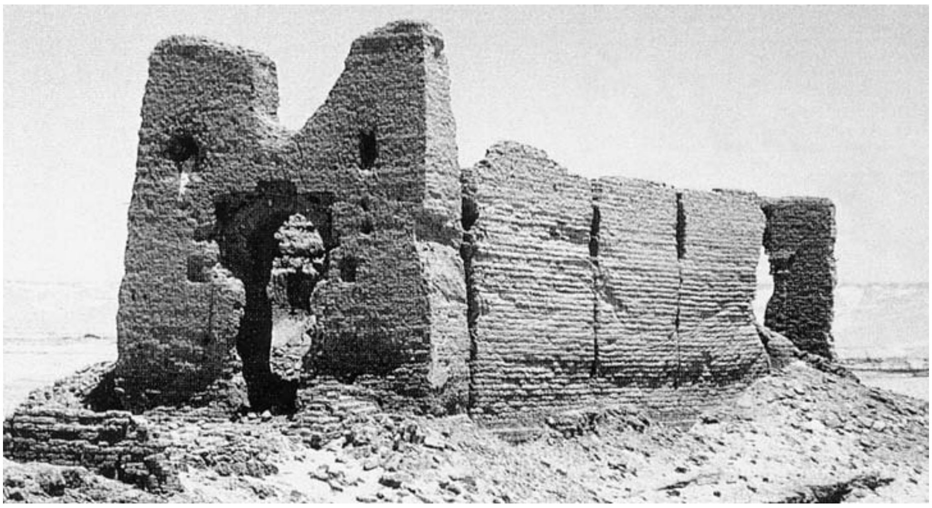
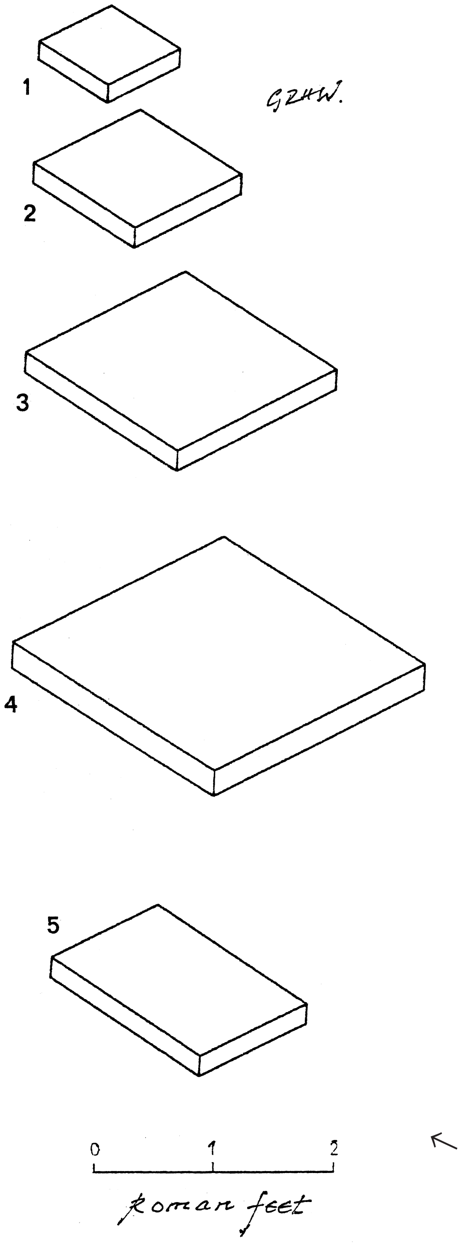
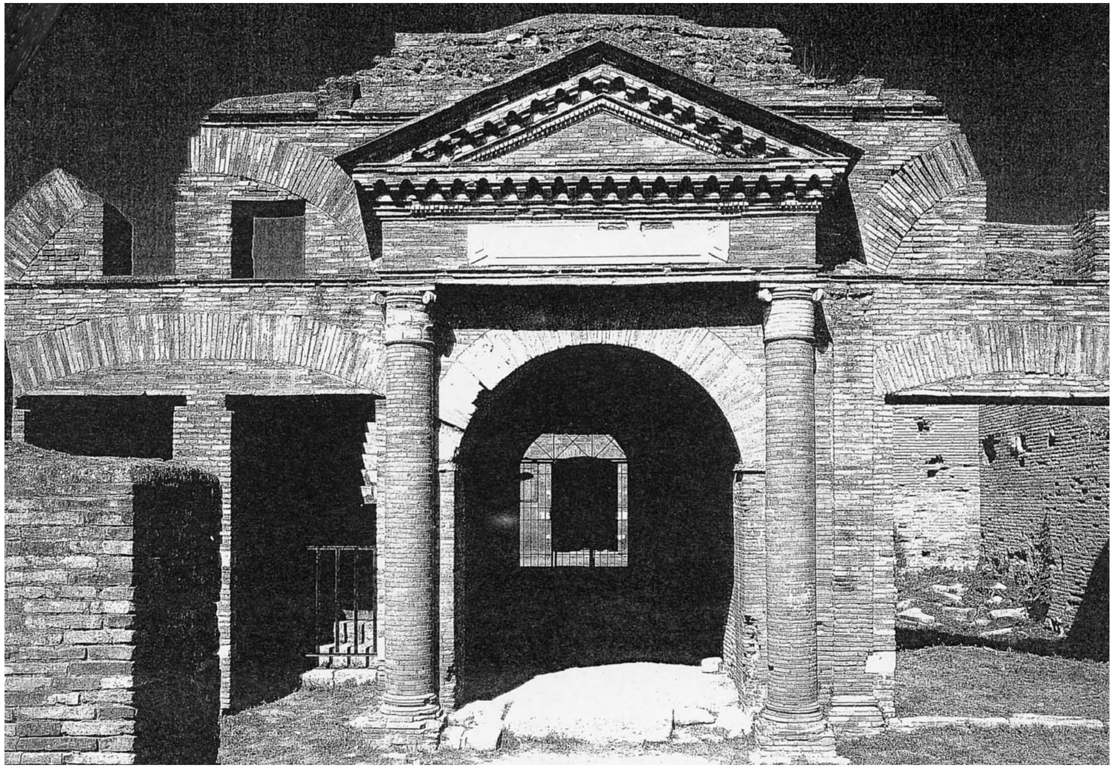




373. Western Desert Oases. Mud Brick Temples. Roman Period. During Roman times there was prolific temple building in mud brick at all the oases so that the number of such temples greatly exceeded those built in stone. This may have been partly due to relative supply of building materials. While it is reasonable to transport building stone by Nile boat to sites in the Nile Valley, transport of building stone across the desert is another matter. On occasions these mud brick temples are well preserved, but the nature of the roofing is not commonly manifest. Examples of both flat mud terrace roofing and vaulted brick roofing exist. *Below*: Tenideh. Mud brick temple, one of a group of three well preserved temples. Western outskirts of Dhaklah Oasis. Roman period. The temple is 29m long and provided with an entrance pylon, so that in the overall it carries on the traditional disposition of a Pharaonic temple. The pylon was furnished with a stone lintel which has disappeared and in consequence the brickwork above it has fallen away in a characteristic arch pattern. After Hölbl III p. 73, fig 108; *Above*: Ain el Beleida. Mud Brick Temple. Khargah Oasis. Roman Period. Corbel vaulted roofing. After Hölbl III, p. 40, fig 56.

← 373A. Ain el Labasha. Mud Brick Temples. Varied Roofing. Northern outskirts Kharga Oasis. Roman Period. 1. North Temple. View of main hall showing emplacement for wooden ceiling/roofing beams. There is a functional reason here for flat mud terrace roofing. The temple is designed with an upper chamber for (concealed) rites; 2. Piyris Sanctuary, industrial annex showing vaulted mud brick roofing as traditionally indicated for utilitarian building. Here the vaulted roofing is of domical form. The larger dome in the foreground is corbelled; while the smaller dome in the rear is constructed with radially set bricks and would have required some form of centering. After Hölbl III p. 48, fig 64; p.49, fig 67.

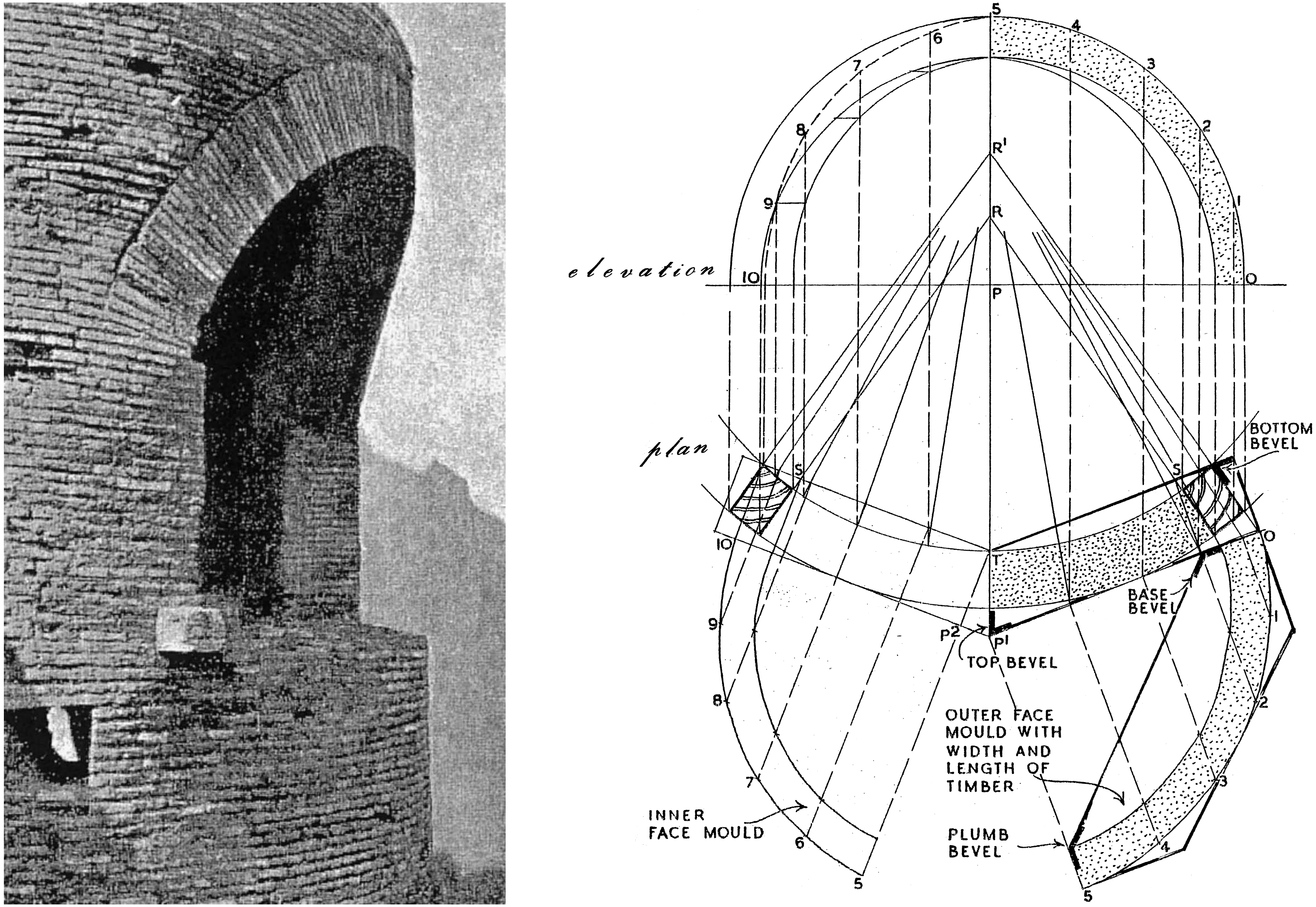




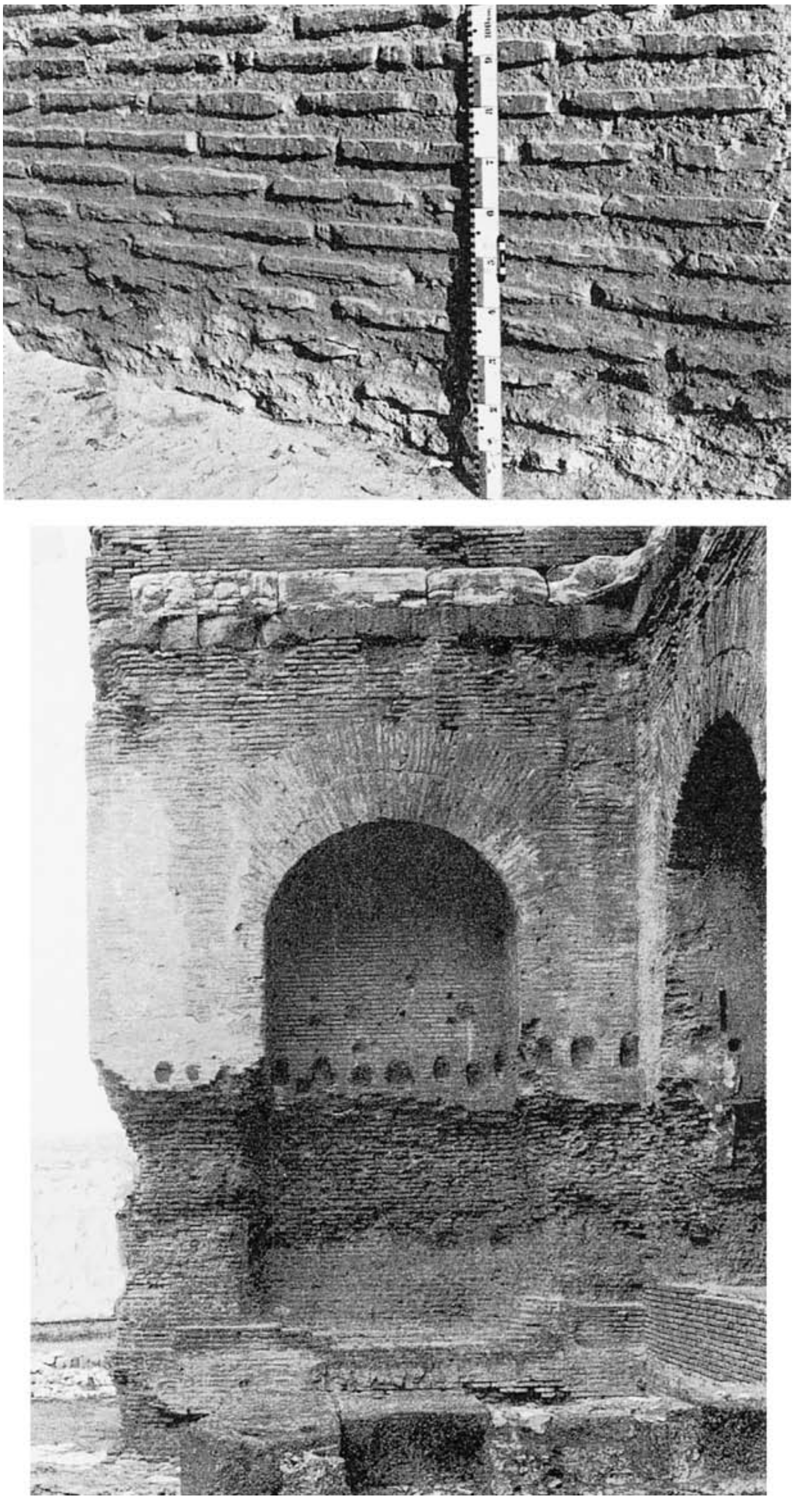
375. Ostia. Typical Façade of Warehouse embellished with Architectural Ornament. Port of Rome. 2nd Century AD. Load bearing burnt brick construction in Rome and its world is not well accounted for, neither historically nor geographically. From the mid 1st Century AD much of monumental Roman Building was constructed in brick faced Roman Concrete (*opus testaceum*). To passing view it is by no means apparent whether such building is solid load bearing brick or brick faced Roman Concrete; and much discussion of brickwork in manuals is carried on without distinguishing the two cases. Even when, broadly speaking, the building construction is known to be Roman Concrete, it is still not clear whether all the design elements of the building are of concrete construction. In the case of these imposing buildings at Ostia the architectural ornament of the façade, e.g. the columns and pediment would seem to be solid brickwork.

↖

374. Standard Roman Burnt Brick Forms. 1. Bessalis (½´); 2. Pedalis (1´); 3. Sesquipedalis (1 ½´); 4. Bipedales (2´); 5. Lydian (Rectangular).



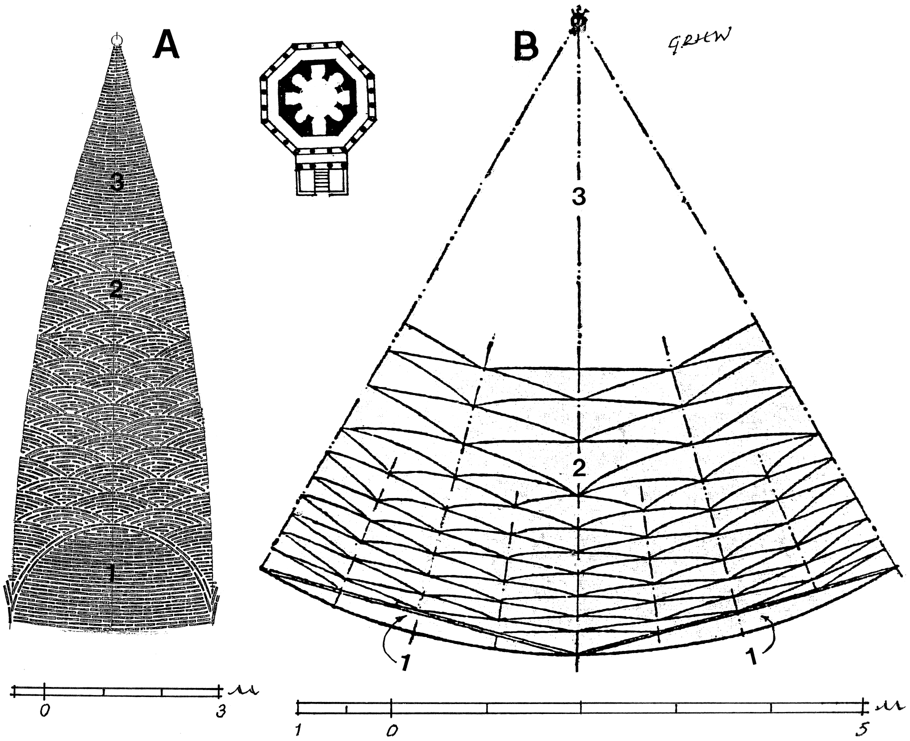
376. Ostia. Arch headed Window expressed in Burnt Brick Masonry, involving the Stereotomy of Curve on Curve Construction (*left*). This feature demonstrates the technical development and excellence of Roman brickwork at the period, whether the construction was solid load bearing brick or brick faced Roman Concrete. To construct this feature in finely dressed stone masonry requires a knowledge of stereotomy. Construction in brick is less demanding in this respect, but subsists. In any event if a wooden window frame were set in the aperture (as is most likely) its shaping requires advanced carpentry as is shown by modern construction drawing (*right*).



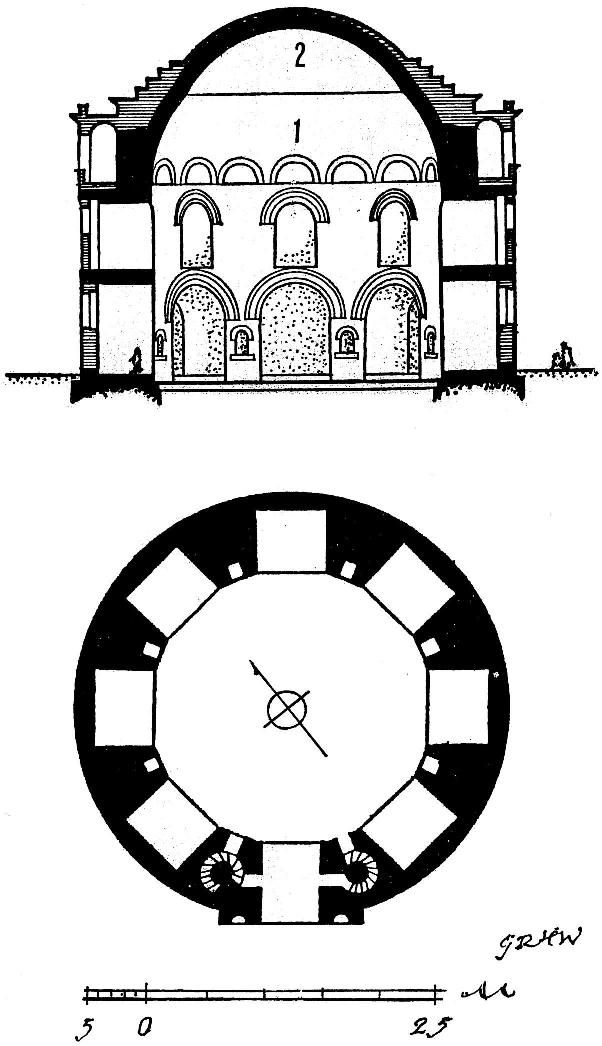
377. Pergamum and Constantinople. Comparative Aspect of Roman and Byzantine Load Bearing Burnt Brickwork. 2nd – 5th Century AD. During the 2nd Century AD Roman Burnt Brickwork achieved a technical excellence comparable with Classical Greek ashlar construction of the 5th Century BC as evidenced by its regular and fine jointing. From this time onwards the thickness of the mortar joints increased, eventually to equal and exceed that of the bricks during Byzantine times. *Key*: *below*: Kizil Avlu Pergamum, 2nd Century AD; *above*: City Walls of Constantinople, 5th Century AD.

378. Baiae. So called Temple of Diana (perhaps the Nymphaeum of a Bath Building). Bay of Naples 150 AD – 200 AD. View of surviving remains showing in section the construction of the wide span (29m) dome. The construction of the building was singular. The drum was of *opus mixtum* concrete, but the dome was of solid brickwork laid in horizontal courses using a highly cementitious lime mortar (which may have given it the consistency of concrete). The brick structure formed a corbelled dome which accounts for its tall (ogival) profile instead of the hemispherical profile obtaining in normal Roman Concrete domes (e.g. the Pantheon); its profile being conditioned in the first instance by the cohesive strength of the brick. This construction could show a traditional competence in Roman solid burnt brickwork which may bear on Early Byzantine brick construction. After Adam, fig 450.

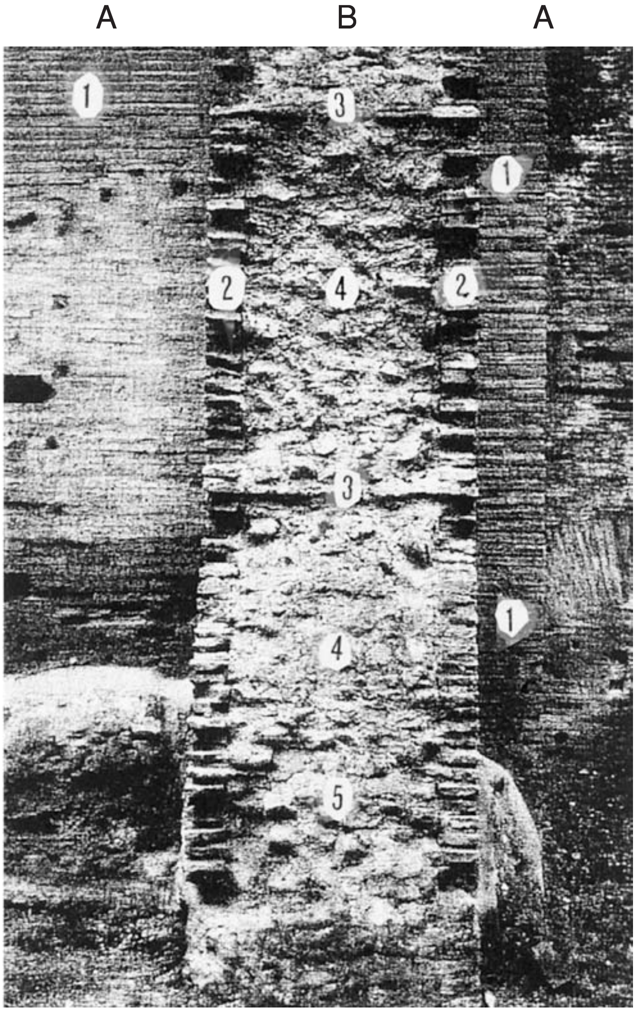
A



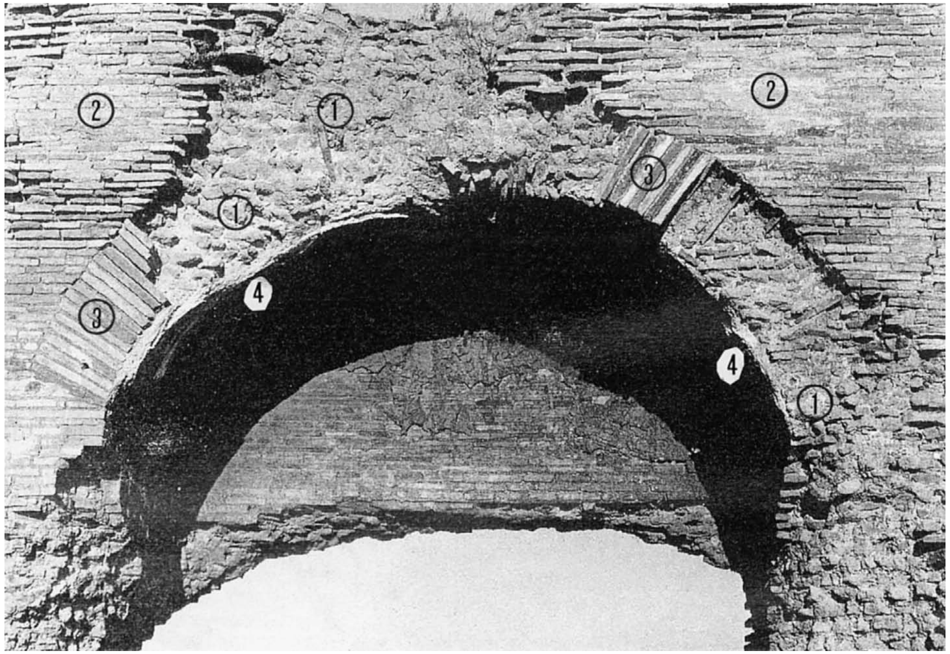
379. Spalato (Split). Dome of the Mausoleum in Diocletian's Palace. Dalmatia ca. 300 AD. The brickwork of this dome is very advanced in both its structure and its construction. The dome was of hemispherical design, ca 14m in diameter; and the shell was built up in two independent skins, each ca 33 cms thick. It is the masonry of the inner shell which is intricate, while that of the outer shell is stereotyped. This indicated that the motive of the brick devices of the inner shell was to avoid centering as far as possible – i.e. when the inner shell was completed with a bare minimum of centering, it served as centering for the construction of the outer shell. The brickwork of the inner shell varies dramatically according as the stance of the curvature permits. The lowest register where the stance is nearly vertical is built on the plan of an inscribed dodecahedron (12 sided polygon) each side ca 3.50m in length. On these sides are erected a series of 12 continguous arches ca 1.80m high which are bricked up by bricks laid in horizontal courses. Above this there is a register of 5m where the shell of the dome is built up of successive bands of segmental arches, assembled in scale pattern. This construction extends to where the stance of the curvature becomes virtually horizontal. Here the brick masonry reverts to normal form and during construction was supported on centering. Thus the span requiring centering was reduced from ca 14m to ca 8m. *Key*: A. Development of one sector of the inner shell dodecahedrons. B. Soffite Plan of 2 adjacent sectors of the dome; 1. Vertical Arch raised on one of the inscribed polyhedrons, and bricked up solid; 2. Register of segmental arches arranged in bands; 3. Crown of dome built up in normal brick masonry requiring use of centering during construction. After Robertson p. 256, fig 108.



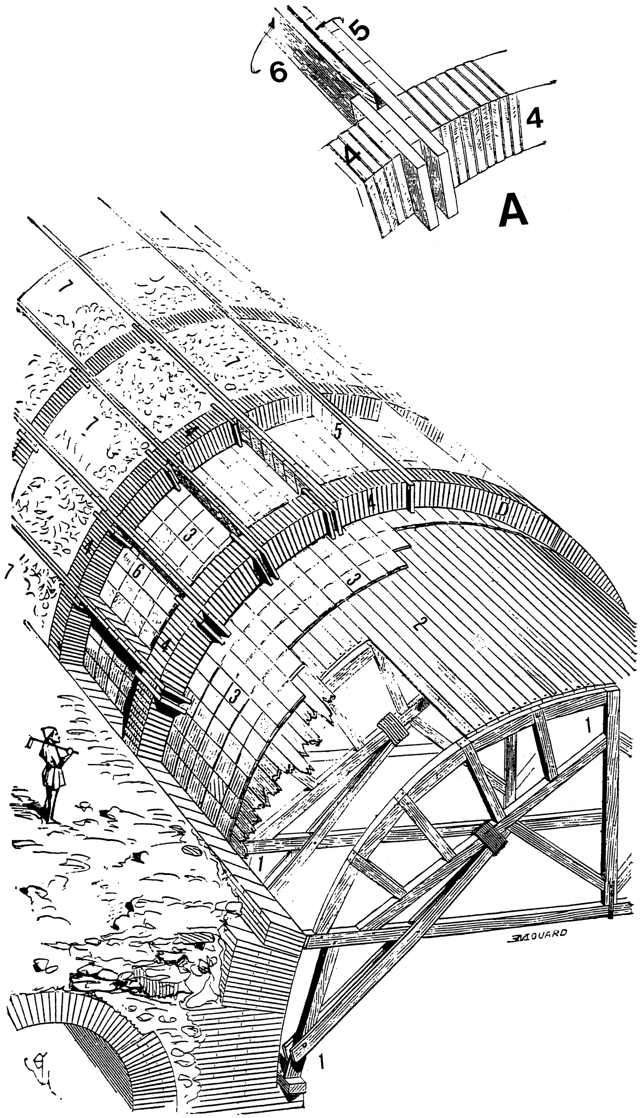
380. Thessalonika. The Mausoleum of Galerius. Macedonia ca 310 AD. This imposing domed mausoleum formed part of an imperial complex including an honorific triumphal arch bestriding the Via Egnatia with which it was linked by a monumental approach avenue. The structure of the mausoleum was complete by ca 310 AD, but it was refurbished on two occasions under Byzantine rule; the first during the 5th century to convert the structure as it stood into a church of St George, and the second after 1000 AD to transform the structure by the addition of an apsed sanctuary etc. The structure of the dome is interesting because it embodies two distinct curvatures, a lower (1) and an upper (2) zone. The lower zone is geometrically part of a hemispherical dome with a span of 24.15m struck from a centre on the level of bases of the topmost ring of arched niches. The upper zone is the crowning part of a hemispherical dome with a span of ca 22m struck on the level of the crown of these niches (i.e. 2.5m higher). The two different curvatures are virtually indistinguishable to casual view (but the distinction may have been augmented by the mosaic decoration). The function of this device was to limit the necessity for the use of centering in the construction of the brick dome. The lower zone (1) has a rise of ca 7m, and accordingly diminishes the span of the roofing from ca 24m to ca 19m (i.e. by ca 5m). It is well possible to construct this shoulder register by corbelled brick set in horizontal courses without the need of centering. However thereafter curvature would have become increasingly horizontal so that the brick construction would have required centering. This requirement, in fact, was further curtailed by the device of a superposed dome of lesser radius, ca 11m, struck from a higher centre (2). This device increases the total height of the roofing by ca 1m, but decreases the span of the dome by 5-6m before the horizontality exceeds that of the lower zone – i.e. the lower portion of zone 2 could also be set without centering thus reducing the remaining span by a further 5-6m, *viz* from ca 19m to ca 13m. Thereby a total reduction in span is afforded of ca 10m – 11m before recourse to centering was necessary to support the bricks during construction. To put this in other terms, if the limiting angle of inclination to the horizontal for corbelling brickwork is not less than ca 55°, then the device of the second dome reduces the span by ca 10m before infringing this limit. Such a device is reminiscent of the concern shown in Ancient Mesopotamian vaulting to maximise the use of corbelling and to minimise that of other types of arcuated construction, which concern is carried over into Parthian and Sassasian building. After Ward Perkins, fig 199.



381. Burnt Brick as Facing in Roman Concrete Construction. Triangular units of burnt brick were used to provide the facing (lost shuttering) for Roman Concrete construction from the mid first century AD onwards (i.e. after the lifetime of Vitruvius, who does not mention this type of construction in his manual). These units were obtained in various sizes by cleanly breaking standard Roman bricks (of various sizes) across on a diagonal. They were set with the diagonal as face, leaving the angle of the original brick to protrude into the wall; thus providing an excellent (saw toothed) bonding with the concrete core. Also standard (flat) Roman bricks were set at regular intervals across these walls as horizontal through courses. The function (or imagined function) is not necessarily obvious. They do not operate as a bonding course to bind together the brick facing and the core so as to remedy the weakness Vitruvius saw in concrete construction, i.e. resolution of the structure into three separate entities, two faces and a core. Rather their positive function in the construction was to compartmentalise the wall into successive horizontal registers, so as to inhibit the liquid mortar seeping downwards leaving the recent construction deprived of the necessary adhesion to bind the aggregate and the mortar mix into concrete (cf Vitruvius II.8.6). In this way such delimited registers effectively register stages of building operations. They were also a convenience in carrying up the putlog type scaffolding employed. On the other hand, like any continuous joint, the through courses constituted a structural weakness in the masonry. In this instance, being in the horizontal plane, the weakness was not against normal stresses due to loading which operate vertically, but against abnormal horizontal stresses, occasioned above all by earthquake. In such circumstances the through courses facilitated toppling and or shearing through at such a level. *Key*: A. *opus testaceum* wall in elevation. B. *opus testaceum* wall in section; (1) *opus testaceum* (burnt brick) facing to concrete walls; (2) *opus testaceum* (triangular burnt brick) facing units in section; (3) *opus testaceum* (entire burnt brick) through courses in section; (4) Concrete core of walls consisting of flat angular rubble aggregate alternating with beds of strong cementitious mortar; (5) Larger units of rubble used as aggregate for strength at the base of the wall. After R. Taylor, fig 48.



382. Ostia. Villa dei Quintillii. Masonry detail showing brick facing clearly distinguished. Latium. ca 150 AD. It is not generally apparent whether brick work presented to view is solid brick masonry or, as here, facing to other construction (here mortared rubble). *Key*: (1) Core masonry of coursed rubble and mortar; (2) *opus testaceum* (burnt brick) facing to core; (3) Decorative brick facing in form of a false archivolt to masonry arch; (4) Brick soffite to arch (= lost shuttering). After Adam, fig 428.



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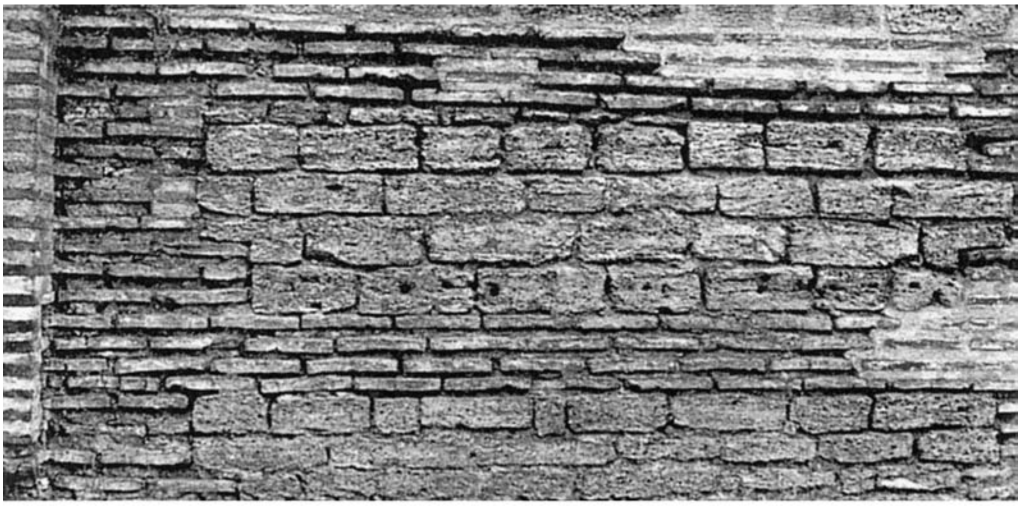
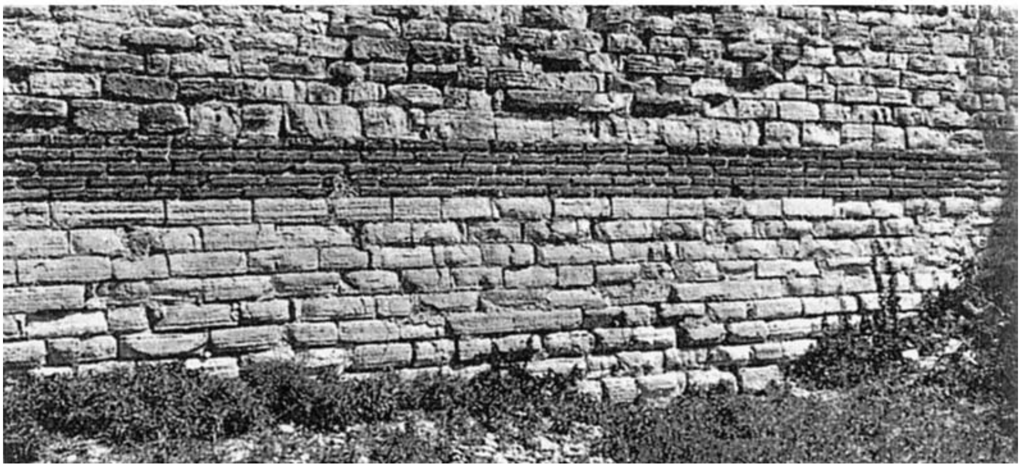
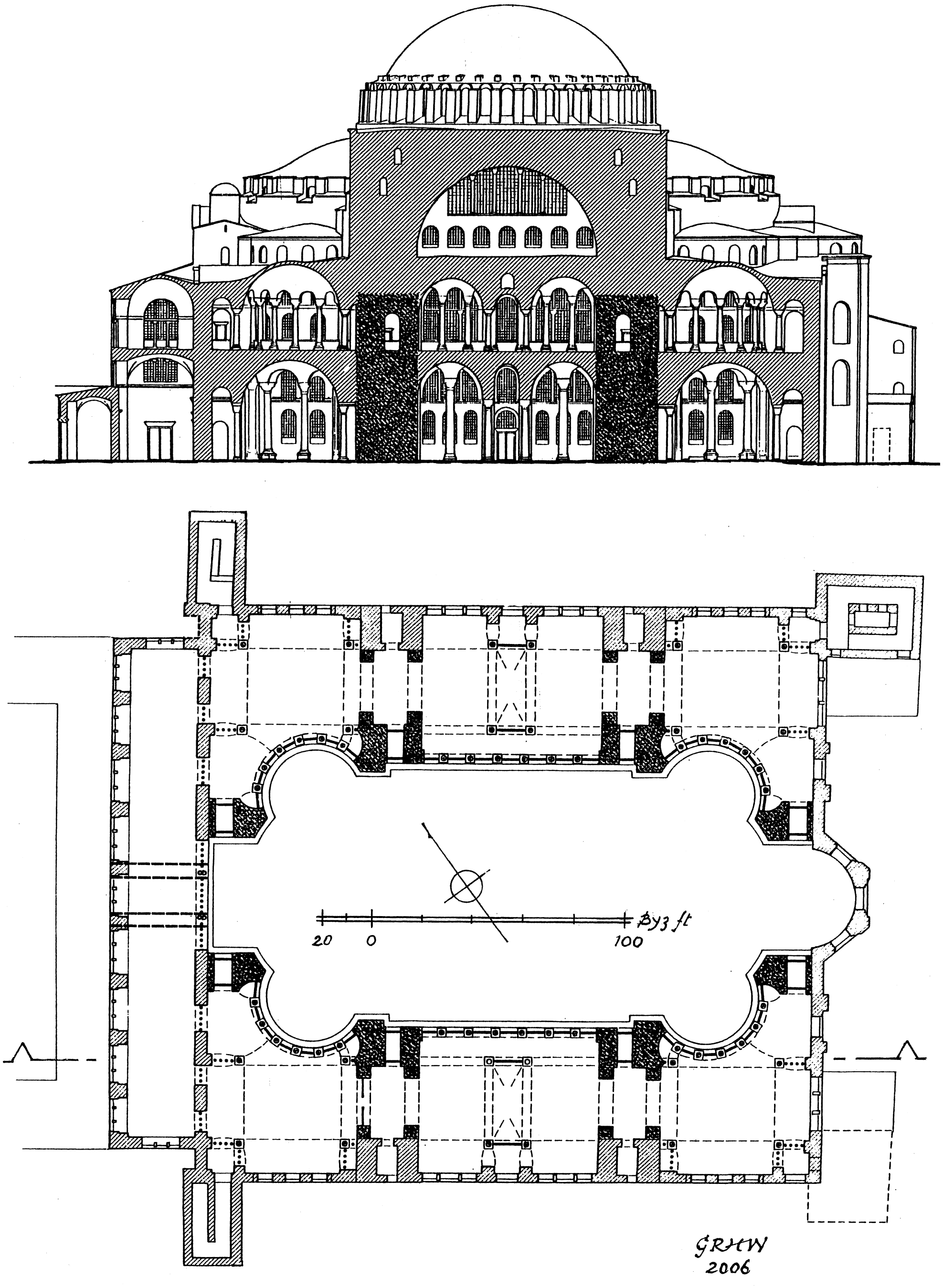
383. Brickwork in the Construction of a Large Roman Concrete Barrel Vault. Viollet le Duc's sketch of work in progress which shows brick as lost shuttering and as soffite to the vault. Heavy timber centering, brick soffite and brick ribbing compartmentalise the concrete. The centering is "flying" from lodgements at the springing of the vault. It is possible that the boarding was not contiguous, but was set with lacunae between the boards, which ran only below the joints between the soffite tiles, thus employing the tiles as part of the centering. This drawing clarifies the function of the brick ribbing. It is generally stated that the function is to compartmentalise the concrete mass so that it does not thrust. This may be an added effect, but it is here evident that the prime purpose is to facilitate the placing of the concrete. Adhesion to the 5 surfaces of the small individual compartments will stabilise the concrete placed compartment by compartment. The inset A shows how the stringer ribbing is set in place, supported by planking fixed into lodgements contrived in the rib arches. *Key*: (1) Flying centering arches; (2) Wooden planks centering/shuttering; (3) Brick soffite of vault (lost shuttering); (4) Brick rib arches; (5) Longitudinal brick ribbing; (6) Wooden plank supports for (5); (7) Concrete vaulting. A. Detail of brick ribbing to larger scale. After Viollet le Duc, Dictionnaire 9, p.466, fig 7.

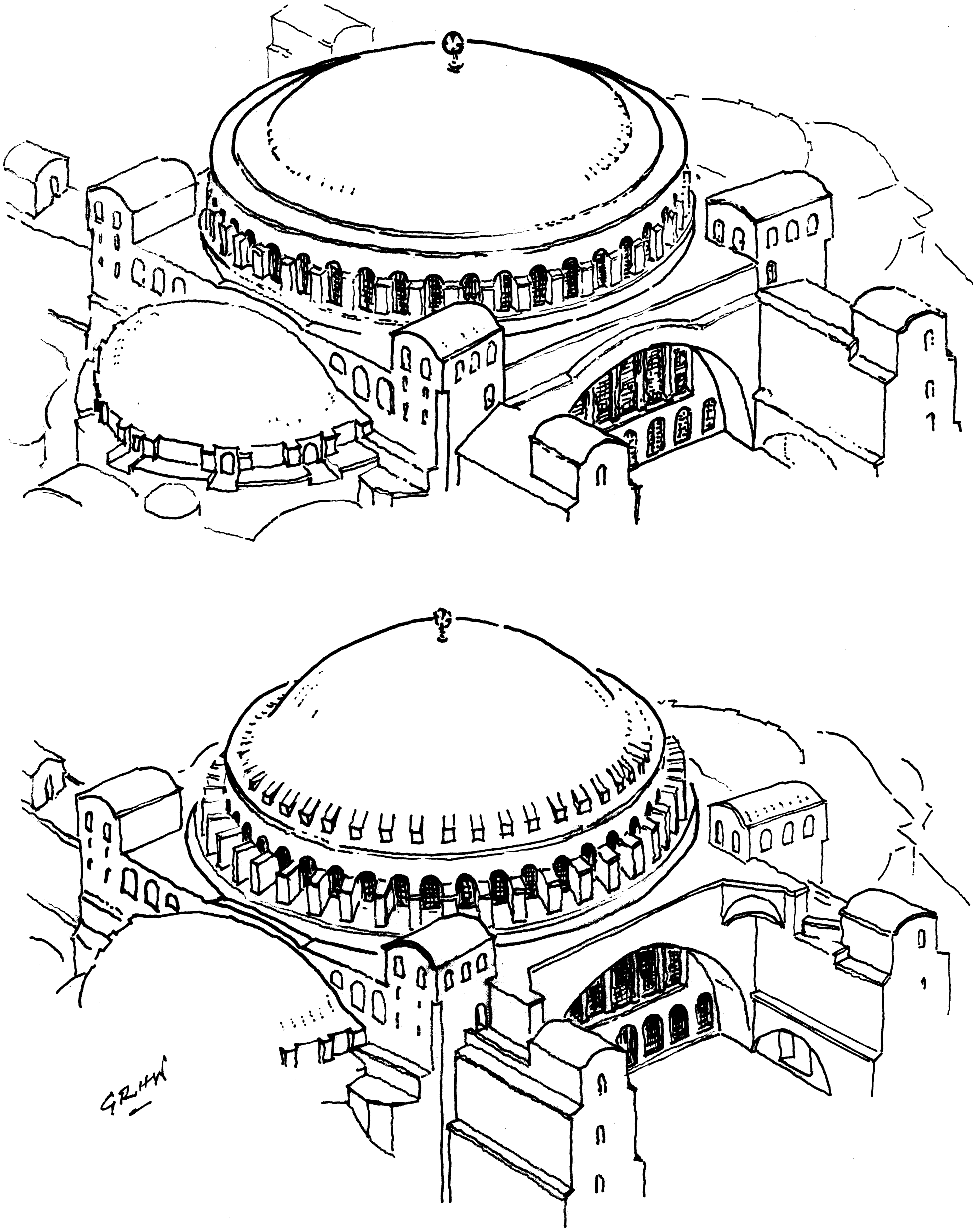




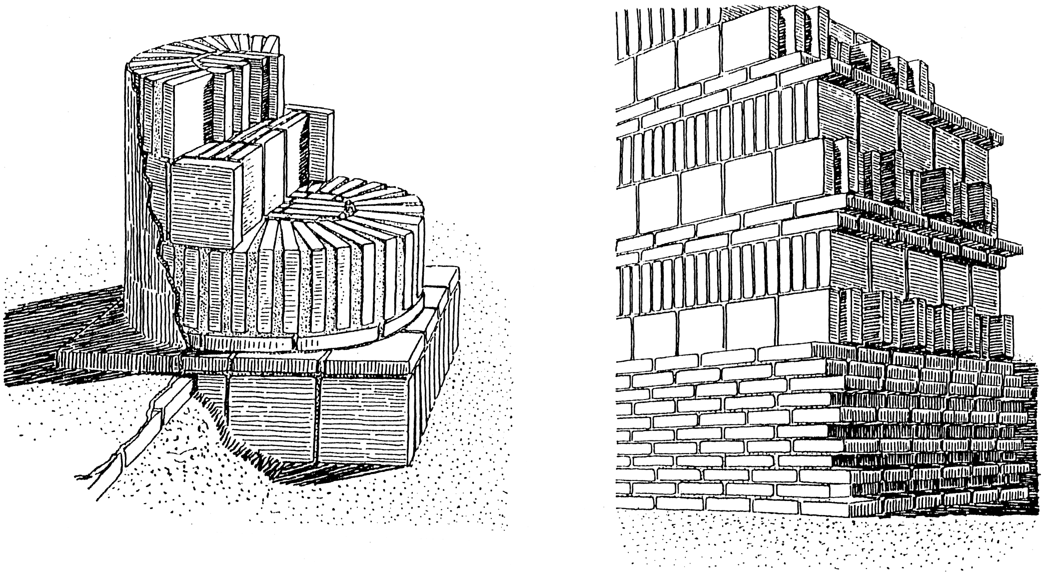
384. Constantinople etc. Byzantine Walling of alternate Registers of Dressed Stone Facing and Through Courses of Burnt Brick Masonry. Balkans ca 400 AD. This type of construction immediately became characteristic of Byzantine walls of monumental aspect, e.g. city walls, external walls of churches etc. Since the dressed stone masonry was facing to a rubble core, this type of Byzantine Wall construction was in some measure a counterpart of Roman Concrete *opus mixtum*. The functional virtue of the brick through courses presumably was considered to parallel that in *opus mixtum*, to restrain the wholesale spalling away of the stone facing. In any event it probably represents the beginning of a taste for variegations in the aspect of significant walls which is certainly a later Byzantine characteristic. *Above*: Constanta/Costanza. Market building. Here the through courses of brickwork are in association with brick coigning – cf Roman Concrete *opus mixtum* (Early 5th Century AD). *Below*: Constantinople Theodosian City Walls. Here the brickwork occurs in a register of 5 courses following a noticeably taller register of stone facing, a common pattern but there are others (Early 5th Century AD). After Mango, pp 10-11, figs 1, 5.



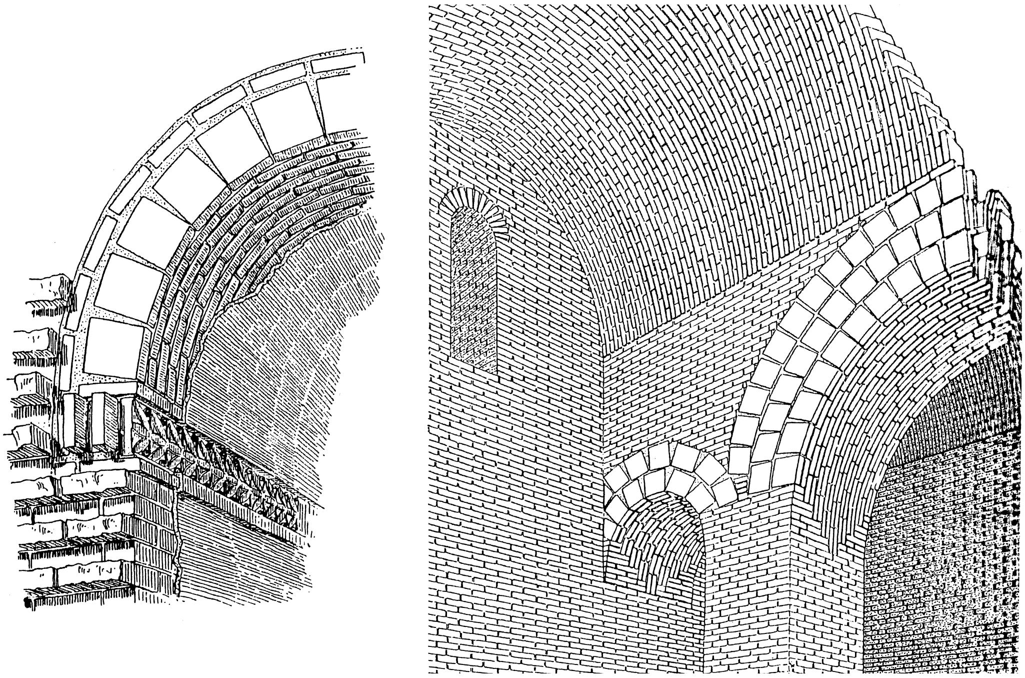
385. Constantinople. Ayia Sophia Cathedral Church. Mixed Materials of Construction apportioned between Structural Elements of a Building according to the induced Stresses. Istanbul 537 AD. The engineer architects of Ayia Sophia accurately differentiated between the stresses induced in the upstanding masonry of the structure, also the weight/strength ratio of the material used in the vaulting although as far as is known they could not quantify these properties according to units of force. *Below*: Plan of Cathedral Church at Gallery Level. *Above*: Long section passing through supporting stone piers of dome on south side. This drawing shows clearly the diversification in strength of building materials employed to accord with the load sustained. The base piers of the domical structure together with the monolithic columns are of igneous stone (rendered black). The remaining structure, including the domes and the vaults is burnt brick (shown hatched); while considerable use has been made of iron tie rods, and of wooden ties and struts to restrain the thrust exercised by the vaulting. After Mainstone, Plans A^3, A^5.



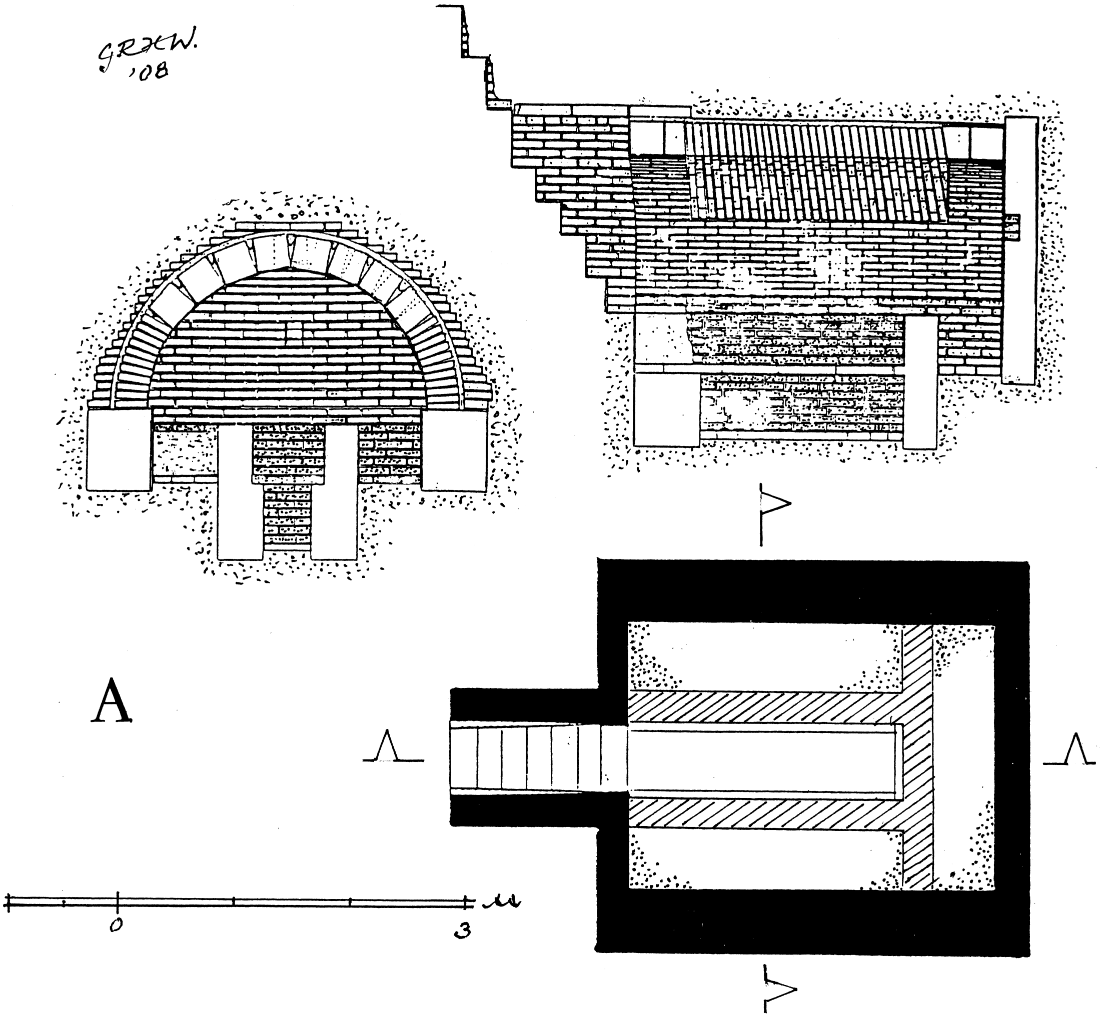
386. Constantinople. Ayia Sophia Cathedral Church. The Design and Construction of Large Span Domical Roofing. Istanbul 537 – 558 AD. The design of the original dome of Ayia Sophia as a continuous dome on pendentives (a saucer dome) appears to have been arrived at by scientific knowledge, not by experimental development along existing lines. Neither in the West nor the East (i.e. Rom oder Orient) are there precursors of this design. It flies in the face of elementary consideration that the stresses induced in a dome vary directly as the span and inversely as the rise (height). Here the span was designed at the maximum and the rise at the minimum ! It can only be assumed that the designers specifically aimed at the magical space defying appearance of an apparently flat roof suspended over a great void. (This was the effect remarked on by all who recorded their impression of it.) If the site were situated in an earthquake free zone, perhaps this magical effect might have survived to the present day to demonstrate the scientific acumen of the designers. After the destruction of the dome by earthquake 20 years later, it was rebuilt on the conventional lines of an independent dome to be on the safe side by greatly increasing the rise. This largely dispelled the space defying illusion. *Key*: Sketch bird's eye views showing: *above*: Original dome of Anthemios, ca 537 AD; *below*: Rebuilt dome of Isadore the younger (ca 558 AD) after destruction of the former dome by earthquake, designed on an independent centre to rise separately above the pendentives. After Conant AJA 43 1939.



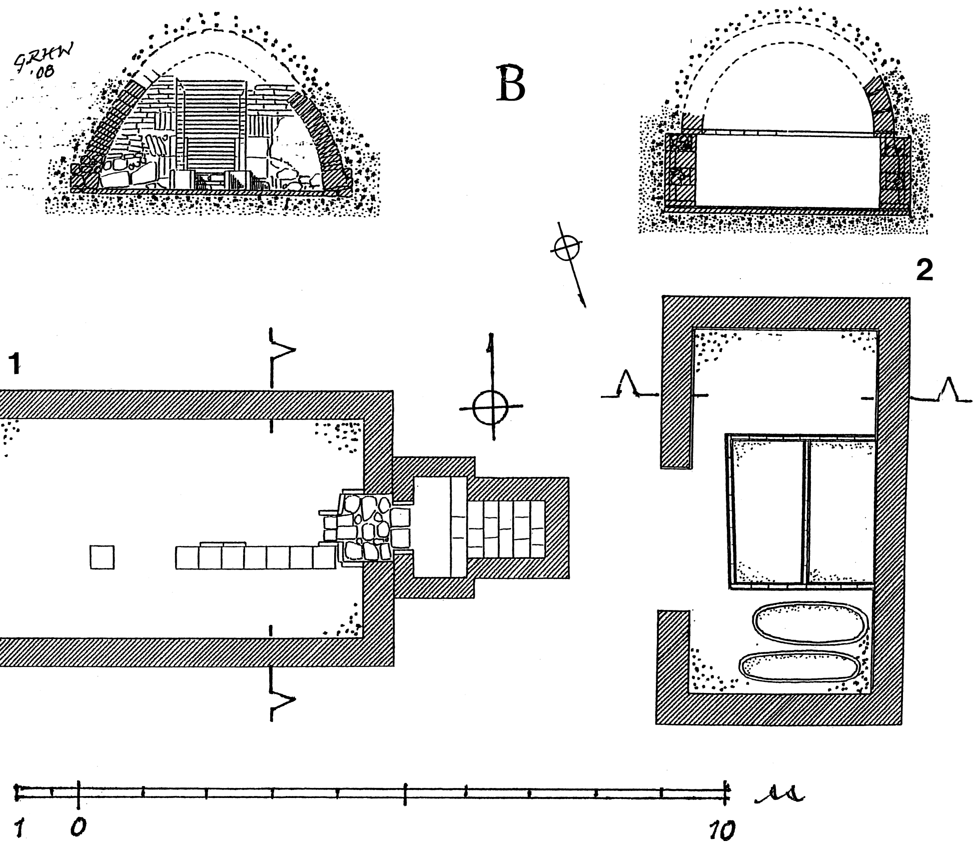
387. Assur Palace. Parthian Brick Masonry Bonding. North Mesopotamia. ca 2nd Century AD. Parthian brick masonry made virtually exclusive use of square bricks, thus carrying on the Mesopotamian tradition into later times. Characteristic bonding was to set such bricks on edge, both as "*carraux*" (stretchers) and as headers in conjunction with bricks set normally on their beds. This afforded strongly patterned bonds, yet this striking aspect was not visible, being concealed by plaster. Also intelligent use was made of bricks on end for column construction, the periphery constituted by a horizontal version of 2 semi circular arches (left). After Pope I, fig 99.



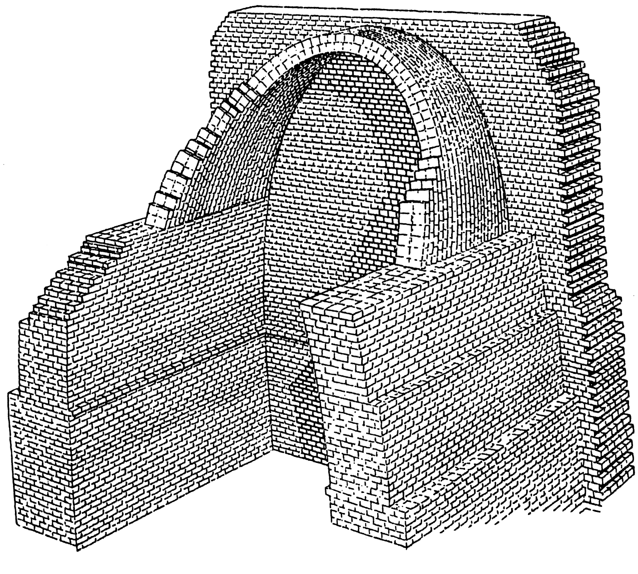
388. Assur Palace. Reconstructed Drawings of (idealised) Arcuated Brick Work. North Mesopotamia. ca 2nd Century AD. These very clear reconstructed drawings are not circumstantial, being made not from surviving detail but constructed to illustrate Reuther's text. They depict arcuated construction of any span as fashioned from square bricks set radially on edge (side) but in the vertical plane, not 'pitched' (i.e. inclined to the rear). Unless the mortar were highly cementitious and quick setting, this construction would require centering. The arch head over the small niche is fashioned by square bricks set radially on their beds, but the span is so restricted that this construction could be effected without centering. After Pope I, pp 424-25, figs 100, 101.



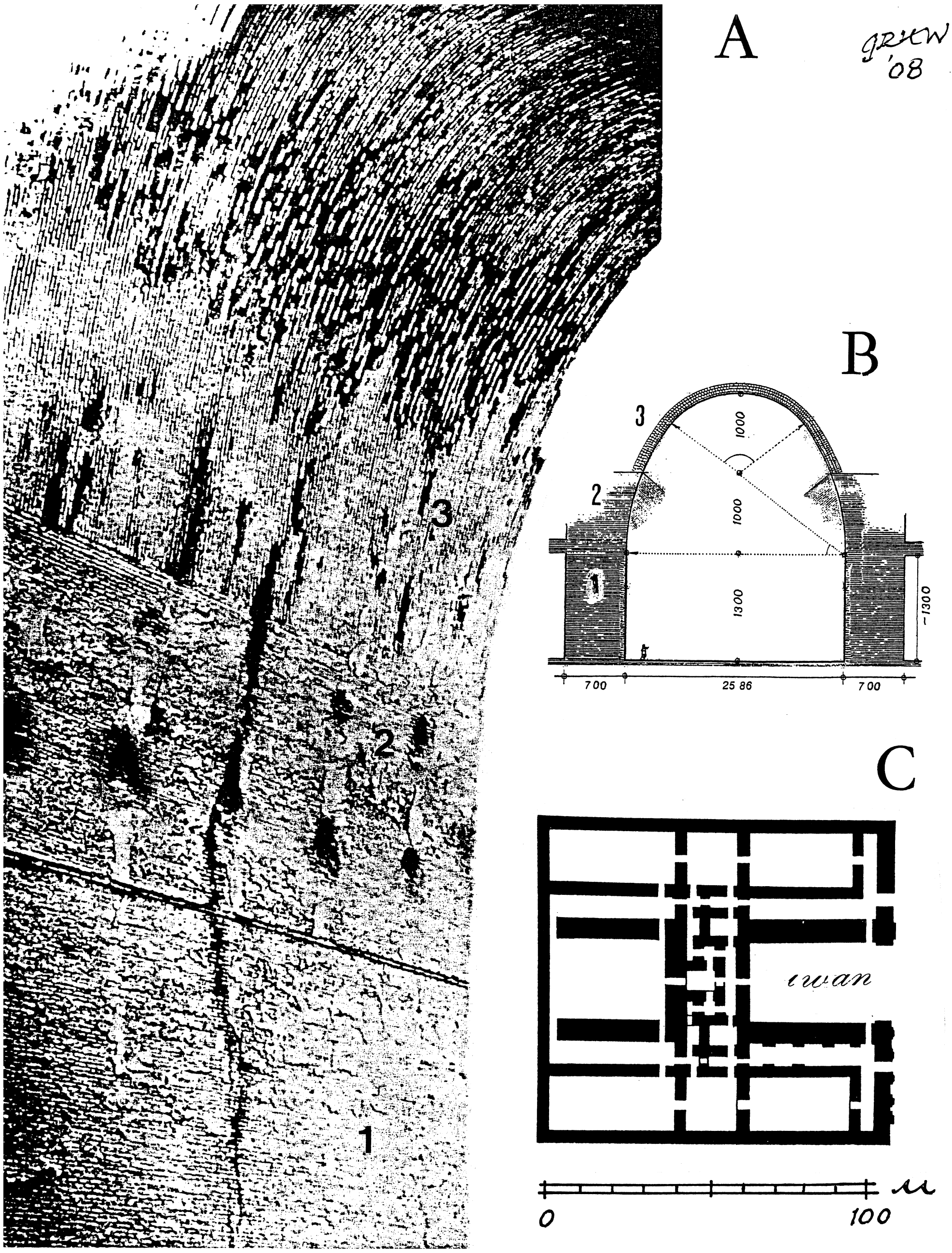
389. Ctesiphon Parthian Burial Crypt. Vaulting Technique. Southern Mesopotamia. This burial crypt of standard long room plan evidences in its construction detail mastery of brick vaulting technique. Bricks are set radially on bed and bricks set on edge are rationally deployed to facilitate vault construction without centering. The shoulders of the vault are carried up in normal brick work set on bed (as in the wall) to half the rise of the vault. Here the stance of the masonry is reasonably vertical and no question of centering arises, yet the span is thereby considerably reduced. Then in the crown of the vault where the stance of the bricks becomes progressively horizontal so that some form of support is required during construction, the construction is changed to a "pitched brick" vaulting for the remaining (reduced) span. Furthermore the inclined pitched brick work is horizontally confined at front and rear by two solid brick arches. After BM 24 1993 p.334, fig 3.



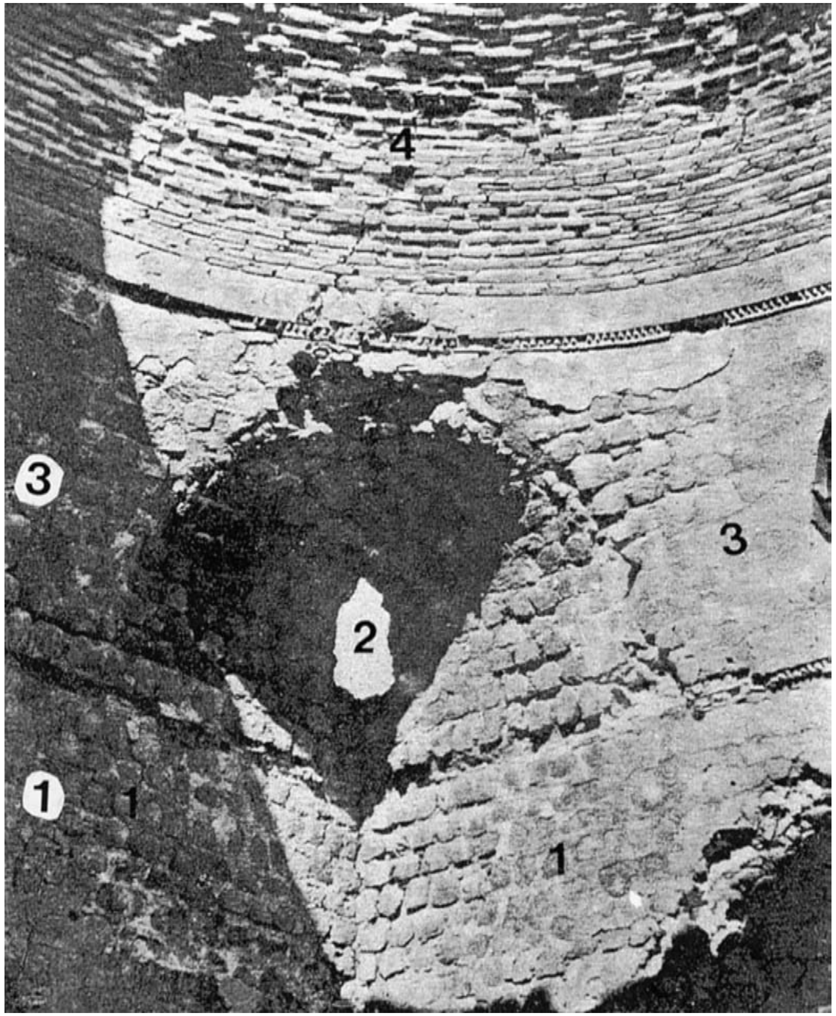
390. 1. Assur Parthian Burial Crypt (13971). Vaulting Technique. Northern Mesopotamia. ca 2nd Century AD. This crypt is of standard long room plan, but the low pointed vault rising from the ground level is unusual. Here again, although the upper part of the vault is destroyed, it seems that the crown was constructed in pitched brick style; 2. Assur Parthian Burial Crypt (13972). Vaulting Technique. This crypt is of unusual broad room plan. Also the vault (although largely destroyed) appears to have been constructed of bricks set on edge, but vertically not pitched. However the span was marginally reduced by stepping the intrados of the vault inwards from the supporting wall faces. After Andrae Patherstadt Taf 50.



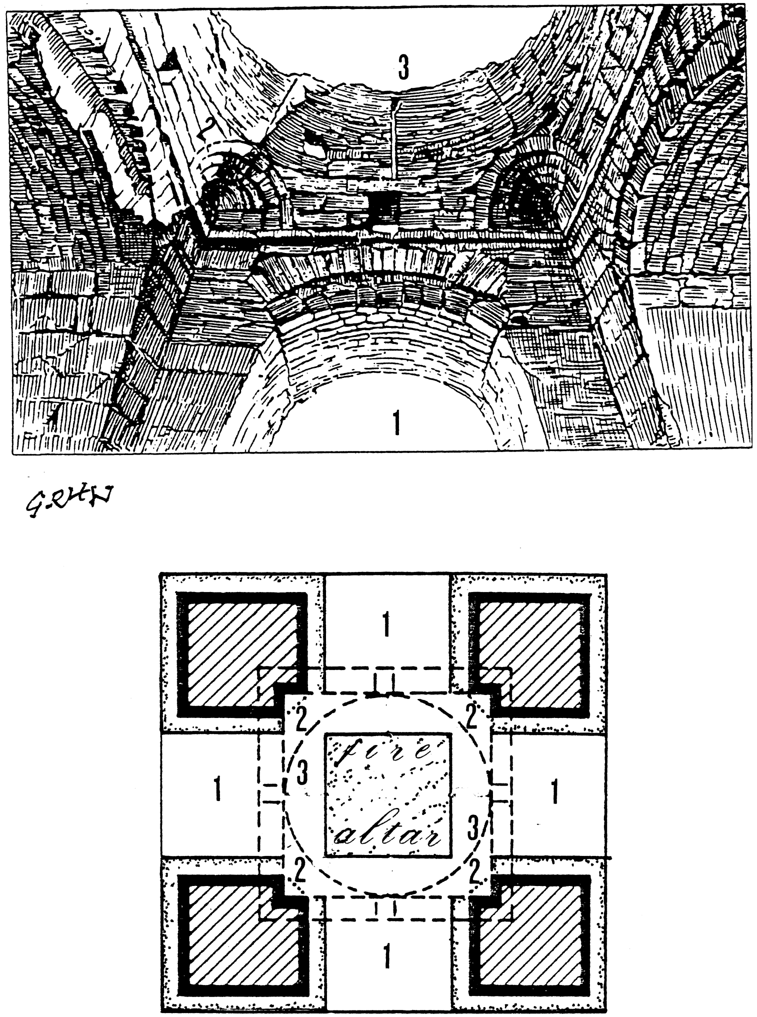
391. Diagram of Pitched Brick Vaulting. Sassanian. The procedure adopted for this type of vaulting enables it to be constructed without temporary support from below (centering). Essential are the square bricks of large format and thin section. They are thus light and afford the greatest possible 'specific surface' (i.e. proportion of surface area to volume). This favours the immediate and strongest adhesion of the quick setting gypsum mortar. The construction requires the prior existence of a rear wall. The bricks are set on edge, but for each successive 'arch' they are not set in the vertical plane but are canted backwards at an angle (pitched) – the first arches resting against the rear wall, and the latest arches each lying back on the bricks in place for a few seconds while the gypsum mortar sets. The span to be pitch vaulted was reduced where advisable by corbelling inward the haunches of the vault. This type of vaulting has remained standard to the present day in Persia, Mesopotamia and also in other regions (where it has been diffused by Arabs). After Pope I, fig 129.



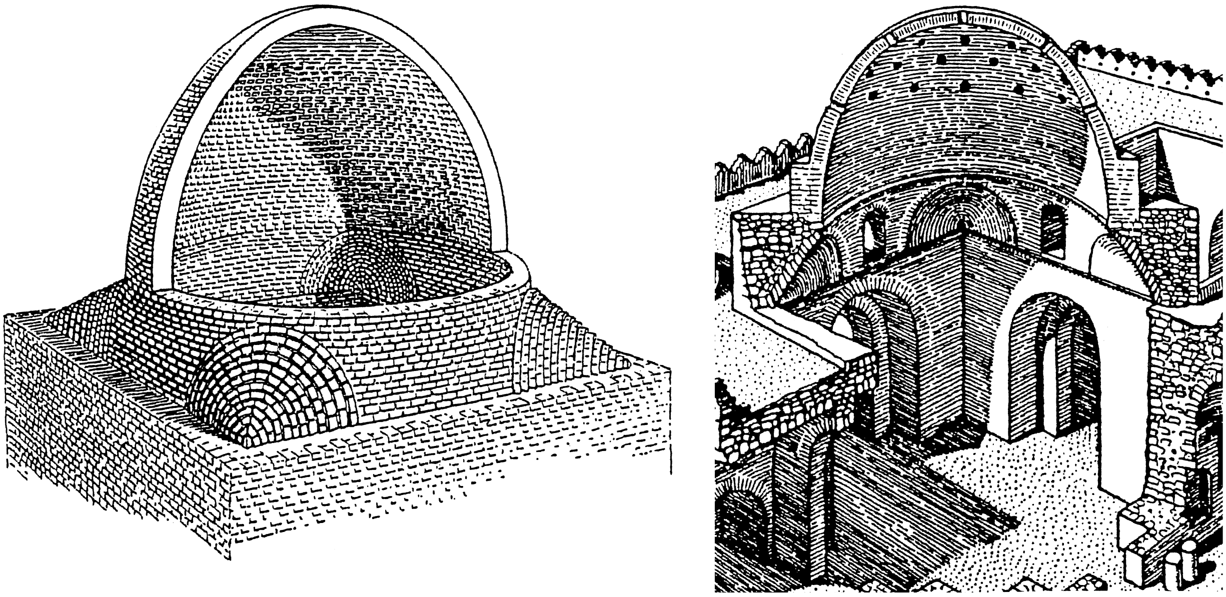
392. Taq I Kisra (Arch of Cosroes). Late Sassasian Dynastic Palace. Vaulting of Iwan Ctesiphon (near Bagdad). 6th Century AD. This outsize brick building was designed to demonstrate the might of the Great King to awe both subjects and foreign envoys received there (cf Persepolis 1000 years earlier). The barrel vault over the great Iwan was a world wonder. It remained by far the widest span (ca 26m) barrel vault until recent times. However the vaulting technique was that practiced by all Parthian and Sassanian builders, based on the ancient Mesopotamian building tradition. The effective span for "voussoir" brick work was reduced as far as possible by corbelling out the shoulders of the vault to a rise of ca 10m and the crown was constructed in pitched brick technique. Thus the work was carried through without centering. *Key*: A. View of inner face of side wall of Iwan from within looking out to exterior. The three registers of brick work are clearly distinguishable: the vertical wall masonry (1); the corbelled shoulders of the vault (2); and the pitched brick crown of the vault (3). B. Diagramatic cross section of Iwan vault showing the three zones of the brick masonry: upstanding wall (1); corbelled shoulders of vault (2); pitched brick crown of vault (3); The vault with a span of ca 26m and a rise of ca 20m is of paraboloid design, and very close to a semi ellipse or rather 3 centred arch in form; C. Key Plan. NB The right hand wing of the façade collapsed after flooding in modern times. After Pope Persian Architecture, fig 46.



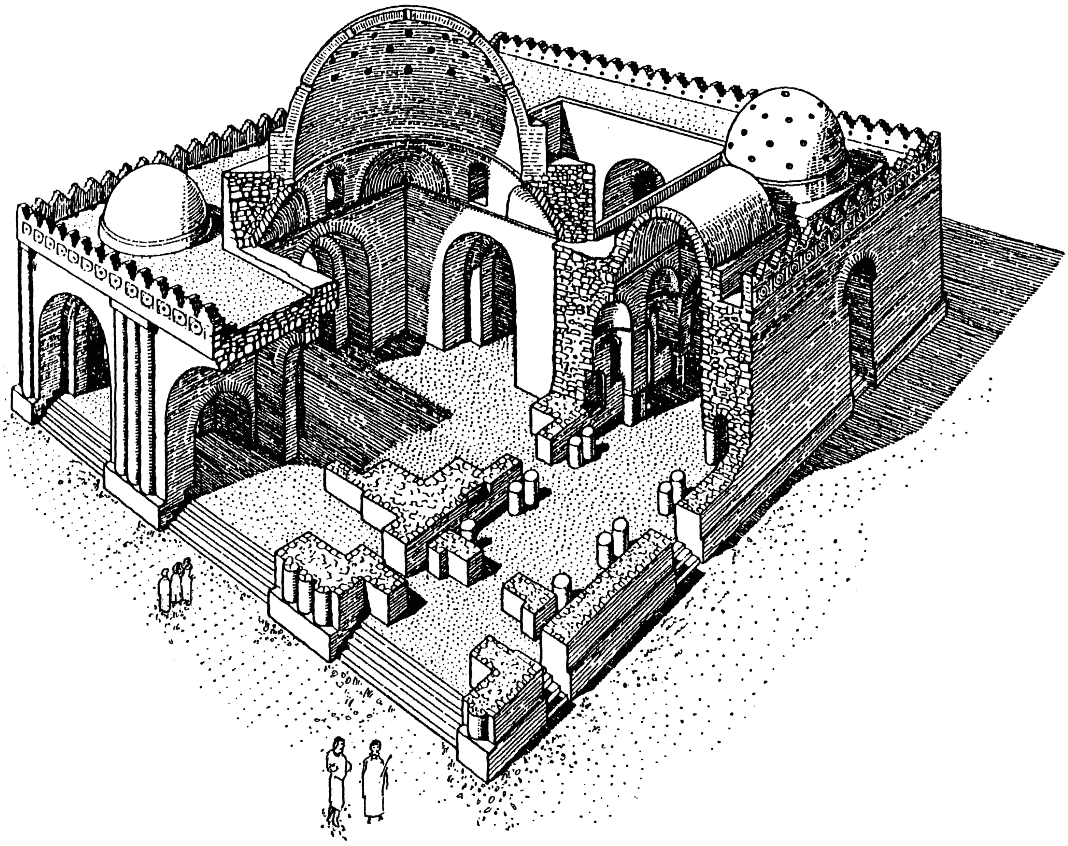
393. Firuzabad. Palace. Squinch Construction Detail. Southern Iran. Sassanian. The construction of this building was basically mortared rubble, but the domes were of burnt brick. *Key*: (1) Rubble walls of (square) chamber; (2) Rubble squinch arch (broken through at rear); (3) Rubble infill between squinches (in the nature of a pendentive) to transform octogon at base into a circle at crown; (4) Dome of burnt brick. After Dieulafoy.



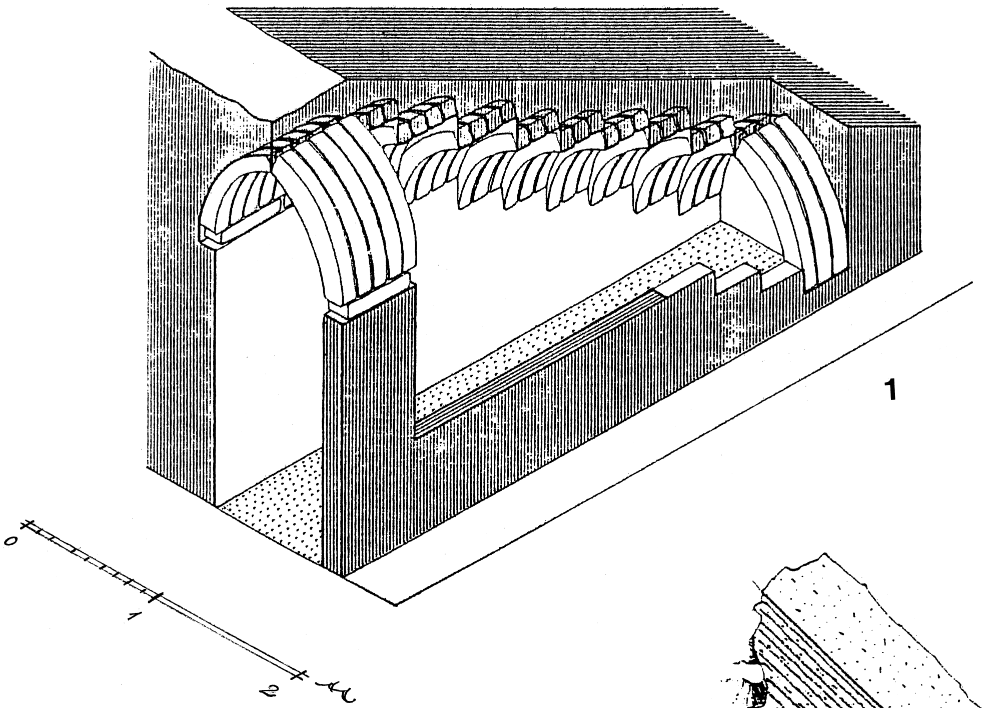
394. The Chahar Taq (The Sassanian Fire Temple). Diagramatic Type Plan and Sketch of Surviving Ruins. There are many surviving examples of this elementary temple plan called “Four Arch”, which shelters a fire altar but leaves it as far as possible in natural surroundings. The building comprises 4 arches between masonry piers (1) furnished with squinches (2) to carry a brick dome (3). After Pope Persian Architecture, fig 70.

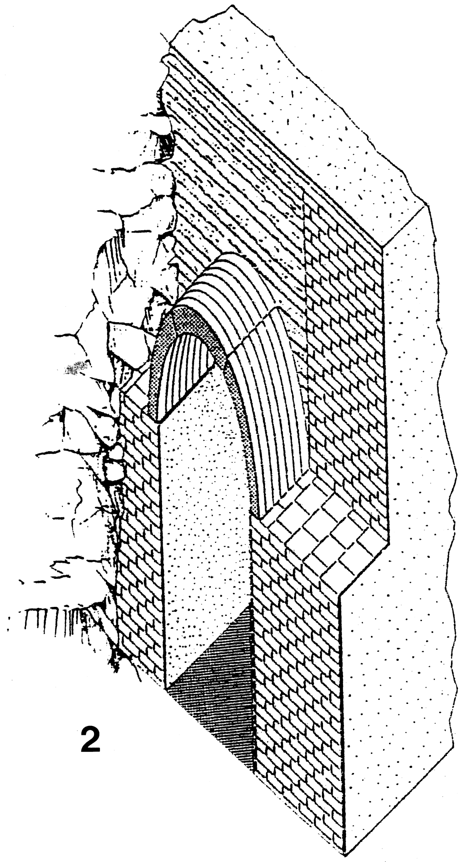


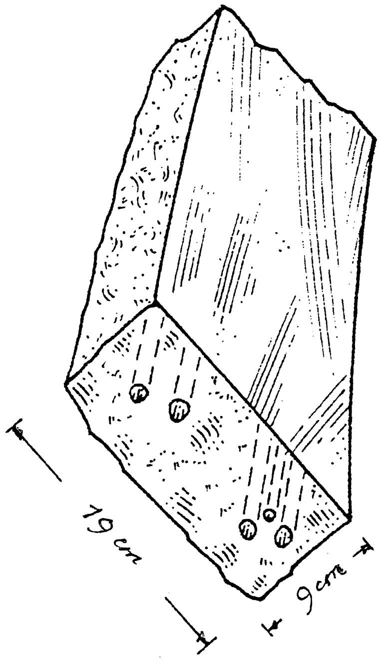
395. Typical Sassanian Dome on Squinches. Structure viewed from exterior (*left*) and from interior (*right*).



396. Sarvestan. The Palace. Cut away Perspective View. Fars (South Western Persia). Late Sassanian, or perhaps early Islamic in Sassanian tradition. This view shows varied material of construction with domed and barrel vaulted roofing. The mixed construction (somewhat similar to Ayia Sophia) comprises coursed rubble for load bearing walls, and brick for vaults and domes. After Pope, Vol I, fig 152.

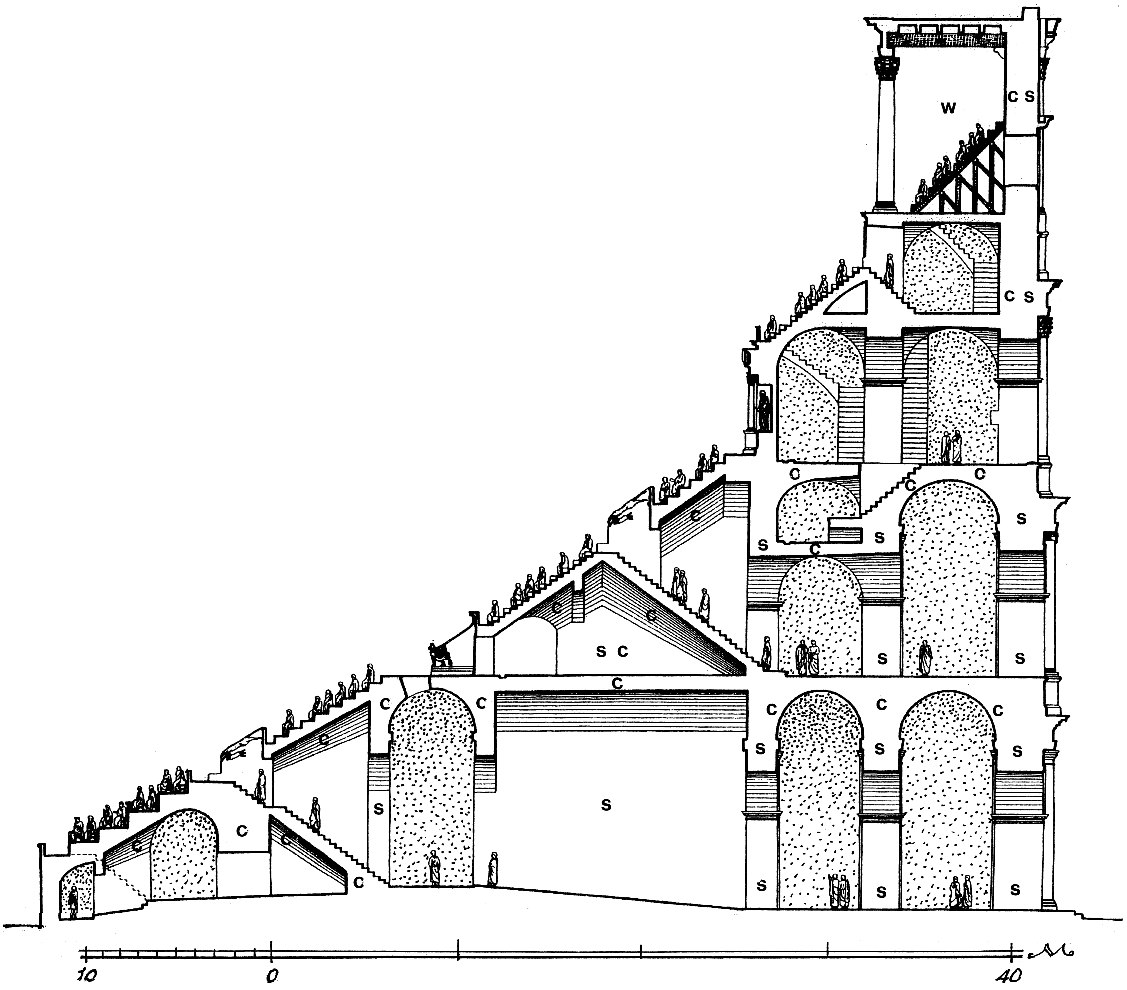




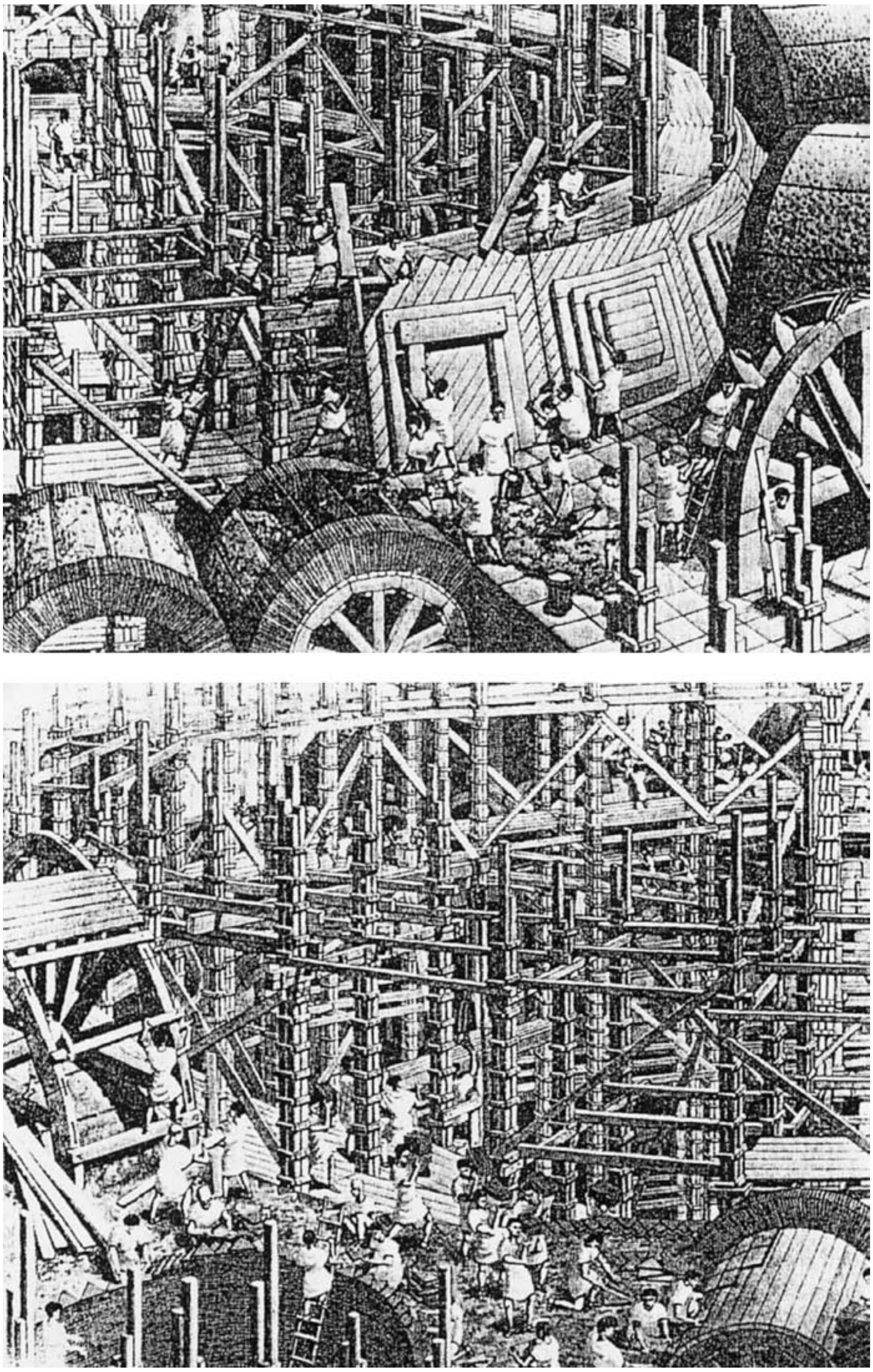


397. Pre-cast Reinforced (pointed) Vaulting Rib. Median – Sassanian. Such elements were originally sun dried mud (brick). In Sassanian times they were gypsum. The tensile reinforcing incorporated was generally reeds. After Huff AMI 23 1990 p.116, fig 17.

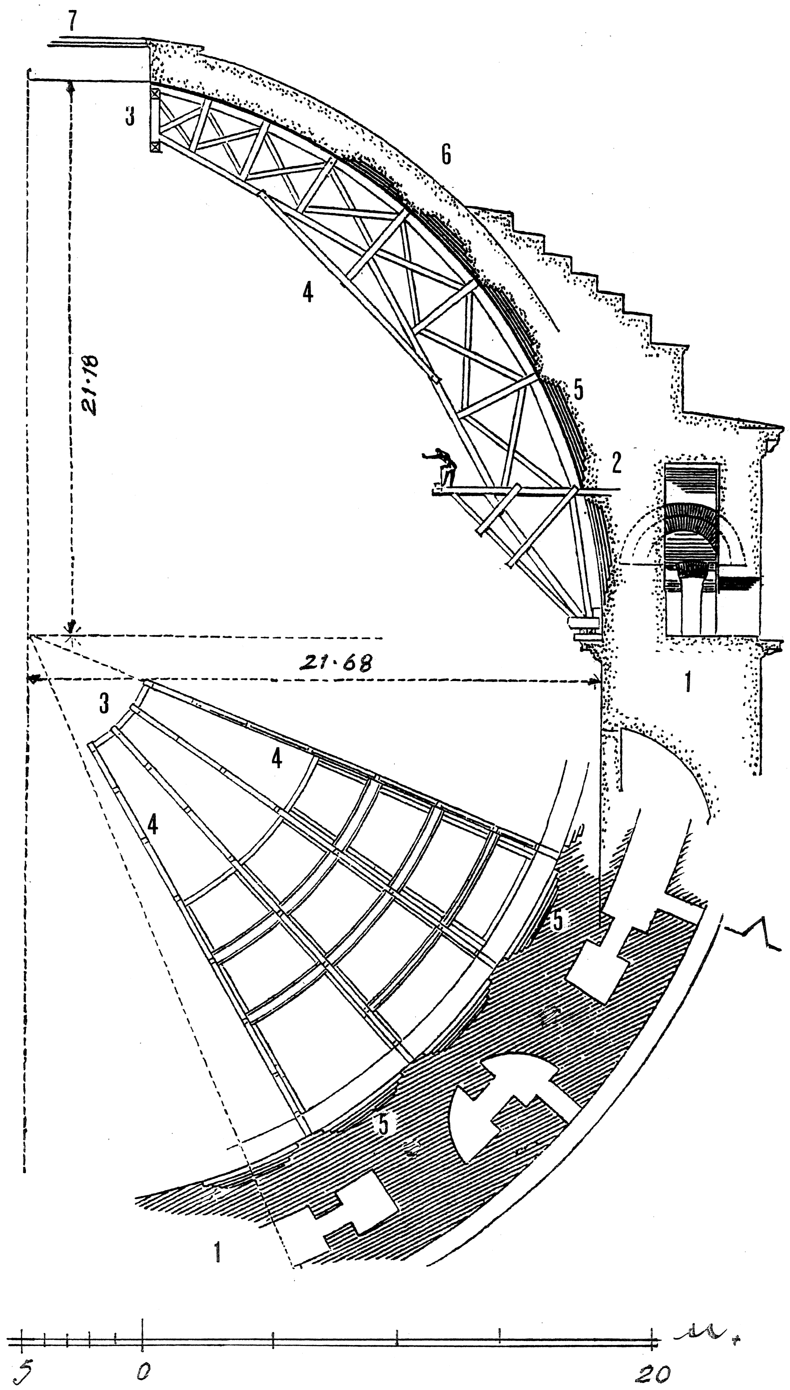
398. Pre-fabricated Plaster Units used in Iranian Vaulting. Examples of this surprising technology occur in Median, Achaemenid and Parthian building and apparently continue on in use until Islamic times. The units consist of moulded segmental ribs of mud or gypsum plaster with a section of ca 20 cms x 10 cms, generally with a reinforcing of pliable wood or reeds. They are set contiguously to give pointed vaulting for small span corridors and stairways. Their nature passes from lost shuttering to structural units. *Key*: 1. Shah-I-Qumis. Parthian ca Later 3rd Century BC; 2. Kuh-I-Khawaja. Sassanian ca Later 3rd Century AD. After Huff AMI 23 1990 pp 110-14;



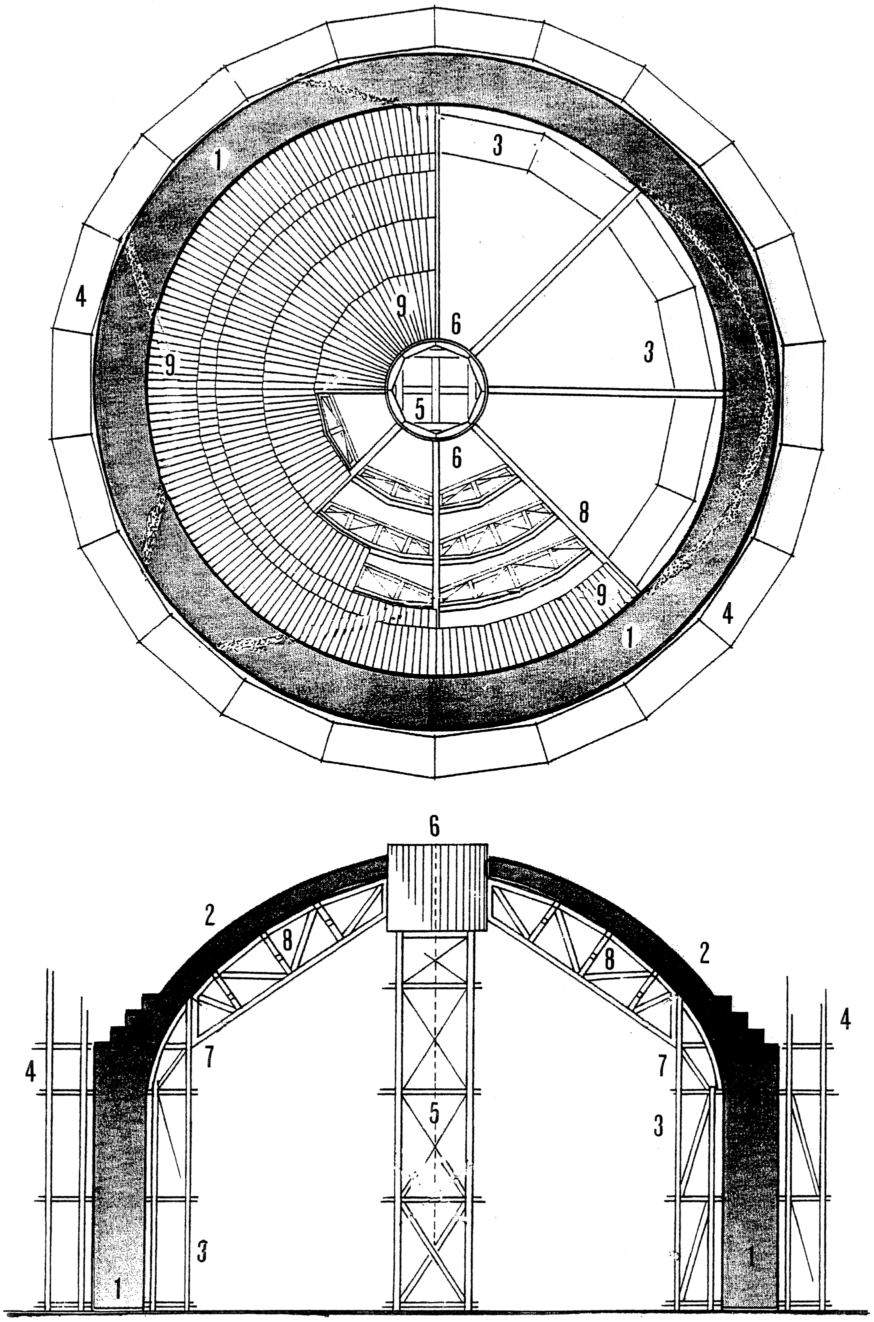
399. Rome. Colosseum (Flavian Amphitheatre). Paradeigmatic Section of Cavea indicating varied material of construction – essentially ashlar stone walling and concrete barrel vaulted roofing. Italy ca 80 AD. This drawing is schematic only, but the overall situation is clearly conveyed. The peripheral structure supporting the highest rows of seating is of massive closely spaced ashlar stone walls with concrete vaulted roofing. The intermediate seating of the cavea is supported by somewhat slighter ashlar stone walls and concrete vaulting, while the lowest parts of the cavea closest to the arena are virtually built entirely in concrete. This distribution is rational, in accordance with the distribution of loads born by the walling; however it results in the closely juxtaposed and interpenetrating setting of the two different materials: ashlar stone and Roman Concrete. Since the requisites for setting these two materials are markedly different, this has given rise to debate concerning the procedures for building the monument and the lifting devices employed for hoisting the ashlar blocks. In this latter connection it is possible to suggest the following. While the ashlar construction for the lower parts of the building may have been carried out entirely with Dikōlos type cranes, it is likely that the upper parts of the construction made use of block and tackle rigged on heavy scaffolding with perhaps the auxiliary use of cranes. *Key*: s = ashlar stone; c = Roman Concrete; w = wood. After Rea, fig 58.



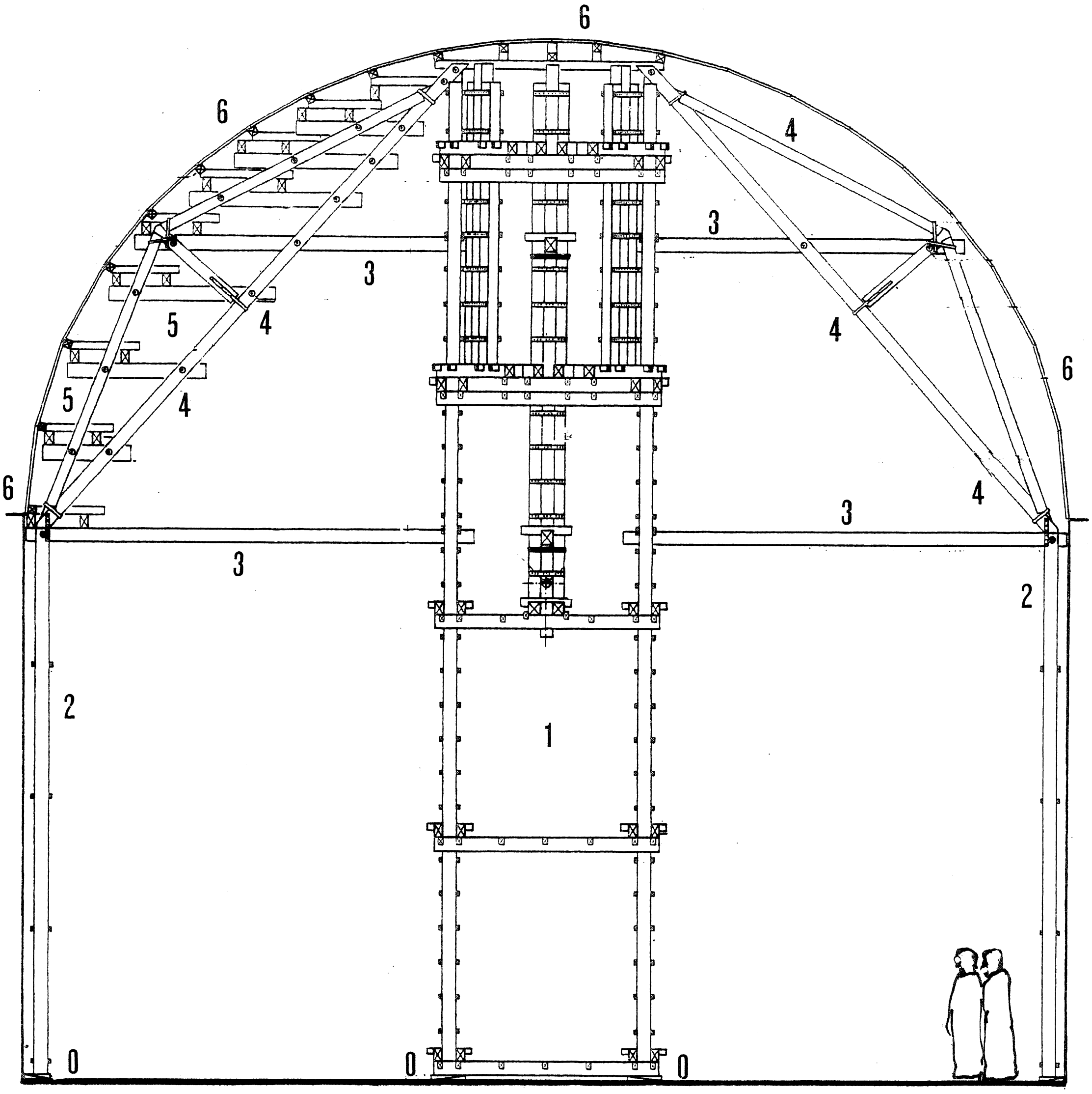
400. Reconstructed Views of standing Centering for large span Concrete Dome showing Forest of Scaffolding rising from Pavement. Roman 1st–2nd Century AD. This arrangement provides for constructing the centering largely *in situ* and serves for all requirements of the work. These requirements include access to any part of the dome face; a spacious working platform wherever needed; facilities for hoisting material (wooden members, bricks, aggregate, mortar etc); support for units of the centering/shuttering during and after construction. Whatever criticism may be levelled against it on grounds of economy or congestion, the scheme answers to all needs of the work and at a glance appears a much more probable scenario than schemes designed to avoid it. After Leacroft. The Buildings of Ancient Rome, figs 12, 13.



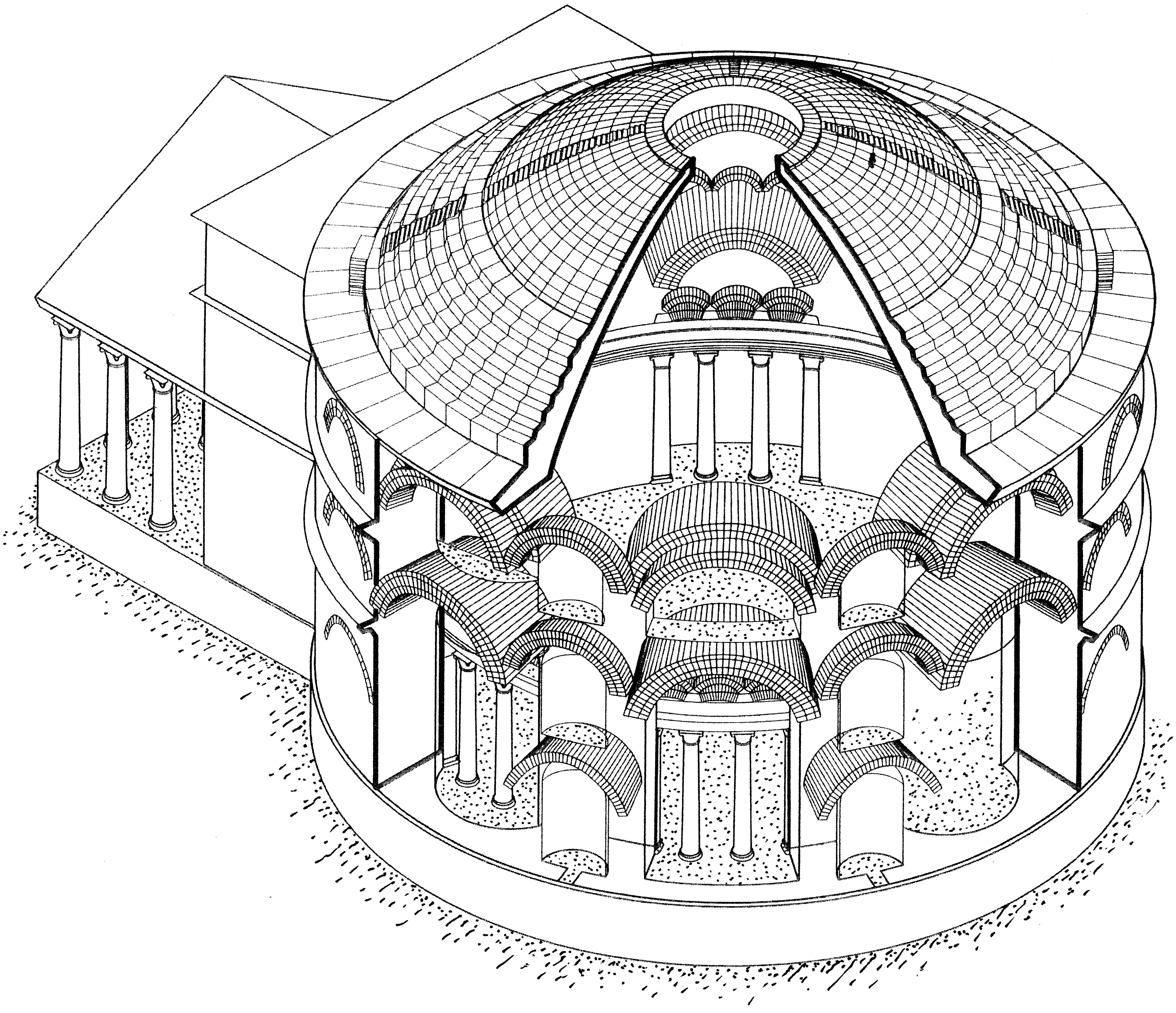
401. Rome. Pantheon Dome. Viollet le Duc's hypothetical Scheme for flying Centering. The heavy trussed segmental ribbing was held in place by compression between a hammer beam arrangement at base of dome and a continuous annular frame at the crown of the dome below the oculus. Not shown on this drawing are: a. How the ribbing was hoisted into position; b. Working platforms for installing the ribbing; c. External working platforms for placing the concrete etc. *Key*: 1. Concrete walling of the rotunda; 2. Hammer beam arrangement at base of dome for holding centering ribs in place; 3. Compression ring at crown of dome holding centering ribs in place; 4. Centering ribs; 5. Moulds for coffered plaster decoration; 6. Concrete dome; 7. Oculus. After Viollet le Duc Dictionnaire Vol 9.



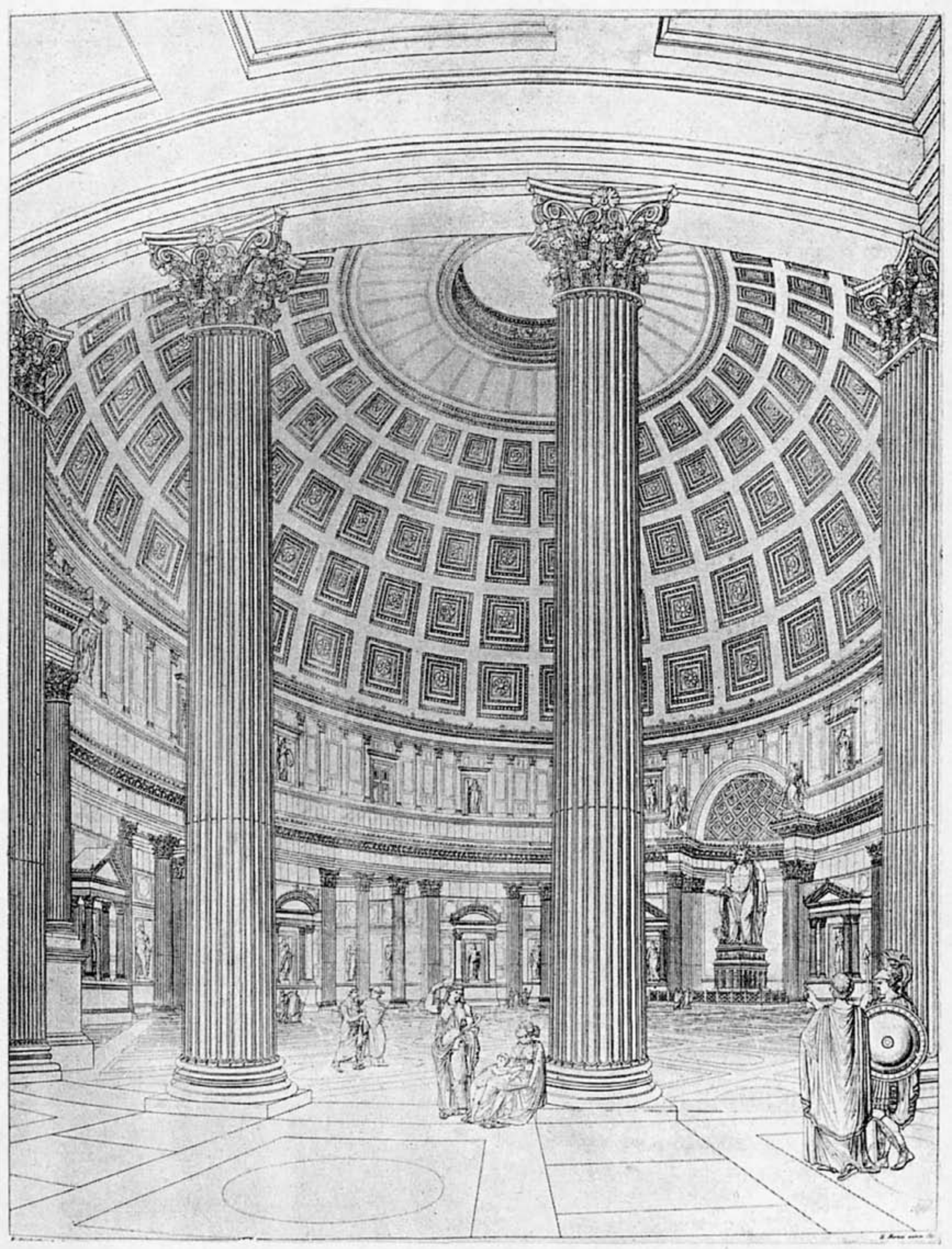
402. Proposed Concrete Dome Centering with Central Tower Support. Roman ca 2nd Century AD. This economic device supports the flying centering by putting the trussed segmental ribbing into compression between the wall scaffolding and the compression cylinder defining the oculus (however it is still operative when there is no oculus). The tall central wooden tower may have owed its inspiration to siege towers which were built to very great height. This drawing does not show: (a) how the ribbing frames were hoisted into position, (b) working platforms for affixing them to their abutment on the wall scaffolding and the central tower, (c) continuation of the external wall scaffolding to provide working platforms for placing the concrete and its tile cladding. *Key*: (1) Concrete walls of rotunda; (2) Eventual concrete dome; (3) Internal scaffolding of rotunda walls; (4) External scaffolding of rotunda walls (NB access scaffolding for placing dome concrete not shown); (5) Central tower support for centering ribs; (6) Compression cylinder holding centering ribs in place; (7) Centering abutted against wall scaffolding; (8) Trussed centering ribs; (9) Timber boarding (lagging) as shuttering for setting concrete. After Rakob fig 17.



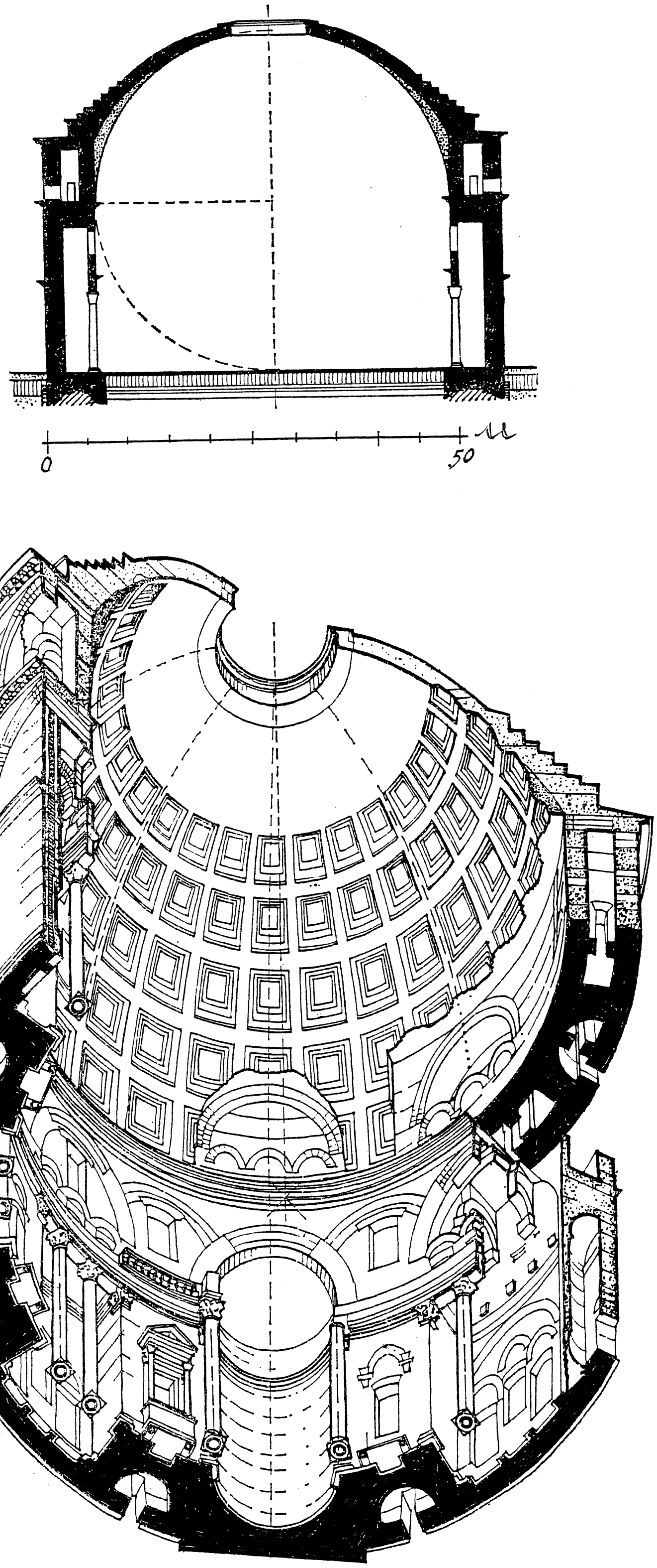
403. Via Praenestina. Mausoleum of the Villa of the Gordiani (the so-called Tor di Schiavi). Proposed centering for the construction of the Dome (span 13.20m) based on Central Tower Support. Rome ca 320 AD. This arrangement is, in effect, standing centering with a space frame medial prop. The details of the timbering are very precise and intricate, but are not individually identified here. It is claimed that they provide such a rigid support as during construction to obviate any subsidence at the crown of the dome with attendant spreading at the haunches. *Key*: (0) Folding wedges; (1) Central tower standing support; (2) Standing support by walls; (3) Horizontal tie/strut; (4) Centering rib primary truss; (5) Timbering to give semi-circular form; (6) Timber lagging or centering or shuttering. After J. Rasch fig 44.



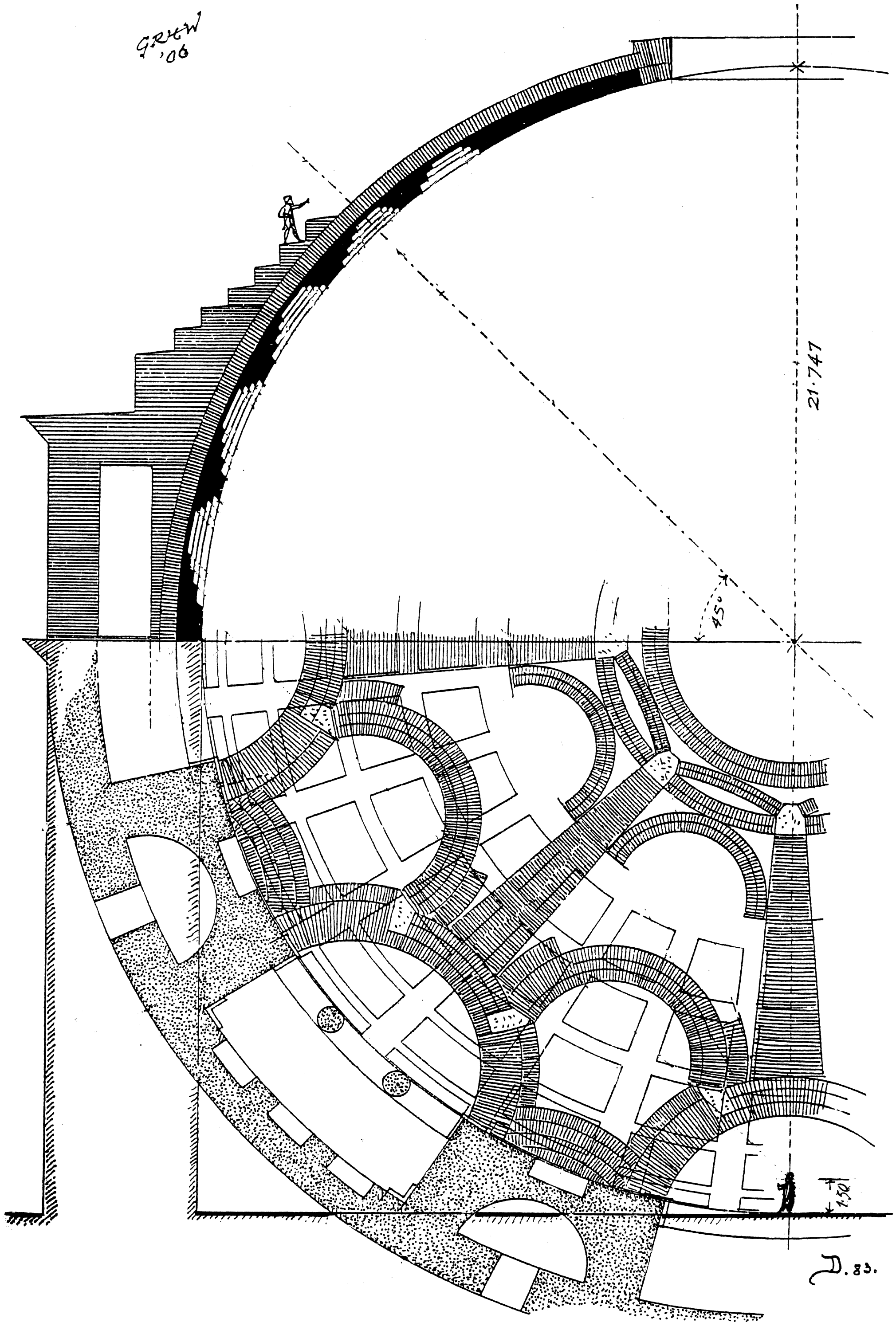
404. Rome. The Pantheon. Sectional Perspective View showing brick Arches incorporated in the Concrete. Italy ca 125 AD. Although externally appearing as a cylindrical wall, the ground plan resolves itself into a series of 8 massive pillars forming columnar exedrae or niches. The construction of the rotunda drum revealed in this cutaway section shows a vertical succession of inbuilt brick arches designed to transmit the load of the superincumbent concrete construction away from the vaulted exedrae and niches onto the intervening pillars; also to relieve the architraves spanning the exedrae columns by directing it onto the columns. NB This drawing does not show any corresponding brick arches (or ribs) in the dome of the rotunda. After Lancaster p.100, fig 8.



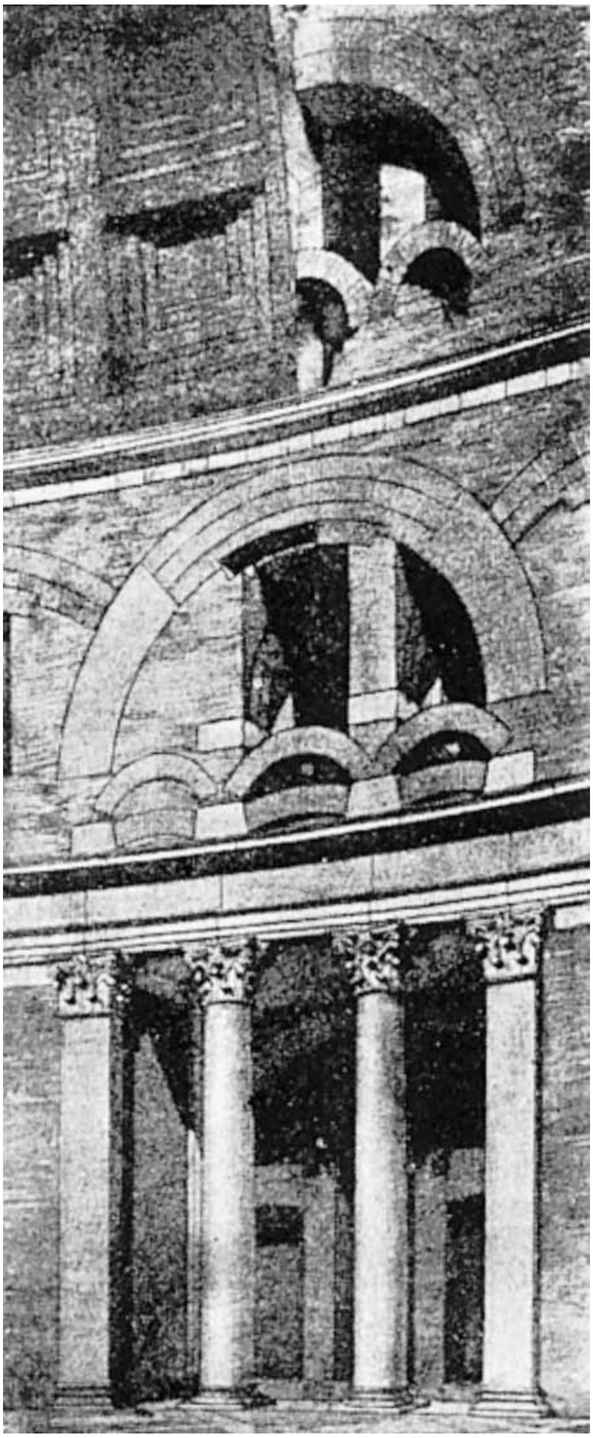
405. Rome. Pantheon. Restored View of Interior. Italy ca 125 AD. The strenuous “intellectual” construction is entirely hidden from view. The ornamental stucco facing and ashlar masonry trappings create an effortless serenity of a world within a world, which is the antithesis of Classical Greek temples where every element in the masonry construction is manifested to view. NB The ‘round house’ of all the Gods is the cosmic monumentalising of Neolithic man’s original ‘round house’ dwelling. After Robertson Pl XVII.



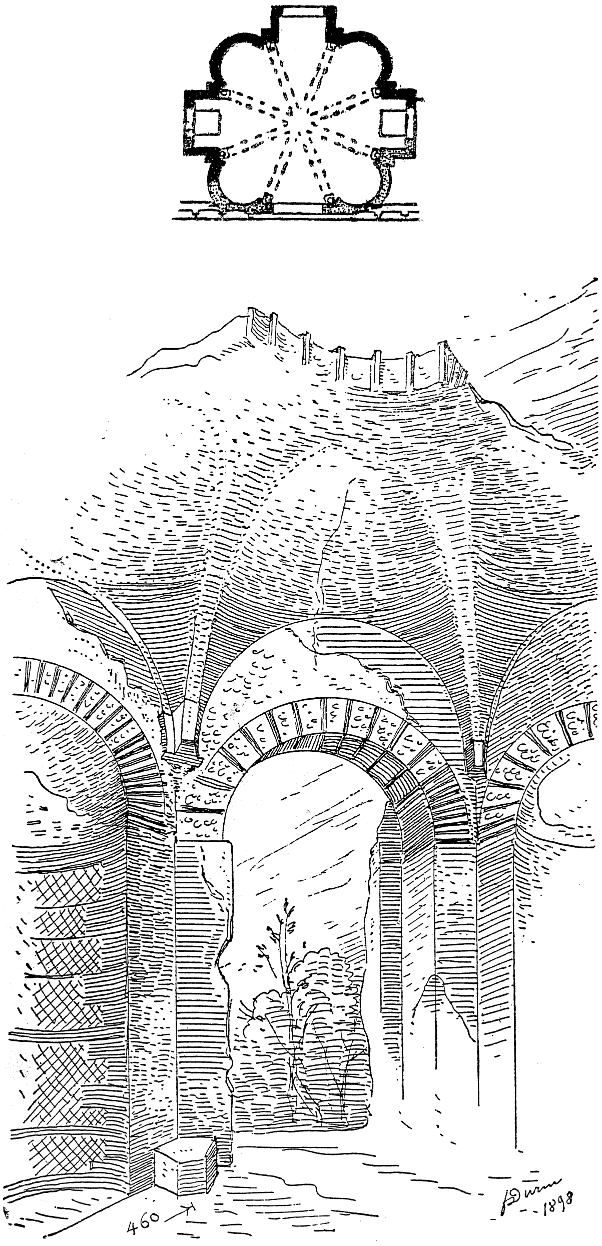
406. Rome. Pantheon. Cross Section and Sectional Axonometric View showing Structure of Walling. Italy ca 125 AD. Cavity walling with discharging arches to transmit the load onto pedestals and columns at ground level. After Ward Perkins Fig 102.



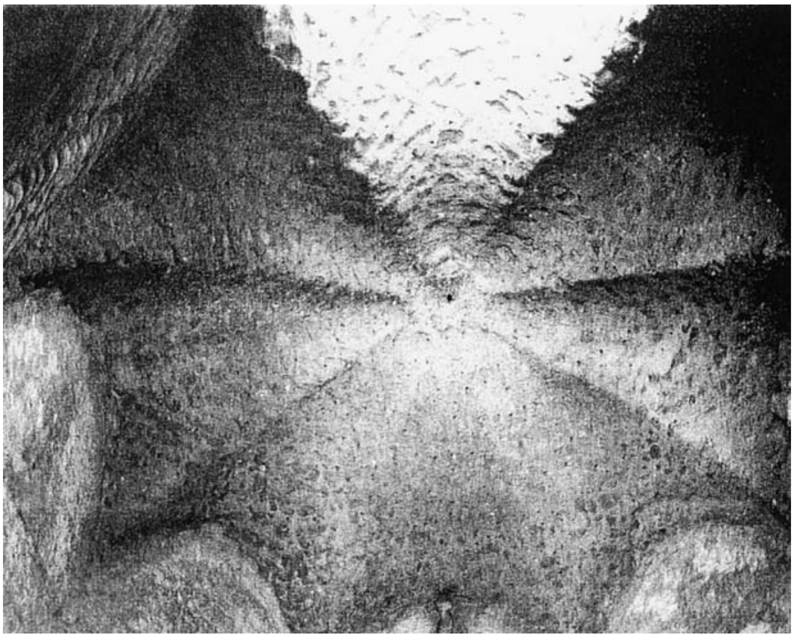
407. Rome. Pantheon. Durm's Analysis of Construction. Italy ca 125 AD. Durm's original drawing with part plan and section superimposed, together with sight lines was intended to show both the construction, with its inbuilt brick arches and also the optics of the design. Here Durm's dimensions, construction lines and sight lines etc have been removed in the interest of simplicity of expression. Durm's sight lines identifying the one feature in both plan and elevation are virtuoso devices of a master of building analysis – and should be studied. The presence of all the inbuilt brickwork shown here by Durm is now disputed. After Durm B d R, fig 299.



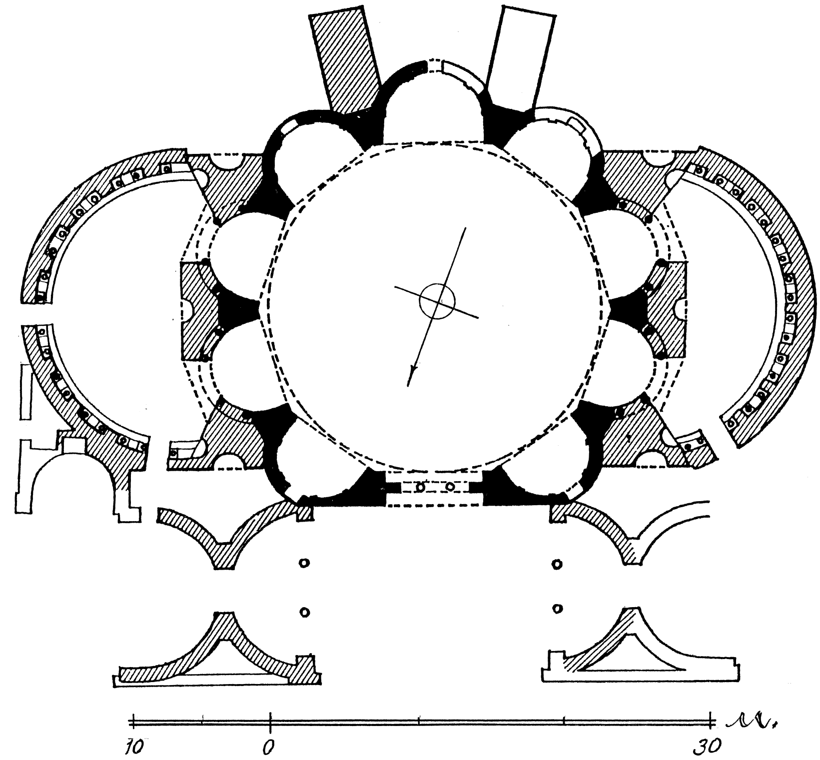
408. Rome. Pantheon. Reconstructed Drawing of (part) Interior showing inbuilt Brick Arches. Italy ca 125 AD. The plaster decoration has been partly stripped away to show the inbuilt brick arches. The presence of the brickwork shown here in the dome is now disputed. After Crema, fig 448.



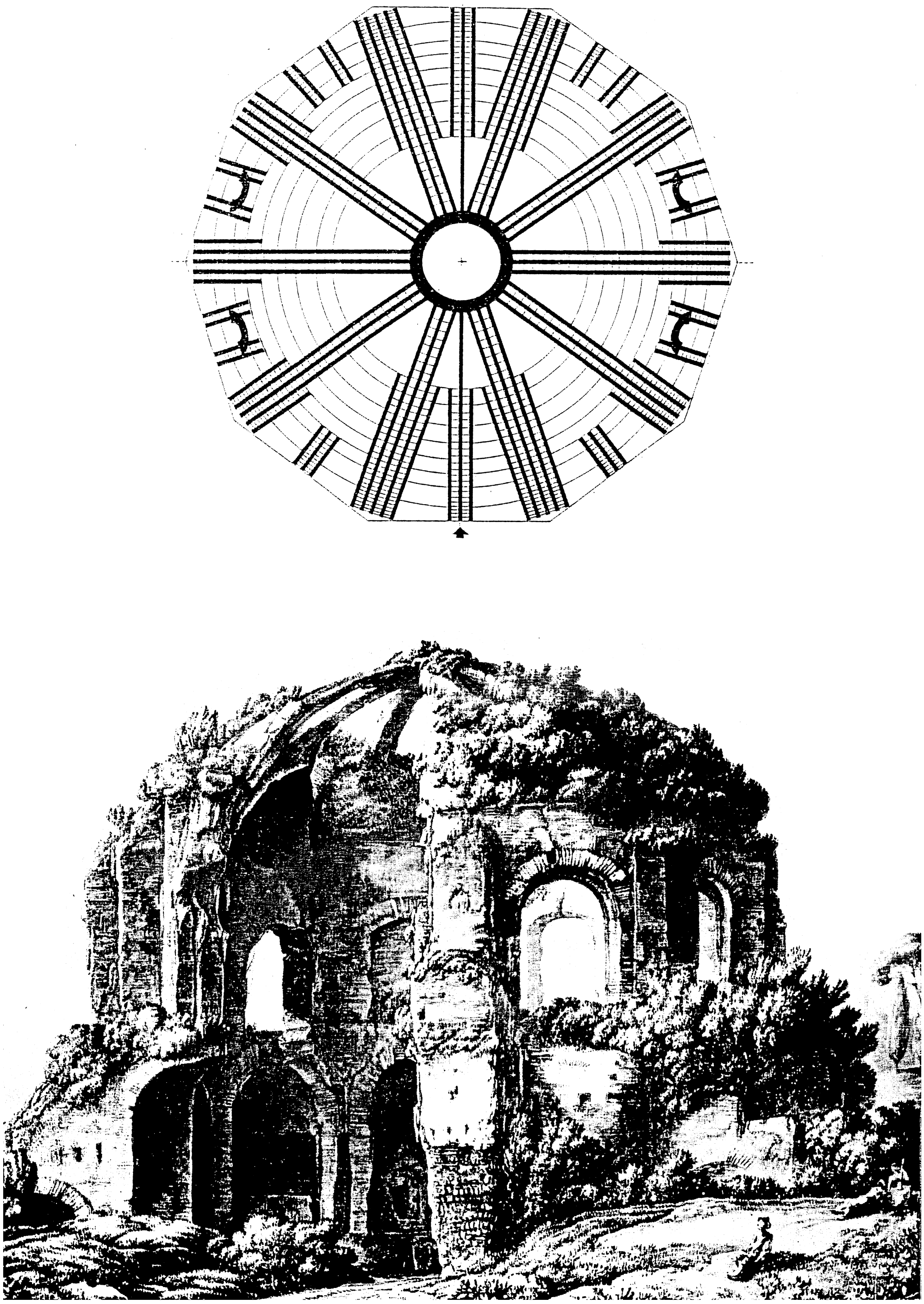
409. Tivoli. Hadrian's Villa The Piazza d'Oro. Lobate/Umbrella Dome. Near Rome ca 130 AD. The baroque virtuosity of planning at Hadrian's Villa fostered the development and diversification of dome construction. Semi-circular exedrae to a square or octagonal plan evoked a ribbed dome with the segments between the ribs arcuated in plan to give a gourd (or pumpkin) effect. Hadrian's personal interest in this device is adverted to in Apollodorus' well known snub. The structural virtue of the device is that it induced an additional compression in the construction. Accordingly it was taken up as constructional form independent of any exedrae planning. After Durm B d R fig 317.



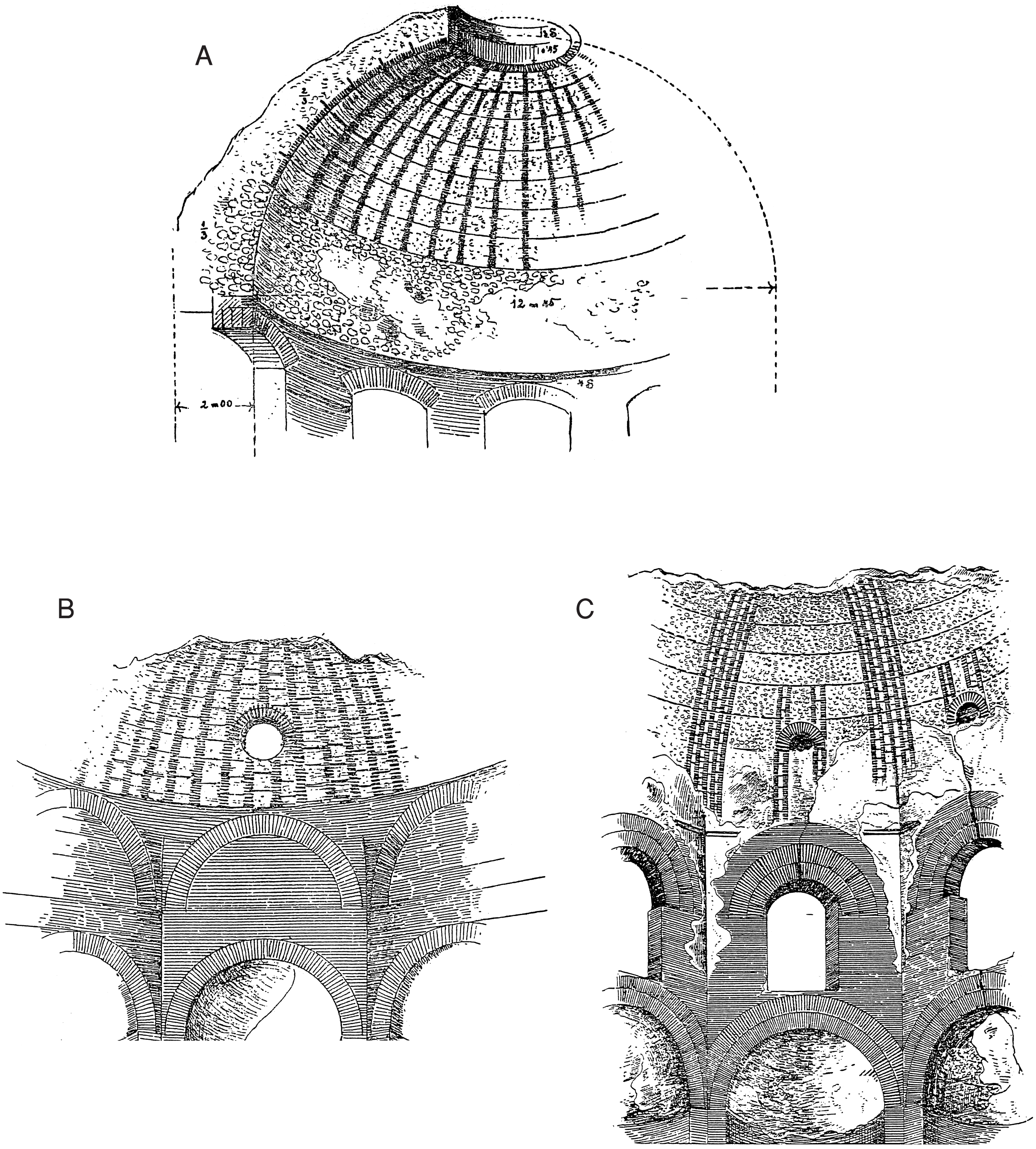
410. Baiae. Baths. View of Soffite of Lobate (umbrella, pumpkin) Dome. Bay of Naples. Hadrianic. This construction is structurally very advantageous The groins discharge vertically downward the main compressive forces of the self load, while segmental cross section of the masonry between them puts this masonry totally in compression horizontally to counteract hoop tension and further transfer the stresses to the groins. After Adam, fig 439.



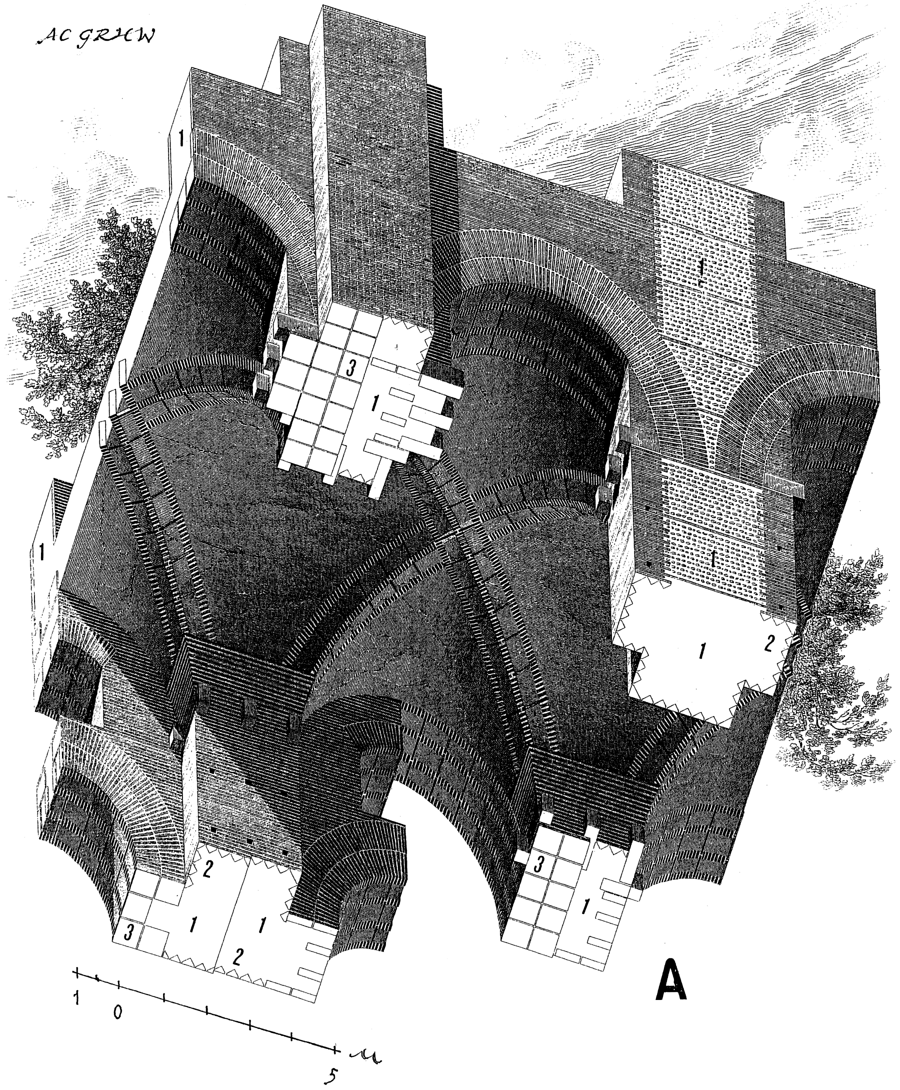
411. Rome. Plan of the Pavilion in the Licinian Gardens (Temple of Minerva Medica). Italy ca 310 AD. Late *opus testaceum* pavilion on a decagonal plan with semi-circular exedrae. Later additions to the plan (hatched) provided two large semi circular apses and an apsidal vestibule. After Ward Perkins fig 194.

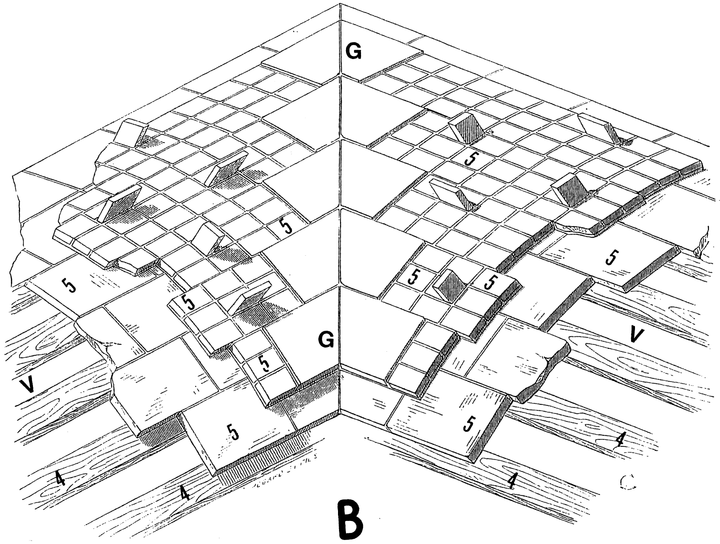


412. Rome. Pavilion in the Licinian Gardens (Temple of Minerva Medica). Italy ca 310 AD. The major radial arches here are revealed to have had a statical function since they long subsisted as independent structural entities after much of the infilling concrete had fallen away. *Key*: *below*: A drawing of Franz Innocenz Kopell 1780 showing some of the brick ribbing of the dome still standing after the concrete encompassing them had fallen away; *above*: Reconstructed diagram showing symmetrical positioning of the radial brick in the concrete dome. After Rasch fig 48b.

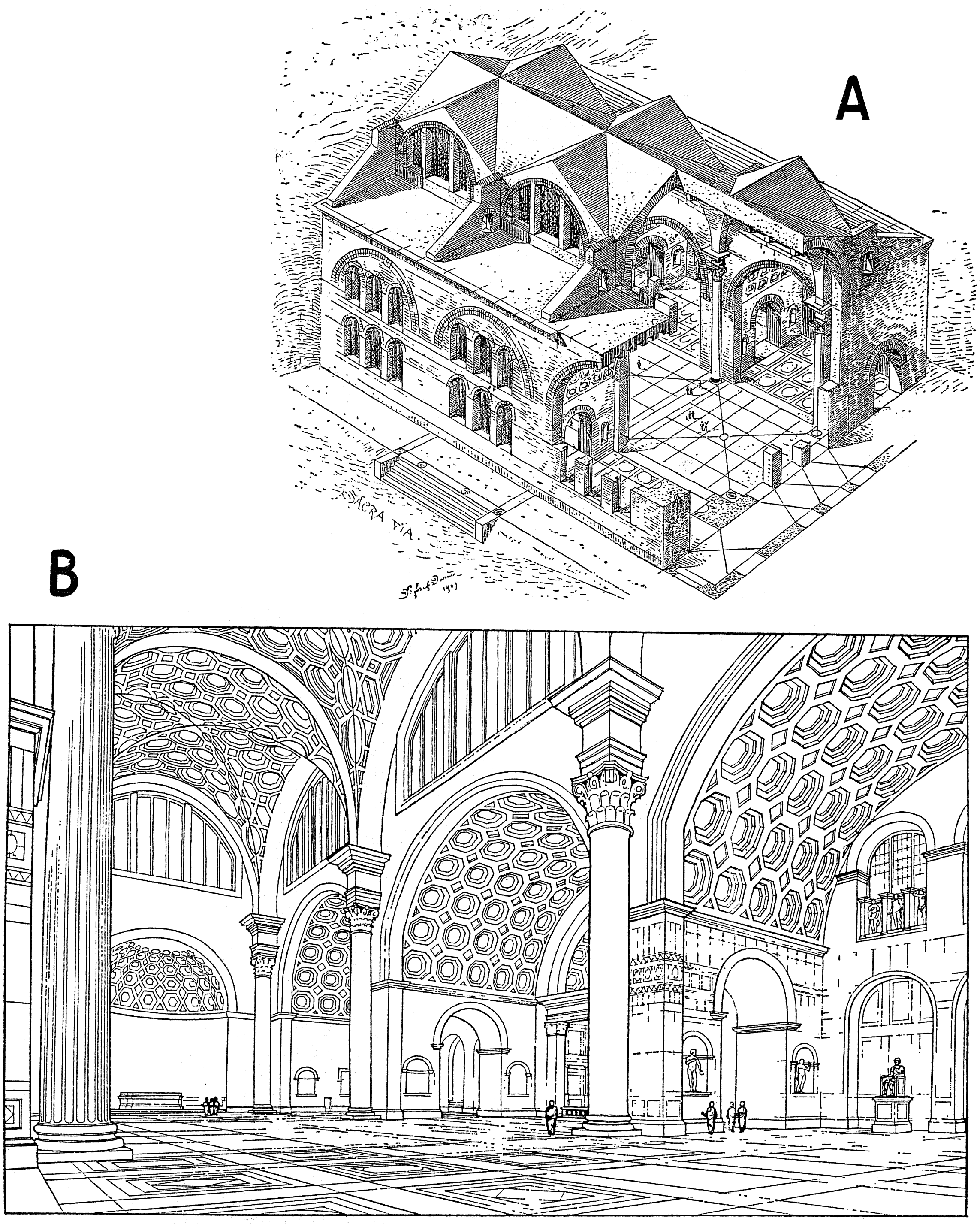


413. Rome and Environs. Large Span Concrete Domes showing inset radial Brick Arches. 2nd – 4th Century AD. In Imperial times concrete domes on a monumental scale became standard roofing. Although differences in detail of construction occurs, there are several common developments:. (1) Centering (soffite shuttering) was minimised as far as possible; (2) Radial brick arches were incorporated in the concrete; (3) The concrete was graded so that heavier aggregate was used in the lower parts of the dome. Durm's expressive drawings show something of these developments. The presence of an oculus at the crown considerably reduces the centering/shuttering required. Brick radial arches, often loosely referred to as nerveture or ribbing are revealed in some instances to have no statical function. As drawn here the only purpose they could fulfil is formwork to aid in the placing of the concrete. The section of A shows the heavier *caementia* (rubble) used at the base (springing) of the dome. *Key*: A. "Tempio della Tosse" Tivoli; B. Baths in the Villa Gordiani, Via Praenestina; C. "Temple of Minerva Medica" Licinean Gardens, Rome. After Durm B d R figs 295, 292, 307.





414. Choisy’s Diagramatic Illustration of Roman Concrete Cross Vaulting to demonstrate its Advantages. A. Axonometric View of Soffite of Concrete Cross Vaulting; B. Diagram of Centering/Shuttering for Cross Vaulting. Once the wooden framework has been correctly set up then no further questions of stereotomy arise in the construction of the vault, the concrete being placed in horizontal layers as normal for walls. Also Choisy here illustrates his general program of incorporation in the concrete of a considerable amount of brickwork taking the form of radial arches. Whether or not Choisy’s drawings of individual instances accurately show existing brickwork or whether they are schematic has been discussed. Allowing the existence of such brickwork, it has also been debated what its intended function may have been – additional (lost) formwork to facilitate the placing of the concrete; compartmentalising the mass of plastic concrete so as to reduce stresses and pressures ? Whatever may be the case with radial brick arches set in concrete domes, it has never been asserted that such arches in cross vaults were structural ribs and the cross vaulting the rib vaulting of Late Romanesque and Gothic construction. Roman cross vaults were groin vaults not rib vaults however the inset brick work may be disposed. The arches were inset into the concrete mass, the concrete was not set as infill tegument between them. The weakness of Choisy’s illustration is that he avoids reference to all difficulties in the construction of the centering. Ideally he should have drawn a detail of the centering construction in axonometric view parallel to that of the vaulting soffite. Slight though the difficulties may be compared with dressing the groin stones of each masonry course so that the groin does not wave, both the planks and the bricks of the shuttering where they abut to form the groin must be cut to the correct bevel so as to give a straight groin. It is an interesting question whether this was done beforehand or *in situ*. *Key*: (1) Roman Concrete; (2) *Opus testaceum* brick facing; (3) Whole brick voussoirs and through courses; (4) Open frame centering planks; (5) Lost brick centering/shuttering; (V) Intersecting vaults; (G) Groin. After Choisy pl VIII, fig 43.



415. Rome. Basilica of Maxentius, “The Basilica Nova”, 307–312 AD. This monumental building was eventually finished (with adaptions) by Constantine. It forms a striking end piece to accounts of ancient building construction. In essence the grandiose cross-vaulted nave follows in the train of the cross-vaulted halls of the great thermae (e.g. the Baths of Caracalla). However the transverse, barrel vaulted aisles (of unprecedented span) transform the design and construction of the building from a great central hall flanked by secondary apartments into a unified rectangular building of very great compass. It is the last great vaulted rectangular building of the Ancient Western World. *Key*: A. Axonometric view of the basilica showing both the internal and external design (after Durm); B. Perspective view of interior revealing the unified design comprising both cross-vaulted nave and barrel vaulted aisles (after Ward Perkins, fig 102).