GEOLOGICAL EXPLORATION IN MURZUQ BASIN

Editors: M.A. Sola & D. Worsley

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PREFACE

Continuing the successful series of conferences on the geology of Libya sponsored by the National Oil Corporation, the University of Sabha hosted 'The Geological Conference on Exploration in Murzuq Basin' in September 1998. In spite of Sabha's remote position, 700 km south of Tripoli, not alleviated by international sanctions to air travel to and from Libya, over 400 delegates attended the conference. This good response, combined with presentations of almost 40 papers on all aspects of the geology of Murzuq Basin and surrounding areas, resulted in a stimulating meeting. A concluding panel discussion also covered future exploration challenges – both in Murzuq Basin itself and in other frontier exploration areas such as Kufrah Basin. The conference was also a great social and cultural success thanks to the efforts of the staff of NOC and Sabha University. Following the conference there were two highly popular excursions, one to Wadi Tanezzuft and Ghat on the western margins of Murzuq Basin, the other to Wadi ash Shati on the basin's northern flank.

This volume contains 24 of the papers presented at the conference. We have not grouped these contributions into specific themes, believing that readers will thereby better appreciate the breadth of topics covered – from palaeontology and biostratigraphy to geophysics, from ore geology and petroleum exploration to water resources, ranging over the entire geological column from the Precambrian to the Present. The book concludes with a bibliography covering all geological aspects of this challenging area.

Many papers herein naturally relate to ongoing hydrocarbon exploration and production. These contributions give an excellent overview of present status, although not yet fully answering the challenges we still face in order to better understand the ultimate petroleum potential of this vast province. The effects of late Ordovician glaciation on reservoir distribution and – not least – the subsidence, uplift and thermal history of the basin and the consequent timing and history of hydrocarbon generation and migration still have to be satisfactorily defined. We have also noted that many workers still attribute local tectonic events to distant and often irrelevant orogenies in Europe and North America: further exploration in coming years will demand much more precise analyses of the timing, causes and mechanisms of local tectonic processes.

We have tried – not always successfully- to maintain a consistent use of geographical and stratigraphical nomenclature in our editing and have followed the National Atlas of Libya and the geological map series of the Industrial Research Centre. As noted in the closing panel debate at the conference, there is an acute need for the adoption of a unified stratigraphical nomenclature in this area and throughout northern Africa. We thank all authors for willingly revising their contributions to meet our demands, both in scientific, orthographical and other respects. Scientific reviews have involved colleagues from many institutions and countries – we are grateful to all who have taken the time to help ensure the high standard of the resultant papers.

Our special thanks to Ms. Rosalind Waddams for her scientific and technical assistance in the entire editing process and not least in the final production of text and graphics – without her we would not have reached our goals. Editing this volume has been a demanding but enriching task: we hope that the final product will stimulate the next stage of exploration in this challenging .

The Editors
Tripoli, June 2000

ACKNOWLEDGEMENTS

The organising committee are most grateful to the National Oil Corporation and the University of Sabha for sponsoring and co-organising the conference held in Sabha in September 1998. Special thanks also to the National Oil Corporation for its generous support in production of this resultant volume, entitled 'Geological Exploration in Murzuq Basin'.

Our sincere thanks to Mr. Abdullah Salem El-Badri, the then Secretary of the General People's Committee for Energy, Mr. Hamouda Mohammed El-Aswad, the then Secretary of the People's Committee of the National Oil Corporation and Chairman of the Conference and Dr.A. El Faakhry, Secretary of the People's Committee of Sabha University and Co-Chairman of the conference for their continued support to ensure its success. Thanks also to the staff of NOC and Sabha University whose efforts secured the success of this significant international event, and to all members of the various committees for their work from the early planning phases of the conference through to the publication of this volume. The Technical Committee contributed greatly to the success of the conference – as reflected in the number and quality of the papers presented and produced herein. Last but not least, our sincere thanks also to the Excursion Committee for its significant concluding contribution to this successful meeting.

The various companies, research institutions, and universities working in Libya also deserve our thanks for their scientific contributions and logistical support, all of which contributed greatly to the success of the conference – in particular Agip Oil Company, Arabian Gulf Oil Company (AGOCO), Industrial Research Centre (IRC), North African Geophysical Exploration Company (NAGECO), Petroleum Research Centre (PRC), Repsol Oil Operations, Sirte Oil Company, Umm al-Jawaby Oil Service Company, Veba Oil Operations, Waha Oil Company and Zueitina Oil Company. Also to Saga Petroleum Mabruk who generously gave D. Worsley time and facilities to participate in the editing process.

Dr. Mustafa Sola, the Secretary of the Conference and Editor-In-Chief of this volume, has ensured the success of this whole project; our sincere thanks to him and to all his assistants who worked willingly and efficiently in the conference secretariat. We also greatly appreciate the Editorial Committee's efforts to ensure the high scientific standard of this volume.

If Allah wills, this conference and the proceedings presented herein will have contributed to the ongoing exploration of our country and we look forward to further meetings on the sedimentary basins of Libya.

E.A. El Hamyouni
Member of the People's Committee and
General Manager, Joint Ventures Division
National Oil Corporation

GLOSSARY OF ARABIC AND LOCAL NAMES

abu	father of
abyar	wells
aqirah/t	mudflat
awlad	sons, family
ayn, awaynat	spring, springs
bab	door, gate, pass
bahr	sea
bani	children or descendants of
bin	son of
bir, bi'r,	well
birkah/t	temporary pond
buhayrah/t	small cultivated area(s), lake(s)
dalou	bucket used in old wells
darari	children
jinn, jenoun	devil, devils
dur	hills around or beside a plain
ehi	peak, rocky hill
eilat	family of
emi	mountain, massif
fesh-fash	soft, loose soil
fonduq	yard, hotel/hostel
ghareb	west
gilf	escarpment
halaq	small wadi
hamadah/t	rocky desert plateau
hasy	shallow well, waterhole
ibn	son of
idhan	sand sea
ilwah/t	hill
irq, erg	sand sea
jabal	mountain
jaemmah	mosque
kabir	big, large, great
kaf	cliff, ridge, spur
karkur	wadi, valley
kharrubah/t	carob tree
kharmah/t, kharaymah/t	pass, passes
maghreb	NW Africa in general
marabat	tomb, shrine, holy man
marsa	small port, cove
minqar	point, ridge, spur
nahr	river
nakhla	palm tree
naqazzah/t	terrace
oued	wadi
qabilah	tribal area
qabr	tomb
qararah/t	low, flat-topped hill(s)
qaryah/t	village, villages
qasr	fort, palace
ramlah/t	dunes, dune area
ra's	promontory, spur
sabkhah/t	arid evaporitic flat
sahel	shore, coastal area
sahra	desert
saniyah/t	small farm
sarir	gravel plain
sawani	small farms
shati, shatt	beach, shore
suq	market
tadrart	mountain, massif
tanezzezzeft	alum, black dye
tarso	high plateau
tassili	barren plateau
tawil/ah/t	long
tmad	shallow well, waterhole
wadi	valley, watercourse
waha	oasis
washkah/t	palm scrub/bush
waw	crater
zahr	escarpment, plateau
zawiyah/t	religious education centre

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Geological Exploration in Murzuq Basin
M.A. Sola and D. Worsley, editors.

CHAPTER 1

Groundwater Salinity Variations in the Cambro-Ordovician Aquifer of Eastern Jabal al Hasawnah, the Great Man-made River Project, Libya

A. BINSARITI and FAWZI S. SAEED[1]

ABSTRACT

In December 1994 an exploratory drilling programme was initiated by the Great Man-made River Authority (GMRA) to investigate groundwater quality deterioration in the vicinity of exploration well No. 29 which taps the Cambro-Ordovician aquifer of northeastern Jabal al Hasawnah, a region currently being developed as a groundwater resource of the Great Man-made River Project. In this region the main Cambro-Ordovician aquifer is overlain by a shallow carbonate aquifer of Paleocene/late Cretaceous age – herein referred to as the Zimam aquifer, with a basal aquitard composed predominantly of marly limestone, clay and shale.

The present investigation reveals that downward vertical leakage from the saline Zimam aquifer to the underlying Cambro-Ordovician sandstone aquifer can occur through fracture zones in similar conditions to those now confirmed to exist in the vicinity of exploration well 29A/94 and possibly in the locality of production well No. 125 on line D5 of the northeastern Jabal al Hasawnah Wellfield. However, leakage of saline water from the Zimam aquifer into the Cambro-Ordovician aquifer is not evident in the exploration wells drilled at three locations north and northeast of well 29A/94.

Water quality data from the newly drilled production wells confirm the existence of increased salinity at the southern extremities of well production lines A1, B1, C3 and C5. This increased salinity is attributed to groundwater flow of lower quality waters emanating from basinal rim zones (platform limestone) that are known geologically to be very susceptible to fracturing, a feature which facilitates vertical downward flow from the overlying Zimam aquifer. Elsewhere in the Cambro-Ordovician aquifer vertical leakage is less significant as the Zimam basal aquitard is sufficiently thick.

INTRODUCTION

In December 1994 an exploratory drilling programme was initiated by The Great Man-made River Authority (GMRA) to investigate ground-water quality deterioration encountered in the vicinity of exploration well 29/89 tapping the Cambro-Ordovician aquifer of northeastern Jabal al Hasawnah, a region currently developed for the extraction of 2.5 MCM/day of water to be conveyed to the Jeffara Plain (Fig. 1). Besides borehole 29A/89, three additional exploration

[1] Great Man-made River Project, P.O. Box 641-9468, Benghazi, Libya. Fax: 061 222830-8899404.

wells were drilled as shown in Fig. 2 (denoted as RE-2DA, RE-4 and RE-3D). Exploration well 29A/94 was drilled 50 m north of exploration well 29/89 in order to check out any possible faulty completion of that well.

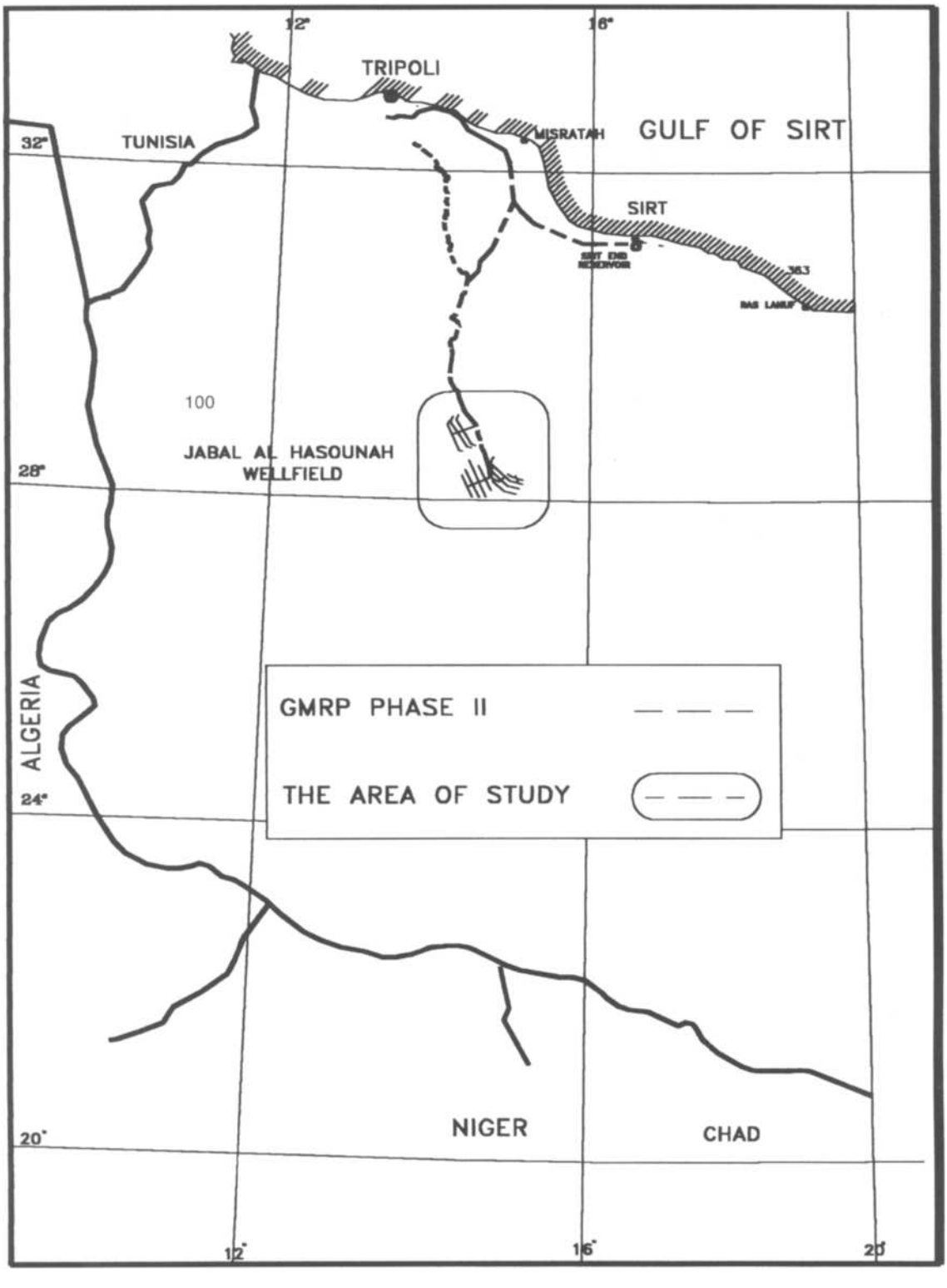

Figure 1. Regional overview showing study area.

Objective of this Study

The objective of this study is to assess the salinity distribution extent and its origin in the wellfield areas, using the results obtained in 1994 exploration activities combined with the water quality data obtained from the drilling of 104 production wells in the northeastern Jabal al Hasawnah Wellfield.

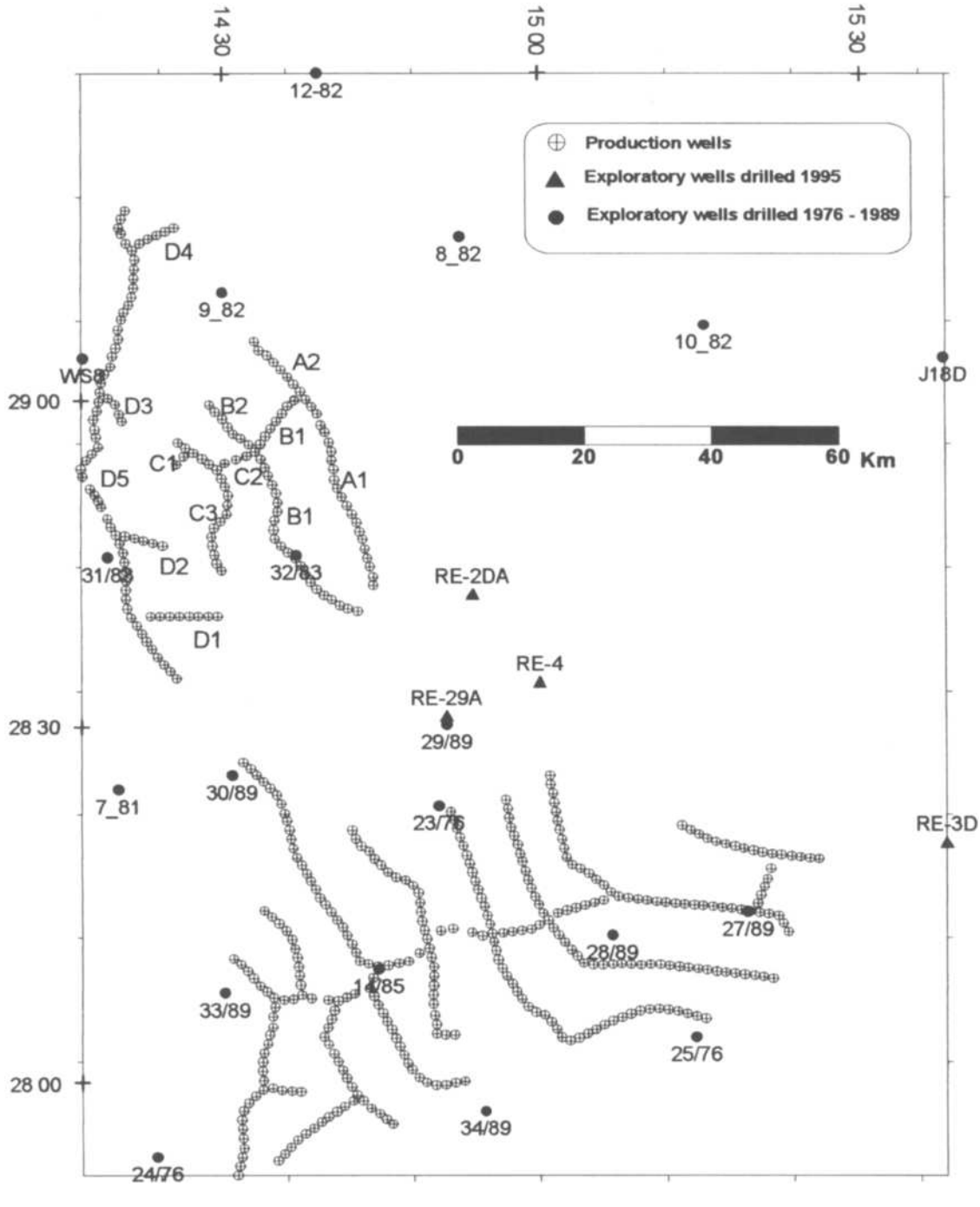

Figure 2. Location map of the eastern and northeastern Jabal al Hasawnah wellfields.

THE GREAT MAN-MADE RIVER PROJECT (PHASE II)

Location

Phase II is known locally as the Western Jamahiriya System (WJS). The wellfields are situated to the east and northeast of Jabal al Hasawnah (a region with no aquifer zone, Fig. 1). The wellfield layout is illustrated in Fig. 2. This layout consists of two wellfields; the northeastern field is bounded by longitudes 14°13′00″ and 14°48′00″ E and by latitudes 29°42′00″ and 29°16′00″ N. This wellfield is almost entirely situated in the northern confined zone and is predetermined to provide a production rate of about 0.5 MCM/day. The second wellfield is situated to the east of Jabal al Hasawnah and is predetermined to provide the remaining rate of 2.0 MCM/day.

The wellfield configurations were optimised to minimise the effects of waterlevel drawdown in the wellfields and in surrounding agricultural development projects already in the region. Wellfield discharge was initially planned at a rate of 2.0 MCM/day and subsequently increased to 2.5 MCM/day. Individual well discharges were predetermined as 45 l/s and 56 l/s, and well spacing of 1500 m was assumed in the optimising scheme. Predicted model heads after 50 years of abstraction were judged acceptable.

GEOLOGY

The dominant feature of the study area is the Gargaf Uplift, a huge broad anticlinal structure of Caledonian-Hercynian origin with an E-W trending axis (Fürst and Klitzsch, 1963). This structure constitutes the northern boundary of the Murzuq Basin, which is filled by Palaeozoic and Mesozoic sediments of marine and continental origin. The Gargaf Uplift consists essentially of Cambro-Ordovician rocks with occasional minor basement exposures and Tertiary volcanic flows or plugs. Upper Cretaceous and Paleocene rocks of the Zimam Formation unconformably overlie the northern flank of the Gargaf Uplift. The geological succession relevant to eastern and northeastern Jabal al Hasawnah is given in Table 1.

The Zimam Formation

This formation includes the Lower Tar Member (Maastrichtian), which consists of claystone, marl and gypsum with intercalations of sandy calcarenite. The Lower Tar Member is overlain by the Upper Tar Member (Paleocene), which consists of sandstones with a unit of conglomerate

Table 1. Geological succession in the Gargaf Uplift region

Age	Aquifer	Lithology	Thickness (m)
Recent/Pleistocene	—	Sand dunes – sabkhas – basalt	—
Paleocene/late Cretaceous	Zimam	Clay, limestone, marl, dolomite and gypsum	0–250
Ordovician-Cambrian	Palaeozoic	Sandstone and quartzite alternating with silts and shales	300–800
Precambrian	—	Metamorphic and granitic rocks	—

and sandy clay. The overlying Had Member (also of Paleocene age) consists of dolomites and interbedded calcilutites forming the Zimam Aquifer, whose basal aquitard is formed by the Lower Tar Member.

The Cambro-Ordovician (Hasawnah Formation)

This formation consists of quartzitic sandstone. Devonian sandstones and the intervening Silurian shaly aquitard have both been eroded away from eastern and northeastern Jabal al Hasawnah, leaving only the Cambro-Ordovician as a single sandstone aquifer. The lithological range is from coarse to fine-grained sandstones with minor siltstone interbeds. The sandstones are variably poorly to well cemented with quartz overgrowths and there are occasional friable fine-grained sandstone beds.

Hydrogeologically, it is important to note the presence of a continuous 50 to 75 m thick quartzitic unit in the uppermost Cambro-Ordovician succession. This horizon is believed to result from long-lasting pre-Devonian weathering (Hea, 1971; Dubay, 1980) and is also associated with the development of confined aquifer conditions in the Cambro-Ordovician aquifer. Such conditions have also been observed in the area of Wadi Tanezzuft on the southwestern margin of the Murzuq Basin (Dubay, 1980).

General Tectonic Framework

The Cambro-Ordovician rocks were structurally disturbed by the Caledonian orogeny, which produced a significant NNW-SSW discontinuity trend and associated small-scale faults. Tectonic movements in the late Palaeozoic and through the Mesozoic resulted in an ENE-WSW discontinuity trend comprising the Gargaf Uplift with its associated faults. In this study, special consideration is given to the system of faults developed on the basin margins as a result of differential basinal subsidence that occurred subsequent to the deposition of the Upper Cretaceous and Paleocene sediments.

HYDROGEOLOGY

The water quality distribution pattern in the study area is dominated by the existing geological structure, which allows hydraulic interconnection between aquifers with variable water quality.

The Cambro-Ordovician Aquifer

This is considered to be the main aquifer in the Gargaf region and consists of fractured sandstone with intergranular porosity (average core porosity of 20%). The aquifer is developed over a large area and shows a transmissivity ranging from 1500 to 2000 m^2/day. The field storativity ranges from 2.2×10^{-5} to 2.0×10^{-3} in the confined areas while in the unconfined areas it may be as high as 6.4×10^{-2}. Because of extensive local erosion of the Cambro-Ordovician succession, combined with basinal rim (platform) tectonic effects, hydraulic connections are developed with other aquifers in the upper sequence in areas north of the Gargaf Uplift.

The Zimam Aquifer

Particular reference is made in this study to the Paleocene-Cretaceous Zimam aquifer, which is considered to be in a perched position in relationship to the main Cambro-Ordovician

groundwater body since the aquifer has poor hydraulic properties as well as high salinity. Figure 3 is an isopach map of the Zimam Formation, showing that the formation and its basal aquitard wedge out to the southwest. The following structural elements mapped by Jurak (1978) in the study area are relevant to this work:

Exploration well 29/89 (14°51′00″ E, 28°30′05″ N) is located on the intersection of two concealed faults as shown in Fig. 3. There are several faults in the vicinity of the production well D5–125 and D5–126 in the northwestern part of Fig. 3.

The presence of these faults, combined with information on water quality variations obtained during well testing, confirms the establishment of hydraulic connections between the Zimam and Cambro-Ordovician aquifers.

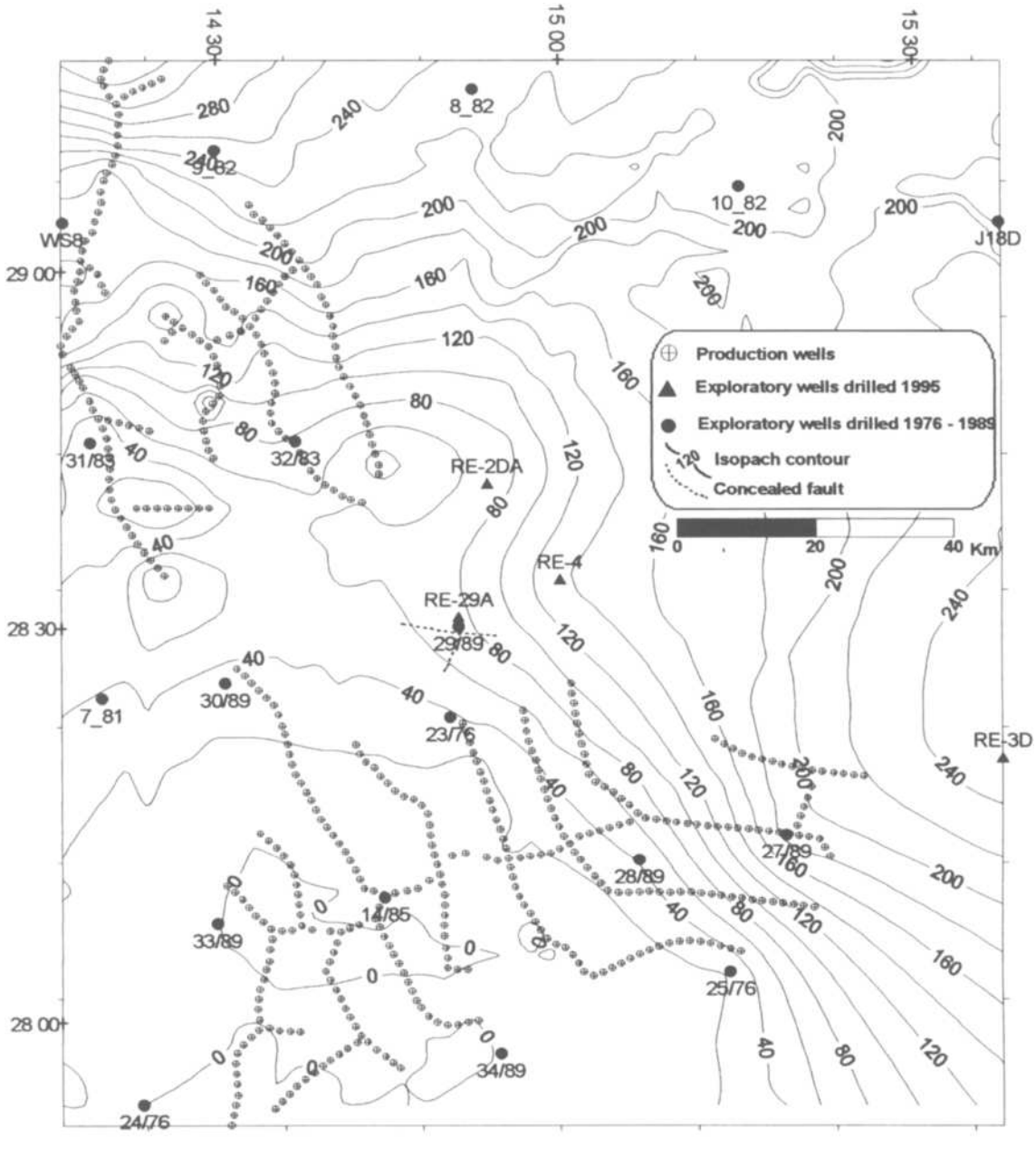

Figure 3. Isopach map of the Zimam Formation (metres).

Idrotecnico (1982), in their hydrogeological modelling study of Wadi ash Shati – Al Jufrah and Jabal al Hasawnah, assumed a NW-SE trending fault extending from the southeast, located between exploration well 23/76 and well 29/89 to the northwest, passing approximately 6 km east of well WS-8. The fault was assumed to justify a reduction of transmissivity necessary to increase the local hydraulic gradient resulting from model calculations. It was not possible otherwise to reproduce the steady state piezometric configuration between the Murzuq Basin and northern Fezzan. Later, in 1983 the two exploratory wells 31/83 and 32/83 were drilled to ascertain the presence of this assumed fault and the low transmissivity zone. This exploratory drilling did not confirm the presence of this fault. Subsequent modelling studies of the Western Jamahiriya Hydrogeological System (WJS) have modified the original Idrotecnico (1982) geological concepts, including the elimination of the assumed Gargaf fault.

Groundwater Heads

The Cambro-Ordovician forms an extensive regional aquifer, which is assumed to have continuity from the Murzuq Basin in the south to the Al Hamada Al Hamra Basin in the north. Flow direction from the Murzuq Basin is mainly to the north and northeast.

The steady state piezometry in the east and northeast of Jabal al Hasawnah was measured in exploration wells and piezometers prior to the start of any important abstractions. The quasi-steady state hydraulic head distribution is illustrated in Fig. 4. This figure indicates a relatively flat hydraulic gradient of 1 to 5000 in the south (north of Wadi ash Shati), which can be interpreted as an indication of relatively high aquifer transmissivity. Northwards, the hydraulic gradient shows a uniform and steeper pattern (2 to 5000). Regional groundwater flow direction as indicated by the piezometry is mostly to the northeast, where the aquifer discharges into the large coastal sabkhas of Tawarga. However, some of the flow north of Jabal al Hasawnah is diverted to the Kiklah and Upper Cretaceous aquifers higher in the stratigraphic succession.

RESULTS OF EXPLORATION ACTIVITIES

Exploration Well 29A/94

This borehole, with its associated shallow and deep piezometers, confirms the high salinity of the Cambro-Ordovician aquifer at this location (TDS = 2292) and the relatively low specific capacity value of 1.47 l/sec/m. In addition, a single-stage pumping test proved conclusively that the salinity encountered at this location is entirely due to vertical leakage from the intensively fractured Zimam aquifer. The drawdown in the shallow piezometer measured a total of 0.5 m and the specific electrical conductivity of the pumped Zimam aquifer amounts to 7352 μs/om, corresponding to a value of specific electrical conductivity of 3850 μs/om at 28°C of the pumped water of the Cambro-Ordovician aquifer.

A pumping test performed on piezometer 29ZA gave a specific yield estimate of 0.044 l/sec/m, indicative of low transmissive characteristics of the Zimam aquifer. In this location, the Zimam basal aquitard amounts to 34 m of clay and shales.

Exploration Well 2DA

This well, located about 25 km northeast of well 29A/94, has a total depth of 480 m and a Zimam Formation thickness of 72 m. The total dissolved solids in the Cambro-Ordovician

aquifer measure 649 mg/l, indicating virtually no leakage from the Zimam aquifer. An aquifer transmissivity estimate of 357 m^2/day was obtained from a pumping test performed on well

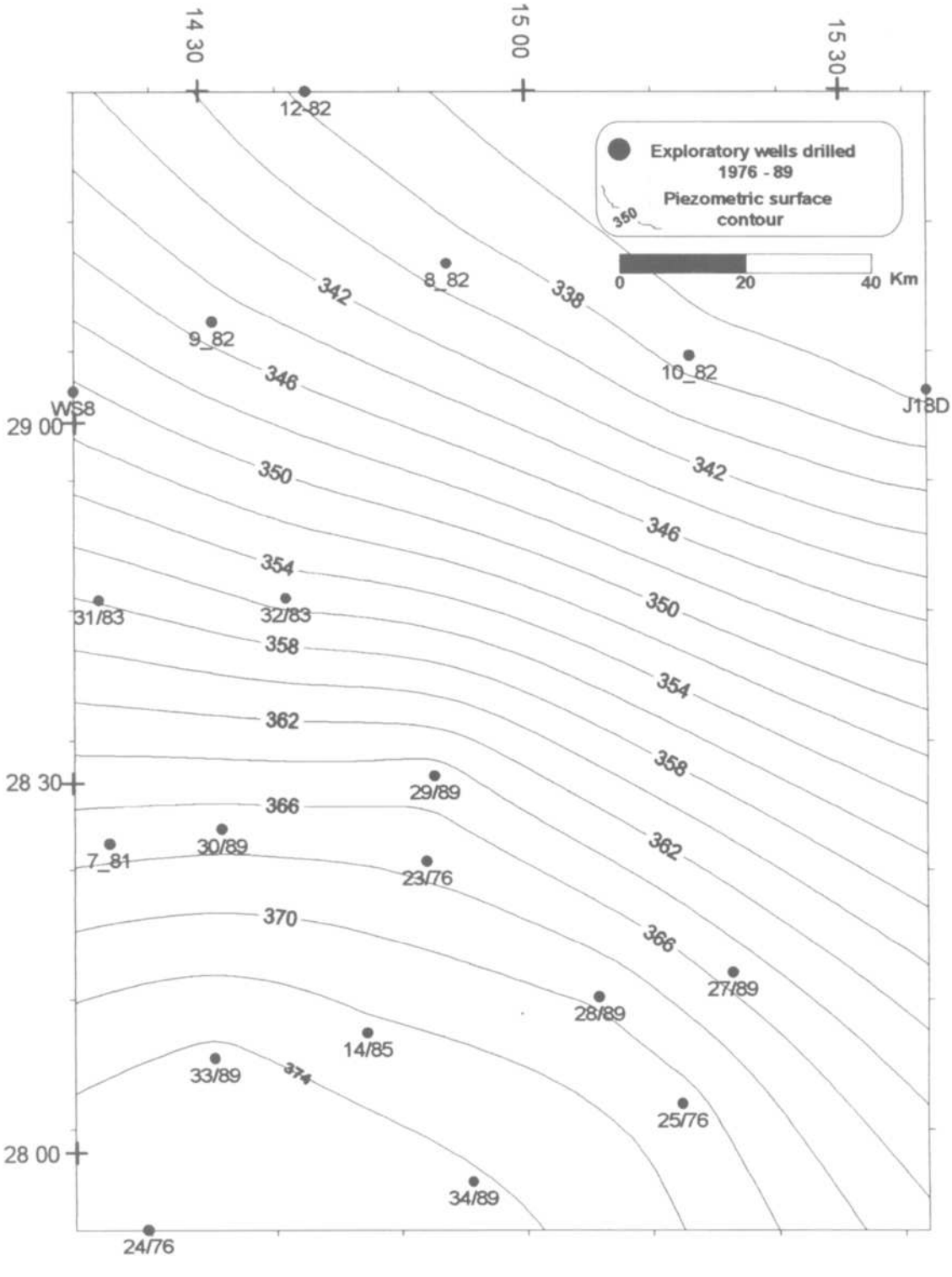

Figure 4. Quasi-steady state hydraulic head distribution of the Cambro-Ordovician aquifer in the region of Jabal al Hasawnah (contours in metres).

2DA; this value is considered to be low when compared with the Cambro-Ordovician regional transmissivity range. Piezometer 2S is a neighbouring shallow piezometer to well 2DA, with a total depth of 64.47 m completed in the Zimam aquifer with total dissolved solids of 4480 mg/l (7000 μs/om at 20°C). This value is comparable with the corresponding value obtained from the shallow exploration well 29AZ/94.

Exploration Well 4

This well was drilled to a total depth 435.2 m (b.g.l.). Two lost circulation zones were encountered during drilling of this well, the first in the interval 40 to 142 m and the second from 310 to 316 m (b.g.l.). Chemical analysis of pumped water yielded total dissolved solids of 940 mg/l and aquifer transmissivity of about 1125 m^2/day.

Exploration Well (3D)

This well was drilled to a total depth of 500 m (b.g.l.). The Zimam aquifer is 34 m thick and the Zimam aquitard is relatively thick, amounting to 225 m. Appreciable vertical leakage from the Zimam aquifer is not anticipated at this location due to the thick confining layer combined with the lack of fracturing.

Summary

Table 2 summarises the results of the 1994 exploratory activities. The final results of these activities indicate the following:

- The 18 to 34 m thick Zimam aquifer consists of limestone and marly to dolomitic limestone; this saline aquifer has very low yield potential,
- The Zimam Formation basal aquitard ranges from 27 m thick at well 29A/9A to a maximum of 225 m at well 3D/94. The occurrence of substantial vertical leakage through this aquitard depends both on its thickness – the thicker the aquitard the less probable that significant leakage may occur – and also on the presence of fracturing which augments leakage potential.
- The salinity of the Zimam aquifer reaches a maximum value of 4480 mg/l of TDS as measured in the shallow piezometer 29ZA/94. This saline aquifer has insignificant yield potential even in locations where leakage is proved to be perceptible as in the case of exploration well 29ZA/94. This indicates its limitation in providing recharge by leakage and thus its future effect on water quality of the Cambro-Ordovician aquifer can be considered as somewhat limited.

Accurate ground elevations of these exploration wells are not available to assess groundwater flow characteristics of the Zimam aquifer.

DISTRIBUTION OF SALINITY IN THE CAMBRO-ORDOVICIAN AQUIFER

Figure 5 depicts the distribution of total dissolved solids in the groundwater of the eastern and northeastern Jabal al Hasawnah wellfields. The data used in the analysis include all hydrochemical data derived from existing exploration wells (a total of 22 wells with associated piezometers) and 104 recently drilled production wells on production lines A1, B1, C1, C2, C3 and D5 as previously indicated in Fig. 2.

Table 2. Summary of results of exploratory well drilling in 1994, northeastern Jabal al Hasawnah

Well No.	Coordinates	Total Depth (m)	Formation	Zimam Thickness (m)	Zimam Aquitard Thickness (m)	Electrical Cond. μ/s/om	TDS mg/l	SW Level (m) (b.g.l.)
RE-2DA	Lat. 28°44′00″ N Long. 15°00′00″ E	4.80	C-O	15	51	1290	649	190.5
RE-25	Lat. 28°44′00″ N Long. 15°00′00″ E	66.47	Zimam	10	48	7000	4480	-
RE-4	—	435.2	C-O	104	—	1540	940	198.02
RE-3D	Lat. 28°25′00″ N Long. 15°36′00″ E	500.00	C-O	34	225	—	801	169.85
RE-29A	Lat. 28°30′00″ N Long. 14°50′00″ E	445.00	C-O	44	27	3850	2293	152.22
RE-29ZA	Lat. 28°30′27″ N Long. 14°50′57″ E	68.00	Zimam	18	45	11060	7000	31.07

Figure 5 suggests that the distribution of salinity in the areas of the wellfields is dominated by three anomalies. The first major anomaly is centred on well 29A/94. The second anomaly is situated at the southern end of production line D1, 41 km northwest of well 29A/94 and includes

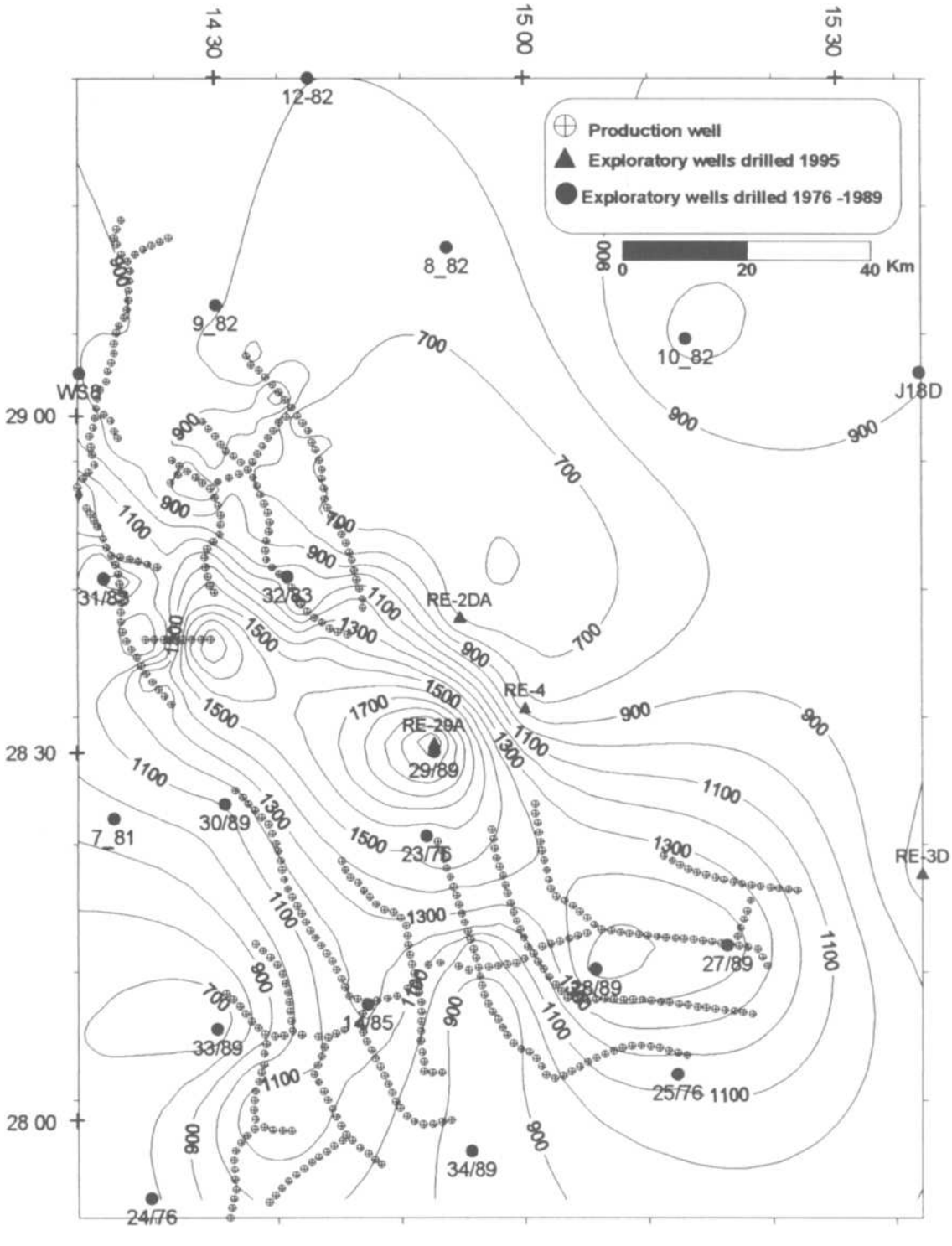

Figure 5. Distribution of Total Dissolved Solids (mg/l) in the Cambro-Ordovician aquifer in the region of Jabal al Hasawnah.

the interval from well 150 to 153 inclusive. The third anomaly is located on line D5 (wells 125 and 126) where the measured TDS range from 1632 to 1983 mg/l.

Apparently, the locations of these anomalies fall on a perimeter coinciding with the southern rim of the Al-Hamada Al-Hamra Basin. The rim development of platform limestones and dolomites is usually associated with widespread rock fracturing. For these reasons, the basin rim represents a more favourable environment for the aquifers than its centre. The occurrence of minor tension faults on the flanks of sedimentary basins is common in response to differential subsidence. This phenomenon is well illustrated by the presence of swarms of quartzitic ridges on the northeastern flank of the Kufra Basin (Schoutte, 1976).

Salinity Profiles

Figure 6 shows profiles of total dissolved solids in mg/l along production lines A1, B1, C3 and D5. Salinity variations along these lines can be interpreted as follows:

Line A1 shows a gradual increase in total dissolved solids starting at well 26 (957 mg/l) and increasing steadily to a value of 1243 mg/l at well 30 at the southern end of the line. This increase in salinity is interpreted as a manifestation of groundwater flow from the area of well 29A/94.

Similar conditions are also noted at the southern end of the wellfield production line B1, where an increased salinity gradient can be demonstrated in the interval limited by well 55 and well 60.

Line D5 shows a more complex salinity profile than the previous profiles. The northern third of the profile is mainly dominated by the relatively high salinity centred at wells 125 and 126. The southern third of the profile is mainly influenced by salinities emanating from the distal end of production line D1.

GROUNDWATER HYDROCHEMISTRY

The hydrochemical characteristics of this Cambro-Ordovician's aquifer can be better understood if the chemical quality of the water is studied on a regional scale.

The chemical quality of the Cambro-Ordovician-Devonian aquifer of Wadi ash Shati is uniform both vertically and horizontally and Dubay (1980) and Idrotecnico confirmed that there are no noticeable differences in chemical composition between water in the Devonian and the Cambro-Ordovician sandstone aquifer. This reflects the existence of direct contact between the two aquifers with no intervening aquitard.

Figure 7 is a Schoeller diagram of the average concentrations of anions and cations obtained from chemical analyses of water samples from Wadi ash Shati and the NEJAH wellfields. The diagram shows how the chemical composition of the water of the Palaeozoic aquifers in Wadi ash Shati changes its chemical composition in the course of its migration northward in response to a change in the geological environment.

Figure 8 is a Piper diagram showing the relative chemical compositions of groundwater of the Cambro-Ordovician of Wadi ash Shati and the NEJAH wellfields; this figure defines the pathway of evolution of water chemistry as groundwater migrates from the region of Wadi ash Shati (TDS = 515 mg/l) to the NEJAH region with an average TDS of 912 mg/l. The piper diagram depicts a gradual change in dissolved chemical constituents. According to the concept of hydrochemical facies suggested by Back (1961), the facies change from the cation-anion sets

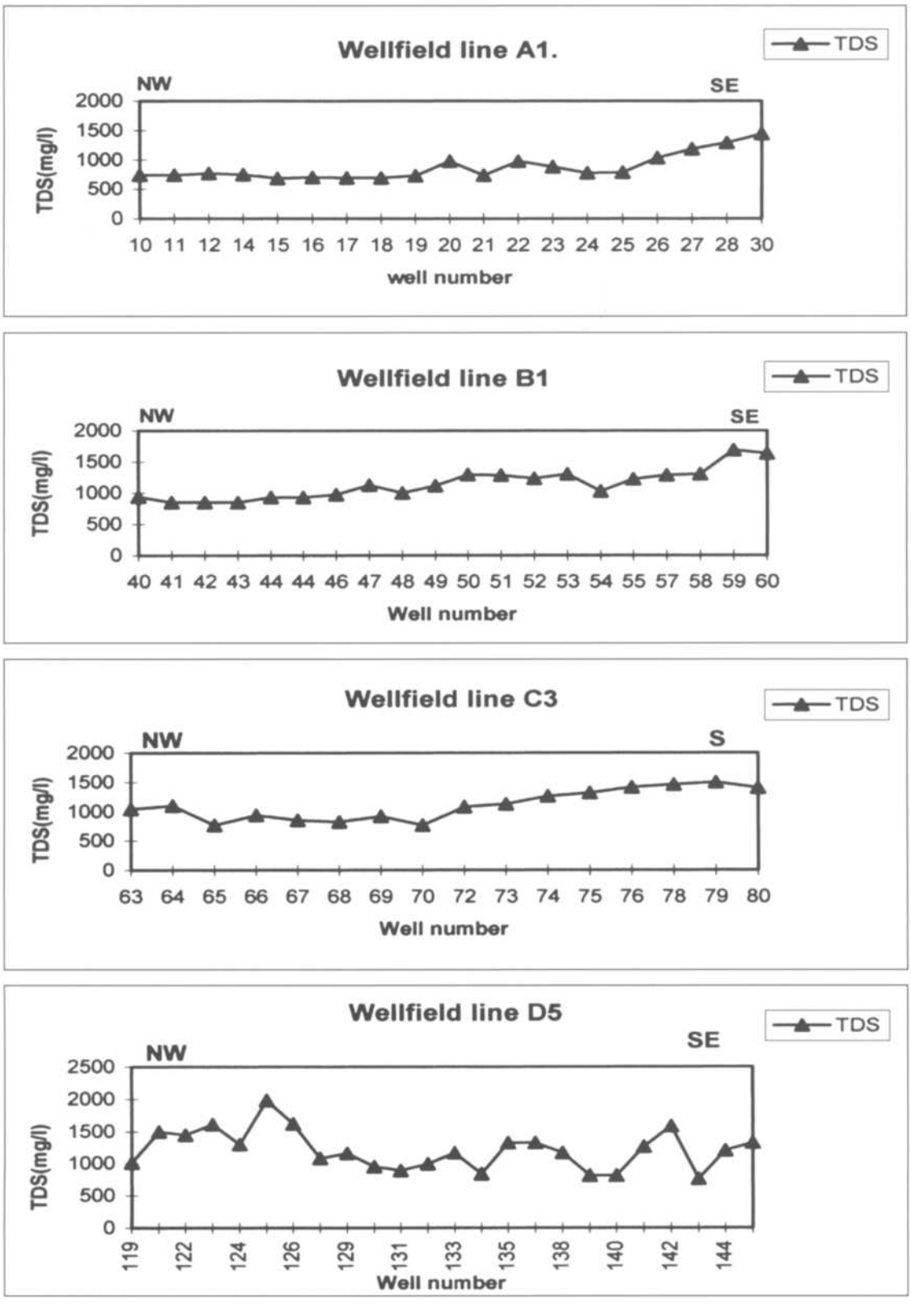

Figure 6. Profiles of total dissolved solids (mg/l) along production lines A1, B1, C3 and D5.

(sodium–calcium–magnesium) – (chloride–sulphate–bicarbonate) at Wadi ash Shati to (calcium–sodium–magnesium) and (chloride–sulphate–bicarbonate).

The geochemical process responsible for this facies evolution is the dissolution of carbonate rocks in the water of the Zimam aquifer and the subsequent leakage of the saline water into the Cambro-Ordovician aquifer as it migrates northwards.

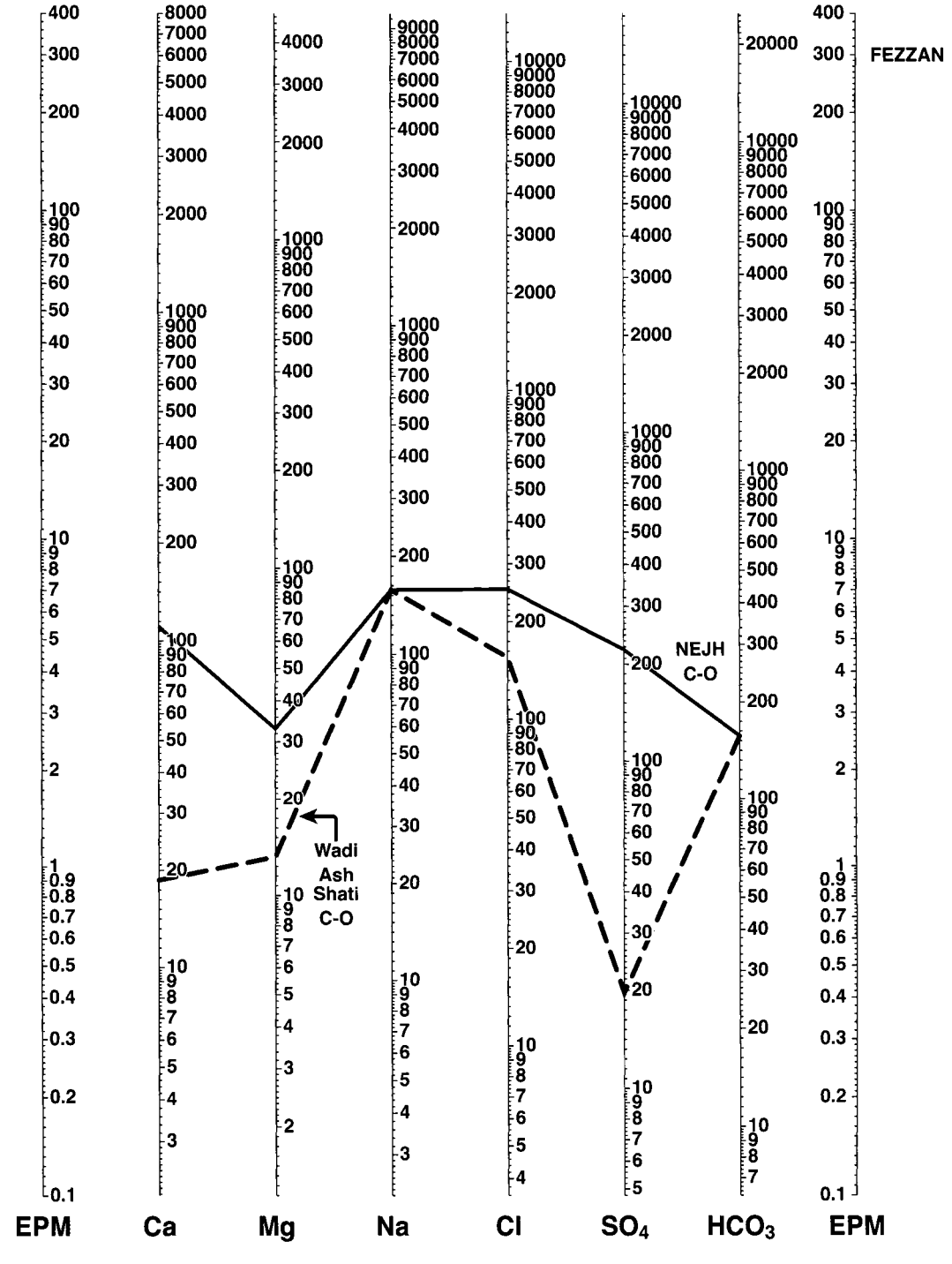

Figure 7. Schoeller diagram comparing groundwater from Wadi ash Shati and the NEJAH wellfields.

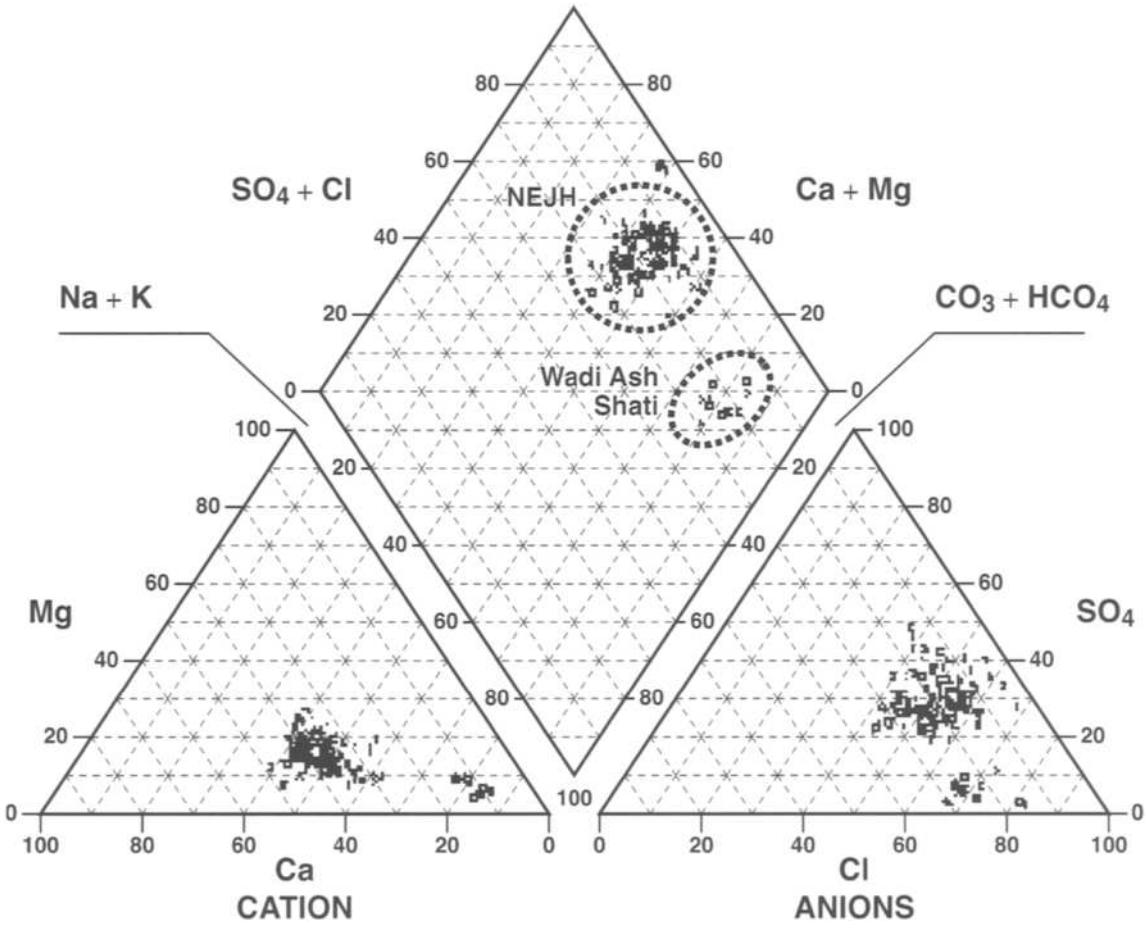

Figure 8. Piper diagram comparing groundwater from Wadi ash Shati and the NEJAH wellfields.

CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation indicate that the geological environment prevailing in this region dominates groundwater salinity in the region of eastern and northeastern Jabal al Hasawnah.

The rim (platform) limestone and dolomite of the Zimam aquifer are characterised by the occurrence of fractures allowing vertical hydraulic connection whereby saline water of the Zimam aquifer leaks down into the fresh water of Cambro-Ordovician aquifer.

The total dissolved solids content of the water of the Palaeozoic aquifer of Wadi ash Shati areas is approximately doubled as it migrates northwards.

The Zimam aquifer is considered as a perched aquifer of low yield potential. In addition, the saline centres are limited to the basinal rim, and thus their effect is localized.

It is recommended that groundwater chemical quality should be monitored on a regular basis at selected piezometric locations covering the rim areas of the basin, so as to maintain optimal management policy for the groundwater resource development.

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CHAPTER 2

Magnetostratigraphy as a Potential Tool for Correlation in the Murzuq Basin Illustrated by an Example from the Triassic Snorre Reservoir in the Northern North Sea

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ABSTRACT

Magnetostratigraphy is an important tool for the chronostratigraphical subdivision and dating of sedimentary sequences that are otherwise difficult to correlate and date because of the lack of correlative biostratigraphical events. The precondition for a successful magnetostratigraphical analysis is the preservation of the primary magnetic minerals. These are commonly destroyed during deep burial if certain geochemical conditions prevail. The important factors are particularly: (1) the availability and reactivity of organic matter for sulphate reduction and the concentration of sulphide, (2) the concentration of iron minerals, (3) the temperature and pressure conditions and (4) Eh and pH conditions. The continental nature of many formations in the Murzuq Basin and the relatively limited burial depth indicates that several of these units may be suitable for magnetostratigraphic analysis. These are for example Palaeozoic formations such as the Mamuniyat Formation, parts of the Akakus Formation, the Tadrart Formation, and the Marar and Assedjefar formations. Also the Triassic to Cretaceous continental clastic deposits in the central parts of the basin should be eminently suitable for magnetostratigraphic analysis.

This chapter presents an example of the use of magnetostratigraphy to establish a chronostratigraphical framework for continental redbed sediments. The studied succession is the Upper Triassic Lunde Formation in the Snorre Oil Field in the northern North Sea area. Cores from 4 wells through a 400 m thick red bed sequence were analysed. The study resulted in a considerable improvement of the stratigraphic resolution as 13 normal and reverse polarity zones could be established and correlated to the polarity zones E13 to E19 of the established polarity time scale for the Newark Basin in northeastern USA. This correlation implies that the deposition occurred from the early Norian to early Rhaetian, with an average accumulation rate of 0.04 mm/a.

INTRODUCTION

Upper Triassic sediments in the North Sea area comprise thick sequences of continental red beds, which were deposited in fault-bounded basins during the initial stages of rifting of the

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Pangea supercontinent. Biostratigraphical data is sparse and restricted to rare occurrences of palynomorphs. A stratigraphic framework for these sediments has therefore been lacking. The work presented here was carried out with the purpose of establishing such a framework using magnetostratigraphy.

The palaeomagnetic study was carried out on four well cores from the Snorre oil field in the northern North Sea area (Fig. 1). The study revealed the presence of 13 normal and reverse polarity zones in the 400 m thick red bed sequence in the Lunde Formation of late Triassic age. This provides a chronostratigraphic framework within which sequence stratigraphic modelling could be carried out.

SEDIMENTOLOGY

The Triassic sediments were deposited in an intracratonic basin, which originated as a rift in the northern North Sea area during an episode of active crustal stretching (Nystuen et al., 1989). During most of the Triassic, the rifting was followed by subsidence and the sediments deposited in this continental environment contained no significant primary organic matter. The rivers flowed to a coastline that is believed to have been located a hundred kilometres to the north in the Møre Basin area or in the Sogn Graben to the east (Nystuen et al., 1989).

The sediments may be assigned to the following three lithofacies: brown to greyish red mudstone, greyish to greenish mudstones and grey to very light grey sandstones. The red mudstone lithofacies includes components with grain sizes varying from clay to coarse silt and fine sand which were deposited in interchannel areas as flood plain and levee deposits. The red colour is due to early diagenetic hematite pigmentation. The greyish to greenish mudstones were deposited on alluvial plains as overbank sediments. The bleached colour is due to diagenetic dissolution of hematite. The light grey sandstones are laminated and sporadically cross-bedded. These sandstones were deposited in fluvial channels. Numerous thin (< 10 cm) calcrete horizons occur within all three lithofacies. They provide evidence of soil formation and are important for the determination of sample intervals for the palaeomagnetic study.

MAGNETIC ANALYSIS OF THE SAMPLES

The samples were primarily taken from the red mudstone facies because most of the time interval displayed by this succession is represented in these sediments due to their generally low sedimentation rates. In addition, this facies has the best magnetic properties (Fig. 2). The greyish mudstones were also sampled, while fewer samples were taken from the grey sandstones as they are assumed to have been deposited relatively quickly.

The magnetic polarities of the samples were determined from principal component analysis of the demagnetisation data. The demagnetisation was carried out by heating the samples in an oven shielded from the ambient magnetic field. The magnetic measurements were carried out on a high-sensitivity magnetometer with a noise level of less than 1% of the intensity before demagnetisation. The final stratigraphic results were based on data from the mudstones. Thin section analyses were carried out to determine the minerals carrying the magnetic remanence and to investigate the sediments for diagenetic changes that could have affected the magnetisation. Examples of demagnetisation data are shown in Fig. 2.

The red mudstones have high NRM (natural remanent magnetisation) intensity and contain two magnetic components. One relatively strong secondary component is removed at low demagnetisation temperature while a weaker, characteristic remanent magnetisation, ChRM, remains stable up to almost 700°C. The unblocking temperature of approximately 700°C indicates that the ChRM is carried by hematite. The grey mudstones have a lower NRM-

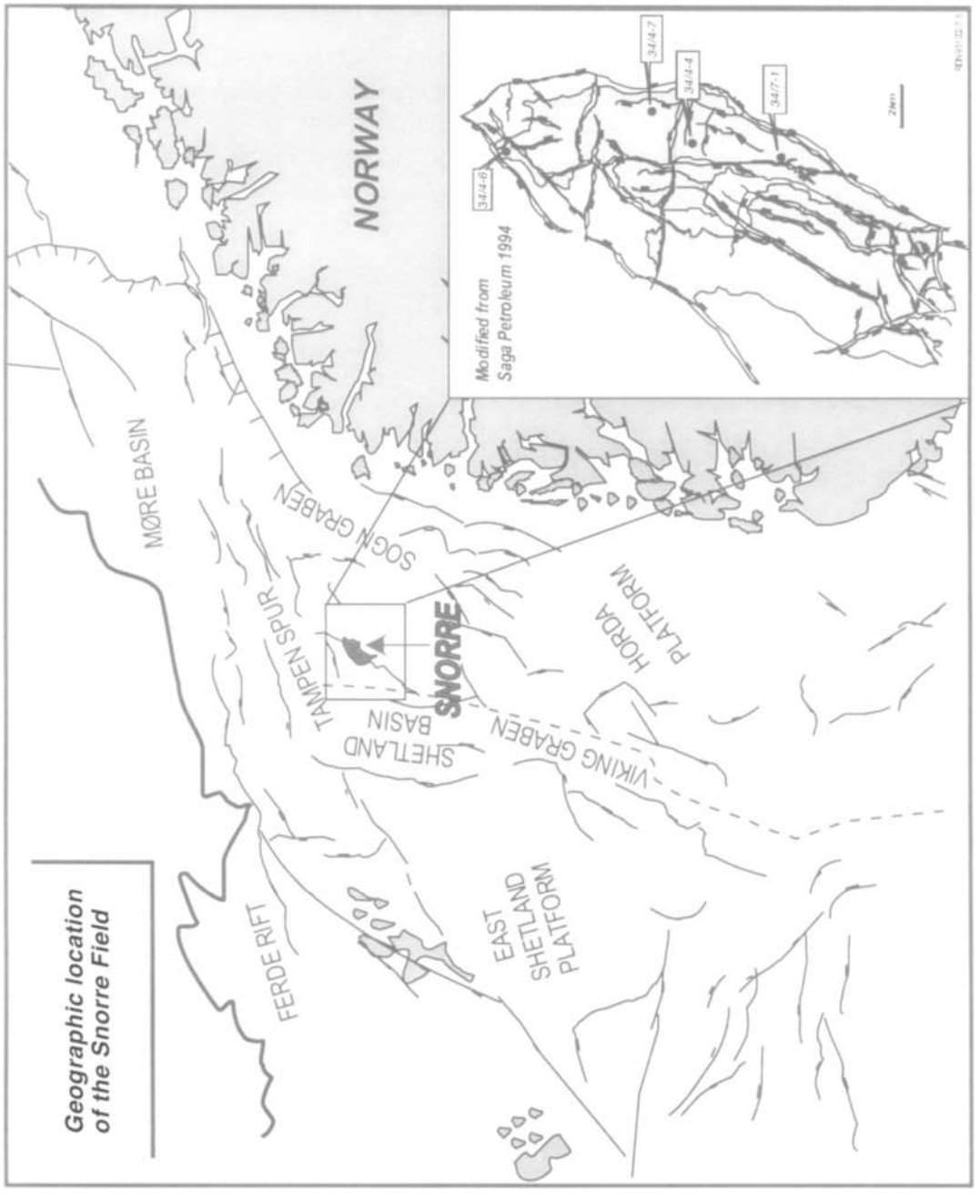


Figure 1. Geographical location of the Snorre oil field and the studied wells, modified from Diesen et al. (1995).

intensity. Most of the magnetisation is removed at demagnetisation temperatures below 300°C. In some samples a weak magnetisation persists to higher demagnetisation temperatures. The light grey sandstones have very low NRM-intensity, the secondary magnetisation dominates and the palaeomagnetic properties are poor.

MAGNETOSTRATIGRAPHY AS A CORRELATION AND DATING TOOL

The good magnetic properties of the red beds in the Snorre reservoir make magnetostratigraphy a promising tool for the establishment of a high-resolution chronostratigraphic framework for these sediments. Magnetostratigraphy is based on the fact that the geomagnetic field has repeatedly reversed its polarity in geological time and that the geomagnetic field direction is

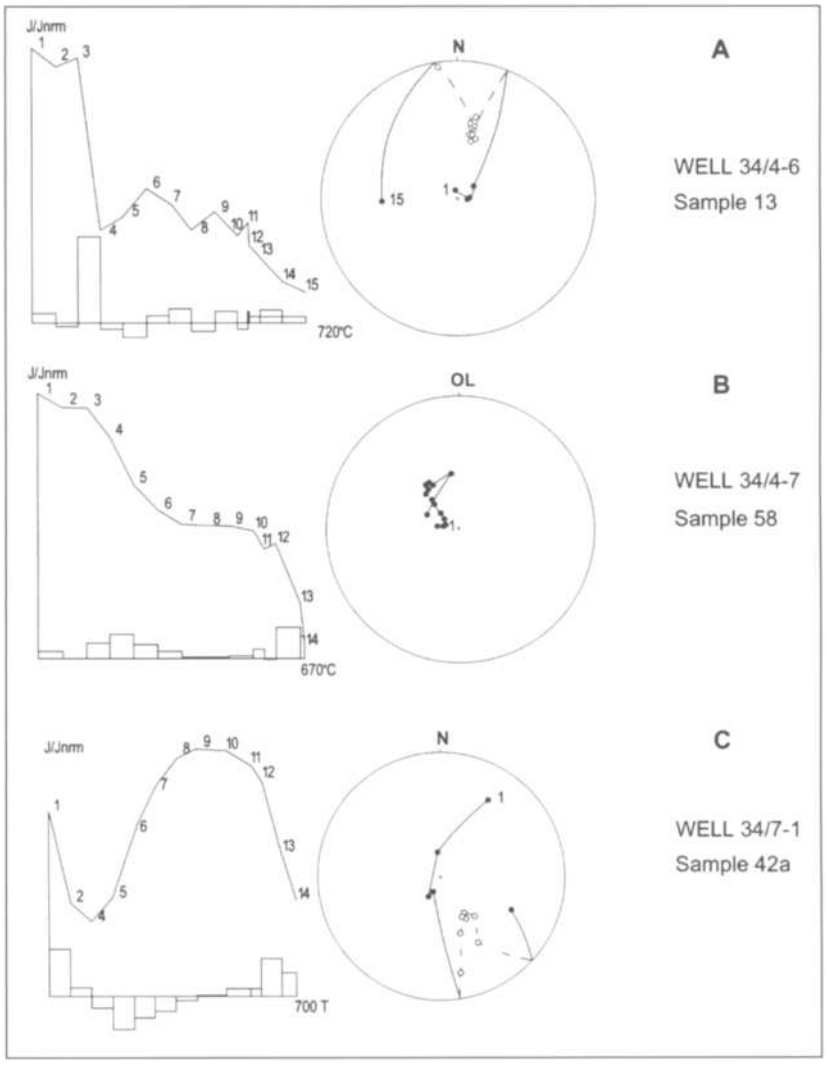


Figure 2. Demagnetisation data of samples from red mudstone displayed as intensity decay plots and stereographic projections. The intensity decay curves show that the magnetisation consists of two components. The primary magnetisation is defined by a stable endpoint in the temperature interval between 330°C and 660°C. The magnetisation is completely removed after heating at about 700°C. From top: (a) Sample 13 (well 34/4–6) with reverse polarity, (b) Sample 58 (well 34/4–7) with normal polarity and (c) Sample 42a (well 34/7–1) with reverse polarity. The rise in intensity during demagnetisation reflects the removal of a normal component directed opposite to the reverse, primary component.

recorded in sediments by depositional and post-depositional processes. A local magneto-polarity stratigraphy (MPS) established within a region may be used as reference for stratigraphical correlation. If the primary magnetisation is still present in the sediment the correlation is chronostratigraphically based. As shifts of polarity are thought to occur within 5,000 years, the boundaries between polarity zones are sharp. Once identified, the magnetic polarity zones may be used for chronostratigraphical correlation in the same way as marker beds such as volcanic ash marker beds.

If the MPS can be correlated to a global polarity time scale (GPTS), this further enables age dating and calculation of accumulation rates. This last step, however, is not always possible. It requires additional chronostratigraphical information or the analysis of thick sedimentary sequences with similar or known accumulation rates so that the pattern of the polarity zones may be recognised in the GPTS.

If the sediment has been remagnetised after the time of deposition and/or the primary magnetic minerals dissolved it may be impossible to determine the primary magnetic component. In this case the apparent MPS cannot be used for chronostratigraphy. For subsurface well cores from petroleum reservoirs the possibility for remagnetisation is high due to the changing geochemical environment that the sediments have experienced during diagenesis. Sulphide-rich brines may have dissolved the primary magnetic minerals and caused growth of new magnetic phases. These geochemical changes are most likely to occur in high-permeable lithologies. If authigenic magnetic minerals have formed during diagenesis the magnetic polarity may thus show a strong correlation with lithology as seen for example in some Jurassic shallow marine sediments in the North Sea (Beyer, 1995). In such sediments the apparent magnetostratigraphy may have some value as a lithological correlation tool but cannot be used for chronostratigraphy.

The probability for complete remagnetisation increases with burial and proximity to HC plumes. From a study of three areas of HC seepage, Reynolds et al. (1993) recognised two mechanisms for the generation of aqueous sulphide leading to formation of magnetic iron sulphides: Sulphate reduction by anaerobic bacteria and thermochemical reduction of sulphate. The first process occurs at low temperatures (5° to 85°C), in sediment containing reactive detrital organic matter. The latter occurs at higher temperatures (> 100°C) and is associated with carbonate rocks that act as the source of the sulphate.

Important factors governing the destruction of iron oxides and subsequent formation of iron sulphides (Thompson and Oldfield, 1986; Canfield and Berner, 1987; Burton et al., 1993; Reynolds et al., 1993; Machel, 1995) may be summarised as: (1) the availability and reactivity of organic matter for sulphate reduction and the concentration of sulphide (which depends on availability of sulphate and reactive iron), (2) the concentration of the iron minerals and their surface area, (3) temperature and pressure and (4) Eh and pH conditions.

Both the depositional environment and the changing diagenetic environment are thus important for the degree of remagnetisation. A shallow marine reducing depositional environment characterised by a high input of organic matter promotes the destruction of iron oxides and subsequent formation of iron sulphides. In contrast, an arid continental depositional environment is favourable with respect to the preservation of detrital and early diagenetic iron minerals. The low sulphide concentration, the low content of organic material and the lack of a significant source of sulphate further provide favourable conditions in the studied deposits.

APPLICATION TO THE MURZUQ BASIN

Because of their composition and the relatively limited burial depth several of the Palaeozoic formations in the Murzuq Basin may still contain a remanent magnetic component of the

magnetisation acquired at the time of deposition. Possible suitable formations are for example the Mamuniyat Formation, parts of the Akakus Formation, the Tadrart Formation and the Marar and Assedjefar formations. All of these formations have a composition that indicates that magnetic grains may have been oriented by the geomagnetic field at the time of deposition and may have been preserved through their geological history. Whether the formations have become remagnetised by diagenesis may be determined by magnetic analysis of samples. Some younger suitable rocks for palaeomagnetic analysis are the continental Mesozoic rocks, particularly the red beds which may have favourable properties similar to the Triassic rocks in the North Sea.

The quality of the palaeomagnetic results may be evaluated by calculating the mean direction of the primary magnetism and the radius, $\alpha 95$, of the 95% cone of confidence (the cone within which there is 95% probability that the true mean direction lies). The mean direction may subsequently be used for the calculation of a palaeomagnetic pole and dating of the sediment by comparison with known palaeopole positions. A practical way of doing this is to calculate the expected palaeomagnetic directions for the specific area and compare these with the calculated mean direction. If the geographical orientations of the samples are unknown the statistical calculations may be based solely on the inclination values by the use of Kono statistics (Kono, 1980). Figure 3a shows the statistical data for four polarity zones from the Snorre Field and the ages obtained by comparison with the expected palaeomagnetic inclinations shown in Fig. 3b. In general the inclination values of approximately 42° correspond well with a Late Triassic age. The results from the reverse polarity zones have the largest uncertainty. This is probably a result of a partial overlap of the primary and secondary magnetic components preventing a complete isolation of the primary (reverse) component in some samples. For the same reason the absolute values of the mean inclinations become smaller for the reverse polarity zones than for the normal polarity zones.

Figure 4b shows the palaeomagnetic normal polarity directions expected to be found in sediments of different ages in the Snorre area and in the Murzuq Basin. The Murzuq Basin crossed the equator during the late Permian: As the geomagnetic field direction is horizontal at the equator, the corresponding expected palaeomagnetic directions have very low or zero inclinations (Fig. 3b), which complicate an unambiguous determination of the polarity of non-oriented samples. In late Triassic and Jurassic times, the northward movement stopped and the time resolution based on palaeopole positions for this period is therefore poor (Fig. 3b). However, the inclination is steep enough to enable an unambiguous polarity determination for the establishment of a local magnetostratigraphy which may be used for correlation purposes and – provided that the studied sequence is long enough – for dating by correlation with the established GPTS. Similarly, the older Palaeozoic formations were deposited in the southern hemisphere at sufficient distance from equator to make the establishment of a local magnetostratigraphy possible.

ORIGIN OF REMANENT MAGNETISATION IN THE SNORRE RESERVOIR

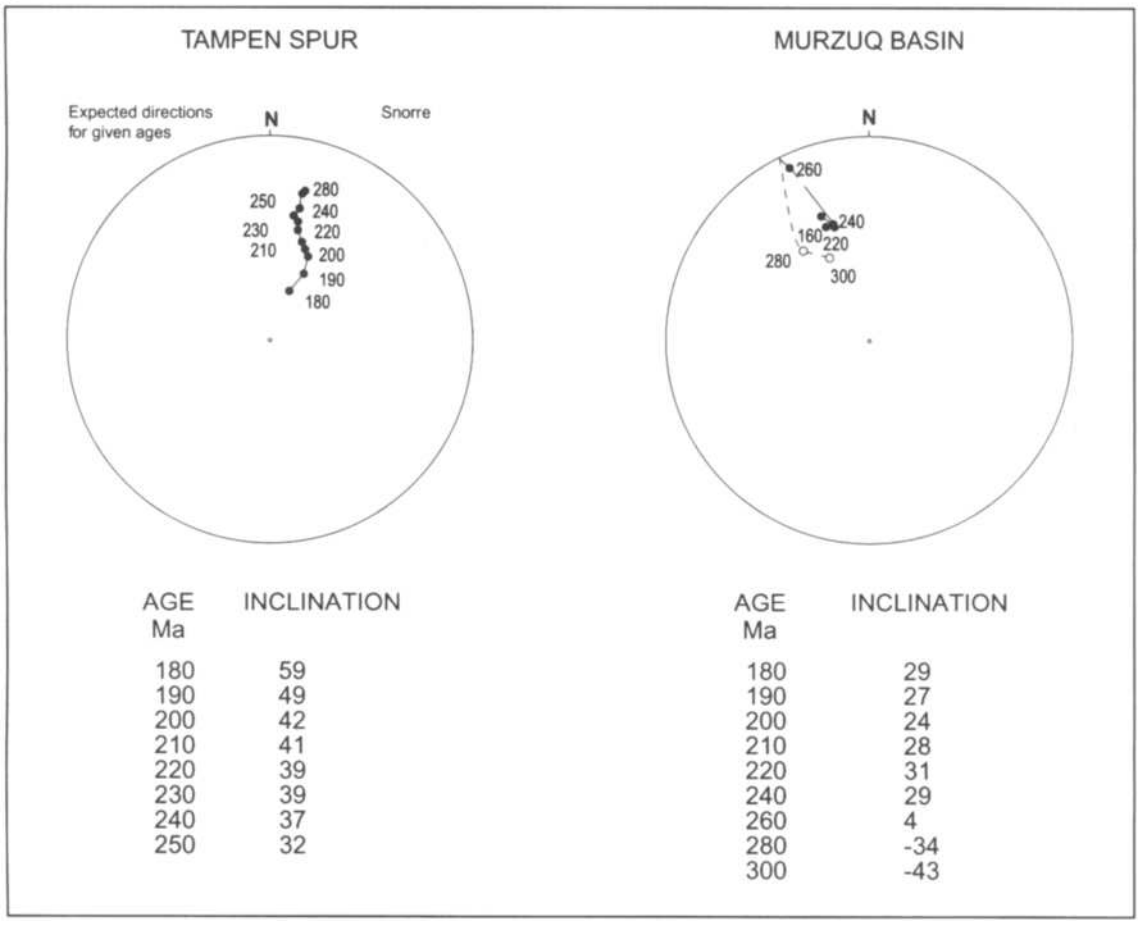
Polished thin sections of all facies were studied to determine the timing of the hematite pigmentation, possible occurrence of detrital iron oxides and diagenetic changes of iron minerals. A colloidal magnetite solution was applied to the surface of the sections to detect magnetic areas. Strongly magnetic areas are present in detrital grains of ilmenite where the magnetite colloids were attracted by exsolution phases of hematite. Similar ilmenite grains occur in the grey mudstone facies but here part or all of the hematite phase has been dissolved. No authigenic magnetite or iron sulphides were detected. The dissolved iron has thus probably been removed from the sediment.

The red pigmentation was formed very early as seen from the coloured areas of non-compacted, calcite-cemented areas. It was apparently formed penecontemporaneously with the calcrete and before the initial compaction of the sediment. It is therefore concluded that a possible ChRM of the red mudstones is primary because of the presence of strongly magnetic detrital grains, the early formation of hematite pigmentation, the approximately 42° mean inclination of the ChRM components (Fig. 3) and because of the theoretical considerations with respect to depositional environment, sulphide concentration and lack of reactive organic material.

(a)

Polarity zone	WELL	N	K	MEAN INC.	alpha95	Corre-sponding age Ma.
R8,R9, R10,R11,R 12,R13	34/4-4 & 34/7-1	52	24.33	35.14	4.09	(220-250)
N6,N7	All 4 wells	75	32.05	43.10	2.82	200
R3,R4,R5	34/4-7 & 34/4-4	24	51.84	34.97	4.15	(240-250)
N1,N2,N3	34/4-7	23	42.91	41.45	4.67	200-210

(b)



AGE Ma	INCLINATION
180	59
190	49
200	42
210	41
220	39
230	39
240	37
250	32

AGE Ma	INCLINATION
180	29
190	27
200	24
210	28
220	31
240	29
260	4
280	-34
300	-43

Figure 3. (*a*) Statistic calculations of the mean directions calculated by the use of Kono statistics (Kono, 1980), which treat directions on a sphere when the declinations are unknown. (N: Number of samples, k: precision parameter, α95: Cone of confidence). (*b*) Comparison with the expected Triassic palaeomagnetic directions for the Tampen Spur area and for the Murzuq Basin.

The dissolution of hematite is confined to the permeable sandstones and the adjacent bleached mudstones, thus explaining the relatively low intensities and poor palaeomagnetic quality of these facies. It is further concluded that reduced iron was removed from the system by the brines that dissolved the hematite and that no significant remagnetisation has occurred.

MAGNETOSTRATIGRAPHIC CORRELATION

The magnetostratigraphical correlation is shown in Fig. 4 where also the previous correlations based on logs (Nystuen et al., 1989) and palynomorphs (Eide, 1989) are shown. It is seen that the magnetic analysis has provided a considerably improved stratigraphic resolution compared to these previous correlations. In addition, the magnetostratigraphic correlation has a truly chronostratigraphical significance. There is no disagreement with the previous correlation except in the uppermost part of core 34/4–6 where the previous lithological correlation between 34/4–6 and 34/7–1 seems to be diachronous according to the magnetostratigraphy. In these cores the shorter polarity zone R6 occurs on each side of the log correlation line 1. Only the polarity zones N6, R6 and N7 are present in all four cores. Some variations exist between the polarity zone patterns of the two wells 34/7–1 and 34/4–4. Two thin polarity zones, R7 and N10 (or N9) are present in well 34/4–4, while absent in well 34/7–1. Both of these zones are short and the absence in well 34/7–1 may be explained as a result of erosion.

The interval N8-R8 is considerably thicker in well 34/7–1 than in well 34/4–4. According to M. Bergan (pers. comm., 1995), a distinctive sandstone with extraformational clasts occurs in the three cores 34/7–1, 34/4–6 and 34/4–4. The base of this sandstone may define a sequence boundary (Figs 5 and 6). Apparently the draining rivers incised a valley at least 25 meters deep at a time of base level fall. This may explain the variations in polarity zone pattern for this interval.

DATING

During recent years the Triassic GPTS has been considerably improved by the Newark Basin Coring Project in which nearly 7 km of drill cores from a thick Triassic red bed sequence have been studied (e.g. Kent et al., 1995, Olsen et al., 1996). Besides magnetostratigraphy, the combination of cyclostratigraphy and absolute dating of basalts in the uppermost part of the sequence has provided exceptionally detailed information about the Triassic palaeomagnetic field.

Figure 6 shows a suggested correlation between the Newark Basin polarity scale and the MPS from the Snorre Field. Besides the knowledge that the Lunde Formation is of late Triassic age this correlation is based on two factors: the polarity zone pattern and the occurrence of unconformities. The relatively long normal polarity zones are correlated with the E17 to the E15 sequence of the Newark Basin Scale, which is well dated by cyclostratigraphy and by absolute dating of basalts. The uppermost part of the studied succession dominated by reverse polarity is correlated with the Rhaetian and uppermost Norian. The correlation is supported by the presence of the unconformity thought to reflect an end-Norian relative sea level fall (e.g. Haq et al., 1988). The suggested correlation with the GPTS implies that the studied interval represents approximately 11 Ma, corresponding to an average accumulation rate of about 0.04 m/ka.

CONCLUSIONS

The sedimentary succession in the Snorre Field is thought to be relatively complete because of the tectonic setting. Although the dating of the sediments has been difficult because of poor

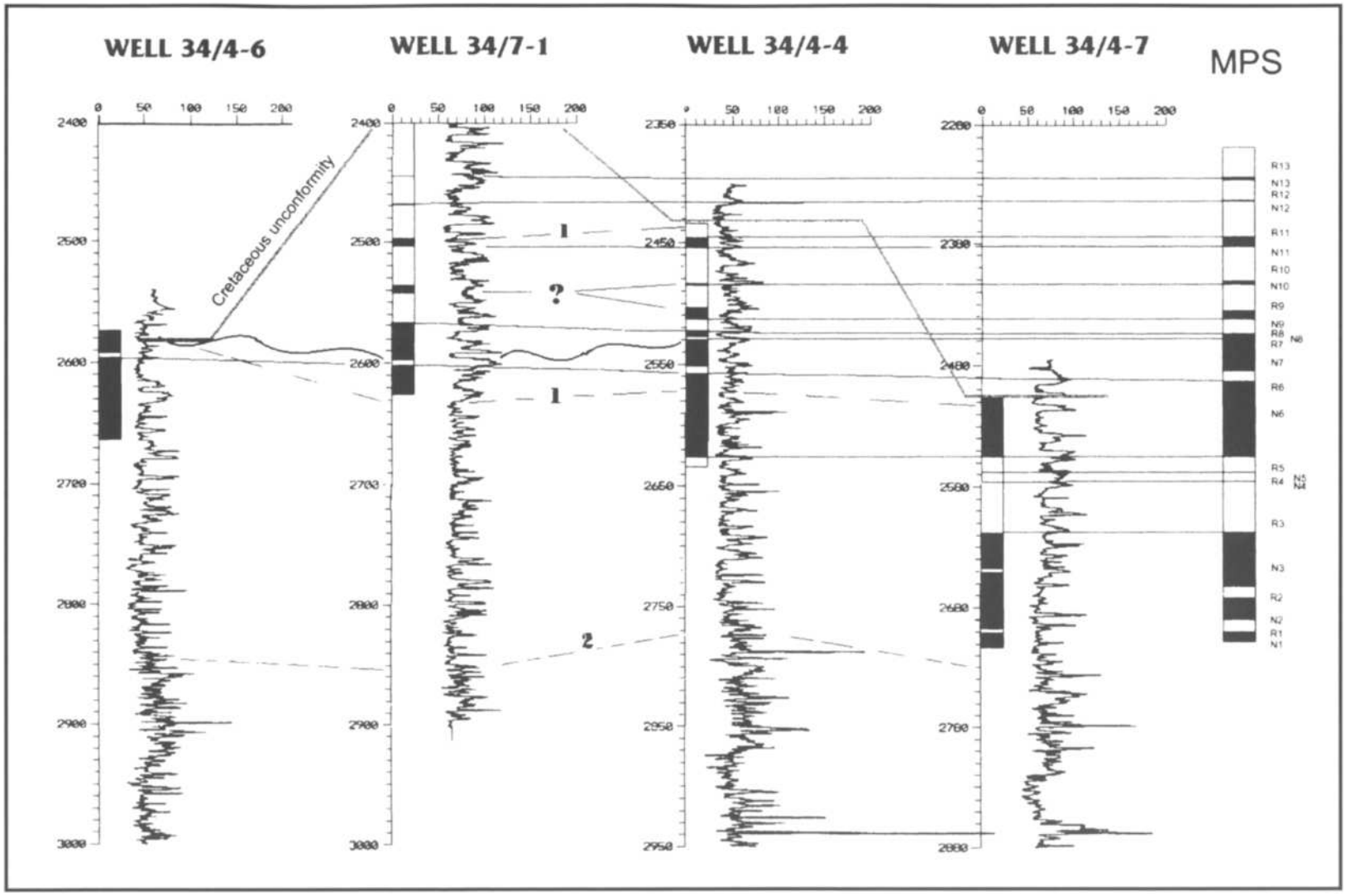


Figure 4. Magnetostratigraphic correlation of the four wells in W-E cross-section. The unconformity is indicated by the wavy line. Previous correlations shown with dashed lines: (1) log correlation (Nystuen et al., 1989) (2) biostratigraphical correlation based on palynomorphs (Eide, 1989).

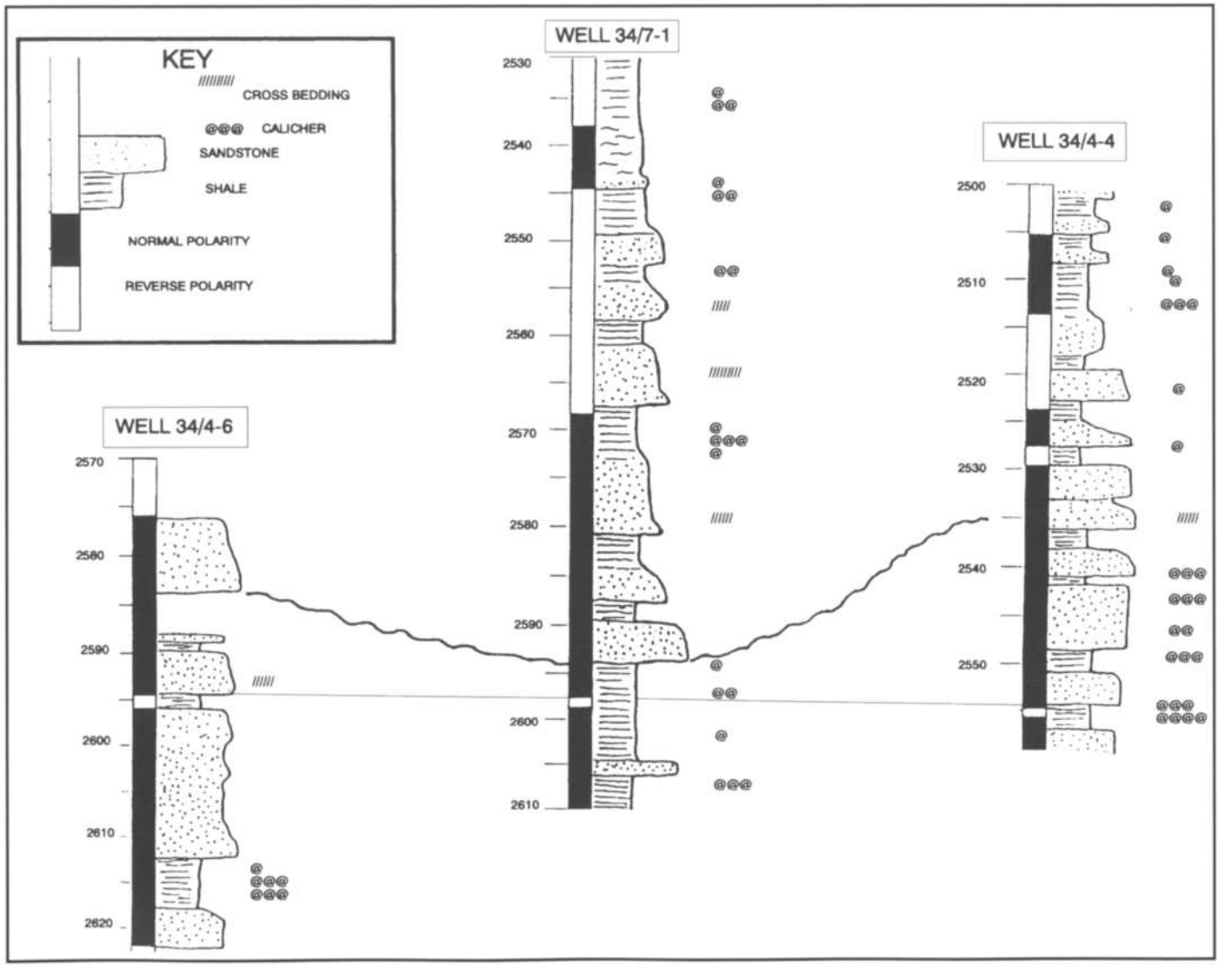


Figure 5. The unconformity present in three wells. The cross section is perpendicular to palaeoflow direction.

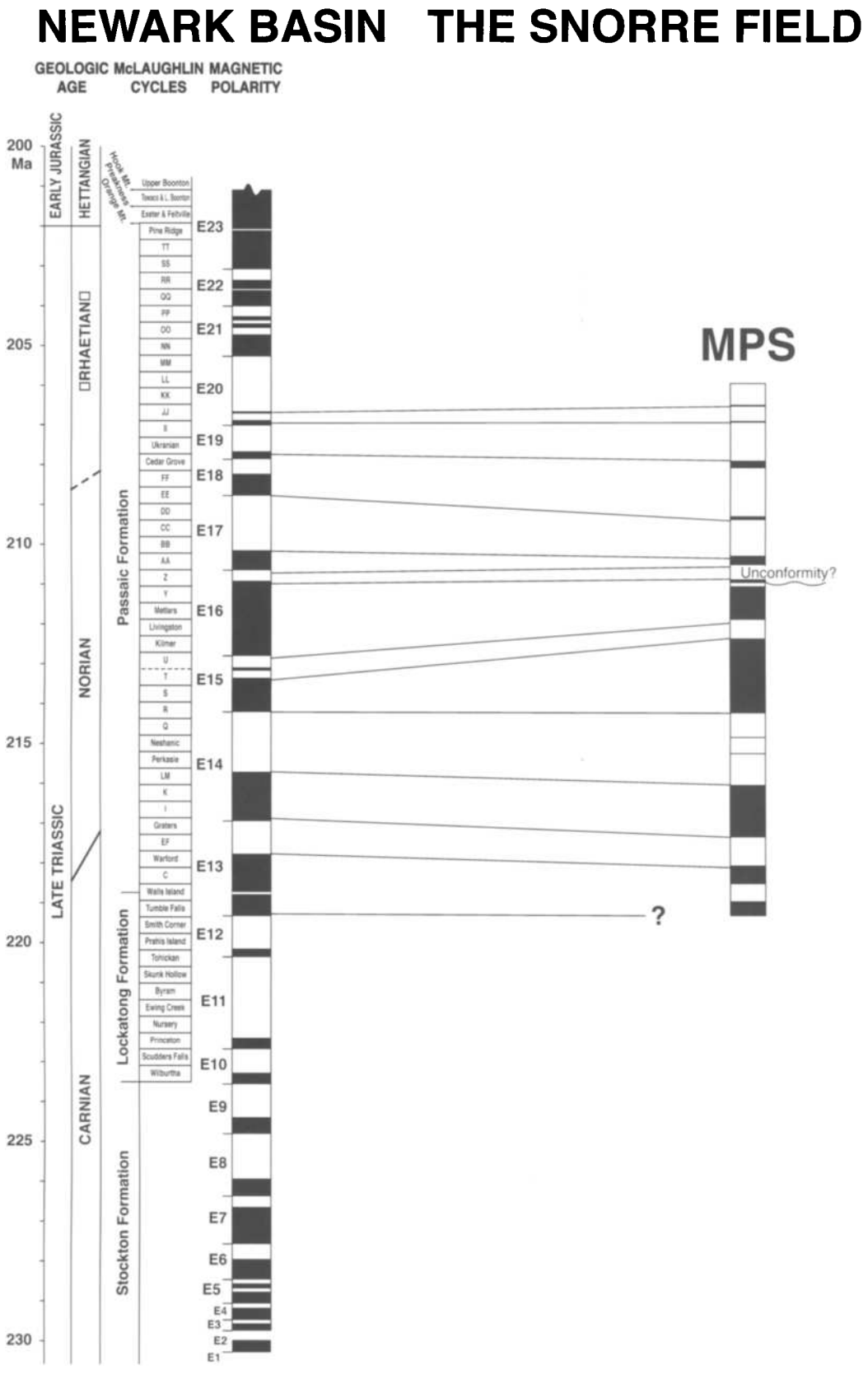


Figure 6. Suggested correlation with the Newark Basin established by Kent et al., 1995.

biostratigraphical data, the use of magnetostratigraphy has considerably improved both time resolution and dating. The local magnetic polarity scale established in this study correlates well with the Newark Basin polarity scale established in northeastern U.S.A. According to this correlation the studied sequence was deposited over a time interval of approximately 11 Ma from the Early Norian to the Early Rhaetian.

This work shows the potential of magnetostratigraphy as a tool for the chronostratigraphical subdivision and dating of sedimentary sequences that are otherwise difficult to correlate and date because of the lack of correlative biostratigraphical events. As such difficulties apply to several formations in the Murzuq Basin it may be a relevant tool to use in this area.

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CHAPTER 3

Possible Structural Influence on the Genesis of Bir Nagaza (Al Awaynat) Radioactive Mineralisation

BASHIR M. YOUSHAH[1] and NAJIB EL HATIMI[1]

ABSTRACT

The Triassic Zarzatine Formation in the Bir Nagaza region of southwestern Libya is known for the occurrence of radioactive mineralisation. Uraniferous mineralisation in the area occurs in the Zarzatine Formation as irregularly distributed concentrations of secondary minerals forming yellow coatings on detrital fragments, or as impregnations filling northerly-directed cross bedding.

The localization of this mineralisation has previously been interpreted as topographically controlled, with leaching of the already existing radioactive minerals from the upper levels of the Triassic Zarzatine Formation and subsequent redeposition in lowland areas. Gravity data have been used to calculate and draw a Bouguer gravity anomaly profile. Comparison with calculated profiles for different subsurface bodies shows that the profile matches well with that of a subsurface fault. Modelling indicates the existence of a northerly trending normal fault with downthrow to the west. Digital interpretation of Landsat thematic data shows the existence of a fault in the Zarzatine Formation south of latitude 26° and recent fieldwork has verified its existence at least in the northern part of the Al Awaynat map sheet.

This integration of multidisciplinary data with field studies indicates that the Bir Nagaza region has been affected by previously unmapped fault systems that have played an important role in the region's evolution. Radioactive occurrences in the Bir Nagaza region are located in a limited N-S oriented zone to the east of the normal fault system trending 150°–170°. We conclude that surface water has played an important role in the concentration of the Bir Nagaza radioactive elements, but these concentrations have been controlled by tectonic elements rather than by present-day topography. Better understanding of faulting and fracturing in the region will help to determine the most favourable locations for the concentration of radioactive mineralisation.

INTRODUCTION

The Bir Nagaza area, which lies on the western flanks of the Murzuq Basin (Fig. 1), has been explored for uranium since 1974. From 1979 to 1982 the area was subjected to an extensive exploration program including airborne gamma-spectrometry and magnetometry.

This survey led to the detection of several radiometric anomalies. These anomalies have been further studied by detailed ground radiometric surveys that included sampling, analysis and

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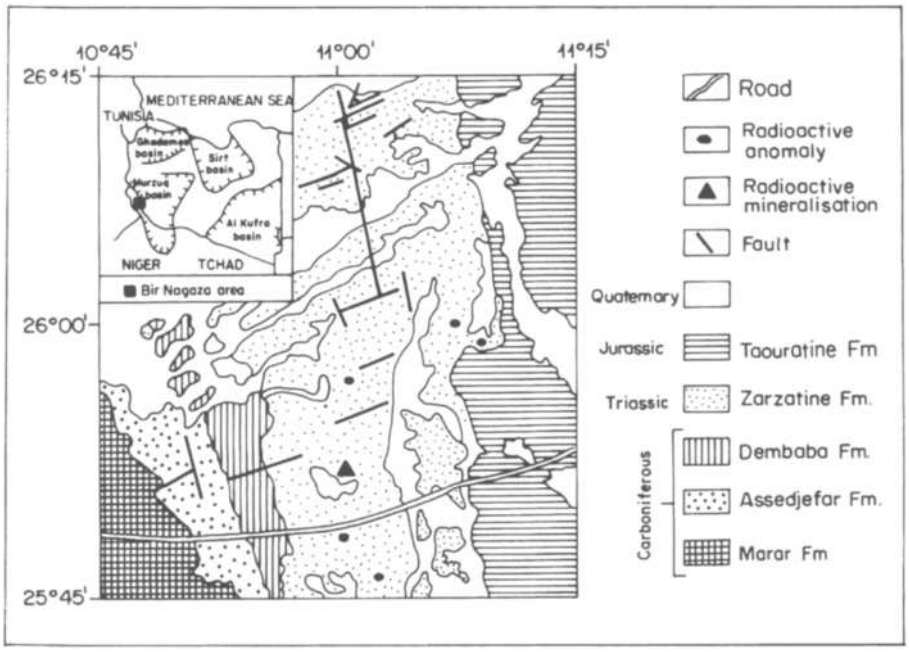

Figure 1. Location and geological sketch map of Bir Nagaza area.

mapping. More than 50 geophysical radioactive anomalies have been located by this survey, some of them significant with visible shows of uraniferous mineralisation (Assaf and Aburkes, 1980). Of these, the Bir Nagaza area is considered the most important. The anomalies and the mineralisation are of debatable origin and commerciality (Al Mehdi et al., 1991).

According to the explanation given by Baegi et al. (1991) and restated by Assaf et al. (1994), the concentration of radioactive mineralisation in the area reflects Recent topographical influence. These workers suggested that the mineralisation is the result of recycling of already existing radioactive minerals from the upper levels of the Zarzatine Formation to the east, with subsequent redeposition in lowland areas to the west (Fig. 2).

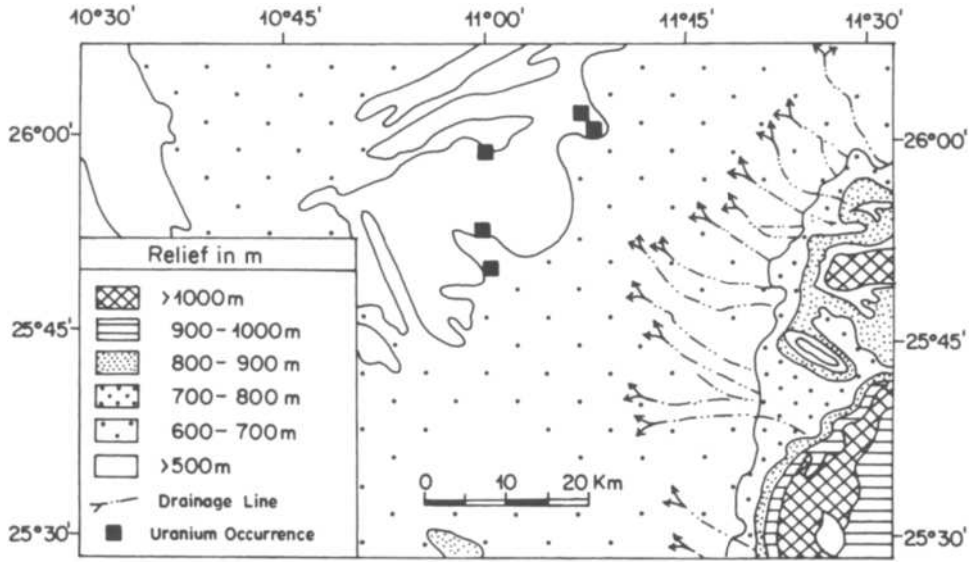

Figure 2. Topographical sketch map of the area.

AGE		ROCK UNITS	THICKNESS (m)
Period	Stage		
Jurassic	Late	Taouratine Formation	>210
	Early		
Triassic		Zarzatine Formation	100-130
Carboniferous	Moscovian	Analcimolite beds	40-98
	Bashkirian	Dembaba Formation	
	Namurian	Assedjefar Formation	60-130
	Visean	Collenia beds	70-250
	Tournaisian	Marar Formation	

Figure 3. Lithostratigraphic sequence in the Bir Nagaza area.

GEOLOGY OF THE AREA

The Bir Nagaza area represents the northern part of the Al Awaynat map sheet (NG 32–12) and the southern part of the Wadi Irawan sheet (NG 32–8) of the geologic map of Libya on a scale of 1:250,000 (Fig. 2). The stratigraphic succession in the area is shown in Fig. 3. Quaternary deposits cover a significant part of the area and include various types of deposits (Jakovljevic, 1984; Komarnicki, 1984).

Palaeozoic Formations

The Palaeozoic formations occur along a broad NNW-trending belt in the western part of the area.

Mrar Formation

The Mrar Formation (Tournaisian to Viséan) varies from 70 to 250 m thick and overlies the Devonian Ouan Kasa Formation (which is not exposed in the area). The upper part of the formation is characterized by *Collenia* colonies, distinguished as the *Collenia* Bed. Lithologically this formation comprises both gypsiferous siltstone and sandstone and ferruginous and calcareous sandstone interpreted as having a shallow marine origin.

Assedjefar Formation

The Assedjefar Formation (Viséan to Namurian), which varies from 60 to 130 m thick, conformably overlies the Mrar Formation. The lower part of the formation consists of siltstone, sandstone and calcareous fossiliferous sandstone. The upper part is composed of siltstone, marl, sparitic limestone and fossiliferous limestone. A characteristic feature of this formation is the

presence of large sandstone concretions with a spherical or mushroom shape, up to 1.5 m in diameter, in the sandstones of the lower part of the formation.

Dembaba Formation

The Dembaba Formation (Bashkirian–Moscovian) has a conformable contact with the underlying Assedjefar Formation. The formation varies from 40 m to 98 m thick and consists of calcareous siltstone, marl, calcirudite and sparitic calcirudite lowermost, passing up into oolitic sandstone with analcime towards the top. The lower parts of this formation were deposited in a shallow marine environment and the upper parts in a continental to coastal plain setting. The ochre-coloured Dembaba analcimolitic sandstones are overlain by thinly bedded and parallel-laminated grey-green and brownish-red siltstone, silty sandstone, and cross bedded fine to medium grained sandstone of the Zarzatine Formation.

Mesozoic Formations

The Mesozoic formations outcrop in a narrow NNW trending zone in the central part of the area. They comprise the Triassic Zarzatine Formation and the Taouratine Formation of Jurassic age. These units almost exclusively represent continental clastic sedimentary rocks.

Zarzatine Formation

The Zarzatine Formation outcrops in the area along a N-S trending zone, with maximum thickness in the north (up to 130 m), thinning gradually to about 100 m in the south. The formation (Fig. 4) consists of numerous alternations of thick sets of red to reddish-brown siltstone and cross-bedded fine- to medium-grained sandstone, with less frequent conglomeratic interbeds and lenses. Fossil spores and pollen indicate a Triassic age (Jakovljevic, 1984).

The Zarzatine Formation unconformably overlies different units of the Dembaba Formation. Its base is usually marked by a thin (10 to 20 cm) bed of conglomerate with carbonate cement, overlain by an alternation of reddish-brown to greyish-green siltstone and claystone with variegated brownish-red to brownish-green quartz sandstones. A clear characteristic of this formation is the dominance of siltstones over all other rock types. The siltstone and sandy siltstone occurs in 12 to 15 m, locally up to 30 m, thick units that form numerous alternations with fine-grained sandstone. Siltstones and claystones are mostly parallel laminated, but often massive. These rocks usually contain variable amounts of gypsum, mostly as stains or irregular accumulations along fissures and joints, indicating its late introduction.

The sediments of the formation show sudden variations both vertically and laterally and up to five depositional rhythms can be recognized. All these sediments were deposited in a continental setting of fluvial channels, alluvial plains and lakes. The uppermost Zarzatine Formation was subsequently subaerially exposed, probably still in the Triassic, and subjected to strong fluvial erosion, leading to the development of a 3 to 4 m thick lateritic horizon.

Taouratine Formation

The Taouratine Formation (Jurassic) lies unconformably on the lateritic beds of the Zarzatine Formation. The upper contact with the Messak Formation (not exposed in the area) is also unconformable and is marked by a thin layer (up to 0.5 m) of red silty claystone. The maximum thickness of this formation in the area is 240 m. It is composed of alternations of cross-bedded

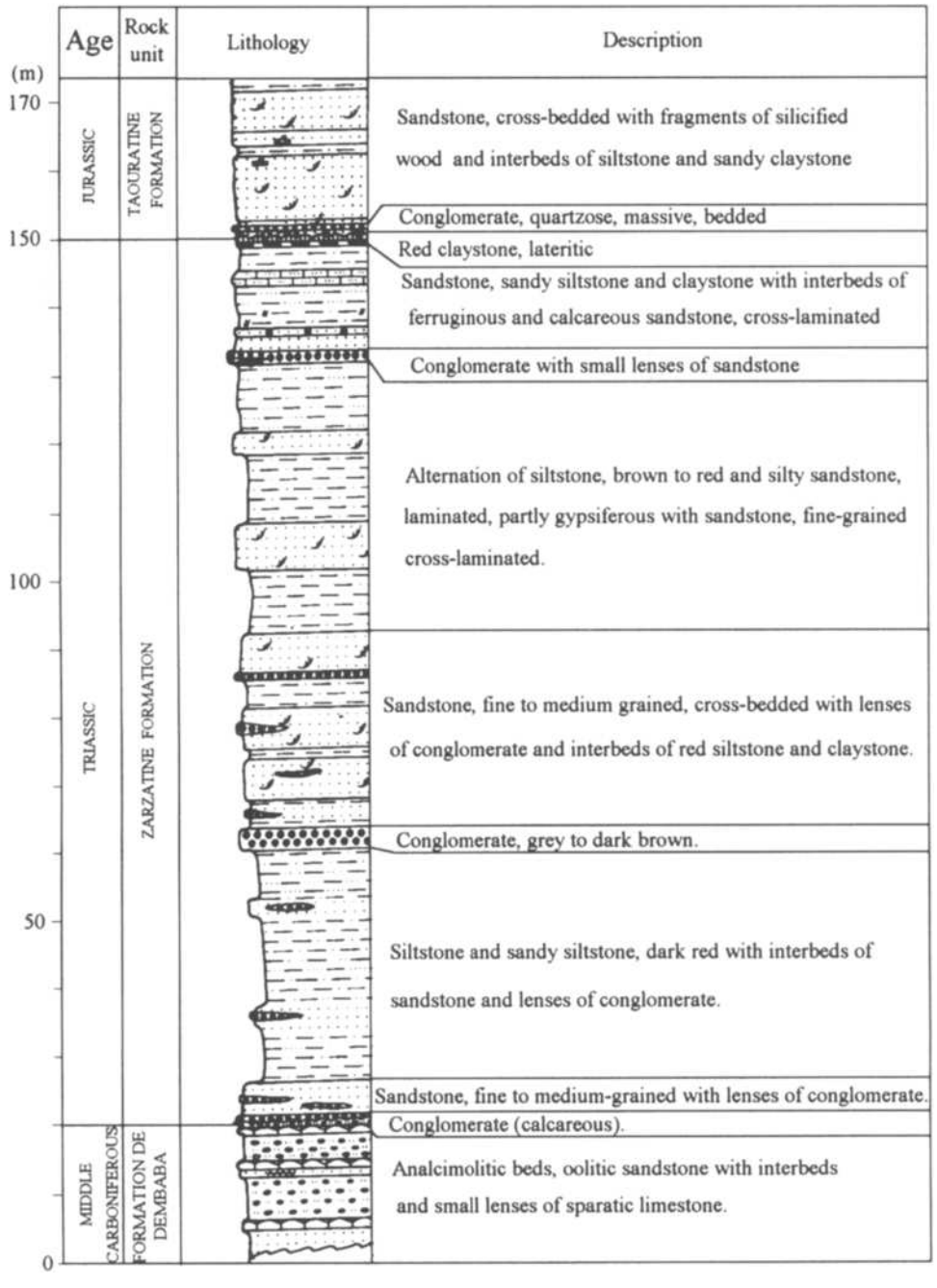

Figure 4. Composite section of the Zarzatine Formation (Jakovljevic, 1984).

and parallel-bedded sandstone, conglomerate, siltstone and claystone deposited in braided rivers, with periodical lacustrine phases.

Quaternary Deposits

Quaternary deposits occur over much of the area. They include aeolian sand dunes and sand sheets, wadi deposits and fluvio-aeolian deposits that cover large areas. Sabkha sediments fill the internal drainage basins, some of which are up to 5 km in diameter.

MINERALISATION IN THE AREA

Uraniferous mineralisation in the Bir Nagaza area occurs in the Zarzatine Formation as irregularly distributed concentrations of secondary minerals forming yellow coatings on detrital fragments or as impregnations filling northerly-directed cross bedding in sandstones.

The highest radioactive mineral concentrations are often associated with completely limonitised, calcified or carbonised plant remains and wood logs. Dark grey calcite, gypsum and dark brown ferruginous concretions are characteristic of all mineralised zones. Carnotite appears to be the principal uranium mineral present (Assaf and Aburkes, 1980).

GRAVITY INTERPRETATION

The Survey Department of Libya (SDL) has undertaken extensive gravity measurements as part of its regional mapping program. Most of the data measurements were made on primary and secondary roads in Libya and a data profile for the road crossing the Bir Nagaza area has been obtained from SDL (Fig. 1).

For each profile data point there is a number, location in geographic coordinates, elevation above mean sea level and the free air anomaly of the station. Using these data, the Bouguer anomaly for each point as well as its location in UTM coordinates, and the distance between each two adjacent points have been calculated. The data are plotted in a two-dimensional Bouguer anomaly profile along the road in the form of gravity against distance.

Comparison of the Bir Nagaza Bouguer anomaly profile with calculated profiles for different subsurface bodies shows that the profile matches well with that of a subsurface fault (see for example the model curves given by Nettleton, 1976; Dobrin, 1976; Telford et. al., 1976 and Goodacre, 1991).

Using the La Cost and Romberg software GMODEL, it was possible to carry out a digital interpretation of the profile data. Interpretation of the profile in Fig. 5 shows a normal fault with downthrow to the west.

This fault is not shown on the published geologic map of the Bir Nagaza area, but digital interpretation of the Landsat thematic data (Youshah and El Hatimi, in press) shows the existence of the fault in the Zarzatine Formation south of latitude 26° and recent field work has verified the existence of this fault at least in the northern part of the Al Awaynat map sheet. The geological map to the north of latitude 26° (Komarnicki, 1984) shows a fault running in a N-S direction through the Zarzatine Formation, which is in good agreement with the interpretation obtained from the Landsat and gravity data.

The integrated interpretation of existing geological maps, Landsat thematic data, the Bouguer gravity profile and the results of recent fieldwork are compiled in the structural map shown in Fig. 6.

REGIONAL TECTONICS

The analysis of multidisciplinary geophysical, remote sensing and geological data and the field study indicate that the Bir Nagaza area has been affected by fault systems which have played an important role in the evolution of the present day tectonic elements of the region. These fault systems are aligned in three major sets: N-S, NE-SW and NW-SE (Fig. 6). The N-S direction represents reactivation of ancient basement faults, while the others are newly formed structures.

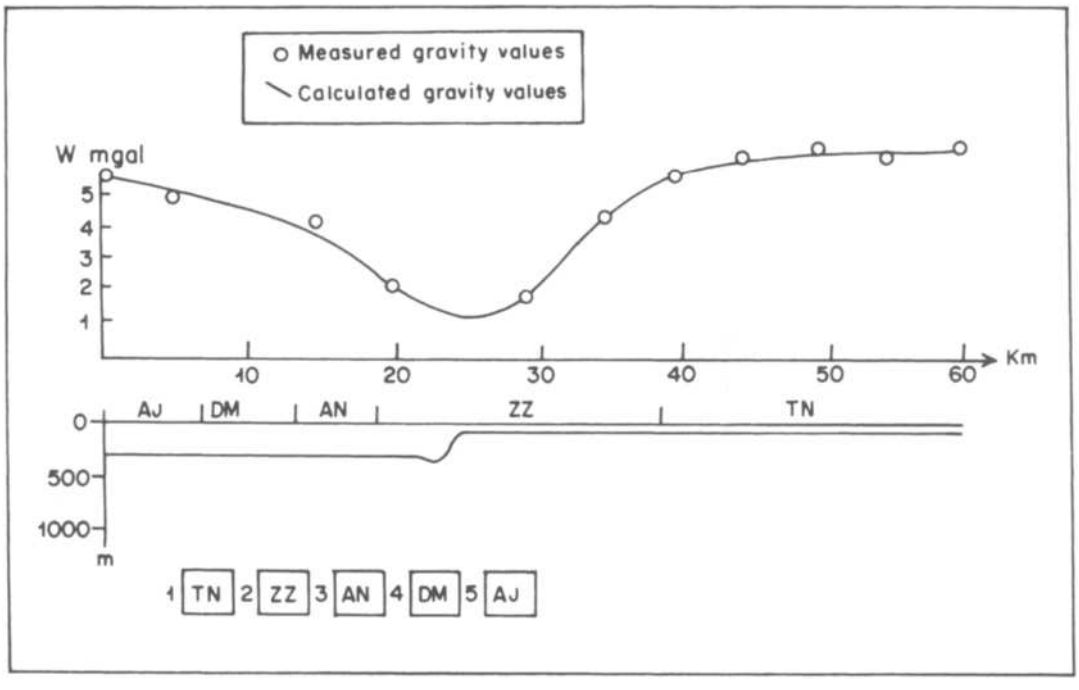

Figure 5. Bouguer gravity profile across Bir Nagaza area: (1 – Taouratine Formation, 2 – Zarzatine Formation, 3 – Analcimolite beds, 4 – Dembaba Formation and 5 – Assedjefar Formation).

The field microtectonic analysis that has been carried in the region of Bir Nagaza allows us to establish a chronological record of the events that have affected the region until the Quaternary. There is evidence of two main tectonic phases in the area:

A tensional phase was responsible for the mobilization of the old basement faults; these were rejuvenated as normal faults, dissecting the region into a series of horsts and grabens. This phase is represented by a system of normal fault sets oriented in the direction 150° to 170° (S 30° E to S 10° E).

A compressional phase was later responsible for N-S folding, which affected all the formations and resulted in sinistral strike-slip faults oriented in a NW-SE direction (azimuth 110° to 140°) and dextral strike-slip faults oriented in NE-SW direction (azimuth 50° to 70°). These strike-slip faults cut the normal fault systems and they are located in a compressive deformation field characterized by a maximum horizontal compressive constraint (σ^1) oriented in an E-W direction.

IMPLICATIONS FOR RADIOACTIVE MINERALISATION

The emplacement of radioactive minerals in the Bir Nagaza area is concentrated in a limited zone oriented in a N-S direction to the east of the normal fault system which trends at 150° to 170°. Examination of the structural sketch map of Fig. 6 shows that most of these radioactive concentrations are localized near the intersection nodes of fault systems generally oriented at 150° to 170° and 50° to 70°.

Assaf et al. (1994) interpreted this radioactive mineralisation to be the result of accumulation by surface waters flowing from a topographically higher zone to the east of the Bir Nagaza area.

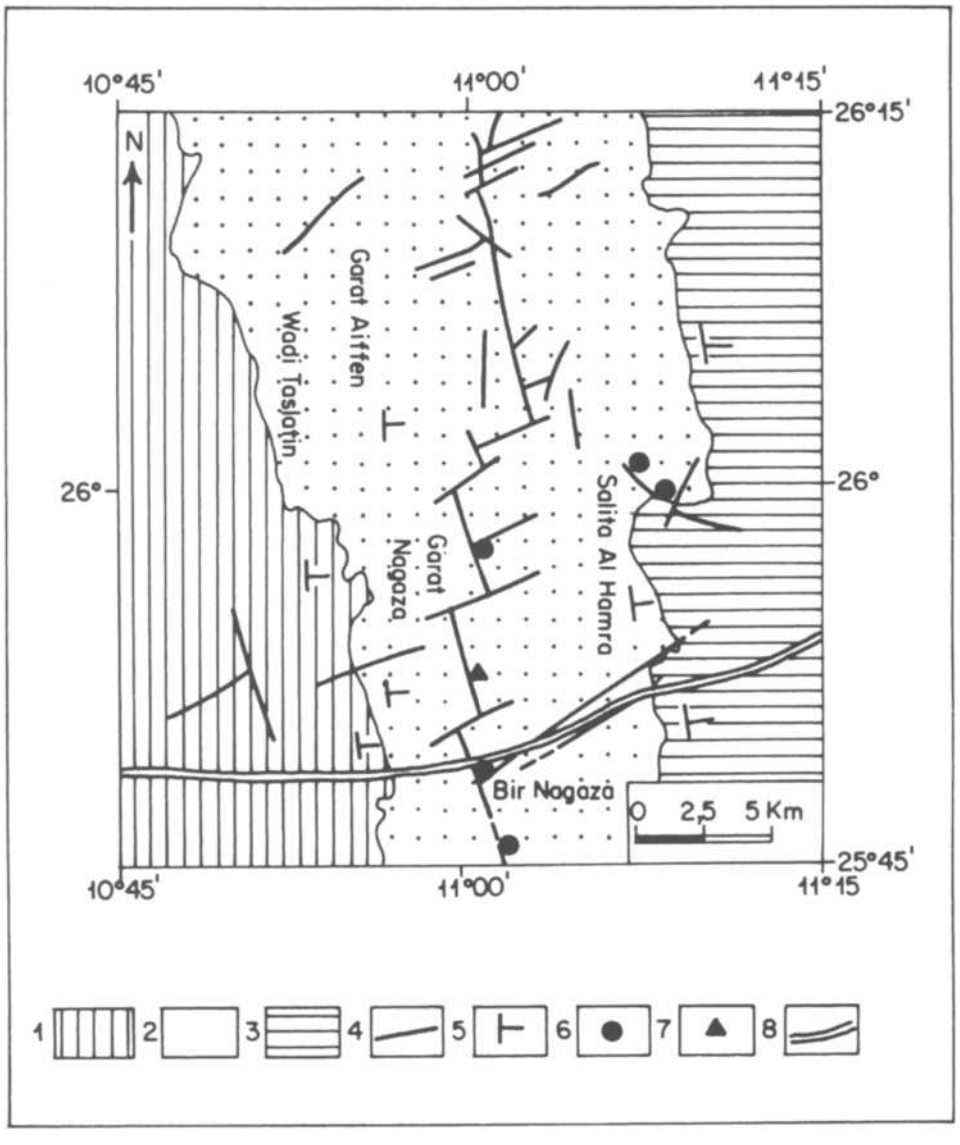

Figure 6. Structural sketch map of Bir Nagaza area: 1 – Carboniferous (Mrar, Assedjefar and Dembaba formations), 2 – Triassic (Zarzatine Formation), 3 – Jurassic-Cretaceous (Taouratine Formation), 4 – faults and fractures, 5 – strike and dip, 6 – minor radioactive mineralisation, 7 – major radioactive mineralisation and 8 – road.

In our view the mineralisation has been controlled by the regional tectonics of the area, rather than by the topography.

CONCLUSIONS

Integrated geological and geophysical studies of the Bir Nagaza area suggest that surface water has played an important role in the concentration of radioactive elements. However, these concentrations have been controlled by the regional tectonics of the area rather than the topography. Better understanding of faulting and fracturing in the area will help to determine the most favourable locations for concentration of the radioactive mineralisation.

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CHAPTER 4

A Palaeontological Review of the Devonian and Carboniferous Succession of the Murzuq Basin and the Djado Sub-Basin

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ABSTRACT

This chapter presents a synthesis of several palaeontological studies, mostly published in French, on the Devonian and Carboniferous faunas and biostratigraphy of the Murzuq Basin and its southerly extension, the Djado Sub-basin.

Lower Devonian formations outcrop extensively along the western flanks of the Murzuq Basin. The Tadrart Formation (Lochkovian/Pragian) shows a characteristic ichnofacies, but no diagnostic macrofaunas have yet been found. The more fossiliferous Ouan Kasa Formation (Emsian) was originally defined in the eastern parts of Jabal Akakus. Both formations are recognised over a distance of about 400 km as far south as the Djado Sub-basin.

The best and most fossiliferous Middle and Upper Devonian sections are located near Awaynat Wanin, on the western flanks of the Gargaf Uplift. Faunal and stratigraphical correlations of these sections with those in the nearby Wadi ash Shati area, on the northern flank of the Murzuq Basin, are good. The stratigraphic framework for this succession has been established in accordance with presently accepted stage divisions: viz. the Eifelian, Givetian, Frasnian and Famennian. The succession was mostly deposited in shallow water environments where brachiopods dominated the benthic communities; about 60 brachiopod species and several bivalves have been described from these communities. Some of the studies reported herein deal with the faunas collected in the Tahara and Ashkidah formations (Lower Tournaisian).

Palaeontological studies have proved to be very useful for geological mapping and have given a better understanding of the major late Devonian transgression that occurred during the deposition of the Dabdab and Talagrouna formations, both of late Frasnian age. The consequent onlap is well documented in the Murzuq Basin and is now also demonstrated herein in the Djado area.

The Murzuq Basin and Djado Sub-basin show a subcontinuous belt of Carboniferous exposures along their flanks, but detailed knowledge of this succession is still uneven. For instance the Wadi ash Shati outcrops, located on the basin's northern flank, are stratigraphically limited. The northwesternmost Murzuq Basin – the Zaghir area located west of the Awbari Sand Sea – shows the best Carboniferous exposures. The

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Carboniferous Illizi/Zaghir Basin covers an area of about 180,000 km^2. Several field studies carried out during the sixties were mainly devoted to the Carboniferous macrofaunas of this basin in eastern Algeria. In Libya, more recent papers have described the palaeontological and stratigraphical aspects of this succession. Three Carboniferous units – the Marar, Assedjefar and Dembaba formations show a maximum cumulative thickness of about 1000 to 1200 m. Macro- and microfaunas have been used to define thirteen biozones from the Upper Tournaisian to the Lower Moscovian in the Zaghir area.

The first major Carboniferous transgression is dated as late Tournaisian by a rich and diversified fauna including brachiopods and goniatites with *Muensteroceras*. The Upper Viséan is characterised by ammonoids such as *Beyrichoceras hodderense* and *Goniatites striatus*, together with '*Collenia*' type stromatolitic build-ups. The Upper Marar contains several endemic brachiopods. The Namurian (Assedjefar Formation) is well defined by goniatites such as *Neoglyphioceras*, *Cravenoceras* and *Anthracoceras,* while many other macrofaunas have little stratigraphic significance. The carbonates of the Dembaba Formation mark the last marine Carboniferous transgression in this area. This episode is highlighted by the presence of large nautiloid cephalopods such as *Metacoceras* and *Domatoceras* together with cosmopolitan brachiopods known from America to China.

The Zaghir Carboniferous sections provide a biozonation that can be applied throughout the whole southwestern Libyan Province. There are gradual facies changes southwards towards the Djado Sub-basin, where the basal Marar Formation is the most fossiliferous part of the succession and represents the first marine Carboniferous transgression, as in the Murzuq Basin. The last marine transgression also reached the far south of the Djado Sub-basin, but the southern equivalent of the Dembaba Formation does not contain carbonates: these are replaced by sandstones alternating with green and red shales. The whole Carboniferous succession of the Djado area contains low diversity benthic communities with affinities to similar early Carboniferous platform faunas of North America, Russia and Australia.

INTRODUCTION

This chapter presents a regional review of the Devonian and the Carboniferous succession in the large area extending through western Libya and the Murzuq Basin to the northeastern Niger Djado Sub-basin.

The review takes into account several publications concerning the Carboniferous stratigraphy, macro- and micropalaeontology of the Algerian Illizi Basin and of the flanks of the Murzuq Basin in Libya. Stratigraphical field sections are also presented from the Djado Sub-basin for the first time. These are supplemented by an overview of the Carboniferous succession drilled in two old boreholes in the central Djado Sub-basin (KR1 and KO1). In this way the Devonian and Carboniferous succession extending over a large part of the central Sahara is now described and discussed in modern stratigraphic terms. Old collections from the first stages of exploration have also been restudied and revised.

In Western Libya, previous works have provided correlations in accordance with European stratigraphical standards (the Ardenno-Rhenish and Bohemian successions). Moreover complementary studies of Devonian conodonts, present in the calcareous facies, have proved to give valuable biostratigraphic information. Studies of selected core chips established correlations between surface and subsurface developments of the Awaynat Wanin Group and the Ouan Kasa Formation (Weyant and Massa, 1985). Another interesting and useful microfossil group is

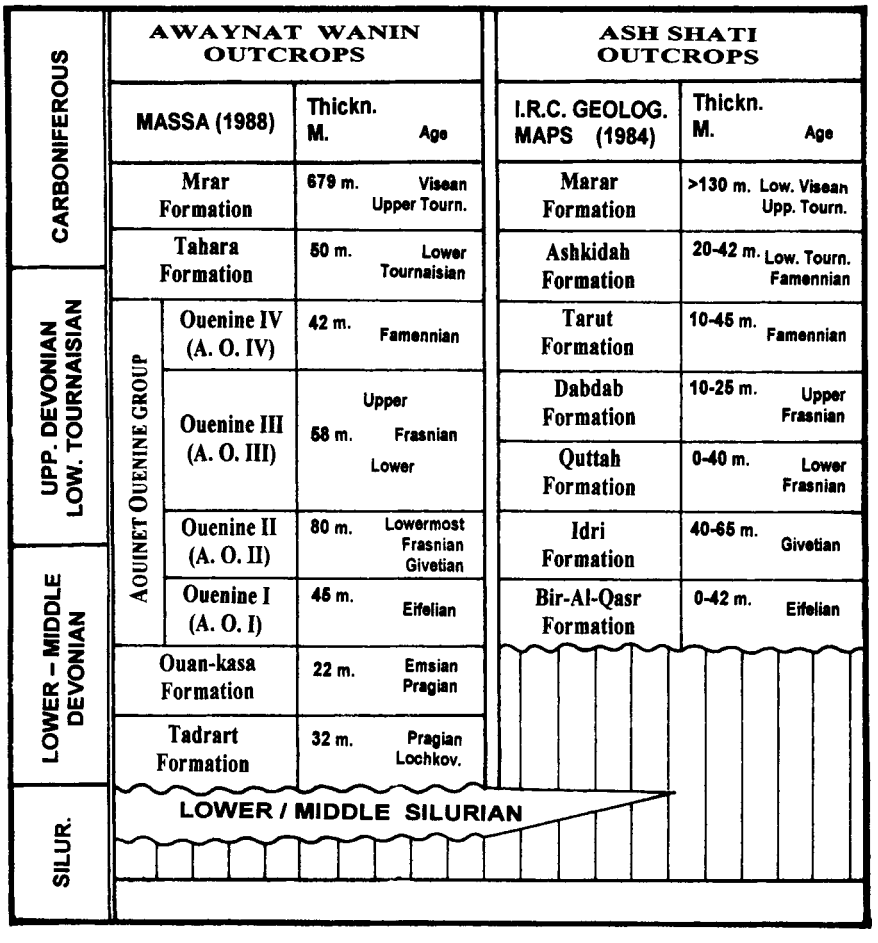

Figure 1. Devonian correlation between the Awaynat Wanin and Wadi ash Shati areas (from Mergl and Massa, 1992).

represented by the tentaculitids, which are well represented in Devonian marine strata of western Libya, both in outcrop and the subsurface (Hajlasz et al., 1978).

More recent publications include the doctorate thesis by Massa (1988) that includes two chapters on the Devonian and the Carboniferous succession and a monograph on Devonian and lower Carboniferous brachiopods and bivalves from western Libya by Mergl and Massa (1992).

Field and drilling operations were carried out from 1957 to 1963 in the Djado Sub-basin by the Bureau de Recherches Pétrolieres (BRP) and its subsidiary companies. A geological map on the scale 1:500 000 was one of the results of this work: this was edited and produced by B. Plauchut, BRP's geologist and Party Chief at the time (Plauchut and Faure, 1959). The present authors have revised and clarified the stratigraphical results obtained by the BRP teams, so new correlations can now be proposed between Libya and northern Niger. These new studies clearly demonstrate that the Djado Sub-basin is an extension of the Murzuq Basin.

DEVONIAN

Gargaf – Outcrops of the Awaynat Wanin Group and Wadi ash Shati 'Series'

Figure 1 shows the stratigraphic correspondence between the two complementary charts used in our contribution. Both are important:

The Awaynat Wanin exposures in the type area on the southern margin of the Ghadames Basin can be applied to subsurface data from the northern part of the basin. The original Aouinet Ouenine Formation of Lelubre (1946) was revised and redefined by several workers until Massa and Moreau-Benoit (1976) suggested raising the unit to group level and introduced a series of informal units named Aouinet Ouenine I to IV. We will here refer to the Awaynat Wanin Group using Libyan orthography, but still term the informal subdivisions as AO I to IV. The whole Devonian succession thickens significantly northwards and in the Ghadames Basin there is a complete Lower Devonian development and all four mid/upper Devonian units (AO I, AO II, AO III and AO IV) can be recognised (Mergl and Massa, 1992). The outcrops around Awaynat Wanin are 330 m thick, while the succession in the centre of the Ghadames Basin is more than 900 m thick.

The second chart concerns the Wadi ash Shati area, from B'ir-al-Qasr in the west to Brak in the east. A local nomenclature was established for geological mapping of the 1:250 000 sheets 'Idri' and 'Sabha' (Seidl and Röhlich, 1984; Pařízek et al., 1984). As shown in Fig. 1, satisfactory regional stratigraphic correlations can be made between the outcrops to the west and south of the Gargaf uplift.

Figure 2 is an up-to-date version of the Awaynat Wanin section, which was considered by Bellini and Massa (1980) as the best locality to serve as a Devonian reference section for the Libyan Ghadames Basin. The granulometric log is a valuable tool to trace the sedimentary evolution of successive Devonian units and the whole Devonian appears to be represented. The lower Devonian forms a single 54 m thick unfossiliferous megasequence. Dating is based on correlations by Massa (1988) with subsurface data in the central Ghadames Basin. The 225 m thick middle and upper Devonian development is richly fossiliferous (Plates 1 and 2).

A reference section in the western part of Wadi ash Shati has been selected from near the town of Idri (Fig. 3). This location is most suitable for two reasons, as far as the northern Murzuq Basin is concerned: the mid and upper Devonian is complete and thick (175 m) and richly fossiliferous horizons in the basal B'ir-al-Qasr Formation have a clear Eifelian age (Plates 3 and 4). It is important to note the absence of the lower Devonian in this area. The presence of the 'Lower *Bifungites Marker*' (L.B.M.), which is also present in the Awaynat Wanin area in the lower Frasnian, should also be noted (compare Figs. 2 and 3).

Ghat Area

The lower Devonian extends over the whole of the western Libyan Ghadames and Murzuq basins and is also developed in the Djado Sub-basin. It comprises two units that together form a single megasequence, viz. the sandstone-conglomerate Tadrart Formation and shales and siltstones of the Ouan Kasa Formation. This megasequence has been correlated to the Lochkovian/Pragian/Emsian stratigraphic interval (Massa, 1988). It shows similar thicknesses of around 350 m throughout the western Murzuq and the northern Ghadames basins and subsidence of the two basins may have been roughly comparable during this time.

Ghat–Tadrart Formation

The Tadrart Formation outcrops in a continuous belt along the western flank of the Murzuq Basin and into its southern extension – the Djado Sub-basin of northern Niger. This is clearly shown in the map of Plauchut and Faure (1959). This Devonian exposure belt is also apparent on the simplified map shown in Fig. 4 that demonstrates the connection between southwestern Libya and northern Niger. On this western basinal flank, the Ouan Kasa Formation conformably

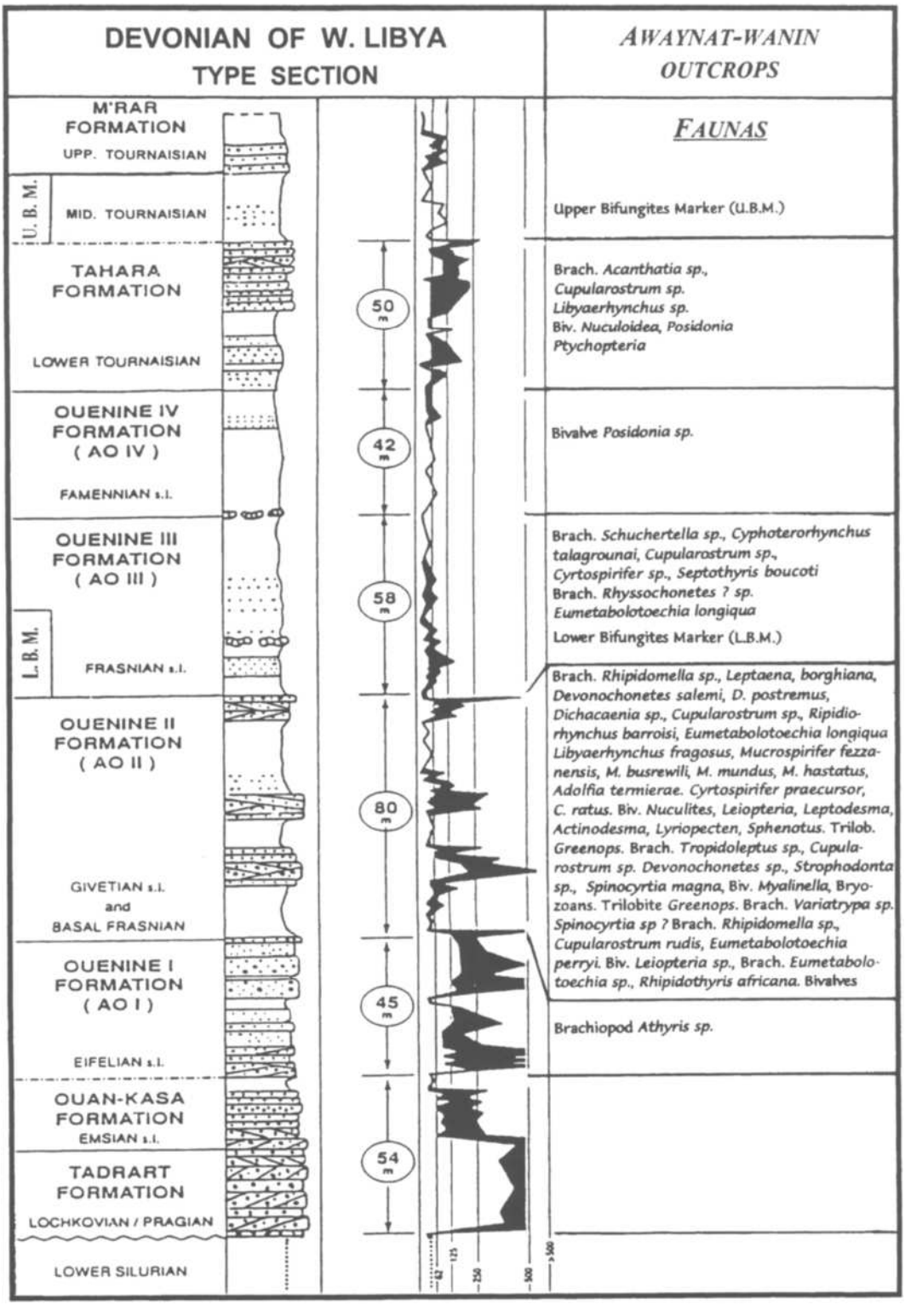

Figure 2. Devonian succession in Awaynat Wanin, southern Ghadames Basin (from Massa, 1988).

overlies the Tadrart Formation's sandstones (Fig. 5). The stratigraphic position of the Tadrart Formation has been mainly based on its ichnofacies and its relation to under- and overlying units. A notable regional sedimentological synthesis was carried out by Clark-Lowes (1985) on the Libyan western basinal flank, where the unit is about 300 to 350 m thick. Some

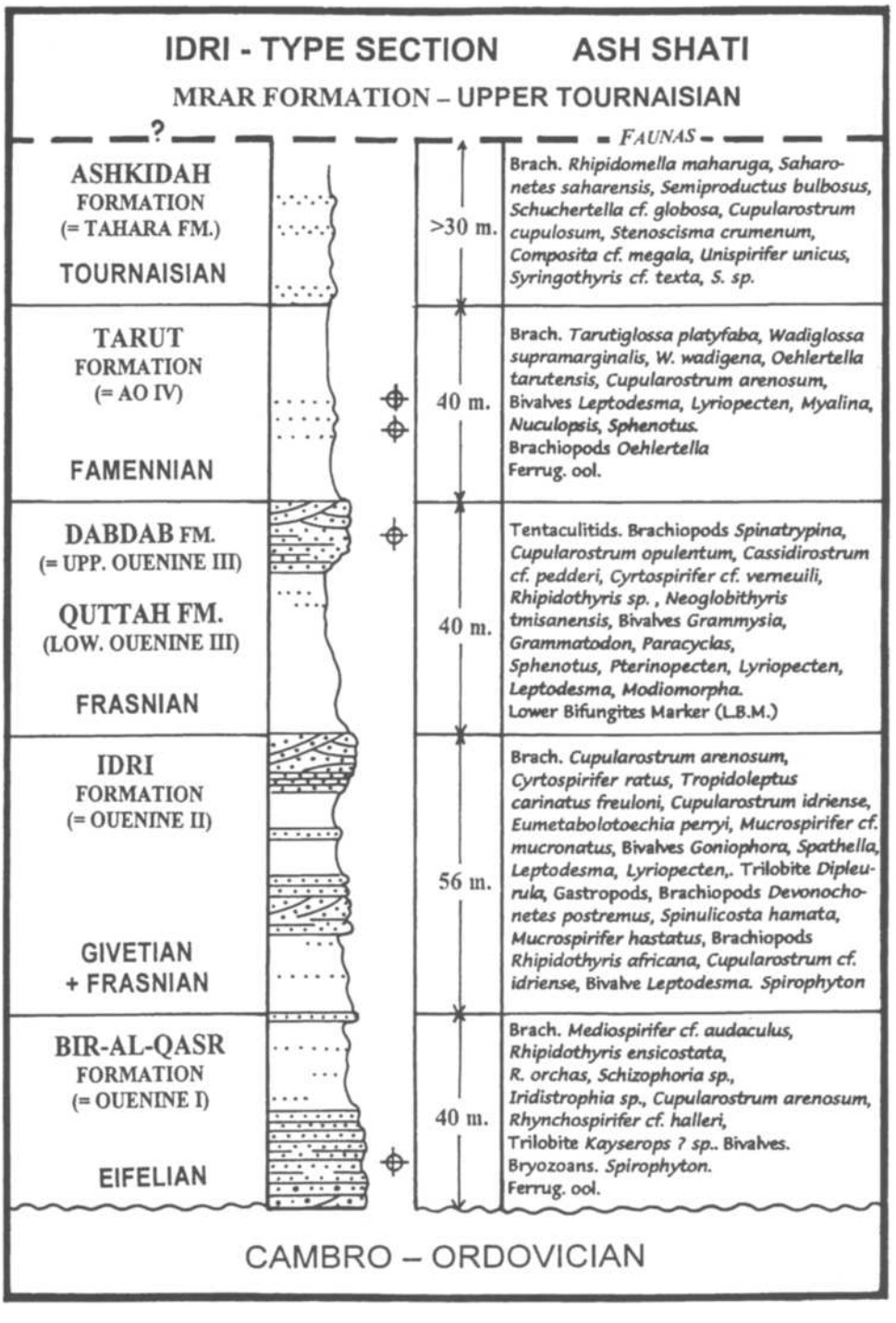

Figure 3. Devonian succession around Idr, western Wadi ash Shati area. northern Murzuq Basin (from Mergl and Massa, 1992).

supplementary data, with a more stratigraphic and regional aspect, were later presented by Massa (1988).

Ghat–Ouan Kasa Formation

The important Gour Iduka section (Fig. 5 and Plate 5) is located east of Ghat (approximate coordinates 24°35′ N, 10°55′ E). This locality displays the type section of the Ouan Kasa Formation, and is located close to the type section of the Tadrart Formation. The section contains a rich fauna that provided the first stratigraphic correlation of this unit (Massa, 1988).

The Emsian age assigned to this formation in the nineteen-sixties (Burollet, 1960) was based on identifications of *Arduspirifer arduennensis* (Schnur) and other varieties of *Arduspirifer* known in the Ardenno-Rhenish basin. The association displays a pre-Eifelian character, and the correlation suggests a dating in the upper part of the early Devonian (uppermost Praghian or Emsian *sensu lato*).

The Ouan Kasa Formation comprises a 40 m development of shales and silty shales alternating with fine sandstones and calcareous siltstones; the percentage of primary carbonate beds varies from 15% to 25%. As far as the faunas are concerned, the commonest species is the acrospiriferid brachiopod *Spinella paulula*; the genus *Spinella* is well known in the Emsian of

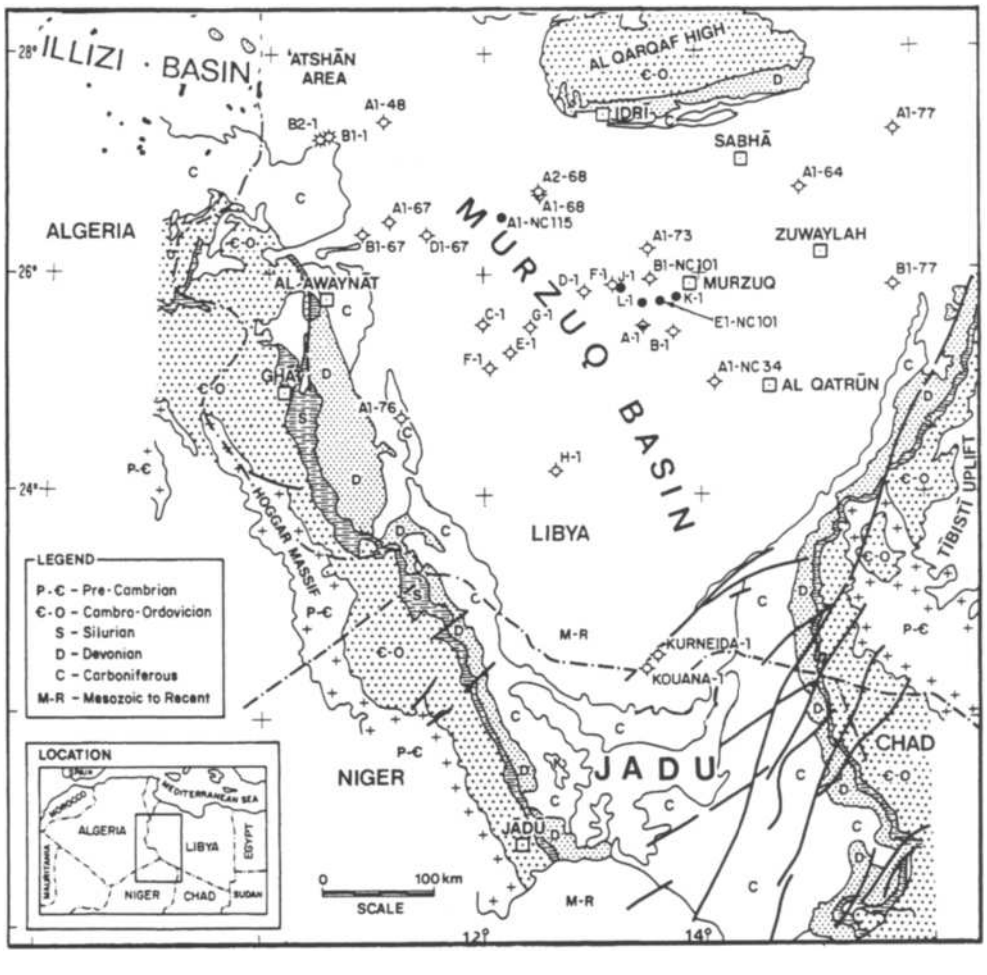

Figure 4. Location map of the Murzuq Basin and its extension into Niger (from Meister et al., 1991).

Australia and Nevada. The trilobite *Homalanotus (Dipleura) simplex* also indicates a general Emsian age. Some of the siltstones and fine-grained sandstones yield a wealth of tentaculitid species (Hajlasz et al., 1978) known elsewhere from the early Devonian, viz. *Vlajovites* cf. *antarcticus*, *Styliolina uralica* and *S. glabra*, together with a microfauna of the arenaceous

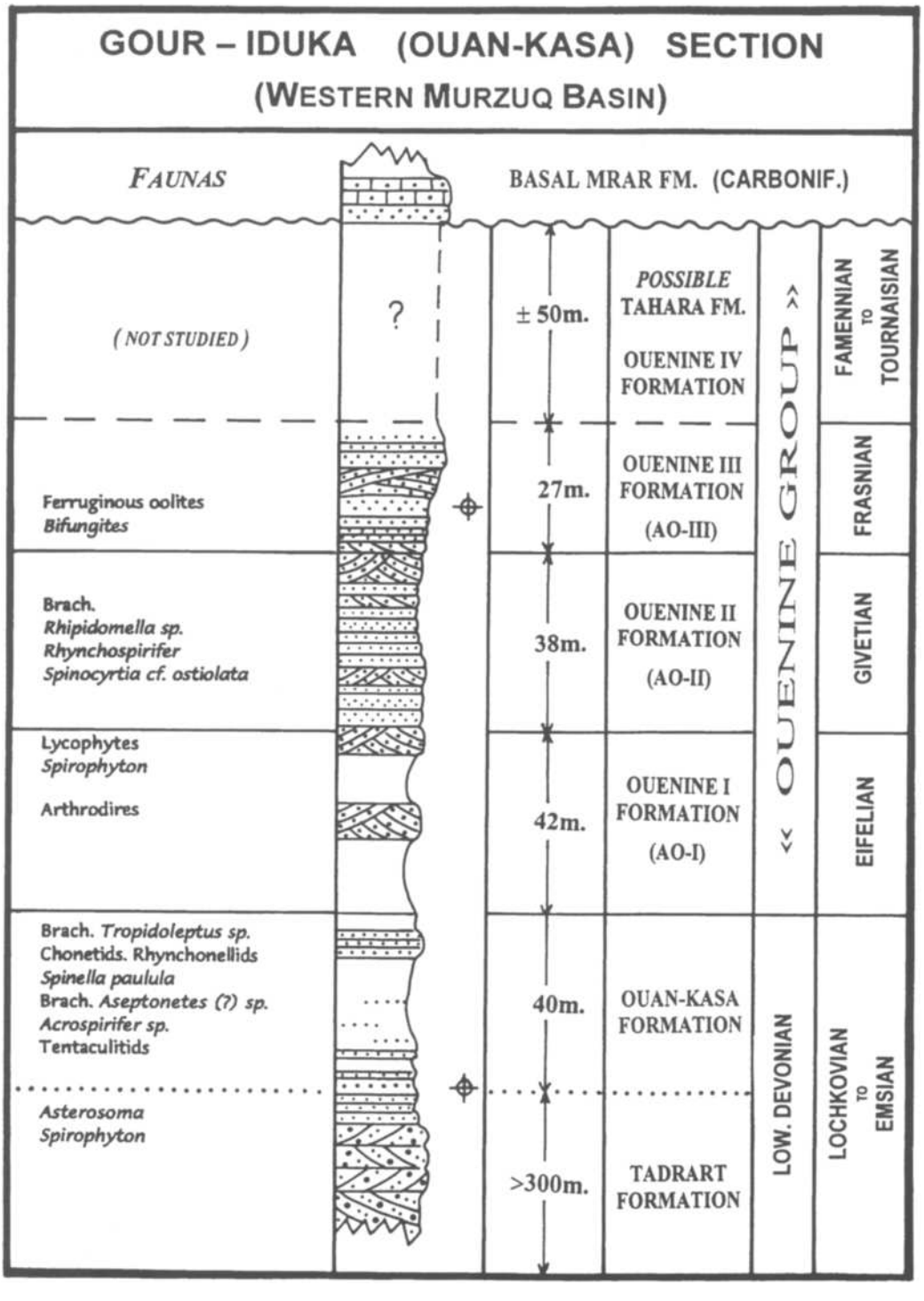

Figure 5. Devonian succession of Gour Iduka, western flank of the Murzuq Basin (from Massa, 1988).

foraminifera *Parathurammina* and *Irregularina*, which are primitive forms reported from the lower Devonian of Siberia.

Ghat–Awaynat Wanin Group

The Gour Iduka section also shows good exposures of apparently conformably overlying Middle to Upper Devonian fossiliferous strata. The succession, as shown in Fig. 5, commences with Awaynat Wanin units I and II, which are about 80 m thick. Brachiopods have been collected from unconsolidated sandstones in the upper parts of this section: the occurrence of *Spinocyrtia ostiolata* confirms correlation to the Givetian. The upper parts of the Gour Iduka section are found on a flat plain with only scattered outcrops and AO III and possibly uppermost unit IV are difficult to study. The exact thickness is unknown, probably 75 m. The abundance of *Bifungites* suggests that the Frasnian (AO III) is represented: this is the classic 'L.B.M.' horizon, also known in the Awaynat Wanin and Idri sections and on the eastern flank of the Murzuq Basin, both in outcrop and subsurface. The *Bifungites* ichnofacies is a good regional Frasnian marker usually associated with ferruginous oolites, as in the Gour Iduka section. The uppermost part of the section is considered as a possible but unconfirmed 'AO IV' equivalent.

In conclusion, overlying a complete lower Devonian section of about 350 m, the total thickness of the middle to upper Devonian could be 150 to 170 m. The relationship between the Tadrart and Ouan Kasa formations has previously been interpreted incorrectly. Klitzsch (1969) for example assigned a middle Devonian age to the Ouan Kasa Formation as also did Clark-Lowes (1985). Along the western flanks of the Murzuq Basin and in western Djado, from NW to SE spanning a distance of some 500 km, the lower Devonian megacycle is complete. The basal Tadrart Formation appears to pass continuously up into the Ouan Kasa Formation, which is open marine and its richly fossiliferous strata give a reliable Emsian dating. These units are overlain by middle Devonian strata in an apparently continuous section.

These considerations are important, first to appreciate the correct local relationships between the lower and middle Devonian strata and second to correctly determine the ages of the Devonian succession in wells drilled in the central parts of these two basins. Sometimes, for example, lower and middle Devonian strata are missing altogether and the Devonian succession starts with Frasnian transgressive strata.

East Tihemboka–Talagrouna Formation Type Section

An Upper Devonian outcrop of limited extent occurs on the eastern flank of the 'Tihemboka Arch' – a major structural feature in the Libyan-Algerian boundary area. The approximate coordinates of the type section are 26°08′ N, 10°23′ E.

This section (Fig. 6) is only about 20 m thick. It starts with coarse sandstones overlying middle Llandovery fossiliferous shales, followed by alternating sandstones and silts. The Upper Devonian is unconformably overlain by fossiliferous upper Tournaisian strata. The Devonian sandstones have yielded a rich and well-preserved marine fauna assigned to the *Cyphoterorhynchus* Community. Besides *Cyphoterorhynchus* itself, other common taxa include various bivalves and the brachiopods *Leioproductus*, *Cyrtospirifer* and *Septothyris boucoti*. A late Frasnian age for the Talagrouna Formation is also clearly suggested by its common tentaculitids (*Dicriconus, Multiconus*) described by Mergl and Massa (1992). In this section, the Famennian is absent either because of non-deposition or by erosion and removal during the Upper Tournaisian transgression. It is important to emphasize the transgressive character of the late Frasnian, because it marks a major palaeogeographic event. The Famennian unconformity has been recognized in the Wadi as Shati area (Collomb, 1962), in several wells in the Murzuq Basin

(unpublished reports), and in the northeastern Djado Sub-basin, both in outcrop (Jacqué, 1962) and the subsurface.

Djado Sub-Basin

The lower Devonian lithofacies on the western flanks of the Djado Sub-basin are so similar to southwestern Libya that the standard Libyan nomenclature may be applied.

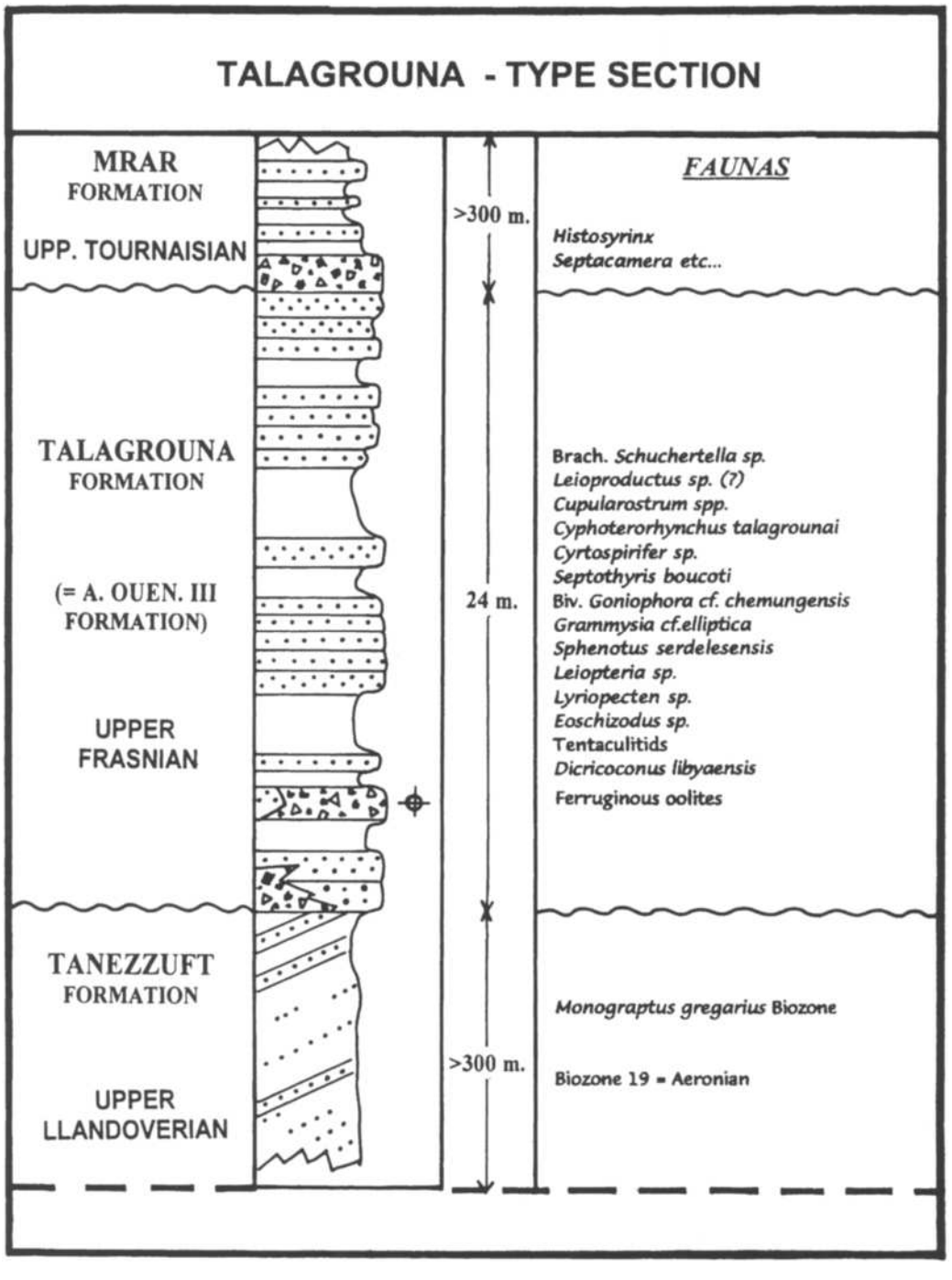

Figure 6. Upper Devonian of the Talagrouna area, northwestern Murzuq Basin.

Djado Sub-Basin–Tadrart Formation

As in the Ghat area, the contact between the Akakus Formation and the basal Tadrart Formation is clearly visible as a palaeosol rich in plant and root fragments, often silicified, with a haematite enriched interface between the two units. This contact was first described by Freulon (1964) and it represents the main Caledonian unconformity in the area. This often shows an angular discordance of 2° to 5° between underlying and overlying units, but in one locality (near In Ezzan), the angular unconformity is reported to reach 45°.

The Tadrart Formation here shows the typical facies of cross-bedded or cross-laminated sands, coarse sandstones and granular to conglomeratic sandstones. Thinly bedded siltstones in the middle of the section show ripple-marks and an ichnofacies with the trace fossils *Fraena*, *Palaeophycus*, *Skolithos*, diverse bilobate fucoids, and rare *Spirophyton*. It is important to note the absence of large *Arthrophycus*, which is characteristic of the underlying Akakus Formation. Common plant fragments, possibly belonging to the psilophyte taxa *Arthrostigma* and *Aneurophyton* were reported by Clark-Lowes (1985).

Djado Sub-Basin–Ouan Kasa Formation and Awaynat Wanin Group

The Ouan Kasa Formation has been traced far to the south of the Djado area. Its main fossiliferous horizon has been located 50 km east of the Chirfa Oasis (20° 55′ N, 12° 43′ E), a distance of approximately 400 km from the Gour Iduka section. Both localities show similar lithofacies, with predominant purple shales and fine-grained sandstones, about 30 to 40 m thick.

The middle and upper Devonian Awaynat Wanin Group equivalent is about 150 m thick and consists of roughly equal amounts of shales and siltstones and fine-grained sandstones with common *Spirophyton* and *Skolithos* (=*Tigillites*). Other fossils have little stratigraphic value (bivalves, crinoids and plant fragments).

Detailed study will probably show this Devonian succession to be more fossiliferous than present knowledge suggests. The '*Spirophyton* ichnofacies' is a valuable Devonian stratigraphic marker known in both the Murzuq and Djado areas. This ichnofacies is not known in the Silurian and the Carboniferous but occurs in the middle of the lower Devonian and is also common in middle and upper Devonian strata.

In conclusion, the Awaynat Wanin Group seems to be complete in the western Djado area. The uppermost strata could possibly be assigned to the Tahara Formation, but this correlation cannot be confirmed biostratigraphically. Several wells in the central Murzuq Basin have encountered Tahara sandstones (Al Muzughi and Al Magtouf, 1981).

East and South Djado–A Brief Review

Extensive outcrop areas favour the study of Devonian sequences in this sub-basin. The existing geological map (Plauchut and Faure, 1959) allows correct location of the large Devonian exposure belt in northern Niger.

The Silurian Akakus Formation is developed in its characteristic fine-grained sandstone facies, rich in *Arthrophycus* (='*Harlania*'). The erosive contact to the overlying Tadrart Formation shows an angular discordance of 2° to 4°. The Tadrart Formation's lithofacies are similar in both the Murzuq and Djado basins (cross-stratified coarse sandstones, conglomerates and even breccias). Previous important observations (e.g. Jacqué, 1962) demonstrate early Devonian synsedimentational faulting activity in the Tadrart Formation; this may explain the frequent and rapid lateral changes in thickness – from 10–20 m to 150 m.

Detailed study of the middle/upper Devonian Awaynat Wanin Group equivalent has not been possible. The general lack of marine faunas in all sections, with only the common trace fossil *Spirophyton* indicating marine conditions, does not allow any precise datings or correlations. Lateral thickness variations are also rapid in this succession, passing from 10 to 100 m within a few kilometres. Overall thinning occurs southwards to near the probable maximum southern extension of the Djado Sub-basin. The Frasnian transgression (AO III) is suggested in several sections by Frasnian strata resting directly on the Tadrart Formation. The lithofacies is predominantly shaly, often with dark grey shales and ferruginous oolites.

An alternative interpretation is that the Awaynat Wanin Group is not developed and that the lower Carboniferous basal Marar Formation directly overlies the Tadrart sandstones. These two alternatives support the concept of polyphased early and late Caledonian structural events.

CARBONIFEROUS

A monograph of Carboniferous macrofaunas in Libya was published by Massa et al. (1974). In addition, micropalaeontological studies have helped to establish a detailed stratigraphical framework in these areas. Specimens are not very abundant but are sufficiently common in the Illizi-Zaghir basinal sections; the three main groups studied are ostracods, foraminifers and conodonts. Ostracod assemblages were shown to provide useful stratigraphical and palaeontological information by Bless and Massa (1982). Conodont determinations by Weyant and Massa (1985) were supplemented by additional studies of Weyant and Massa (1991). Two publications deal with the foraminifera of the Carboniferous of Libya (Massa and Vachard, 1979; Vachard and Massa, 1984), both giving descriptions of microfacies containing algae and foraminifera that allow correlation between Libya and the Illizi Basin. Finally, Massa (1988) presented a synthesis of the whole Palaeozoic succession, including the Carboniferous.

Several recent publications have dealt with the Carboniferous of western Libya, which is now relatively well known. However, it should be noted that most of the petroleum exploration has been carried out in the Illizi Basin of Algeria so that the majority of early stratigraphical studies were published in French (Dubois, 1960; Remack-Petitot, 1960; Lys, 1979, 1985; Legrand-Blain, 1980, 1985a, 1985b, 1986; etc.). Until now the Illizi and Ghadames basins have been considered separately. In our view, however, these two basins were parts of the same depositional complex during Carboniferous times. Hence we propose the term 'Illizi-Zaghir' Basin for this whole 180 000 to 200 000 km^2 region. The wide plateau covered by the Awbari sand sea represents the Zaghir area (often spelled Zegher on old maps), which extends in an E-W direction (Fig. 7). The Carboniferous largely outcrops in this area and includes the Marar, Assedjefar and Dembaba formations in the southeastern Tinghir Hammada (Bellini and Massa, 1980). In the present review, two composite reference sections have been selected, one representing the Illizi Basin and the other the Zaghir area (Figs 8 and 9).

The most valuable macro- and microfaunas (mainly foraminifera and conodonts) are discussed herein in order to augment the data described previously and to strengthen the proposed datings of successions located on the western and eastern sides of the Algerian-Libyan border (Fig. 10). The stratigraphical nomenclature used in this paper refers to the classical Dinantian succession of Belgium for the Lower Carboniferous and to the terminology proposed by the International Carboniferous Congress (1975) for the marine Upper Carboniferous of the Russian platform. The Carboniferous development of western Libya has been defined on the basis of both outcrop and subsurface data and the total thickness of the five formations described herein is about 1000 to 1200 m, including the Permo-Carboniferous Tiguentourine Formation. These units were first described by Bellini and Massa (1980), later supplemented by Massa (1988).

In a regional perspective, correlation between the southern part of the Ghadames Basin and the northern and central parts of the Murzuq Basin are possible in the sense that lateral facies changes are generally gradual, particularly in the Marar and Assedjefar formations. However, the correlations become more doubtful in the upper Dembaba Formation because the marine carbonates present in the northern areas disappear near the Niger-Libya frontier, passing laterally into red shales and sandstones.

Zaghir–Marar Formation

The lower parts of the formation consist of about 50 m of dark grey shales and marls containing several fossils, including goniatites (section in Fig. 8). A black phosphatic bed, with nodules rich in radiolarites, is developed at the base. Higher up the facies is mainly shaly (80% green and dark grey shales) with minor fine-grained sandstones and siltstones that may be ferruginous and/or dolomitic.

Near Al Awaynat, on the northwestern flanks of the Murzuq Basin, the basal Carboniferous rests directly on Lower Devonian or Silurian strata with a well-defined unconformity. The faunas found in this area have been described by Massa et al. (1974). Our dating of an Upper Tournaisian age is confirmed by the brachiopod genus *Fusella* (the '*Spirifer tornacensis*' group).

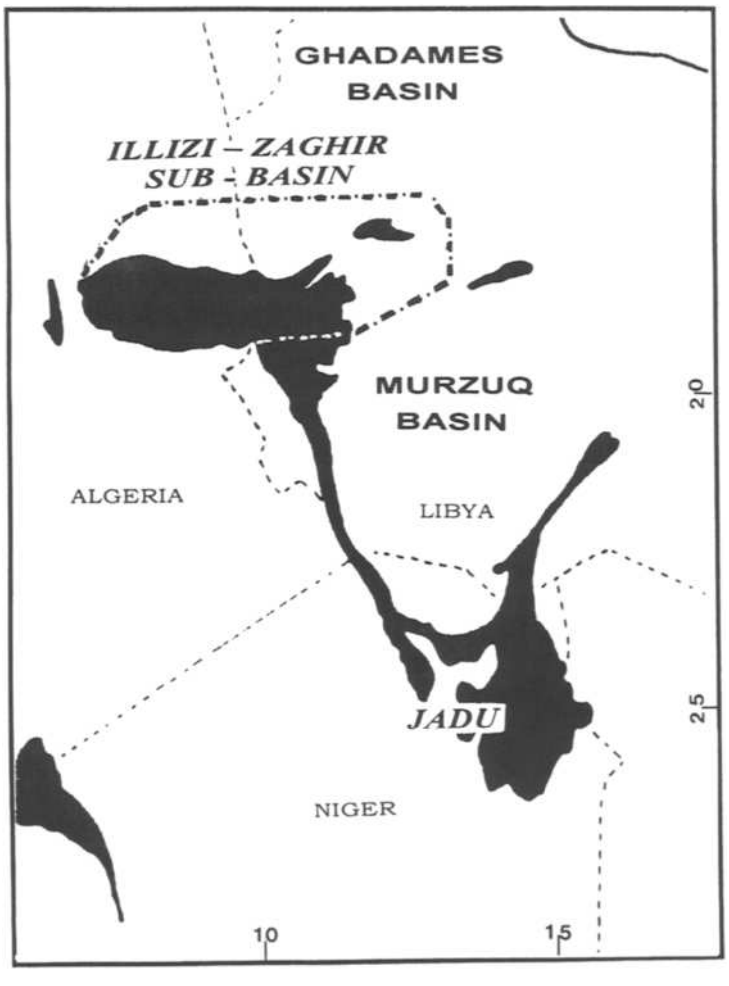

Figure 7. Simplified map of the Illizi-Zaghir Carboniferous Basin.

In the Wadi ash Shati area, equivalent faunas are assigned to the *Prospira* Community. An upper Tournaisian age is also confirmed by the presence of *Muensteroceras* and other goniatites (Fig. 8) discovered at the base of the Awaynat Wanin section of the Marar Formation. This section contains a faunal assemblage with both endemic and cosmopolitan elements, including fish fragments, bivalves, nautiloid cephalopods (Orthoceratidae), corals and crinoids. Among endemic forms, the brachiopods *Histosyrinx* and *Septacamera* (= *Paurogastroderhynchus*) have been found in a sandy lithofacies of beach origin. Both these taxa are of regional interest as they

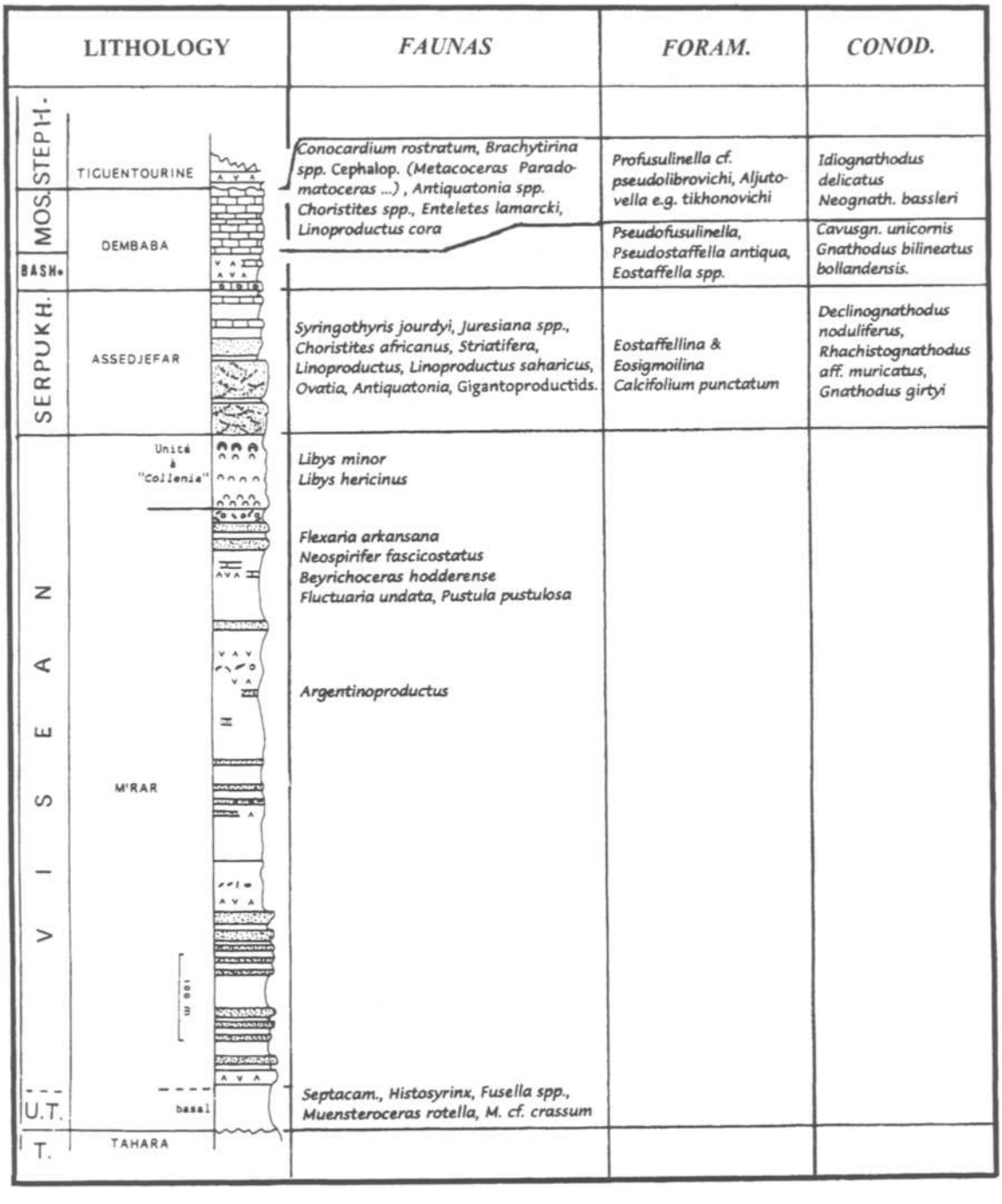

Figure 8. Zaghir Carboniferous section: lithology and faunas (modified after Coquel and Massa, 1993).

also occur in the Upper Tournaisian of the northern and southern Hoggar (Legrand-Blain, 1974). This indicates that the basal Carboniferous marine ingression was synchronous throughout the central and eastern Sahara.

The upper Marar Formation displays a monotonous succession of shales and marls with few fossiliferous horizons. Two significant taxa are *Beyrichoceras* and *Fluctuaria undata*, because they characterise the Upper Viséan stage, more precisely termed 'V3C' in the Belgian nomenclature (Fig. 8). This age is also supported by the occurrence of *Goniatites striatus*.

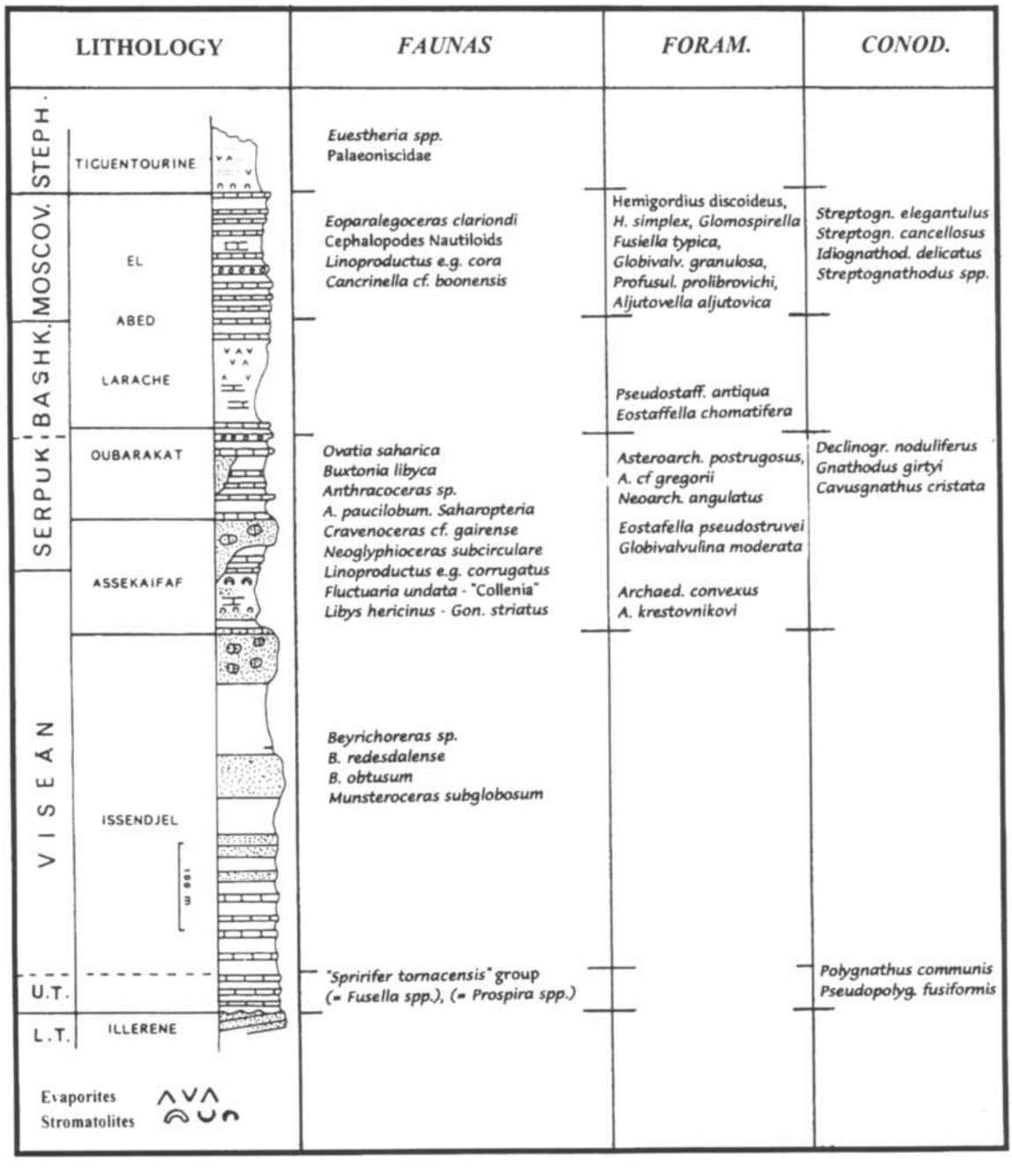

Figure 9. Illizi Basin – Carboniferous section: lithology and faunas (modified from Coquel and Massa, 1993).

The '*Collenia* Bed' contains 4 to 5 stromatolitic levels (each 0,5 to 1,5 thick), which are used as lithologic markers. Associated with these are micrites, dolomicrites, breccias, oolites, dolomitic shales and anhydrite in the form of cement or as nodules. The stromatolites indicate an intertidal or supratidal environment corresponding to lagoonal mud flats that were periodically flooded. Among the fossils of the *Collenia* Bed, two characteristic Saharan taxa, *Neospirifer fascicostatus* and *Saharopteria* (*Pachypteria*) are worth mentioning.

Zaghir–Assedjefar Formation

Cross-bedded sandstones characterise most of this formation while the upper third consists mainly of carbonates (packstones) and marls. Only two biozones have been identified because most of the lithofacies do not favour the preservation of macrofaunas. The lower biozone is

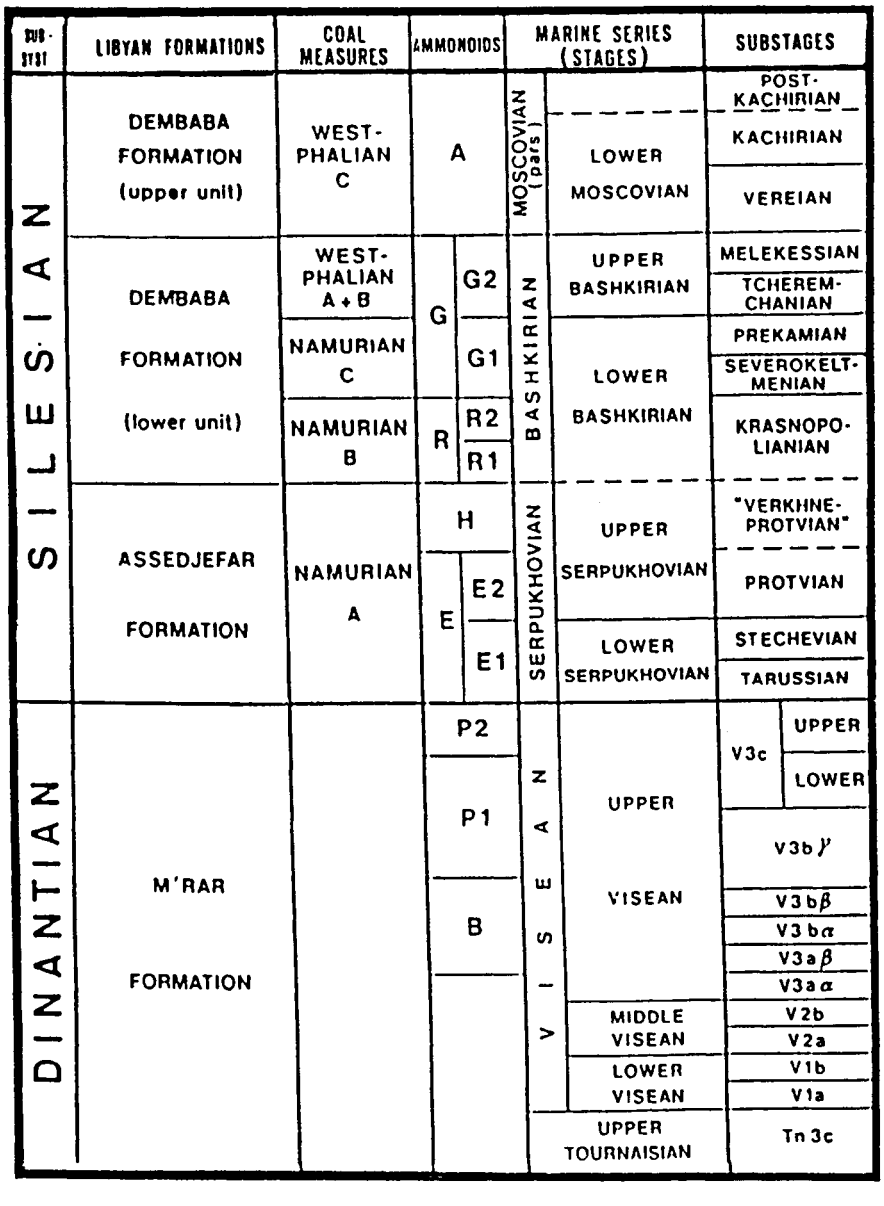

Figure 10. Carboniferous stratigraphy in eastern Algeria and western Libya.

characterised by the alge *Calcifolium punctatum* and the upper by the two foraminifera *Eostafellina* and *Eosigmoilina*. These clearly establish a Serpukhovian age (Belgian E1 and E2). Correlation with the type sections of the upper Assekaifaf and Oubarakat formations in the Illizi Basin is excellent because diagnostic goniatites such as *Cravenoceras*, *Neoglyphioceras* and *Anthracoceras* (Fig. 11) have been found in these formations.

Zaghir–Dembaba Formation

The Lower Dembaba Formation begins with oolitic limestones and green to red dolomitic marls, but green gypsiferous shales dominate the unit. Macrofaunas are poor but foraminifera (Fig. 8) indicate a Bashkirian age.

The lithology of the Upper Dembaba Formation is rather monotonous, with about 80% carbonates, but the microfacies developed are highly diversified (biopelmicrites, oolitic grainstones, wackestones, mudstones with several pyritised plant fragments, etc.). Macrofaunas are abundant, diversified and well preserved. The rich macrofaunal associations (Massa et al., 1974) and the microfauna shown in Fig. 8 clearly demonstrate a Moscovian age.

The Illizi Basin

The Carboniferous succession oversteps several levels of the Silurian and/or the Devonian from the west to the east in the Illizi Basin (Dubois, 1960). This basal unconformity is well defined in outcrops in the northern Tassili-n-Ajjer. Different formations were defined within the Carboniferous during the nineteen-sixties and the major stratigraphic units are now well established.

Illizi–Issendjel Formation

This formation is made up of marls, silty shales and sandy limestones, with sedimentological features resembling those described by Whitbread and Kelling (1982) in the deltaic Marar complex of the southern part of the Ghadames Basin. In the Illizi area, the base of the formation is dated as Upper Tournaisian and this is well constrained by the brachiopod association. Higher strata containing species of *Beyrichoceras* suggest a Middle Viséan age. Uppermost strata have been referred to as the 'Mushroom sandstones' because weathering and erosion have produced characteristic mushroom shaped outcrops.

Illizi–Assekaifaf Formation

The lower parts of this unit consist of marls and limestones including a *Collenia* stromatolitic horizon. In its upper parts a second 'Mushroom sandstone' horizon forms a good local marker. Both horizons are laterally extensive. Foraminifera discovered in the middle part of the formation, such as *Eostafella pseudostruvei*, indicate a Late Viséan to Early Serpukhovian age, which is also supported by a rich fauna of ammonoids and brachiopods (Fig. 9).

Illizi–Oubarakat Formation

The lower and middle members consist of silty shales with frequent limestone interbeds. Among the foraminifera, *Neoarchaediscus angulatus* indicates a late Serpukhovian age.

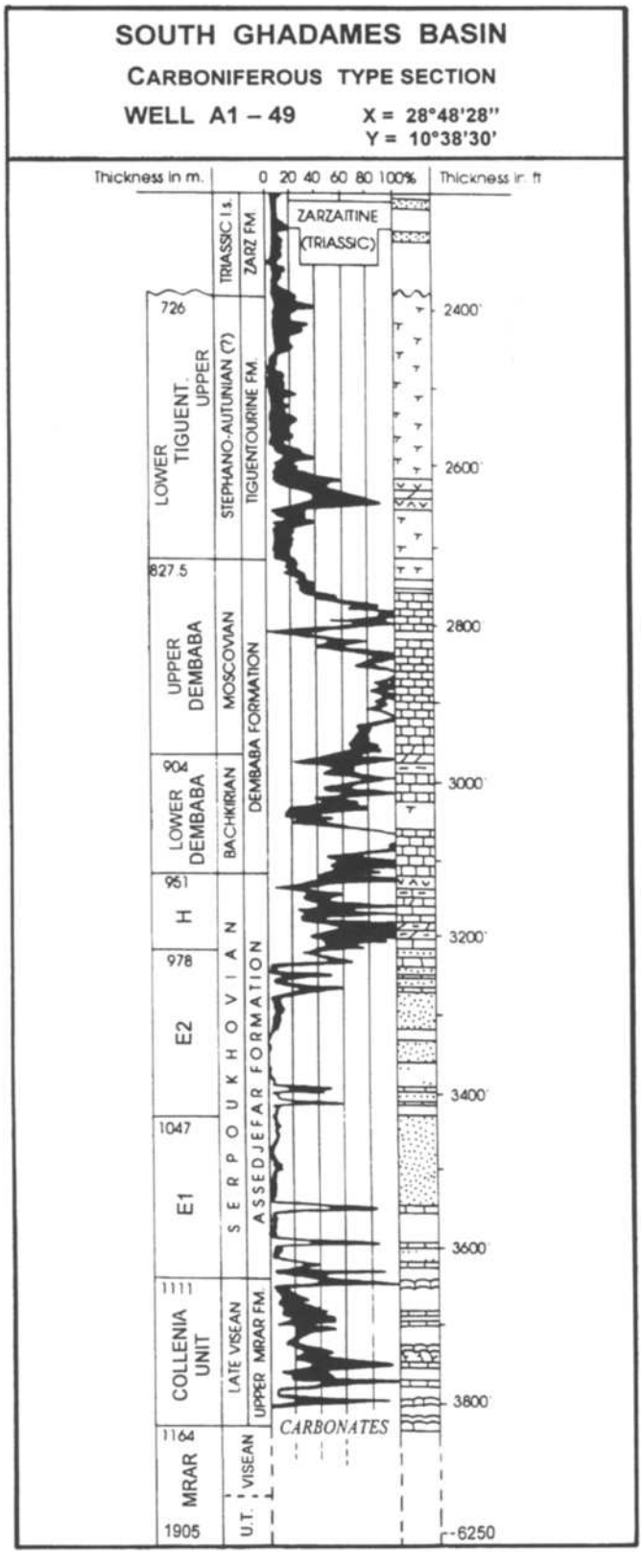

Figure 11. Typical Carboniferous succession, log from well A1–59, eastern Illizi-Zaghir Sub-basin (from Massa, 1988).

Illizi–El Adeb Larache Formation

The lower part of the formation is a thick shaly unit with several gypsum interbeds: it is dated to the Bashkirian from an association of foraminifera including *Pseudostafella antiqua* and *Eostafella chomatifera*. Carbonate facies dominate the upper part of the unit, with limestones and dolomites. An early Moscovian dating is based on foraminifer and conodont associations as well as large nautiloid cephalopods (*Domatoceras*, *Metacoceras* etc.).

Three biozones have been defined from the foraminiferal assemblages in the upper part of the Al Adeb Larache Formation (Massa and Vachard, 1979):

The *Aljutovella* Biozone of the Lower Moscovian,
The *Profusulinella* Biozone (also with the ammonoid *Eoparalegoceras*, dated as Kashirian,
The *Glomospirella* Biozone dated post-Kashirian and possibly Podolskian.

The uppermost biozone, containing *Hemigordus discoideus*, indicates a nearshore facies of Myatchkovian age. Following this last marine episode, the Carboniferous sea definitively retreated from eastern Algeria and western Libya.

Illizi–Tiguentourine Formation

The total thickness of this formation is about 200 m: its dating must be considered as tentative due the scarcity of fossils in the sediments. The following description is mainly based on the works of Fabre (1970) and Bertrand-Sarfati and Fabre (1972).

The lower part is made up of red and green shales with primary dolomites indicating a fluviatile or lagoonal environment. The lower half contains thin layers of stromatolitic limestones rich in *Euestheria* (*E. simoni* and *E. tenella*) associated with palaeoniscid and selachian fish fragments. In the upper part, there is a massive gypsum bed (2 to 4 m thick) and reddish cross-bedded sandstones indicate a fluvial environment with evidence of aeolian influence.

The lower part of the formation is assigned to the continental upper Carboniferous interval, while the upper part is given a general pre-Triassic (perhaps Permian) assignation. This correlation is partly based on the occurrence of unstable heavy minerals (disthene, hornblende, hypersthene) in the upper part of the formation: these might be related to the erosion of pre-Permian volcanics and are unknown in the lower part of the formation.

The lithofacies and thickness of the Tiguentourine Formation in the *Zaghir* area are very similar to those described in the Illizi Basin.

Outcrops in Eastern Fezzan

The Carboniferous succession largely outcrops in the eastern Murzuq Basin between 24° and 22° N in the Dor El Gussa area: the Carboniferous was first studied in this area by Lelubre (1948, 1952) and Jacqué (1962). The facies displayed here are comparable to those described in the Zaghir area (Massa, 1988) and lateral equivalents of the Marar, Assedjefar and Dembaba Formation are well developed.

Eastern Fezzan–Marar Formation

The base of this 450 m to 500 m thick development contains a ferruginous oolite with Carboniferous fossils (chonetids and *Septacamera*). The basal Marar Formation comprises about

60 m of shales with several dolomitic limestones and fine-grained calcareous sandstone interbeds. This horizon, which is an excellent marker southwards into the Djado Sub-basin, is dated to the late Tournaisian. Upsection there are coarse-grained yellow sandstones and green shales with some interbeds of fine-grained calcareous sandstones and ferruginous oolites; the 'Mushroom facies', already noted, has been found in some places. Despite the lack of faunas, the Marar Formation is considered as Viséan except for its base, which could be late Tournaisian in age.

Eastern Fezzan–Assedjefar Formation

This formation comprises a 60 m to 120 m succession of green shales and calcareous interbeds with brachiopods and bryozoans. Foraminifera and conodonts indicate a Serpukhovian (early Namurian) age.

Eastern Fezzan–Upper Dembaba Formation

This 70 m to 90 m thick unit comprises green to red-brown shales, sometimes gypsiferous, with lenses of sand- and siltstones. Two thick calcareous cliff-forming beds, slightly dolomitic, are highly fossiliferous. Conodonts indicate a Moscovian age (Weyant and Massa, 1985). Macrofaunas are represented by large nautiloid cephalopods such as *Domatoceras*, *Paradomatoceras* and *Ephippioceras*.

Eastern Fezzan–Tiguentourine Formation equivalent

This is represented by about 50 m of sandy red shales associated with barren red sandstones. These sediments are considered as equivalents of Unit JC-6/7 defined in the subsurface and outcrops of the central Djado Sub-basin.

Outcrops of Eastern Djado

To the south, towards border areas to northeastern Niger, thicknesses remain similar but there are some facies changes relative to the formations described from eastern Fezzan: limestones decrease in the Assedjefar and Dembaba formations and diagenetic cone-in-cone structures become more common, as also do sand and gypsum interbeds. All these features indicate that environments became less marine-influenced and more lagoonal in this direction.

We will now present a composite section for the eastern Djado Sub-basin of northern Niger, based on outcrops between 23° 30′ and 23° N (Fig. 4).

Djado Sub-Basin faunas

In the late nineteen-fifties, French geological teams were assigned to a large-scale reconnaissance of the Djado area. Fossils collected in the course of this fieldwork were deposited in the Natural History Museum in Paris for palaeontological investigation. This original collection has now been partially retrieved, together with both geographic locations and measured field sections. Three main fossiliferous horizons were sampled during the field

reconnaissance (Fig. 12), viz. the Upper Tournaisian, Upper Viséan and the basal and middle parts of the Serpukhovian. All these samples, mostly associated with calcareous sandstones or limestones, have been restudied and these new palaeontological results are presented in the last part of this chapter.

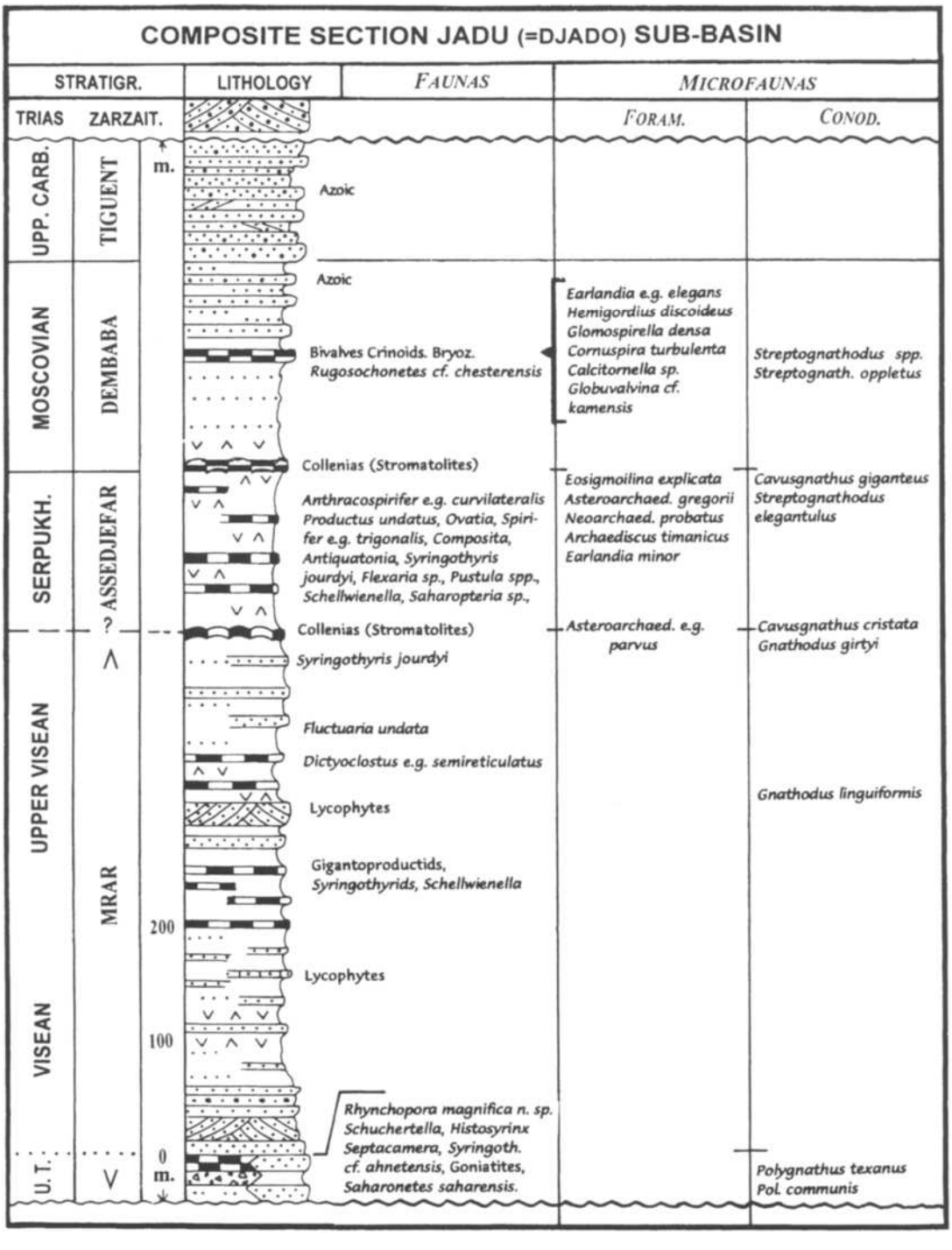

Figure 12. Composite section of Carboniferous outcrops in the Eastern Djado Sub-basin: lithology and faunas.

Eastern Djado–Marar Formation

The formation is about 450 m thick in this area. Its base, resting unconformably upon Devonian strata, is represented by conglomeratic sandstones and cone-in-cone limestones with various fossils. Brachiopods (mainly chonetids), bivalves, crinoids, gastropods and orthocone nautiloids are preserved in overlying green shales. Conodonts are also present. These fossiliferous strata are about 40 m thick. Fine-grained beige sandstones alternating with silty and more or less gypsiferous shales represent the upper part of the formation.

Eastern Djado–Assedjefar Formation

Marine influence is more apparent in this 160 m thick formation; oolitic limestones and *Collenia* (stromatolites) are common and the associated green shales contain primary gypsum. The formation can be dated to the Serpukhovian from two beds containing foraminifera.

Eastern Djado–Dembaba Formation

The base of this 80 m to 120 m thick development contains a marker horizon that is well known both from outcrops in eastern and southern Djado and in the subsurface from wells drilled in the centre of the sub-basin. This is called the 'Blue Limestone Marker' in the BRP reports but its lithological characteristics may differ from one area to another (*Collenia* beds or organic-rich limestones or gypsiferous limestone). In our composite section, it has not been possible to confirm the Moscovian age of this marker, although it is assigned to the Dembaba Formation. The dating of this formation in the area is essentially based upon foraminifers and conodonts discovered in another limestone in the same succession (Fig. 12).

The formation otherwise comprises red and white shales with a few blue to black limestone beds. It is thought to represent a lagoonal facies of Moscovian age. This assessment is essentially based on lithological correlation as no diagnostic fossils (only gastropods) have been found.

Eastern Djado–Tiguentourine Formation

This 100 m thick formation is assigned to the continental Upper Carboniferous. The sediments become increasingly sandy (fine red micaceous sandstones) upwards, with shaly interbeds. This unit may be a lateral equivalent of the Madama sandstone and is represented by unit JC-6 in the subsurface of the basin (see below).

The Subsurface of the Djado Sub-Basin

The most accurate data on the Carboniferous development in the subsurface of this area come from two boreholes:

'Kourneida, (KR1)', coordinates 22°40′50″ N, 13°36′10″ E, and
'Kouana, (KO1)', coordinates 22°40′04″ N, 13°31′18″ E.

These two wells are close to each other and can be easily correlated, so that lateral variations in the succession can be documented. Correlations with an outcrop in the south-central part of the sub-basin are also proposed (Fig. 13). A local lithostratigraphic scheme is proposed for the

Djado Sub-basin, although the terminology for the interval between the Upper Tournaisian and the base Triassic (units 'JC-1 to 7' in ascending order, 'J' for Djado and 'C' for Carboniferous), is informal and based on well KR1.

Unit JC-1 (26 m from 1,337 m to 1,363 m): Upper Tournaisian

Micaceous black shales and siltstones are very fossiliferous, with chonetids and goniatites. This unit has locally been called the 'Dada Shale' based on an outcrop at 20°15′ N and 14° 05′ E.

Unit JC-2 (463 m from 900 m to 1,337 m): Viséan

This unit consists of dark grey and black shales, often silty (90% of the unit), with some fine-grained sandstones. Some thick calcareous sandstones are well developed in the unit. A 2 m

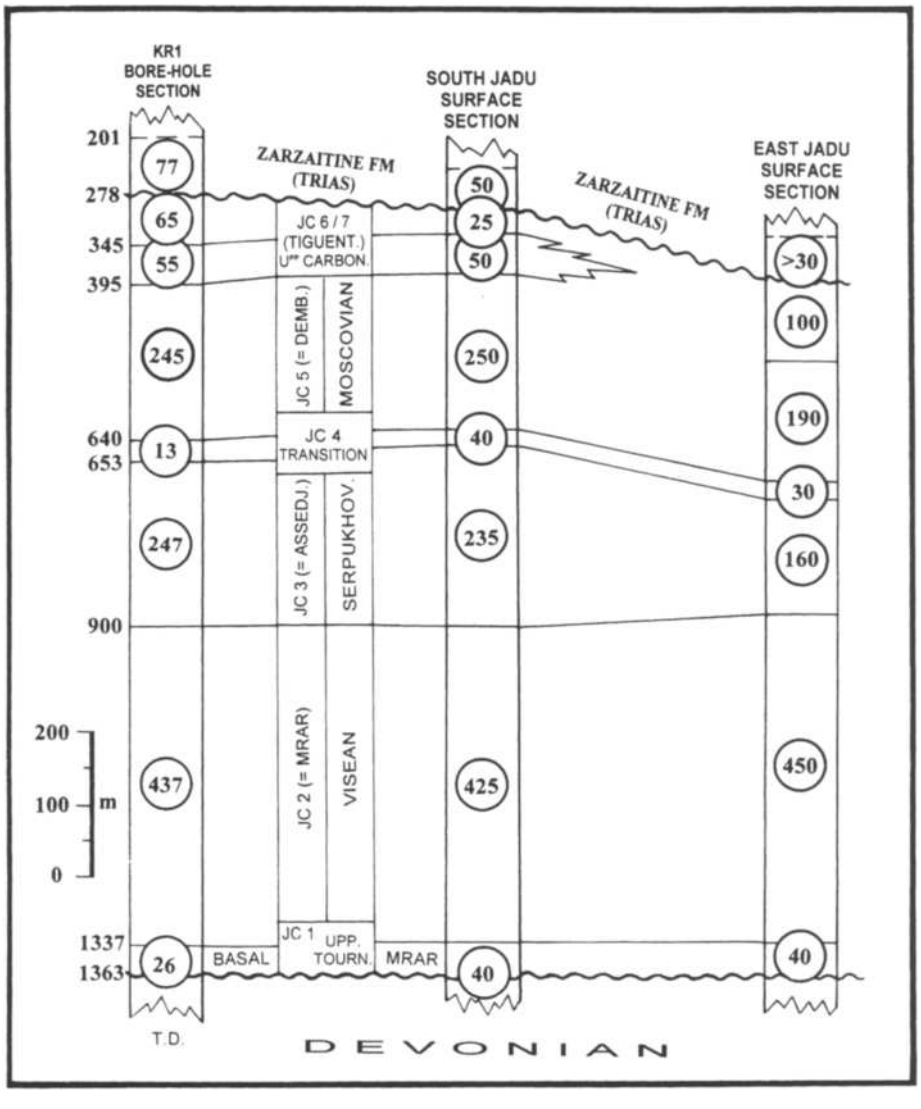

Figure 13. Regional correlation of the southern Djado Sub-basin Carboniferous succession from subsurface and outcrop data.

thick carbonate bed containing gastropods (bellerophontids) found uppermost correlates approximately to the Viséan to Serpukhovian transition (Fig. 12).

Unit JC-3 (247 m from 653 m to 900 m): Serpukhovian

Unit JC-3 shows a similar general shale facies to the underlying unit, but with frequent interbeds of gypsiferous shales, fine-grained calcareous sandstones and siltstones. Some lignite and black plant fragments occur.

Unit JC-4 (13 m from 640 m to 653 m): uppermost Serpukhovian to base Moscovian

A white massive anhydrite bed that is a good regional marker and is tentatively dated to the Bashkirian overlies bluish limestones and shales. This unit has also been found on the eastern flank of the sub-basin. It should be noted that definite Bashkirian age strata have been confirmed only in the northwestern Murzuq Basin (Massa and Vachard, 1979).

Unit JC-5 (245 m from 395 m to 640 m): Moscovian

Red, brown, purple and yellow shales with a high sand content also have frequent interbeds of fine-grained calcareous sandstone and siltstone. Some silicification (chalcedony) takes the form of nodules or thin interbeds. Two carbonate grainstones (between 472 and 492 m) have yielded porcellanous foraminifers including *Cornuspira turbulenta*, *Cornuspira parva* and *Globovalvulina minima*. This bed represents the last marine episode on the southern margins of the Murzuq Basin.

Unit JC-6 (55 m from 345 m to 395 m): Lower Tiguentourine equivalent – probably upper Carboniferous

White fine-grained sandstones, with interbeds of red plastic shales and sandstones with carbonate cement, are locally called the 'Madama sandstones' because they are exposed near and around Madama, a military fort in the central part of the basin. This facies is unfossiliferous and probably represents a continental environment.

Unit JC-7 (74 m from 278 m to 345 m): Upper Tiguentourine equivalent – probably uppermost Carboniferous

Red or violet plastic clays are often silty and contain black carbonate ooids rich in manganese oxide. A thin volcanic microbreccia was observed at 304 m in KR1. The age of this unit is unconfirmed, although it can probably be correlated to the uppermost Carboniferous or basal Permian Tiguentourine beds.

Zarzaitine equivalent (77 m from 201 m to 278 m): Triassic

Haematitic red shales and coarse sand and gravels (7 m) mark the unconformable contact with JC–7; the remainder of the unit comprises monotonous unconsolidated sands with quartzitic

gravels. In well KO1 (Fig. 6), a 315 m thick sandy shale succession overlies this unit. This is not dated but could be an equivalent of the Upper Zarzaitine and – in part – the Taouratine Formation of Jurassic age, both these units being well known in the Illizi Basin and in the subsurface of the central Murzuq Basin.

DEVONIAN AND CARBONIFEROUS PALAEOGEOGRAPHY OF W LIBYA AND NW NIGER

The regional stratigraphy of this enormous area, extending from southeastern Algeria to northeastern Niger and including two flanks of the Murzuq Basin, highlights the main palaeogeographic changes in the area during Devonian and Carboniferous times. Considering the size and nature of the study area, the brief summary below is necessarily tentative. We should also note that palaeobotanical and palynological studies, which have provided excellent results in the Palaeozoic of other North African basins, have not been included in this review.

The regional late Frasnian transgression represents one of the most important Devonian events in the region. This marine invasion of large areas has already been recognised by geologists working in Libya such as Collomb (1962) who described the 'Chatti Formation', Jacqué (1962) who described the 'Meerschema Formation' in the eastern Murzuq Basin and Massa (1988) who described the 'Talagrouna Formation' in western Murzuq. This late Frasnian transgression is now seen to have extended southwards into the Djado Sub-basin.

Structuring of present-day uplifts and arches was possibly initiated during the early to middle Devonian because sediments of this age are relatively thin or missing over these palaeostructures – although condensed deposits of mainly black radioactive shales do occur during major highstand periods, such as in the late Frasnian. The regional Famennian regression is more important in the Murzuq-Djado area than in the Ghadames Basin: this regression, well known over the whole African platform, was followed by renewed transgression in the Early Carboniferous (Conrad et al., 1986).

During the Upper Tournaisian a new transgression occurred in the central Fezzan region and it is worthwhile to note some differences between the flanks of the Murzuq-Djado area: the eastern Tibesti coast formed a large sandy flat and euxinic marine conditions were quickly established over the entire area. The basin's western coast was different and morphologically varied, with embayments, islands and capes. This explains why the first Carboniferous sediments in this area may be palaeosoils, continental sands rich in plant fragments or ferruginous oolites (Chauvel and Massa, 1981).

The environments that prevailed southwards during the Viséan are increasingly continental in aspect, with monotonous sequences of sandstones, siltstones and shales in which alluvial conditions are indicated by carbonaceous shales with lignites and lycophyte fragments. These sediments were called 'Viséen à Plantes' by the first field geologists working in the Djado and are characterised by a lack of marine fossils and a high frequency of plant fragments such as lycophytes, lycopods and psilophytes.

Certain facies that are encountered only in the Viséan/Lower Namurian of the Djado Sub-basin highlight the continental character of this succession. These include concretionary limestones of travertine type indicating a lacustrine environment and caliche beds typical of soils in arid climates. *Collenia* stromatolitic beds have already been mentioned; these are laminated columnar structures resulting from periodic algal growth. They are known in the Illizi Basin (uppermost Viséan), in the Murzuq Basin (lower Serpukhovian) and in the Djado Sub-basin and cannot be considered as synchronous markers as they reflect purely local conditions in an overall generally tropical and humid environment; they may also be reworked and redeposited in different units of late Viséan to Moscovian age.

The sea retreated from the region in the latest Carboniferous. A widespread continental horizon containing calcitised wood without any internal structure contains fragmented trunks up to 6 m long and 15 cm in maximum diameter; this may represent a regionally extensive palaeosol.

PALAEONTOLOGY

Faunas of the Ghadames Basin: Awaynat Wanin Area

The mid- to upper Devonian sequence in the Awaynat Wanin area, ranging from the Eifelian to the Famennian, is richly fossiliferous – particularly in the Givetian to Frasnian interval (Fig. 2 and Plates 1, 2). Faunas consist of brachiopods and bivalves and several other less common invertebrates. Several authors have described elements of this fauna, the most comprehensive data being provided by Boucot et al. (1983) and Mergl and Massa (1992).

Awaynat Wanin Area–AO I

The oldest fossiliferous beds at the top of AO I contain a low-diversity fauna, including poorly preserved *Athyris* sp. and unidentifiable bivalves. The community is referred to a shallow subtidal environment.

Awaynat Wanin Area–AO II

AO II is highly fossiliferous, with distinct benthic communities being concentrated in sandstones at the tops of three sedimentary cycles (Van Houten and Karasek, 1981; Vos, 1981).

The sandstones in the lower part (cycle I) have yielded a low-diversity *Rhipidothyris* Community, with a dominance of the coarsely costate terebratulid *Rhipidothyris africana* and rare rhynchonellids (*Eumetabolotoechia* and *Cupularostrum*). Their preservation, with a markedly high percentage of articulated shells, indicates a calm but shallow marine environment.

Sandy levels in the upper part of cycle I contain the *Eumetabolotoechia* Community. The large rhynchonellid *Eumetabolotoechia* sp. is associated with coarsely ribbed, medium-sized rhynchonellids (*Cupularostrum* sp.), an orthid (*Rhipidomella* sp.) and abundant bivalves (*Leiopteria* sp.). Disarticulation of the shells and traces of abrasion indicate an agitated shallow subtidal environment.

Siltstones in the lower part of the overlying cycle IIa (Vos, 1981) have yielded the more diverse *Spinocyrtia* assemblage, characterised by the large spiriferid *Spinocyrtia magna*, together with minute rhynchonellids (*Cupularostrum*) and diverse but less abundant brachiopod genera (*Rhipidomella*, *Tropidoleptus*, *Stropheodonta*, *Devonochonetes* and rare productids). In addition to brachiopods, the large bivalve *Myalinella* as well as encrusting and ramose bryozoans, rugose corals and trilobites (*Greenops, Phacops*), are common. This fauna indicates a deeper, calmer subtidal environment and a latest Givetian age.

A different, taxonomically distinct fossil association is present in the uppermost part of cycle IIa and in cycle IIb. This is characterised by spiriferid genera (*Cyrtospirifer* and *Mucrospirifer*), indicating an early Frasnian age. The rapid succession of different brachiopod associations suggests generally low rates of sedimentation.

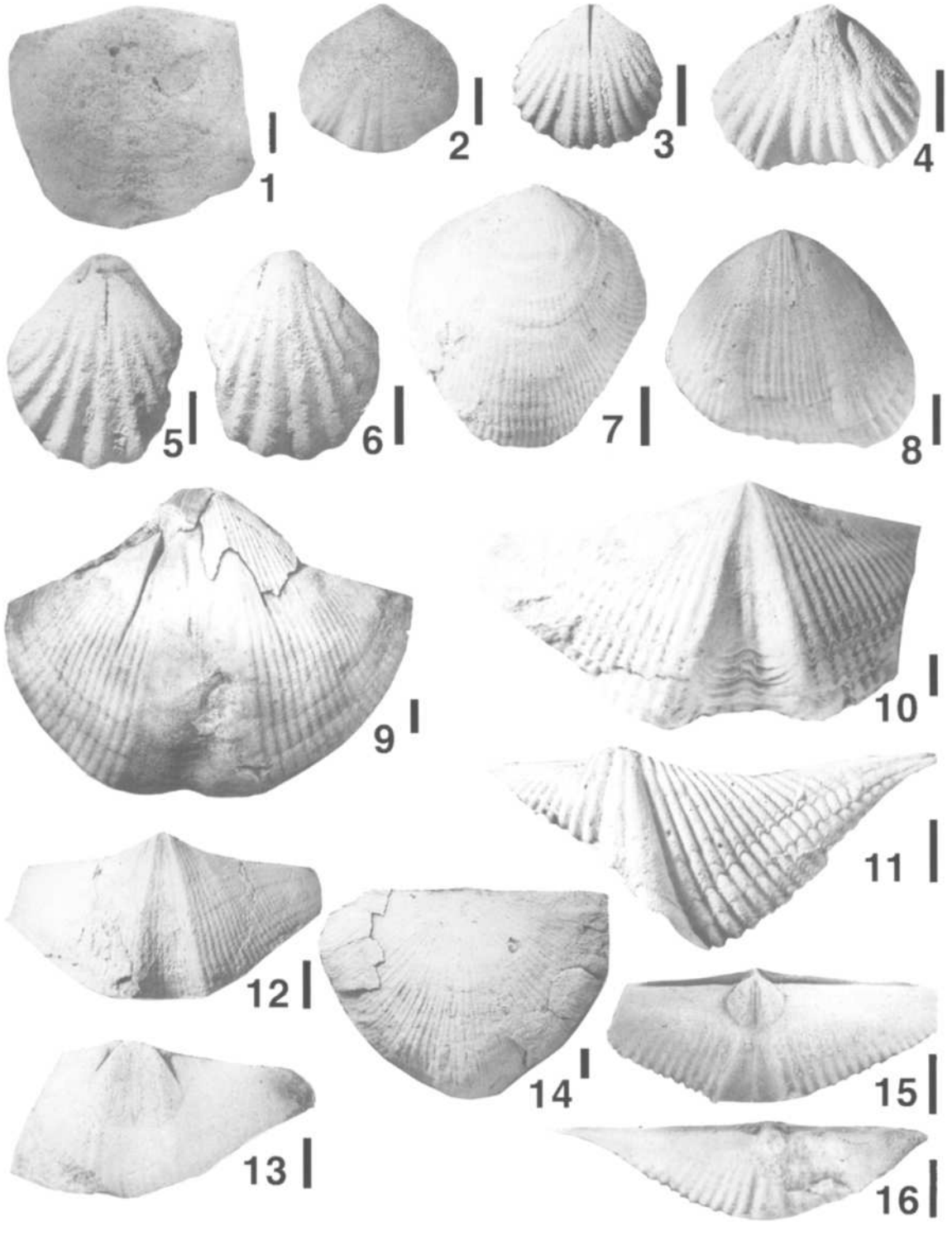

Plate 1. (*for description of plates see end of chapter*)

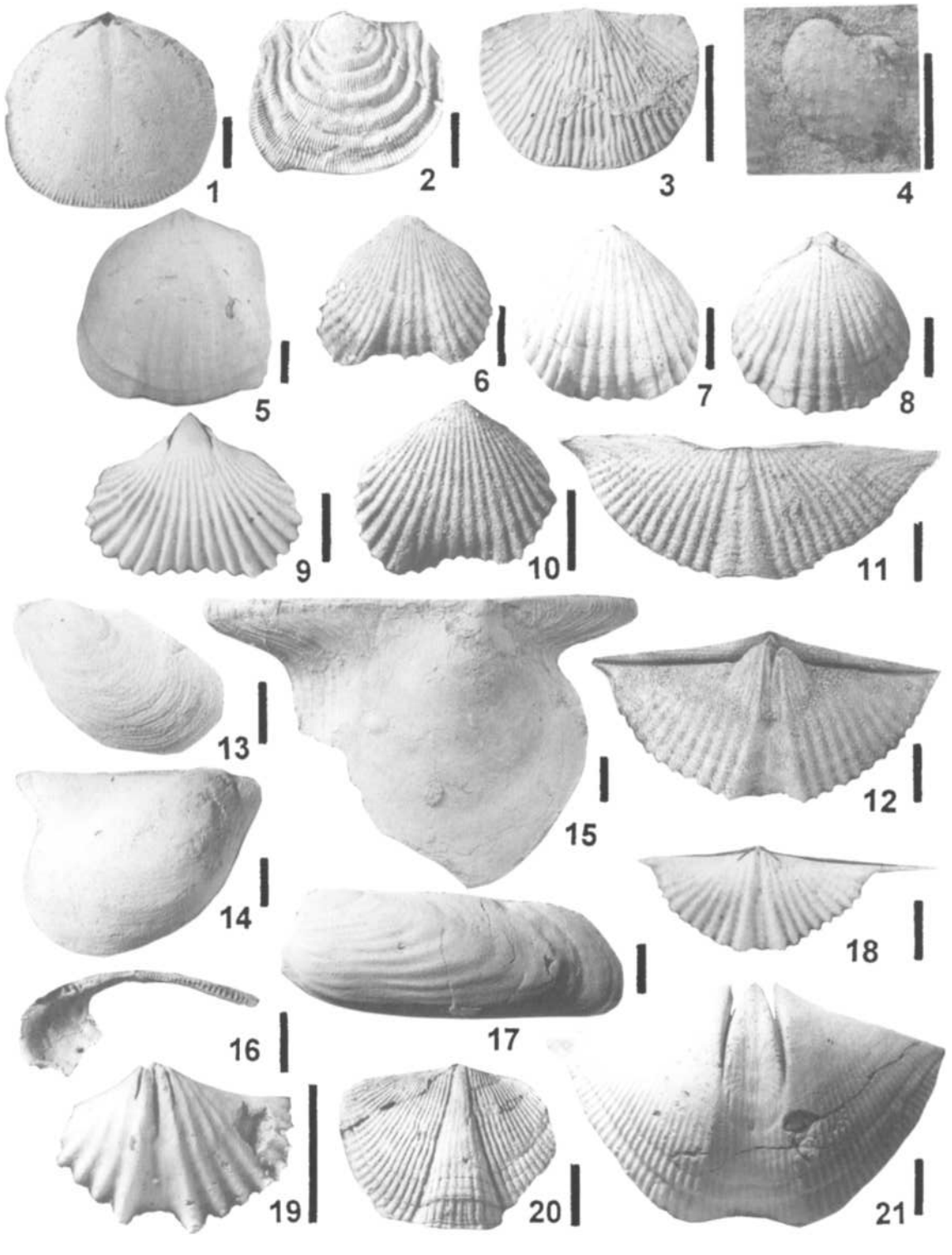

Plate 2.

Particular sandstone levels may be distinguished by characteristic, 'marker' species belonging to rapidly evolving lineages (e.g. the mucrospiriferid lineage *Mucrospirifer mundus – M. busrewili – M. hastatus – M. fezzanensis* and the cyrtospiriferid lineage *Cyrtospirifer praecursor – C. ratus*). Spiriferids are associated with abundant, generally weakly costate rhynchonellids of which *Libyaerhynchus fragosus* is dominant. Less common rhynchonellids are *Eumetabolotoechia longiqua* and *Ripidiorhynchus* cf. *barroisi*. Other brachiopods (*Rhipidomella*, *Leptaena*, *Dichacaenia*, *Devonochonetes* and *Adolfia*) are even less common. The absence of *Tropidoleptus* is significant. Bivalves are abundantly represented (*Nuculites*, *Leiopteria*, *Leptodesma*, *Actinodesma*, *Sphenotus* and *Lyriopecten*) while other benthic invertebrates (e.g. loxonematid and mourloniid gastropods, encrusting bryozoans, crinoids, and the trilobite *Greenops*) are rare. Tentaculites are not common (*Tentaculites lardeuxi*; Hajlasz et al., 1978). The *Mucrospirifer* and *Libyaerhynchus* assemblages are interpreted as shallow subtidal communities that occupied sandy bottoms affected by moderate to strong currents. There is evidence of taphonomic size sorting, disarticulation, fragmentation and accumulation of the shells. These communities mark an episode of maximum benthic diversity in the Devonian succession of this area.

The rapid changes between different fossil assemblages in AO II may be explained by the model of deltaic sedimentation presented by Vos (1981). Terebratulid and rhynchonellid communities (*Rhipidothyris*, *Eumetabolotoechia* and *Libyaerhynchus* communities) at the tops of sedimentary cycles correspond to the progradational, shoaling phases of the deltaic complex, while the associations with abundant spiriferids and chonetids (middle part of cycle IIa, Vos, 1981) indicate somewhat deeper environments developed during transgressive phases. The taxonomic composition indicates close affinities to coeval communities on the eastern margin of Laurentia (Bowen et al., 1974; McGhee, 1976; McGhee and Sutton, 1981; Brett, 1986). It is noteworthy that the sandstones with the *Libyaerhynchus* Community were known to Beyrich (1852) almost 150 years ago.

Awaynat Wanin Area–AO III

In contrast to AO II, this unit is quite poor in body fossils. The lower part is rich in *Bifungites* (Fig. 2), a typical ichnofossil of nearshore environments (Gutschick and Lamborn, 1975). Shelly fossils are uncommon in most of the unit but claystones have yielded a chonetid (*Rhyssochonetes*), a rhynchonellid (*Eumetabolotoechia*), bivalves and remains of lingulid brachiopods. A quite different brachiopod association occurs in a ferruginous sandstone in the middle of the unit, where brachiopods are represented by a large rhynchonellid (*Cyphoterorhynchus talagrounai*), a terebratulid (*Septothyris boucoti*) and rare *Cyrtospirifer*, *Cupularostrum* and *Schuchertella*. The fragmentation of the shells indicates that they were reworked before fossilization. The association is identical with the *Cyphoterorhynchus* Community of the Talagrouna Formation on the NW flank of the Murzuq Basin. Sedimentology indicates a deeper, prodeltaic to shelf environment. The age of AO III is probably upper Frasnian.

Awaynat Wanin Area–AO IV

This unit has yielded an uncommon and low diversity assemblage dominated by *Posidonia* sp. This bivalve indicates reduced oxygen levels but offers no clue to the age of this unit.

Awaynat Wanin Area–Tahara Formation

This Devonian-Carboniferous boundary unit is generally poor in fossils, but a rich brachiopod-bivalve assemblage is known in the middle part of the unit. This comprises rhynchonellids (*Cupularostrum* and *Libyaerhynchus*) and the productid *Acanthatia*. Bivalves are small and less numerous (*Nuculoidea* and *Ptychopteria*). The association is of shallow water origin, as indicated by heavy haematisation, the position of the fossil-bearing beds and the low diversity levels. A Famennian age is suggested.

A different fossil assemblage is known from the top of the unit. Sandstones contain the brachiopods *Rhipidomella maharuga*, *Saharonetes saharensis*, *Spinocarinifera* (?) *bulbosa*, *Composita* cf. *megala*, *Syringothyris* sp., *Unispirifer unicus* and others. Bivalves are numerous but are represented mainly by small forms. Moderate diversity, together with a high level of shell fragmentation and current-generated accumulations, indicates a high-energy environment. The association is early Tournaisian (Hastarian) in age and identical with fossil associations from the uppermost part of the Ashkidah Formation in the Wadi ash Shati area.

Awaynat Wanin Area–Marar Formation

This unit consists of shales and siltstones interbedded with sandstones. Its lower part has yielded a low-diversity assemblage with the productid *Acanthatia placita* associated with a rhynchonellid (*Cupularostrum cupulosum*), a chonetid (*Saharonetes saharensis*), a strophomenid (*Schuchertella* sp.), and a lingulid (*Wadiglossa* sp.). This assemblage is definitely of very shallow water origin, with some elements living intertidally. The age is probably early Tournaisian (Hastarian).

A different assemblage from higher in the Marar Formation consists mainly of a small, coarsely costate rhynchonellid (*Cupularostrum minutum*). Less common are spiriferids (*Apousiella*, *Prospira* and *Syringothyris*), as well as other brachiopods (*Oehlertella*, *Schuchertella*, *Saharonetes*, *Martinothyris*, *Composita* and *Acanthocosta*). Bivalves are represented by *Spathella*. The higher diversity indicates a more favourable marine environment. The assemblage's composition is remarkable: apart from the chonetid *Saharonetes saharensis*, none of the taxa have been found elsewhere in the Ghadames and Murzuq basins.

Faunas of the Northern Margin of the Murzuq Basin (Wadi Ash Shati)

The benthic fossils of the Wadi ash Shati area were described in detail by Havlícek and Röhlich (1987), and some new data on the Devonian faunas were later presented by Mergl and Massa (1992). The most significant taxa are shown in Fig. 3 and Plates 3, 4 and 6.

Northern Murzuq–B'ir Al Qasr Formation

Sandstones of the B'ir al Qasr Formation contain an imperfectly known and mostly fragmented fauna, in which the brachiopods *Schizophoria*, *Cupularostrum*, *Iridistrophia* and *Rhynchospirifer*, along with remains of spinocyrtiids, fenestellid bryozoans, bivalves, the trilobite *Kayserops* and tentaculitids are important. The assemblage is probably of Eifelian age. Fossils from the upper part are less diverse and contain only calcitic remains such as the brachiopods *Rhipidothyris*, *Cupularostrum*, *Mediospirifer* and pectinid bivalves suggesting a Givetian age.

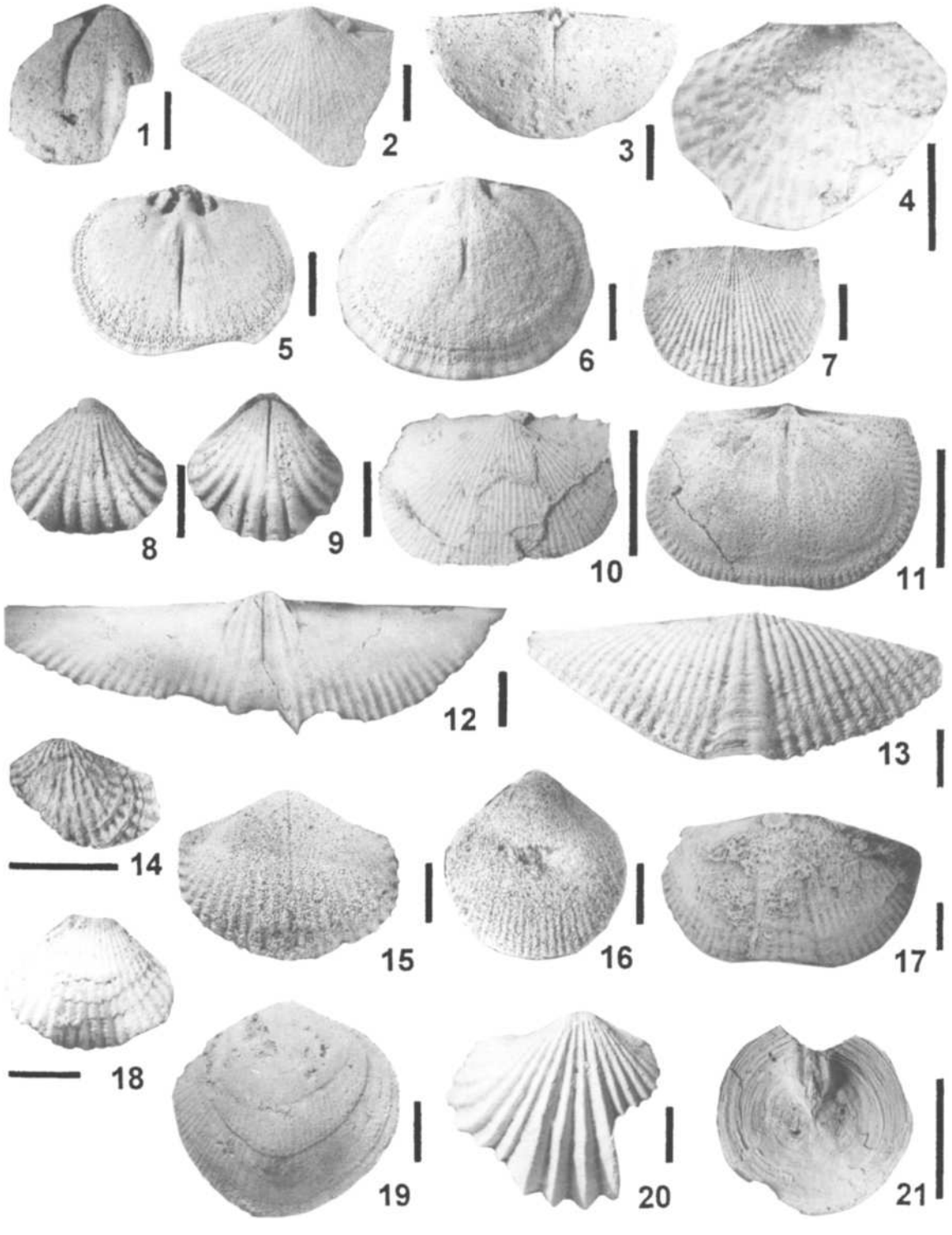

Plate 3.

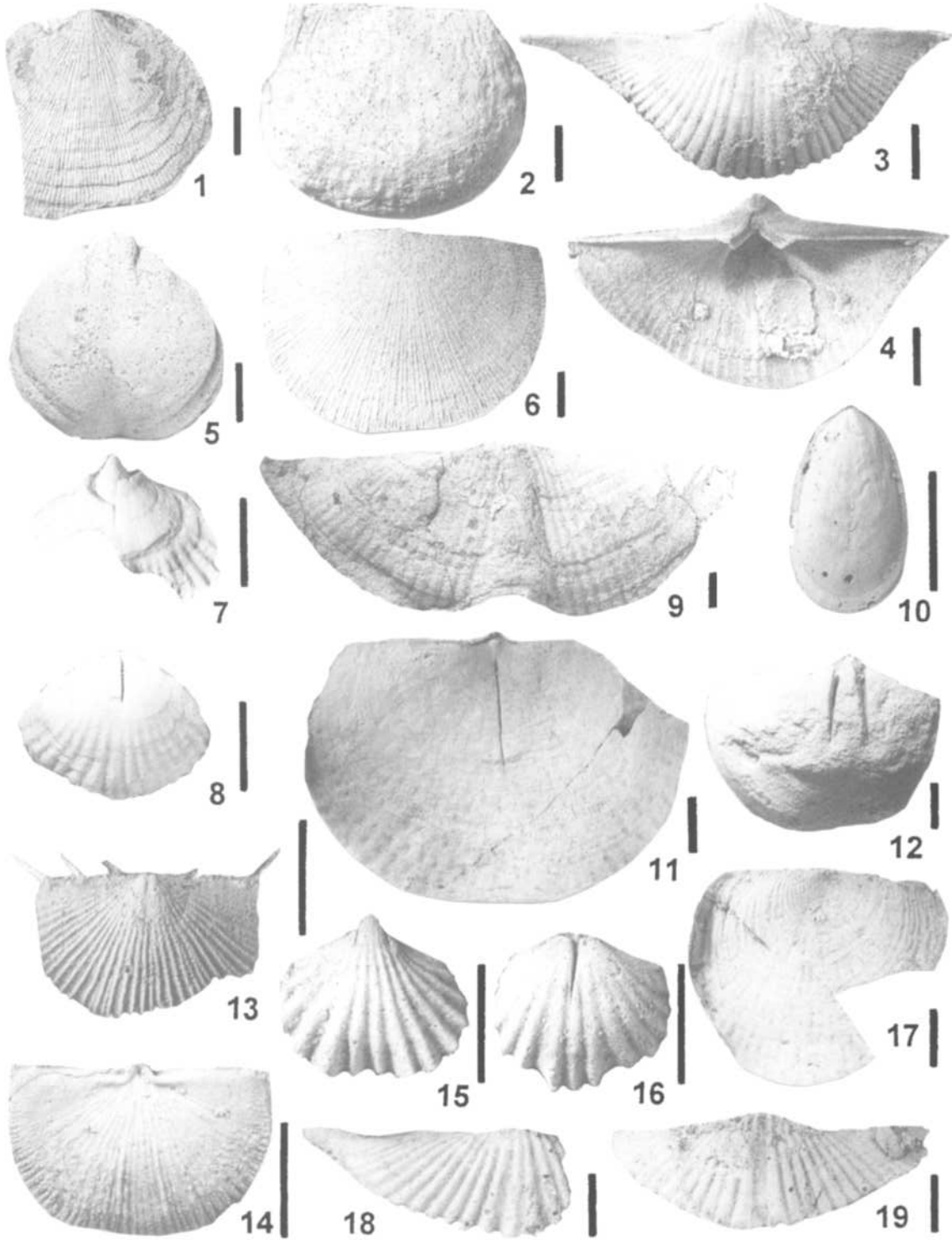

Plate 4.

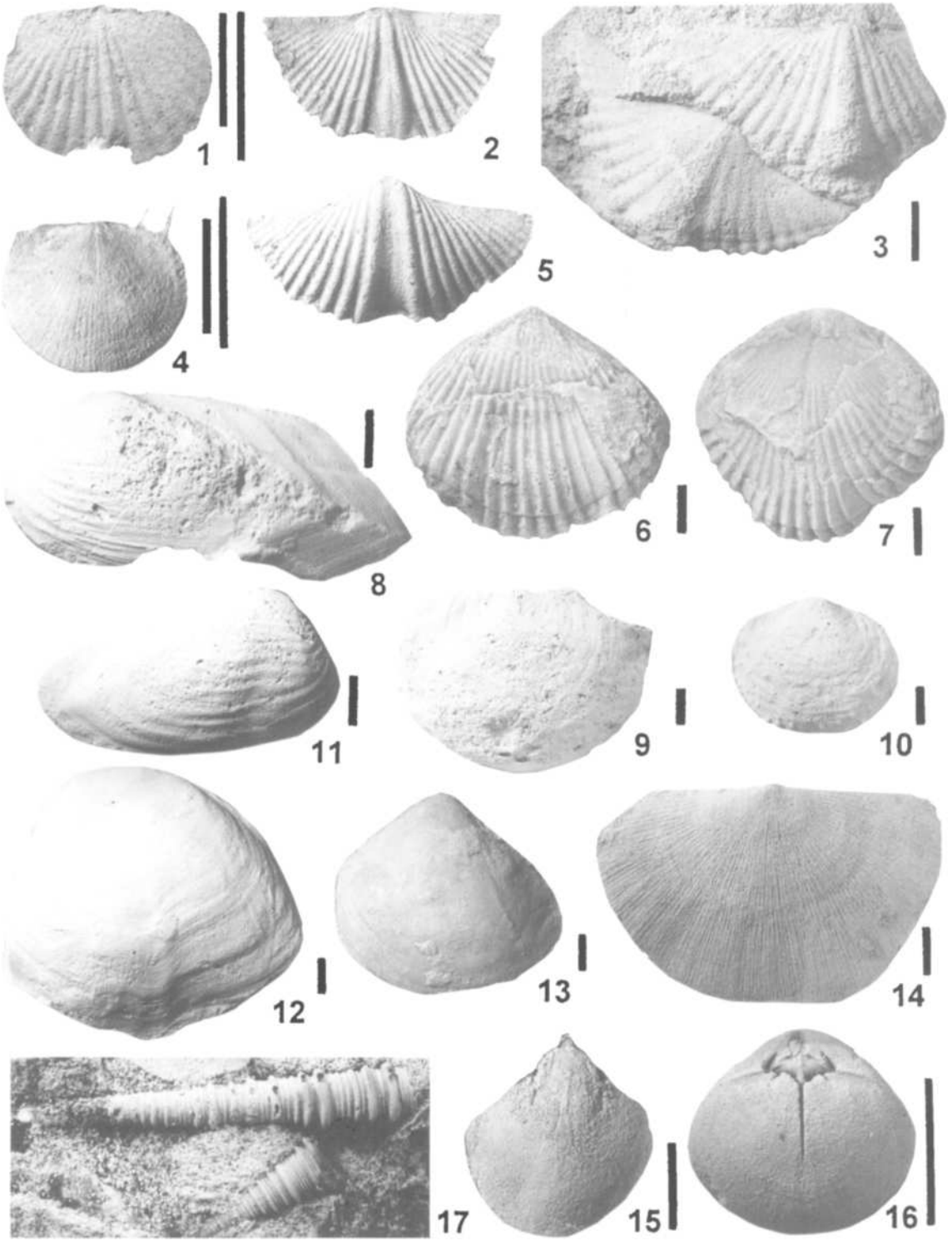

Plate 5.

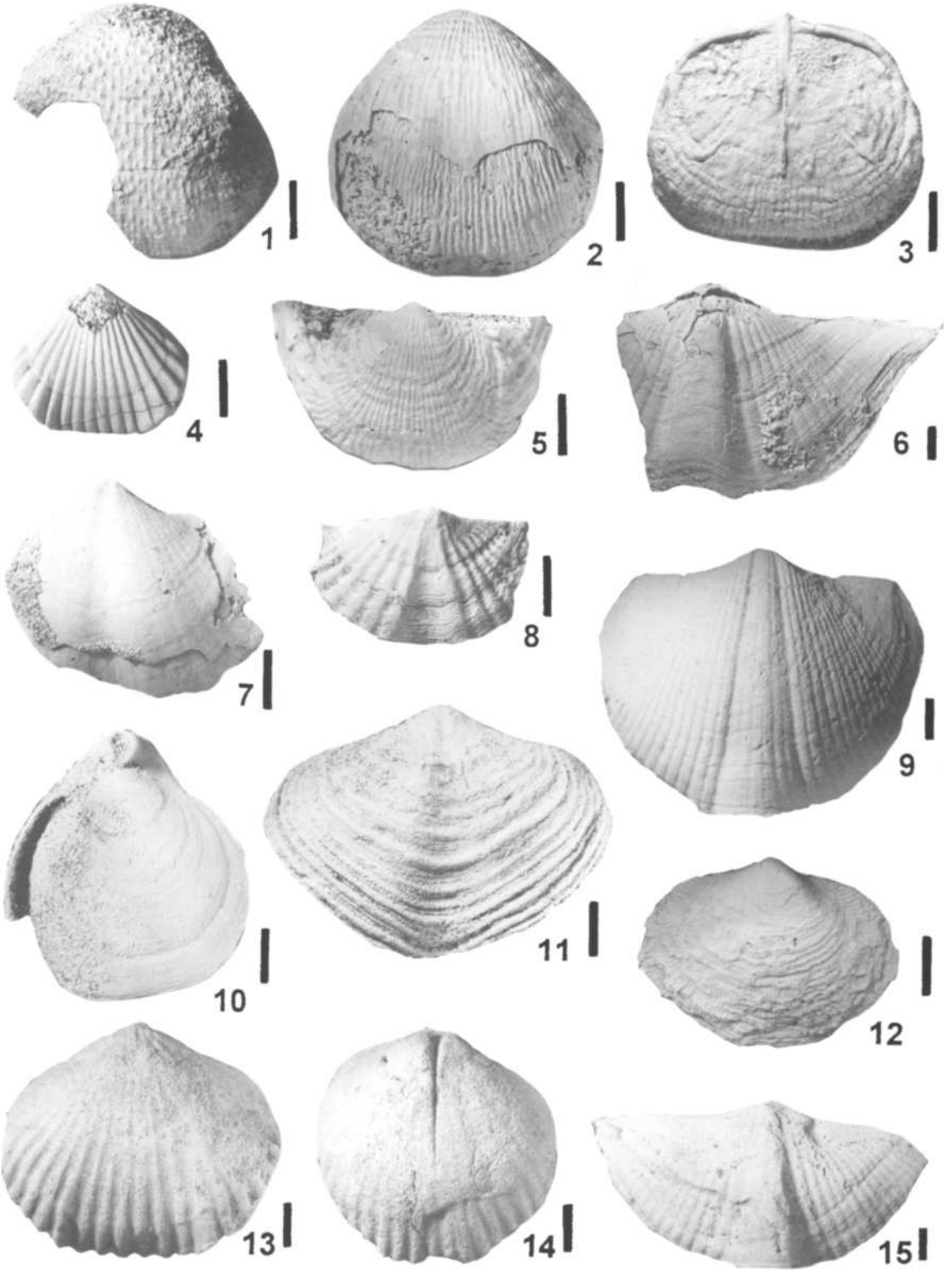

Plate 6.

Northern Murzuq–Idri Formation

This unit contains distinct, brachiopod-dominated assemblages that are very similar to those in AO II of the Awaynat Wanin section. In the *Rhipidothyris* Community in the lower part of the formation, the coarsely costate terebratulid *Rhipidothyris africana* is associated with a less common rhynchonellid (*Cupularostrum idriense*) and the bivalve *Leptodesma*.

The middle part of the Idri Formation contains the *Tropidoleptus* Community. Significant elements are the brachiopods *Tropidoleptus*, *Mucrospirifer*, *Cupularostrum* and *Eumetabolotoechia*. Other fossils are represented by a trilobite (*Dipleura*), gastropods, and diverse bivalves (*Goniophora*, *Spathella*, *Leptodesma* and *Lyriopecten*). Disarticulation and fragmentation of the valves together with a high amount of coarsely costate rhynchonellids indicate shallow-water with current and wave agitated sandy bottoms. A second brachiopod-dominated assemblage contains the chonetid *Devonochonetes postremus* and the rhynchonellid *Cupularostrum arenosum*. Both genera also occur in the upper part of the Idri Formation, where they are associated with the spiriferid *Mucrospirifer hastatus*, the productid *Spinulicosta hamata*, remains of a spinocyrtiid and the trilobite *Greenops*. The age of this assemblage is probably latest Givetian. The top of the formation contains a quite different assemblage with *Cyrtospirifer*, locally abundant *Cupularostrum arenosum* and pectinid bivalves. The presence of *Cyrtospirifer* indicates a Frasnian age. Along with AO II, the Idri Formation has yielded the most diverse and richest shelly associations and these permit a good correlation between the two areas. Cyrtospiriferids in the upper beds are probably equivalent to the *Libyaerhynchus* Community of the Awaynat Wanin section, but the species *Libyaerhynchus fragosus* itself is unknown in the Wadi ash Shati area.

As noted by Seidl and Röhlich (1984) and Havlícek and Röhlich (1987), the assemblage with *Tropidoleptus* is certainly of Givetian age, while the brachiopod assemblage at the top of the Idri Formation is better referred to the early Frasnian.

Northern Murzuq–Quttah Formation

The Quttah Formation contains low diversity shelly assemblages. Sandstones in the lower part are rich in the ichnofossil *Bifungites fezzanensis* (Fig. 3), while shale interbeds contain remains of the lingulid *Wadiglossa*. Sandstones in the upper part of the formation have yielded many spiriferids close to *Cyrtospirifer verneuili*, the rhynchonellids *Cupularostrum opulentum* and *Cassidirostrum* cf. *pedderi* and various bivalves (*Pteriopecten*, *Lyriopecten*, *Leptodesma*, *Modiomorpha*, *Grammysia*, *Grammatodon*, *Paracyclas*, and *Sphenotus*). Sandstones at some levels have also yielded remains of a large terebratulid (*Neoglobithyris tmisanensis*) associated with fish remains (bone beds). A shallow subtidal environment with extensive sandy bottoms is suggested; these offered a favourable habitat for burrowing bivalves, but were generally less appropriate for epibenthic brachiopods. Fragmentation, size sorting and abrasion also suggest high-energy conditions. The silty and shale horizons, sometimes with remains of lingulids, probably mark a transgression with calm, perhaps oxygen-deficient conditions and restricted communication with open marine conditions (Seidl and Röhlich, 1984).

Northern Murzuq–Dabdab Formation

The Dabdab Formation is generally poor in fossils. Common lingulid brachiopods and placoderm debris indicate a low-diversity, very shallow lagoonal environment. Fragments of articulate brachiopods are rare, but shells of the atrypid *Spinatrypina* indicate a pre-Famennian age for the upper part of the formation.

Northern Murzuq–Tarut Formation

The Tarut Formation is characterised by a low diversity brachiopod and bivalve fauna. Shales in the lower part of the formation contain organophosphatic brachiopods (*Tarutiglossa*, *Wadiglossa* and *Orbiculoidea*), while numerous bivalves (*Leptodesma*, *Lyriopecten*, *Myalina*, *Nuculopsis* and *Sphenotus*) are found in sandy beds. Articulate brachiopods occur in ferruginous oolites and in siltstone interbeds in the upper part of the formation. Together with abundant lingulids (*Wadiglossa supramarginalis* and *Oehlertella tarutaensis*), there is the coarsely ribbed rhynchonellid *Cupularostrum arenosum* and the bivalve *Myalina*, both with calcitic shells. Placoderm and cladoselachiid bones are also common. Lithofacies and fauna indicate near-shore, lagoonal and swamp environments. The base of the Tarut Formation probably corresponds to the basal AO IV beds of the Awaynat Wanin area. A Famennian age is suggested.

Northern Murzuq–Ashkidah Formation

The Ashkidah Formation is generally poor in fossils, which are mostly represented by the organophosphatic brachiopods of the genera *Oehlertella* and *Wadiglossa*. A richer faunal assemblage is present only in the upper part of the formation (the 'brachiopod sandstone marker' of Seidl and Röhlich, 1984). This assemblage is dominated by articulate brachiopods, whose shells are densely packed at some horizons. Characteristic taxa include the spiriferids *Unispirifer unicus*, *Syringothyris* cf. *texta*, and *Syringothyris* sp., the productid *Spinocarinifera* (?) *bulbosa*, and the chonetid *Saharonetes saharensis*, together with *Schuchertella globosa*, *Rhipidomella maharuga, Composita* cf. *megala, Stenoscisma crumenum*, *Cupularostrum cupulosum* and fragments of the crinoid *Platyhexacrinus*. This association indicates a shallow but fully marine environment.

The age of the formation is poorly constrained, but the upper part with the 'brachiopod sandstone marker' is definitely of early Tournaisian age, while microfossils from the lower parts of the formation have a late Famennian–early Tournaisian transitional character (Seidl and Röhlich, 1984).

Northern Murzuq–Marar Formation

Fossils in the Marar Formation cluster into several distinct associations. The sandstones in the lower part of the formation often contain the chonetid *Saharonetes saharensis*, the lingulid *Wadiglossa* and the productid *Dictyoclostus* sp. A quite different association in the middle of the formation is characterised by the dominance of the large spiriferid *Prospira platycosta*, associated with the terebratulid *Balanoconcha micropuncta*, spiriferids (*Brachythyris* sp., *Tylothyris* sp., *Syringothyris* cf. *texta*) and other brachiopods (*Antinoconchus lamellosa*, *Pleuropugnoides* cf. *pleurodon*, *Marginatia* sp., *Pustula* sp. *Schuchertella* sp.), gastropods, bivalves and crinoids. The *Prospira* Community is restricted to a pebbly greywacke in the Ashkidah area. This association is notable because of its low percentage of rhynchonellids and the complete absence of chonetids, which are common elsewhere in the Marar Formation.

A different benthic association in coquinoid limestones in the upper part of the formation is dominated by the large productid *Dictyoclostus* cf. *semireticulatus*. Other brachiopods are represented by the spiriferid *Phricodothyris* sp. and a small undeterminable chonetid (Havlícek and Röhlich, 1987).

Fossils in the lower part of the Marar Formation are diagnostic of the late Tournaisian, while the upper part of the formation is likely to be early Viséan in age (Seidl and Röhlich, 1984).

Younger Carboniferous units do not outcrop in the Wadi ash Shati area.

Faunas of the Western Murzuq Basin

Western Murzuq–Ouan Kasa Formation

The first fossiliferous units in the Devonian on the western margin of the basin (Fig. 4 and Plate 5) comprise sandstones with poorly preserved spiriferids (*Acrospirifer*), undeterminable atrypid and chonetid brachiopods, an early Devonian trilobite (*Dipleura*) and crinoid columnals. This association reflects a shallow subtidal habitat, as shown by low species diversity and the disarticulation and sorting of the valves into coquinoid beds.

Better-preserved fossils occur in siltstones. The generally small-sized brachiopod fauna is characterised by a small spiriferid (*Spinella*), chonetids, poorly preserved rhynchonellids and dalmanellids. Of particular interest is the presence of *Tropidoleptus*, which generally indicates a pre-Frasnian age. Associated tentaculitids (*Styliolina*, *Vjalovites*) indicate an Emsian age for the assemblage (Hajlasz et al., 1978), which is widespread along the western margin of the Murzuq Basin and also extends farther to the SE: the same horizon with *Spinella* and *Tropidoleptus* is also known from the Djado Sub-basin in northern Niger.

Western Murzuq–Talagrouna Formation

The Talagrouna Formation comprises siltstones interbedded with quartzitic sandstones. Fossils are common throughout the unit (Fig. 5 and Plate 5), and are mainly represented by large bivalves (*Goniophora*, *Grammysia*, *Sphenotus*, *Lyriopecten*, *Leiopteria, Eoschizodus*) and smaller indeterminable nuculids. Brachiopods are also abundant, with the large rhynchonellid *Cyphoterorhynchus talagrounai*, the spiriferid *Cyrtospirifer*, the productid *Leioproductus*, the orthotetacean *Schuchertella* and the minute terebratulid *Septothyris boucoti*. Among the common large tentaculitids, *Dicricoconus libyensis* prevails. Brachiopod and bivalve shells are only slightly reworked and thus reflect the original benthic community. The *Cyphoterorhynchus* Community resembles the shallow-subtidal benthic communities of the Upper Devonian in the Central Appalachians (Bowen et al., 1974; McGhee, 1976; McGhee and Sutton, 1981; Brett, 1986). Their age is probably late Frasnian, roughly coeval with the middle part of AO III in the Awaynat Wanin area and the top of the Dabdab Formation in Wadi ash Shati.

Western Murzuq–Marar Formation

Overlying the late Devonian hiatus, the Marar's haematitic basal beds contain a rich fauna typical of the *Prospira* Community. There are abundant spiriferids (*Prospira platycosta* and *Syringothyris* sp.), associated with other brachiopods (*Balanoconcha micropuncta*, *Antinoconchus lamellosus*, *Pleuropugnoides* cf. *pleurodon*, *Cleiothyridina* sp., *Marginatia* sp., *Pustula* sp., *Schuchertella* sp.), rare bivalves and rugose corals. Low levels of shell fragmentation and numerous articulated whole shells in this diverse community indicate calm and fully marine conditions.

Another distinct assemblage (Fig. 5) consists of the large, subglobose rhynchonellid *Paurogastroderhynchus serdelesensis* (= *Septacamera*), the syringothyrid *Septosyringothyris vautrini* (= *Histosyrinx*), the productid *Setigerites*, and a poorly preserved chonetid. This assemblage is known throughout the basin and has also been documented on the opposite eastern flank of the Murzuq Basin. It is late Tournaisian in age.

The upper part of the formation (Fig. 10) yields faunas with abundant productids, characteristically with *Fluctuaria*, *Argentiproductus, Libys*, the rhynchonellid *Cupularostrum*, the syringothyrid *Syringothyris* cf. *hannibalensis*, athyrids and diverse other benthic invertebrates (bryozoans, bivalves and corals). The fauna is probably of late early Viséan age. A

different benthic assemblage, known from stromatolitic beds ('*Collenia* Unit', Upper Viséan), is characterized mainly by productid brachiopods (*Dictyoclostus*, *Libys*, *Linoproductus*) associated with *Protoniella*, *Pleuropugnoides*, spiriferids (*Neospirifer*, *Syringothyris*), bivalves and corals (Massa et al., 1974).

Western Murzuq–Assedjefar Formation

The fauna of this unit was described by Massa et al. (1974). The lower fossiliferous horizons contain productids (*Echinoconchus*, *Flexaria*, *Juresiana*, *Linoproductus*, *Striatifera*, *Productus* and *Gigantoproductus*). Other brachiopods include *Schellwienella*, *Rugosochonetes*, *Pleuropugnoides* and *Syringothyris jourdyi*. The latter species is of a great stratigraphical significance as it is a marker for the early Namurian throughout the whole Sahara (Legrand-Blain, 1970), and has also been reported from the Al Awaynat area (Rossi, 1939). The associated fauna is remarkably rich, with diverse gastropods, bivalves, bryozoans and the rare trilobite *Linguaphillipsia*. These lower Assedjefar beds have a clear early Namurian aspect.

A similarly rich benthic fauna comes from the upper fossil-bearing horizon of the Assedjefar Formation. Along with some elements already common in the lower part of the unit (e.g. the genera *Linoproductus*, *Productus* and *Syringothyris*), there are new elements, of which the productids *Ovatia* and *Antiquatonia* are significant.

Western Murzuq–Dembaba Formation

The fauna of the Dembaba Formation (Fig. 10) consists mainly of brachiopods of the genera *Schizophoria*, *Enteletes*, *Linoproductus*, *Conocardium* etc. These faunas suggest a Moscovian age.

Faunas of the Djado Sub-basin

The limited Devonian faunas known from this area have not been restudied in the present work. As may be expected, fossiliferous sites and levels in the Carboniferous (Fig. 12 and Plate 7) are generally scattered in this area. Moreover, available samples are limited, which makes determinations and the reconstruction of the original taxonomic spectrum difficult. Thus, the data presented below will certainly be improved by further studies.

Djado–Marar Formation

The sandstones in the lower part of the Marar Formation contain a brachiopod-dominated community with abundant, medium-sized specimens of the coarsely costate syringothyrid *Syringothyris* cf. *ahnetensis*, locally associated with a large new rhynchonellid taxon (*Rhynchopora magnifica*). Less abundant brachiopods at more or less the same level near the base of the Carboniferous sequence are *Saharonetes saharensis* and *Schuchertella* sp. The brachiopods occur in densely and often chaotically, packed beds, commonly as isolated or broken valves, although some complete shells are also present. Bivalves are rare.

The basal sandstones of the Marar Formation, resting unconformably on Devonian strata, contain the taxa *Schuchertella* sp. and *Syringothyris* sp., although in very restricted numbers. These resemble the association of the 'brachiopod sandstone marker' in the Ashkidah Formation

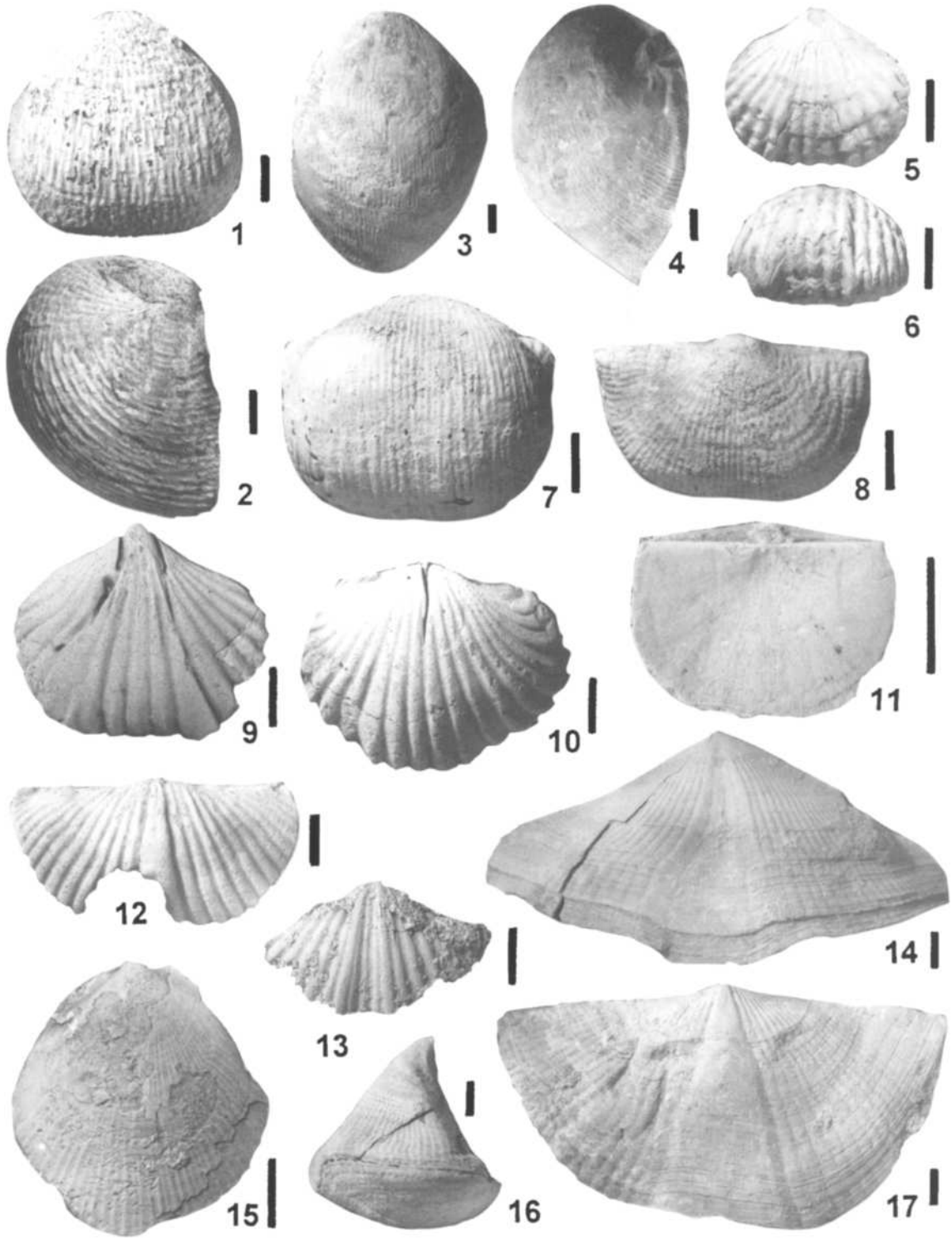

Plate 7.

of the Wadi ash Shati area. Another distinct, but low-diversity, association at the base of the Carboniferous is characterised by the rhynchonellid *Paurogastroderhynchus serdelesensis*. The age of both associations is latest Tournaisian.

Sandstones in the upper Marar Formation contain the characteristic late Viséan productid *Fluctuaria undata*.

Djado–Assedjefar Formation

The Upper Viséan and Lower Namurian are generally poor in fossils but a calcareous sandstone has yielded shells of a large *Schellwienella*, associated with less common productids. A second brachiopod association is early Namurian in age; sandy limestones contain mainly productids (*Flexaria*, *Antiquatonia* and *Ovatia*), but other brachiopods are also represented by the widespread genera *Rhipidomella*, *Composita*, *Syringothyris* and small rhynchonellids. Another association of early to middle Namurian age is characterised by the large syringothyrid *Syringothyris jourdyi*, and the rare terebratulid *Beecheria*. An early Namurian age is also documented by the presence of *Anthracospirifer* gr. *curvilateralis*. Other poorly preserved brachiopods include the productid *Ovatia*.

Djado–Dembaba Formation

The upper part of the marine Carboniferous (Moscovian) in the Djado Sub-basin has yielded an assemblage consisting exclusively of the chonetid *Rugosochonetes* cf. *chesterensis* (Fig. 12), which is commonly articulated, but with abraded external surfaces. This assemblage is probably Moscovian in age.

In conclusion, the lower and mid-Carboniferous shelly assemblages of the Djado Sub-basin show low diversities and represent shallow marine environments. The assemblages are dominated by productids, coarsely ribbed rhynchonellids and spiriferids, with a few terebratulids or strophomenids. As stated by previous authors (e.g. Legrand-Blain et al., 1987), there are taxonomic affinities with Carboniferous faunas of North America (e.g. *Flexaria*, *Anthracospirifer*, *Rugosochonetes*), while most of the recorded faunal elements have a worldwide distribution (*Schellwienella*, *Ovatia*, *Cupularostrum*, *Syringothyris*, *Beecheria*). Only a few elements may be considered as endemic to the Murzuq Basin, such as the rhynchonellid *Paurogastroderhynchus serdelesensis* and the syringothyrid *Septosyringothyris vautrini*, both from the Upper Tournaisian. *Saharonetes*, which is widespread in the Murzuq Basin, is also known from Ghana (Racheboeuf *et al.*, 1989).

INTRABASINAL AND EXTRABASINAL RELATIONS OF FAUNAS

The southeastern margin of the Ghadames Basin (Awaynat Wanin area) and the northern margin of the Murzuq Basin (Wadi ash Shati area) provide the most complete, most fossiliferous and best-documented Devonian sections. Although now belonging to different basins, these two areas show a very similar distribution of characteristic shelly faunas, permitting a reliable correlation between these two areas. Carboniferous fossiliferous strata are well known in the southern Ghadames and northern and northwestern parts of the Murzuq Basin, but become sparse along the basin's southwestern margin and into the Djado Sub-basin.

The following well-documented and stratigraphically restricted benthic communities are important for intrabasinal correlation (in ascending order):

- ***Tropidoleptus* Community**. Characterised by dominance of the orthid *Tropidoleptus carinatus freuloni*, this low- to medium-diversity community is present in AO II of the Awaynat Wanin area and in the Idri Formation of Wadi ash Shati. A latest Givetian age is highly probable: although the genus *Tropidoleptus* ranges into the Frasnian (Cooper and Dutro, 1982), its acme is in the Givetian (Isaacson and Perry, 1977). The typical environment of the *Tropidoleptus* Community is shallow subtidal.
- ***Libyaerhynchus* Community and related communities**. Typically developed in the Awaynat Wanin area, with the spiriferids *Mucrospirifer* and *Cyrtospirifer* and the rhynchonellids *Libyaerhynchus*, *Ripidiorhynchus* and *Eumetabolotoechia*. The community is also known from the western part of the Wadi ash Shati area. The presence of several species of *Mucrospirifer* has a great significance for detailed correlation between both areas. The association of *Cyrtospirifer* and *Eumetabolotoechia* indicates an early Frasnian age for the *Libyaerhynchus* and related communities.
- ***Neoglobithyris* and *Cyphoterorhynchus* communities**. Despite differences and limited data, both communities appear to be good stratigraphic markers of the mid-upper Frasnian. *Neoglobithyris tmisanensis* (upper part of the Dabdab Formation in Wadi Ash Shati) or a closely related species (*Septothyris boucoti*: Mergl and Massa, 1992) is probably also present on the western flank (Talagrouna Formation) of the Murzuq Basin, as well as in the Awaynat Wanin area (AO III). Obviously this terebratulid has a wide areal extent.
- ***Saharonetes* Community**. A rich brachiopod assemblage ('brachiopod sandstone marker' of Seidl and Röhlich, 1984) in the top of the Ashkidah Formation (Wadi ash Shati area) has its counterpart in the top of the Tahara Formation (Awaynat Wanin area). This community is characterized by *Unispirifer unicus*, *Rhipidomella maharuga* and other brachiopods, while associated species (e.g. *Saharonetes saharensis*) have a wider stratigraphic range. The typical *Saharonetes* Community is early Tournaisian (Hastarian) in age.
- ***Prospira* Community**. This community was originally described from the lower part of the Marar Formation in Wadi ash Shati (Havlícek and Röhlich, 1987), but it has also been found in the Marar Formation on the western flank of the Murzuq Basin in the basal Carboniferous transgressive beds (*Fusella* Community in original diagnosis of Massa et al., 1974). The community is unknown, however, in the Awaynat Wanin area. The *Prospira* Community includes many elements unknown at other levels in the Murzuq Basin (e.g. the genera *Antinoconchus*, *Brachythyris*, *Tylothyris*, *Balanoconcha* etc.), although they otherwise have a worldwide distribution in this period. This community indicates a favourable, thoroughly marine environment and may be used as a good stratigraphical marker for the late Tournaisian in different parts of the Murzuq Basin.
- ***Septosyringothyris* Assemblage**. This assemblage is named after the syringothyrid *S. vautrini*, which is locally associated with the large rhynchonellid *Paurogastroderhynchus*. It has not yet been found in the Wadi ash Shati, but is present near the base of the Marar Formation both on the western and eastern margins of the Murzuq Basin and also in the Djado Sub-basin. The age of this association is probably late Tournaisian.
- ***Syringothyris jourdyi* Assemblage**. This assemblage is characterized by the large syringothyrid *S. jourdyi*, some productids and the terebratulid *Beecheria*. It is known from the western margin of the Murzuq Basin and from the lower Namurian of the Djado Sub-basin. *S. jourdyi* is a characteristic species for the western Sahara (Legrand-Blain, 1970).
- **Lingulid Community**. By comparison with modern *Lingula*, this community is generally thought to represent intertidal, brackish and warm conditions. However, as suggested by Emig (1997), fossil lingulids tend to occur during periods of drastic or catastrophic ecological change. Recent lingulids live in compact and stable sediments under the influence of moderate currents and normal salinity. None of the recent species is adapted to brackish-water conditions, although they can survive strong salinity variations. Thus low salinity and brackish

conditions cannot be inferred from the mere presence of fossil lingulids. In the Murzuq Basin, the lingulid-bearing beds, often with ferruginous cement, probably represent intertidal but wholly marine, sandy environments. Marine swamps (similar to modern mangroves) provide the best models for the lingulid-bearing beds. Their appearance near the Devonian-Carboniferous boundary probably reflects extreme eustatic fluctuations at this time, while their stratigraphic significance is very low.

- **Bivalve Communities**. Along with the brachiopods, bivalves are the most common and often the only, macrofossils in some beds. Their diversity is rather high and more detailed study would certainly permit the discrimination of discrete assemblages. Burrowing bivalves, with diagnostic morphologies (elongate outline, burrowing sculptures), indicate bottoms inhabited by infaunal or semi-infaunal filter feeders. However, there are also epibyssate forms, largely pectinids. It is only our insufficient taxonomic knowledge that makes this group stratigraphically useless while their mere presence is sufficient to recognize fully marine environments.

BIOGEOGRAPHIC AFFINITIES OF DEVONIAN AND CARBONIFEROUS FAUNAS

The biogeography of the Saharan intracratonic basins has been summarized by Boucot et al. (1983) for Devonian brachiopod faunas in general, by Racheboeuf (1990) for Devonian chonetid brachiopods, by Mergl and Massa (1992) for Devonian-Tournaisian brachiopod faunas, by Legrand-Blain (1986, 1995) for Carboniferous productids and spiriferids and by Legrand-Blain et al. (1987) for other Carboniferous invertebrates. Generally, Early to Middle Devonian faunas of the eastern Saharan domain have close affinities to the Old World Realm, although there are occasional influxes of elements from the Eastern American Realm. In contrast, late Givetian and Frasnian faunas contain many elements with Eastern American Realm affinities, such as *Mucrospirifer, Spinocyrtia*, *Eumetabolotoechia* and *Devonochonetes*. Carboniferous biogeographic relationships are less evident, except for the occurrence of some North American elements (e.g. *Anthracospirifer*) in the Namurian. The late Devonian to early Carboniferous productids of North Africa (Legrand-Blain, 1995) include *Acanthatia*, a characteristic genus of North America.

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Note that fossils figured in Plates 1 to 7 are stored in the following depositories according to the abbreviations given in the plate texts: **FSL**: material housed in the collections of Centre National de la Recherche Scientifique, Lyon University, Lyon, France; **IRCT**: material housed in the Industrial Research Centre, Tripoli, Libya; **VH**: material housed in the Museum of Dr. B. Horák, Rokycany, Czech Republic.

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DESCRIPTION OF PLATES (BAR = 5 mm IN ALL PLATES)

PLATE 1. (p. 67). Ghadames Basin: Fossils from the Awaynat Wanin area (AO I: 1, AO II: 2–16).

1. *Athyris* sp., dorsal valve, FSL 413.125.
2. *Eumetabolotoechia* sp., dorsal valve, FSL 413.098.
3, 4. *Cupularostrum rudis* Mergl and Massa, dorsal and ventral valves, FSL 413.074.
5, 6. *Rhipidothyris africana* Boucot, Massa and Perry, dorsal and ventral valves, FSL 413.218.
7. *Variatrypa* sp., dorsal valve, FSL 413.119.
8 *Eumetabolotoechia perryi* Boucot, Massa and Perry, dorsal valve, FSL 413.101.
9. *Spinocyrtia magna* Mergl and Massa, ventral valve, FSL 413.168.
10, 11. *Mucrospirifer mundus* Mergl and Massa, ventral and dorsal valves, FSL 413.142, FSL 413.143a.
12, 13. *Cyrtospirifer praecursor* Mergl-Massa, ventral valves, FSL 413.184.
14. *Stropheodonta* sp., dorsal valve, FSL 413.034.
15, 16. *Mucrospirifer hastatus* Mergl-Massa, ventral and dorsal valves, FSL 413.146a, FSL 413.149.

PLATE 2. (p. 68). Ghadames Basin: Fossils from the Awaynat Wanin area (AO II).

1. *Rhipidomella* sp., dorsal valve.
2. *Leptaena borghiana* Mergl and Massa, ventral valve, FSL 413.018.
3. *Devonochonetes salemi* Mergl and Massa, ventral valve, FSL 413.035g.
4. *Spinulicosta hamata* Mergl and Massa, ventral valve, FSL 413.049.
5. *Eumetabolotoechia longiqua* (Beyrich), ventral valve, no number.
6–8. *Libyaerhynchus fragosus* Mergl and Massa, two ventral and dorsal valves, VH 7631, VH 7620.
9, 10. *Ripidiorhynchus cf. barroisi* (Rigaux), two ventral valves, FSL 413.085, FSL 413.087.
11, 12. *Mucrospirifer fezzanensis* (Mathieu), dorsal and ventral valves, VH 76O7a, VH 7608.
13. *Leptodesma* sp., left valve, VH 7607b.
14. *Leiopteria* cf. *dekayi* Hall, right valve, VH 7633b.
15. *Actinodesma erectum* Conrad, right valve, VH 7632.
16. *Nuculites* sp., right valve, FSL 513.276.
17. *Sphenotus* sp., left valve, FSL 413.266.
18. *Mucrospirifer busrewili* Mergl and Massa, ventral valve, FSL 413.035j.
19. *Adolfia termierae* Mergl and Massa, ventral valve, FSL 413.176a.
20, 21. *Cyrtospirifer ratus* Mergl and Massa, dorsal and ventral valves, FSL 413.196, FSL 413.197.

PLATE 3. (p. 71). Murzuq Basin: Fossils from the Middle to Upper Devonian, Wadi ash Shati.

1. *Schizophoria* sp., ventral valve, IRCT, B'ir al Qasr Formation.
2. *Iridistrophia* sp., ventral valve, IRCT, B'ir al Qasr Formation.
3. *Rhynchospirifer* cf. *halleri* Paulus, dorsal valve, IRCT, B'ir al Qasr Formation.
4. *Spinulicosta hamata* Mergl and Massa, dorsal valve, FSL 413.050, Idri Formation.
5–7. *Tropidoleptus carinatus freuloni* Boucot, Massa and Perry, dorsal, ventral and dorsal valves, VH 7611, VH 7612, VH 7612, Idri Formation.
8, 9. *Cupularostrum idriense* Havlíček, ventral and dorsal valves, VH 7629, Idri Formation.
10, 11. *Devonochonetes postremus* Mergl and Massa, ventral valves, FSL 413.023a, FSL 413.025, Idri Formation.
12, 13. *Mucrospirifer hastatus* Mergl and Massa, ventral and dorsal valves, FSL 413.145, FSL 413.023c, Idri Formation.
14. *Spinatrypina* sp., dorsal valve, IRCT, Dabdab Formation.
15. *Cassidirostrum* cf. *pedderi* McLaren, dorsal valve, IRCT, Quttah Formation.
16. *Rhipidothyris orchas* Havlíček, ventral valve, IRCT, B'ir al Qasr Formation.
17. *Cyrtospirifer* sp., dorsal valve, FSL 413.204, Quttah Formation.
18. *Cupularostrum opulentum* Havlíček, ventral valve, FSL 413.070, Quttah Formation.
19. *Neoglobithyris tmisanensis* Havlíček, ventral valve, IRCT, Quttah Formation.
20. *Cupularostrum cupulosum* Havlíček, dorsal valve, IRCT, Ashkidah Formation.
21. *Oehlertella tarutensis* Havlíček, ventral valve, IRCT, Tarut Formation.

PLATE 4. (p. 72). Ghadames and Murzuq Basins: Fossils from the Upper Devonian to Lower Carboniferous, Wadi ash Shati (11–19).

1. *Rhipidomella maharuga* Havlíček, ventral valve, VH 7614, Ashkidah Formation.
2. *Spinocarinifera (?) bulbosa* (Havlíček), dorsal valve, VH 7618, Ashkidah Forma-

tion.

3, 4. *Unispirifer unicus* Havlíček, ventral valve, FSL 413.122c, FSL 413.122b, Ashkidah Formation.

5. *Composita* cf. *megala* (Tolmatchov), ventral valve, IRCT, Ashkidah Formation.

6. *Schuchertella* cf. *globosa* (Tolmatchov), ventral valve, VH 7616, Ashkidah Formation.

7, 8. *Stenoscisma crumenum* (Martin), ventral and dorsal valves, IRCT, Ashkidah Formation.

9. *Syringothyris* cf. *texta* (Hall), dorsal valve, IRCT, Ashkidah Formation.

10. *Wadiglossa supramarginalis* Havlíček, dorsal valve, IRCT, Tarut Formation.

11. *Acanthatia placita* Mergl-Massa, dorsal valve, FSL 413.052b, Marar Formation.

12. *Martinothyris* sp., ventral valve, FSL 413.213, Marar Formation.

13, 14. *Saharonetes saharensis* Havlíček, ventral and dorsal valves, IRCT, VH 7603, Marar Formation.

15, 16. *Cupularostrum minutum* Mergl-Massa, ventral and dorsal valves, FSL 413.081, FSL 413.084, Marar Formation.

17. *Acanthocosta* sp., ventral valve, FSL 413.058a, Marar Formation.

18, 19. *Apousiella* sp., dorsal and ventral valves, FSL 413.159a, FSL 413.160, Marar Formation.

PLATE 5. (p. 73). Murzuq Basin: fossils from the Ouan Kasa and Talagrouna formations.

1. *Tropidoleptus* sp., dorsal valve, FSL 413.016, Ouan Kasa Formation.

2, 5. *Spinella paulula* Mergl and Massa, dorsal and ventral valve, FSL 413.139, FSL 413.137b, Ouan Kasa Formation.

3. *Acrospirifer* sp., two dorsal valves, FSL 413.132, Ouan Kasa Formation.

5. *Aseptonetes* ? sp., ventral valve, FSL 413.041, Ouan Kasa Formation.

6, 7. *Cyphoterorhynchus talagrounaensis* Mergl and Massa, complete shells, FSL 413.114, FSL 413.041, Talagrouna Formation.

8. *Goniophora* cf. *chemungensis* (Vanuxem), left valve, FSL 413.259, Talagrouna Formation.

9, 10. *Leioproductus* sp., dorsal and ventral valves, FSL 413.063, FSL 413.061, Talagrouna Formation.

11. *Sphenotus libyaensis* Mergl and Massa, right valve, FSL 413.263, Talagrouna Formation.

12. *Grammysia* cf. *elliptica* Hall and Whitfield, left valve, FSL 413.272, Talagrouna Formation.

13. *Eoschizodus* sp., left valve, FSL 413.271, Talagrouna Formation.

14. *Schuchertella* sp., ventral valve, FSL 413.039, Talagrouna Formation.

15, 16. *Septothyris boucoti* Mergl and Massa, ventral and dorsal valves, FSL 413.226, FSL 413.230, Talagrouna Formation.

17. *Dicricoconus libyensis* Hajlasz, Massa and Bonnefous, two shells, Talagrouna Formation.

PLATE 6. (p. 74) Murzuq Basin: Fossils from the Marar Formation (1–15).

1, 3. *Pustula* sp., ventral and dorsal valves, IRCT.

2, 5. *Marginatia* sp., ventral valve, IRCT.

4. *Pleuropugnoides* cf. *pleurodon* (Phillips), ventral valve, IRCT.

6. *Syringothyris* cf. *texta* Hall), dorsal valves, IRCT.

7. *Brachythyris* sp., ventral valve, IRCT.

8. *Tylothyris* sp., ventral valve, IRCT.
9. *Prospira platycosta* Havlíček, dorsal valve.IRCT.
10. *Balanoconcha micropuncta* Havlíček, complete shell, IRCT.
11. *Antinoconchus lamellosus* (Leveille), ventral valve, IRCT.
12. *Cleiothyridina* aff. *tomiensis* Besnossova, ventral valve, FSL 413.126.
13, 14. *Paurogastroderhynchus* (=*Septacamera*) *serdelesensis* Massa, Termier and Termier, ventral and dorsal valves, FSL 413.117, FSL 413.118.
15. *Septosyringothyris vautrini* Massa, Termier and Termier (*Histosyrinx*), dorsal valve, FSL 413.209.

PLATE 7. (p. 79) Djado Sub-basin: Carboniferous fossils.

1, 2. *Flexaria arkansana* (Girty), ventral valve, Assedjefar Formation.
3, 4. *Ovatia* sp., ventral valve, Assedjefar Formation.
5, 6. *Cupularostrum* sp., complete shell, Assedjefar Formation.
7, 8. *Antiquatonia insculpta* (Muir-Wood), ventral valve, Assedjefar Formation.
9, 10. *Rhynchopora* sp., ventral and dorsal valves, Marar Formation.
11. *Chonetes* cf. *chesterensis* (Weller), complete shell, Dembaba Formation.
12. *Syringothyris* sp., dorsal valve, Marar Formation.
13. *Anthracospirifer* gr. *curvilateralis* (Easton), ventral valve, Assedjefar Formation.
14, 16, 17. *Syringothyris jourdyi jourdyi* Douvillé, ventral valve and side view to complete shell, Assedjefar Formation.
15. pectinid bivalve, left valve, Dembaba Formation.

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CHAPTER 5

The Absolute Age of the Quaternary Lacustrine Limestone of the Al Mahrúqah Formation – Murzuq Basin, Libya

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ABSTRACT

Lacustrine limestone bearing deposits were discovered in the endorheic Murzuq Basin more than 60 years ago. Their presumed geological age has ranged from the Jurassic to the Holocene. In this study, four different limestone types have been distinguished by different methods. Estimated erosion rates during the Neogene and the elevation of the lacustrine limestone exposures indicate a Quaternary age for the oldest remnants of the paleolake deposits in the continental Murzuq Basin.

Evidence for three levels of a Quaternary paleolake in Fezzan and their corresponding extents has been integrated. We present a new definition of the Quaternary 'Al Mahrúqah Formation' and use this term for all Quaternary carbonate rock units hereafter. The Al Mahrúqah Formation as redefined now comprises three members, viz. the Brak Member (limestone of the former Al Mahrúqah Formation), the Bi'r az Zallaf Member (sandy thin limestone beds) and the Aqar Member (*Cardium* shell-bearing limestone).

Absolute ages are required to establish a precise chronology. Preliminary results of mass spectrometric uranium-series ages are presented. The $^{230}Th/U$ ages of the three different lake levels correspond to the Marine Isotope Stages (MIS) 11 (about 380 ka) for Brak Member, MIS 7 (about 240 ka) for the Bi'r az Zallaf Member and Mis 5e (about 128 ka), the Eemian Interglacial, for the Aqar Member. These absolute ages of the Pleistocene limestone beds are of global importance for the reconstruction of paleoclimate during the Quaternary. The dates support previous evidence that the pluvial phases in arid northern Africa correspond to the warmer interglacial events of the moderate climatic zones of the northern hemisphere.

INTRODUCTION

Based on geomorphological investigations, estimates of the geological ages for the younger limestone beds in the Murzuq Basin have ranged from the Jurassic to the Holocene. Desio

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(1936) was the first geologist who studied the younger limestone beds in the Murzuq Basin. His 'Calcari di Murzuch' ('Murzuq Limestone') was interpreted as Cretaceous marine sediment by Banerjee (1980), while Pagni (1938) had classified this limestone as Jurassic in age. Bellair (1944, 1947 and 1953) supposed a Pliocene to Quaternary age, Lelubre (1946a, 1946b and 1952) assumed a Neogene age and Collomb (1962) a Miocene age for these deposits. Later Hecht et al. (1963) and Desio (1971) differentiated between the 'Murzuq Limestone' (Neogene to Quaternary) and 'Schillkalke' (lumachelle – limestone, coquina beds) of Upper Pliocene to Lower Pleistocene age. Goudarzi (1970) presented detailed information based on fossils in sandy marls in the Murzuq-Traghan valley, suggesting evidence for fresh-water sediments of Pleistocene to Holocene age. Other fossils in Wadi ash Shati area give indications for deposits of salty lakes or of estuarine origin with brackish environments of probable Tertiary age.

Petit-Maire et al. (1980) and Gaven (1981, 1982) published radiometric ^{230}Th/U ages on 21 *Cardium* shells collected from the limestone deposits of twelve locations in Wadi ash Shati. These results were the first absolute chronological time markers from this region. Most samples consisted of calcite reflecting possible but not indisputable postsedimentary recrystallization of the shells and open-system conditions for the uranium-thorium system. The uncorrected ^{230}Th/U ages ranges from 40 ± 2 ka to 173 ± 16 ka (1σ standard deviation). Eleven of these analyses form a cluster around 132 to 136 ka (Gaven, 1981; 1982). Gaven concluded that there was an important humid phase of unknown duration around 130 to 140 ka and a less extensive humid phase around 90 ka.

At the beginning of the nineties the Section 3 of the Joint Geoscientific Research Institute (GGA) started radiometric ^{230}Th/U age determinations of lacustrine limestone samples from Wadi ash Shati. Six limestone / marl samples from the uppermost deposits around 400–500 m.a.s.l were collected by Thiedig, El Chair and Ziegert in 1992 in the western lake area of Wadi ash Shati. All samples consisted of calcite. The uncorrected ^{230}Th/U ages range from 190 ± 12 ka to 320 ± 27 ka (Uh 888, 1042, 1044, 1046, 1047) (1σ standard deviation). One sample yielded an age of >350 ka (Uh 1045). The plot of the ^{234}U/^{238}U activity ratios versus the ^{230}U/^{238}U activity ratios indicated closed-system conditions for all samples. An isochron calculation yielded 286^{+109}_{-53} ka using all samples except Uh 1047, corresponding to MIS 9.

At that time the idea of the three different levels of a Quaternary mega-paleolake in the Fezzan was born. The development of thermal ionization mass spectrometry (TIMS) for the measurement of ^{230}Th and ^{234}U abundances has since resulted in a large improvement of the precision of the ^{230}Th/U ages. In order to check the hypothesis of three lake levels, TIMS ^{230}Th/U ages were essential to develop a precise chronology of the three types of Tertiary to Quaternary limestone beds.

GEOLOGY AND SITE DESCRIPTION

Geological and Morphological Development of the Murzuq Basin

The basic framework of basinal and high areas was developed in most of the old Precambrian cratonic areas of Africa during Paleozoic and Mesozoic times. Granites and other Pan-African basement rock types were eroded and covered by marine and continental dominantly clastic sediment from the lower Palaeozoic up to the Cretaceous. The Murzuq is one of the major basins in northern Africa and is over 600 km in diameter. Subsidence of the Murzuq Basin continued until the early Tertiary, accompanied by an almost continuous basin infilling of up to approximately 2500 m. Strata on the flanks dip generally towards the basin center, exposing all rock units around the flanks in a concentric pattern. Cambro-Ordovician sediments form the

outer margin of the basin on a Precambrian basement. The most dominant relief-forming rock unit within the basin is the sandstone of the Mesák Formation (former 'Nubian Sandstone', (see Klitzsch, 1963, 1974; El Chair et al., 1995) partly cemented by silica. The flat-topped Mesák mountain ridge forms partly the innermost circle of the structure of the basin between the towns of Al Awaynat, Awbari, Sabha and Murzuq. It divides the inner part of the basin from a northern depression extending north to the Gargaf Uplift. The Murzuq and Awbari sand seas have been progressively deflated since the late Cretaceous (Klitzsch, 1974) and have been filled during Quaternary by large lakes several times.

Geochronological Investigations

After many years of research by numerous geologists on the age of the limestone beds in the Murzuq Basin, the large mapping program (Geological map of Libya, scale 1 : 250 000) by the Industrial Research Centre in the northern part of the basin has given a much better understanding of these beds' development. The geological mapsheets illustrating deposits of Quaternary limestone of Idri (Parizek et al., 1984), Sabha (Seidl and Röhlich, 1984), Al Fuqahá (Woller, 1984), Awbari (Štefek and Röhlich, 1984), Tanahmú (Mrázek, 1984) and Tmassah (Koráb, 1984) were mapped by a group of Czech geologists. West and north of this area, Yugoslavian and Russian geologists mapped the geological sheets Hásí Anjíwal (Roncevic, 1984), Wádí Iráwan (Komarnicki, 1984), Bi'r Anzawá (Protić, 1984), Qararat al Marar (Gundobin, 1985) and Hamadat Tanghirt (Berendeyev, 1985).

Pale coloured limestone-forming cliffs are conspicuously widespread and prevalent on the northern margins of Wadi ash Shati. They unconformably cover Cambro-Ordovician, Devonian, Carboniferous and Upper Cretaceous rocks and constitute the 'Al Mahrúqah Formation' (Seidl and Röhlich, 1984). Collomb (1962) had previously described fresh-water deposits east of Hasi Anjiwal as 'Miocene lacustre' while Parizek et al. (1984) presumed a late Pliocene to early Pleistocene age for these strata. Domáci et al. (1991) summarized the results of the Czech group as regards Neogene and Quaternary investigations in northern Fezzan. These workers distinguished two facies of Plio-Pleistocene age: a predominantly carbonate facies with only local and subordinate basal conglomerates, which they assigned to the 'Al Mahrúqah Formation', as well as a mixed facies with sand and siltstone. Grubic et al. (1991) summarized the geological studies of the Yugoslavian mapping group in the northwestern part of the Murzuq Basin and reported late Pleistocene bivalves, gastropods and a variety of palynomorphs. They interpreted the observations as an "indication of the possible presence of a continuous or a discontinuous series of limited freshwater basins from the Pliocene to the Pleistocene" (Grubic et al., 1991). According to our interpretation most of these lacustrine limestones belong to the Brak Member, some to the Bi'r az Zallaf Member and only a few to the Aqar Member. The absolute age of some of the lacustrine limestones in the northwestern Murzuq Basin has not yet been investigated and still remain unknown.

More than 15 years ago Thiedig and El Chair discovered limestone outcrops in the Awbari sand sea valleys between sand dunes. In the following years they visited many parts of the Murzuq Basin in order to study the lacustrine limestones, which then were assumed to be of Tertiary to Quaternary age (Figs 1 and 2). In 1981 they initiated radiometric ^{230}Th/U age determinations from the inner Awbari Sand Sea performed by the GGA and obtained unpublished dates on cemented root pipes from sandy limestone. Further ^{230}Th/U dates (GGA) from different localities and topographical positions in Wadi ash Shati and the Murzuq-Traghan-Tmassah-valley were published by Thiedig and Ziegert (1995).

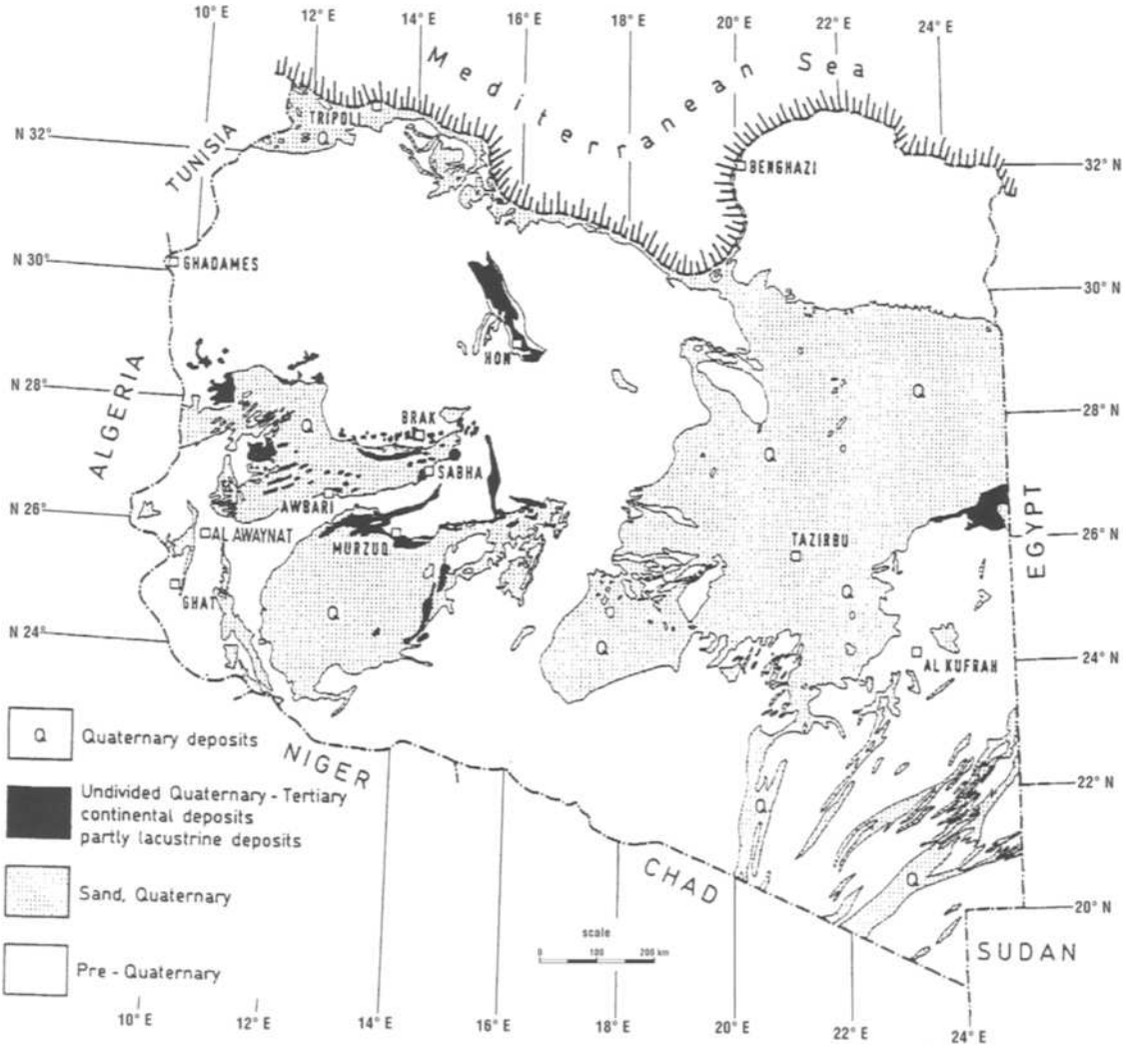

Figure 1. Distribution of Quaternary deposits in Libya, (modified after National Atlas of the S.P.L.A.J., 1978).

Al Mahrúqah Formation – Types of Lacustrine Limestone

The term 'Al Mahrúqah Formation' was introduced by Seidl and Röhlich (1984) for a carbonate rock unit of unknown Tertiary or Quaternary age overlying pre-Tertiary formations on the northern margins of the Murzuq Basin. The name is derived from the village Al Mahrúqah, 25 km west of Brak in Wadi ash Shati. Our own geomorphological, sedimentological and petrographical studies suggest that the different lacustrine limestone types of the Awbari and the Murzuq sand seas may be subdivided into three groups. We classify these units' characteristic features by means of:

b. their topographical position (height above sea level in relationship to the surrounding relief),
c. the structure of the limestone (bedded or massive, brecciation, weathering surface),
d. colours,
e. impurities (clastics, gravel, sand, silt, organic detritus, fossils), and

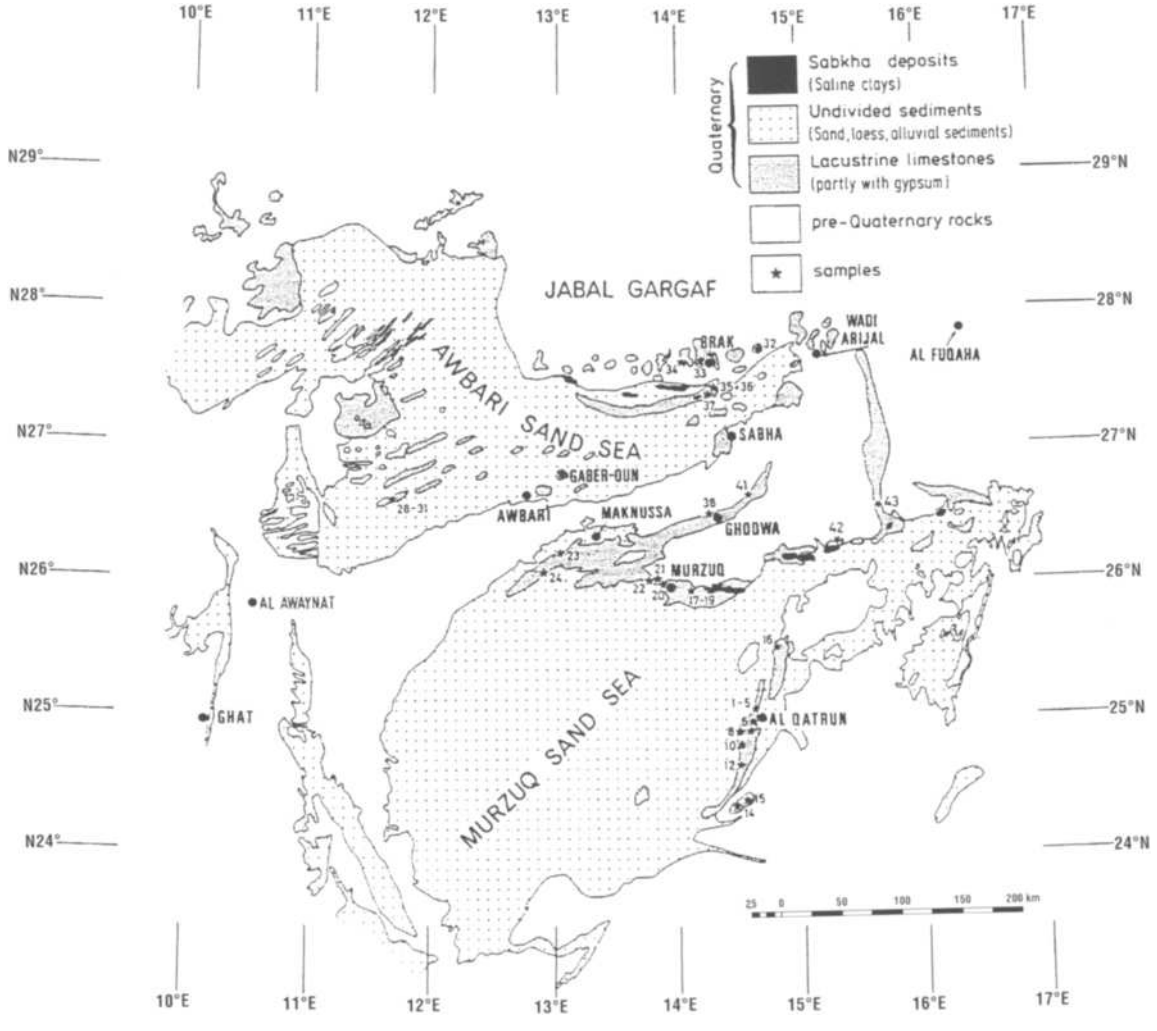

Figure 2. Distribution of limestone-bearing lacustrine and sabkha deposits in SW Libya, with locations of investigated samples.

f. geochemical data.

Based on our results a new stratigraphic terminology for the Quaternary deposits in the northern Murzuq Basin is introduced (Figs 1 and 2). The established name 'Al Mahrúqah Formation' will be retained for all Quaternary carbonate rock units hereafter while three separate limestone-bearing units are defined as members:

b. Brak Member (the former 'Al Mahrúqah Formation'): massive brecciated limestone,
c. Bi'r az Zallaf Member: sandy thinly bedded limestone,
d. Aqar Member: *Cardium* shell-bearing limestone.

An understanding of the drainage system of the endorheic Murzuq Basin is necessary for interpretation of the hydraulic system and the extents of the different paleolake levels (Figs 3 and 4). In this respect the elevation of each limestone's exposure is most important. Unfortunately this determination is extremely difficult because the available maps have only 50 m contour lines on a scale of 1 : 250 000. All coordinates of the geographical positions given in the following text, except for the three type localities, have been determined using a conventional GPS equipment which, unfortunately, does not permit accurate determination of elevation.

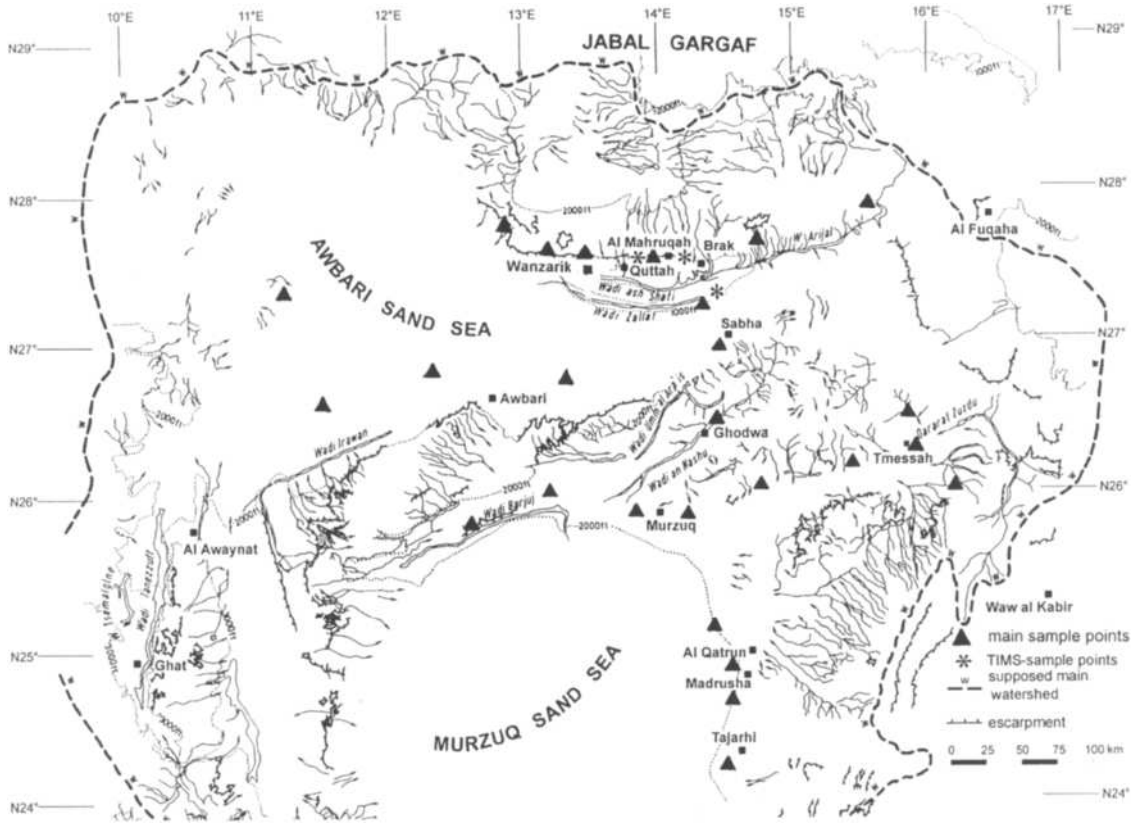

Figure 3. Distribution of TIMS and other main sample points in northern Murzuq Basin.

Brak Member

The Brak Member is identical with the development of the original 'Al Mahrúqah Formation' as defined by Seidl and Röhlich (1984). The type locality is situated on a table mountain 5 km E of Al Mahrúqah (27°30′28″ N, 14°04′00″ E) in Wadi ash Shati. Here the Brak Member unconformably overlies the weathered Carboniferous Marár Formation and reaches its maximum thickness of about 12 m (Plates 1 and 2a). Its base consists of sandy to chalky limestone with a creamy-white colour. The main limestone is often white to grey spotted with streaks and pseudobrecciated intervals. The upper beds show irregular cherty silicification of the massive limestone. Some rather poorly developed bedding planes are visible NE of Quttah in a quarry (coordinates of the quarry for ^{230}Th/U-samples are 27°29′15″ N, 13°49′55″ E, not exactly identical with the position on the 1 : 250 000 geological map sheet Sabha, Fig. 3).

The Brak Member is widely developed through the northern part of the Murzuq Basin. Two main exposure areas are known. The largest of these extends over more than 300 km along the southern margins of the Gargaf High from the Idri/Al Mahrúqah/Brak road junction in the west to Al Fuqaha in the east. Large areas of Neogene to Pleistocene deposits west and northwest of Idri have been mapped as far as to the Algerian boundary and are documented on the Geological map of Libya 1 : 250 000, mapsheets Hásí Anjíwal (Roncevic, 1984), Bi'r Anzawá (Protic, 1984), Wadi Íráwan (Komarnicki, 1984) and Hamadat Tanghirt (Berendeyev, 1985). Since we have not yet had the possibility to visit these areas, we cannot be sure if these clastic and limestone deposits also belong to the Brak Member. If they do, as suggested herein because of

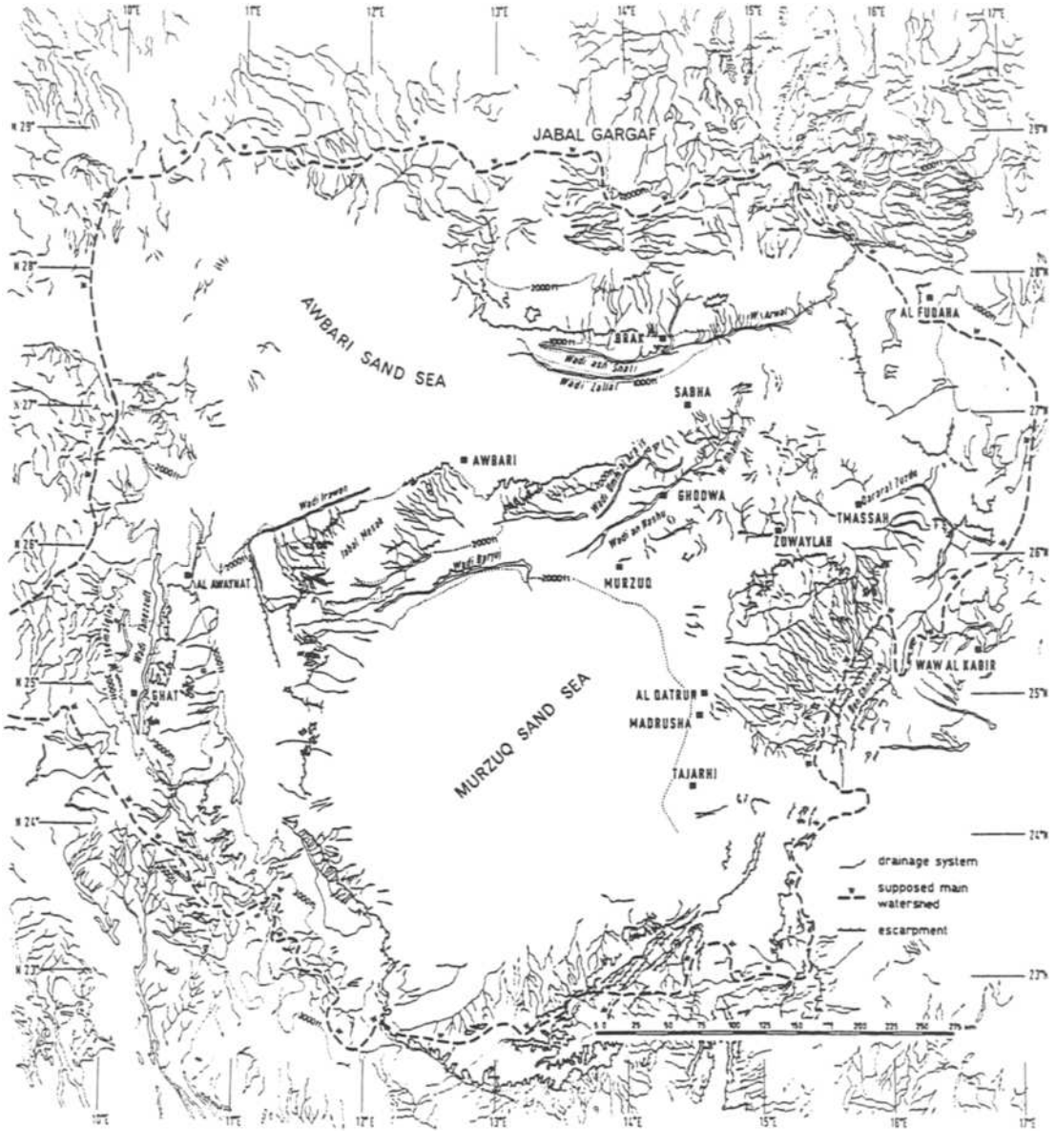

Figure 4. Drainage system of the endorheic Murzuq Basin with projected main watershed (modified from Operational Navigation Chart 1: 1 000 000, sheets H-3, H-4, J-4, 1979, DMAAC Distribution Division (C-44), National Ocean Survey, Riverdale, MD U.S.A.).

their apparent elevation, the Brak Member is developed laterally over a more than 500 km long exposure belt.

The second area of exposure extends from Murzuq to Tmassah (200 km east of Murzuq) into the 5 km to 20 km wide 'Qattusah channel' (Q.Ch. in Fig. 5), which extends about 120 km to the north and was almost certainly connected with the eastern end of the exposure belt along the southern margin of the Gargaf Uplift.

The present-day topmost exposures of the Brak Member in Wadi ash Shati occur at about 460 m to 420 m above sea level, rising to 450 m above sea level to the east (Fig. 6). Mapsheets suggest that outcrop elevations of 475 m a.s.l. drop southwards to about 440 m a.s.l. in the channel area (Serir al Qattusah) north of Tmassah. Outcrops in the area west and northwest of

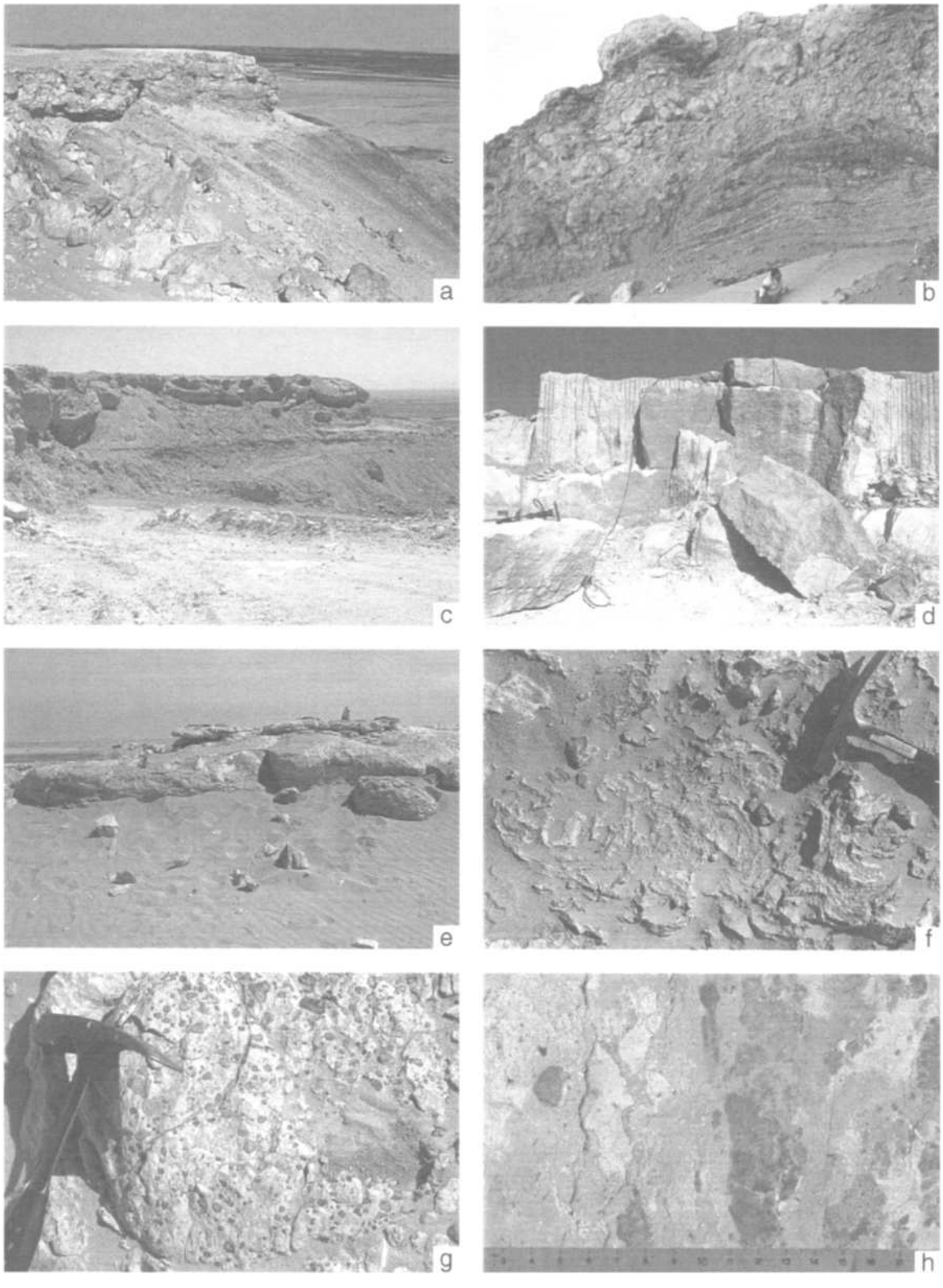

Plate 1. (*for description of plates, see end of chapter*)

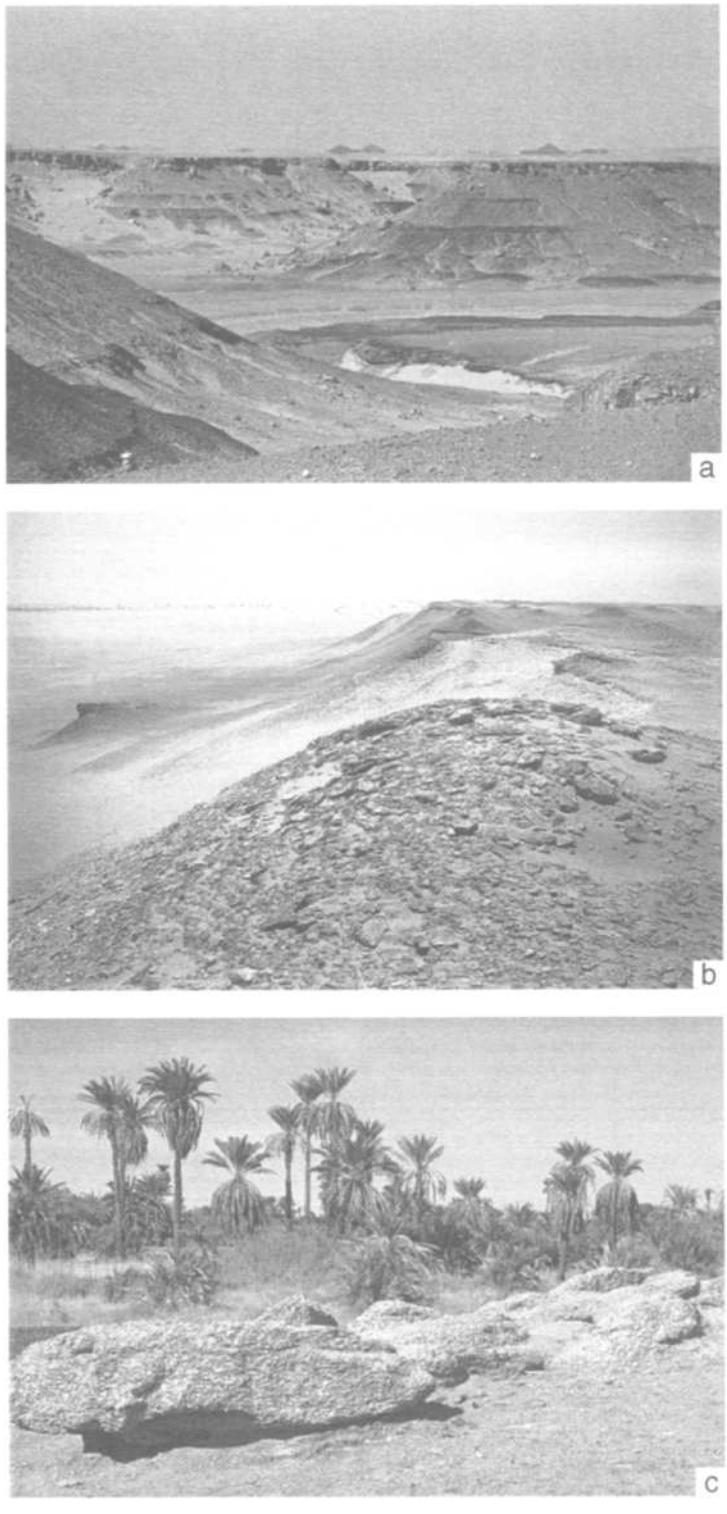

Plate 2.

Figure 5. Brak Member phase (approx. 380 ka) with suggested outline of the paleolake, 'Q.Ch'. = Qattusah Channel.

Idri reach an elevation of 500 m in the dune valleys on the Hamadat Tanghirt mapsheet (Berendeyev, 1985), rising to more than 550 m a.s.l. on the Hási Anjiwál sheet (Roncevic, 1984).

Koráb (1984) and Domác et al. (1991) reported an interesting sequence of sandy limestone below the Brak Member (former Al Mahrúqah Formation) in the Qattusah area (Tmassah and Al Fuqaha geological sheets). This is the only case where older Pleistocene sediments were found below the Brak Member. We do not know if they represent an older part of the Brak Member or deposits of older lacustrine cycles.

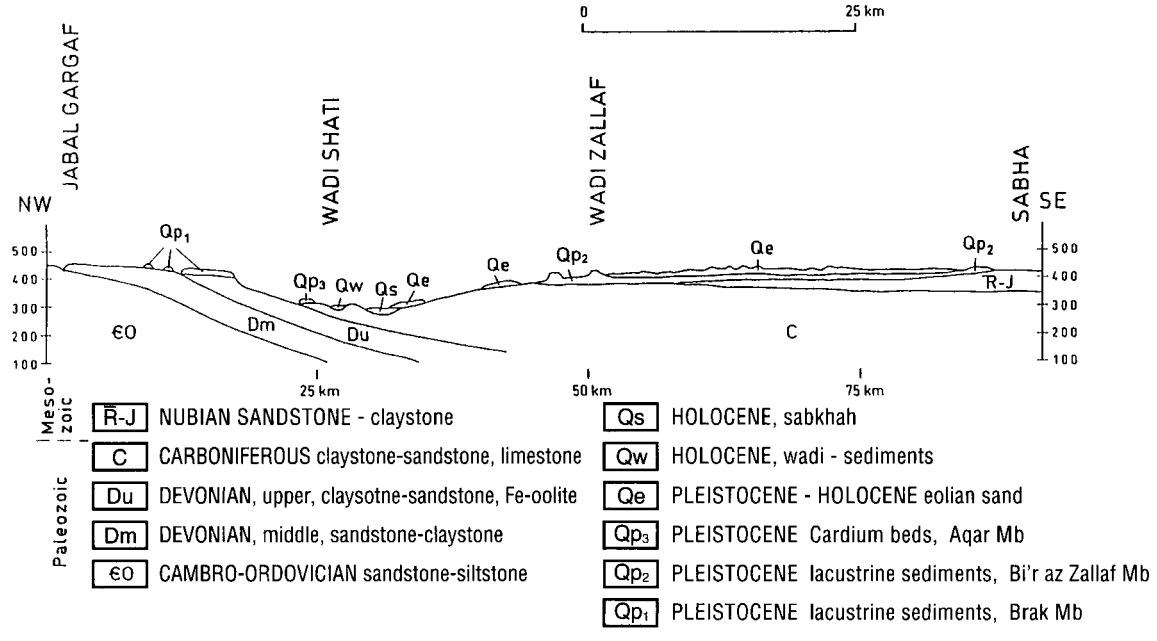

Figure 6. Geological section through Wadi ash Shati with three levels of Pleistocene limestone-bearing members (paleolake levels).

Large-scale fossil landslides of 'Pliocene/Pleistocene' age on the Mesák Mallat and Hamadat Manghini escarpments reported by Grunert and Busche (1980) and Busche (1980) could coincide with the limits of our paleolake during the Brak and Bi'r az Zallaf phases.

One remarkable feature is the asymmetric distribution of the Brak Member. It occurs mainly on the northern margin of both sand seas in Wadi ash Shati and in the Murzuq-Traghan valley. The reason for this phenomenon may be higher lime precipitation on the rather shallow rise of the northern slope compared to the steep cliff of the southerly dipping Mesák Formation on the southern margin of the paleolake in the Wadi Al Hayal (Awbari). Changing water levels and possible water currents in the lake could also have influenced the precipitation of carbonates. We have estimated the deepest point of this paleolake to have been situated south of Al Mahrúqah village, with depths of some 80 to 100 m, comparable to the present relief in Lake Tchad.

Bi'r az Zallaf Member

Until now this member has been included in the indefinite term 'continental deposits' of Plio-Pleistocene or Neogene age. We define outcrops near Bi'r az Zalláf about 18 km southeast of Brak as the type locality (27°26'27" N and 14°13'53" E), referring to the explanatory booklet of the Sabha geological mapsheet (Seidl and Röhlich 1984, p.87). Typical exposures of the member are shown in Plate 2, fig. b and in Plate 3.

The maximum thickness of this sequence is about 25 m. The base typically shows light greenish friable argillaceous silt or sandstone, partly cemented by halite. The conspicuous greenish color of the sandstone below the thin-bedded limestone could represent reworked sandstone of the Upper Cretaceous Bin Affin and Tar members (Zimám Formation) as reported on the Al Waskah geological mapsheet (Woller, 1978).

We interpret vertical 'burrows' as representing precipitation of carbonate around the roots of reeds growing close to the shallow shore of the paleolake (Plates 4i and 5b). Thinly bedded, partly dolomitic limestone is common and diffuse cherty silicification is visible at the exposed

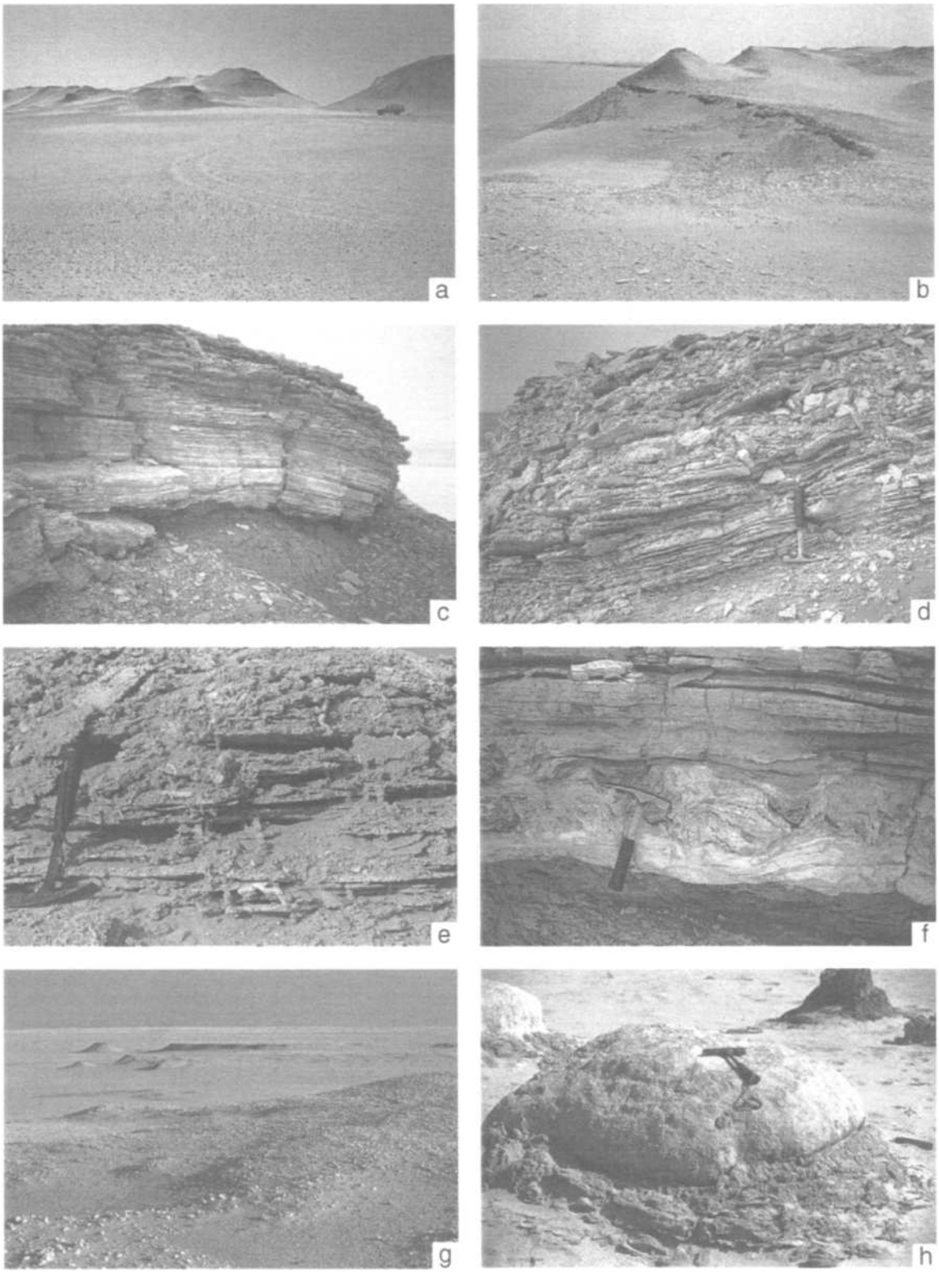

Plate 3.

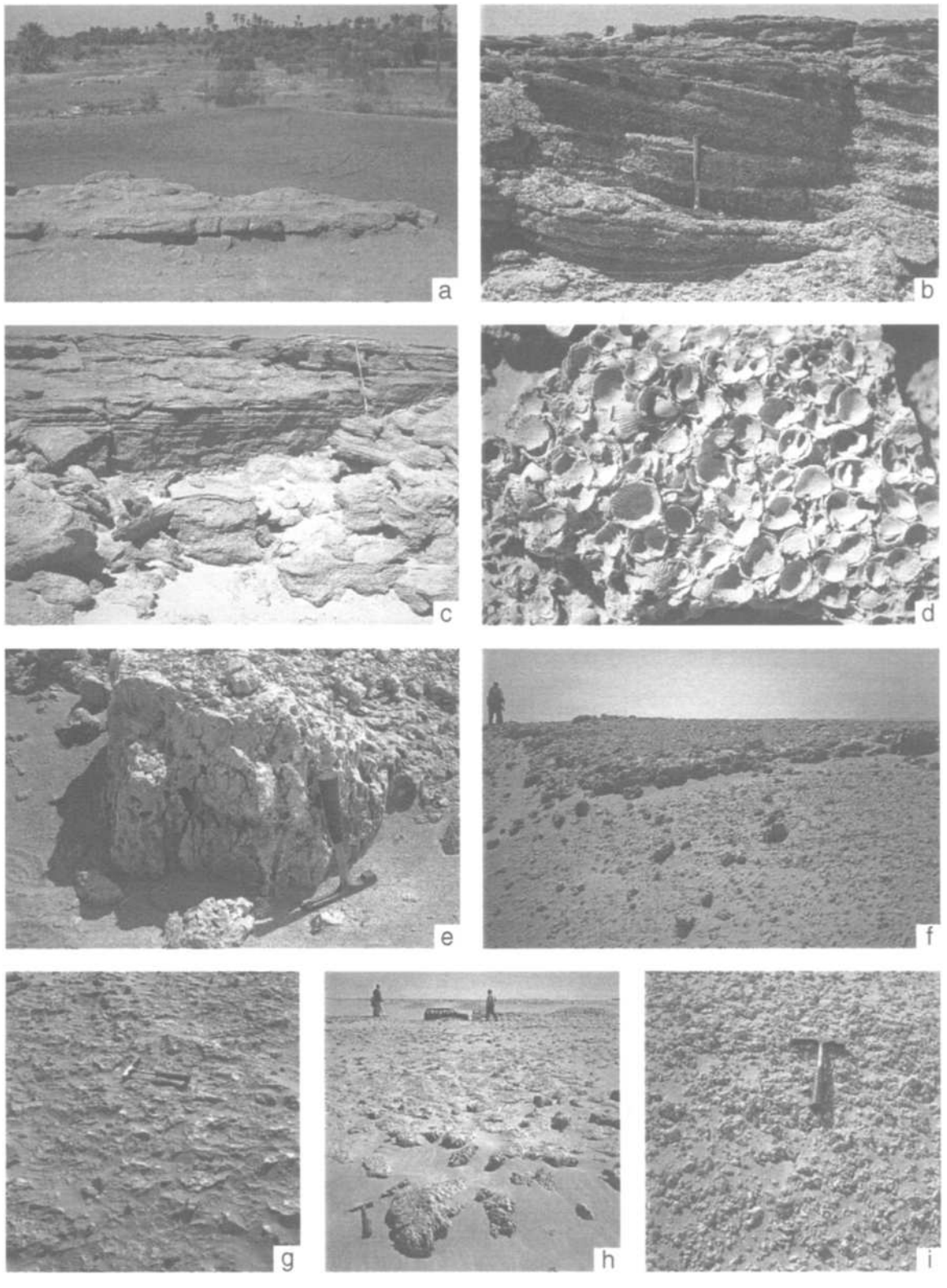

Plate 4.

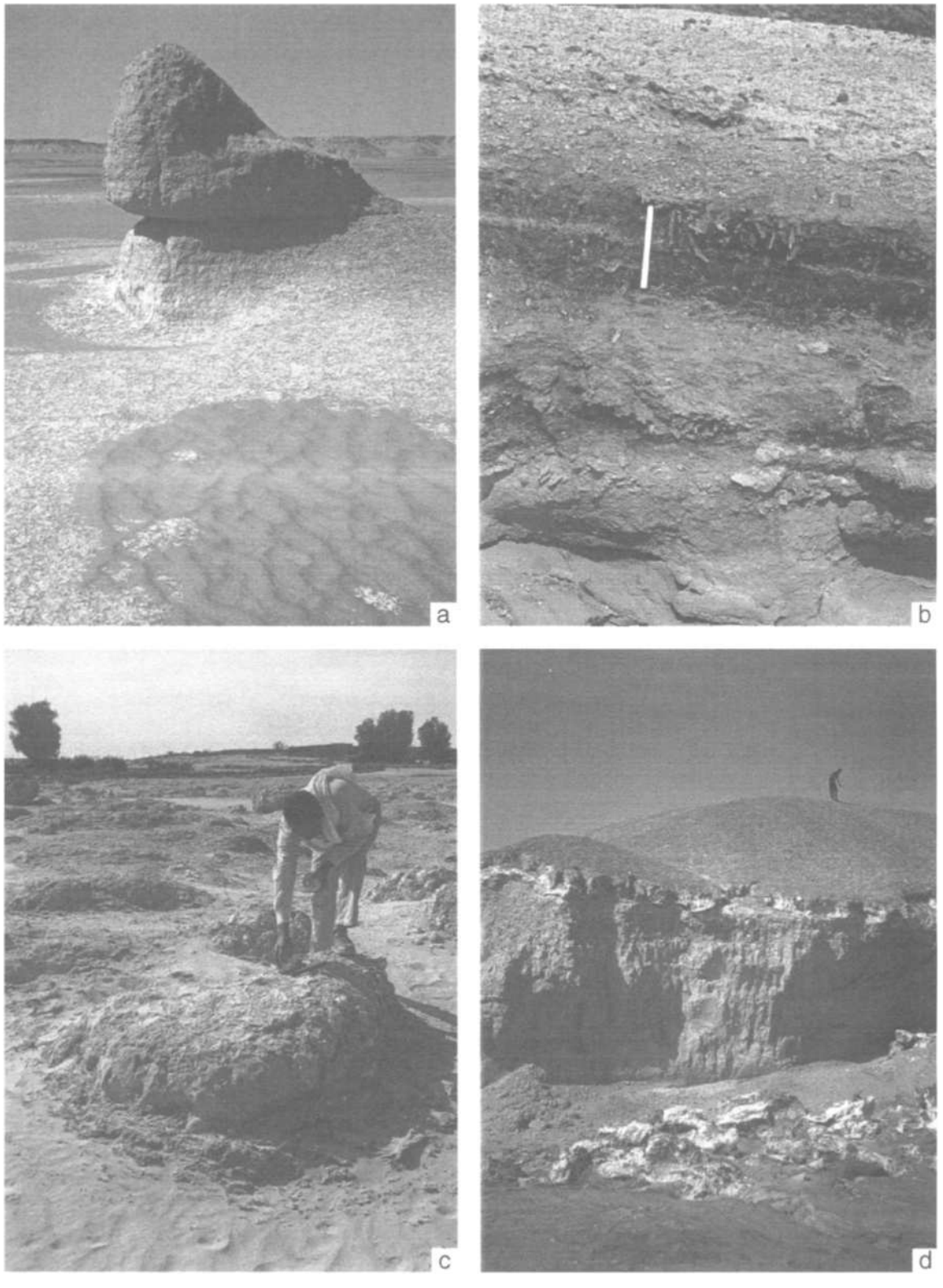

Plate 5.

surfaces. At some locations gypsum beds are intercalated with collapsed horizons (Plate 3f) showing a light brownish to creamy-white color. Fossils are rare and poorly preserved. Seidl and Röhlich (1984) reported fragments of ostracodes, characeae and remnants of small fishes.

This Bi'r az Zallaf Member shows a wide distribution. Large areas exist south of Wadi ash Shati on the northern margin of Ramlat az Zallaf, mostly preserved as isolated relict hills due to the limestone cover. We have also found exposures near Sabha and Ghodwah and at several locations on the northern margin of the Murzuq Sand Sea, in the valley east of Murzuq to Traghan, Zuwaylah and further to Tmassah and west of Murzuq in Wadi Barjuj (50 km southeast of Awbari), all of which we consider to belong to the Bi'r az Zallaf Member. Exposures on small residual hills about 30 km southeast of Tmassah show very similar sequences of greenish argillaceous sandstone intercalated with thinly bedded limestone and gypsum. Similar sequences are common along the eastern margin of the Murzuq Sand Sea between north of Al Qatrun and Tajarhi. Samples for ^{230}Th/U-dating were taken from a table mountain (inselberg or residual hill) located at 27°25′58″ N, 14°23′28″ E (Plate 2b). Our topographical data differs slightly from those of our Czech colleagues (27°26′27″ N, 14°23′28″ E in Seidl and Röhlich, 1984), but we consider this to be the same hill or at least one close by.

The elevation of the present topmost exposures of the Bi'r az Zallaf Member in the Wadi ash Shati area approaches 350 m a.s.l. in the east, rising to about 410 m a.s.l. in the west. It is not known whether sequences on some residual hills are incomplete because of erosion. Near Sabha we found the Bi'r az Zallaf Member at 420 m, in Ghodwah at 460 m, in Murzuq at 460 m, near Tmassah at 460 m, on the table mountains southeast of Tmassah at 450 m and in Al Qatrun at 460 m (all elevations above sea level). In a Recent sabkha area east of Tmassah we discovered numerous large stromatolites at an elevation of 410 m a.s.l., indicating the presence of a lake. These possibly belong to the Bi'r az Zallaf Member (Plate 5c and Plate 3h). Summarizing our observations, it is clear that the outcrop area of the Bi'r az Zallaf Member is smaller than that of the Brak Member (Figs. 5 and 7). In addition, the paleolake level reflected by the deposits of the Bi'r az Zallaf Member was lower than that of the older lake level of the Brak Member. The already existing sand dunes in the Awbari Sand Sea were islands in the large lake.

Aqar Member

Coquina beds with *Cardium glaucum* in Wadi ash Shati have been reported and classified as 'Continental deposits of Plio-Pleistocene age' by several authors. Six outcrops with *Cardium* shell occurrences were mapped by Goudarzi (1970), eleven by Petit-Maire (1982). The first radiometric ^{230}Th/U age determinations from Wadi ash Shati (Petit-Maire et al., 1980) were performed using samples of the lacustrine limestones of the Aqar Member.

The name Aqar Member is derived from a small village 11 km W of Brak in Wadi ash Shati. The type locality occurs in an outcrop about 10 km E of Quttah and 0.6 km south of the main road (sample locality number XV in Petit-Maire, 1982; p. 17) located at 27°28′40″ N and 13°53′10″ E. Another reference locality is located 1 km SW of Al Mahrúqah village (Plate 2c, 27°29′45″ N, 14°00′37″ E) in a sabkha region (sample locality number XIV in Petit-Maire, 1982). Our TIMS samples are taken from outcrops on the main road about 5 km E of Aqar.

Parts of these outcrops superficially look like monomict assemblages of *Cardium* shells, but they do also contain other smaller bivalves, gastropods, ostracodes and foraminifers. *Cardium* shells touch each other only at a few points where the shells have been cemented together forming a consolidated rock (Plate 2c and Plate 4d). Interstices were originally empty and are now partly filled by eolian sand. The beds may be up to 1 m to 5 m thick. Isolated outcrops with small *Cardium* shells are widespread over an area of about 80 km by 15 km between Wanzarik (mapsheet Idri, Parizek et al., 1984) and east of Brak (mapsheet Sabha, Seidl and Röhlich, 1984)

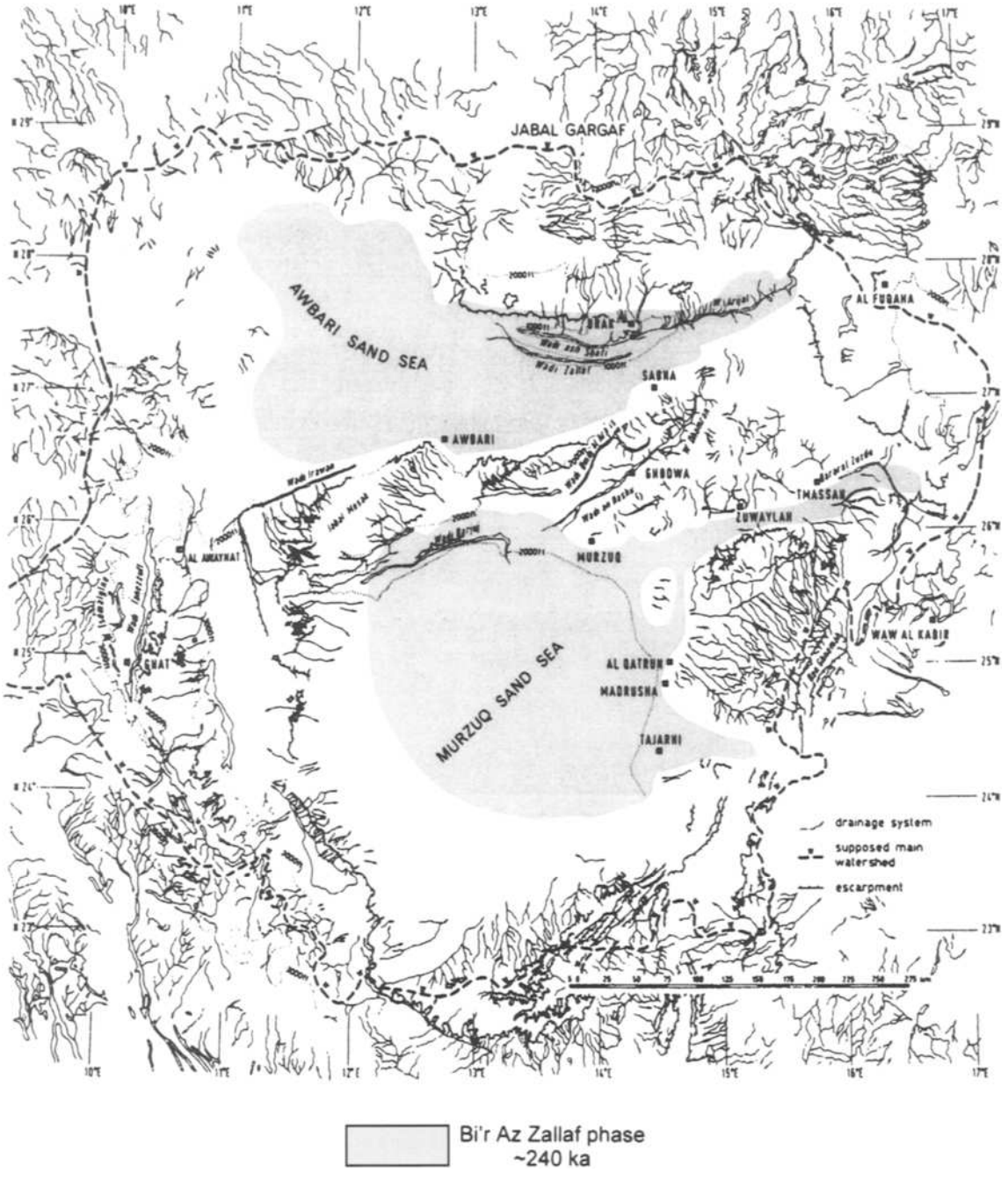

Figure 7. Bi'r az Zallaf Member phase (approx. 240 ka), with supposed outline of the paleolake.

on two terraces about 345 m and 325 m a.s.l. (Domaci et al., 1991). Topographical data regarding the Wadi ash Shati region published by Petit-Maire (1982) differ from those of the geological mapsheet Sabha (Seidl and Röhlich, 1984) – for instance: the lowest exposure is pointed out to be at 256 m a.s.l. in the former, while an elevation of 289 m a.s.l. is indicated by the mapsheet.

These *Cardium* occurrences are thought to indicate deposition in a brackish water paleolake (Gaillard and Testud, 1980). So far no similar outcrops have been found elsewhere in the Murzuq area. The proposed restricted extent of the paleolake at this phase is shown in Fig. 8.

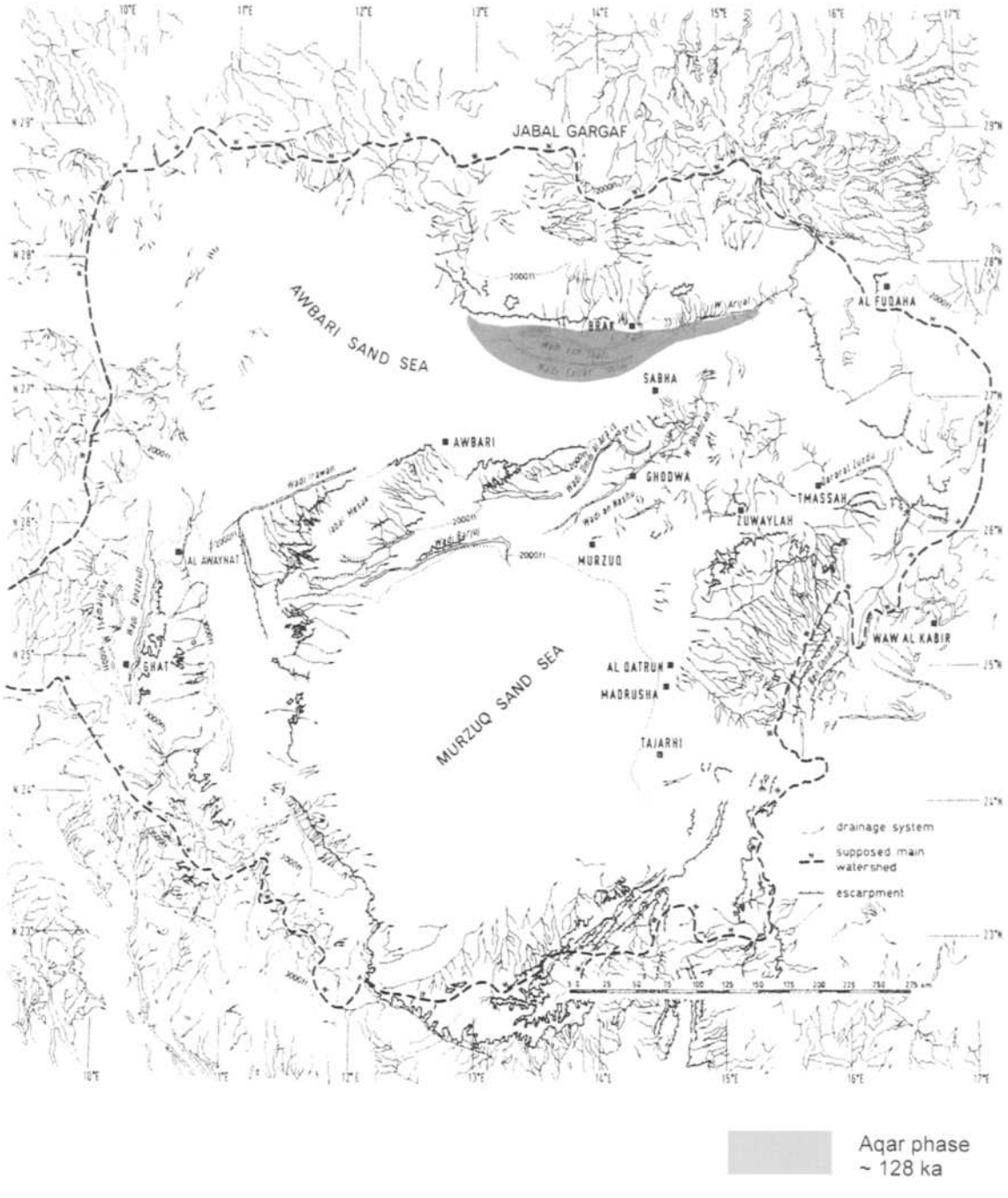

Figure 8. Aqar Member phase (approx. 128 ka), with supposed outline of the paleolake.

Fluvioeolian deposits

Some fluvioeolian deposits have been observed in the Murzuq Basin. One notable such deposit is found in small qarárat (morphological depressions formed by deflation) about 15 km north of Wadi Kunayr (geological map Al Fuqahá sheet: Woller, 1984). Deflation has originally produced an endorheic depression in an exposure of the relatively soft Silurian Tanezzuft shale. The bottom of this depression is about 10 m deeper than the main surface level in the surroundings and the depression is about 2 km wide. The depression has at one stage been filled with greyish

soft argillaceous material, but today only a few pillars up to 4 m high are preserved as remnants of this fluvioeolian sediment (Plate 5a). The poorly consolidated clay shows weakly defined bedding planes. These remnants represent the filling of a temporary paleolake with fluviatile clay and eolian input of Quaternary age. The deposits have then been eroded by the wind during the Holocene.

Calcrete

Large areas of calcrete in and around the Awbari and Murzuq sand seas are well known and very common. These form large plains and can easily be identified even from large distances because of their high light reflection unless they are covered by sand and gravel. Single limestone clasts of different sizes are greyish to blue greyish. They mostly cover wadi terraces and sand or gravel plains, building serirs. Sometimes they adapt to the morphology of hills and encrust them (Plate 5d).

The calcrete is often riddled with holes and its irregular surface is mostly shaped by wind erosion. Its thickness ranges from 5 to 20 cm. Frequently only fractions of wadi terraces are cemented, since sand and gravel are very commonly imbedded. However, sometimes thicker pure limestone crusts are found.

This calcrete is developed at different elevations e.g. south of Awbari on top of the Mesozoic sandstone at 550 m a.s.l., south of Al Awaynat at 680 m, close to Qabr Awn in the Awbari sand sea at 490 m, near Sabha at 420 m and near Jarmah at 460 m. They reflect continuous formation in semi-arid climatic conditions (Geyh and Eitel, 1998).

Aspects of Human Neo- and Paleolithic Settlements

The Sahara has been settled by humans for a long period of time. In 1850 the German explorer Heinrich Barth made the first discoveries of Neolithic rock carvings in the Fezzan. The archaeologist Frobenius (1937) published his extensive documentation of hundreds of rock carvings and wall paintings created by inhabitants of the area some thousands of years ago. Ziegert (1967, 1969) presented results of intensive geological and field studies of Neo- and Paleolithic human activities from the Jabal Bin Ghanimah and northern Tibesti areas of the Murzuq Basin. Beautiful rock carvings (with large crocodiles, hippopotami, giraffes, elephants and many other animals), tools and coloured wall paintings in the surroundings of the Murzuq and Awbari sand seas were made by Meso- and Neolithic people. According to ^{14}C dates these were created during the younger Late Pleistocene and Holocene humid phases (Ziegert, 1978; Mori, 1978). Some years earlier Graziosi (1969) reported on the prehistoric development of Fezzan.

Further studies, mostly during the last 8 years by Ziegert (pers. comm., 1998) show a dense settlement in Wadi Al Hayah (Adjal) in front of the cliff of the Mesozoic Mesák Formation. The northern slopes and foothills of the Mesák cliff are identical with the southern margin of two levels of the paleolake. During phases with higher precipitation, the Mesák Formation could have been a source of groundwater, with springs located close to the probably brackish paleolake (Brak phase) and the Paleolithic settlements. Ziegert recently discovered dark ash layers of burnt reed together with artefacts in a gully of a recessive inlet cut into the cliff near Al Ghrayfa (Plate 5b). There are no absolute age determinations of this settlement as yet. Lacustrine sediments of Neolithic age in the Murzuq Basin have not yet been reported.

ANALYTICAL METHODS

^{230}Th/U Disequilibrium Dating

The laboratory for thermal ionization mass spectrometry (TIMS) at the GGA has provided the possibility to check the hypothesis of three different lake levels in the development of the mega-paleolake.

Methodological Background

Uranium-series disequilibrium dating has been applied preferentially to Quaternary marine and terrestrial carbonates as well as to organic-rich sediments for more than three decades. The dating range extends beyond that of the ^{14}C dating method and may reach back to a maximum of about 500 ka.

The ^{230}Th/U-dating method is based on the disturbance of the radioactive equilibrium between ^{238}U and its radioactive daughters by geochemical processes. In an initial system ^{234}U (half-life = 245 ka) decays to ^{230}Th (half-life = 75.4 ka) as a function of age. Two basic requirements have to be fulfilled for the application of this process as a dating method: a chemically closed system for uranium and thorium during its aging and the absence of initial detrital ^{230}Th (which is usually correlated with ^{232}Th). For further details on the uranium-series dating methods see Ivanovich and Harmon (1992).

Analytical Procedure

Thermal ionization mass spectrometric (TIMS) ^{230}U/^{234}Th determinations have been carried out on calcite samples of less than 1.6 g. They were weighed and dissolved in an HNO_3/HCl mixture. A ^{229}Th and a ^{233}U/^{236}U double-spike were added. Uranium and thorium were separated from the equilibrated leach solution by co-precipitation with $Fe(OH)_3$ and finally separated and purified by ion-exchange chromatography. The two fractions were loaded on rhenium filaments and the uranium and thorium isotopic ratios were measured by high-resolution thermal ionization mass spectrometry (Finnigan MAT 262, equipped with a RPQ filter).

Calculation of ^{230}Th/U ages

^{230}Th/U ages were calculated assuming closed-system conditions and negligible initial ^{230}Th. The isochron method was applied for the correction of detrital contamination. It is based on the assumption of a two-component mixing of detrital and radiogenic ^{230}Th. For one accurate age at least two or rather more coeval samples with different U and Th content have to be analyzed. We have used a modified procedure for the calculation of the isochron age (Geyh, 1994), which takes into account the normalization of ^{230}Th and ^{234}U to ^{232}Th to avoid the otherwise misleadingly enlarged errors.

RESULTS

The names, geographical locations and stratigraphical positions as well as first preliminary results of the analyzed samples of the Wadi ash Shati paleolake levels are shown in Fig. 3 and Table 1. Two sigma standard deviations are reported. Initial ^{234}U/^{238}U activity ratios ranged between 1.05 and 1.34, the U and Th concentrations ranged from 0.5 to 1.5 and from 0.03 to 0.2

Table 1. Results of the mass-spectrometric analyses: for locations of the TIMS-samples see Fig. 3

TIMS–Hv	Ident	Location	Stratigraphic Position [m above s.l.]	Age Estimate	Preliminary TIMS $^{230}Th/U$ Age [ka]	MIS
108	10078	27°29′15″ N 13°49′55″ E	~420	Pleistocene–Pliocene	380	11
104	10074	27°25′58″ N 14°23′28″ E	~380	50–110 ka or older		
105	10075	18 km SE Brak				
106	10076					
107	10077					
Isochron (Except TIMS-Hv 106)					240	7
102	10072	27°31′24″ N 14°06′09″ E	~345	50–110 ka (Eemian)		
103	10073	17 km W Brak				
Isochron 102 + 103					128	5e

ppm respectively, with one exception each. The $^{230}Th/^{232}Th$ activity ratios were larger than 17 except for the *Cardium* shells of the Aqar Member, indicating only minor detrital contamination by allochthonous thorium for the Brak and the Bi'r az Zallaf Member. The plot of the $^{234}U/^{238}U$ activity ratios versus the $^{230}U/^{238}U$ activity ratios verified closed-system conditions for all samples.

Although preliminary, the $^{230}Th/U$ ages of the three limestone members are in good agreement with the stratigraphic sequence of the sediments. The presumed oldest limestone of the Al Mahrúqah Formation with the largest distribution and thickness – the Brak Member (TIMS-Hv 108) – yielded an uncorrected $^{230}Th/U$ age around 380 ka, which appears to correlate with MIS 11. Further analyses are necessary to evaluate a reliable absolute time marker. This TIMS $^{230}Th/U$ age is in reasonable good agreement with the radiometric isochron age of 330^{+80}_{-45} ka (1σ errors). Four limestone samples of the following younger terrace, the Bi'r az Zallaf Member with thinner deposits, yielded an isochron age around 240 ka (TIMS-Hv 104–107). This can be correlated with MIS 7. Two samples from the Aqar Member, the lowest terrace with *Cardium* shells, yielded an isochron age around 128 ka (TIMS-Hv 102 + 103) and can be correlated with MIS 5e.

DISCUSSION

The Murzuq Basin was influenced by marine environments in the Paleozoic and became a more or less continental basin without marine outlet from the Permian onwards. This continental

phase was interrupted only by the marine Maastrichtian transgression, which reached the northeastern margins of the Murzuq Basin. Last remnants of the uppermost Cretaceous sandstone are situated 50 km northeast of Sabha. During the long period of about 65 million years through the Tertiary the continental endorheic Murzuq Basin was formed mainly by deflation rather than by fluvial erosion during humid intervals. These processes carved out the Mesák Ridge between the present large sand sea areas. The two separated depressions of the Awbari and Murzuq sand seas have to be much older than the studied remnants of the paleolake levels.

The dip and the increasing thickness of the Cretaceous Mesák Formation into the center of the basin indicate continuous subsidence of the Murzuq Basin up to the Tertiary. There is however no evidence for Maastrichtian or Paleogene sedimentation in the inner parts of the Murzuq Basin.

In contrast, the elevation of the Brak Member limestone decreases towards the center of the basin by 30 m to 50 m. Reasons for this could be imprecise measurements, erosion, changing water level in the paleolake or maybe even a small continuation of subsidence. The relief of the oldest paleolake level in the Murzuq Basin is very similar to the present morphology. Most of the Brak Member occurrences in the northeast of the basin are located on soft sandstone of the Maastrichtian Bin 'Affin Member (Sabha and Al Fuqaha geological sheets), the youngest Mesozoic deposit. Lacustrine fossils do not permit differentiation between Pliocene and Quaternary deposits.

During highstand, the oldest known Quaternary Brak phase of the paleolake 'Fezzan' covered the Awbari and Murzuq sand seas, which are separated by the Mesák mountain ridge. The two parts of the paleolake were connected through the Qattusah channel and by groundwater

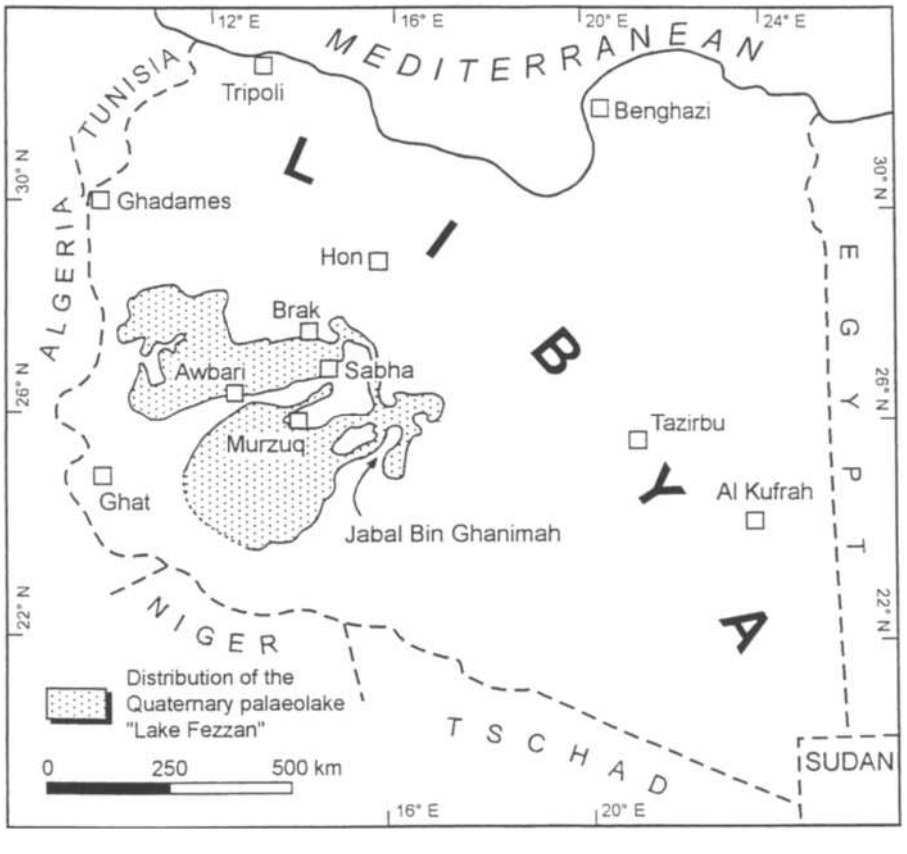

Figure 9. Contours of the Quaternary 'Paleolake Fezzan' (Brak Member, approx. 380 ka) in SW Libya.

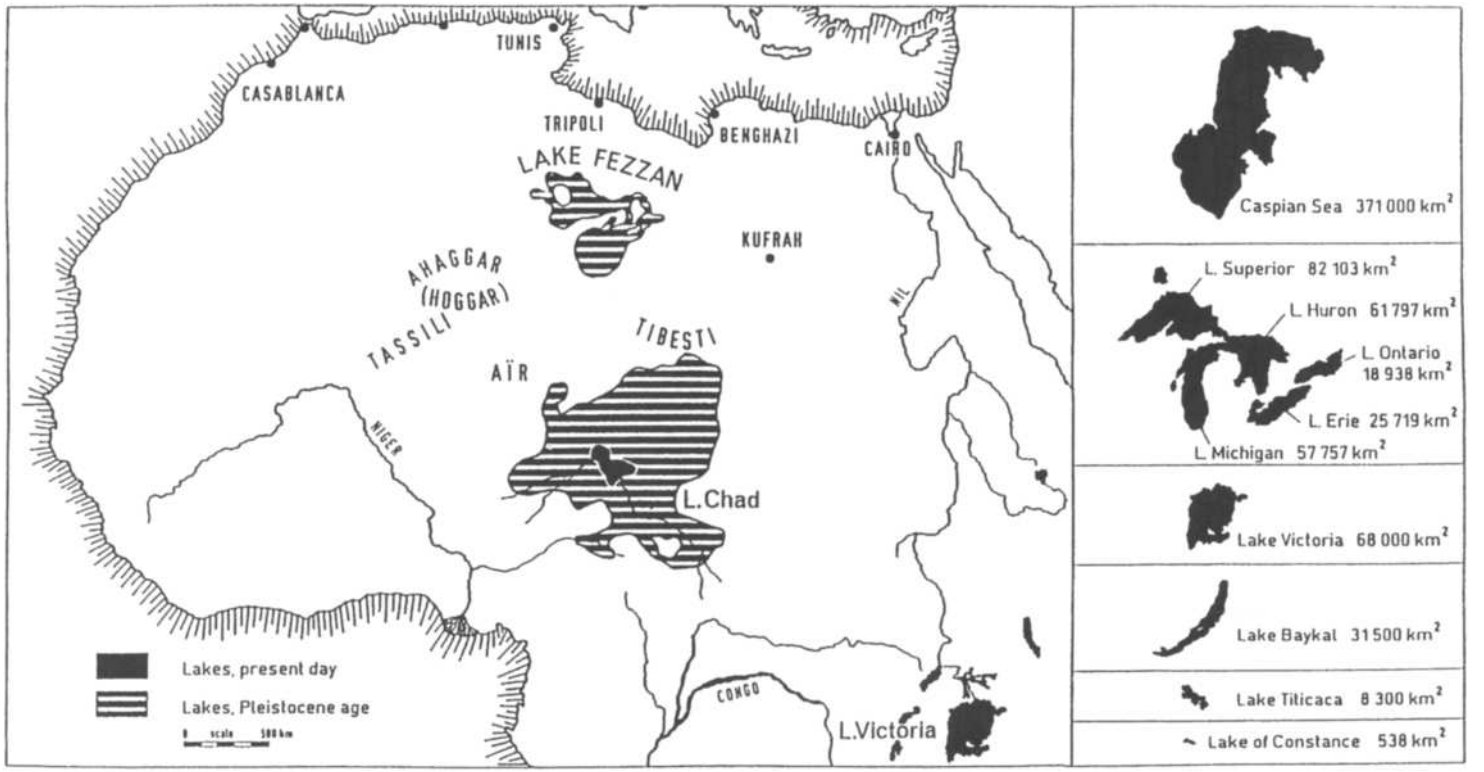

Figure 10. Proposed paleolake of Al Mahrúqah Formation (only Brak Member, approx. 380 ka), present-day lakes in North Africa compared with largest lakes of the earth (on same scale).

percolating through the porous Mesák Formation. Therefore the water level was similar in both areas. This paleolake level of the Brak Member (Figs 9 and 10) covered about 120 000 km^2 to 150 000 km^2 and was double the size of the largest African lake of today – Lake Victoria – but smaller than the largest expansion of Lake Tchad. The sand of the Awbari and Murzuq sand seas dunes existed already during the Pleistocene before the Bi'r az Zallaf phase and may be of Tertiary origin. Modern dunes in both sand sea areas developed on the former lake bottom during the younger Quaternary. The ^{230}Th/U age of about 380 ka for the Brak Member corresponds to MIS 11. Further analyses will be carried out to develop our understanding of this phase.

The paleolake phase of the Bi'r az Zallaf Member was smaller and shallower than that of the Brak Member. 'Lake Fezzan' was now separated into two lakes divided by the Mesák Plateau between the Awbari and Murzuq sand seas. The paleolake of the Bi'r az Zallaf Member in Wadi ash Shati and the Awbari Sand Sea covered approximately 30 000 km^2 to 50 000 km^2 and yielded an isochron age of 240 ka, which correlates to MIS 7.

The youngest lake level, represented by the Aqar Member, filled only the Wadi ash Shati depression, which was deflated by the wind after the deposition of the Bi'r az Zallaf Member and covered about 2000 km^2. A detritus-corrected TIMS ^{230}Th/U age of about 128 ka corresponds to the Eemian interglacial in northern and middle Europe (MIS 5e) and the Monastir Transgression in the Mediterranean.

Some Recent lakes in the Awbari Sand Sea have been charged by fossil groundwater – both fresh and saline – for several thousands of years from the same aquifer systems as the old paleolake 'Fezzan' (Chair, 1984; El Chair, 1991; Burdon, 1977; Burdon and Gonfiantini, 1991; Sonntag, 1985).

A drilling core from the east Atlantic has provided the first continuous paleoclimatic record of the last 135 ka years off the West African coast. The influence of fresh water was deduced from palynology and high dinocyst productivity (Lézine and Casanova, 1991). The age of the Aqar phase of the paleolake in the Wadi ash Shati coincides with the age of this core section and with other late Pleistocene dates from several North African localities. This shows the global importance of the paleolake levels described herein. Recently Yan and Petit-Maire (1994) published similar results from the Afro-Asian arid/semi-arid transitional zone. A decrease in rainfall was associated with the cold glacial maximum. Major rainfall phases in present-day arid northern Africa coincided with warmer interglacial events in the more northerly climatic zones.

CONCLUSIONS

We have found evidence for three levels of an extended Quaternary mega-paleolake in Fezzan, Libya. The three members of the redefined Quaternary Al Mahrúqah Formation have been divided into the Brak Member, the Bi'r az Zallaf Member and the Aqar Member. This 'Fezzan' paleolake may have covered areas ranging from about 150 000 to 2000 km^2 over the last 400 ka, containing freshwater during peak humid phases and becoming brackish during the last Aqar phase. This concept is supported by Meso- and Paleolithic cultural remains along the proposed shorelines.

The ^{230}Th/U ages of the three lake levels are in good agreement with the stratigraphic sequence of the sediments. They correspond to MIS 11 (about 380 ka) for the Brak Member, MIS 7 (about 240 ka) for the Bi'r az Zallaf Member and MIS 5e (about 128 ka) for the Aqar Member.

These absolute ages of the Pleistocene limestones are of global importance for the reconstruction of Quaternary paleoclimate in central North Africa. Our results indicate coincidence between pluvial phases in arid Africa and the interglacial events in the moderate

climate zones, supporting previous evidence of several authors (Shackleton and Opdyke, 1976; Kukla, 1978; Petit-Maire et al., 1980; Gaven, 1981, 1982; Lézine and Casanova, 1991). The ^{230}Th/U ages confirm the geological concept of three periods of a fresh water lake with different levels, indicating a highly variable precipitation history in the Sahara between 400 and 100 ka.

Further results and details on the chronology of these lake levels are expected from the ongoing study.

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DESCRIPTION OF PLATES

PLATE 1. (p. 96) Al Mahrúqah Formation, Brak Member (Quaternary).

a. Cliff forming massive lacustrine limestone on top of Carboniferous Marár Formation, top level about 450 m a.s.l., 40 km NE of Brak, E of Wadi ash Shati, 27°38′40″ N, 14°41′10″ E.

b. Cliff of limestone nodules (top), below folded thin-bedded sand- and siltstone of Carboniferous Marár Formation, darker beds in middle are basal conglomerates of Al Mahrúqah Formation, (same locality as Plate 1, fig. a).

c. Cliff of massive lacustrine limestone, access road to the quarry about 6 km E of Quttah (Wadi ash Shati), N 27° 29′ 30″, E 13° 51′ 10″.

d. Massive lacustrine limestone of Brak Mb (Al Mahrúqah Fm) in the quarry about 6 km E of Al Mahrúqah village (Wadi ash Shati), on top of the inselberg, N 27° 30′ 20″, E 14° 04′ 30″.

e. Massive lacustrine limestone about 10 km north of Tmassah.

f. Concentric stromatolitic structure in lacustrine limestone, 10 km north of Tmassah.

g. Wind polished surface of coarse grained sandy lacustrine limestone, same locality as Plate 1, fig. c.
h. Pseudobrecciated parts of lacustrine limestone, same locality as Plate 1, fig. d.

PLATE 2. (p. 97) Al Mahrúqah Formation – all three members

a. Massive lacustrine limestone of the Brak Mb, forming uppermost main cliff above Carboniferous Marár Formation. About 40 km NE of Brak (Wadi ash Shati), 27°38′40″ N, 14°41′10″ E.
b. Thinly bedded lacustrine limestone of the Bi'r az Zallaf Mb. Residual hills on the northern margin of Ramlat az Zallaf, about 18 km SE of Brak (Wadi ash Shati), 27°25′58 N, 14°23′28 E.
c. *Cardium glaucum* bearing lacustrine limestone of the Aqar Mb, close to sabkha area 1 km south of Al Mahrúqah (Wadi ash Shati), 27°29′45″ N, 14°00′37″ E.

PLATE 3. (p. 100). Al Mahrúqah Formation, Bi'r az Zallaf Member.

a. Residual hills of lacustrine limestone near Bi'r az Zallaf, about 18 km SE of Brak at the northern margin of Ramlat az Zallaf, 27°25′58″ N, 14°23′28″ E.
b. Thinly bedded lacustrine limestone, 18 km SE of Brak, same locality as Plate 3a.
c, d. Thinly bedded lacustrine limestone, same locality as above.
e. Thinly bedded lacustrine limestone with interbedded gypsum, same locality as above.
f. Thinly bedded lacustrine limestone and gypsum, underlying greenish friable argillaceous siltstone, with collapse structures in the middle gypsum bed, same locality as above.
g. Residual hills of lacustrine limestone with interbeds of sandstone and gypsum, 25 km SE of Tmassah, 26°15′36″ N, 16°01′17″ E.
h. Stromatolite on claystone (area of a field of stromatolites) 1 km E of Tmassah, approx. 26°23′30″ N, 15°47′50″ E

PLATE 4. (p. 101). Al Mahrúqah Formation, Aqar Member and calcrete.

a. *Cardium* bearing coquina beds of the Aqar Mb, sabkha area in the background, 1 km south of Al Mahrúqah in Wadi ash Shati, 27°29′32″ N, 14°00′39″ E.
b. Cross-bedded *Cardium glaucum* limestone of the Aqar Mb, road cut 5 km W of Aqar village in Wadi ah Shati, 27°31′26″ N, 14°06′06″ E.
c. *Cardium glaucum* bearing limestone of the Aqar Mb, same locality as Plate 4b.
d. *Cardium* shells densely packed and carbonate cemented, same locality as above.
e. Massive karstified calcrete some km south of Al Qatrun.
f. Calcrete cover on sand and wadi deposits, some km south of Al Qatrun.
g. Karstified calcrete on wind-sculpted plain north of Al Qatrun.
h. Wind-sculpted plain, with calcrete covering wadi deposits: cliff-forming calcrete covers softer deposits, protecting these against wind erosion, near Tajarhi.
i. Small pieces of calcrete with root concretion pipes indicate high groundwater level, near Al Qatrun.

PLATE 5 (p. 102) Fluvioeolian deposits, ash layers, stromatolites, calcrete

a. Pillar of argillaceous fluvioeolian sediment in the endorheic depression (qarárat) of Silurian Tanezzuft shale about 105 km ENE of Brak and 15 km north of Wadi Kunayr (equivalent to Brak or Bi'r az Zallaf phase ?).
b. Two ash layers of burnt reed penetrated by vertical pipes of cemented sand around

roots of reed in wadi deposits near El Ghrayfa, 25 km E of Awbari (Bi'r az Zallaf Mb)

c. Large stromatolites resting on clay, 1 km E of Tmassah, close to a Recent sabkha. These possibly belong to the Bi'r az Zallaf Mb, about 410 m a.s.l., approx 26°23′30″ N, 15° 47′50″ E.

d. Massive limestone cover of calcrete on top of hills of greenish friable sandstone (Bi'r az Zallaf phase, E of Murzuq.

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CHAPTER 6

Carboniferous and Devonian Stratigraphy – the M'rar and Tadrart Reservoirs, Ghadames Basin, Libya

F. BELHAJ[1]

ABSTRACT

Devonian and Carboniferous strata comprise about two thirds of the total Paleozoic clastic basin fill and contain a number of major hydrocarbon-bearing sandstone reservoirs in the Ghadames Basin. A large palynological data base, including 57 selected wildcat wells, forms the basis for litho- and biostratigraphic interpretation and has contributed to our understanding of the nature and distribution of Devonian and Carboniferous sandstone reservoirs.

Devonian strata attain a maximum thickness of over 4000 feet in both the northwestern and northeastern portions of the basin. These strata onlap the western end of the paleohigh around the Gargaf Uplift that first formed during late Silurian time. Devonian strata have been uplifted and eroded in the northern part of the basin. The Tadrart Formation comprises predominantly sandstone with minor mudstone. It is the basal Devonian unit and forms a major hydrocarbon reservoir. It ranges in age from the Gedinnian to the late Emsian. Continental to shallow marine and inner neritic depositional environments prevailed. The provenance of the Tadrart clastics is the Gargaf Uplift and more northerly and southerly regions. Hydrocarbons in this reservoir are sourced from Lower Silurian radioactive shales.

Carboniferous strata attain a maximum thickness of over 5000 feet in the west. These strata were uplifted and eroded during early Triassic time in the northern and eastern portions of the basin. The M'rar Formation is the basal unit of the Carboniferous section. It contains many rhythms of sandstone and shale of deltaic origin deposited in shallow to outer neritic settings. This formation ranges in age from the Tournaisian to late Serpukhovian. The hydrocarbons in the M'rar reservoirs may have been sourced from Upper Devonian radioactive shales and possibly from Lower Silurian shales.

INTRODUCTION

The Ghadames Basin is a major North African Paleozoic Basin, with almost equal portions in both Libya and Algeria, while in Tunisia there is only a relatively small narrow area. The Libyan sector of the Ghadames Basin is bounded by the Gargaf Uplift in the south, the Jabal Nefusah uplift in the north and the Sirte Basin in the east (Fig. 1). The Ghadames Basin formed during

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the early Paleozoic and existed until the Permian as an intracratonic sag basin, containing a mainly clastic sedimentary section more than 15000 feet thick. The Paleozoic section is unconformably overlain by Mesozoic and Tertiary strata (Figs 2, 3).

Exploration activities in the Ghadames Basin started in the early 1950s. Since then, considerable work has been carried on the geology of the basin independently in Libya, Algeria and Tunisia but there has been little exchange of geological data between the three countries. This has resulted in separate stratigraphic nomenclatures and correlation charts. Matching these nomenclatures can be difficult, at best, in both a vertical and horizontal sense. Formation boundaries generally have not been selected at the same stratigraphic level, and the true lateral

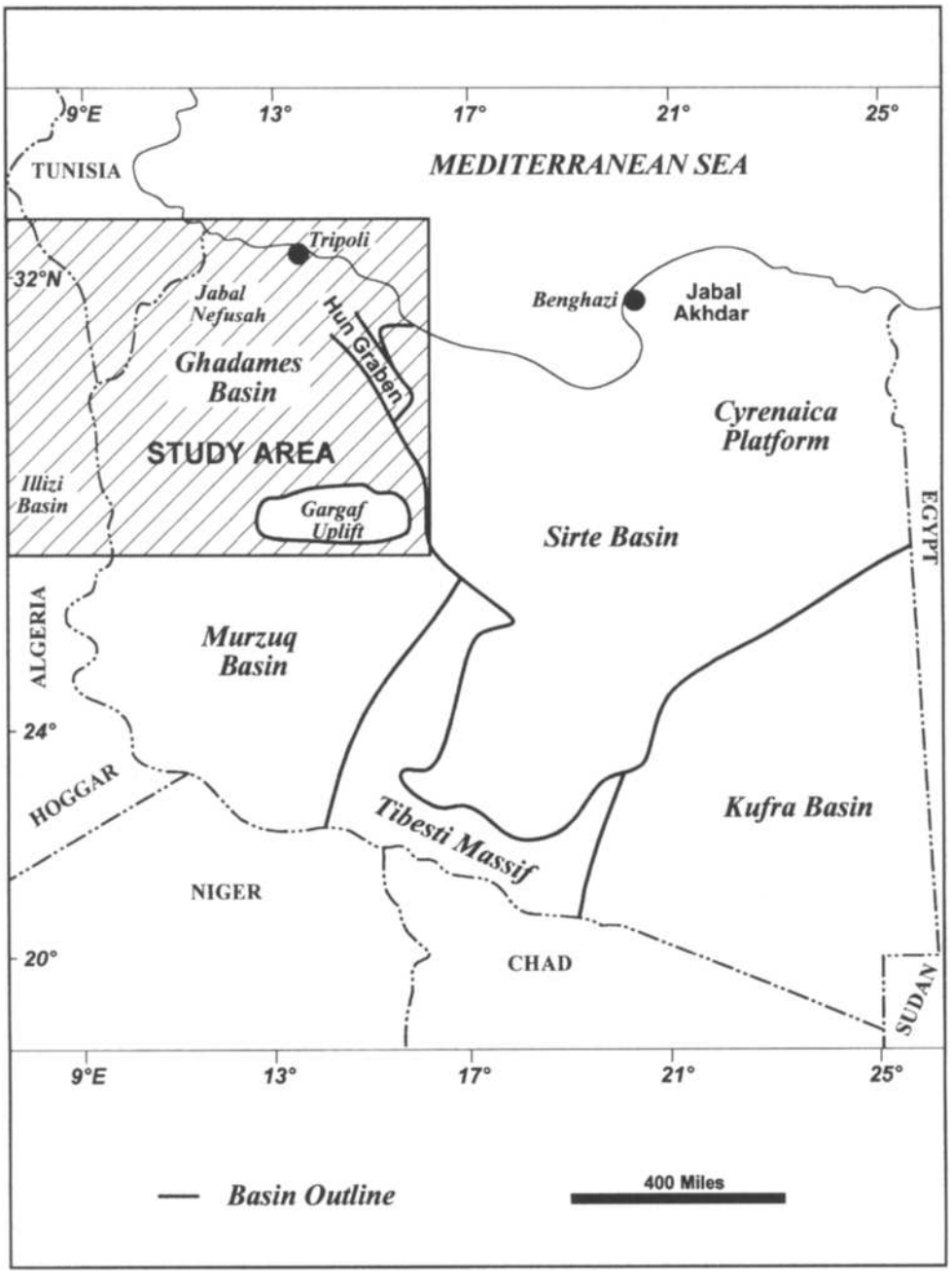

Figure 1. Location map of the study area.

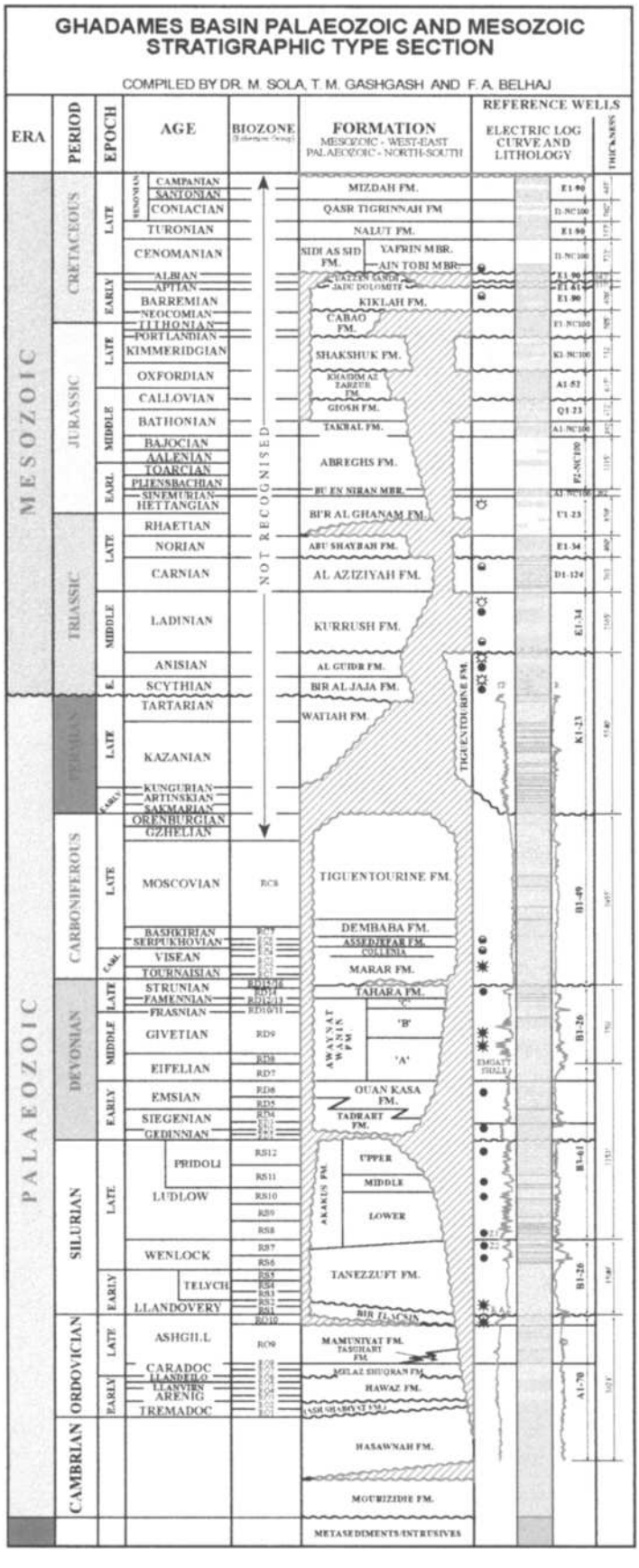

Figure 2. Ghadames Basin stratigraphic section.

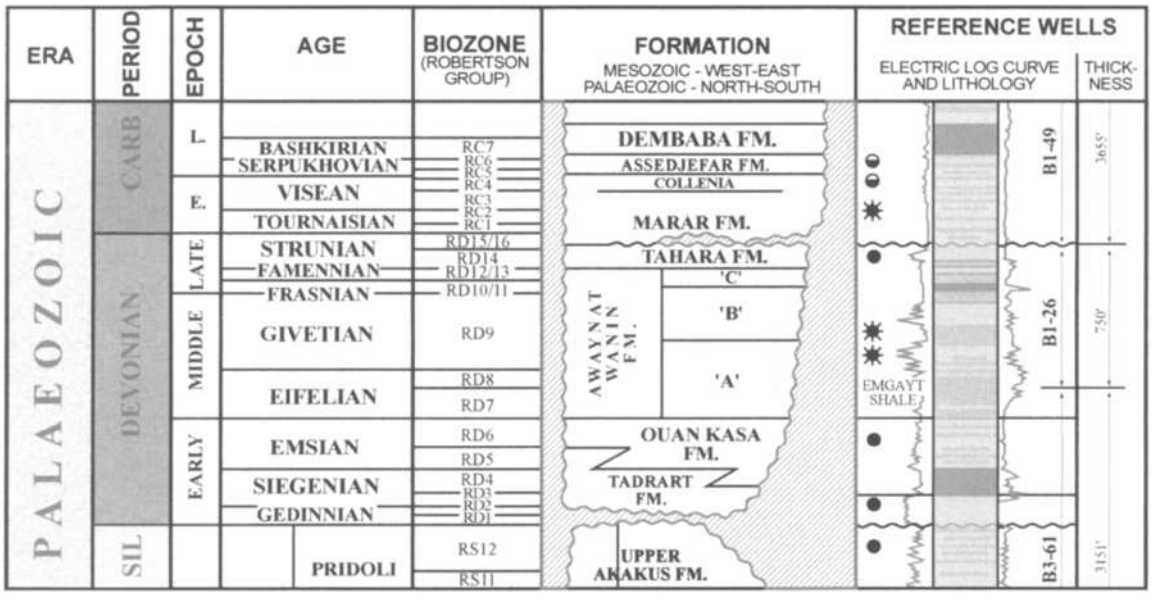

Figure 3. Devonian-Carboniferous succession.

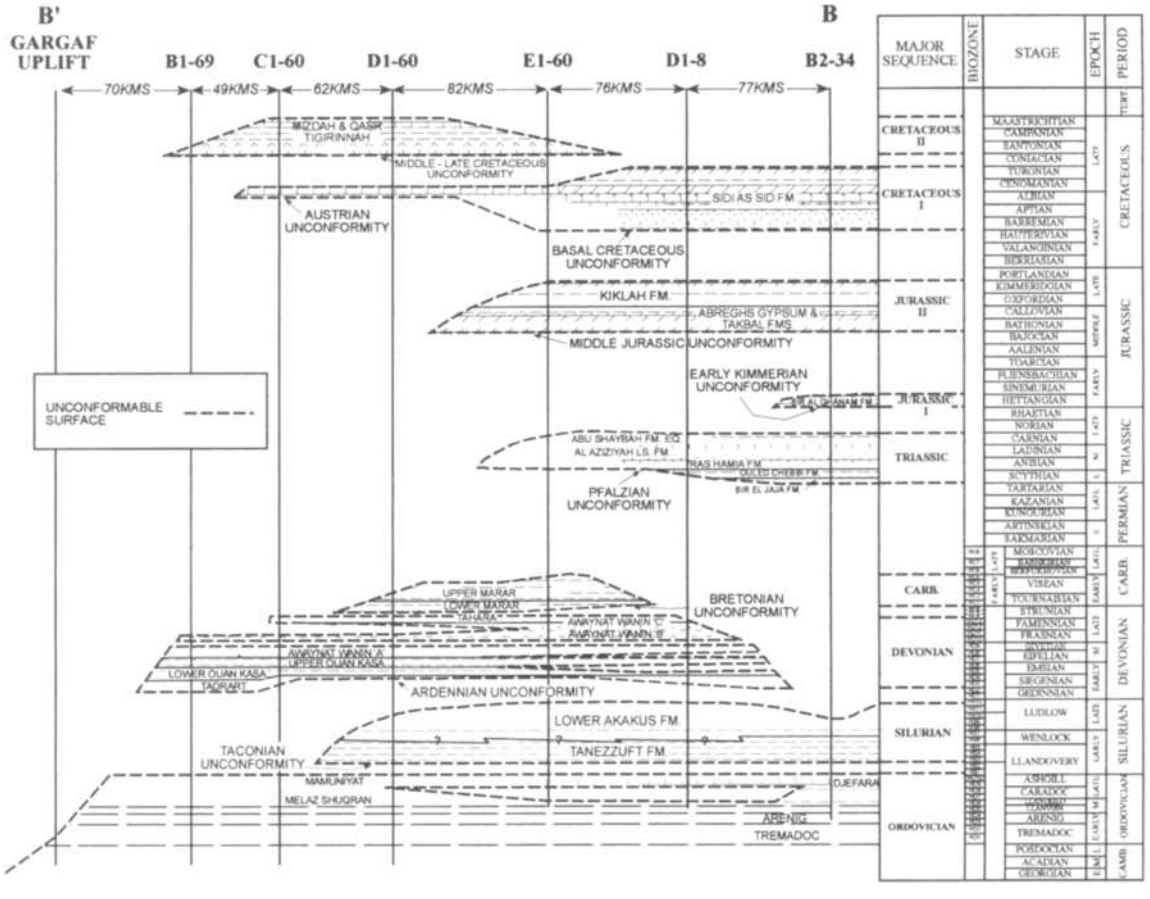

Figure 4. Chronostratigraphic chart (Wheeler diagram) through wells B2–34, D1–8, E1–60, D1–60, C1–60 and B1–69.

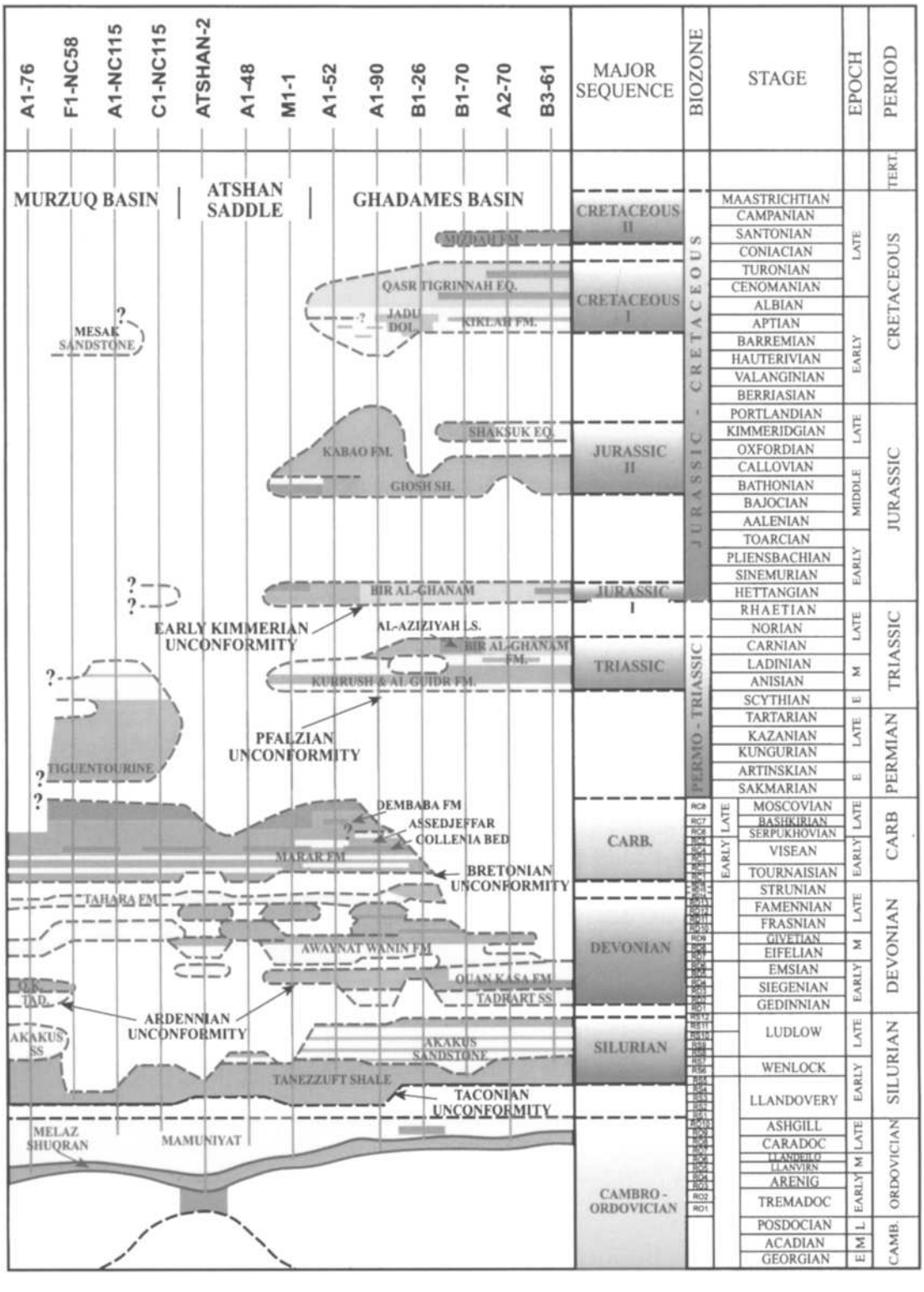

Figure 5. Chronostratigraphic chart (Wheeler diagram) of the Ghadames Basin in relation to the Murzuq Basin.

distribution of individual units and their bounding surfaces are difficult to follow over national borders. In the literature, many type sections and type areas of Paleozoic rock units have been described from exposures on the Gargaf Uplift and the western flank of the Murzuq Basin, as well as from the subsurface of the Ghadames Basin.

The objective of this study is to give a review of the Upper Paleozoic section, with special emphasis on the Devonian Tadrart Formation and Carboniferous M'rar Formation.

GEOLOGICAL HISTORY

Intermittent tectonism has repeatedly affected the Ghadames Basin region and these tectonic phases have been related to periods of worldwide diastrophism. The basin was uplifted during middle and late Ordovician time and the associated stratigraphic hiatus has often been assigned to the regional Taconic unconformity. Major uplift also occurred at the end of the Silurian Period, producing the so-called regional Ardennian unconformity. These uplifts produced the Gargaf Uplift and an unnamed N–S trending positive gentle structural feature that separates the eastern Ghadames from its western regions (Fig. 4).

The basin was again gently uplifted during late Devonian time and this resulted in the Bretonian unconformity. Considerable uplift occurred again at the end Carboniferous and during the Permo-Triassic as a result of various Hercynian tectonic phases (Fig. 5).

STRATIGRAPHY

In Libya, the type sections of Devonian and Carboniferous rock units are located in several regions: the western exposed flank of the Murzuq Basin, the western part of the Gargaf Uplift and in the subsurface of the Ghadames Basin. The general lithology and contact relationships of both Devonian and Carboniferous rock units have been discussed by Banerjee (1980) in the Stratigraphic Lexicon of Libya and by a series of other authors.

A dataset from the subsurface of the Ghadames and Murzuq basins and from outcrops on both the eastern and western flanks of the Murzuq Basin and the Gargaf Uplift has been compiled and includes results of detailed electric log correlations and a comprehensive palynological examination of the Paleozoic section in 45 exploration wells (Fig. 6). Samples processed for palynological analysis were 50 feet composites of well cuttings taken at 10 feet intervals. In addition, lithological descriptions have been made with an assessment of depositional environment. An additional twelve wells located in the Murzuq Basin and the eastern portion of the Ghadames Basin were analysed and reviewed by Robertson Research (1992). These results have been included in the study.

Numerous geological cross-sections have been constructed together with maps showing thickness, percentage of sandstone, subcrop, facies and depositional environments. Of these, four cross-sections (Figs 7, 8, 9) and several maps are presented herein.

DEVONIAN

The Devonian section reaches a thickness of more than 4000 ft. in the subsurface of both the northern and eastern parts of the Ghadames Basin (Fig. 10). Devonian units onlapped the Gargaf paleohigh (Fig. 5) creating numerous stratigraphic and structural-stratigraphic traps where many Devonian hydrocarbon accumulations have been discovered, such as the Al Hamra fields in Concession 66.

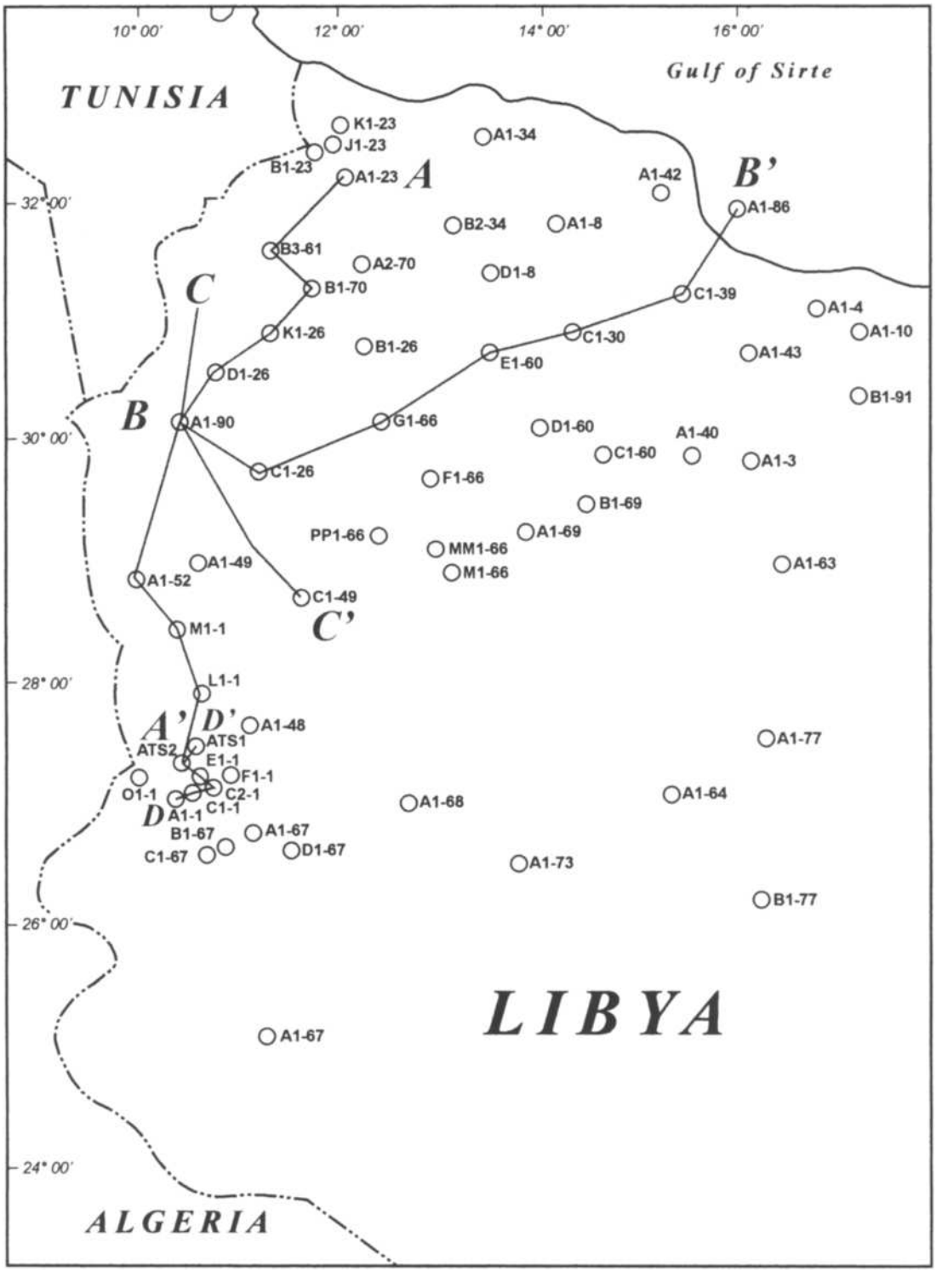

Figure 6. Index map showing location of wildcat wells studied by Robertson Research (1992) and lines of cross-sections in Figs 7, 8 and 9.

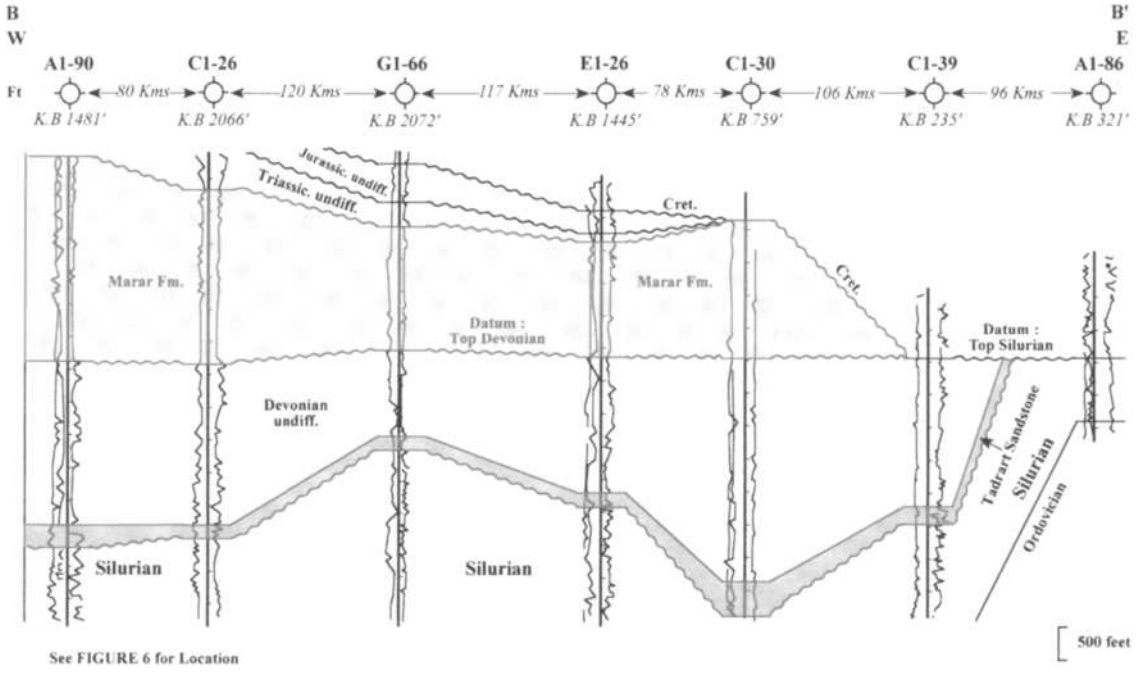

Figure 7. East-West cross-section through the Paleozoic succession in the Ghadames Basin highlighting the Tadrart and M'rar formations.

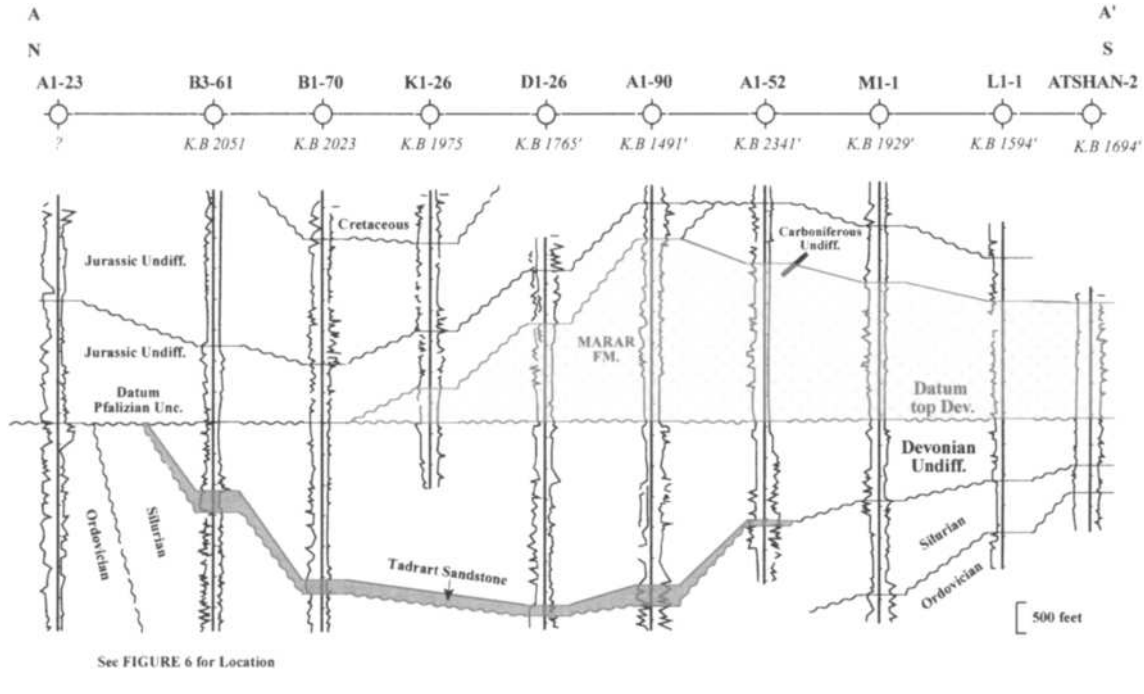

Figure 8. North-South cross-section through the Paleozoic succession in the Ghadames Basin highlighting the Tadrart and M'rar formations.

Generally, the Devonian strata can be divided into three distinct lithological units (Fig. 3). The lower Tadrart Formation is of continental to marine origin and includes both arenaceous and minor argillaceous strata. The middle unit is represented by the Ouan Kasa Formation, consisting mainly of alternating shale, siltstone and sandstone. In addition, there is an interval of limestone and dolomite that is restricted to the northern Ghadames Basin. The upper unit includes the Awaynat Wanin and Tahara formations. Belhaj (1996) recognized five sedimentary cycles in this upper unit. These cycles comprise alternating shale, siltstone and sandstone. Radioactive shale and limestone units are also present in the upper two cycles. Sedimentation during the Devonian was interrupted repeatedly by numerous local unconformities (Fig. 5).

In the northern and northeastern parts of the Ghadames Basin, Devonian sediments were uplifted and eroded during the Hercynian Orogeny, creating unconformity traps for hydrocarbons, sealed by post-Carboniferous strata. Regional structural trends are oriented NW–SE and E–W on and around the Gargaf Uplift on the southern flanks of the basin. There, the Devonian section is relatively thin with many local unconformities (Fig. 4), creating numerous potential exploration plays.

Tadrart Formation

The Tadrart Formation was introduced by Burollet (1960). Its type section (25°38′45″ N, 10°13′00″ E) is located in the Tadrart Mountains in southwestern Libya. A reference section (24°36′30″ N, 11°04′00″ E) was described by Klitzsch (1969) from the Ghat area. There, the

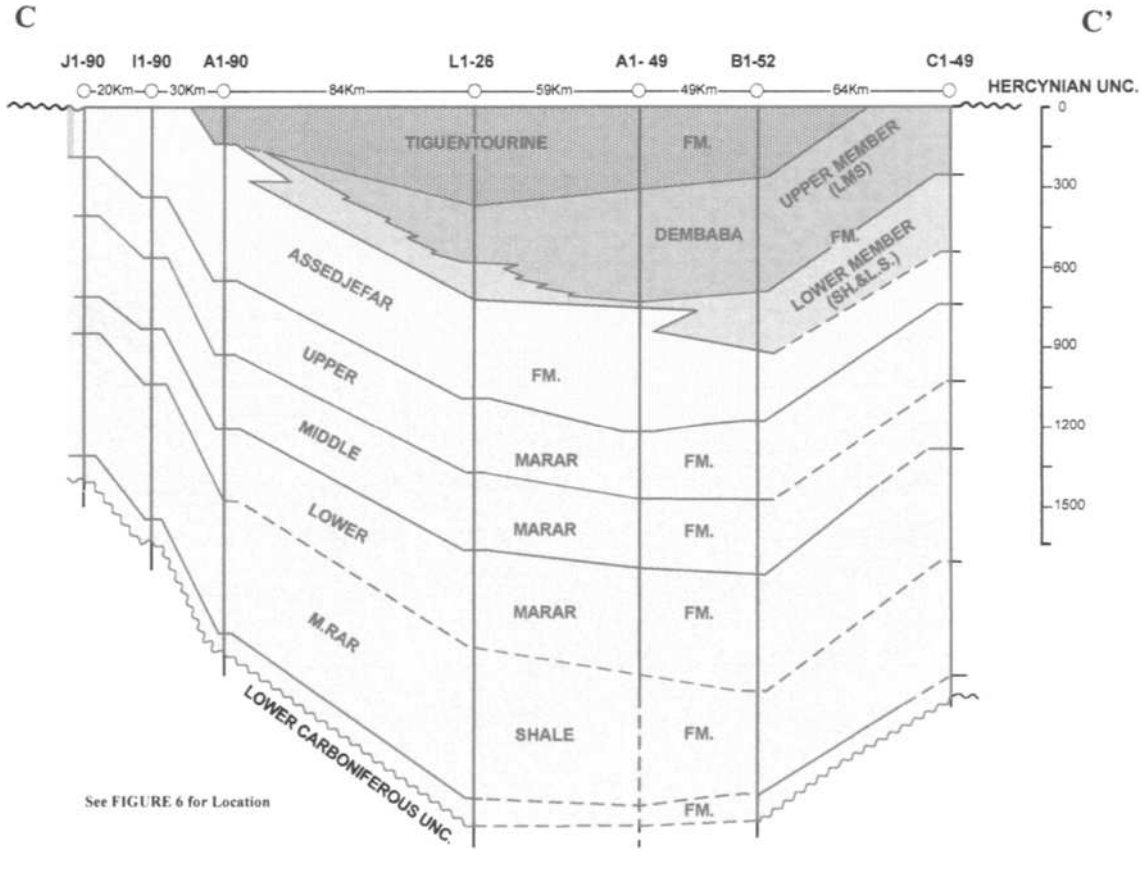

Figure 9. N-S cross-section through the Carboniferous section.

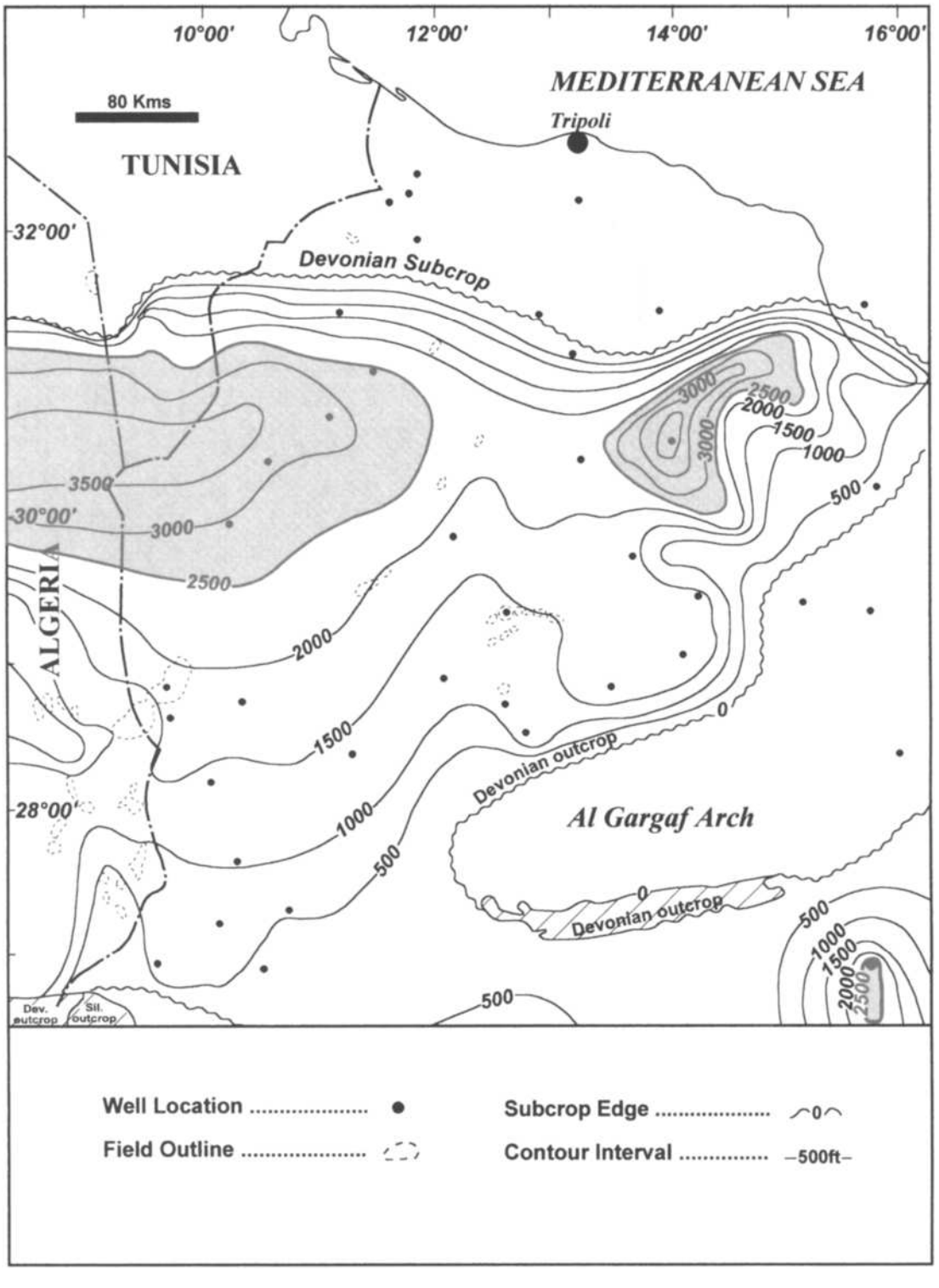

Figure 10. Isopach map of Devonian strata showing outcrop areas and the Devonian erosional limits.

formation attains a thickness of 1040 ft and comprises continental to marginal marine white to brown, sometimes ferruginous, sandstone, massive to cross-bedded with rare plant remains in the lower part and thinly bedded marine sandstone with abundant trace fossils in the upper part. The base is marked by ferruginous beds that unconformably overlie the Silurian Akakus Formation. The Tadrart Formation is overlain by a shale and sandstone sequence of Emsian age (Banerjee, 1980). An unpublished report by Garea (1984) suggests that the formation's upper boundary in the E1–60 well (Fig. 11) is of early Emsian age, in agreement with the work described herein.

The Tadrart Formation represents the first unit to be deposited after the Caledonian Orogeny almost everywhere in the Ghadames Basin. However, the formation is not present, probably due to non-deposition, in the Atshan area, to the west of the Gargaf Uplift and in a small area in the northern part of the Ghadames Basin. The formation is also absent due to erosion in the northern and eastern parts of the basin as a result of Hercynian uplift (Figs. 11, 12).

In the subsurface, the Tadrart Formation reaches a thickness of more than 600 feet in three separate areas in the northwestern, the northeastern and the southern parts of the basin (Fig. 13). Sandstone distribution within the formation indicates that there were at least two major provenance areas, one to the south and the other to the northwest (Fig. 14).

The age of the Tadrart Formation ranges from Gedinnian to late Emsian (Fig. 15) based on the following palynological markers: *Lopozonotriletes poecilomorphus, Emphanisporites PSI/ 133, Riculasphaera fissa, Stenozonotriletes agrabilis, Dictyotriletes emsiensis, Geminospora*

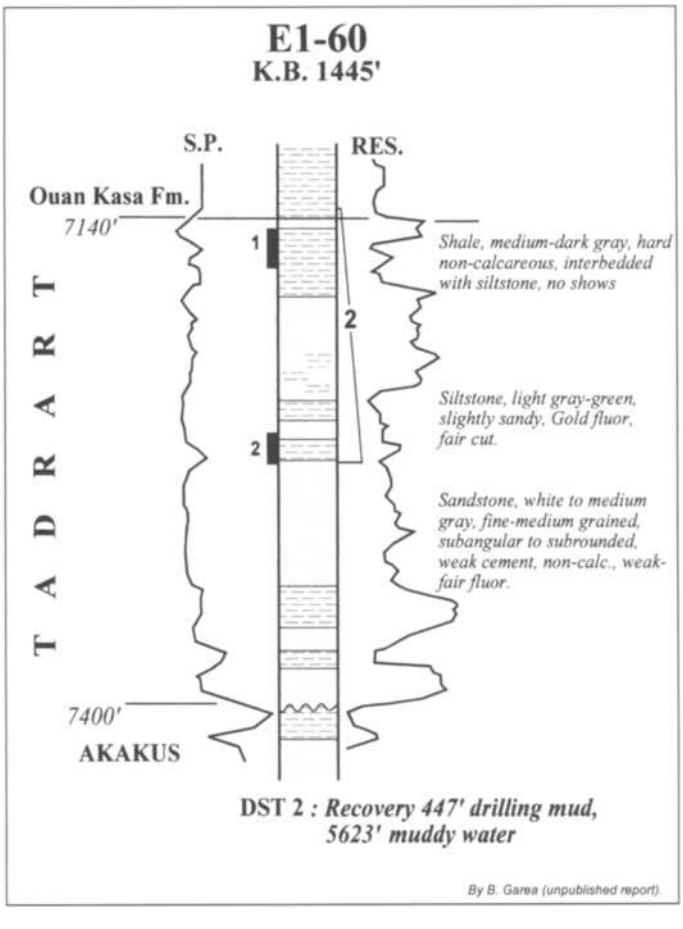

Figure 11. Tadrart Formation in well E1–60.

papillata, Brochotriletes hudsonii, Camptozonotriletes aliquantus. Camptozonotriletes caperatus, Dictyotriletes favosus, Ozotobrochion furcillatus, sensu Richardson and Lister 1969, *Multiplicisphaeridium escobaidas, Brochotriletes macgregori, Multiplicisphaeridium asombrosum,* and *Veryhachium cantabricum.*

The distribution of the various units of the Tadrart Sandstone and their general age relationships reflect the infilling of relief created by late Silurian uplift. The age distribution map shown in Fig. 15 also reflects the environmental mosaic shown by units in the Gargaf area.

In the subsurface, the Tadrart Formation consists dominantly of sandy units with subordinate gray silty mudstone. Sandstones are translucent white to brownish-gray in color, ranging from poorly sorted, coarse and angular to well sorted, very fine to fine-grained. Their environment of deposition ranges from moderate to high-energy inner neritic to marginal marine in the southern and northern parts of the basin. This is suggested by the presence of both acritarchs and

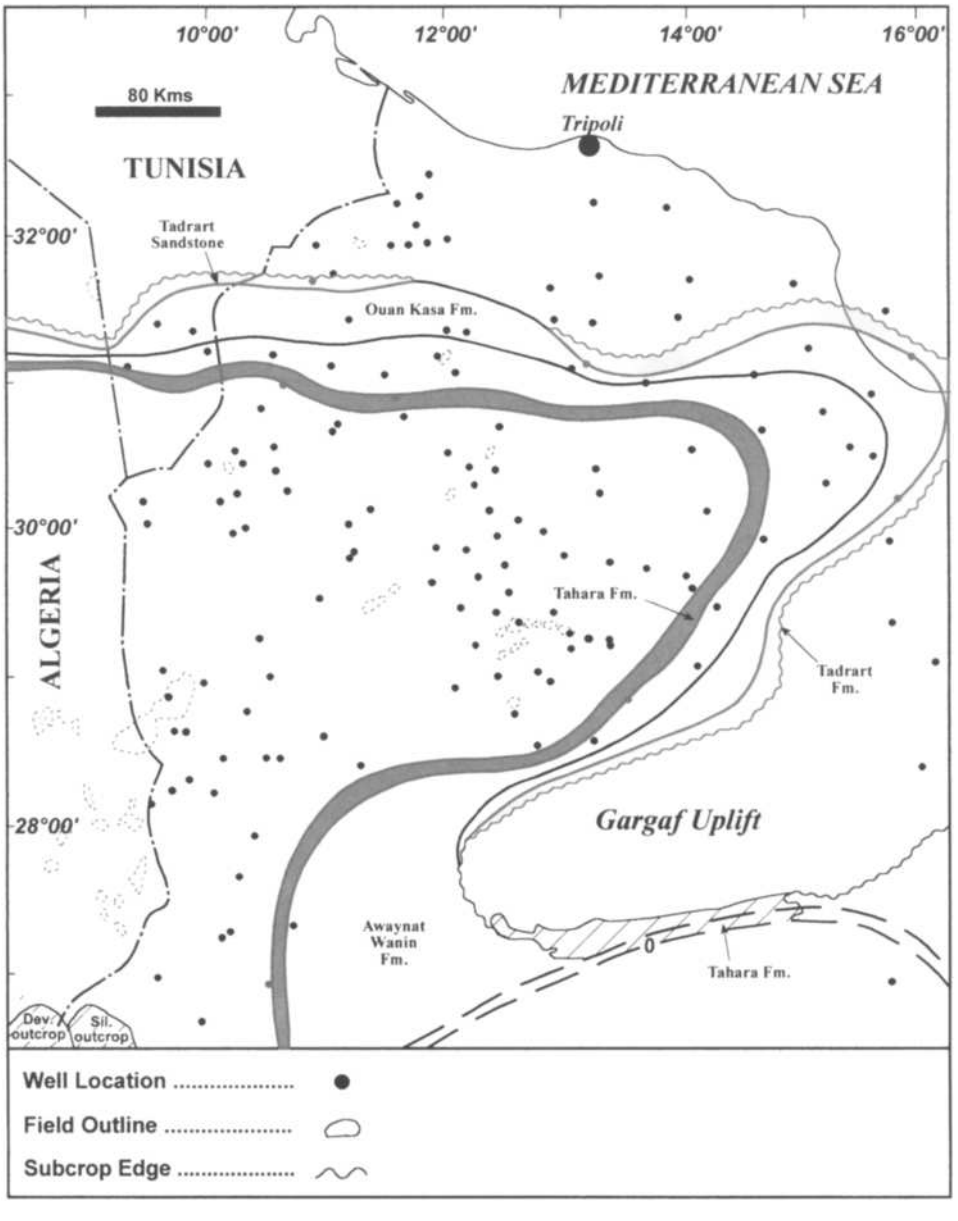

Figure 12. Subcrop and outcrop belts of Devonian formations.

miospores, as well as by the lithofacies. The environment of deposition in the central parts of the basin generally is low to moderate energy marine (inner neritic), as suggested by the presence of abundant miospores and microplankton and mixed argillaceous and arenaceous lithologies. The barren sections in some areas in the north (Well B3–61), central (Well A1–90) and the southern (Well C1–49) parts of the basin may indicate deposition in continental to marginal marine environments.

Late stage freshwater flushing has taken place in the southern and southeastern parts of the basin. This flushing may be associated with the Gargaf Uplift and Hoggar Massif recharge areas (Fig. 16). Freshwater flushing on the northern flanks seems to be limited to the vicinity of the Nefusah Uplift.

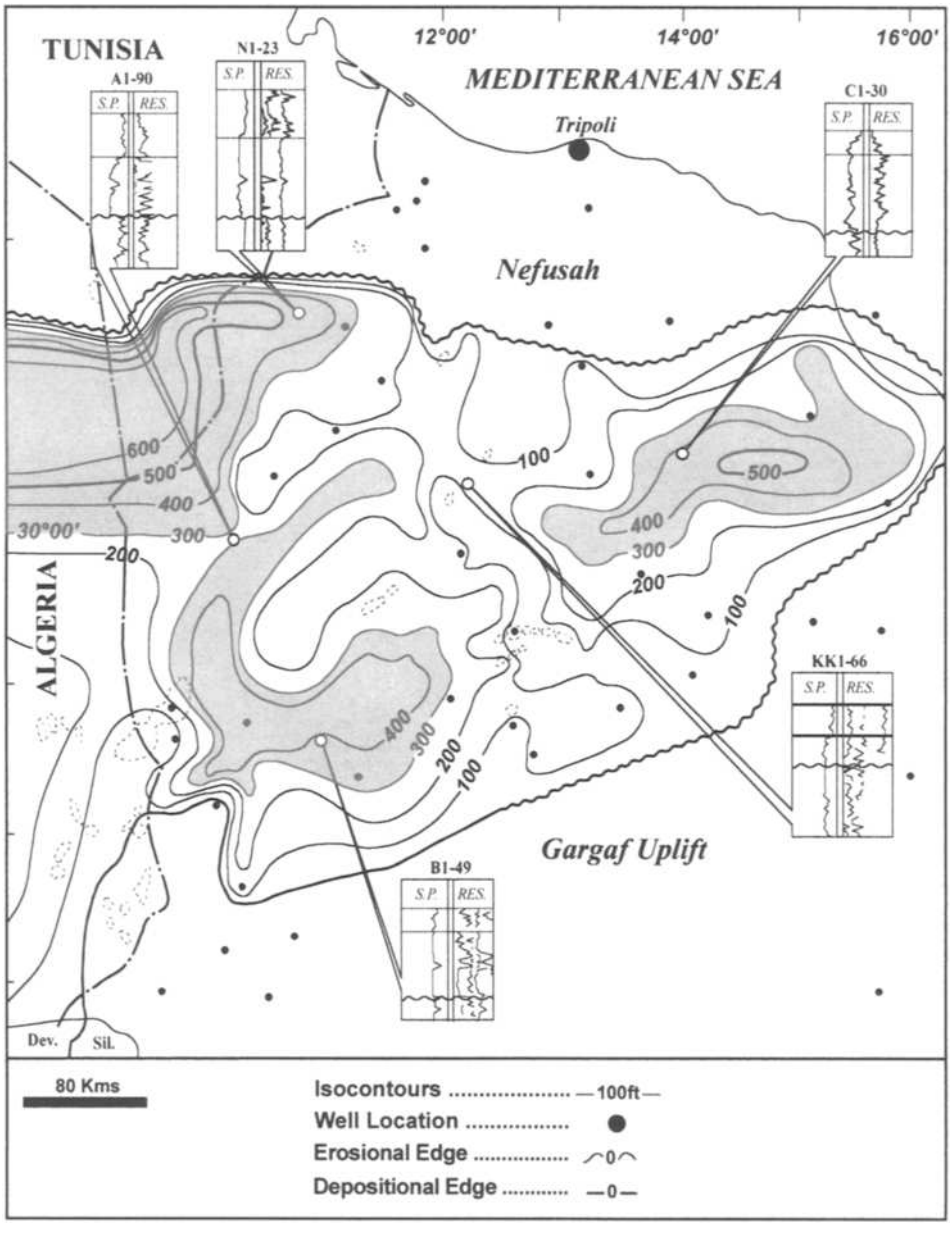

Figure 13. Isopach map of the Tadrart Formation showing erosional limits, depositional limits and five diagrammatic electric log patterns of reference wells.

Hydrocarbon discoveries and shows in the Tadrart Formation appear to be related to north-south trending structures along the Gargaf Uplift and east-west trending structures across the Ghadames Basin, extending into Algeria along the structural trend that separates the Illizi Basin from the Ghadames Basin (Fig. 17). Hydrocarbon accumulations may also be present along parallel trends in other areas. These observations are based on the setting of the fields in Concession 66 and on other discoveries along these major structural trends (Fig. 17) In the northern parts of the basin, the Tadrart Formation is truncated and may be sealed by Triassic shales. In addition, in the southern part of the basin, the formation's sandstones have excellent preservation potential in stratigraphic and combined stratigraphic-structural traps. Hydrocarbon accumulations may be present in areas where the overlying shaly Upper Devonian strata form a top seal, and the Tadrart Sandstone is directly underlain by the source rock of the Tanezzuft shale, in areas where the Akakus sandstones have been eroded away.

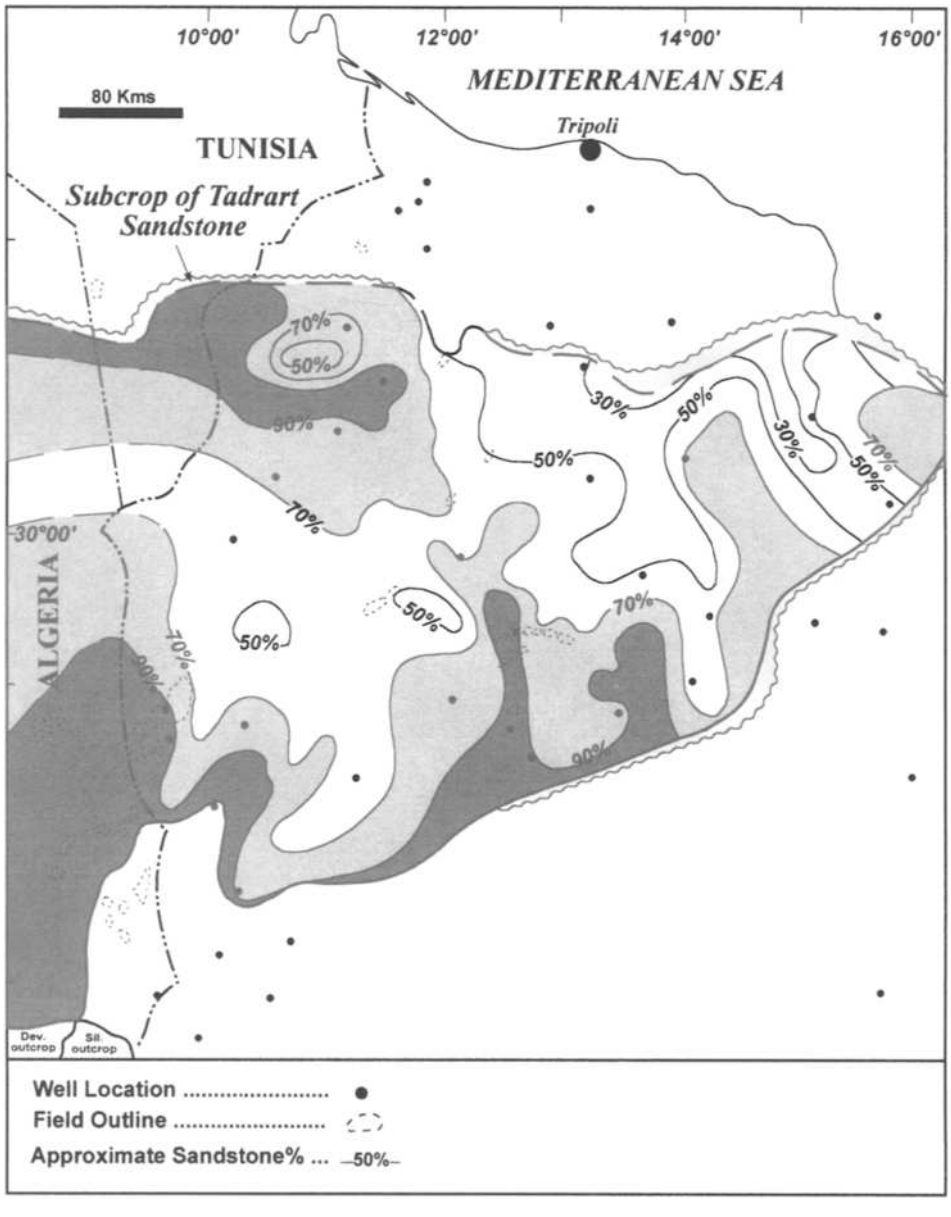

Figure 14. Sandstone percentage distribution map of the Tadrart Formation.

CARBONIFEROUS

Carboniferous strata reach a thickness of more than 5000 ft in the deepest parts of the western Ghadames Basin (Fig. 18). Maximum thicknesses of about 3500 ft have been recorded in outcrops on both flanks of the Murzuq Basin and on the western and southern flanks of the Gargaf Uplift. The Carboniferous section is separated from the underlying Devonian strata by a regional unconformity reflecting early Hercynian tectonic events. It is also separated from the overlying Mesozoic section by the major regional Hercynian unconformity. Carboniferous strata generally include mixed lithologies of shale, siltstone, sandstone and limestone. The main lithostratigraphic units that are represented are the M'rar, (including the *Collenia* marker beds), Assedjefar, Dembaba and Tiguentourine formations (Fig. 2). The subcrop map of these formations is shown in Fig. 19. The regional north-south trending paleohigh that was effective

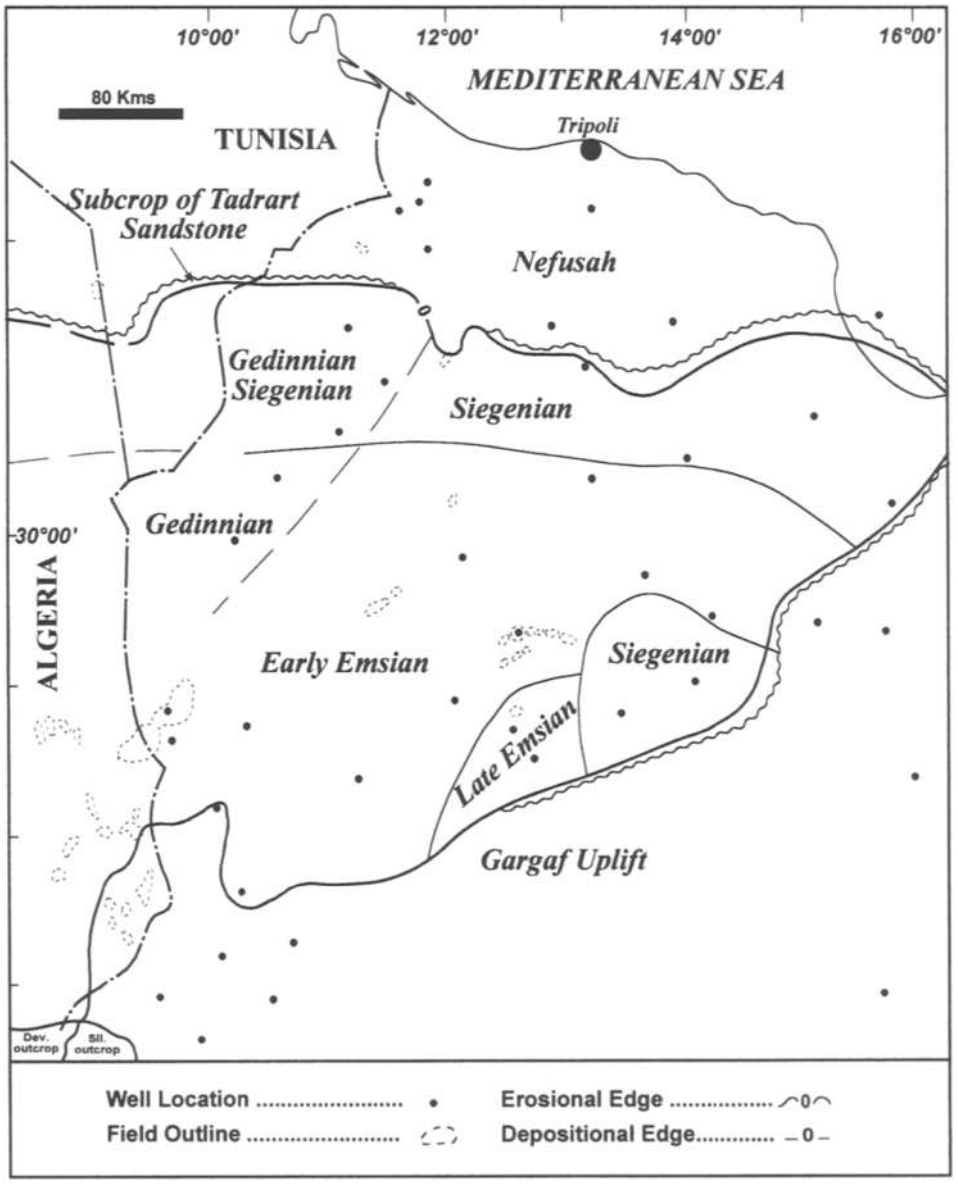

Figure 15. Age distribution map of the Tadrart Formation.

in the Devonian also affected Carboniferous sedimentation and resulted in a thin Carboniferous section along its axis, dividing the basin into two sub-basins; a larger one to the west and a smaller one to the east (Fig. 18).

M'rar Formation

The M'rar Formation was first introduced by Lelubre (1948), with its type section in the Qararat el M'rar hills at 28°20′ N, 12°15′ E in the southern Ghadames Basin. The formation comprises a sequence of alternating silty micaceous shales and micaceous, fine-grained and often ferruginous sandstone with interbedded siltstone and minor limestones. The thickness of the M'rar Formation at outcrop in the southern Ghadames Basin reaches 2590 ft, whereas on the eastern flanks of the Murzuq Basin it reaches 1900 ft. The formation unconformably overlies the Awaynat Wanin Formation in the Gargaf Uplift area. The contact between the M'rar Formation

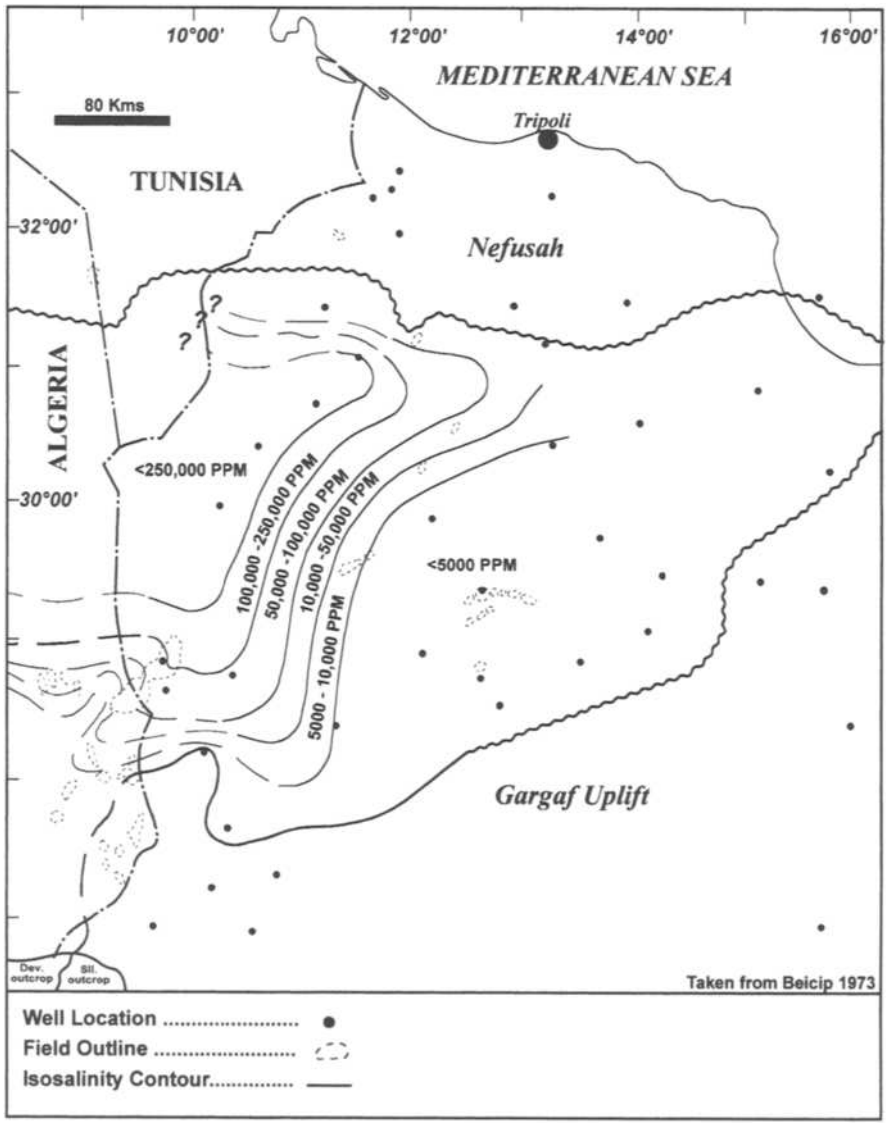

Figure 16. Isosalinity map of the Tadrart Formation.

and the underlying Devonian strata is marked by a 3 ft thick basal conglomerate sandstone bed in Dor al Gussa on the eastern Murzuq margins (Klitzsch, 1963).

This sequence shows repeated rhythms varying in thickness from 5 to 100 ft. Each rhythm grades upwards from deep-water shale to sandstones deposited in a coastal environment. The shales are medium dark gray to olive gray, often silty and micaceous. The sandstone varies from very fine to coarse-grained. A depositional model established for outcrop sections in the type area and extended into the subsurface of the northern Ghadames Basin shows that the M'rar is composed of 15 such coarsening-upward rhythms, representing a deltaic depositional environment (Whitbread and Kelling, 1982). These clastic components are supplemented with a few beds of limestone and dolomite uppermost in the formation. The formation's development in well A1–49 (Fig. 20) was used as a subsurface reference section by Massa (1988).

The subsurface thickness of the M'rar Formation reaches more than 3500 ft in the western part of the Ghadames Basin (Fig. 21). The thickness distribution indicates that a local sub-basin

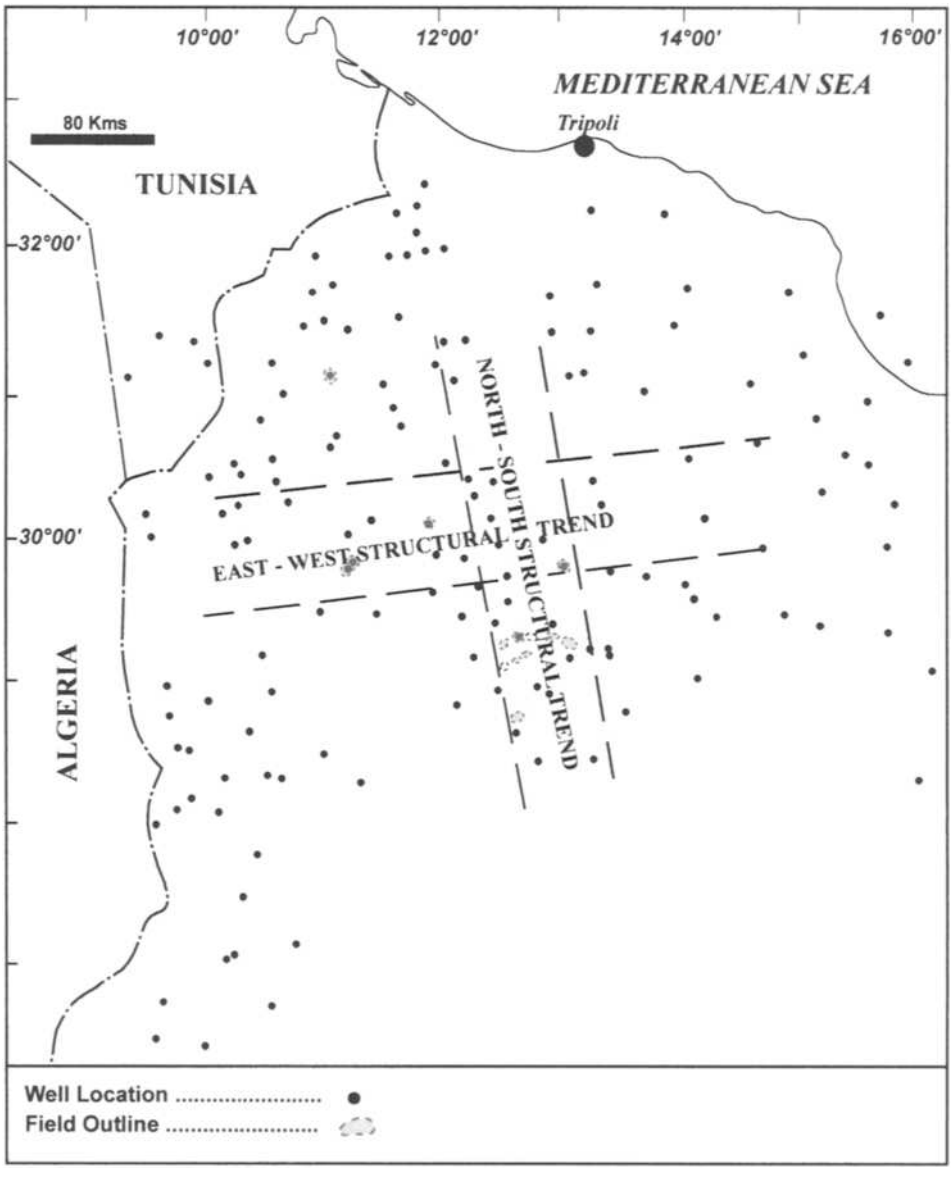

Figure 17. Location map showing hydocarbon accumulations in Tadrart reservoirs.

is also present in the eastern part of the basin. A pronounced structural paleohigh, trending SE & NW through the Gargaf Uplift, separates the two areas of thick deposits. The M'rar Formation may be divided into three distinct lithological units represented by lower, middle and upper megacycles (Fig. 22).

The M'rar Formation has been dated to the Tournaisian to late Serpukhovian based on the following palynological markers: *Dictyotriletes fimbriatus, Umbonatisporites baculatus, Verruciretusispora famenensis, Waltzispora lanzonii, Spelaeotriletes pretiosus, Diatomozonotriletes fragilis, Aratrisporites saharensis, Exochoderma* JL/24, *Radiizonates genuins, Vallatisporites agadesi, Densosporites variiomarginatus, Schultzospora campyloptera, Schopfipollenites ellipsoides, Camptozonotriletes cyrenaicus*, and *Spelaeotriletes giganteus.*

The distribution of the Tournaisian-Viséan and late Viséan to Serpukhovian strata of the M'rar Formation is shown in Figs 23 and 24. The effects of Hercynian uplift are shown by the absence

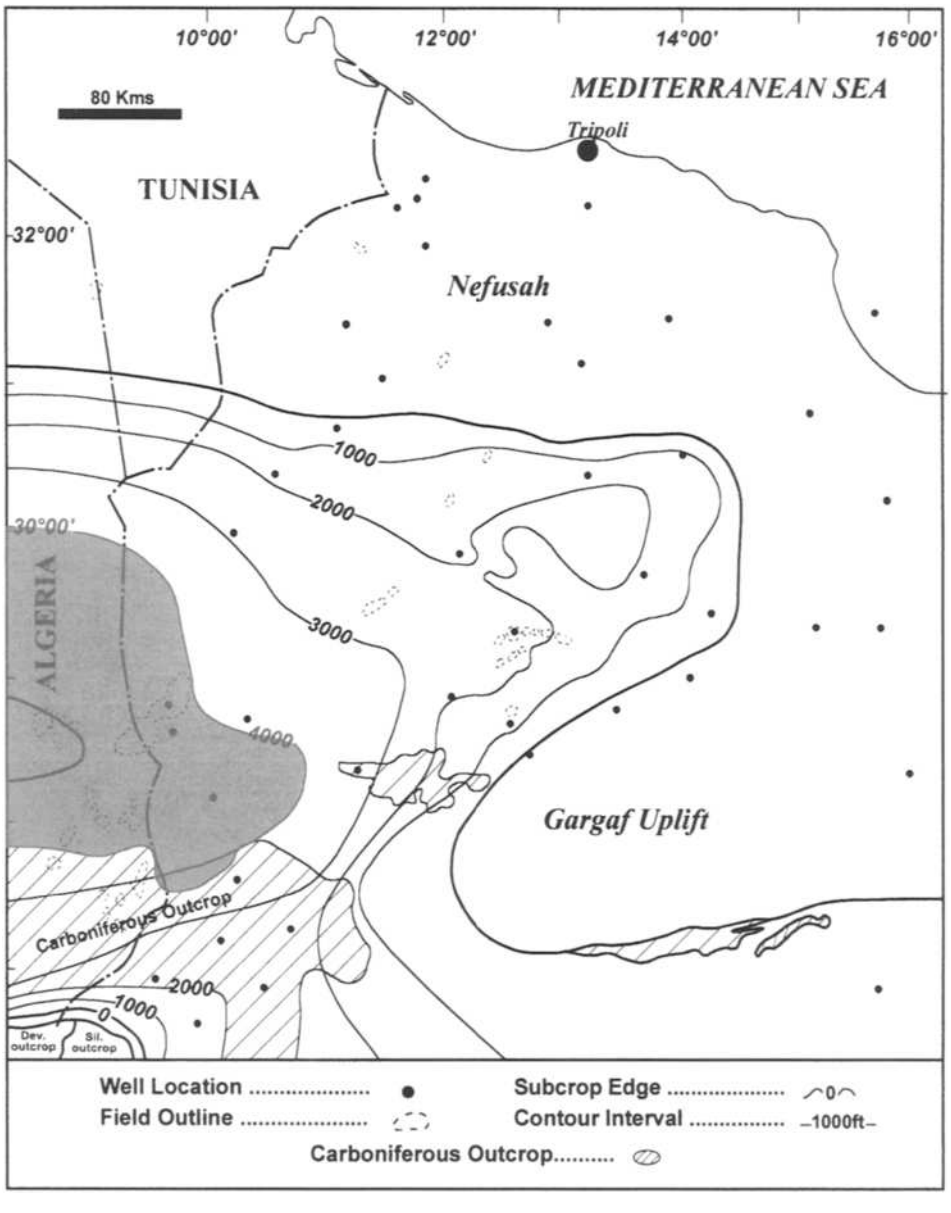

Figure 18. Isopach map of the Carboniferous strata.

of late Serpukhovian to late Viséan strata to the west of the Gargaf Uplift and to the north of the Ghadames Basin. Deposition of these units was affected by the central paleohigh in the Gargaf Uplift area. The environment of deposition ranges from inner neritic to marginal marine as suggested by an abundance of miospores, common microplankton, but lesser occurrences of acritarchs.

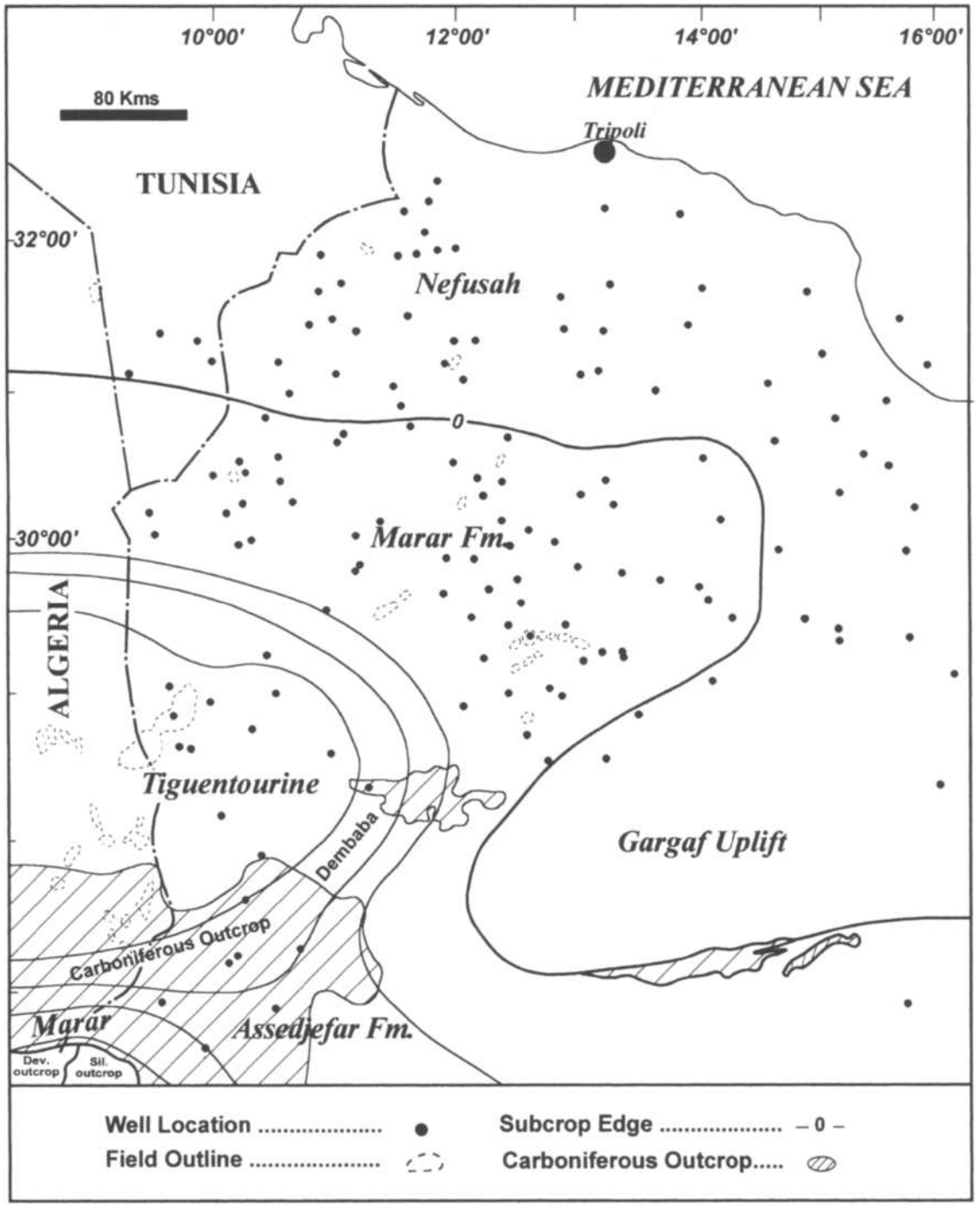

Figure 19. Subcrop and outcrop belts of Carboniferous formations.

From the available data, it is evident that hydrocarbon discoveries in the M'rar Formation are concentrated in the southwestern Ghadames Basin. There, the M'rar sandstones are generally shallower than in the northern areas (Fig. 25). Hydrocarbon potential in other areas is considerable, particularly adjacent to the Gargaf Uplift, along structural highs and fringing the Hoggar uplift. Intra-Carboniferous source intervals in the Ghadames Basin are generally thermally immature to early mature. However, based on wells D1–26 and C1–30, Carboniferous

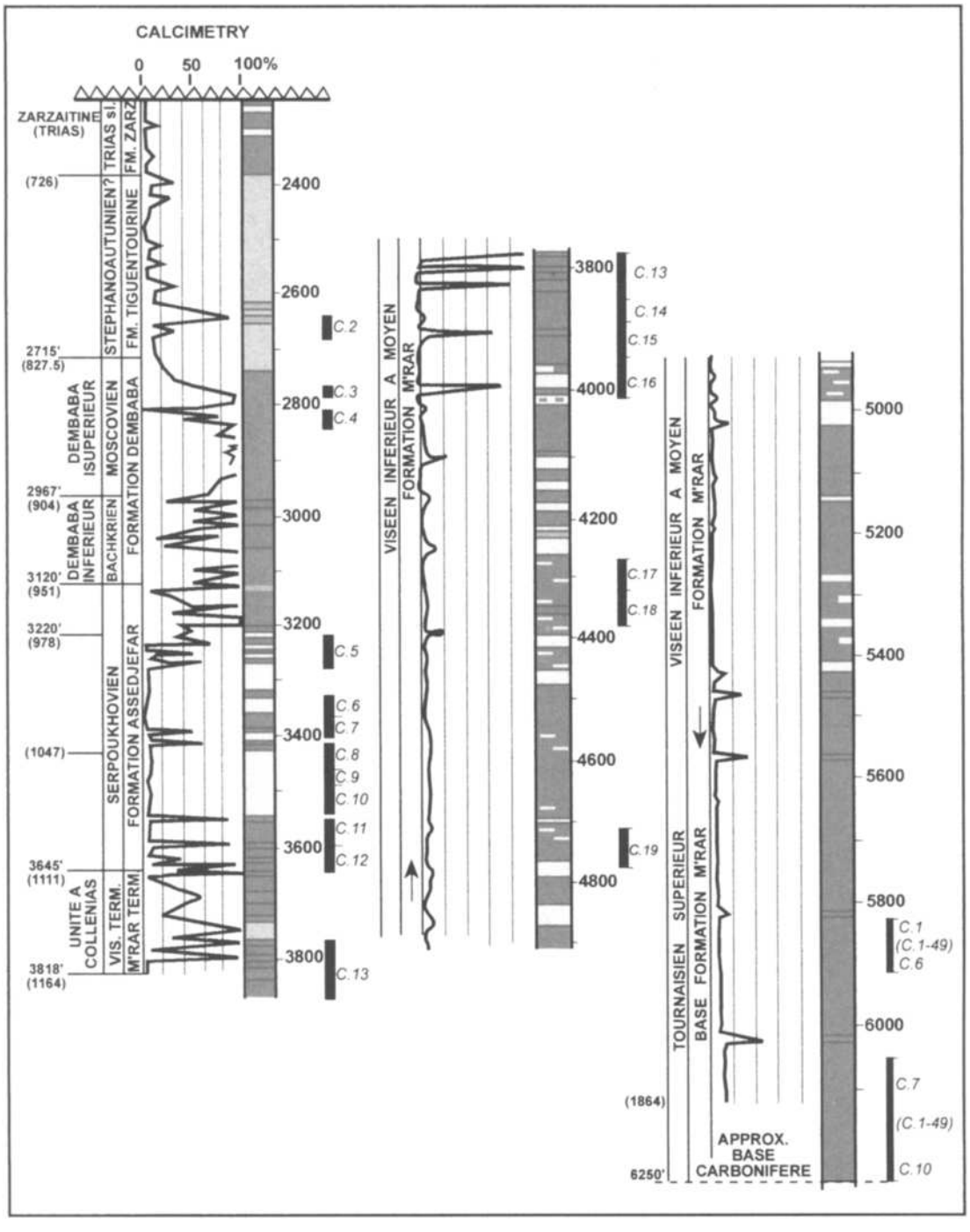

Figure 20. Typical log through the Carboniferous section, well A1–49.

reservoirs may trap hydrocarbons generated from older source rocks in Devonian and Silurian shales, provided that vertical migration can be invoked along major faults.

CONCLUSIONS

The Devonian section is separated from the underlying Silurian and older rocks by a major unconformity, reflecting Ardennian orogenic events. The contact with overlying Carboniferous strata is also erosive and unconformable as a result of late Devonian uplift. Triassic, Jurassic and Cretaceous strata overlie the truncated Carboniferous and older section as a result of Hercynian and younger tectonism.

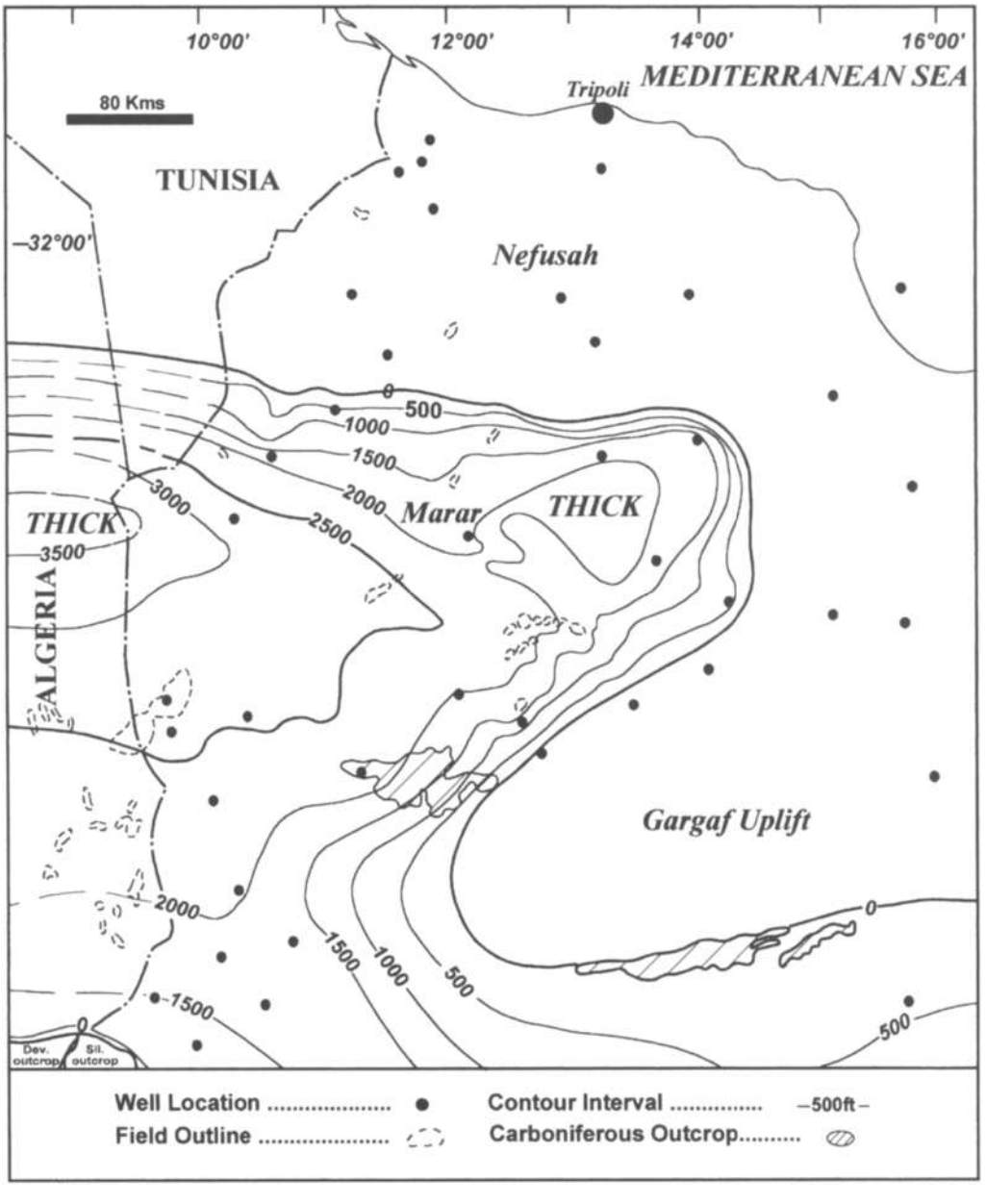

Figure 21. Isopach map of the M'rar Formation.

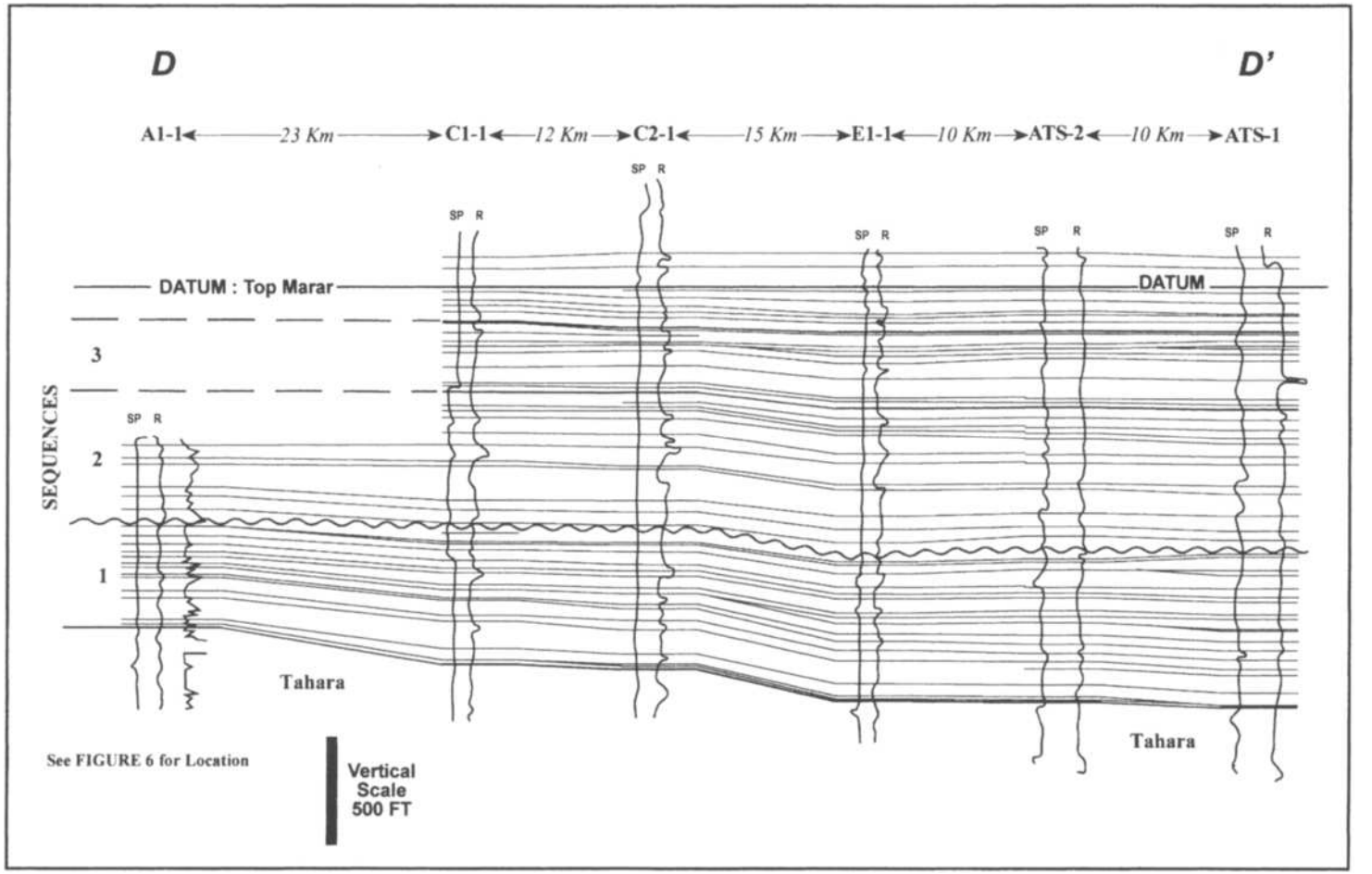

Figure 22. The three members of the M'rar Formation in the southern Ghadames Basin.

The Tadrart Formation is dominantly composed of sandstones deposited in moderate to high energy, inner neritic to marginal marine environments. The formation ranges in age from the Gedinnian to late Emsian. The formation's sandstones have two main provenance areas; one lies to the south and the other to the north of the present basin and the resultant sands have excellent reservoir characteristics. The M'rar Formation (Tournaisian to late Serpukhovian) is represented by alternating shale and sandstones deposited in inner neritic to marginal marine environments.

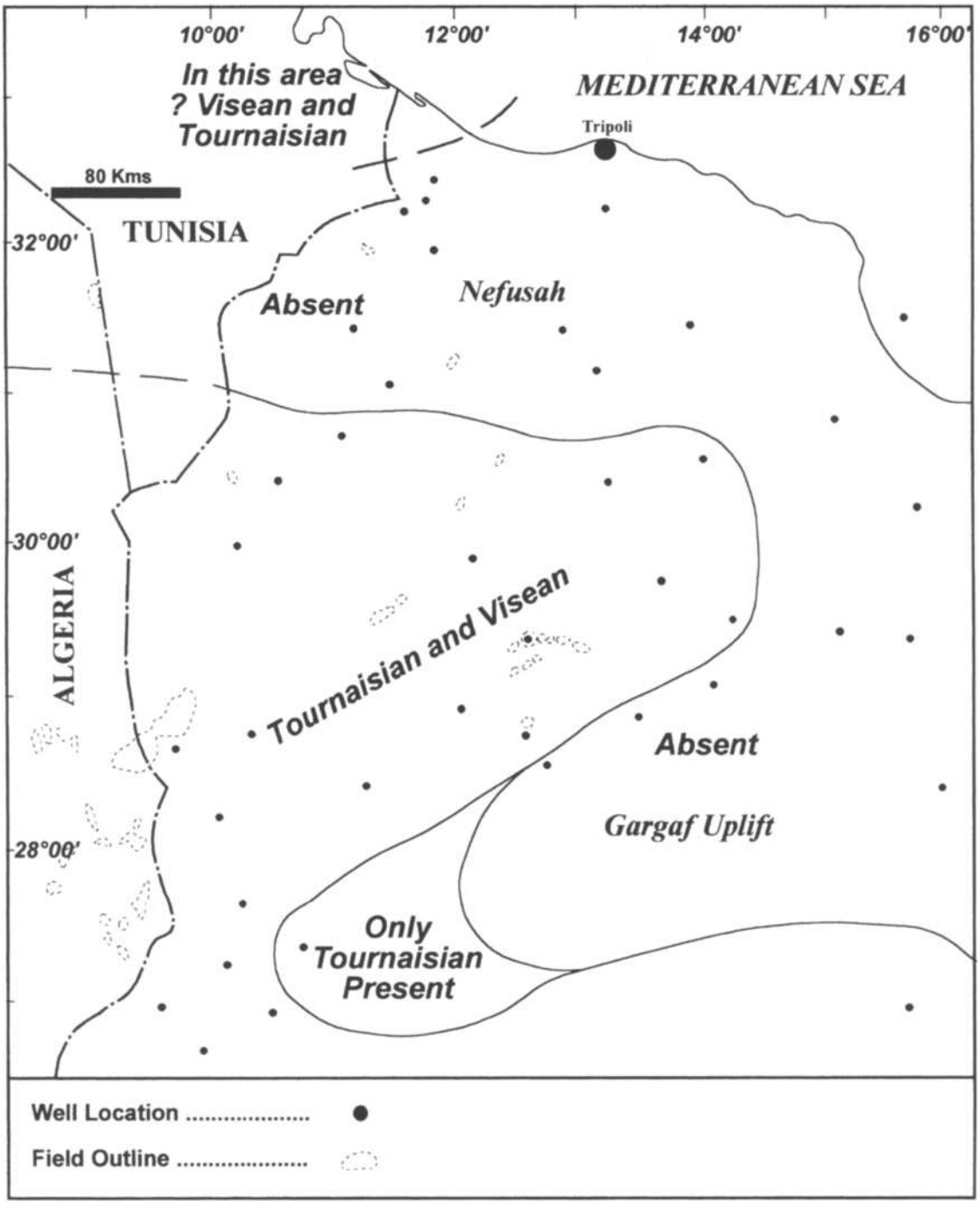

Figure 23. Geographical distribution of Tournaisian and Viséan strata (M'rar Formation).

Hydrocarbon discoveries and shows in the Tadrart Sandstone occur in stratigraphic and stratigraphic-structural traps generally related to north-south trending structuring along the Gargaf Uplift and east-west trending structures across the Ghadames Basin. Future hydrocarbon potential may be present in the northern areas of the basin where the Tadrart Sandstone is truncated and sealed by Triassic shales and along north-south trending structures. The M'rar Formation's hydrocarbon discoveries are concentrated mainly in the southern Ghadames Basin. Additional hydrocarbons may be present in areas adjacent to the Gargaf Uplift, along structural highs and fringing the Hoggar uplift, providing that there are suitable migration paths from older hydrocarbon generating zones.

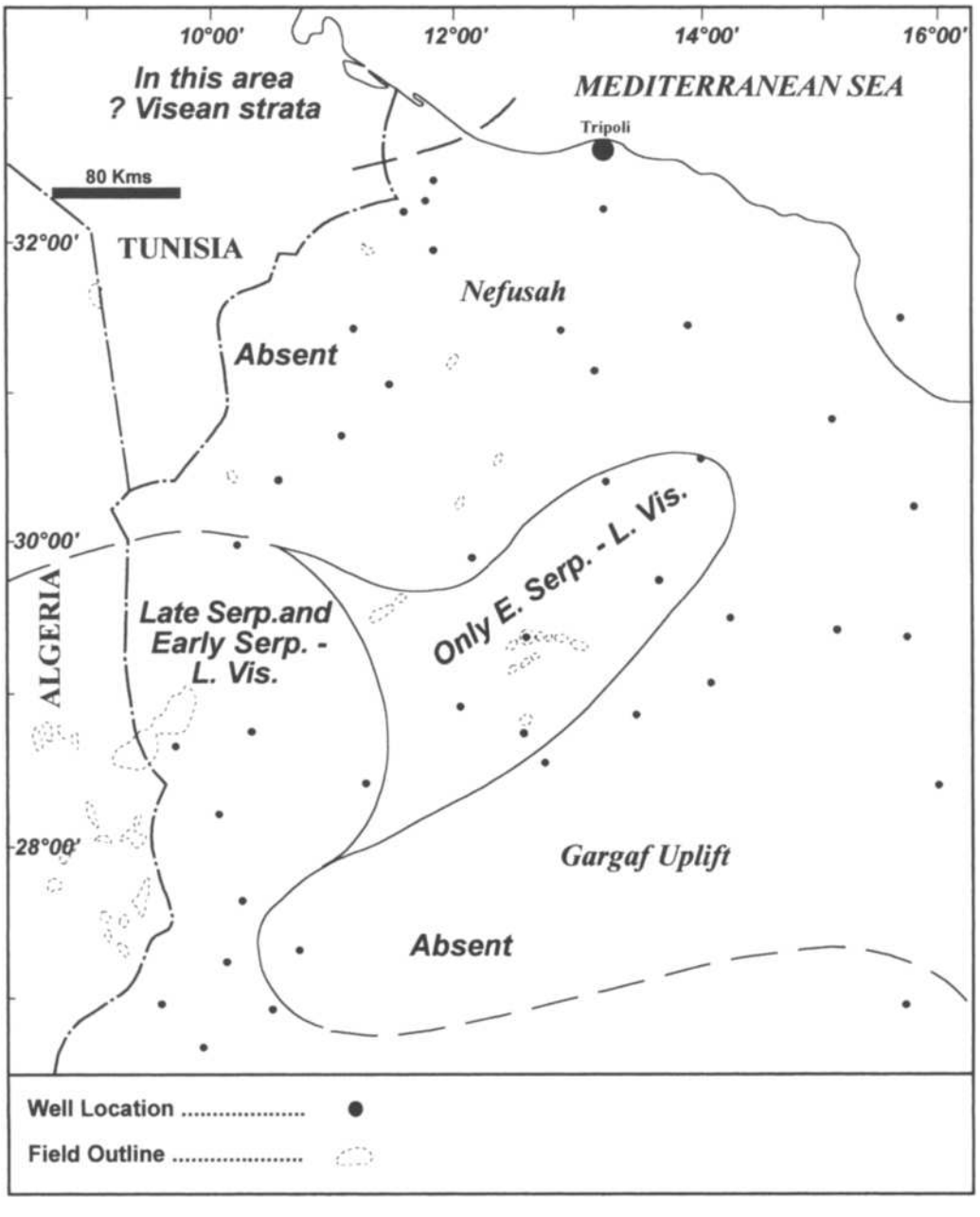

Figure 24. Geographical distribution of Serpukhovian and Late Viséan strata (M'rar Formation).

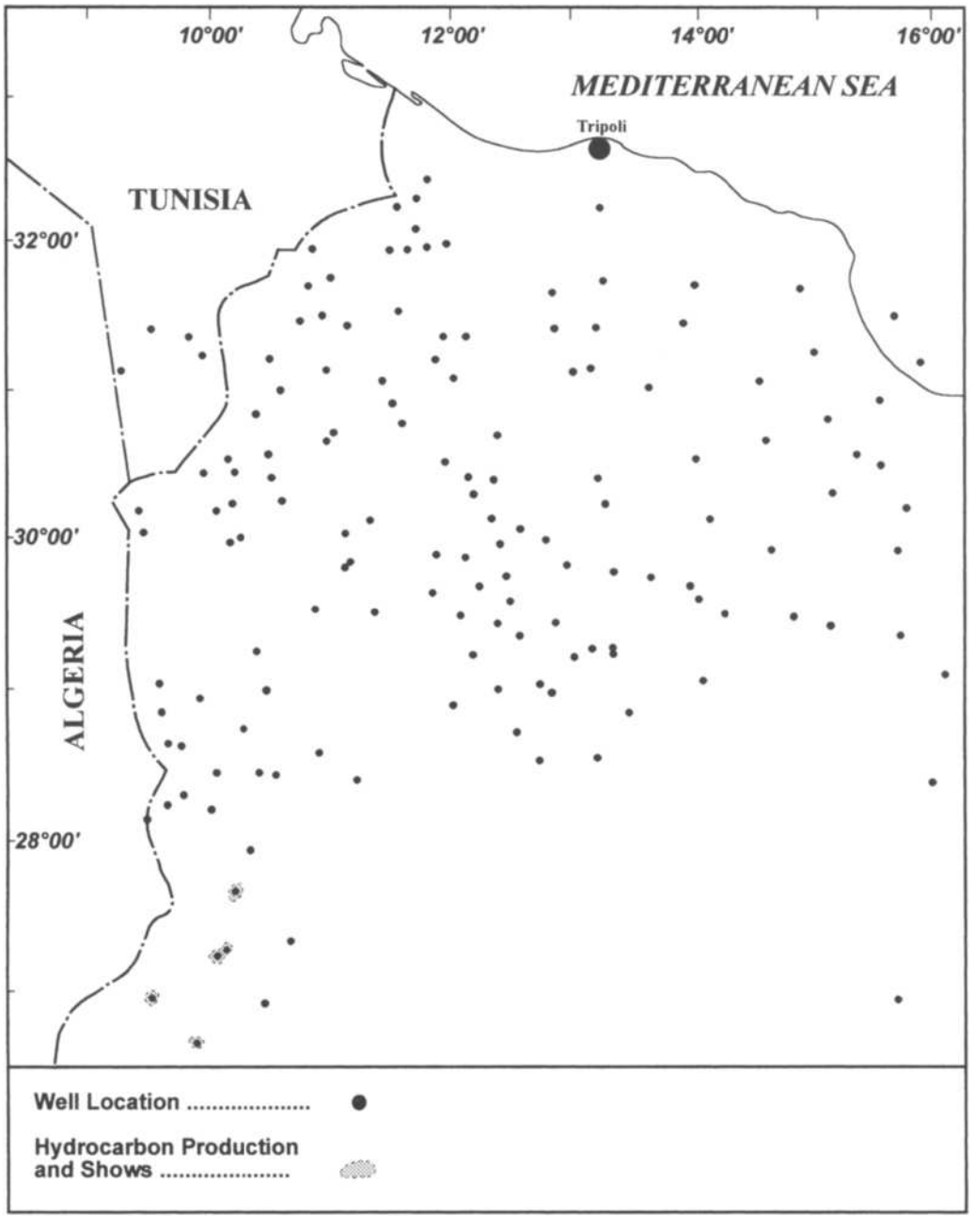

Figure 25. M'rar Formation hydrocarbon production and shows.

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CHAPTER 7

The structural development of the Murzuq and Kufra basins – significance for oil and mineral exploration

EBERHARD H. KLITZSCH[1]

ABSTRACT

TheMurzuq and Kufra basins were subject to several significantly different phases in their structural development during the Phanerozoic. The present-day shape of both basins reflects a Variscan and Mesozoic overprint on an older structural relief. During early Palaeozoic time, NNW trending horst and graben structures controlled far-reaching transgressions to the south and southeast, extending at least as far as the eastern Ennedi Mountains in Chad and the northern and central parts of Niger. These transgressions may even have reached parts of the Congo Basin. During the early Silurian and possibly also during part of the Ordovician, shale with source rock potential up to several hundred metres thick was deposited locally in northern Niger and at least several tens of metres of similar shale have been recorded along the Sudan-Chad border. Thus, there is potential for Silurian and Ordovician shales with source rock quality in the southern Murzuq Basin in Libya and possibly also in the southwestern Kufra Basin; these areas therefore provide interesting targets for oil exploration. Differential E–W to SW–NE uplift during late Mesozoic times resulted in erosion of older strata in some areas and deposition of mainly continental strata in others. During these periods, soil formation and related weathering processes most likely formed deposits of industrial raw materials such as bauxite and kaolinite locally in southern Libya, similar to those encountered in Egypt and Sudan. The interpretation herein represents results from fieldwork in Egypt, Sudan, Chad and Jordan (carried out during the last twenty years) as well as results from earlier fieldwork in Libya and Niger.

DEVELOPMENT UNTIL THE VARISCAN COLLISION

The geological development of the central and the eastern Sahara in late Palaeozoic to early Mesozoic time was postulated by Klitzsch (1970) to have been controlled by pre-existing structural relief (Fig. 1). Later research and fieldwork has supported and developed this original hypothesis. The main result of this work is evidence of the extension of this structural relief eastwards as far as the Arabian Peninsula and southeastwards into Chad and Sudan. The main features of the early to mid Palaeozoic structural relief can be briefly summarised as a system of NNW to N striking horst structures developed during Cambrian to early Ordovician time, forming wide elongate troughs and basinal areas that became the routes for long-distance

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transgressions to the south or southeast whenever the northern part of Gondwana was invaded by the sea. Consequently these structurally low areas were covered by relatively thick sequences of marine strata during highstand. During periods of regression, these were the sites of nearshore marine or continental sedimentation. The intervening uplifted or horst areas were subject to reduced sedimentation and/or erosion.

The best area to study this development in surface exposures is the early Palaeozoic horst structure at Mouridie on the southeastern rim of the Murzuq Basin in Libya. At this location, approx. 15°30′ E and 24° N, lower Silurian shale directly overlies Proterozoic basement and/or a thin cover of Ordovician strata, while WSW and ENE of this area at least several hundred metres of pre-Ordovician sandstone and conglomerate are present on the downthrown sides of NNW striking faults (see also, Klitzsch, 1963, 1970). This horst can be traced as a gravity high through the whole northeastern Murzuq Basin as far as Jebel Gargaf. Its northern prolongation is probably responsible for the division of the Libyan sector of the Ghadames Basin into a western and an eastern part with differing subsidence histories. The horst later became the core of the Tripoli-Tibesti Uplift (Fig. 1).

Another area giving clear field evidence for this postulated structural relief is that between Gilf Kebir in SW Egypt and Jebel Tageru South of Wadi Howar in NE Sudan. There, the Cairo-Khartoum Uplift (Fig. 1) is bordered by strata typical for the edges of structurally high areas: west to northwest transported sandstones of Ordovician and Silurian age are interbedded with shallow marine sands and deltaic sediments. Further west, along the Sudanese-Chad border in the eastern Ennedi Mountains, marine shales, probably of early Silurian age, are at least 50 to 100 metres thick. They indicate the presence of a trough or graben bordering the Cairo-Khartoum Uplift to the west and striking NNW towards the western part of the Kufra Basin in Libya (Klitzsch et al., 1993). Further west, within the Ennedi Mountains towards Fada, the shale facies disappears near the Tripoli-Tibesti Uplift and is replaced by interbedded, shallow marine sandstone (with abundant *Cruziana* and *Harlania* trace fossils) and fluvial sandstone.

A similar situation can be observed on the eastern rim of the Cairo-Khartoum Uplift towards the Syrian-Arabian-Trough. At Jebel Dirurba NW of Port Sudan, Ordovician and Silurian fluvial, deltaic and nearshore marine strata (again with a characteristic *Cruziana* fauna) suggest sediment transport towards the east and northeast, indicating the palaeotopography (Dieker, 1996). In southern Jordan, a progressively more open marine development of contemporaneous strata is seen from west to east.

In Libya it is therefore predicted that distal marine shale of early Silurian age and possibly also shale of Ordovician and Devonian age are present in the western part of the Kufra Basin. Similar, but thicker deposits are already verified in the southern parts of the Murzuq Basin in Libya and in northern Niger.

Along the western edge of the Cairo-Khartoum Uplift, outcropping Silurian strata overlie Proterozoic ultrabasics, altered to kaolinite and bauxite, in a large area between Wadi Howar and Jebel Tageru. This alteration is believed to have taken place during favourable climatic conditions prior to early Silurian sedimentation. The Silurian sediments then protected these deposits from erosion. Similar deposits may have formed elsewhere in comparable palaeogeographic situations (Wipki, 1995).

DEVELOPMENT AFTER THE VARISCAN COLLISION

The Variscan collision of Gondwana with the Laurasian northern plates resulted in the formation of Pangaea, which, soon after formation, began to disintegrate again along east-west trending fault systems, followed by transgressions to the west. The main remnants of the collision are shown by the folding of the Anti-Atlas in Morocco and by large areas of uplift and partial

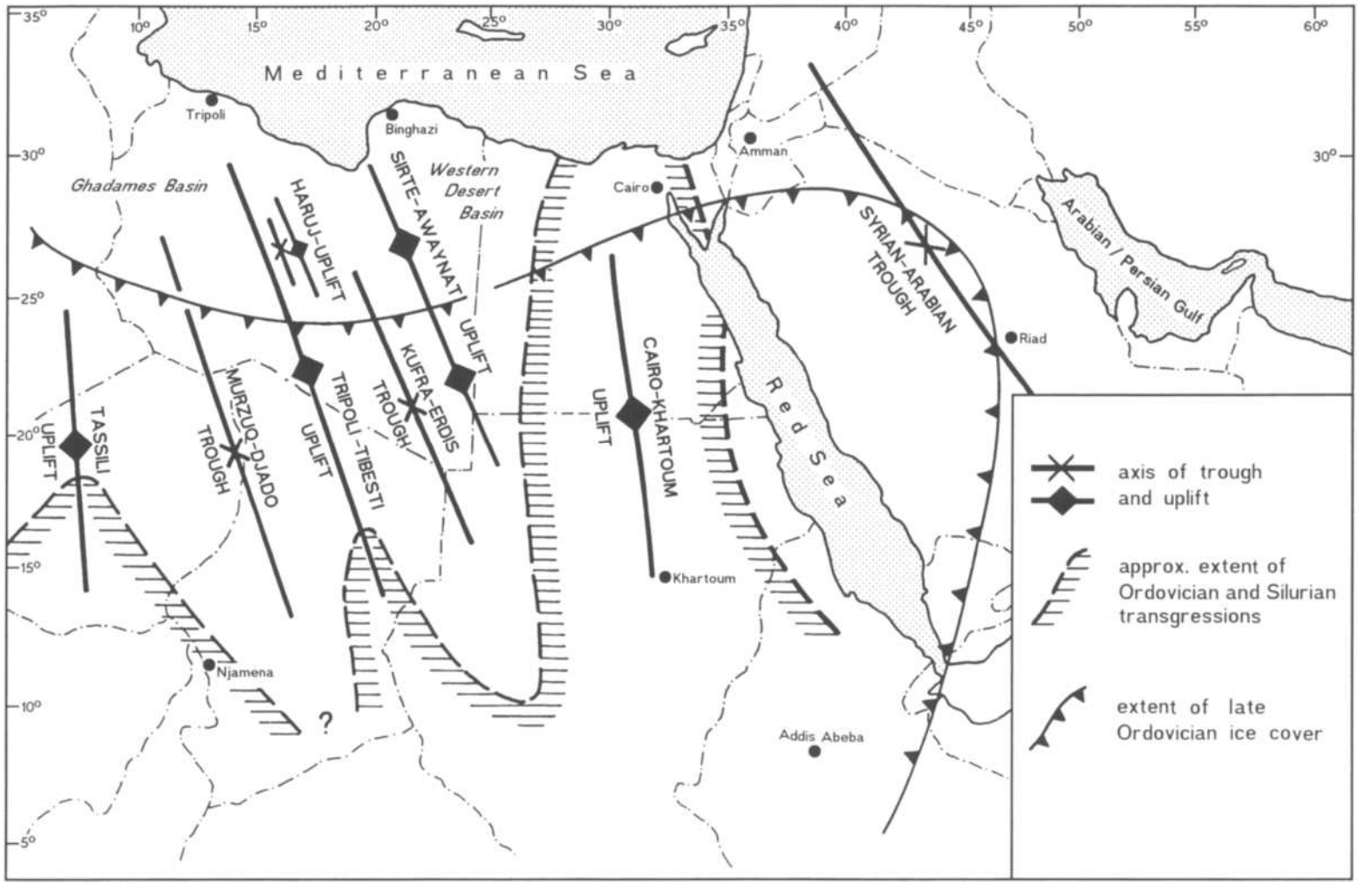

Figure 1. Structural relief of NE Africa and Arabia prior to the Variscan collision.

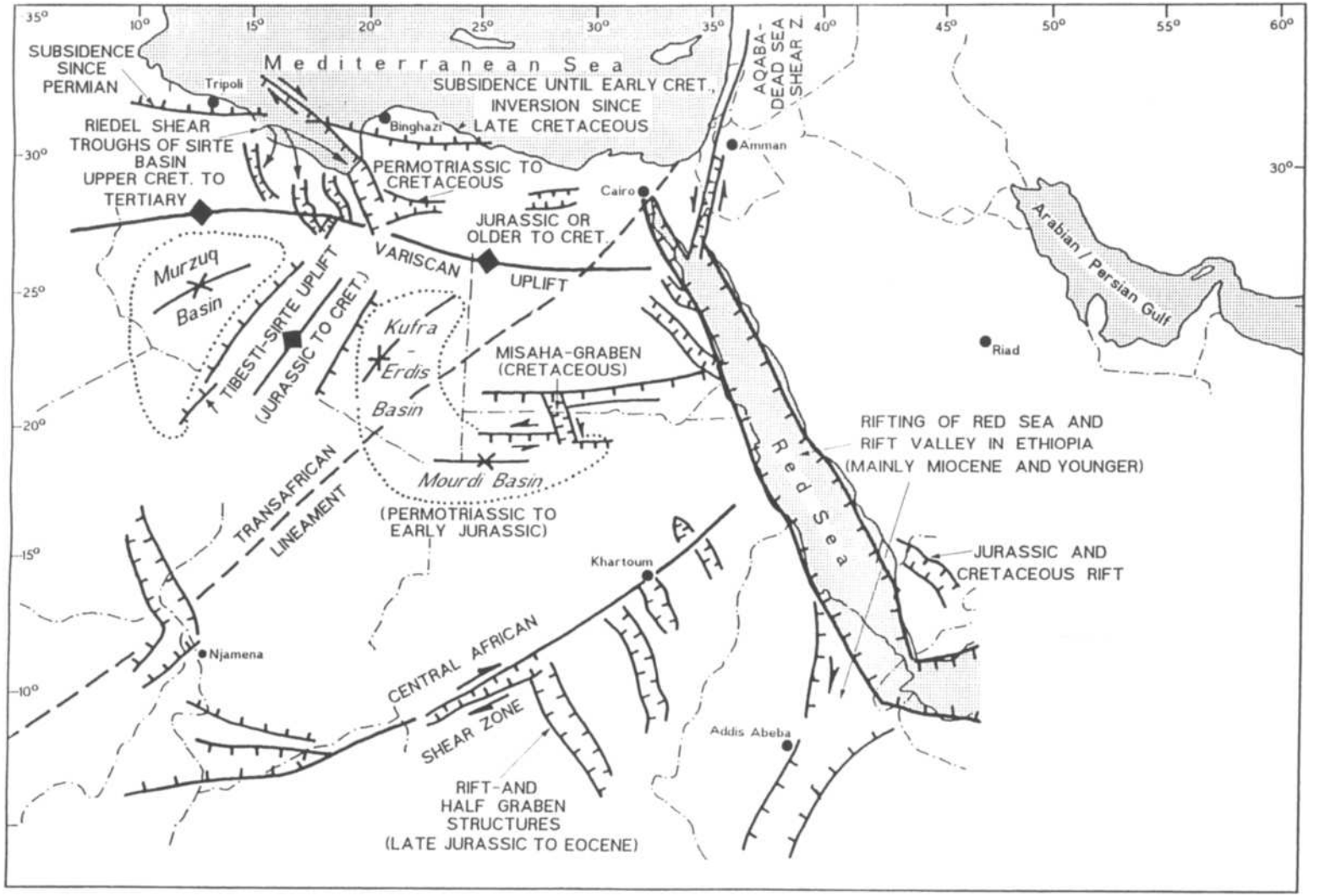

Figure 2. Important structural elements that developed after the Variscan collision.

erosion in Algeria, Tunisia, Libya, Egypt and even further east. Consequently the early Palaeozoic structural relief was overprinted by east–west striking structural elements. In Libya the Jebel Gargaf Uplift separated the Murzuq-Djado Trough from the Ghadames Basin. Further east, this Variscan tectonism resulted in the erosion of Palaeozoic strata in large parts of the Sirte Basin and in Egypt (Fig. 2 and Klitzsch, 1996).

The uplift of large areas in northern Libya and Egypt was accompanied by rifting and/or faulting along the present-day Mediterranean and also along the Egyptian/Sudanese border towards southern Libya. At the same time, or somewhat later, rifting and magmatism affected parts of the uplifted area. In the eastern Sirte Basin, and probably also in NW Egypt, continental Permotriassic to early Cretaceous rift-basins developed, partly accompanied by magmatism. Magmatism also affected the east–west striking fault systems in southern Egypt.

South of the large uplifted area of northern Libya and Egypt, continental sedimentation filled the now totally reoriented Murzuq, Kufra and Erdis basins. It seems likely that at the beginning of this continental development the Kufra and Murzuq basins formed one large sedimentary province, probably with multiple depocentres. Permotriassic sediments in both the eastern Murzuq and western Kufra Basin comprise mainly fine-grained sandstone and mudstone. There are no indications for any uplift separating these basins. Upper Jurassic to Lower Cretaceous sediments are much coarser grained in these areas, indicating new changes in structural and sedimentational patterns. At this time, the Tibesti-Sirte Uplift developed, separating the newly created Murzuq Basin from the Kufra Basin. The reason for the formation of this large SW–NE striking arch is difficult to understand. The strike direction however is more or less parallel to the Trans-African Lineament, which has been reactivated at several periods in geological history.

On the western side of the Tibesti-Sirte Uplift, local folding took place (Jebel Ati) and lateral movements along NE striking faults displaced the older Tripol -Tibesti Uplift by 20 to 30 km in a dextral sense. Erosion of the Tibesti-Sirte Uplift continued, and during late Cretaceous time, the sea entered the northern part of the uplift area and during Paleocene and Eocene time it transgressed even further south towards the present-day foreland of Tibesti. Meanwhile the Murzuq and Kufra basins 'starved'; they were largely cut off from their sediment supply and deposition was directed northwards towards the Sirte Basin area, where the well-known graben-horst structures developed as the result of east-west to southeast-northwest movements along the coast of northern Libya and Egypt.

Sedimentation in the Murzuq and Kufra basins slowed and stopped during the early Cretaceous, after the deposition of thick sequences of purely continental strata. A shallow sea covered only the northeasternmost flanks of the Murzuq Basin and the northernmost Kufra Basin in late Cretaceous and Paleocene to Eocene time.

CONCLUSIONS

Murzuq Basin

The Murzuq Basin should be subdivided into two main areas in terms of hydrocarbon exploration potential. The Murzuq-Djado Trough (Fig. 1) is an exclusively Palaeozoic structural element filled with strata of Cambrian to Carboniferous age, including several hundred metres of lower Silurian shale that locally provide an excellent to fair source rock potential. Devonian and Carboniferous shales may also have source potential, but are not necessarily mature. Hydrocarbons may have been generated from Devonian or early Carboniferous source rocks in areas where later subsidence caused subsequent thick sedimentation, such as in northern and

northwestern Murzuq, where post-Carboniferous strata reach thicknesses of over 1,700 metres. However, the main source rock within the Murzuq-Djado Trough is the lower Silurian Tanezzuft Shale. Until now the main reservoir rock has been fluvio-glacial sandstone of late Ordovician age, which provides the reservoir in several oil fields. Younger sandstones, such as sand sequences within the Devonian, however, can also have fair to good reservoir quality with cap rock sequences within the Devonian strata or at the base of the Carboniferous.

The eastern edge of the Murzuq-Djado Trough forms the western part of an early Palaeozoic horst striking from Mouridie NNW towards the western part of the Gargaf Uplift (Tripoli-Tibesti Uplift) from about 14°30′ E and 24° N to about 12°45′ E and 27°30′ N (Klitzsch, 1970, Fig. 5). All areas east of this line have a different hydrocarbon potential, as the Silurian source rock is largely absent. The early Palaeozoic structural relief subdivided this area into a series of NNW-striking horst and graben or uplift and trough structures, in contrast to the very consistent and much larger Murzuq-Djado Trough. The Silurian Tanezzuft Shale exposed in troughs, for example north of Wadi Cneir around 15°25′ E and 27°30′ N and within the Dor el Gussa area between 26°20′ N and 25°15′ N, is not present locally in areas east of the Tripoli-Tibesti Uplift (Fig. 1). Silurian strata are not present in wells A1–64, A1–77 and B1–77. Some areas east of the Tripoli-Tibesti Uplift do contain Silurian strata, but their occurrence is restricted and the shales probably have not been buried deeply enough to be mature. The northeastern part of the Murzuq Basin underwent a different structural history until the mid- or late Carboniferous and was only incorporated in the present day Murzuq Basin when the Variscan collision formed the Jebel Gargaf as a major structural element. It was at this time that continental basins – including Murzuq – developed south of this Variscan Uplift. The major sedimentational phase in these basins lasted from the Permian (or latest Carboniferous) to the Jurassic. The formation of the Tibesti-Sirte Uplift (most likely mainly during the early Cretaceous) resulted in erosion of all the sediments of the northeastern Murzuq Basin within the area of uplift. It also affected the Murzuq-Djado Trough in structural terms. Continuous faults with large throws formed, trending approximately SW through the southern part of the Murzuq-Djado Trough and at Jebel Ati an eighty kilometre long anticline was formed. Other anticlines may well be present under the younger cover further west.

Kufra Basin

The Palaeozoic history of the Kufra Basin was similar to that of the Murzuq Basin. Both the Kufra and Murzuq basins show local variations in geology affecting their petroleum potential. The eastern part of the Kufra basin, including the Jebel Gardeba, Kufra and Jebel Awaynat areas, is situated on the early Palaeozoic Sirte-Awaynat Uplift. This uplift has reduced thicknesses of Cambrian to Carboniferous strata and parts of this succession may be absent in places. The lower Silurian Tanezzuft Shale is not developed as a source rock. This area is close to a large palaeohigh, the Cairo-Khartoum Uplift, which provided a source for shallow marine sands to the west. Between Gilf Kebir in southwestern Egypt and Jebel Tageru in northwestern Sudan, Ordovician and Silurian sediments were deposited on either side of a persistent shoreline (Fig. 1).

The Sirte-Awaynat Uplift lies slightly to the west of the maximum extent of the Silurian transgression, and hence, marine Silurian source rocks are thought to be absent from that area. The influence of this palaeohigh can be seen further north in the present-day Sirte Basin, where it is represented by a number of blocks between the Sarir and the Amal areas. Within the Kufra Basin the Sirte-Awaynat Uplift is associated with younger magmatism, for example at Jebel Arkenu, Jebel Awaynat and Jebel Kissu.

The potential area of interest for hydrocarbon exploration in the Kufra Basin is west of the Sirte-Awaynat Uplift and the foreland of the Sirte-Awaynat Uplift. The Silurian source rock shale facies is exposed in the Ennedi Mountains along the Sudanese-Chad border. This is exactly where Klitzsch (1970) postulated the axis of the early Palaeozoic Uri Trough, but since that time, distal marine shale has been recorded in the Eastern Ennedi Mountains. Thus, the western and southwestern parts of the Kufra Basin may be of interest for oil exploration (see also Schandelmeier & Reynolds, 1997). Further work should focus on resolving the question as to whether or not an adequate thickness of overlying strata is present, both to permit maturation and to provide effective seals.

Younger structural episodes such as the Variscan collision and the formation of the Tibesti-Sirte Uplift also affected the Kufra Basin. The Variscan collision formed the Mourdi Sub-basin (Fig. 2) and deformed the Sirte-Awaynat Uplift between Jebel Awaynat and Jebel Gardaba. At this time probably a large continental basin reached from the Mourdi Basin in northwestern Sudan to the northwestern part of the present day Murzuq Basin. The Tibesti-Sirte Uplift formed towards the end of Jurassic time but probably mainly during the early Cretaceous, interrupted the post-Variscan continental sedimentation and modified older structural elements. The Uri area (western Kufra Basin) represents the extension of the Palaeozoic Dor el Gussa Trough of the NE Murzuq Basin, the eastern Ennedi Mountains comprising the southeastern continuation of this trough during the deposition of the Silurian shales. Younger overprint makes it difficult to reconstruct the original geological situation and its exploration potential. This will need more fieldwork and subsequent seismic investigation. Figs 1 and 2 show schematic interpretations based on work carried out to date.

Mineral Exploration

The kaolinite and bauxite deposits south of the Wadi Howar area in NW Sudan provide an example of exploitable deposits within the Palaeozoic sequence. The source material is provided by ultrabasic Proterozoic rocks, which were exposed to weathering processes during a significant time period probably during the early or middle Ordovician. They were later covered by shallow marine sediments of Silurian age and so were protected from later erosion. Similar deposits may also occur in Libya. In Sudan these deposits are located on the edge of the early Palaeozoic Kufra Basin.

Other economic deposits include glass sands. In many areas around the Murzuq and Kufra basins, the Silurian sandstones are locally very pure white sands, and should provide excellent material for glass production. In Egypt similar sands of Cambrian and Carboniferous age are mined for this purpose at Sinai and along the western side of the Gulf of Suez.

In several areas of Sudan, Mesozoic (mainly Cretaceous) continental sediments have been transformed by weathering and leaching processes into kaolinite. In some areas, fossil soils reach thicknesses of more than 100 metres. These strata are of interest for kaolinite prospecting and extraction.

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CHAPTER 8

Petroleum source and reservoir rock re-evaluation in the Kufra Basin (SE Libya, NE Chad, NW Sudan)

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ABSTRACT

The Kufra Basin is a large, underexplored, Palaeozoic intracratonic sag basin in SE Libya and NE Chad with extensions into NW Sudan and SW Egypt. The basin fill consists of shallow marine to fluvial deposits ranging in age from Infracambrian to Cretaceous. Geologically, the basin is very similar to the Murzuq Basin, which recently presented Libya with its largest oil discovery for over a decade. Most of the hydrocarbon play elements known from the Murzuq Basin also occur in the Kufra Basin: thick, porous Cambro-Ordovician sandstones are present and could form good reservoirs, lower Silurian shales may act as effective seals, and there are potential structural traps in seismically defined fault blocks. However, the source rock potential of the Kufra Basin is currently unclear. One of the two main source rock candidates in the basin is a lower Silurian shale unit (Tanezzuft Formation). The Tanezzuft shales have been described as being up to 130 m thick in outcrops at the basin margins, but the shales are thin and mostly replaced by siltstones and sandstones in two dry exploration wells drilled between 1978 and 1981 in the northern part of the basin. Hot shales developed at the base of this widespread Silurian shale unit form important source rocks in many areas of North Africa and Arabia. These hot shales are interpreted to have been deposited in palaeodepressions, such as incised valleys of the preceding lowstand, or in intrashelf basins during the initial transgression after the melting of the late Ordovician ice cap. The areal distribution of the organic-rich unit is therefore discontinuous. Fieldwork in the Kufra Basin has shown that the basal Tanezzuft horizon is mostly not exposed on the northern and eastern margins of the basin. A detailed evaluation of the lower Silurian source rock potential may require shallow stratigraphic drilling. Deep Infracambrian rift grabens have been interpreted on seismic lines from the Kufra Basin and, in analogy to Oman and Algeria, could contain organic-rich intervals; this succession in the Kufra Basin may contain a second major potential source rock and warrants further investigation.

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INTRODUCTION

The Kufra Basin is a large, Palaeozoic intracratonic sag basin which lies in SE Libya and NE Chad ('Erdis Basin') with extensions into NW Sudan ('Mourdi Basin') and SW Egypt (Fig. 1). It is bounded by four basement-high structures, namely the Tibesti Massif (including Jebel Nuqay and Jebel Dohone) in the west, the Jebel Awaynat Massif (including Jebel Asba) in the east, the Ennedi and Borkou mountains in the south, and the Calanscio Arch (Jebel Dalma) in the north (Figs. 2, 3). Outcrops of lower Palaeozoic strata are restricted to these areas. The Kufra Basin has been poorly explored geologically and the source rock development in the basin is still especially unclear.

HISTORY OF GEOLOGICAL RESEARCH

The first geologist in the Kufra Oasis was G. Rohlfs, who visited the area in 1879 (Klitzsch, 1994). Some of the first geological samples from the Kufra Basin were collected by Hassanein Bei (1924) and studied by Moon (1924) and Hume (1924). Geological expeditions to the eastern Sahara were carried out by Bagnold and Sandford during the early 1930s and these included stratigraphic studies of outcrops on the southern margin of the Kufra Basin (NW Sudan and Ennedi Mountains in Chad: Sandford, 1935). A geological map of the Borkou-Ennedi-Tibesti area (Chad) was published by Wacrenier (1958).

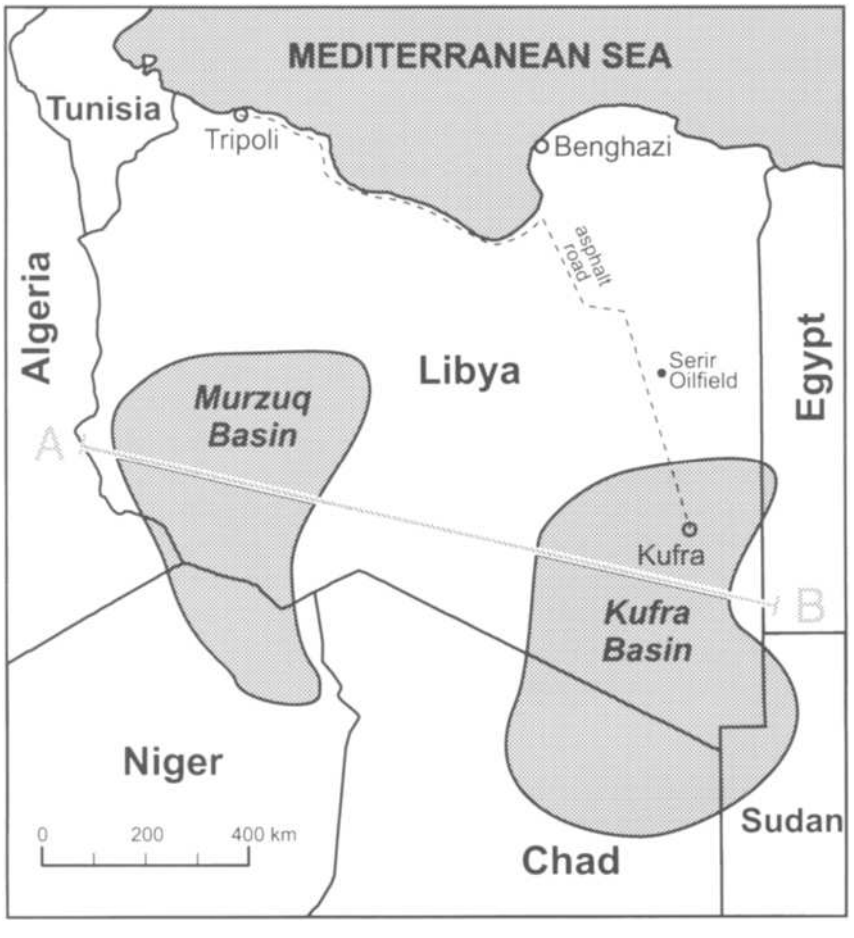


Figure 1. Location map of the Kufra and Murzuq basins. Cross section A-B is illustrated in Fig. 2.

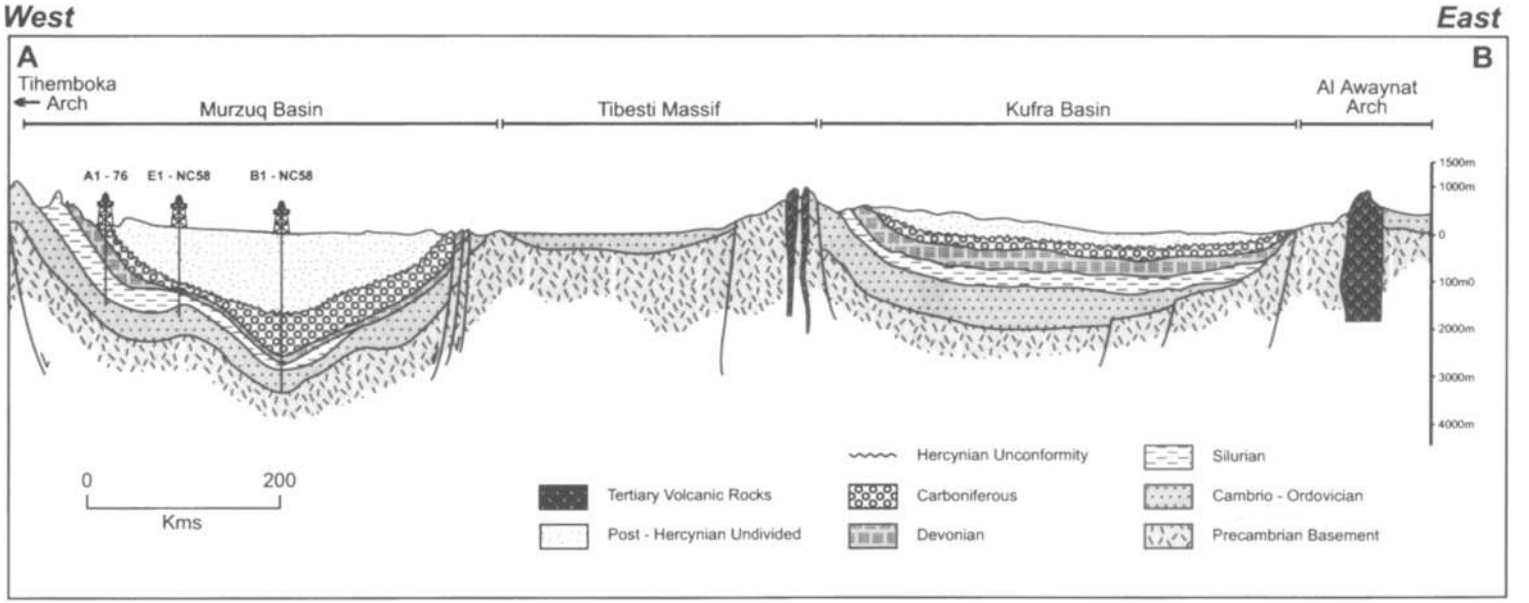


Figure 2. Cross section of southern Libya through the Kufra and Murzuq basins. After Bellini and Massa (1980: Kufra) and Fisher (pers. comm., 1999).

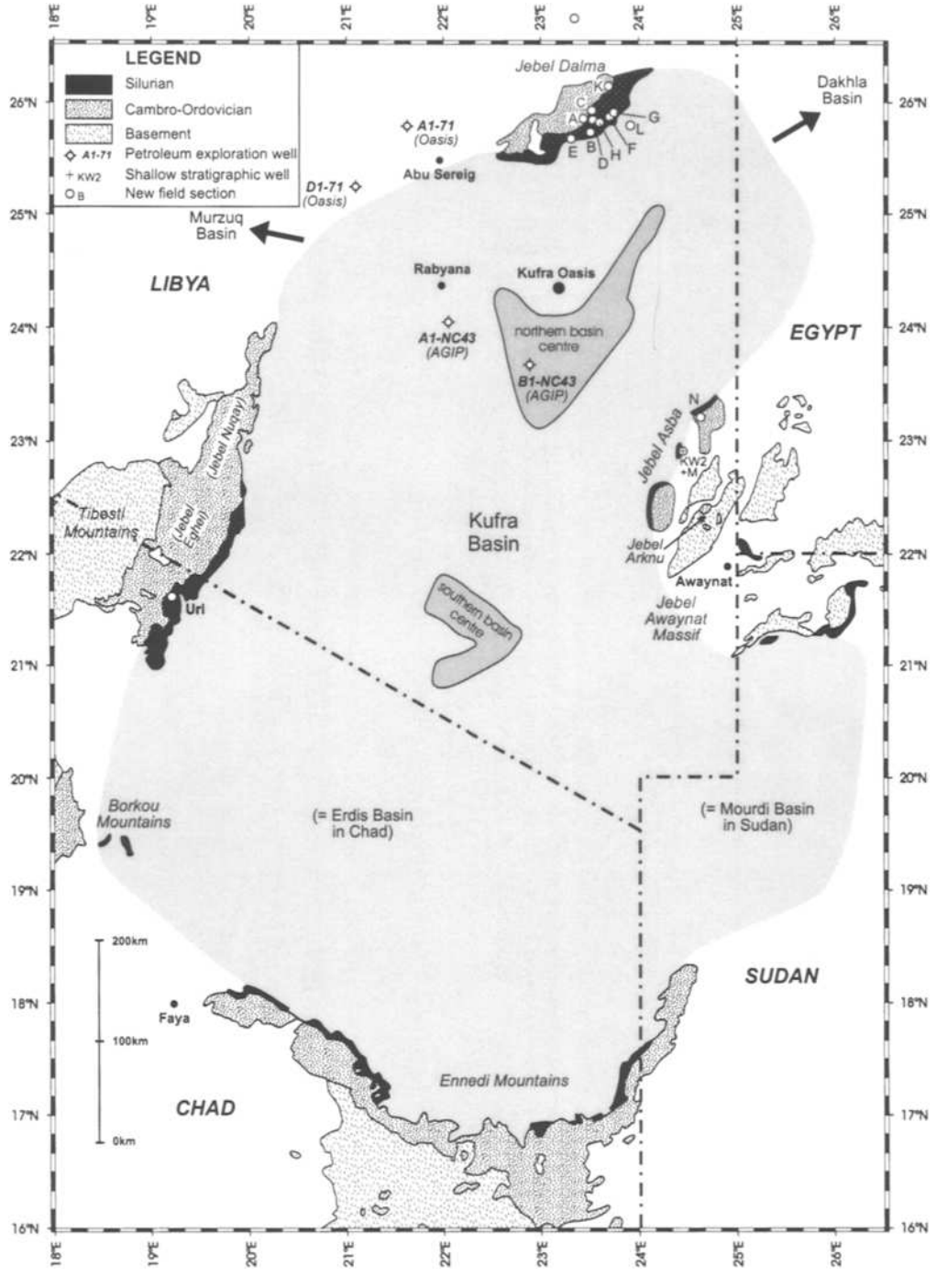


Figure 3. Kufra Basin with its confining basement highs. Geological base map after GIS online data set of Cornell University (see Seber et al., 1997) and IRC (1985a). A northern and a southern sub-basin with total sedimentary thicknesses of more than 3.5–4 km are developed. Only two deep exploration wells have been drilled in the Kufra Basin (A1-NC43 and B1-NC43 by AGIP). The Oasis wells A1–71 and D1–71 are located outside the Kufra Basin.

Increased geological interest in the Kufra Basin arose in the 1950s when D'Arcy Exploration Co. Ltd (British Petroleum) carried out aerial and ground surveying in SE Libya (Martinez, 1995; Gurney, 1996: 22) in the search for petroleum. Other oil companies studied the basin in

the 1960s (Libya: John, 1962; Burollet, 1963; Vittimberga and Cardello, 1963; Chad: de Lestang, 1968; Deynoux et al., 1985: p. 444–454). During this period Oasis drilled two dry exploration wells (A1–71, D1–71), testing structures in an area just north of the Kufra Basin (Rusk personal communication, 1999). In the Chadian part of the basin, fieldwork, seismic surveys and drilling of five shallow coreholes into Silurian-Carboniferous strata took place. The first satellite-image based geological study of the Kufra Basin was published by Pesce (1968) using photographs from the U.S. Gemini space missions.

Between 1975 and 1981 AGIP N.A.M.E. carried out a comprehensive hydrocarbon exploration programme including tellurometry, photogeology, field-based stratigraphy, palynomorph biostratigraphy, aeromagnetics, and the acquisition of 2189 line km of seismic data (Bellini and Massa, 1980; Grigagni et al., 1991 and unpublished AGIP reports, e.g. Bellucci et al., 1976; Bellini et al., 1976; Bellini, 1976). AGIP drilled two deep wildcat exploration wells to basement, with A1-NC43 reaching a depth of 3019 m and B1-NC43 a depth of 4164 m. Both wells penetrated the entire Palaeozoic succession, which consists predominantly of sandstones. Although 50 to 100 m thick Silurian shales have been described from all major outcrops on the margins of the Kufra Basin (De Lestang, 1968; Bellini and Massa, 1980; Bellini et al., 1991), these shales were <30 m and lean in the two exploration wells (Bellini et al., 1991). In the absence of a major potential source rock and because of the negative petroleum results, the exploration programme in the area was abandoned by AGIP in 1981 (Bellini et al., 1991).

A detailed sedimentological field study of the Palaeozoic succession on the eastern margin of the Kufra Basin (Jebel Asba, Jebel Arknu) was carried out by Turner in the 1970s (Turner, 1980, 1991, 1992; Turner & Benton 1983). Stratigraphic field data from the Chadian and Sudanese parts of the Kufra Basin were published in the 1980s and 1990s by a group from the Technical University of Berlin (Klitzsch, 1981; Hissene Mahamoud, 1986; Klitzsch and Wycisk, 1987; Klitzsch et al., 1993; Semtner et al., 1997).

In 1985, Robertson Research conducted a comprehensive evaluation of the petroleum potential of NW Sudan on behalf of the Geological Research Authority of Sudan. The World Bank-funded study included gravity data acquisition, surface stratigraphic traverses and compilation of a geological map based on satellite image interpretation.

In 1989 AGOCO, on behalf of NOC, commissioned a seismic survey (about 4612 line km) in the Kufra Basin that mainly covered the region south of the area previously explored by AGIP (Bezan, 1991; Oun et al., 1996). Additional AGOCO studies included gravity and magnetic modelling as well as organic geochemistry of samples from the two AGIP exploration wells. In the search for microseeps, soil and sediment samples were taken by AGOCO over seismically defined structural traps and lineaments and these were geochemically analysed for thermogenic gases (Said et al., 1998). Recently, a geological mapping project by the Industrial Research Centre (IRC) of Libya has been completed in the Jebel Dalma area, but the map is as yet unpublished.

The results presented in this contribution originate from a basin evaluation project conducted jointly by Lasmo plc (London), the Petroleum Research Centre (PRC) of Libya and the University of Wales, Aberystwyth, in collaboration with several other British universities (see also Lüning et al., 1999).

AREA OF STUDY AND FIELDWORK

The Kufra Basin area is one of the most remote parts of the Sahara. Apart from the Kufra Oasis itself (Fig. 3), with its large groundwater reserves (e.g. Fisk and Pennington, 1976) and more than 25000 inhabitants (Göttler, 1998), most of the area is more or less devoid of any life due

to the extreme aridity. The few settlements [e.g. Uri, Awaynat, Rabyana and Zigan (or Abu Sereig) are located around water wells that are up to 200 km or more apart.

A three-week field study of Palaeozoic outcrops on the northern (Jebel Dalma) and eastern (Jebel Asba) margins of the Kufra Basin (Fig. 3) was carried out in March/April 1998 in order to examine the lower Palaeozoic sedimentary rocks of the basin with emphasis on potential petroleum source rocks. Following extensive regional reconnaissance work, 12 sections were measured (Fig. 4 and Lüning et al., 1999) and more than 200 samples collected for organic geochemistry, palynology, graptolite biostratigraphy, ichnology and sedimentary petrography (Table 1). Unfortunately, all palynomorph samples turned out to be barren, most probably reflecting (sub-) recent oxidation as a result of weathering in this extreme desert climate.

The Cambro-Ordovician to upper Silurian succession studied in Jebel Dalma is exposed along an almost 100 km long major wadi, where the uppermost part of the lower Silurian Tanezzuft shales lie at or beneath the wadi floor. The harder Cambro-Ordovician and upper Silurian sandstones form steep mountains along both wadi flanks. The western end of the wadi opens into a sand sea with high sand dunes. In Jebel Asba, erosion is more advanced, with the lower Palaeozoic rocks exposed in inselbergs of varying dimensions.

Due to the great distances, limited infrastructure and the extreme climate in the area, a fully autonomous camp with sufficient food and energy supplies was set up for the fieldwork in Jebel Dalma and was later moved to Jebel Asba (Fig. 3). Shortwave radio communication and precautions for vehicle breakdowns were established in order to meet basic safety standards. Descriptions of the logistics of previous expeditions to the Kufra Basin area have been given by Hassanein Bey (1924), Mahrholz (1968) and Bellini et al. (1976).

Locations in the field were determined by GPS satellite navigation supported by topographic maps prepared by the Russian Military Geographic Institute (1:200 000), photogeology maps (1:100 000, not ground-proven, compiled by AGIP: Bellucci et al., 1976), Landsat images, TPC flight charts (1:500 000) and the latest geological map of the area (1:1 000 000, IRC, 1985a).

The Palaeozoic outcrops on the western (Eastern Tibesti Mountains in Libya and Chad) and southern margins (Borkou and Ennedi mountains in Chad) of the Kufra Basin were not visited during the expedition in view of potential landmine hazards in these areas (Blake, 1994; United Nations Demining Database, 1995; Simons, 1996; Göttler, 1998: 376).

LOWER PALAEOZOIC STRATIGRAPHY AND DEPOSITIONAL HISTORY

The sedimentary succession in the Kufra Basin can be subdivided into eight major stratigraphic units, namely the Infracambrian (upper Neoproterozoic to lowermost Cambrian), undifferentiated Cambro-Ordovician, the lower Silurian Tanezzuft Formation, lower to upper Silurian Akakus Formation, lower Devonian Tadrart Formation, middle and upper Devonian Binem Formation, Carboniferous Dalma Formation and the post-Hercynian Nubian Formation (Fig. 5) (modified after Bellini et al., 1991; Bezan, 1991).

Infracambrian (late Precambrian to early Cambrian)

An Infracambrian rift graben system with syn- and post-rift infill of several kilometres thickness but undetermined lithologies has been interpreted on seismic lines acquired in 1989 by AGOCO from the southern part of the (Libyan) Kufra Basin (Bezan, 1991; Forum Exploration, 1995; Mohamed, 1998). The Infracambrian stratigraphic position of the graben fill in the AGOCO interpretation is based on regional ties of overlying seismic horizons to Palaeozoic outcrops with well-established ages. Further evidence for Infracambrian strata in the Kufra Basin comes from

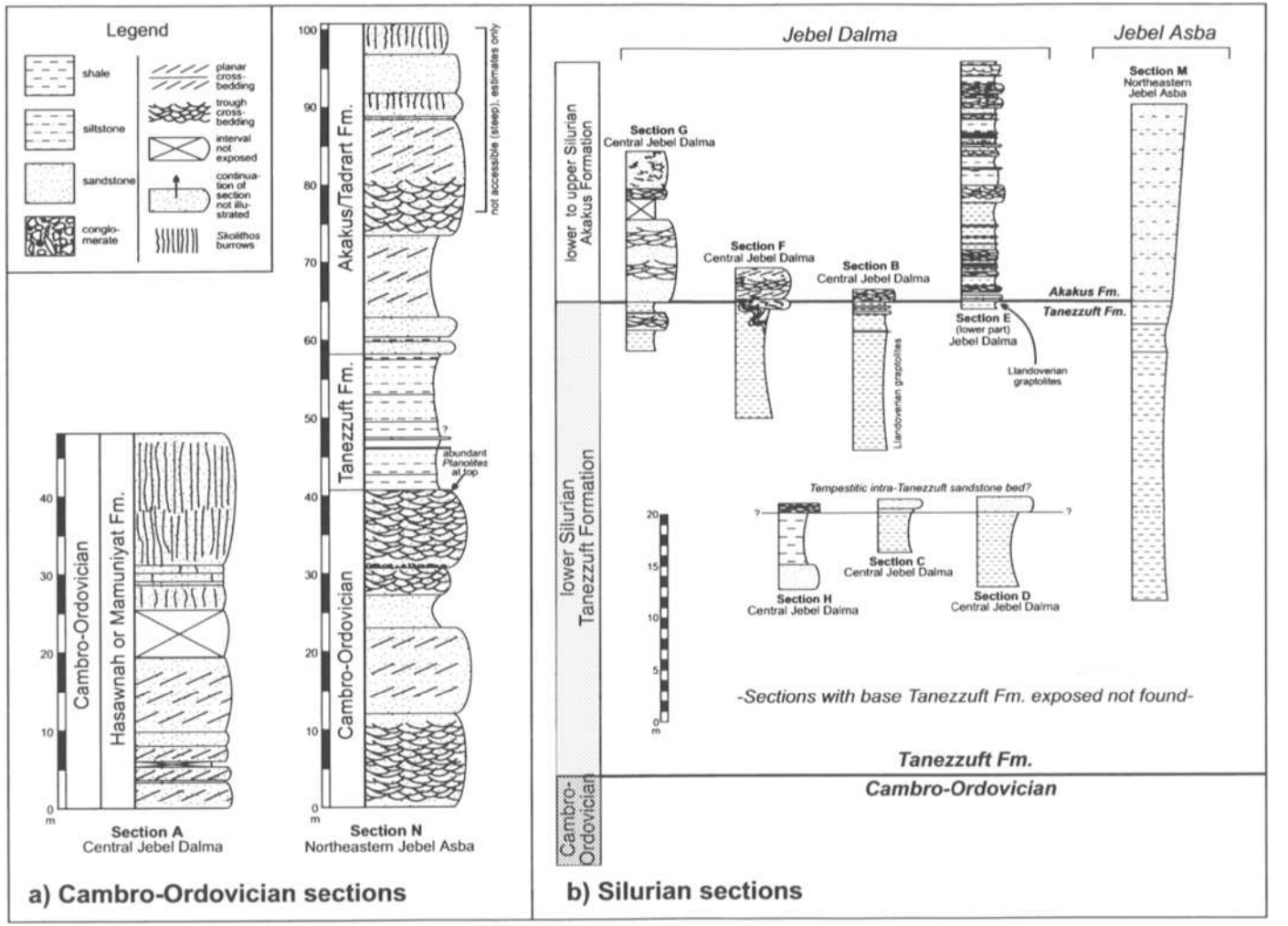


Figure 4. Cambro-Ordovician and Silurian stratigraphic field sections logged in Jebel Dalma and Jebel Asba in March/April 1998 (see Table 1 for summary).

Table 1. Sections measured in the Kufra area during the field season March/April 1998 (see Fig. 4 and Lüning et al., 1999)

Section No.	Locality	Coordinates	Stratigraphic range	Length of section
A	Central Jebel Dalma	25°51'29'N 23°30'05'E	Cambro-Ordovician	48 m
B	Central Jebel Dalma	25°50'45'N 23°36'27'E	Upper Tanezzuft-lower Akakus fms.	15.5 m
C	Central Jebel Dalma	25°54'14'N 23°36'03'E	Tanezzuft Fm.	5.2 m
D	Central Jebel Dalma	25°54'07'N 23°36'20'E	Tanezzuft Fm.	8.8 m
E	Central Jebel Dalma	25°44'02'N 23°34'00'E	Upper Tanezzuft-Akakus Fm.	240 m
F	Central Jebel Dalma	25°56'50'N 23°45'09'E	Tanezzuft Fm.	14.5 m
G	Central Jebel Dalma	25°57'09'N 23°45'31'E	Tanezzuft Fm.	19.3 m
H	Central Jebel Dalma	25°55'00'N 23°41'37'E	Tanezzuft Fm.	8.3 m
K	Northern Jebel Dalma	near 26°06'37'N 23°46'26'E	Evaporite – dolomite series Upper Cretaceous	24 m
L	Central Jebel Dalma	northwest of 25°55'18'N, 23°54'01'E	Contact zone upper Akakus Fm. – lower Tadrart Fm.	1.5 m
M	Northeastern Jebel Asba	22°54'15'N 24°21'28'E	Upper Tanezzuft Fm. – lower Akakus Fm.	48 m
N	Central Jebel Asba	23°07'40'N 24°26'51'E	Cambro-Ordovician to Silurian/Devonian	101 m

a rock unit exposed on the northeastern flank of Jebel Arknu (Fig. 3), which is marked on the geological map of SE Libya as 'Upper Proterozoic' (IRC, 1985a). In the map legend (IRC, 1985b), the series is described as being composed of limestones, meta-greywackes, conglomerates, siltstones and shales. The carbonates were reported to be 'compact and coarsely crystalline' (personal communication, Dr R.A. Alkhazmi, 1998). The apparent (low-grade?) metamorphism of these rocks at outcrop may be associated with heating by the Eocene Jebel Arknu intrusion (Atherton et al., 1991; Flinn et al., 1991).

On a continental scale, similar shale-carbonate facies are developed both east and west of the Kufra Basin. In Oman and Saudi Arabia, for example, such sediments have been widely studied and are interpreted to have been deposited in large pull-apart basins (Husseini and Husseini, 1990; Talbot and Alavi, 1996). Some of the related megafaults of the Najd fault system may have also extended into the Kufra Basin area.

A two-stage model for the development of Infracambrian grabens in the Kufra and Egyptian Dakhla basins was proposed by Schandelmeier (1988) on the basis of unpublished CONOCO

data from NW Egypt (including seismic profiles, aeromagnetic and well data) and outcrop studies. He assumed that during the late Pan-African orogeny, a series of pull-apart basins formed along the NE-trending Transafrican Lineament ('TAL' of Keeley, 1994; = 'Pelusium Line' of Neev, 1977; Neev et al., 1985) due to dextral transpressive movements along this megashear. During the early Cambrian, activity associated with the Pan-African orogeny waned and the shearing stopped. Soon afterwards, a new ENE–WSW oriented extensional stress field produced NNW-striking graben and horst structures, with the older pull-apart basins forming the deepest parts of the composite relief (Schandelmeier, 1988). An extensional collapse of the Pan-African orogen in NE Africa was postulated by Greiling et al. (1994) for Infracambrian times between 600 and 575 Ma, although M. Smith (personal communication, 1998) has pointed out serious errors in their arguments and observations and favours a transtensional mechanism for Infracambrian extension in NE Africa.

Infracambrian deposits in neighbouring areas.

An Infracambrian succession, termed the Mourizidie Formation (Jacqué, 1962; Burollet and Byramjee, 1969) has also been described from the Murzuq Basin. The unit overlies metamorphic basement with a marked angular uconformity and is itself overlain by the Cambrian Hasawnah Formation. The Mourizidie Formation consists exclusively of fine-grained cross-bedded sandstones.

In NE Libya, a thick, sandy succession, interpreted as having been formed in a restricted marine environment, contains Neoproterozoic (Late Riphean, 650 to 1000 Ma) acritarchs (Baudet, 1988; El-Arnauti and Shelmani, 1988). A few metres of ?Early Cambrian limestones containing stromatolites and archaeocyathids were described from the Sinai Peninsula by Omara (1972).

Infracambrian source potential.

In Oman, Saudi Arabia and elsewhere, the Infracambrian succession contains significant amounts of organic-rich shales and carbonates, making the Infracambrian deposits one of the most important source rocks in Oman (e.g. Husseini and Husseini, 1990). A similar facies has been also reported from NW Africa. An Infracambrian carbonate-shale succession with black shale horizons has been described from outcrops in western Algeria by Moussine-Pouchkine and Bertrand-Sarfati (1997). Their tectono-depositional model includes extensional graben development with partly organic-rich stromatolitic bioherms on the elevated footwall side and marls and black shales on the deeper hangingwall side of faults.

Total Infracambrian thicknesses of up to 1400 m have been interpreted on seismic sections from the Kufra Basin (Forum Exploration, 1995). The Infracambrian succession is regarded herein as a second major potential source rock in the basin and it clearly deserves serious future attention.

Cambro-Ordovician (Hasawnah and Mamuniyat formations)

Sedimentary rocks of Cambrian and Ordovician age remain undifferentiated in the Kufra Basin because biostratigraphically relevant fossils are mostly absent. During Cambro-Ordovician times, the Kufra Basin area was dominated by braided fluvial to shallow marine sandy facies with rare marine shaly intercalations (Bellini et al., 1991; Turner, 1980, 1991). A similar facies

also prevailed in the Kufra area during late Ordovician times when major glaciation affected large parts of North Africa and Arabia. A better understanding of the late Ordovician (peri-) glacial relief in the Kufra Basin is important because the resultant palaeodepressions are interpreted as representing favourable locations for hot shale deposition during the early Silurian (see below).

Tillites have been described from several parts of North Africa, including Libya (Bellini and Massa, 1980; Klitzsch, 1981), Algeria (Beuf et al., 1969), and SW Egypt (Beall and Squyres,

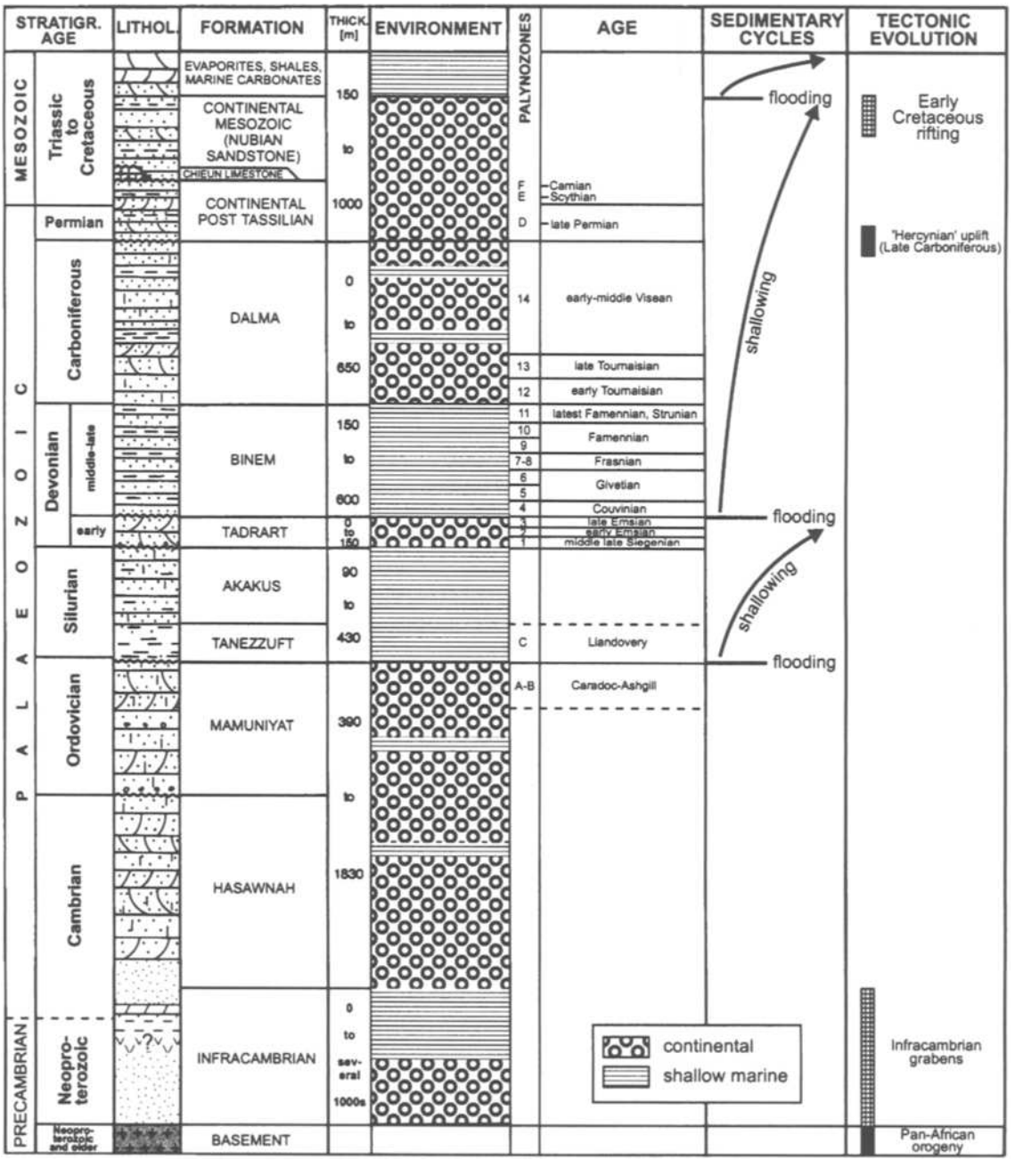


Figure 5. Stratigraphy of the Kufra Basin (modified after Bellini et al., 1991, and Grigagni et al., 1991). Palynozones based on results from AGIP wells A1-NC43 and B1-NC43 (Grigagni et al., 1991). Low-order shallowing upwards cycles modified after Turner (1991).

1980). Semtner and Klitzsch (1994) considered that the maximum extent of the late Ordovician glaciation may have been along the northern parts of the Murzuq and Kufra basins. However, typical glacial sediments have not been found in Jebel Dalma or Jebel Asba (our sections A and N, Fig. 4; Turner, 1980, 1991; Bellini et al., 1991). According to Brenchley et al. (1994), the late Ordovician glaciation lasted for a period of 0.5 to 1 Ma in the late Ashgill.

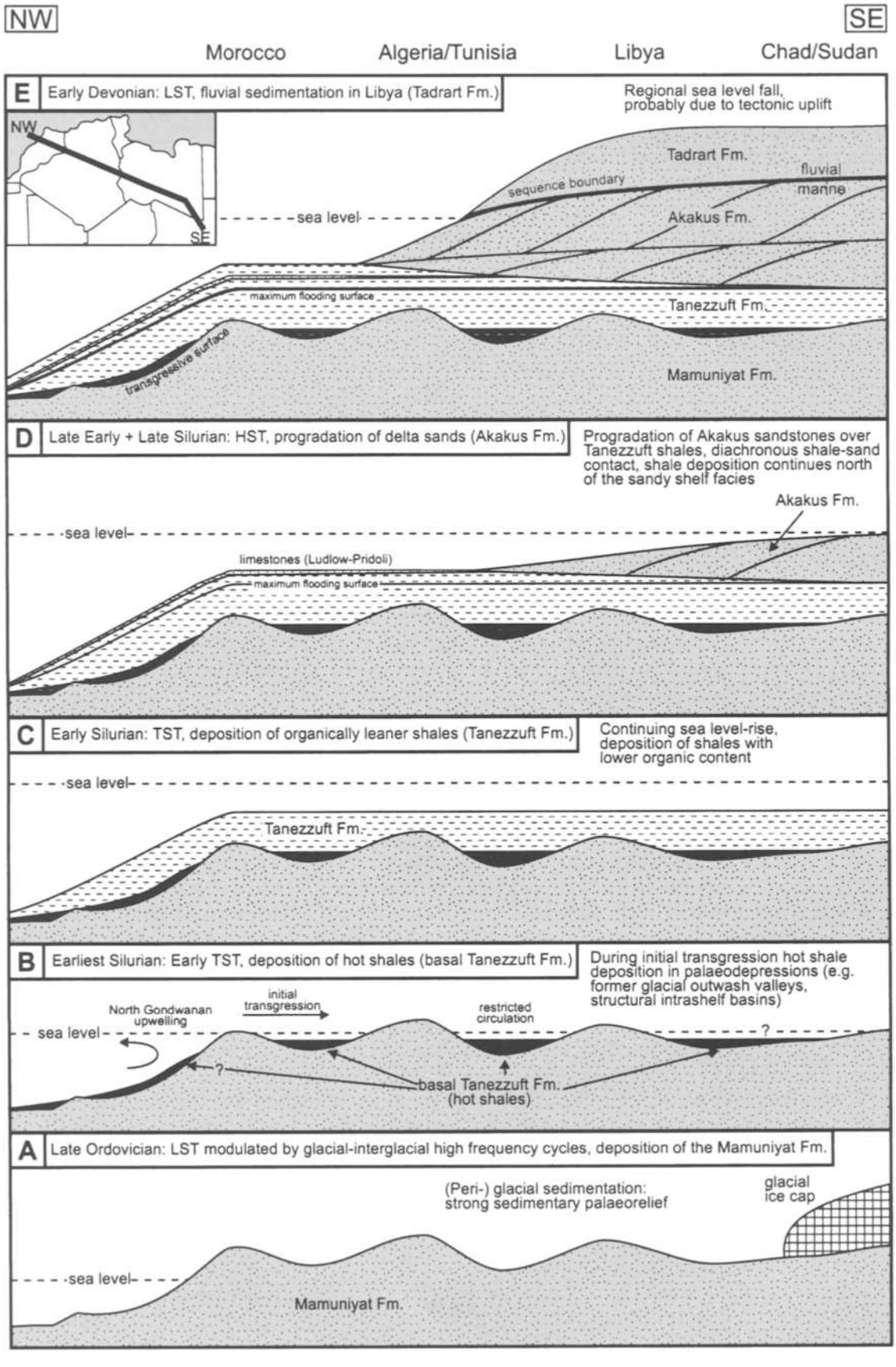
In areas directly affected by the late Ordovician glaciers, end moraines, ground moraines near the glacial front, and glacial deposits deformed by melting of buried ice may be responsible for most of the glacial palaeorelief. In periglacial areas, such as the Kufra Basin (at least the Libyan part), glacial outwash rivers may in places have deposited thick sand lobes (which may have also provided a nucleus for the early Silurian delta systems; see below) and may have incised deeply in other areas.

In analogy, a late Ordovician (peri-) glacial palaeorelief at the base of the lower Silurian shales was described from Saudi Arabia by Vaslet (1990: p. 155) and McGillivray and Husseini (1992: their Fig. 6). Vaslet (1990) documented deep late Ordovician valleys, probably incised by glacial outwash streams from the same area. Similar features were described by Smart (1998) from the base of the late Ordovician Mamuniyat Formation in the Murzuq Basin of SW Libya and by Ghienne and Deynoux (1998) from Mauritania. Driggs (1993) found a considerable palaeorelief which markedly influenced the lateral thickness distribution of overlying Silurian shales above similar, mainly fluvially filled late Ordovician channels in Algeria (width 2–8 km, depth 100–200 m). A late Ordovician glacial palaeorelief was also described by Bellini and Massa (1980: p. 50) from the Kufra Basin, although only inferred from present-day morphology (observed mainly in the central east, less obvious in central west, almost missing in the northeast).

In this study the Cambro-Ordovician succession was studied in sections A (Jebel Dalma) and N (Jebel Asba) (Figs. 3, 4). The unit is composed mainly of fine to medium, partly coarse, sandstones with intercalations of a few conglomeratic beds. Typical sedimentary structures observed in the Cambro-Ordovician strata include wave and current ripples, gravel lenses, conglomeratic lag deposits, load casts and shale intraclasts. Convolute bedding and similar dewatering structures are common at certain horizons. Soft sediment deformation, including large scale slumps (T. Glover, personal communication, 1998), is a characteristic feature in the Mamuniyat Formation of the Murzuq Basin, where it is interpreted to be a consequence of sediment instability caused by glacially related sea-level changes.

In section A (Fig. 4), metre-scale planar cross-bedding dominates the lower part and may represent a braided delta plain facies (facies 1 in Turner, 1980). The upper part of section A is dominated by medium-grained sandstones intensely bioturbated by *Skolithos* (also called 'piperock', e.g. Droser, 1991). As in many similar cases (Droser, 1991), a high-energy nearshore facies is assumed for the Cambro-Ordovician piperock in Jebel Dalma. A similar *Skolithos*-dominated succession was described by Vos (1981) from the Ordovician Hawaz Formation in the Gargaf Arch and also occurs in Cambro-Ordovician sandstones near Ghat (both Murzuq Basin, SW Libya).

Section N in Jebel Asba is located about 300 km south of section A (Figs. 3, 4) and includes a 20 m thick shale-dominated middle part, sandwiched between thick planar and trough cross-bedded sandstones. Abundant *Cruziana acacensis* were found in sandstone beds immediately overlying the shale unit (note revised species identification by Prof. Seilacher, contrasting earlier results reported in Lüning et al., 1999). *Cruziana* is typical of the distal shelf *Cruziana* facies of Seilacher (1967) and in the studied section marks the transition from muddy deeper shelf facies into upper shoreface sandstones. *Cruziana acacensis* is restricted to the Silurian (e.g. Crimes, 1981; Seilacher, 1991) and thereby indicates here that the thin shale unit in section N represents the Tanezzuft Formation, which is anomalously thin in this location. The underlying sandstones are consequently interpreted to be Cambro-Ordovician in age and were probably


NW
SE
Morocco
Algeria/Tunisia
Libya
Chad/Sudan
E
Early Devonian: LST, fluvial sedimentation in Libya (Tadrart Fm.)
Regional sea level fall, probably due to tectonic uplift
NW
SE
sea level
Tadrart Fm.
fluvial
marine
sequence boundary
Akakus Fm.
maximum flooding surface
Tanezzuft Fm.
transgressive surface
Mamuniyat Fm.
D
Late Early + Late Silurian: HST, progradation of delta sands (Akakus Fm.)
Progradation of Akakus sandstones over Tanezzuft shales, diachronous shale-sand contact, shale deposition continues north of the sandy shelf facies
Akakus Fm.
sea level
limestones (Ludlow-Pridoli)
maximum flooding surface
C
Early Silurian: TST, deposition of organically leaner shales (Tanezzuft Fm.)
Continuing sea level-rise, deposition of shales with lower organic content
sea level
Tanezzuft Fm.
B
Earliest Silurian: Early TST, deposition of hot shales (basal Tanezzuft Fm.)
During initial transgression hot shale deposition in palaeodepressions (e.g. former glacial outwash valleys, structural intrashelf basins)
North Gondwanan upwelling
initial transgression
restricted circulation
sea level
?
?
basal Tanezzuft Fm. (hot shales)
A
Late Ordovician: LST modulated by glacial-interglacial high frequency cycles, deposition of the Mamuniyat Fm.
(Peri-) glacial sedimentation: strong sedimentary palaeorelief
glacial ice cap
sea level
Mamuniyat Fm.

formed in palaeoenvironments ranging from upper shoreface to braided delta plain (facies 5 to 8 of Turner, 1980). The porosities of the medium to coarse-grained Cambro-Ordovician sandstones were determined in thin section to range between 12 and 19% (3% intergranular pores, 12% dissolution pores on average).

Fair to good amounts of TOC ranging from 1.5 to 1.9% were reported from shale interbeds in the Cambro-Ordovician succession of the deep AGIP wells A1-NC43 and B1-NC43. TOC values of up to 6.56 % were also recorded from an ?Ordovician 10 m-shale interval in A1-NC43. Locally, organic-rich Ordovician shales are also known from Algeria, e.g. in the Oued Mya and Mouydir basins (the El Gassi Shales, Azzel Shales and 'Argilles microconglomeratiques' in the Lower, Middle and Upper Ordovician, respectively).

Lower Silurian (Tanezzuft Formation)

The lower Silurian in North Africa and Arabia is represented by a widespread hemipelagic shale unit (e.g. Klitzsch, 1968), which was deposited during a major transgression (Ross and Ross, 1988). In many areas of North Africa and Arabia, hot shales typically occur at the base of this Silurian shale unit and form an important source rock for these regions (e.g. Jabour and Nakayama, 1988; Klemme and Ulmishek, 1991; Mahmoud et al., 1992; Aoudeh and Al-Hajri, 1995) (Fig. 6). These hot shales are interpreted to have been formed synchronously during the initial transgression in palaeodepressions (e.g. Aoudeh and Al-Hajri, 1995) (Fig. 7). Areal distribution of this organic-rich unit, therefore, is laterally highly variable. During the later stages of the early Silurian sea-level rise, palaeo-oceanographic conditions changed towards a more oxygenated state and organically lean shales were deposited.

The lower Silurian Tanezzuft Formation in the Kufra Basin consists of shales, which are green, red and light grey at outcrop, and interbedded wavy, rippled or hummocky cross-stratified light grey to reddish-brownish siltstone to fine sandstone beds. Exposures of this soft shale-dominated unit are rare. Inselbergs, as in section B (Jebel Dalma) and section M (Jebel Asba) (Figs 3, 4), with exposed shale sections of 14 m and 29 m respectively, are fortunate exceptions. In most cases, erosion has removed all shales down to a resistant horizon, such as the top Cambro-Ordovician sandstones or fine sandstone interbeds in the upper Tanezzuft succession. In Jebel Dalma, these resistant beds make up most of the wadi floor of the belt marked as 'Tanezzuft Formation' on the Geological Map of Libya 1:1 000 000 (IRC, 1985a).

Figure 6. General depositional model for late Ordovician to early Devonian sediments in North Africa with emphasis on lowermost Silurian hot shales. Systems tracts belong to a 2nd order sequence. (A) Deposition of lowstand sandstones during the late Ordovician glaciation produced a strong glacial and periglacial relief which was superimposed on larger, structural shelf undulations, probably inherited from the Pan-African and Infracambrian tectonic phases. (B) Melting of the glacial ice cap during the earliest Silurian led to a significant sea-level rise and rapid flooding of large areas of North Africa. Hot shale formation was restricted to the earliest phase of the transgression so that organic-rich deposits were only deposited in palaeodepressions, whereas palaeohighs lack the hot shales. (C) The later stages of the early Silurian sea-level rise eventually led to laterally uninterrupted (but now lean) shale deposition in most parts of North Africa. The uppermost shales in the extreme southeast were deposited during the latest TST. (D) After the rate of sea-level rise began to decline, highstand deltas started to build out from the northern Gondwanan coast into the shaly Silurian shelfal sea. The delta system had not reached the northwesternmost parts of North Africa by the early Devonian where pelagic limestones were deposited instead. (E) A significant sea-level fall during the early Devonian led to deposition of fluvial lowstand sandstones (which are underlain by a major sequence boundary) in Libya and neighbouring areas. In some areas, the period is marked by non-deposition and erosion, with underlying sediments partly removed down to Cambro-Ordovician levels.

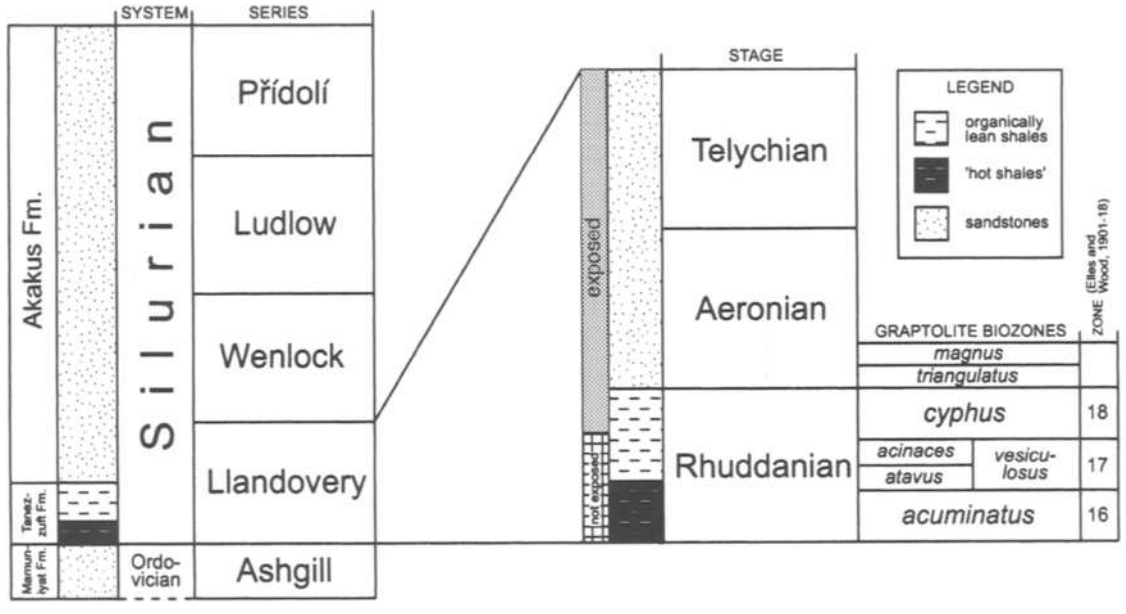


Figure 7. Silurian stratigraphy, graptolite biozones and stratigraphic position of potential hot shale unit in the Kufra Basin.

During an extensive reconnaissance trip to the westernmost part of the Jebel Dalma area, most inselbergs marked on the geological map (IRC, 1985a) as 'Tanezzuft Formation' were found to be Cambro-Ordovician sandstones. For example, a hard, characteristic *Skolithos* piperock (as in section A) was found at 25°37′29″ N, 22°53′03″ E. Correct stratigraphic interpretations of these outcrops can be found in the AGIP photogeology maps (Bellucci et al., 1976) and in Bellini et al. (1991). In the photogeology maps, however, many Tanezzuft areas are shown which during our geological reconnaissance work were found to be mostly light grey platy fine sandstones of the Akakus Formation or Cambro-Ordovician light grey medium sandstones bioturbated by *Skolithos*. The light colours may have misled the AGIP photogeologists to interpret all light coloured areas as Tanezzuft outcrops. It should be pointed out that the AGIP photogeology maps were not ground-controlled prior to completion.

Locally in Jebel Dama and Jebel Asba, the flat wadi floor consists of greenish shales that represent undefined levels of the Tanezzuft Formation. In some cases, there are exposures with 0.5 to 7 m vertical shale succession, some of which have been measured in detail (Table 1). However, a complete Tanezzuft section with contacts to both Cambro-Ordovician (Mamuniyat Formation) and middle/upper Silurian (Akakus Formation) sandstones is not exposed in the two areas studied. An exception is section N in Jebel Asba where, however, the Tanezzuft shales are anomalously thin (see above). Elsewhere, outcrops of the lower part of the Tanezzuft Formation, which are of utmost importance for any source rock evaluation in the Kufra Basin, have not yet been found. It is therefore not surprising that all 50 shale samples collected from the newly measured Tanezzuft sections (Table 1) yielded TOC values of less than 0.2%. The samples originate from the middle and upper parts of the Tanezzuft Formation, which is known to be organically lean in the neighbouring Murzuq Basin and elsewhere.

The basal Tanezzuft Formation may also be rarely exposed in either the eastern Tibesti area (Libya), the Chadian Silurian outcrops or the easternmost Ennedi Mountains in NW Sudan (see details in Lüning et al., 1999). One of the few places in the Kufra Basin where the basal part of the Tanezzuft shales has been accessed is the 60 m deep stratigraphic well KW-2 (Fig. 3), drilled by AGIP in 1975 in the Jebel Asba area close to our section M (Fig. 4). The drilling rig was

apparently located on top of an exposed Tanezzuft shale horizon that forms a flat shaly wadi floor at this locality. The exact stratigraphic position of this top level, and hence the original vertical distance to the now eroded top of the Tanezzuft Formation, is unclear. Cores in the middle of the shale unit at 18–19 m and 30–31 m apparently yielded the graptolite *Climacograptus medius* (Grigagni et al., 1991; specimen not re-examined as part of the present work), suggesting, if correctly identified, an uppermost Ordovician (Hirnantian) to lower Middle Llandoverian (early Aeronian) age (cf. Rickards, 1976) (Fig. 7). The top Mamuniyat sandstones lie at a depth of 50 metres. The Mamuniyat-Tanezzuft contact was cored for 0.2 m ('sample 5' in KW-2 log; Bellini, 1976), of which only 50% of the material was recovered. The next closest sample (another 'sample 5' in the KW-2 log, 1 m of fully recovered core) lies about 11 m above the first 'sample 5'. These two samples seem to represent the only material obtained from the basal Tanezzuft Formation. It is unclear if the organic richness of these samples was measured. Unfortunately, the largest part of the basal Tanezzuft interval remained uncored and apparently was not carefully studied in the cuttings. The KW-2 well was not petrophysically logged.

The general absence of basal Tanezzuft outcrops on the margins of the Kufra Basin and the small amount of existing subsurface data highlights as somewhat premature the statements given by some authors (e.g. Turner, 1991: p. 1722; Selley, 1997b; Boote et al., 1998; Keeley and Massoud, 1998) that the Tanezzuft shales lack all oil source rock characteristics in the Kufra Basin.

Thicknesses of lower Silurian shales in the Kufra Basin

Although several Tanezzuft shale sections are now available from all four Palaeozoic outcrop regions, it is still not feasible to compile reliable isopach maps even for these areas. Bellini et al. (1991) published thickness information for the Tanezzuft Formation in the three Libyan Palaeozoic outcrop areas of the Kufra Basin. For Jebel Dalma, they reported thicknesses from a few metres to 130 m, for Jebel Asba from less than 18 m to 82 m, and for the eastern Tibesti area a progressive increase in thickness from a few metres in the north (but erosively overlain by Mesozoic sandstones) to more than 100 m near the Chad border. However, our recent fieldwork in Jebel Dalma and Jebel Asba, does not support the thickness data published by Bellini et al. (1991) due to the poor outcrop discussed in detail above.

The middle and lower parts of the Tanezzuft Formation are not exposed in either area and the total thickness of the formation cannot be properly determined. The Tanezzuft sections measured by AGIP in the Jebel Dalma area were not published, with the exception of thickness data and coordinates (Bellini and Massa, 1980: their Table 2). Of the three Tanezzuft sections logged by AGIP in Jebel Dalma, two (C-9, 56 m of shales; C-24, 70 m of shales) seem to lack the lower part of the Tanezzuft, whereas in one case (C-8, 3 m of Cambro-Ordovician sandstones, 110 m of shale) the Mamuniyat-Tanezzuft contact zone is apparently included in the section. Unfortunately, the outcrops of the AGIP sections in Jebel Dalma were not located during our fieldwork and, consequently, could not be rechecked. Our closest sections are E (6 km NE of C–24), F and G (4 km SE of C-9), and C (1.5 km S of C-8) (Figs 3, 4, Table 1). Without having studied the exact localities of the AGIP sections it remains unclear how much interpolation between outcrops is included in the AGIP data. It has to be noted that straightforward thickness extrapolations are complicated in Jebel Dalma because of hundred metre-scale block faulting (see below).

A 260 m thick shale package with a total of 55 m of sandstone intercalations in the Oasis A1–71 well (Fig. 3), located just north of the Kufra Basin, was previously misinterpreted as representing the Tanezzuft Formation (e.g. Bellini et al., 1976). However, based on correlation with the neighbouring D1–71 well, a Cambro-Ordovician age is more likely (FJA, 1995: plate

Table 2. Minimum thicknesses of the lower Silurian Tanezzuft Formation for different outcrop areas of the Kufra Basin. Note that a full Tanezzuft section does not appear to be completely exposed in most areas

Area No.	Proven minimum thickness of Tanezzuft Fm.	Degree of Tanezzuft coverage	Section/well	Coordinates of section	Reference
Jebel Dalma (Libya)	14 m	lower Tanezzuft shales not exposed	section B	25°50'45'N 23°36'27'E	Lüning et al. (1999)
Jebel Asba (Libya)	54 m	well top in mid Tanezzuft level	shallow stratigraphic AGIP well KW–2	22°56'50'N 24°19'42'E	Bellini (1976)
Tibesti Mountains (Libyan part)	50 m	lower Tanezzuft shales not exposed	AGIP field section TK–14	22°22'55'N 19°51'35'E	Bellini (1976)
Tibesti Mountains (Chadian part)	80 m	lower Tanezzuft shales not exposed	field section Do3	ca. 22°40'N ca. 19°30'E	De Lestang (1968)
Borkou Mountains (Chad)	80 m	lower Tanezzuft shales not exposed	field section 15a	ca. 18°30'N ca. 19°00'E	De Lestang (1968)
Ennedi Mountains (Chadian part)	19 m	lower Tanezzuft shales not exposed	Gourgouro-Azrenga field section	ca. 17°25'N ca. 23°50'E	De Lestang (1968)
Ennedi Mountains (Sudanese part)	40 m	lower Tanezzuft shales not exposed	field survey	ca. 17°40'N ca. 24°10'E	Klitzsch et al. (1993)

12). Palynological data for the A1–71 well seems not to have been collected. An isopach map for the Libyan part of the Kufra Basin based on seismic sections (Bellini et al., 1976) includes the whole succession from base Silurian to top Carboniferous and therefore does not contain useful information about lower Silurian shale thickness trends. However, it is interesting to note that no major southward thinning of the total pre-Silurian (probably even pre-upper Silurian) strata was recorded along a 170 km long NNE-SSW trending seismic line (Ku11: Bellini et al., 1976).

A critical re-evaluation of the existing stratigraphic database yielded minimum thicknesses for the Tanezzuft shales as illustrated in Table 2 (location map in Fig. 3). It is assumed that the total Tanezzuft shale succession probably often reached 100 m and more. When compared with neighbouring basins, the maximum Tanezzuft thickness of around 100 m (?) in the Kufra Basin is significantly less than in the Ghadames (700 m, Klitzsch, 1995) and Murzuq (500 m, El-Arnauti and Shelmani, 1988) basins. We assume that only part of this difference may be explained by the only slightly higher position of the Kufra Basin on the palaeoshelf. We interpret that the earlier onset of the sandy delta progradation in the more proximal Kufra Basin (relative to the Ghadames and Murzuq basins) may have resulted in a much shorter period of shale-dominated deposition (Fig. 6). A significant part of the greater thicknesses in the Ghadames and Murzuq basins may be a consequence of longer, rather than more rapidly accumulating, shale sedimentation. This assumption is supported by the observation that the greatest Tanezzuft thicknesses in the three basins occurs in the Ghadames Basin, which according to graptolite data (Berry and Boucot, 1973) was the last of the three basins to be reached by the sandy progradational facies (Fig. 6). Unfortunately, there are no high resolution biostratigraphic graptolite or chitinozoan data for the entire Silurian shale succession in these three basins. This would be necessary to compare the thicknesses for the lower, middle and upper Llandovery, or even on a biozone scale.

The relationship between the thickness of Silurian shales and distance from the sandy progradational system (which on the undulating North African palaeoshelf is not equivalent to palaeodepth) has also to be considered when evaluating the presence or absence of lower Silurian hot shales in the Kufra Basin. It becomes clear that the comparatively thin development of the Tanezzuft shales in the Kufra Basin in general cannot be used as evidence for the absence of hot shales in this basin, because reduced thickness may simply reflect differences in the post-hot shale depositional history. In order to better understand the hot shale distribution it is important to determine whether some parts of the Kufra Basin were structurally low enough to have been flooded during the initial, earliest Llandovery transgression (during which the hot shales were deposited) or whether the whole Kufra Basin became submerged only later, when palaeo-oceanographic conditions had changed and only organically lean shales accumulated (Fig. 6). Areas with hot shale deposition are not necessarily characterized by increased shale thicknesses.

Tanezzuft – Akakus transition

The transition between the Tanezzuft shales and the overlying Akakus sandstones is gradual almost everywhere in the Kufra Basin and neighbouring areas. Frequency, thickness and grain size of intercalated silt- and sandstone beds in the upper (shale-dominated) 'Tanezzuft' succession steadily increase upward until only thin, and finally no shale interbeds occur in the lower (sand-dominated) 'Akakus' succession (see also Selley, 1997a). Due to this gradual transition, it is often impractical to define a particular horizon as the 'Tanezzuft-Akakus boundary'. This also has implications for interpretations of small differences in isopach data.

Informal reference to a Tanezzuft-Akakus transition zone ('Zone de Passage'; e.g. Freulon, 1964) may be preferred.

HYDROGEOLOGY

The Phanerozoic succession in the southern part of the Kufra Basin (NE Chad) contains three aquifers (Hissene Mahamoud, 1986). These comprise a Cambro-Ordovician aquifer (capped by Silurian shales), an upper Palaeozoic aquifer (capped by Carboniferous shales) and a Mesozoic Nubian aquifer. The Mesozoic Nubian aquifer serves as an important water reservoir for the Kufra Agricultural Project (e.g. Fisk and Pennington, 1976) and the eastern branch of the Great Man-made River Project (e.g. Salem, 1992). The Cambro-Ordovician and upper Palaeozoic aquifers are reported to be overpressured, except at the basin margins (Hissene Mahamoud, 1986). In the AGIP-wells A1-NC43 and B1-NC43 (W and S of Kufra) the whole Palaeozoic succession is freshwater-bearing, with salinity values varying between < 100 and 750 ppm total dissolved salts (AGIP Final Well Reports A1-NC43 and B1-NC43, in Ahmad, 1983; see also cross section in Pallas, 1980: his Figure 4). Correspondingly, Pallas (1980: p. 575) reported a salinity of less than 1000 ppm for the groundwater in the Cambro-Ordovician aquifer NW of the Kufra Basin in Tazerbo. Whilst the Cambro-Ordovician and Silurian hydrocarbon reservoirs of the deeper parts of the basin are possibly protected from flushing, smaller-scale traps around the basin flanks run the high risk of being flushed (Ross, 1985; Boote et al., 1998: 61). However, significant commercial production does occur in the Murzuq and Illizi basins in close association with fresh water.

SUMMARY OF THE PETROLEUM POTENTIAL

On the basis of a critical re-evaluation of existing published and unpublished data, new field work, and analogies with neighbouring basins it is suggested that future exploration efforts in the Kufra Basin should concentrate on investigating two potential plays. An Ordovician-Silurian play concept is characterized by porous Ordovician sandstones as reservoir rocks, lower Silurian shales as cap rocks, and structural traps in fault blocks which are possibly related to Early Cretaceous extension. The source rock potential of the lower Silurian shales remains unclear, because the basal, perhaps locally 'hot', part of the lower Silurian shales has not been adequately studied due to lack of exposure. Similar Ordovician-Silurian plays have been tested sucessfully in the geologically very similar Murzuq Basin.

Two deep basin centres with present-day depths between 3500 and 4000 m (Fig. 3), as well as even deeper Infracambrian rift grabens, have been identified in the Kufra Basin and are interpreted to provide sufficient maturity levels for potential Silurian source rocks. The Infracambrian grabens indicate the possibility of an Infracambrian development which may show a somewhat similar facies to organic-rich Infracambrian successions in Oman (where the unit represents a major source rock) and in Algeria.

A significant number of review reports have evaluated the petroleum potential of the Kufra Basin (e.g. Bezan, 1991; ECL, 1989; FJA, 1991, 1995; Gumati et al., 1996; Khattab, 1981; Klitzsch, 1995; Masera I.O.M., 1988; Ross, 1985; Scott Pickford plc., 1992). All emphasized the unsolved source rock question. The present contribution suggests new ways of addressing the source rock problem that may lead to a more rigorous evaluation of the petroleum potential of the Kufra Basin.

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CHAPTER 9

Geology and Hydrocarbon Occurrences in the Murzuq Basin, SW Libya

K. ECHIKH[1] and M.A. SOLA[2]

ABSTRACT

The cumulative effects of tectonic movements of Palaeozoic, Mesozoic and Cenozoic ages have produced the present-day structural framework of the Murzuq Basin. As a consequence, there are a wide variety of structural styles, fault patterns and trap types, while depocentres have tended to migrate with time. Regional lineaments are probably related to late Precambrian Pan-African fault systems, which largely controlled the early Palaeozoic structural and depositional evolution of this basin. Early Palaeozoic time was characterised by the presence of NW-SE trending linear lows and highs, clearly indicated by thickness variations in the Cambro-Ordovician and Silurian succession. Present-day structuring is related mostly to Hercynian compressional movements, particularly active in the northwestern parts of the basin.

Some 60 exploratory wells have been drilled in the basin, resulting in the discovery of 15 oil pools with around 4000 mmbl of oil in place. Most wells are located on the structurally highest elements in the basin and deeper portions are untested, largely because of the presence of extensive sand dune 'seas'. Finds to date include nine commercial and six technical discoveries. These are all in Upper Ordovician Mamuniyat sandstone reservoirs, sourced by Lower Silurian Tanezzuft shales. Potential younger traps in the Devonian sandstones have as yet only given sub-commercial oil finds in some areas. The main trapping mechanism is structural, often reflecting glacially related palaeotopographical factors, but other subtle trap types may occur, mainly related to stratigraphical truncation and to permeability barriers.

Proven hydrocarbon distribution in the basin reflects the interaction of several factors such as regional structural evolution, trap geometry and age, reservoir quality both in terms of lateral facies variations and diagenetic changes and – not least – source rock quality and maturity. Migration pathways are controlled by reservoir facies variations, the Tanezzuft seal's facies and continuity and by the fault system distribution. In areas where the shaly Bir Tlacsin Formation is developed, this unit seems to act as a barrier for effective and direct communication between source rock and reservoir.

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INTRODUCTION

The studied area contains a large intracratonic basin (Fig. 1) covering an area of over 350 000 km^2. It is bounded to the north by the Gargaf Uplift, to the west by the Tihemboka Arch and to the east by the Tibesti Uplift. To the south, it extends into Niger and is there known as the Djado Basin. The sedimentary section in the central part of the basin has a thickness of 3500 m, comprised mostly of Palaeozoic and Mesozoic rocks. The oldest Palaeozoic rocks outcrop on the flanks of the basin. Cretaceous sediments form an escarpment in the northern and eastern parts, while the central part is covered by the dunes of the Murzuq Sand Sea.

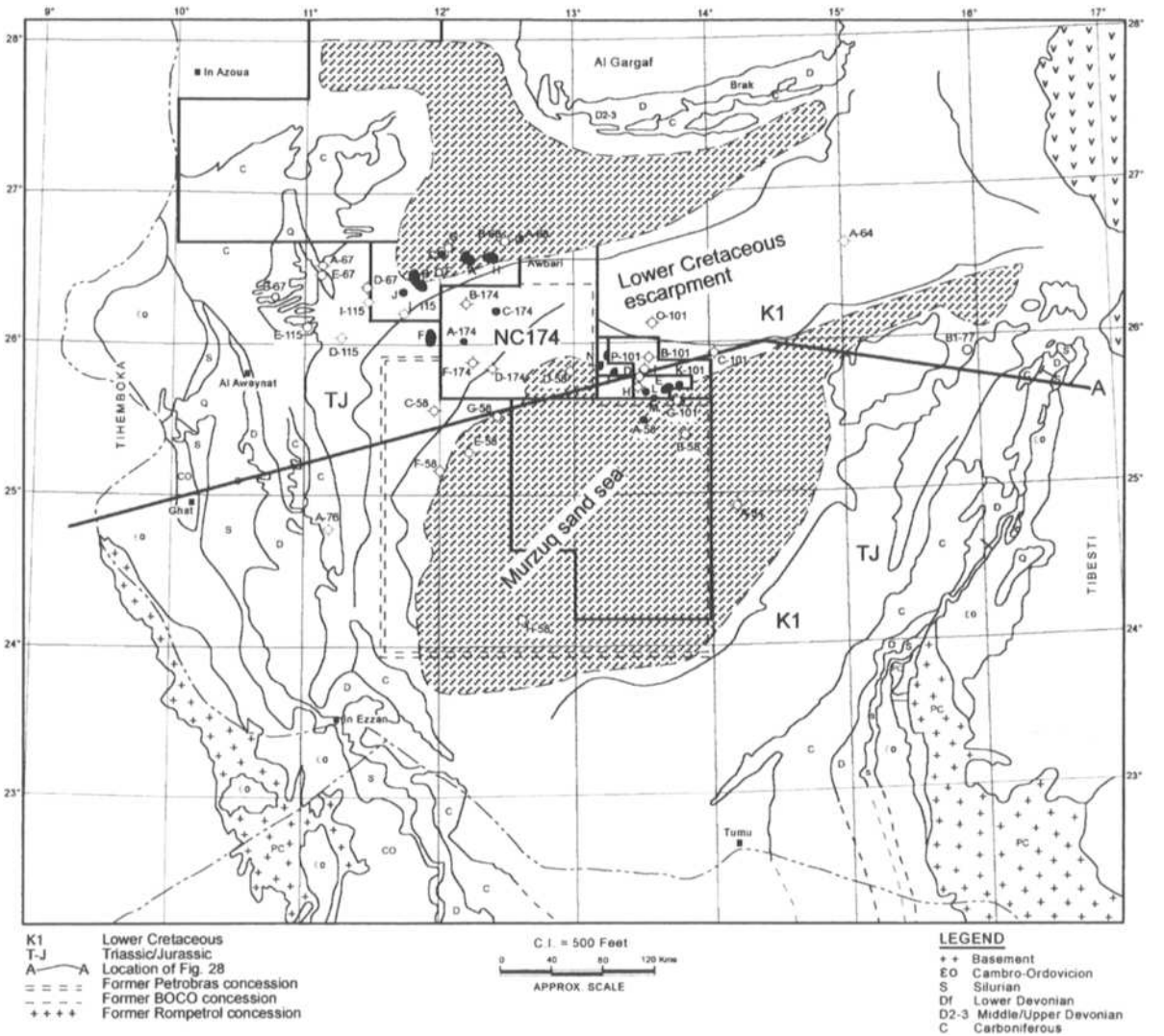
During the last thirty years, geological studies have been carried out by different authors, each dealing with a specific area or a concession and based principally on outcrops or on limited subsurface data. The first syntheses based on new seismic and well data were completed by Braspetro (1984), BOCO (1984), Echikh and Suleiman (1984) and Rompetrol (1986). Later, Echikh (1992a) prepared a regional study based on all previous data acquired by the operating companies. At the present time, after recent exploration successes, it is important to summarise our knowledge of the petroleum geology of this still poorly explored basin. This chapter attempts to integrate all previous studies into a regional synthesis, with emphasis given to factors controlling the hydrocarbon habitat, based on past exploration experience and on dry hole analyses. For the reader unfamiliar with the geology of the Murzuq Basin, the stratigraphy and structural setting of the area will first be briefly reviewed.

STRATIGRAPHICAL SETTING

The first geologists working in western Libya established the broad stratigraphic framework of the Murzuq Basin (Desio, 1936; Lelubre, 1946; Freulon, 1954; Wells, 1955; Brady, 1957; Howard, 1957; Thompson, 1960; Collomb, 1962; Klitzsch, 1963, 1981; Hoen, 1968; Bellini and Massa, 1980). Internal company reports and resultant publications (Castro et al., 1985; Pierobon, 1991) have represented important steps in the advancement of our knowledge of this basin, although the precise ages of some formations and their boundaries are still not well defined. Log correlations are good in the north and northwestern parts of the basin, but difficulties arise in its central and southern portions, where Palaeozoic rocks are characterised by a sandier facies with frequent local erosional unconformities. The surface and subsurface sections use different stratigraphical nomenclatures defined by the operating companies and by the Libyan Industrial Research Centre respectively. There is an urgent need to establish a common nomenclature valid for the whole basin. A stratigraphical chart, based on published work compiled by Echikh (1992a) is presented in Fig. 2. A detailed stratigraphical analysis is however out of the scope of this paper and emphasis will be placed only on those formations of major importance for hydrocarbon exploration.

Ordovician

The typical log response of the Mamuniyat Formation and of the underlying Melaz Shuqran and Hawaz formations is illustrated in Fig. 3. This general subdivision is valid not only for the Murzuq Basin but also for the Ghadames Basin to the north and the Illizi Basin to the west. Regional sedimentological work carried out recently (Blanpied et al., 2000; McDougall and Martin, 2000) has led to a better understanding of the lithostratigraphy of the Ordovician succession. Regional correlations of the Ordovician units (Fig. 4) in the NW corner of the


In Azoua
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Brak
Awbari
Lower Cretaceous escarpment
NC174
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Murzuq sand sea
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Ghat
Tumu
TIBESTI
Ubari
Sebha
Waw an Namus
Edri
Zella
Hasawnah
Dirj
Mourizidie
Ubari Sand Sea
Idehan Murzuq
Idehan Ubari
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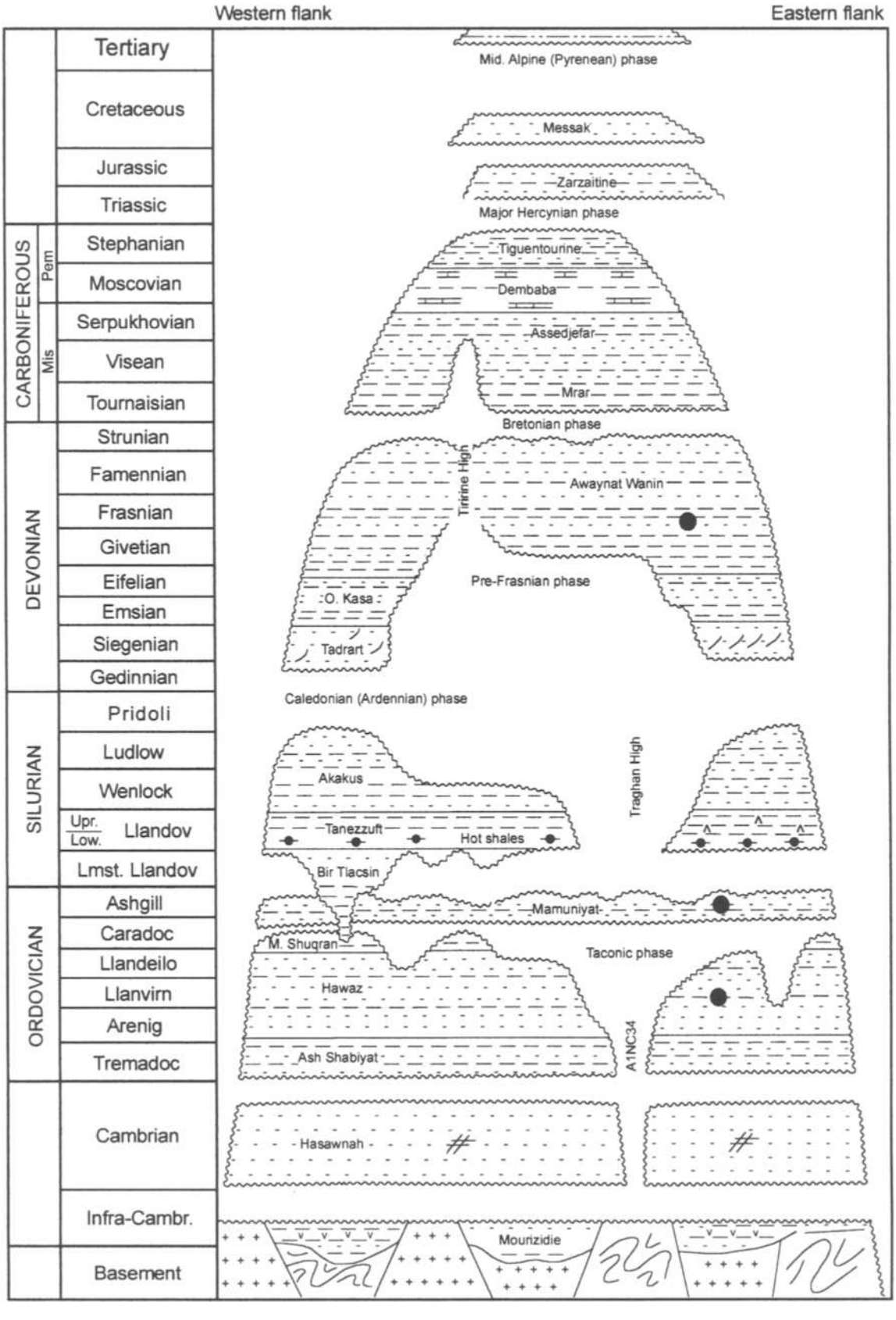


Figure 2. Stratigraphic chart, Murzuq Basin.

Murzuq Basin are made difficult by rapid facies changes and the effects of Taconic tectonic events, with superimposed effects of the late Ordovician glaciation of North Africa. As a result of these events the Melaz Shuqran shales were partly (well D1-NC115) or completely (well H1-NC115) eroded from some palaeohighs in the area. A thin shaly radioactive unit in the Mamuniyat Formation provides a relatively good marker in log correlations; this was deposited unconformably over the lowermost Mamuniyat sands or directly on the Melaz Shuqran Formation.

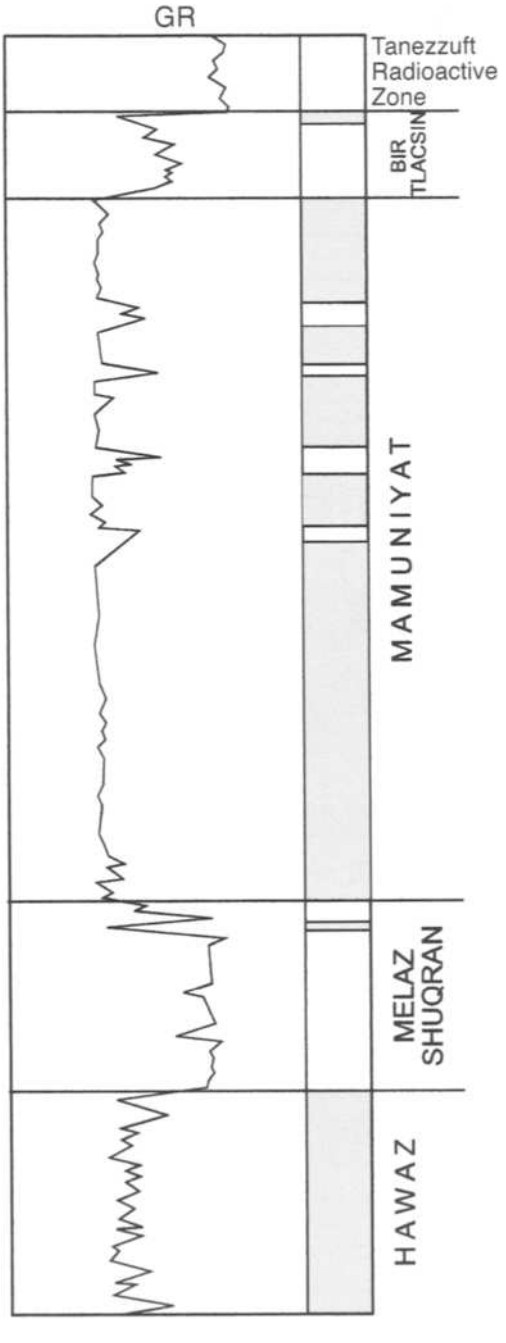


Figure 3. Typical log response of the Ordovician formations; shaded section represents potential reservoirs.

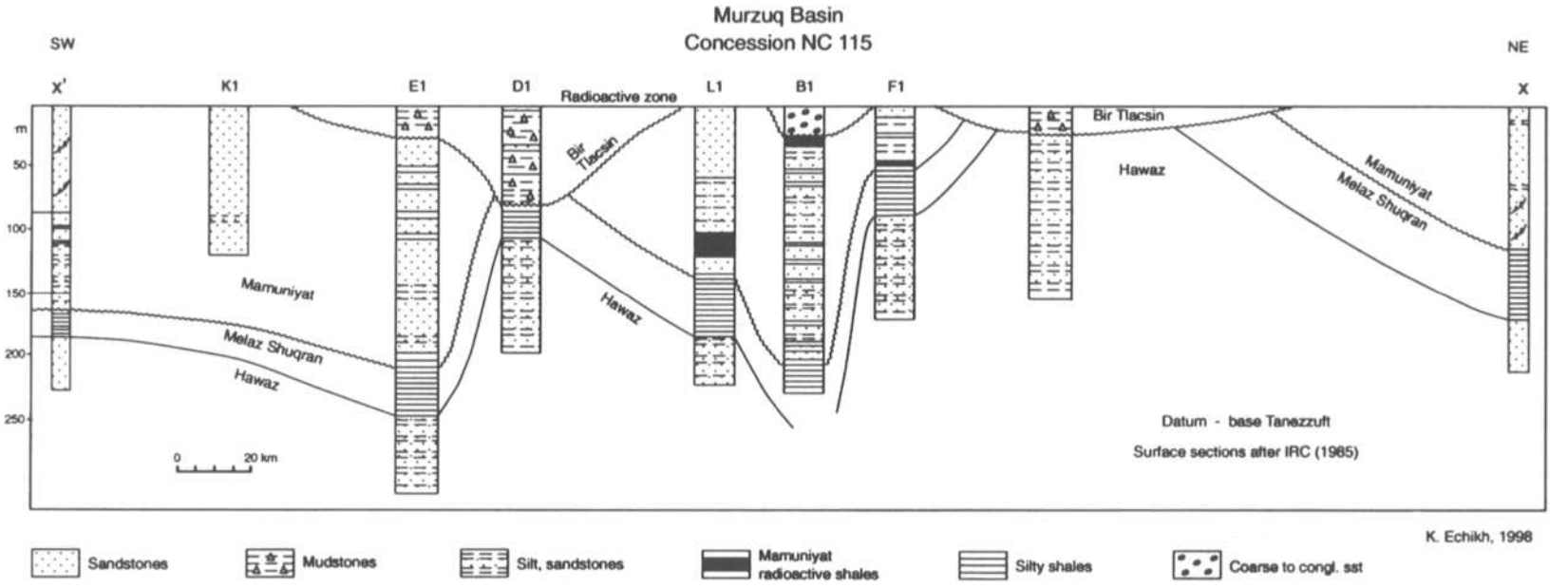


Figure 4. Geological cross section through concession NC115, showing the effects of Ordovician erosion and the depositional pattern of the Bir Tlacsin Formation in deep troughs. Note the presence of the Mamuniyat basal radioactive zone unconformably overlying various Melaz Shuqran units. Line of cross section X–X′ is shown in Fig. 5.

Hawaz Formation

The Hawaz Formation represents the onset of the first major Palaeozoic marine transgression in the area. It consists of alternating fine to medium grained, often quartzitic, sandstones with silty shales, characterised by the presence of vertical tubes of the trace fossil *Tigillites*. The formation's geographical thickness variation is unknown, but values of 60 to 120 m have been reported in outcrops on the basin's northern margins (Parizek et al., 1984).

Melaz Shuqran Formation

This formation represents the highstand of the marine transgression initiated during deposition of the Hawaz Formation. It consists of grey silty shales with dropstones (McDougall and Martin, 2000) interpreted as diamictites, apparently representing sediments deposited in a periglacial environment. The observed outcrops show thickness changes ranging up to 60 m, although the formation is absent due to post-depositional erosion in many areas (Parizek et al., 1984; Radulovic, 1984a, b; Davidson et al., 2000). This formation is well developed in concession NC115 (Fig. 4) where its thickness varies between 30 and 50 m. A sandier facies developed in the central parts of the Murzuq Basin (concessions NC58 and NC101) makes it difficult to distinguish the Melaz Shuqran Formation in that area.

Mamuniyat Formation

Regionally, the Mamuniyat sandstones seem to be present throughout the whole Murzuq Basin, except for eastern areas where data from outcrops (eastern Gargaf, Dur Al Gussah) and a few wells (A1–77, B1–77, and A1–64) indicate its absence. Most wells in concession NC115 have penetrated the whole Ordovician section down to the Hawaz Formation. Wells in concessions NC58 and NC101 reached only the uppermost part of the Mamuniyat Formation, so that its total development there is not known. In Concession NC115, this formation is characterised by rapid thickness variations ranging between 50 and 150 m.

Regional log correlations and core macroscopic observations of the Mamuniyat Formation indicate the presence of four main lithofacies in the Murzuq Basin (Fig. 5) The most common lithofacies is a silica-cemented fine grained, hard, often quartzitic sandstone with vertical to subvertical fractures. This lithofacies dominates the central parts of the basin (Concession NC101, partly NC58). The second lithofacies occurs in southwestern areas around wells F1, E1, G1 and H1-NC58, where the Mamuniyat Formation is characterised by a somewhat siltier facies. The third facies zone dominates northwards from the NC115 oil fields, extending toward the Ghadames Basin. This consists of sandstones and shales deposited in shallow marine environments. The fourth lithofacies has a limited extent, as yet found only in the NC115 B field, and informally called 'the periglacial horizon'. It consists of coarse to granular poorly cemented sandstones.

Lack of data on facies associations and their three dimensional relationships makes it difficult to define a coherent sedimentary model for the Mamuniyat Formation. However, works by different authors (Klitzsch, 1963; Parizek et al., 1984; Radulovic, 1984a, b; Castro et al., 1985; Massa, 1988; Blanpied et al., 2000; McDougall and Martin, 2000) on the Gargaf Uplift and the western flanks of the Murzuq Basin, suggest that the Mamuniyat sediments were deposited in various fluvioglacial, deltaic and shallow marine environments.

Silurian

The most complete Silurian section has been penetrated in the Ghadames Basin, where various operating companies in specific concessions or areas have carried out many studies. The first

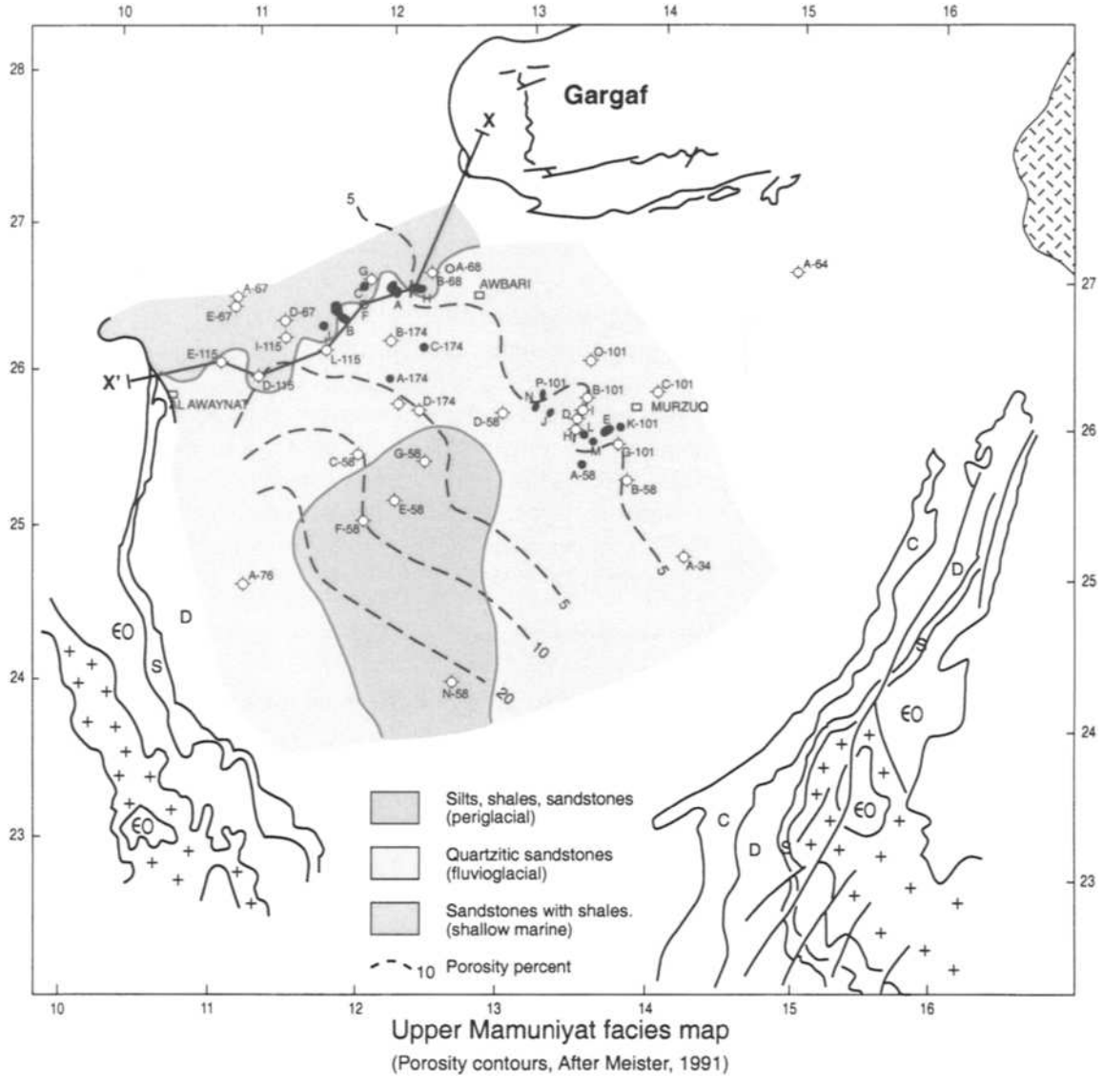


Figure 5. Facies and porosity map of the upper Mamuniyat reservoir (porosity contours modified from Meister et al. (1991).

basin-scale synthesis of the Silurian in the Ghadames Basin was carried out by NOC (Echikh and Suleiman, 1984). Bellini and Massa (1980) and Massa (1988) demonstrated the regional S to N diachronism and the prograding character of the Silurian sediments in western Libya. The Silurian succession in both the Ghadames and Murzuq basins comprises three lithological units: the Bir Tlacsin, Tanezzuft, and Akakus formations.

Bir Tlacsin Formation

A special problem related to the Upper Ordovician and the Ordovician /Silurian boundary relates to the interpretation of the Bir Tlacsin Formation (Echikh, 1992b). The Bir Tlacsin Formation represents a transitional lithofacies between the Mamuniyat Formation sandstones

and the Silurian Tanezzuft shales. Massa and Jaeger (1971) proposed a distinction between the Tanezzuft Formation and an underlying basal transitional zone, which they named the Iyadar Formation (based on exposures in the southern Jabal Akakus) and dated to the early Llandovery. Radulovic (1984a, b), however, noted that this unit is biostratigraphically defined and does not represent a mappable rock unit. In contrast, the Bir Tlacsin Formation is well developed as a clear lithological unit in the area of the same name in the Ghadames Basin. The formation has been correlated throughout the Ghadames Basin (Echikh, 1992b) and Echikh (1998) discussed relationships with its equivalent 'Argiles microconglomeratique' in southern Tunisia and Algeria. A similar development has been penetrated by wells in the Murzuq Basin. The identification of this formation as a separate unit is also important – as discussed later – as it seems to affect the hydrocarbon accumulation potential of underlying reservoirs. The age of the Bir Tlacsin Formation is however still uncertain and may vary locally, so that in some areas deposition of this or equivalent units may have started already in the latest Ashgill, while elsewhere the development seems to have a clear early Silurian aspect. No clear datings have yet been presented for the Murzuq Basin.

The typical log response of the Bir Tlacsin Formation is illustrated in Fig. 6. The top is easy to identify at the base of the Tanezzuft hot shale zone. The base may be difficult to clearly distinguish from the Mamuniyat Formation, particularly close to palaeohighs where the basal shales are silty or sandy. However, these shales' distinct log response, with low separation between shallow and deep resistivities, provides a good criterion for distinguishing the Bir Tlacsin Formation from the underlying Mamuniyat sandstones.

Distribution and thickness variations of the Bir Tlacsin Formation in western Libya follow the same SE-NW trends as those indicated by the underlying Cambro-Ordovician units. This suggests a palaeotopography that was largely a result of erosion caused both by tectonic activity and by the late Ordovician North African glaciation. The Bir Tlacsin Formation was apparently deposited in the remnant relief of the eroded palaeovalleys not completely filled by Mamuniyat sands (Figs. 7 and 8). Maximum thickness of the formation in the Ghadames Basin is 100 m. In the Murzuq Basin the thickest Bir Tlacsin development is found in wells D1-NC115 and E1-NC58 (130 m and 65 m respectively).

The typical Bir Tlacsin facies development consists of shales, often with abundant coarse to granular sand grains, overlain by one or two thin sand units varying from 6 to 15 m thick. In some areas, especially close to palaeohighs (such as the Traghan High), the total formation thins rapidly and its lower parts become very silty, making the distinction from the underlying Mamuniyat Formation difficult. In Braspetro correlations, the Bir Tlacsin Formation is clearly considered as belonging to the lower part of the Tanezzuft Formation. For example, Pierobon (1991) noted "the basal Tanezzuft shows a gradational basal section of interbedded shales and sandstones which would have been derived from reworking of the Cambro-Ordovician substratum under wave and tide action." Present interpretations suggest the Bir Tlacsin Formation as consisting of muddy debris flow sediments. In well D1-NC115, core macroscopic observations indicate that it consists of dark grey greywackés with coarse to granular quartz grains floating in a mud matrix. This lithofacies is similar to the Algerian 'Argiles Microconglomeratiques', which are represented by black mudstones with pebbles, rounded clasts and quartz grains. Fekirine and Abdallah (1998) subdivided the Algerian Bir Tlacsin equivalent into transgressive deposits (lower shales) and highstand upper sands. They suggested that the lower sequence boundary should be related to major glacial events and associated lowstand, whereas the whole sequence represents the fill of a glacio-eustatic cycle. Blanpied et al. (2000) consider their 'Upper Mamuniyat Sand Unit' – here thought to be equivalent to the Bir Tlacsin sandstones – as representing wave dominated shoreface sediments deposited during the basal Silurian transgression.

Tanezzuft Formation

Melting of the late Ordovician ice cap led to eustatic sea level rise, culminating in a highstand with deposition of the Tanezzuft Formation shales. The thickness distribution of these shales (Fig. 9) suggests a depocentre over the western flanks of the present basin and extending towards the present Idhan depression, with maximum thicknesses reaching 1500 feet. Further to the east,

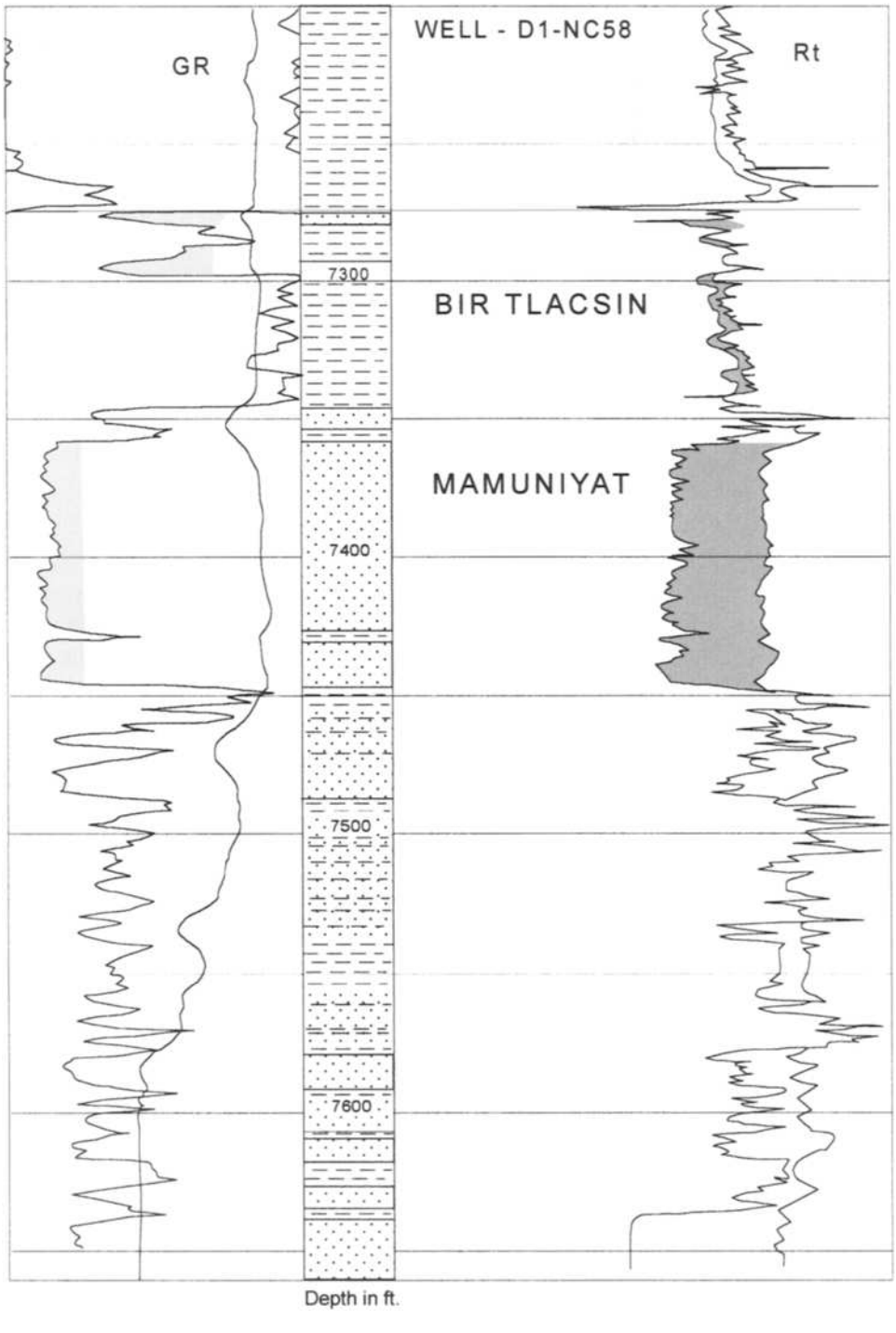


Figure 6. Typical Bir Tlacsin log response. Note the different resistivity log responses of the Mamuniyat and the Bir Tlacsin formations. The latter has a similar response to that of the Tanezzuft shales.

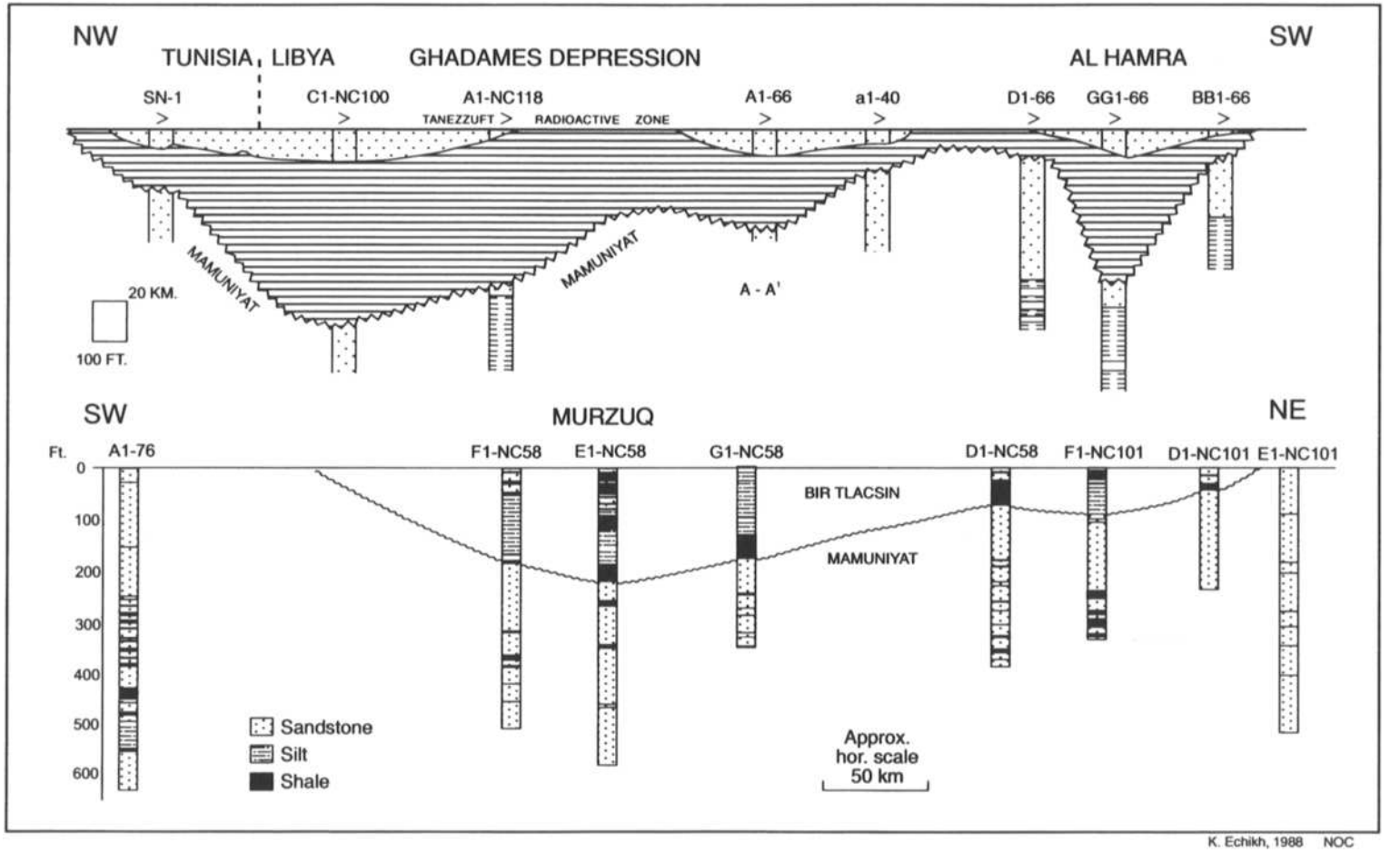


Figure 7. Geological cross-sections in the Ghadames and Murzuq basins showing the Bir Tlacsin Formation's distribution. Note the deep troughs filled with Bir Tlacsin Formation, while this unit is missing over the palaeohighs. Lines of cross sections shown in Fig. 8.

the Tanezzuft shales thin progressively towards the Traghan High (concession NC101), where thicknesses do not exceed several hundred feet. The formation thins and disappears eastwards, the zero line passing between wells K1, E1, B1-NC101 and A1-NC101. The formation has not been encountered in well A1–77 or in other boreholes in the Sebha map-sheet area (Seidl and Röhlich, 1984). However, further to the east, in the northern parts of the Dur Al Gussah area, Mamgain (1980) estimated a 260 ft thick development of the formation based on small

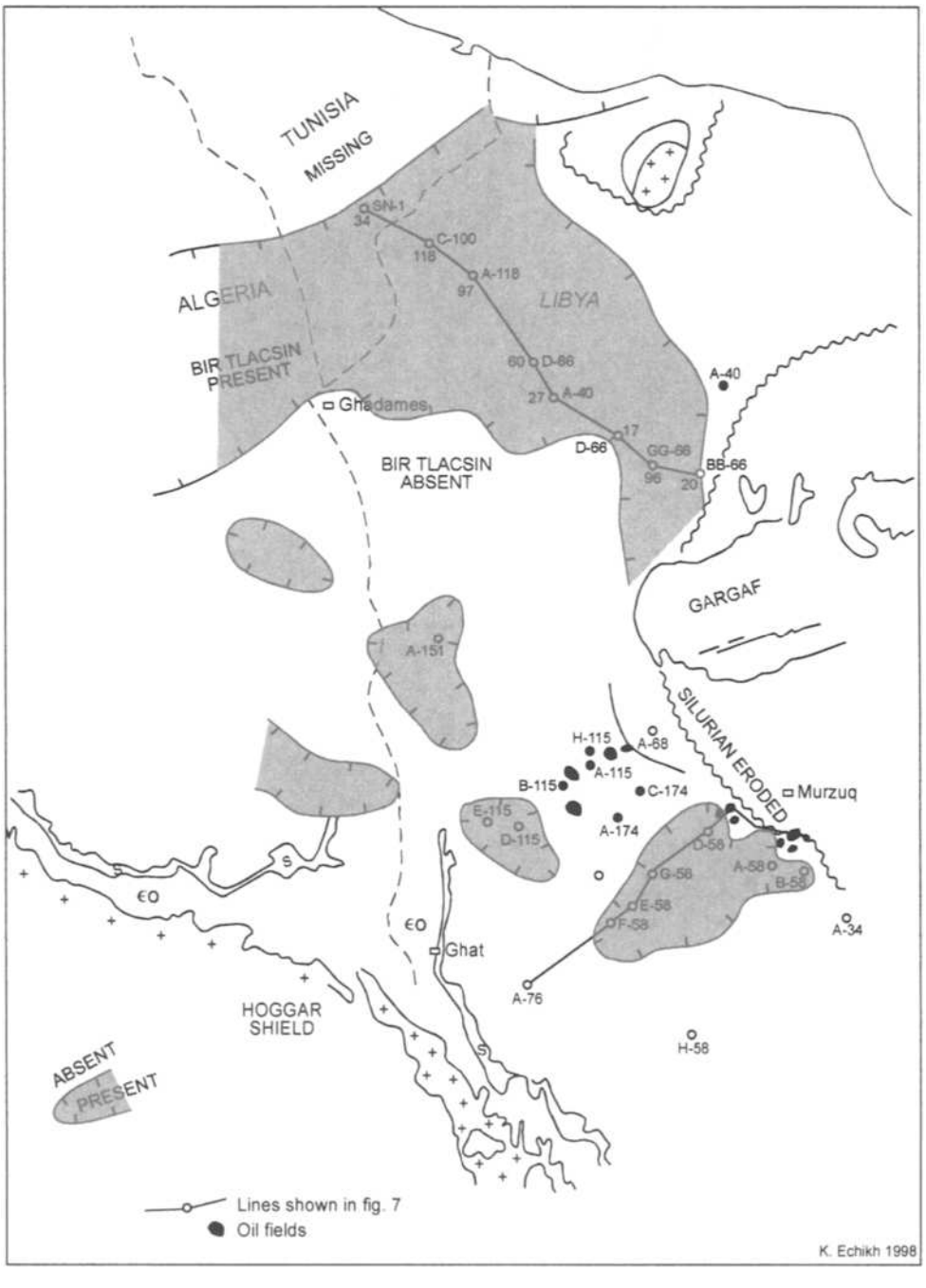


Figure 8. Distribution of the Bir Tlacsin Formation in western Libya (with lines of cross-sections shown in Fig. 7).

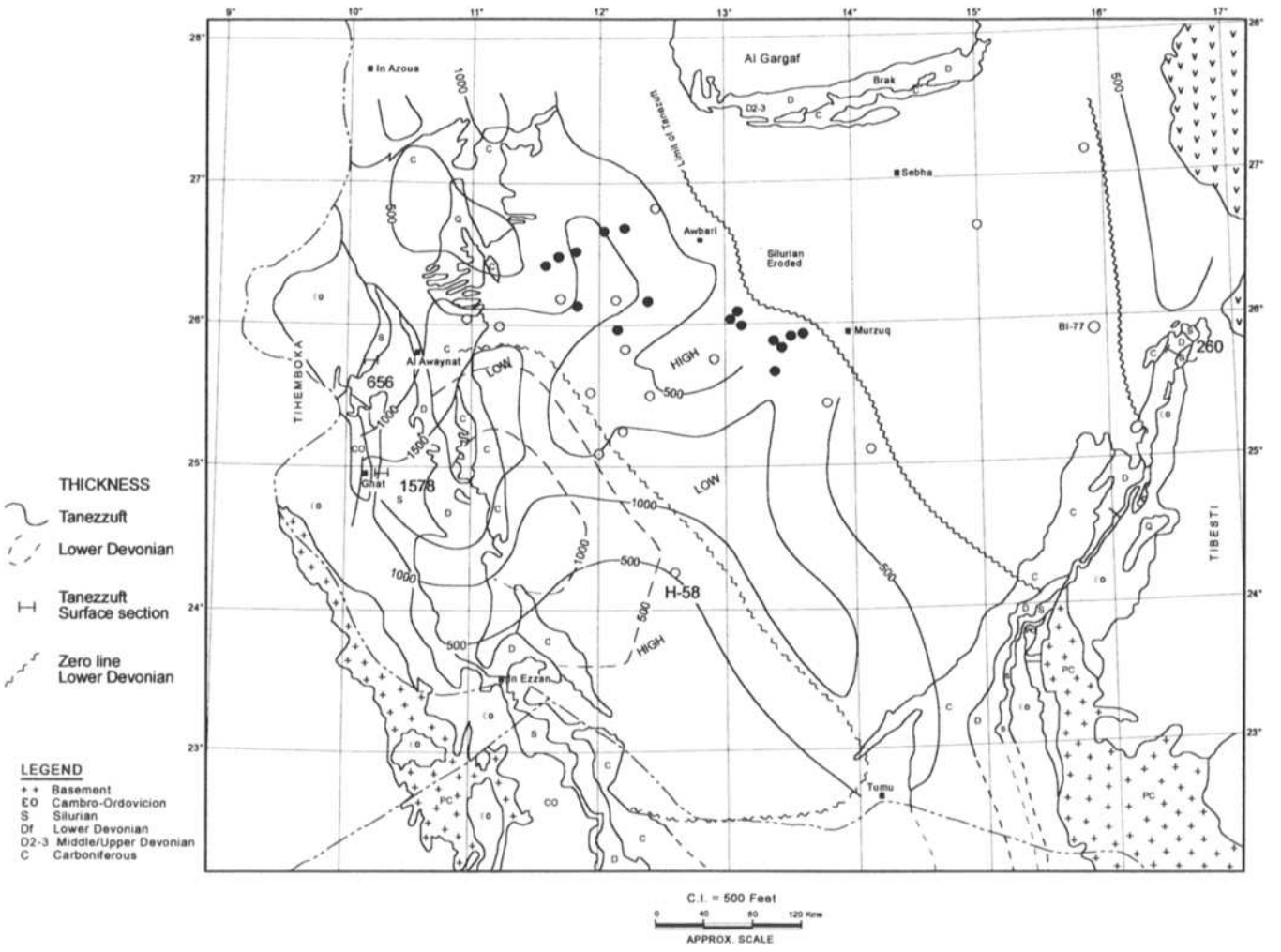


Figure 9. Isopach map of the Silurian (Tanezzuft) and lower Devonian successions: **Silurian** – the Traghan High was already a positive element. Note the presence of a SW-NE trending high separating the Awbari area from the main Idhan depression. **Devonian** – the main depocentre was located over the present western flank of the Murzuq Basin, while the present day Idhan depression remained a positive area.

exposures in Wadi Kunayr, approximately 100 km west of Al Fuqaha. The water well T/2D/0035 near to Al Fuqaha itself penetrated a 2600 ft thick Tanezzuft section (Woller, 1984).

A regional facies change is observed in the Tanezzuft Formation of the Murzuq Basin, particularly from the south and southeast to the northwest. The sand percent map (Fig. 10) indicates an increasing coarse clastic content towards the Traghan and Tiririne highs and towards the southern parts of the basin. This suggests that these were positive areas during the early Silurian, with active clastic input from the south. However, fine dark shales with graptolitic faunas and sideritic lenses (e.g. well C1-NC101) represent the Tanezzuft Formation close to the actual pinchout line. This distal aspect suggests that the area with missing section reflects post-depositional erosion during the late Silurian rather than primary depositional patterns.

Akakus Formation

A fall in relative sea level in the mid-Silurian led to the deposition of the silts and sandstones of Akakus Formation in a system of northwards prograding deltas (Bellini and Massa, 1980; Massa, 1988). Echikh (1984) studied the Akakus Formation in detail in the Ghadames Basin and

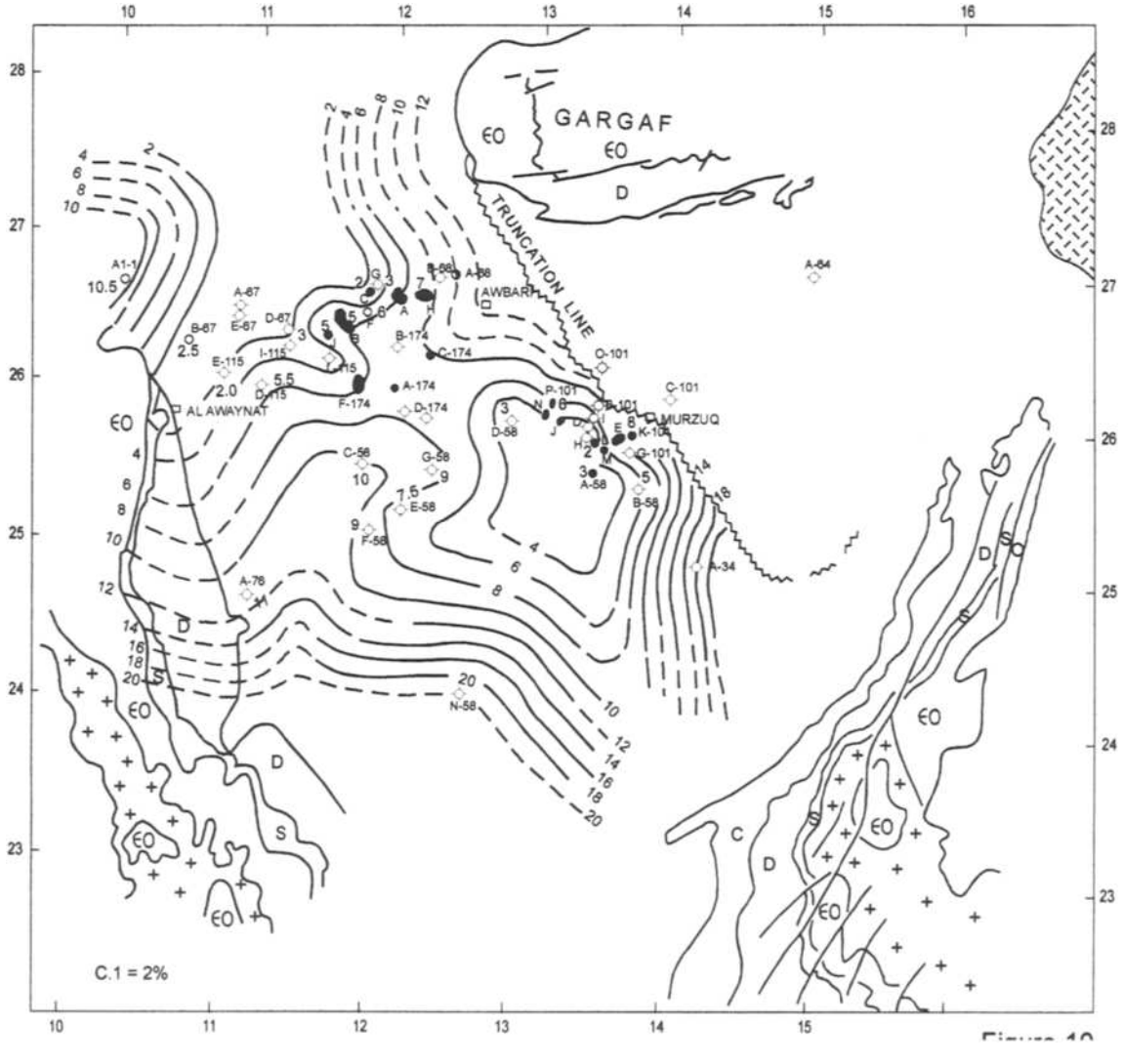


Figure 10. Sand percent map of Tanezzuft Formation (contour interval 2%).

there subdivided it into informal lower, middle and upper units. The formation largely outcrops along the western flanks of the Murzuq Basin. It is still poorly defined in the subsurface, where it has been penetrated by only two wells (A1–76, H1-NC58) with thicknesses of 1100 ft. The formation seems to be missing over the present Idhan depression and over the Traghan High.

Lower Devonian

The Lower Devonian, as in the Ghadames Basin, has been assigned to the Tadrart and Ouan Kasa formations. These formations outcrop largely on the western flanks of the Murzuq Basin. The most recent sedimentological study of the Lower Devonian succession was carried out by Clark-Lowes (1985). In the subsurface, the Lower Devonian has been proved only by wells A1–76 and H1-NC58 in the western part of the basin. As with the Akakus Formation, the Lower Devonian formations are poorly studied and their basin-scale facies distribution is unknown. The maximum thickness encountered hitherto (Fig. 9) has been penetrated by well A1–76 with a value of 1586 ft. These formations thin towards the present central parts of the Murzuq Basin, with a zero line passing close to wells F1-NC58, E1-NC 115 (north) and KR-1 (south, Niger). They are not found over the present Idhan Depression and the Traghan High.

Middle to Upper Devonian

Compared to the Ghadames Basin, the Middle to Upper Devonian succession in Murzuq is represented by a condensed section with a sandier facies and several local erosional unconformities. The name Aouinet Ouenine (Awaynat Wanin following Libyan orthography) was introduced by Lelubre (1946) based on exposures on the western flanks of the Gargaf Uplift. Massa and Moreau-Benoit (1976) subdivided the Awaynat Wanin into units I, II, III and IV to coincide with their biostratigraphically based subdivisions. In the I.R.C. map-sheet descriptions, Parizek et al. (1984) and Seidl and Röhlich (1984) introduced a new stratigraphic nomenclature for the southern Gargaf Uplift, defining 6 formational units in the Middle and Upper Devonian, *viz.* the Bir Al Qasr, Idri, Quttah, Dabdab, Tarut and Ashkidah formations. Precise correlations between the units defined by Massa and Moreau-Benoit (1976) and the I.R.C geologists with subsurface sections is not possible in practice, because of:

- Regional diachronism of the Devonian from the south (Murzuq) to north (Ghadames) as indicated by biostratigraphic analyses completed by Robertson Research International (1992) for Sirte Oil Company,
- An erosional unconformity at the top of the Devonian, so that the upper Famennian and the Tournaisian are missing over most of western Libya (Massa, 1988; R.R.I., 1992),
- Local pre-Givetian and pre- Frasnian erosional unconformities.

Devonian unconformities

Collomb (1962) was the first worker to show the presence of an intra- Frasnian unconformity on the southern flanks of the Gargaf Uplift. The analysis of subsurface palynological data obtained from wells drilled in NC34, NC101, NC58 and NC115 in western Libya and in Algeria (Illizi) indicate clearly that these areas have experienced different Middle to Upper Devonian erosional episodes. Massa (1988) indicated that the Mobil well A1–50 lacks Eifelian so that the Givetian directly overlies the Silurian Tanezzuft Formation. In addition, wells C1-NC58 and E1-NC58 show a stratigraphical break spanning the whole early and middle Devonian so that Frasnian units rest directly on the Silurian. In Algeria (Illizi) various studies indicate that the Middle

Devonian was a tectonically active period on the Ahara High, where Frasnian strata directly overlie differing Lower Devonian units. These movements were particularly active in the northwestern parts of the Murzuq Basin, over the Tiririne, the Tihemboka and the Ahara palaeohighs.

The regional effects of these phases are illustrated in Fig. 11, showing the onlap of different Middle to Upper Devonian units on older Palaeozoic formations. Log correlations in concessions NC58 and NC101 (Fig. 12) indicate significant lateral and vertical facies changes, with the progressive onlap of Awaynat Wanin basal units towards the regional Traghan High. Note also the transgressive character of this formation and its thinning towards this high. The isopach map shown in Fig. 13 indicates thickening southwards to the present-day Idhan Depression and eastwards to Dor Al Gussah where maximum thicknesses reach 450 feet. These thick zones were separated by a common positive area comprising the present Traghan High and the western flanks of the Murzuq Basin.

Carboniferous and Permian

Carboniferous strata largely outcrop on the flanks of the Murzuq Basin, where type sections have been described by Klitzsch (1963) and by Bellini and Massa (1980) and Massa (1988). The subsurface development of the Carboniferous is still very poorly known as the operating companies have focused primarily on the Ordovician and Devonian potential reservoir intervals. The thickest Carboniferous successions, approaching 1000 m, are seen in the southern part of the Idhan Depression, close to the Libyan border with Niger (Fig. 13). Pierobon (1991) indicated a north to south facies change from essentially marine to lagoonal and lacustrine environments. The youngest reliable datings in limestones of the Dembaba Formation suggest mid-Carboniferous Bashkirian and Moscovian ages (Grubic et al., 1991). Overlying evaporitic siltstones of the Tiguentourine Formation have not yielded any age-distinctive fossils, but its conformable contact with the underlying Dembaba Formation and markedly unconformable contact with the Triassic Zarzaitine Formation suggest a latest Carboniferous age. The Permian is generally thought to be missing in the Murzuq Basin and this period is presumed to represent the main phase of Hercynian uplift and fault rejuvenation in the area. Various authors suggest widely differing amounts of uplift and erosion, from as little as 300 m (Davidson et al., 2000) to over 2000 m (Aziz, 2000). This is clearly a subject in need of serious attention.

Mesozoic

The end-Palaeozoic uplift of the region was followed by renewed regional subsidence in the early Mesozoic, apparently still centred on the Idhan Depression, where maximum thicknesses of over 1500 m of Mesozoic strata are preserved. The entire Triassic to Lower Cretaceous succession in the basin is continental in origin, with alluvial and lacustrine environments mainly represented by redbed facies. Facies studies by Lorenz (1980) suggest that the centre of the subsiding basin may also represent the centre of the Mesozoic depositional basin, but coarse sediments were mainly derived from the southerly Tibesti and Hoggar massifs. The three formations in this succession seem to be separated by minor hiati, but the first post-Hercynian period of renewed uplift and tectonism appears to have occurred in the early to mid- Cretaceous, apparently penecontemporaneously with the initial development of the Sirte Basin to the east. Marine Upper Cretaceous onlaps and oversteps all older units along the present northern and eastern flanks of the basin – the original extent of these deposits is unknown, although they probably covered the entire area. The regional effects both of mid-Cretaceous and Tertiary

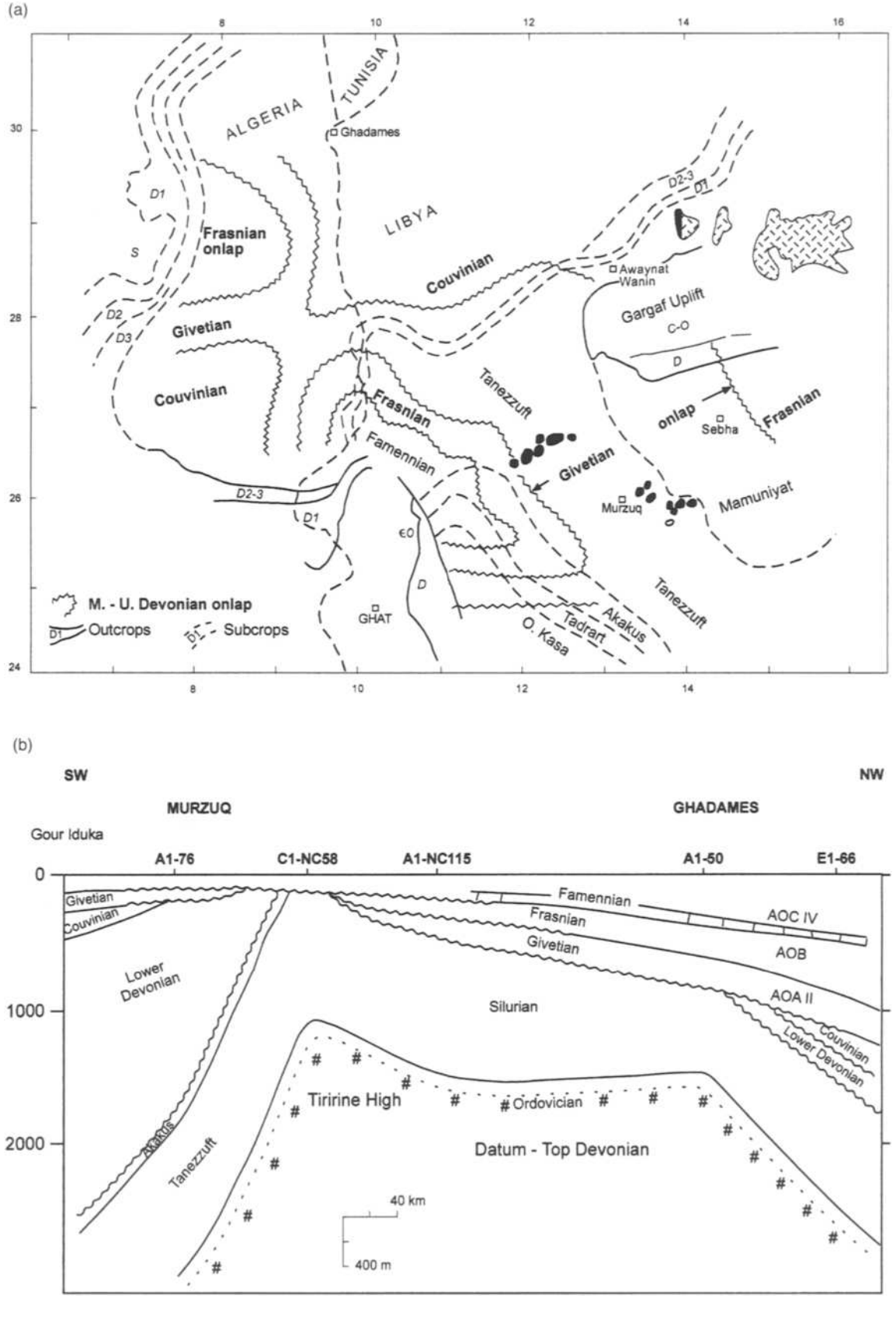


Figure 11. (a) Middle to Upper Devonian erosion and onlap of older units in map section. (b) Middle to Upper Devonian erosion and onlap of various older units in cross-section.

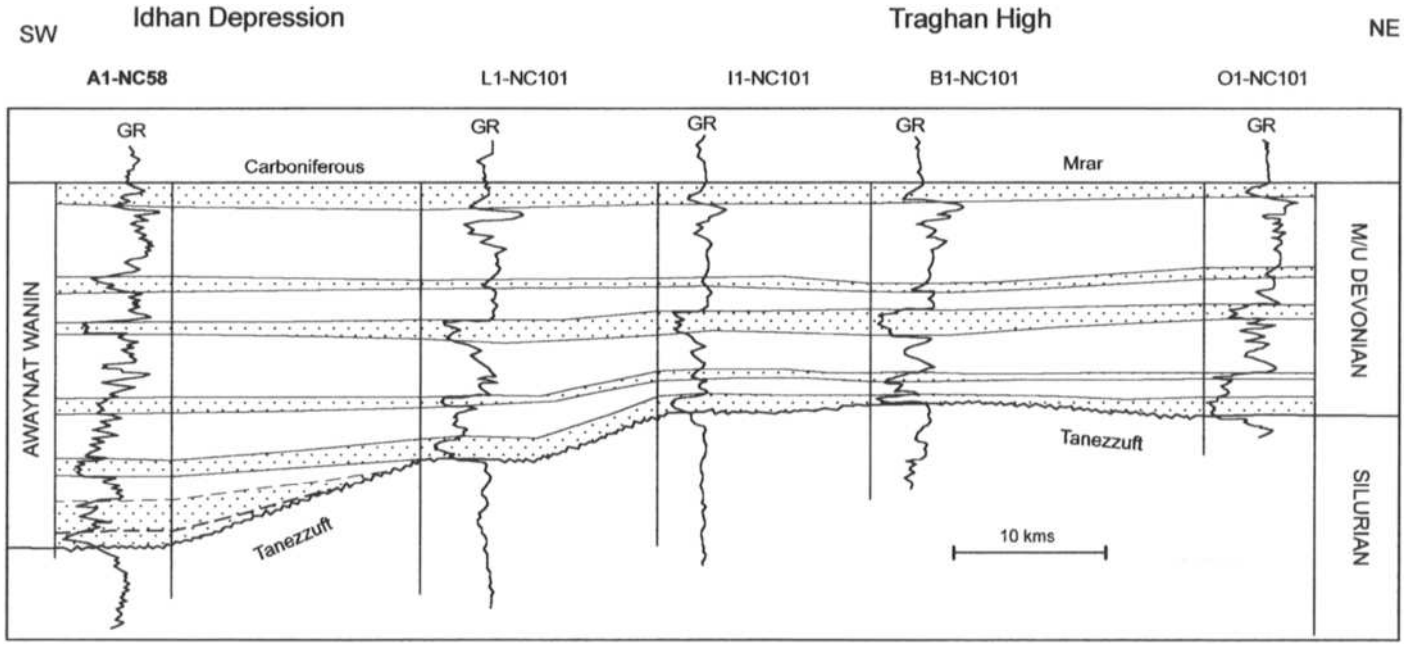


Figure 12. Middle Devonian log correlation. Note the progressive erosion and onlap of the basal units and the facies change towards the Traghan High.

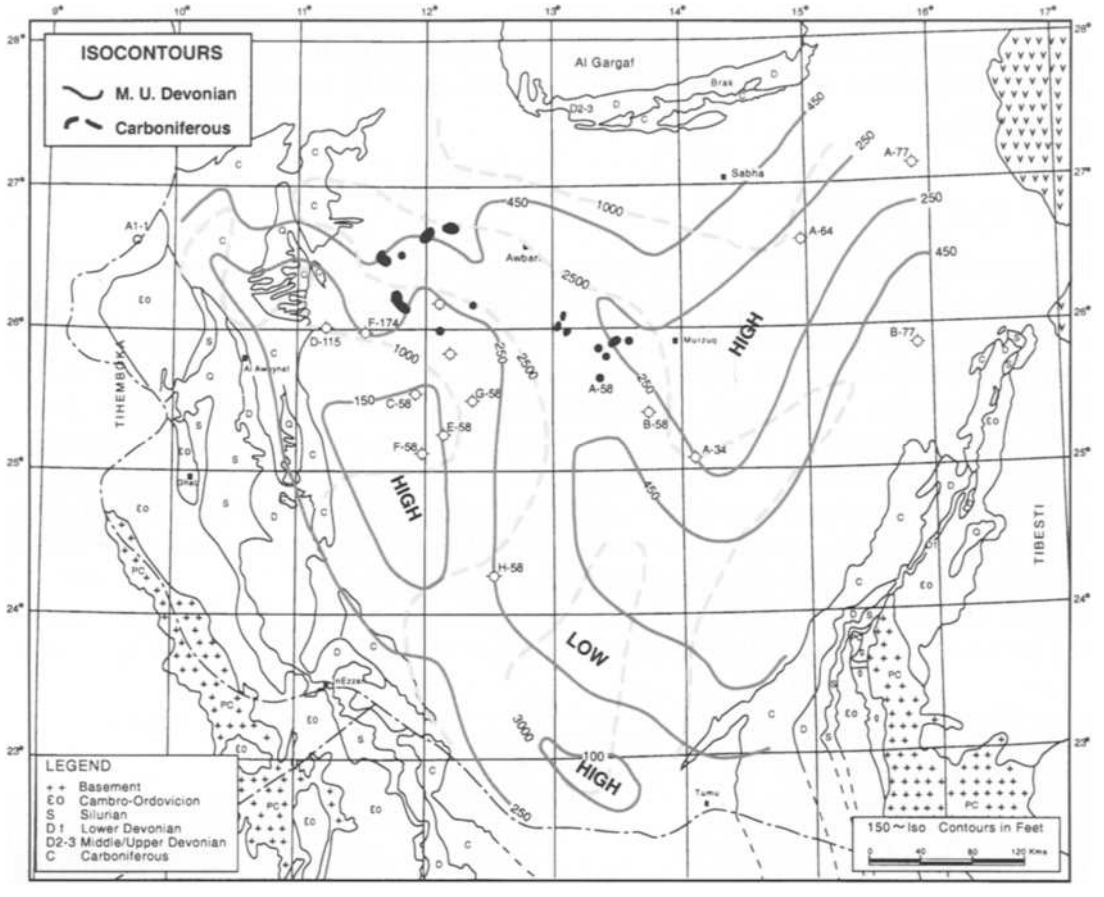


Figure 13. Isopach of the Middle-Upper Devonian and Carboniferous successions. **Devonian** – Note the presence of a regional high along the present western Murzuq flank; progressive uplift of the Tihemboka Arch led to tilting and shifting of this depocentre to the SE to the present-day Idhan depression. **Carboniferous** – Uplift of the Gargaf High led to the shifting of this depocentre to the south: note the triangular shape of the Tiririne High, produced by superimposed SW–NE Hercynian and SE–NW Caledonian trends as noted by Klitzsch (1963).

tectonic events are still uncertain, and there are varying opinions on how much regional uplift accompanied each of these events. Isolated studies have been carried out by individual companies to attempt to quantify these movements, but this also is a topic that needs to be addressed throughout the region. The only younger deposits preserved in the area – as documented by Thiedig et al. (2000) – are of late Quaternary age.

STRUCTURAL SETTING

The present day structural configuration of the Murzuq Basin is shown by the contour map for the top Ordovician (Fig. 14) and by the regional geological cross section (Fig. 15). These figures highlight the major tectonic elements within the basin, including the Tiririne High separating the Al Awaynat and Awbari troughs and the Traghan High (corresponding to the Brak Ben Ghnema Arch of Klitzsch, 1963) between the Awbari and the Dor Al Gussah troughs. The present-day Murzuq Basin did not develop until the Mesozoic. Prior to that, the Palaeozoic basin comprised a series of NW–SE directed horsts and grabens (Fürst and Klitzsch, 1963). In general, fault

density and structural complexity increase from the southern, more stable parts of the basin, towards the northeastern and northwestern portions, as shown by the structural map in Fig. 14. The most complicated and intensely faulted areas are generally located over the Tiririne and Traghan highs.

Tiririne High

The Tiririne High is an asymmetric NW to SE trending structure that is downfaulted to the west. There is a marked change in structural style from the northwestern to southeastern parts of the high (Fig. 16). The northwesternmost part of the high is marked by the regional Tumarolin wrench fault. This fault, which can be identified at the surface, trends in a NNE–SSW direction and extends from the Atshan High southwards over a distance of more than 250 km along the margins of the Tihemboka Arch (Fig. 16). The fault shows about 20 km of right-lateral displacement of Carboniferous units in exposures close to the Tihemboka Arch. In the Atshan area itself, the Tumarolin master fault is associated with an en echelon fold pattern, reflecting oblique compression. Seismic sections show positive flower structures associated with this fault, which originated during transpressional Hercynian movements.

Further to the southeast, early operating oil companies mapped many surface structures. These are related to normal faults trending in a NW–SE direction. They are typically large (Fig.

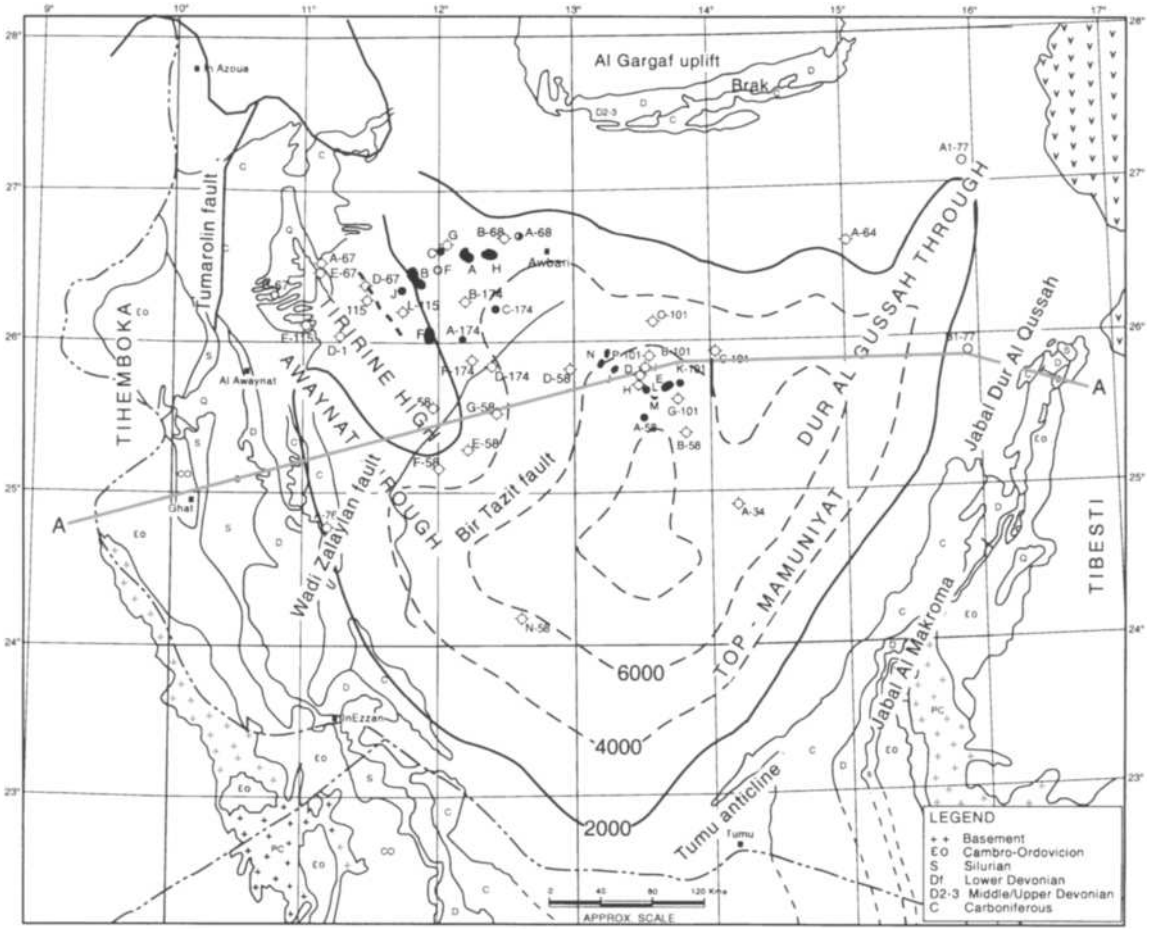


Figure 14. Structural contour map at top Ordovician. Note the increase in fault density over the Tiririne and Traghan highs. A–A′ marks line of section in Fig. 15.

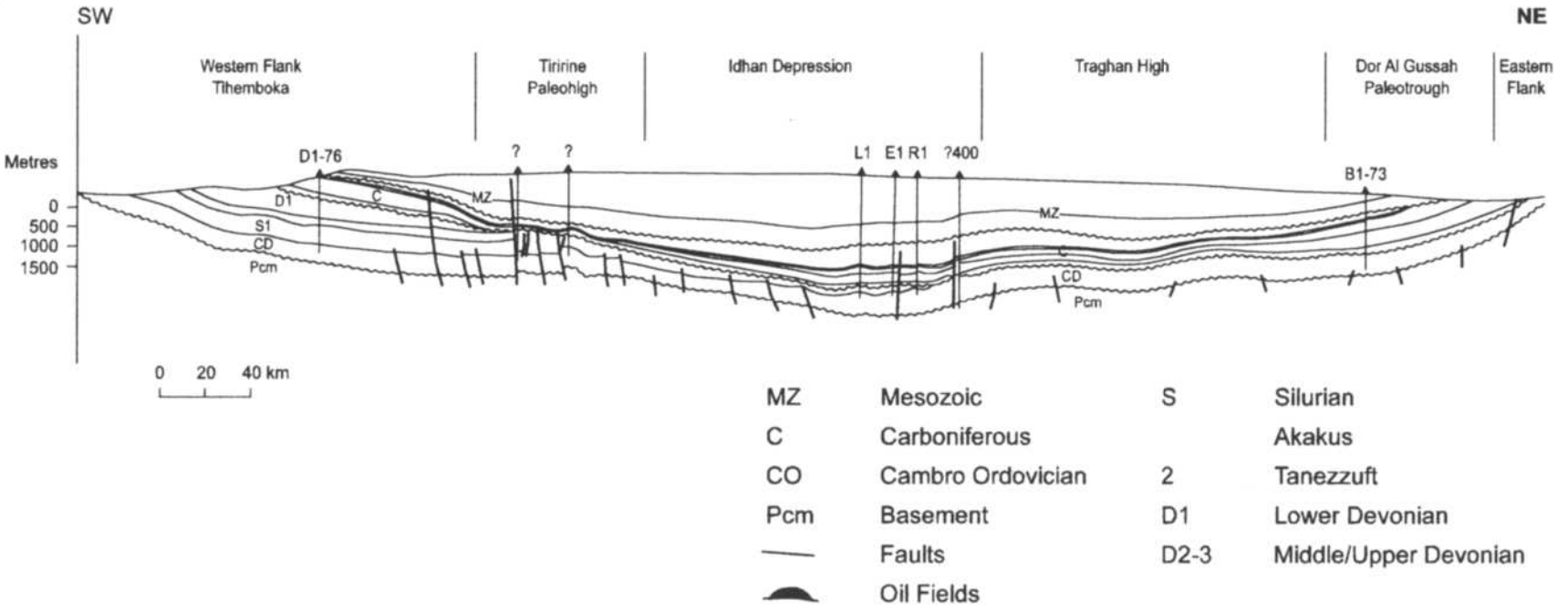


Figure 15. Geological cross section through the Murzuq Basin. Datum: present-day surface. Line of cross-section shown in Fig. 14.

16) – examples being the Haghe and Geramna structures with areas of around 100 km^2 and closures of 120 m. These local features are affected by a series of westward dipping fault sets which have throws of up to 450 m (Geramna structure). Westwards towards the Al-Awaynat Trough, the faults have only affected Devonian or older strata, but eastwards they are post-Carboniferous in age, and reach the present-day surface (Fig. 17A). In the central parts of the Tiririne High, local structures and fault-sets follow the same NW–SE trend, but the anticlines are smaller, ranging between 15 and 25 km^2 in area. Seismic surveys show reverse-faulted structures

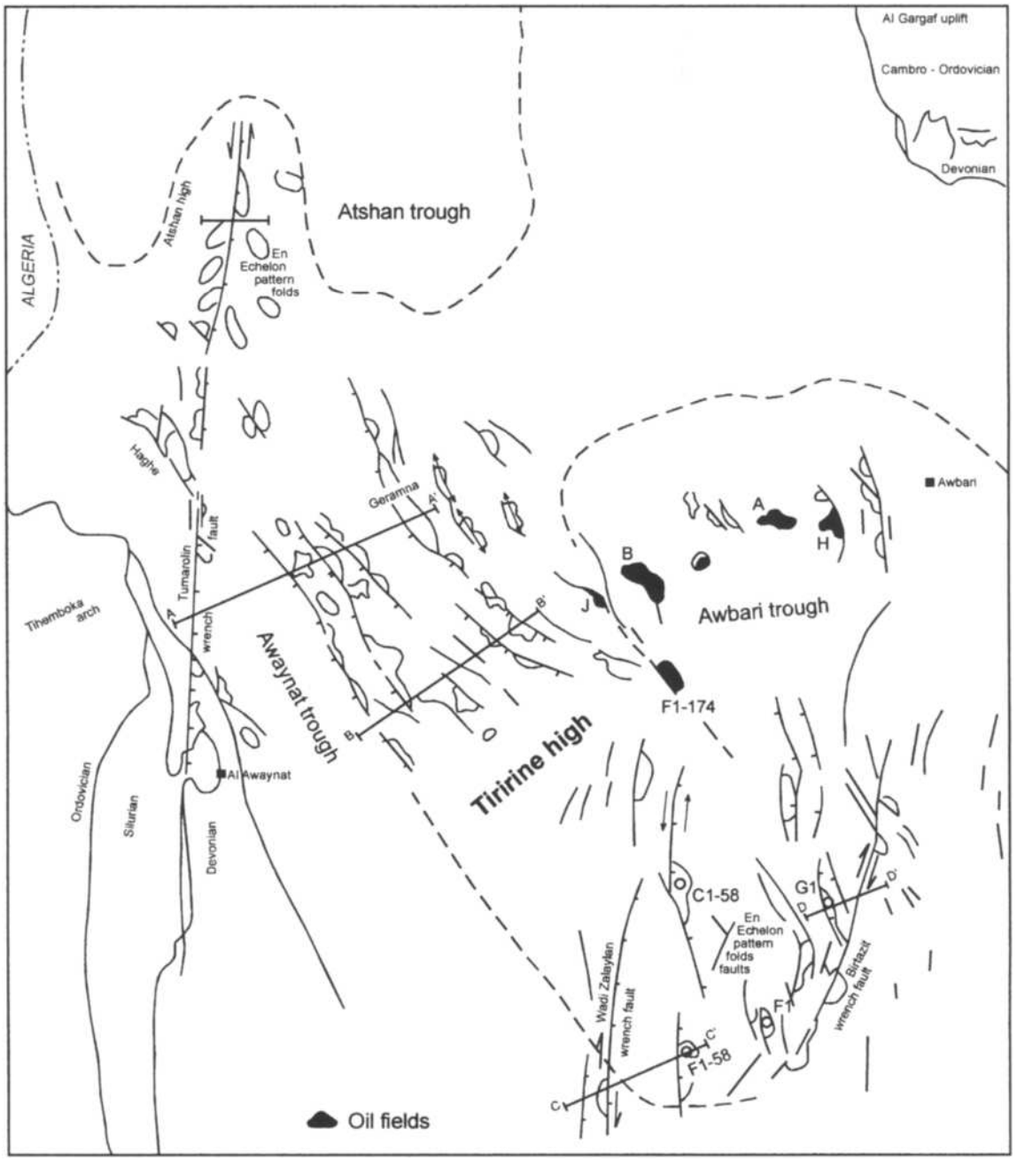


Figure 16. Structural configuration of the northwestern Murzuq Basin. The structural and fault styles change from the NW to SE parts of the Tiririne High. A–A′, B–B′, C–C′ and D-D′ show lines of sections in Fig. 17.

(Fig. 17b). The shift of position of the structural crests on successive profiles and the absence of an oblique en echelon pattern suggest the absence of wrench faulting in the area. Here, the structural styles are probably related to purely compressional movements and this is considered as a transitional zone between the northern and southern parts of the Tiririne High.

The southern part of the Tiririne High (Fig. 16) is the most intensively faulted and complicated area, characterised by the presence of a large local anticline with an areal extent of 120 km^2. This area is cut by two regional wrench faults – the Wadi Zalaylan and Birtazit faults – with trends following the same direction as the Tumarolin wrench fault. The local structures associated with these faults consist mostly of oblique reverse faults forming an en echelon pattern of folds caused by oblique compression. These wrench faults are almost 80 to 100 km long, with a westward throw of 200 m. As in the Atshan area, seismic sections show a positive flower structure, resulting from transpressional wrench fault tectonics (Fig. 17C). These movements led to a right lateral displacement of 10 km at Cambro-Ordovician levels. The E–W trending Hercynian compression reactivated the southern part of the Tiririne High as a zone of sinistral wrench shear. Across the high's central parts, faults change from a westerly to easterly dips.

Awbari Trough

The NC115 C discovery lies on the main axis of this trough (Fig. 16) in the northeasternmost part of the basin. Over the trough's eastern flanks, local structures are characterised by a thinning of the Cambro-Ordovician section on the upthrown side of reverse-faulted anticlines. The thrusts follow the line of older reverse faults, probably Pan-African in origin, which were reactivated during the Caledonian phase. Structuring is seen up to the Hercynian unconformity. The largest structures have hanging-wall rollover anticlines, which seem to be linked to westward dipping thrust planes.

Central Parts of the Murzuq Basin (Traghan High–Idhan Depression)

The Traghan High is affected by several fault-sets; these dip westwards with trends changing from SE–NW to SW–NE in its northern parts. Seismic data indicate the development of various structural styles controlling potential traps in this area (Fig. 18). The first type is related to structural drape over Ordovician glacial palaeotopography (Fig. 18A). Note the progressive onlap of the Tanezzuft basal units against the Mamuniyat palaeohills. The average size and vertical closure of local structures is 20 to 30 km^2 and 70 m respectively. The second structural type (Fig. 18B) is represented by simple and fault-bounded anticlines produced during the Hercynian tectonic phase. These structures are characterised by smaller sizes and closures not exceeding 10–30 km^2 and 40 m respectively. The third type (Fig. 18C) is characterised by local structures that are almost flat at the Ordovician/Silurian level, but show increasing vertical closure upwards in the Mesozoic section.

Eastern Flanks of the Murzuq Basin

Surface mapping in the northeastern parts of the Murzuq Basin (Jabal Dur Al Gussah) shows numerous structures following a NE–SW trend, parallel to the margins of the basin, disturbed by a series of strike slip faults that affect the Devonian (Wells, 1958). These faults dip westwards and continue for up to 100 km, following the same orientation as the Tiririne High and the Tumarolin, Wadi Zalaylan and Bir Tazit wrench faults.

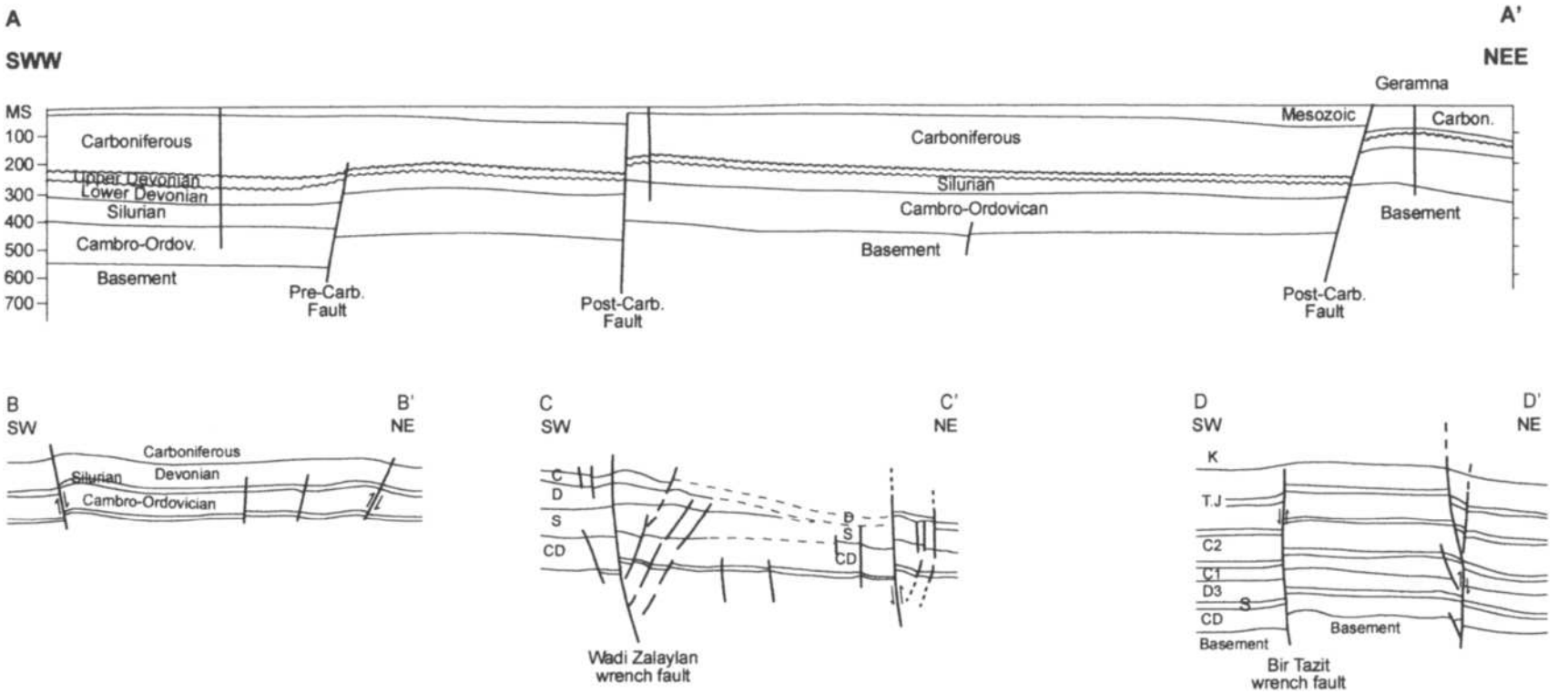


Figure 17. Structural styles over the Tiririne High, cross sections shown in Fig. 16: A–A′: Geoseismic profile showing different fault ages. B–B′: Geoseismic profile through the central part of the Tiririne High with reverse faults produced by contractional fault block movements. C–C′ and D–D′: Geoseismic profiles through the southern Tiririne High with indications of wrench faulting.

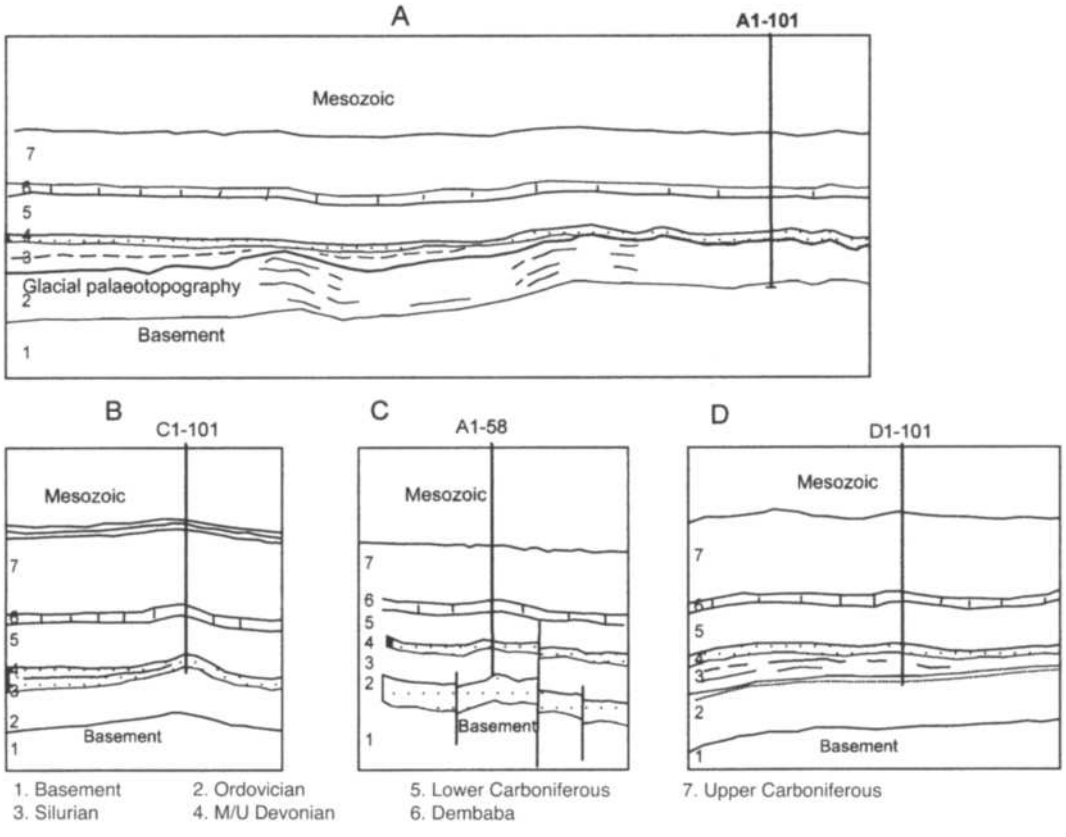


Figure 18. Structural styles in the central Murzuq Basin (concessions NC58, NC101) A: Glacially related palaeotopography. Note the progressive onlap of the Tanezzuft shale units over the Mamuniyat palaeohills. B: Simple unfaulted anticline growing up to Mesozoic levels. C: Normal faulted anticline, with fault activity both in Cambro-Ordovician and Carboniferous times. D: Anticline with closure only at Mesozoic to Devonian levels, no structure at the Silurian/Ordovician.

The most prominent feature of the southeastern part of the Murzuq Basin is the Mouride Fault with a throw of 1000 m (Thompson 1960), dipping westward along a 70 km trace and juxtaposing the Devonian with the Cambro-Ordovician succession. This fault seems to have been active intermittently throughout the Palaeozoic and the Mesozoic. Further to the south, in Jabal Al-Marokma, the Palaeozoic rocks are intensively affected by a series of NE–SW trending faults; probable basement control is indicated by similar orientations of the basement-Cambrian contact. The throw on these faults does not exceed 30–40 m. Westward of this area a number of folds are aligned ENE–WSW, the most prominent of these being the 60 km long Tumu anticline.

TECTONIC EVOLUTION

Palaeozoic Tectonic Events

Middle to late Ordovician

The regional thickness distribution of this succession is poorly known because most wells have penetrated only the uppermost part of the Ordovician section. Seismic data and the few wells

drilled down to basement indicate (Fig. 19) that a series of regional SE–NW oriented highs and lows existed during early Palaeozoic time. The present-day Murzuq and Ghadames basins were connected in one single SE to NW trending structure. The palaeo-Gargaf Uplift formed a continuation of the Traghan High, almost perpendicular to its later E–W trend.

The mid-Ordovician was characterised by tectonic instability, indicated by erosional or non-depositional absence of the Hawaz and/or Melaz Shuqran formations over the Tiririne and Traghan Highs. The principal tectonic activity probably took place during the Llandeilo to Caradoc. The resulting faulted topography in the central and eastern parts of the basin was enhanced by glacially-related erosion resulting in the creation of NW–SE directed palaeovalleys which were later filled by the Ashgill periglacial coarse clastics of the Mamuniyat Formation. This tectonic phase did not create new fault and fold patterns, but was rather characterised by vertical epeirogenic movements along rejuvenated Pan-African fault systems.

Silurian to early Devonian

The western flanks of the Murzuq Basin underwent significant subsidence during the early Silurian, whereas the central parts of the basin remained a positive area where the basal Silurian shales progressively onlapped and infilled the Ordovician erosional relief. The northern part of the Dur Al Gussah trough was also the site of significant subsidence.

Local effects of the main Caledonian orogenic phase, here reflecting collision between West Africa and North America, were initiated around the Silurian/Devonian transition. This resulted in progressively increasing uplift towards the northeast, with total erosion of the Silurian section from present-day northeastern parts of the Murzuq Basin. The resultant peneplain of early Devonian age is shown by Fig. 20. Later in the early Devonian, the western and eastern flanks continued to subside, while the present-day Idhan Depression and Awbari Trough were positive elements, as indicated by the absence of the Tadrart and Ouan Kasa formations in these areas.

Middle to late Devonian

During the middle to late Devonian, the progressive uplift of the Tihemboka Arch led to southeastwards tilting and shift of the depocentre, to the present Idhan Depression. A short-lived pulse of late Caledonian movements led to uplift and erosion of some areas. The major tectonic pulse was pre-Frasnian in age and resulted in erosion of the newly deposited Couvinian succession from the Idhan Depression and the Awbari Trough. The entire Couvinian to Givetian succession was eroded from the basin's western flanks and from the Tiririne High: the Frasnian succession directly overlies Silurian rocks in these areas. The regional effects of this predominantly pre-Frasnian pulse are illustrated in Fig. 11a and 11b.

Carboniferous to Permian (main Hercynian phase)

During the Carboniferous, in response to the development of the Gargaf Uplift, the main depocentre moved to the southern part of the Idhan depression, close to the Libyan border with Niger. The Idhan Depression and the Awbari Trough subsided rapidly, while the western flanks of the Murzuq Basin remained a positive area. During the period prior to collision between Gondwana and Laurasia (from the Viséan to the Permian), various tectonic pulses are indicated by the presence of local unconformities within the Carboniferous succession. The Tiririne High was uplifted at the end of the Viséan, leading to the almost complete erosion and removal of the Assedjefar–Marar (Lower Carboniferous) sequence. Mid-Carboniferous tectonism initiated transpressional movements along a series of NNE–SSW trending wrench faults, producing a NE–SW en echelon pattern of folds on the Tiririne High. By the end of Permian times, the main

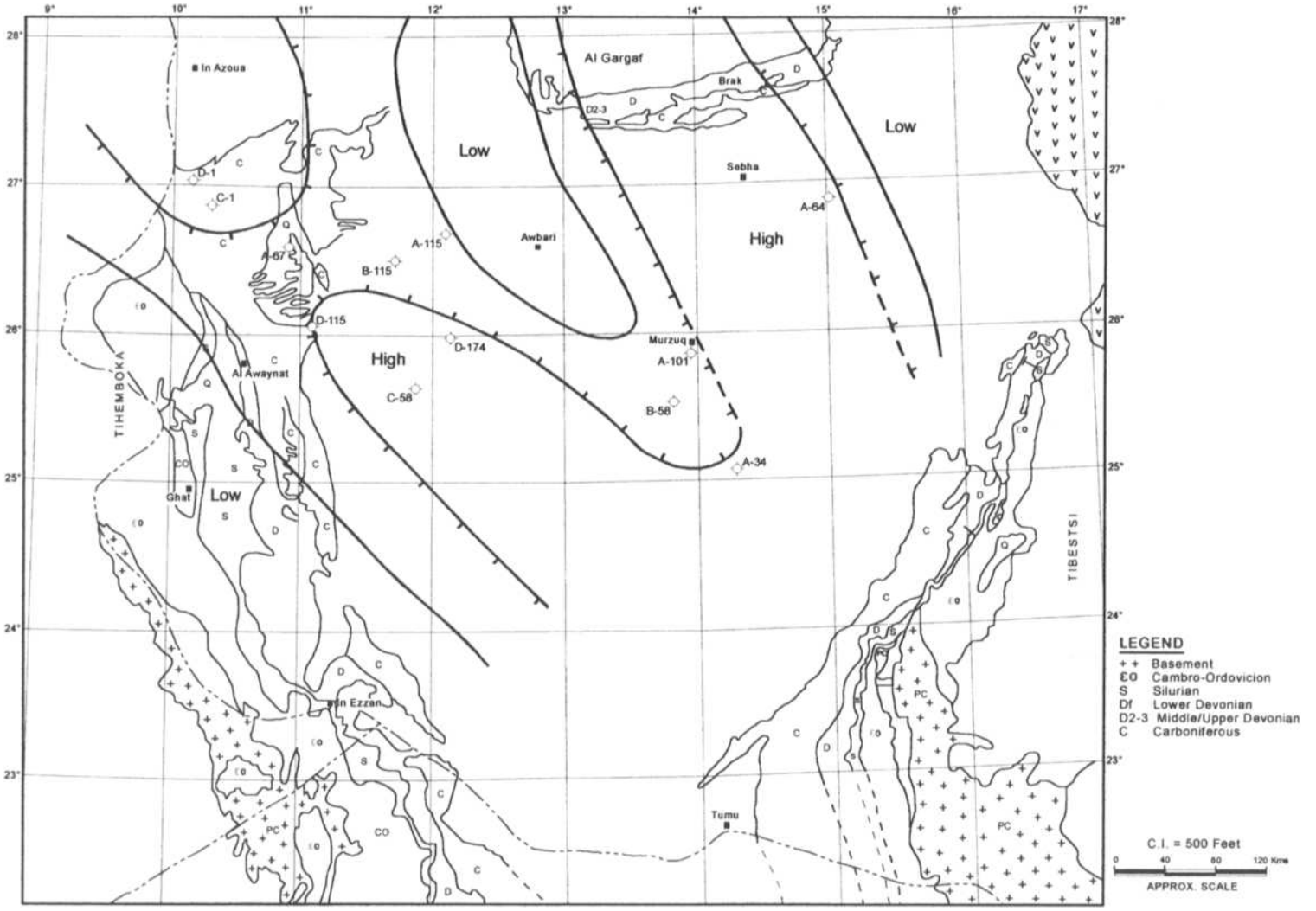


Figure 19. Paleotectonic map end Cambro-Ordovician, based on Cambro-Ordovician thickness distribution, indicating the early Palaeozoic development of SE–NW trending regional highs and lows, extending northwards towards the Ghadames Basin.

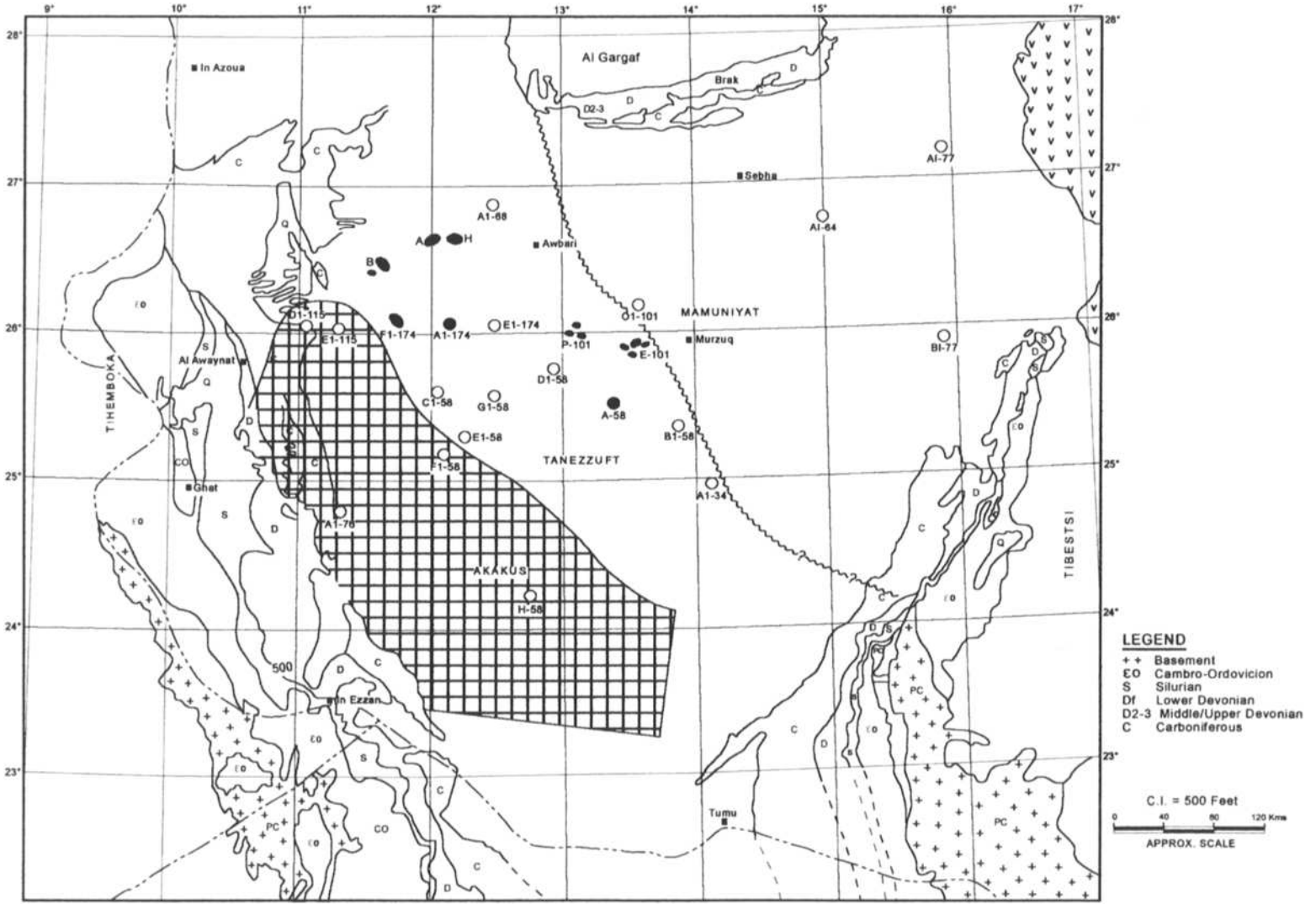


Figure 20. Subcrop map top Silurian (Caledonian unconformity).

Hercynian tectonism had produced new fault systems and folds and probably also reshaped pre-existing early Hercynian structures. The Tihemboka, the Tibesti and the Gargaf uplifts acquired their present final shape during this period.

Mesozoic tectonic events
During the Triassic, left-lateral movements of the African plate and opening of Ligurian Tethys initiated extensional movements, which created slow intracratonic subsidence in the present Murzuq Basin. In the late Jurassic to early Cretaceous local movements, caused by the differential opening of the Atlantic Ocean and extension in the nearby Sirte Basin, produced NW–SE trending faults, such as those cutting the northwestern parts of the Murzuq Basin. Uplift and erosion of the flanking Tihemboka and Tibesti highs during the Mesozoic resulted in the deposition of thick continental sand sequences in the present central parts of the basin.

HYDROCARBON OCCURRENCES

Previous Exploration Efforts

Since 1957, when the first exploration well was spudded in the Murzuq Basin, some 60 wells have been drilled, resulting in the discovery of 15 oil pools with cumulative in-place reserves of 4 billion barrels. Most wells have been located in the structurally highest parts of the basin and deeper portions are largely untested, mainly because they underlie extensive sand dune desert areas. The exploration history of the area can be divided into three main phases:

Frontier period (1957–1978)
Operators who studied the region and acquired acreage were:

- Esso (Concession 1, 1957),
- BP (Concession 64, 1958),
- Amoseas (Concession 73, 1957),
- Gulf (Concession 67, 1958),
- Panamerican (Concession 76, 1978),
- Wintershall (Concession 77, 1961).

Fourteen exploration wells were drilled during this period. Although these only resulted in gas and oil shows, they gave important geological information regarding regional tectonics, potential reservoirs and not least the distribution and quality of the Lower Silurian Tanezzuft Formation source rock interval.

Discovery period (1978–1986)
Concession NC58 – a large area covering 60 000 km^2 – was awarded to Braspetro in 1978. Sedimentological fieldwork and a semi-regional seismic survey indicated the presence of leads characterised by varying structural styles and sizes in different portions of the concession area. The first well, AI-NC58, tested a relatively small structure located in the southeastern corner of the block. This well gave the first sub-commercial oil discovery in Ordovician and Devonian reservoirs. The second well B1-NC58 drilled the hanging-wall of a faulted anticline, but tested only fresh water. The third well C1-NC58 tested another structure in the northwestern part of the

concession area where seismic data show the presence of complicated structures affected by wrench faulting. This well drilled a large structure (127 km^2) but tests here also gave only fresh formation water. The well indicated the presence of a regional intrabasinal high, called the 'Central High' by Braspetro and later renamed the Tiririne High by NOC (Echikh, 1992a). It also gave the following important new geological information:

- The lower to middle Devonian and the lower Carboniferous Mrar/Assedjefar formations are missing in this area,
- Good quality Ordovician reservoirs occur in sandstones of the Mamuniyat Formation,
- The basal Tanezzuft radioactive zone is not present,
- This is a tectonically complicated area with wrench faulting initiated during Carboniferous time.

Several dry wells (E1-, F1- and GI-NC58) in the area have confirmed the presence of the Tiririne High and its low petroleum potential. The last well, HI-NC58, in the southwestern part of Braspetro's concession indicated the absence of good source rocks as only sandy Tanezzuft shales were encountered. Tests in the main Mamuniyat target again gave only fresh water.

Concession NC101 was awarded to BOCO in 1980. The company's main strategy was to test large prospects. The first back-to-back wells – A1-, B1- and CI-NC101 – were drilled on the western flanks of the Traghan High. Only minor oil shows were obtained from Devonian reservoirs, but these wells were important as they demonstrated the eastern limit of Tanezzuft source rock development and the absence of good seals. The first BOCO oil discovery in 1984 was made by well EI-NC101 that tested oil from Mamuniyat sandstones filling palaeotopography created during the late Ordovician glaciation. BOCO drilled a total of 17 exploration wells with 7 oil discoveries.

First Boom period (1986–present day)

Rompetrol was awarded concession NC115 in 1985. The seismic survey acquired over the block indicated the presence of large structures with different structural styles than those previously tested in the Murzuq Basin. The first well AI-NC115 gave the first important oil discovery in the basin, with approximately 500 mmbbl oil in place. Rompetrol later drilled 12 exploration wells to test prospects of various sizes, leading to the discovery of 6 oil accumulations. The most important of these, with large reserves, belong to the B and H fields. Oil was also encountered in Devonian reservoirs (well CI-NC115).

In 1991 Lasmo acquired concession NC174, located south of concession NC115. After sedimentological studies of Palaeozoic sediments outcropping around the basin, a new seismic survey with higher resolution indicated the presence of structures with various styles and sizes in the area. Exploration priority was given to areas located close to Rompetrol Concession NC115 in the northern parts of NC 174. The first well AI-NC174 (drilled in 1993) tested only small quantities of oil from the Mamuniyat reservoir. The next wells (B1, D1, and E1-NC174) were disappointing, but well CI-NC74 also found small oil amounts from the same Mamuniyat target. Later, in 1997, well F1-NC174 discovered the so-called 'Elephant' oil field over a large block-faulted anticline in the northwestern part of the concession area.

Reservoirs and Petroleum Results

Producing fields in the Murzuq Basin all have reservoirs in sandstones of the Ordovician Mamuniyat and Hawaz formations. The Bir Tlacsin Formation is not regarded as a potential reservoir as its poorly sorted argillaceous sandstones are normally tight. Devonian sandstones

are at present regarded as secondary targets within the Murzuq Basin and will be only briefly discussed herein.

Mamuniyat Reservoirs

The Mamuniyat reservoirs are characterised by great lateral and vertical variation of petrophysical properties due to the presence of various facies, as already described in the stratigraphic review above.

The first lithofacies type is represented by clean quartzitic sandstones with poor reservoir properties – porosities varying from 2 to 7%, on average 5%. Thin sections (Meister et al., 1991) show secondary quartz overgrowth produced by burial diagenesis. The area showing this development, located in the central part of the Murzuq Basin, experienced relatively deep burial both during the Carboniferous and the Mesozoic, leading to drastic diagenetic changes in the reservoir properties. Reservoir quality may however be locally improved by fracturing in highly faulted areas.

The second lithofacies dominates the western and southwestern parts of the basin, where the Mamuniyat Formation is characterised by a more shaly facies. Porosities in this area are generally higher, with values between 15 and 20% (Meister et al., 1991). This zone is located over an area that experienced less burial during Carboniferous and Mesozoic times, thus preserving primary porosities in the Mamuniyat reservoirs. The third facies zone in the northwestern corner of the Murzuq Basin is dominated by sandstones and shales deposited in marine environments. Sandstone porosities here have intermediate values, commonly between 8 and 12%. In the B field of NC115 log and core data indicate the local development of a fourth reservoir type, with coarse to very coarse sandstones showing very good reservoir quality: porosities vary from 15 to 20% and permeabilities are high, reaching 2 to 3 D'Arcies.

The Mamuniyat reservoirs in the Murzuq Basin have proven to be more prolific oil producers than is the case in the Ghadames Basin. Until recently finds have been concentrated in two areas in the Murzuq Basin. These are concession NC 101 in the central-northern parts of the Idhan Depression and NC115 in the Awbari Trough (Fig. 1). Finds in NC101 are characterised by low productivity because of relatively poor reservoir quality. The oil net pay in the discoveries is in the range 15 to 45 m, with an average production rate of 400 to 500 BOPD, except for the E-field that can produce 1260 BOPD. Finds in NC115 generally show better rates, typically producing between 600 and 3150 BOPD from a net-pay zone of between 30 and 100 m. The discovery well in the 'Elephant' field in NC174 only some tens of km south of the NC115 fields tested approximately 8400 BOPD from a net pay of 100 m. This discovery has boosted exploration in the Murzuq Basin in general, but in particular has raised expectations for new finds in northern basinal areas in and around licences NC115 and NC174.

Middle-Upper Devonian reservoirs

The Devonian reservoirs are characterised by better petrophysical properties than the Ordovician reservoirs, with porosities ranging between 12 and 23%. Oil has been recovered from these sands in the Murzuq wells A1-NC58, P1-NC101 and C1-NC115, but usually with low rates between 50 and 270 BOPD. Oil shows have been reported in many other wells (M1-, E1-, C1- and F1 I1-NC101). In some wells, logs indicate the possible presence of hydrocarbons, but no tests have been carried out. At present, the hydrocarbon potential of the Devonian reservoirs in the Murzuq Basin (distribution of good quality sand, migration and trapping of hydrocarbons) remains poorly understood. The presence of good quality reservoirs and of proven Devonian source rocks, locally with a high TOC reaching 2% to 4% (e.g. A1-NC58, A1-NC34) makes this

play a promising future target, particularly in more shaly areas of the Murzuq Basin, where good seals are also expected to be present to cap these Devonian sandstone units.

Areal and vertical distribution

Regionally, oil discoveries in the basin (in both NC101, NC115 and in NC174) seem to follow a NW–SE trend from the north-central Idhan Depression to the Awbari Trough. This regional trend is probably related to the early Palaeozoic structural configuration that controlled both reservoir facies development and source rock richness distribution. Oil discoveries in the Mamuniyat Formation of the Murzuq Basin have typically been at depths between 1500 and 3000 metres (RKB). The most common interval between 1500 and 2000 m is represented by the A, B and H fields in licence NC115.

Trapping mechanisms

Structural traps

Most of the discoveries in the basin occur in structural traps. The multiphase evolution of the area has produced a great variety of structural traps of different ages:

- Single anticlines of pre-Hercynian age – generally low-relief and small-sized structures. This trap type is present in concession NC101 and in NC58 (Fig. 21A),
- Normal faulted anticlinal traps are also present in the same concessions. One example is the J1-NC115 oil discovery (Fig. 21B),
- Reverse thrust-faulted anticlines form traps in NC115, e.g. in the H and C fields. The faults contribute to the seal on the eastern flanks of these fields (Fig. 21C).

Palaeomorphological traps

This type of trap represents a combination of structural and geomorphological features and is represented by palaeohighs resulting from Ashgill glacially related erosion. A much debated question is whether this erosion is essentially glacial in origin or represents incision as a result of changing base levels during and after maximum glaciation. The oil discoveries E1–101 and K1–101 are examples of this type of trap (Fig. 21D).

Other possible trap types

In the Illizi Basin of Algeria the Tiguentourine Field provides an example of a diagenetic trap, with a lateral permeability seal provided by increased quartz cementation within the Cambrian reservoir. The T6–1 well encountered a 600 m gas column, whereas wells only a few kilometres to the south and east penetrated a tight, very compact, quartzite. Appraisal wells in licences NC101 and NC115 have discovered significant lateral diagenetic changes within the Mamuniyat reservoir, suggesting diagenetic traps as a possible play-type also in the Murzuq Basin.

Two main types of stratigraphic traps are considered possible in the Murzuq Basin:

- Updip shale-outs of possible Devonian reservoirs because of lateral facies changes towards the Tiririne and the Traghan highs,
- Truncation traps defined by the erosional top surface of the Mamuniyat Formation, with seal provided by the Bir Tlacsin or Tanezzuft shales: this trap type is expected along the eastern flank of the Tiririne High.

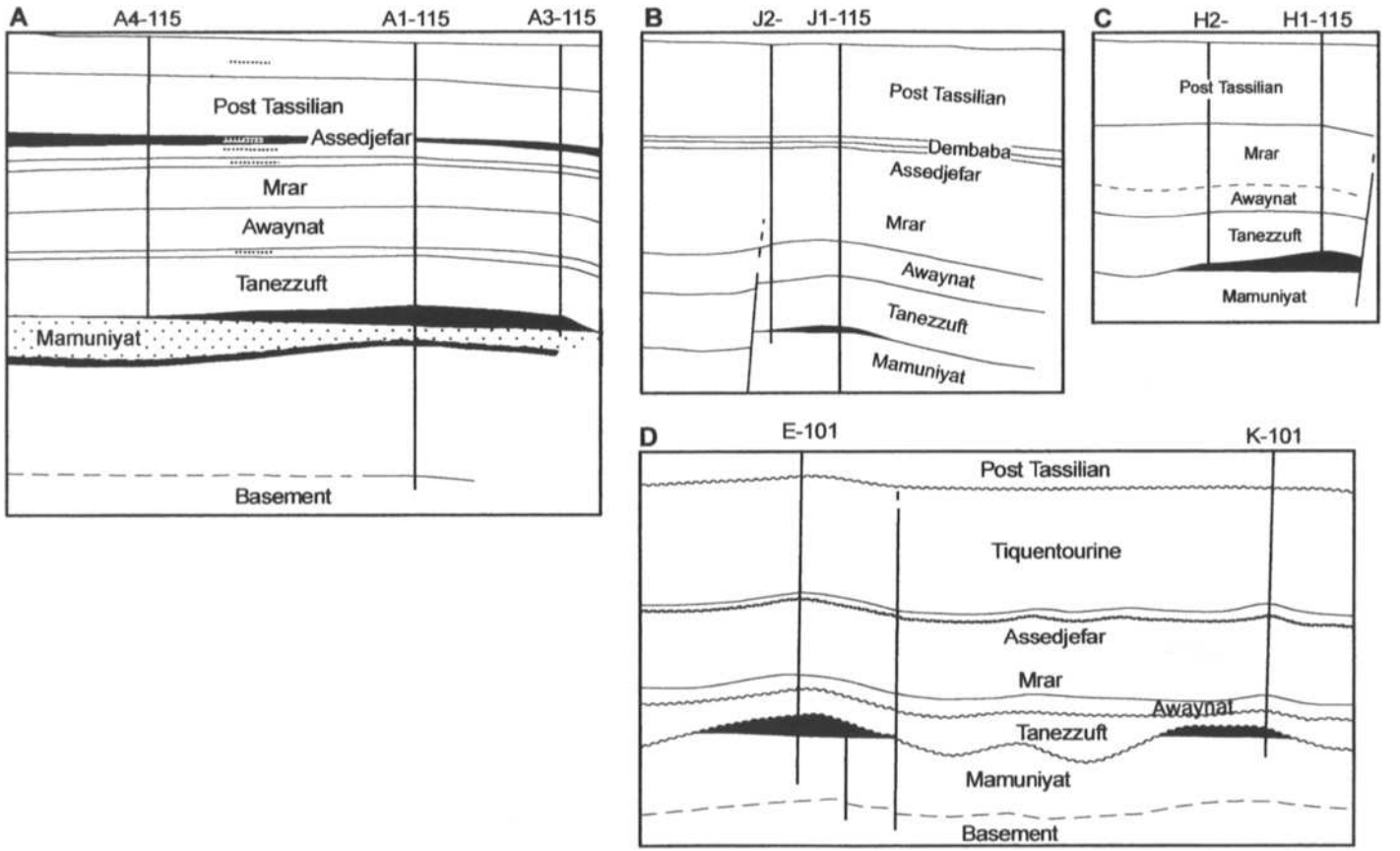


Figure 21. Trapping mechanisms in the Murzuq Basin; A: Simple anticline, B: Normal-faulted anticline, C: Reverse-faulted anticline, D: Glacially related erosional palaeotopography.

Evidence of structural-stratigraphic combination traps, where entrapment and lateral seal are formed by rapid facies changes in the Mamuniyat reservoir over structural crests, is given by appraisal wells drilled in NC101 and NC115. Appraisal well J2-NC101, drilled in a structurally higher position than the discovery well J1-NC101, was completed as dry, due to reservoir quality deterioration. Also, in the F- and J-NC115 structures, appraisal wells drilled a few kilometres from the discovery wells have shown a rapid deterioration of petrophysical characteristics.

Finally, the Tin Fouyé Field in the Illizi Basin is a well-known hydrodynamic trap resulting from downward water movements close to Hoggar outcrops. Similar traps may occur along the margins of the Murzuq Basin where pressure measurements indicate local rapid changes in the potentiometric surface elevation.

FACTORS CONTROLLING HYDROCARBON HABITAT

As noted earlier, discoveries to date in the Murzuq Basin are located along a NW-SE oriented trend from the NC101 discoveries in the northern parts of the Murzuq Depression to the NC115 fields and the new discovery F1-NC174 in the Awbari Trough (Fig. 1). This trend represented a structural low at the end of the Cambro-Ordovician depositional phase (Fig. 19). Within this trend, however, many dry holes have also been drilled, indicating that local geological factors are just as important for the habitat of hydrocarbons in the basin. These factors include source rock quality and distribution, reservoir facies changes, seal facies and continuity, trap size and age and the development of migration pathways.

Source Rock Quality and Distribution

The geochemical database from the Murzuq Basin is still limited; operating companies have carried out some analyses and a few publications are available (e.g. Hamyouni et al., 1984, Meister et al., 1991). Echikh (1992a) made the first attempt to compile all existing geochemical data in a regional evaluation report.

The Silurian (Tanezzuft) and Devonian (Awaynat Wanin C) shales constitute the most widespread source rocks in the Murzuq Basin. The Mamuniyat basal radioactive shales and the Melaz Shuqran shales may also represent possible Ordovician source rocks. The contribution of these Ordovician shales to discoveries in the Murzuq Basin is speculative and therefore not addressed herein. Further, the Devonian shales are too shallow to be of significance as a source in this area. For this reason we will concentrate our discussion on the Lower Silurian radioactive 'hot shale' at the base of the Tanezzuft Formation, the primary source for hydrocarbons discovered to date in the basin.

Lower Silurian Tanezzuft source rock distribution

The basal Tanezzuft Formation radioactive shales have a distinct log response, characterised by high GR and resistivity, with low density and sonic values. As in the Ghadames Basin, when these hot shales are present, the Silurian /Ordovician boundary is characterised on seismic lines by a strong reflection. This interval usually has a TOC between 3 and 5%, reaching 8%. An isopach map (Fig. 22) of the basal radioactive zone indicates that in western Libya the thickest 'hot shale' interval is located in the present-day deepest areas of the Ghadames Basin, where thicknesses reach 100 m. The radioactive zone is missing over some palaeohighs, such as the area separating the Murzuq from the Ghadames Basin, suggesting that these were positive features and the sites of the shallow-water aerated depositional environments. In the Murzuq

Basin itself, this map is based on poor well control, particularly in southern areas. However, here the Tanezzuft radioactive zone is less well developed and less than 30 m thick.

The primary hot shale distribution was apparently controlled by:

- Regional configuration, with clastic input from the south and a marine early Silurian transgression from the northwest giving a deepening basin towards the Ghadames area, with thickening of hot shales in the same direction,
- Local basin topography, leading to the development of hot shales in local lows and non-deposition over the highs.

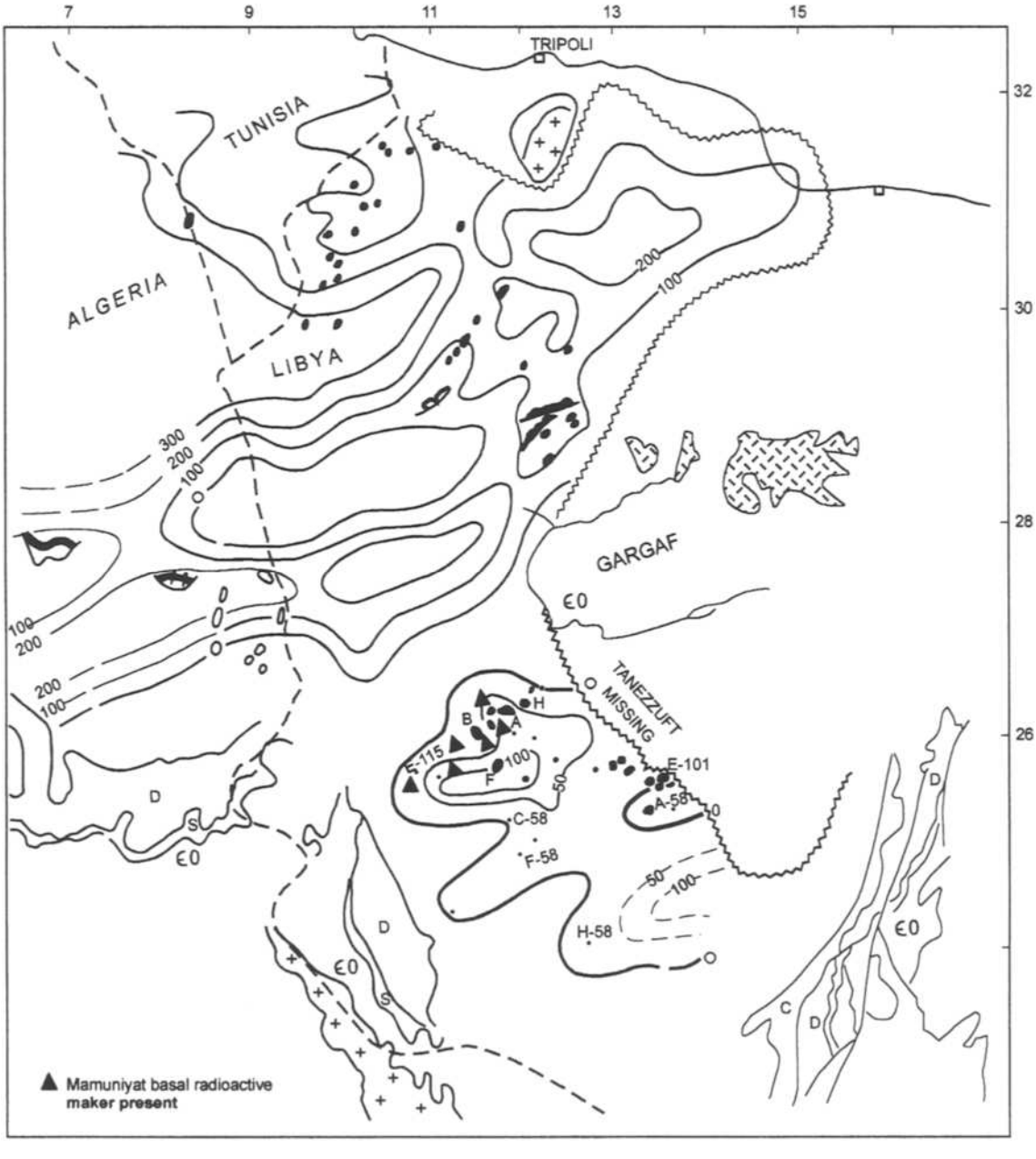


Figure 22. Tanezzuft basal radioactive zone distribution in western Libya.

Tanezzuft facies variations

Source rock quality is dependent on the Tanezzuft shale lithofacies. The relationship between sand content, the depocentre position and source rock quality is illustrated in Fig. 23. This map indicates an increasing coarse clastic content towards the Traghan High and also towards the southwestern and southeastern Murzuq Basin. This suggests that these were positive areas during early Silurian times, influencing the areal distribution of source richness and kerogen type. This is supported by the work of Meister et al. (1991) that indicated a dominance of amorphous kerogen in the central parts of the basin (wells D1-NC58 and A1-NC58), whereas areas towards the southwest (wells E1-NC58 and F1-NC58) and south (well H1-NC58) had organic matter with a more continental character and higher coarse clastic content, both features resulting in poor source rock quality.

Figure 23 also indicates a direct regional geographical relationship between low overall sand content and the presence of hydrocarbons and/or of discovered fields. All oil discoveries are located in areas characterised by coarse clastic contents less than 6%. Almost all dry wells were drilled where the overall sand content in the Tanezzuft Formation is higher. The implications of this observation are uncertain. For licences NC115 and NC174 the areas of low clastic content in the Tanezzuft Formation correspond with areas of relatively thick hot shale (Figs 22 and 23). In contrast, the area of high clastic content in the Tanezzuft Formation that covers the NC101 licence corresponds with an area of very thin/absent hot shale. However, the maps do show that discovered oil in the Murzuq Basin is located in or very close to basinal depocentres where euxinic conditions existed in the early Silurian. Mature source rocks in these areas would be a very likely source for oil discovered in the Murzuq Basin. Long-distance migration, as proposed by Meister et al. (1991) for the Rompetrol fields in NC115, may therefore not be a valid concept.

Source maturity and hydrocarbon generation

Information about source rock maturity is very limited and the existing data are inconclusive. Vitrinite is very rare in most analysed samples (Meister et al., 1991), perhaps because of their age. Data from two wells in NC58 indicate that the Tanezzuft shales in this area at a depth of 2130 to 2332 m are still at an early stage of maturation, with vitrinite reflectance values varying between 0.51 and 0.56 Ro (D1-NC 58) and 0.65 to 0.68 Ro (H1-NC58). It is interesting that other Braspetro wells located in a structurally shallower position today (well C1-NC58) apparently show a higher maturation (1.03) at shallower (1173 m) and younger (Carboniferous) levels, although this might – at least in part – also reflect different measurement techniques (Silurian chitinozoa *contra* true vitrinite in the Carboniferous).

The Tanezzuft shales in the southern Idhan Depression were buried sufficiently during the Carboniferous to Mesozoic period (Hamyouni et al., 1984, Meister et al., 1991) to generate the hydrocarbons trapped in the NC101 fields. However, the Tanezzuft shales in the NC115 and NC174 licence areas were probably not buried sufficiently for such generation during the Carboniferous, although the available data there indicate that the source is now at a late mature stage. Such a high maturity can only be explained either by assuming deep burial prior to the Mesozoic or by past high heat flow. The Tertiary magmatic event with extensive basaltic volcanic activity, well known in the Algerian Hoggar shield and in large areas of Libya on the western flanks of the Sirte Basin, may be the cause of a late and rapid maturity increase in this area.

In the first case, the uplift/erosion related to the major Hercynian and Mesozoic tectonic phases principally affected the marginal parts of the present basin and this cannot explain the high maturity existing in the NC115 licence area at relatively shallow depths. The present authors believe that the second possibility, related to the Tertiary heat pulse event, is probably

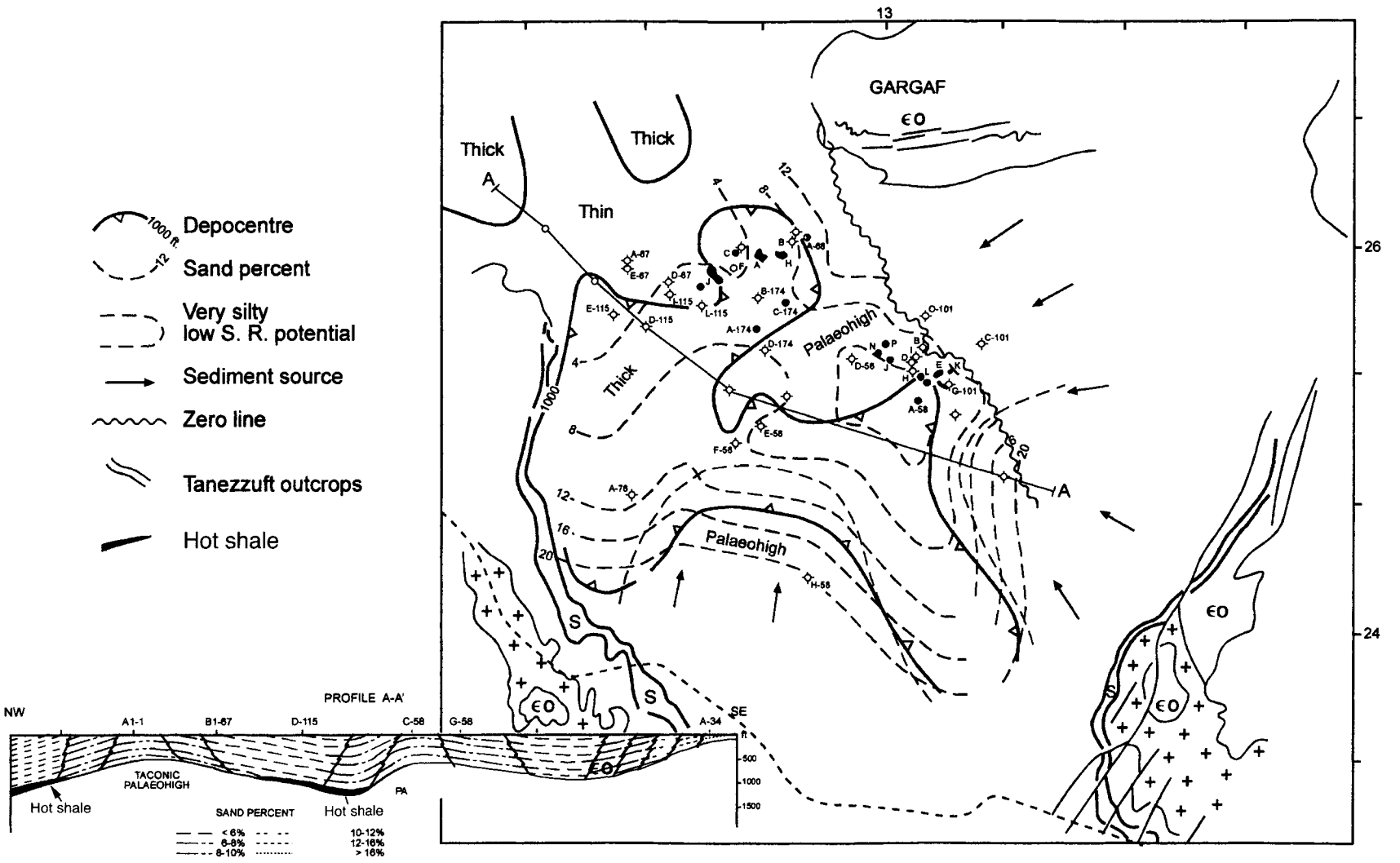


Figure 23. Facies variation and source rock quality of Tanezzuft shales. The basal radioactive zone was deposited in semi-isolated sub-basins with euxinic conditions. Note the apparent relation between the Tanezzuft sand percent and the presence of hydrocarbons.

the main cause for the variations observed. Generation of hydrocarbons from older Ordovician radioactive shales is another possibility to be considered, but the present lack of geochemical analyses from these shales does not allow us to check this hypothesis.

A regional geothermal gradient map (Fig. 24) has been constructed using present day temperatures from BHT, DST and production tests. Temperature data from E-Logs were corrected using the empirical method, wherever drilling circulation time was available. The resultant geothermal gradient map shows a SE–NW trending hot zone centred on NC115 and NC174, but also including some of the NC101 oil fields, flanked by relatively colder areas. This 'hot zone' trends NW–SE in the central Murzuq Basin, apparently also coinciding with the area dominated by Cambro-Ordovician quartzitic sandstones (Fig. 5). These clean quartzitic sandstones are thermally more conductive than the more shaly facies to the southwest. All discovered oil fields as well as the depocentres of the 'hot shale' are located within this main hot zone.

In conclusion, most authors (Hamyouni et al., 1984, Meister et al., 1991, Echikh, 1992a) seem to agree on a late, post-Hercynian (late Jurassic to Tertiary) onset of oil generation in the Murzuq

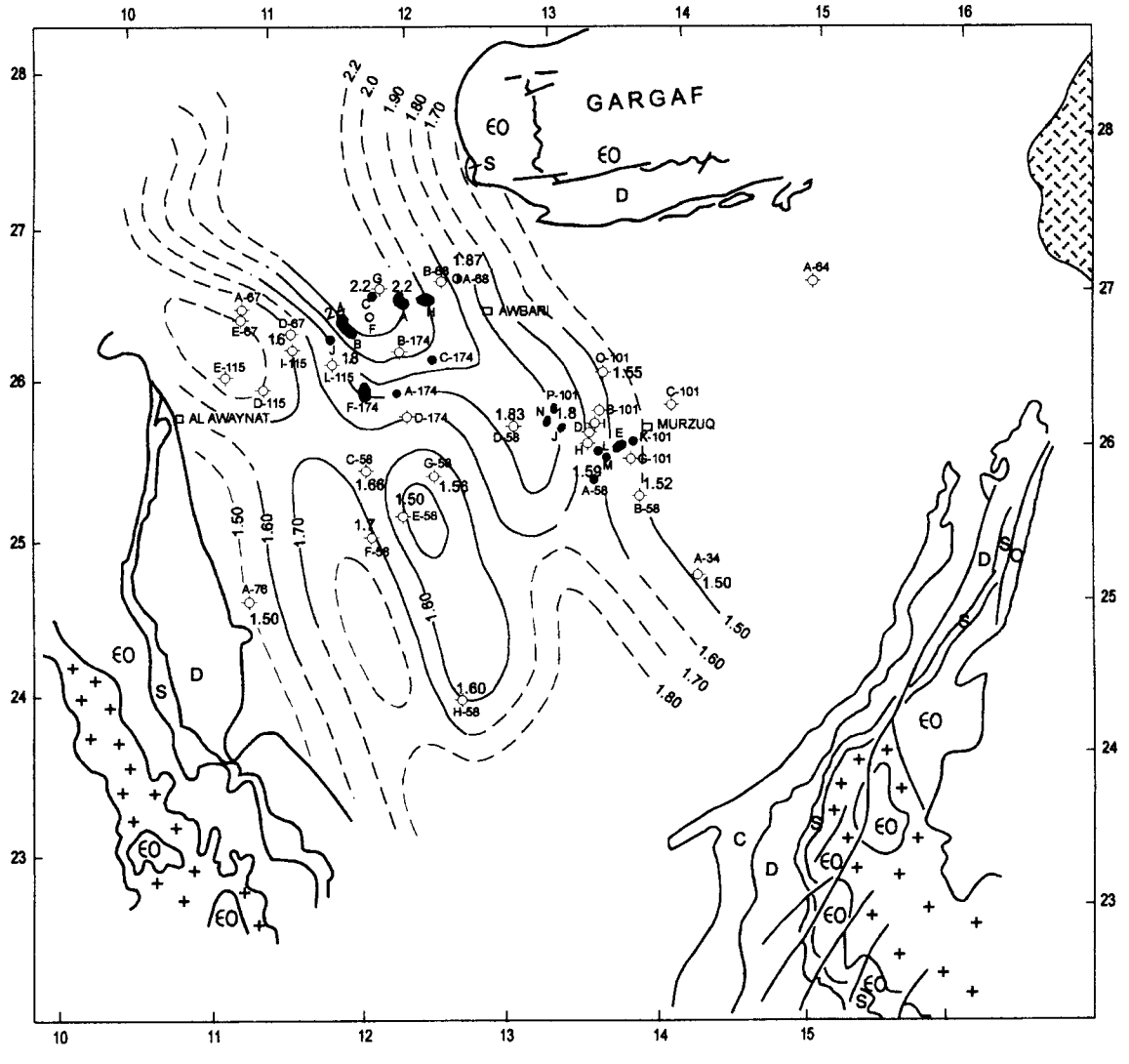


Figure 24. Geothermal gradient map: contour interval 0,10°F per 100 ft. Present known oil-fields tend to associate with the SE-NW trending hot zone.

Basin. The vitrinite reflectance in some Braspetro wells and TTI maturation modelling indicate that the basal Tanezzuft shales generally entered the oil window at a depth of 7000 ft during the late Jurassic to early Cretaceous. Here, as in many other fields, much more systematic regional work is needed, including quantification of thermal history by fission track and fluid inclusion studies.

Reservoir Facies Changes

As discussed earlier, the Mamuniyat Formation displays three general lithofacies in the Murzuq Basin (Fig. 5), viz. shaly silt and sandstone in the southwest, quartzitic sandstone in the central parts of the basin (including NC115 and NC174), grading into alternating shale and sandstone towards the northwest. Locally within these broad facies zones the quality of the Mamuniyat reservoir varies greatly due to local changes in depositional environment and large lateral differences in diagenetic alteration of the sandstone. The oil fields in licences NC115, NC101 and NC174 are examples that show enhanced reservoir quality, but reservoir quality also varies rapidly within these licences, sometimes within the same structure. An example is given by the dry appraisal well F2-NC115 drilled only a few km from the oil discovery well F1-NC115. Similar results were obtained in the A-NC115 and in the E-101 fields. Generally, good reservoirs are found locally in areas characterised by the presence of coarse-grained sandstones, such as those penetrated in the B-NC115 Field. Where fine-grained quartzitic sandstones represent the potential reservoir, intense fracturing may enhance reservoir quality. These local differences in reservoir quality also may affect the distribution of hydrocarbons because of their effects on migration pathways.

Seal Facies and Continuity

The Mamuniyat reservoir is overlain either by the shales of the Tanezzuft Formation or by Middle to Upper Devonian shale. The degree of lateral continuity of the sealing surface, in addition to other factors such as lateral permeability and fault barriers, presents the principal control on the distribution of migration pathways.

The sealing capacity of the Tanezzuft Formation is generally good, especially in areas where the lowermost Tanezzuft shales were deposited in deep marine environments, as in the northwestern parts of the basin. These areas are characterised by the presence of the basal radioactive zone, except for over some local palaeohighs, such as the A-NC115 structure. Over the regional Traghan and the Tiririne palaeohighs, the hot shale interval was never deposited: in these areas the lower Tanezzuft Formation becomes very silty or sandy with a questionable sealing capacity.

In areas where the Tanezzuft Formation is absent or thin, the Mamuniyat reservoir is capped by different Middle-Upper Devonian units with variable sealing capacities. In these areas, as over the western flank of Traghan High, the lack of oil discoveries and the presence of numerous oil shows (Concession NC 101) confirm the lack of effective seals in the Devonian.

Trap Size and Age

The Murzuq Basin shows a wide variety of structural trap types of different ages. In the BOCO concession NC101, productive structures are large with a high vertical closure. This is illustrated by the contrast between the E-NC101 field and the dry structures drilled by wells G1-NC101,

I1-NC101, H1-NC101, all characterised by smaller sizes and significantly lower vertical closures. However, this productivity versus trap size relationship is not valid for the whole Murzuq Basin, since we have many examples, e.g. over the Tiririne High (C-NC58, E-NC58 and F-NC58) where drilling of large structures has given negative petroleum results. This suggests that other factors in addition to pure size also affect the individual structure's productivity in addition to pure size.

Many structures in the Murzuq Basin have developed intermittently throughout geological time. The following general classification of such structures is suggested:

- Structures which formed in pre-Silurian times,
- Structures which developed in Silurian to Devonian time,
- Structures were initiated during the Hercynian tectonic phase,
- Structures which developed up to Jurassic–Cretaceous time,
- Structures initiated during the Tertiary,
- Structures initiated in pre-Hercynian time and modified during the Alpine phase, characterised by structural crest shifts.

In general, oil discoveries in the Murzuq Basin seem to be related primarily to old structures formed in Palaeozoic time with continued or rejuvenated Mesozoic growth.

Migration Pathways

The structural evolution of the Murzuq Basin is characterised by depocentre migration with time, controlling not only lateral changes in depositional environment, but also source rock maturity and migration pathway distributions. Oil discoveries to date are located principally in areas that underwent high rates of subsidence during the Carboniferous (Fig. 13). Hydrocarbon migration pathways are dependent on several factors such as source to reservoir communication, the nature of the seal, lateral changes in reservoir quality and the effects of faulting.

Source rock to reservoir relationship

All oils discovered in the Murzuq Basin so far seem to be sourced from the Lower Silurian Tanezzuft radioactive shale and all known commercial oil accumulations are within the porous sandstones of the Mamuniyat Formation. Communication between these two units seems therefore essential for any successful hydrocarbon accumulation in the basin. The importance of direct contact between source and reservoir in the Murzuq Basin is enhanced by the dominant Mamuniyat lithofacies – generally a relatively tight clean quartzitic sandstone – that is not inducive to long distance migration.

In some areas where the shaly Bir Tlacsin Formation is developed, this unit apparently acts as a barrier for source rock to reservoir communication, preventing direct contact between the Lower Silurian source interval and the underlying Mamuniyat reservoir. The importance of the Bir Tlacsin Formation in this respect is uncertain. There is, however, a clear geographical relationship between the distribution of the Bir Tlacsin Formation and the locations of dry wells *contra* oil discoveries (Fig. 8 and 25).

This correlation between the presence of the Bir Tlacsin and dry wells also seems valid in the Ghadames Basin (both in Libya and Algeria) where the Mamuniyat reservoir has never been found to be oil-bearing in areas where the Bir Tlacsin Formation is present. The only exception in this respect is in the Murzuq Basin itself: the H-field in concession NC115 shows a thin Bir Tlacsin Formation present over the crest of the structure drilled by well H1-NC115 (Fig. 26).

The second well on the H-field H2-NC115 drilled downflank from H1 and found that the Bir Tlacsin Formation was missing there, allowing direct contact between the source rock and the reservoir. In this case, the Bir Tlacsin does not act as a barrier as hydrocarbons have probably migrated from the flanks of the structure.

Seal structural morphology

The migration and concentration of hydrocarbons is dependent on the structural morphology of the sealing surface, which is also the surface under which the hydrocarbons normally migrate from the kitchen area to the structurally highest parts of the basin. The areal distribution of petroleum accumulations is influenced by the structure of the sealing surface. If the highest part of the basin is a regional high, anticlinal in form, hydrocarbons will normally gather on or around this high. If the highest parts of the basin have a synclinal form, such as is the case in the Awbari Trough, the hydrocarbon accumulations may following a curved distribution trend. The latter case is reflected by the oil field distribution in concession NC115 (Fig. 27). A similar distribution of oil accumulations following a curved line is also expected in the Idhan depression, indicating the possibility for future oil discoveries in the northwestern and western portions of this depression.

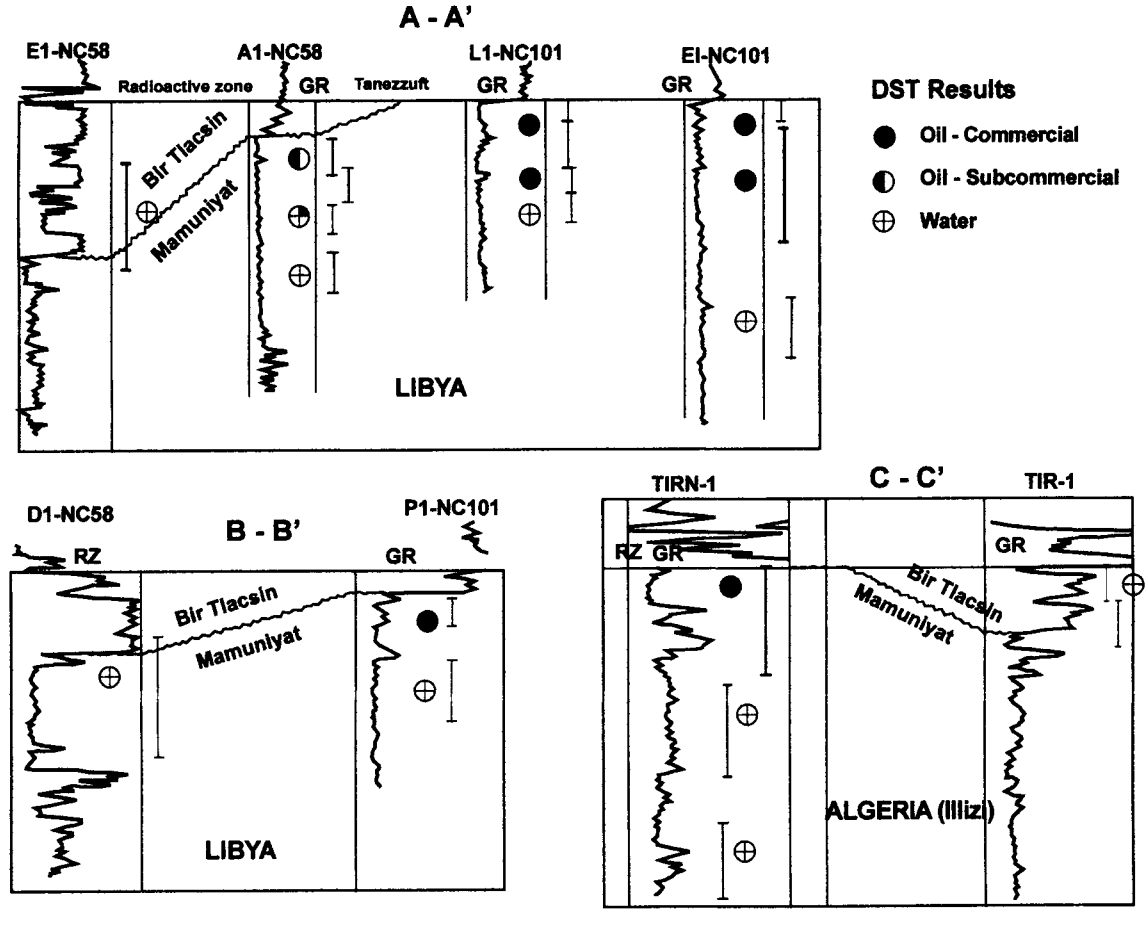


Figure 25. Apparent relationship between the Bir Tlacsin Formation's distribution and the presence of hydrocarbons in Mamuniyat reservoirs.

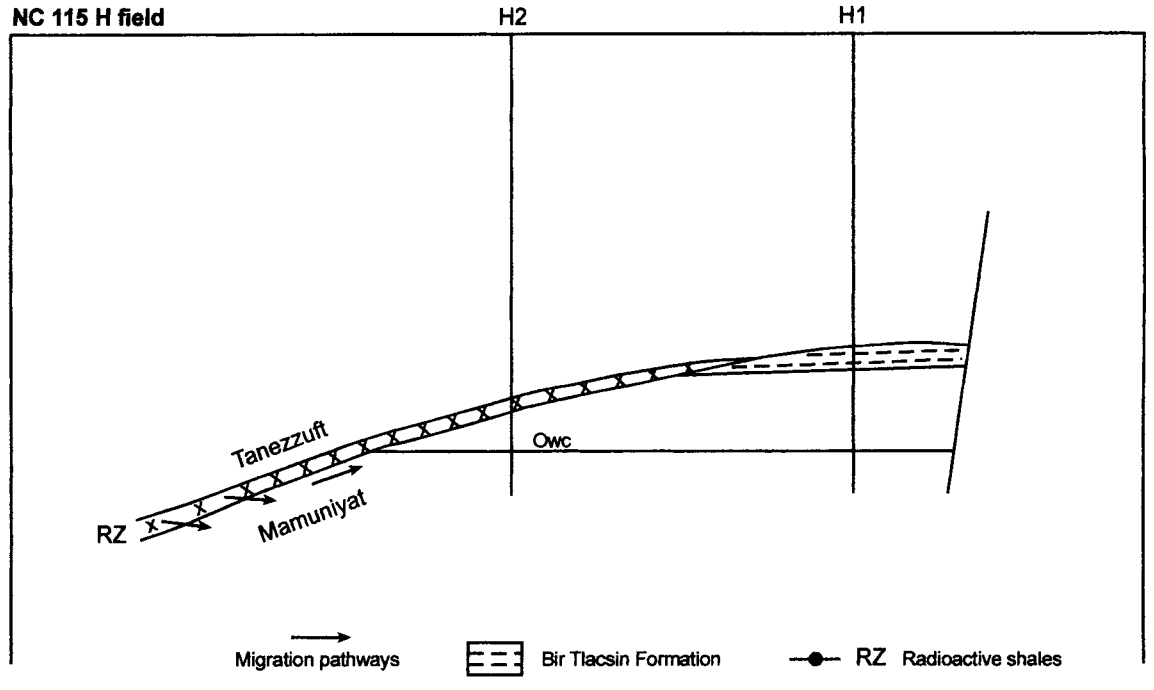


Figure 26. NC115 H-field, illustrating the single known case where the presence of the Bir Tlacsin Formation does not affect the productivity of the structure.

Faults as conduits or barriers

The importance of the vertical migration model is indicated by:

- The presence of oil generated from Tanezzuft shales in Devonian reservoirs (Meister et al., 1991).
- The presence of numerous oil shows in the Devonian over the faulted northern part of the Traghan High,
- The absence of hydrocarbons in the Tiririne High where Mesozoic faults probably served as a conduit, suggesting that these aided the dispersal of hydrocarbons in this area, resulting in leakage to the surface.

Faults in the Murzuq Basin may also act as lateral migration barriers. This possibility is demonstrated by the effects of the regional SW–NE trending wrench-fault sets that extend from the southeastern parts of the Tiririne High (wells E1- and G1-NC58) up to the eastern flank of the Awbari Trough (East from H-NC115). This regional fault system separates the Idhan depression from the Awbari Trough and has probably acted as a barrier for hydrocarbons migrating from the Idhan Depression. This may explain why structures F1-, E1- and G1-NC58 (Tiririne High) and D1- and E1-NC174 (Awbari Trough) gave negative petroleum results. Migrated hydrocarbons from the Idhan Depression probably reached this area but either they then leaked through the Mesozoic sands to the surface (Fig. 28) or they were deflected upwards and northeastwards to the Traghan High (Fig. 27). However, these are only preliminary hypotheses and the effects of fault systems distribution and geometry on hydrocarbon migration pathways is still very poorly understood in the Murzuq Basin.

Petroleum systems in the Murzuq Basin

To date only the Silurian/Ordovician petroleum system has been demonstrated to function in the Murzuq Basin (Boote et al., 1998). Hydrocarbons reservoired in the Ordovician Mamuniyat

Formation's sandstones have been charged from the Silurian Tanezzuft Formation basal radioactive shales. A possible second petroleum system is however related to Devonian reservoirs charged by Devonian and/or Silurian shales. This possibility is supported by the

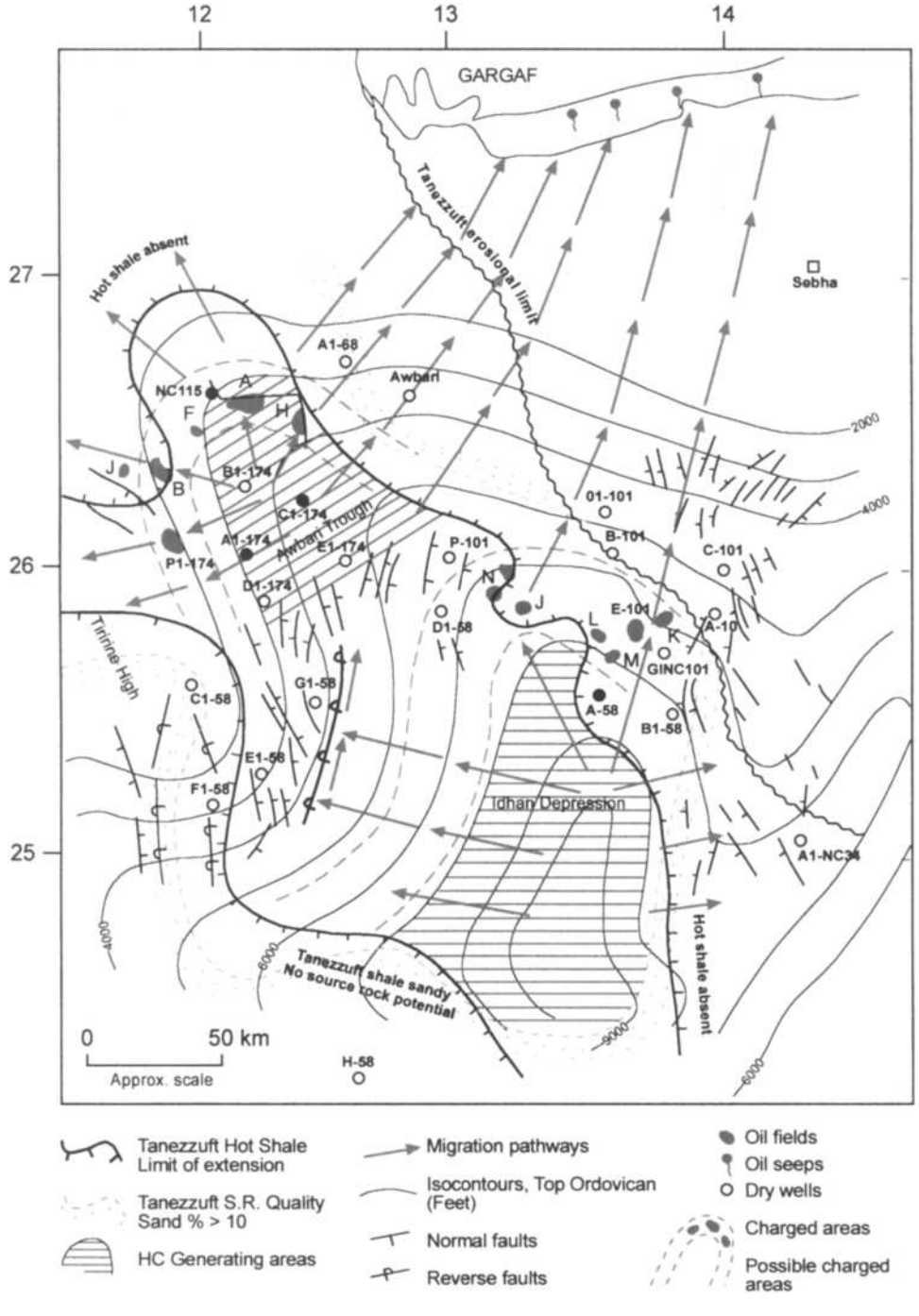
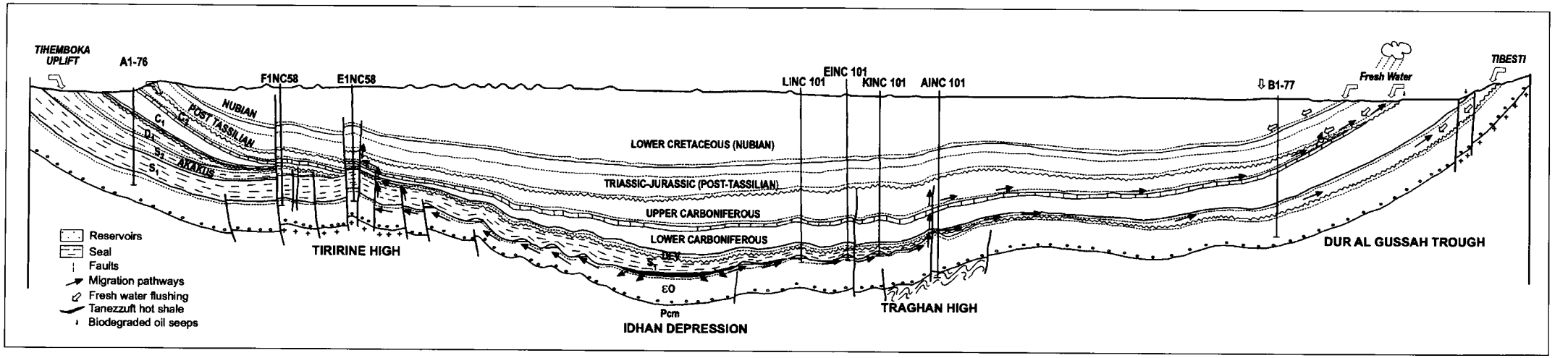


Figure 27. Silurian/Ordovician petroleum system summary map, showing regional factors influencing the areal distribution of oil fields in concessions NC115 and NC101. Note the Bir Tazit fault barrier complex effectively separating the two productive areas in the basin. Structure of the seal also affects this productivity distribution – when the structurally highest part of the basin has a synclinal shape, the charged areas follow a curved line.


TIHEMBOKA UPLIFT
A1-76
F1NC58
E1NC58
LINC 101
EINC 101
KINC 101
AINC 101
B1-77
Fresh Water
TIBESTI
NUBIAN
POST TASSILIAN
AKAKUS
LOWER CRETACEOUS (NUBIAN)
TRIASSIC-JURASSIC (POST-TASSILIAN)
UPPER CARBONIFEROUS
LOWER CARBONIFEROUS
DEV
εO
Pcm
TIRIRINE HIGH
IDHAN DEPRESSION
TRAGHAN HIGH
DUR AL GUSSAH TROUGH
Reservoirs
Seal
Faults
Migration pathways
Fresh water flushing
Tanezzuft hot shale
Biodegraded oil seeps

discovery of subcommercial oil accumulations in concessions NC58 and NC115 and by the presence of numerous oil shows in structurally high areas, e.g. in concession NC101.

The Silurian/Ordovician petroleum system

The basal Tanezzuft hot shales were deposited in NW–SE trending palaeolows such as the Idhan Depression and the Awbari Trough, whose development initiated in the early Palaeozoic. These lows were the sites of euxinic conditions favourable for the deposition of organic-rich shales and they were separated from each other by the Tiririne and Traghan highs, characterised by more condensed shale sequences with a higher coarse clastic input and low source rock potential.

During the Carboniferous, the Idhan Depression became the site of significant subsidence that continued during the Mesozoic and the Tanezzuft source interval probably entered the oil-generating window in this area in the late Jurassic or early Cretaceous.

Preferred routes for hydrocarbon migration were controlled by several factors, including the source/reservoir relationship, the structural morphology of the seal, lateral changes in reservoir quality and fault distribution. Efficient charging was facilitated by the proximity of mature source rocks with regionally continuous and locally fractured Ordovician migration conduits. The importance of direct contact between source and reservoir is enhanced by the dominant Mamuniyat fine-grained sandstone lithology, unfavourable for long distance migration. In some areas, where the Bir Tlacsin Formation is preserved, this unit may act as a barrier for source/reservoir communication. In faulted areas, such as over the Tiririne and the Traghan highs, vertical migration has led to hydrocarbon dispersal and leakage through Mesozoic and Tertiary fault systems.

The multiphase evolution of the Murzuq Basin has produced a great variety of structural traps of different ages. Producing structures are related to traps principally initiated during the Hercynian tectonic phase. Hydrocarbon entrapment has also occurred in traps related to late Ordovician Mamuniyat glacial palaeotopography, as is the case in concession NC101. In the northwestern parts of the Murzuq Basin some Hercynian structures continued their growth during the Mesozoic, while others may have been created by mid-Cretaceous tectonism. Drilling of the latter has however given negative petroleum results to date. In this area, despite the presence of structures with high vertical closure and size, their trapping effectivity was probably affected by wrench faulting that enabled cross-fault communication with younger Devonian and Mesozoic sands. These faults also acted as lateral migration barriers, deflecting migration pathways towards the western flanks of the Awbari Trough.

CONCLUSIONS

The present structural framework of the Murzuq Basin reflects the successive effects of tectonic movements related to Ordovician, Silurian/Devonian, late Palaeozoic, Mesozoic and Tertiary tectonism. Structuring is mostly related to Hercynian compressional movements. The multiphase evolution of this basin has produced a great variety of trap types. The main trapping mechanisms are controlled by structural and glacially related palaeogeomorphological factors, but other more subtle traps may also occur, related to stratigraphic truncation and permeability barriers. The critical elements for migration pathways and play concepts in the Murzuq Basin as we understand them today are summarised in Figs. 27 and 28.

The Silurian/Ordovician petroleum system has proved to be the most prolific target within the Murzuq Basin to date, but present knowledge indicates that no single play concept is valid for the whole Murzuq Basin. The interaction of several key geological factors has clearly controlled the habitat of hydrocarbons in the basin. Present knowledge of such factors as detailed tectonic

evolution, reservoir quality variation, source rock potential and hydrocarbon migration pathways is still very limited.

Migration pathways have been controlled by reservoir facies variations, the Tanezzuft seal structural morphology and continuity and general fault system distribution and timing. In areas where the shaly Bir Tlacsin Formation is developed, this unit seems to act as a barrier for effective and direct source/reservoir communication, adversely affecting the hydrocarbon potential of the underlying Mamuniyat and Hawaz sandstone reservoirs. The long distance migration model proposed by Meister et al. (1991) is probably not effective regionally throughout the Murzuq Basin because of the tight quartzitic nature of the Mamuniyat reservoir, the presence of complicated fault systems and a generally low regional dip.

Potential Devonian reservoirs have not yet been proved to have basin scale productivity. Given the presence of good quality Devonian reservoirs and an effective source rock for this play, the Devonian may have promising potential, particularly in areas where these reservoirs have a good shale seal.

Recent exploration successes in the Murzuq Basin confirm the great potential of a region that is still very much a frontier area. Compared to other basins in the world, the history of exploration in the basin has to date followed a pattern familiar to the petroleum industry, from pre-discovery to 'first discovery boom'. The next step will hopefully be the 'second discovery boom' resulting from technological advances and new geological concepts leading to more effective exploration and the discovery of significant new reserves. A key factor that urgently needs attention is a basinal analysis of the distribution and age of fault system activity and its effect on migration pathways.

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CHAPTER 10

Facies models and sequence stratigraphy of Upper Ordovician outcrops in the Murzuq Basin, SW Libya

N. MCDOUGALL[1] and M. MARTIN[1]

ABSTRACT

The authors have carried out a 9-week field-study of Upper Ordovician outcrops around the Murzuq Basin at the request of a licence group headed by REMSA. The study focused principally on the Ghat and western Gargaf areas, although both Jebel Bin Ghanimah and Dur Al Gussa, on the eastern margin of the basin, were also briefly reviewed.

The units of principal interest were the Mamuniyat and Melaz Shuqran formations. During the course of this study we have informally redefined the stratigraphy of these two units and identified 22 facies associations and five depositional sequences (*sensu* EXXON). These associations reflect deposition in a variety of environments, including braided streams, delta front, delta slope, and storm-wave influenced shoreface to shelf settings. The major facies associations in each stratigraphic unit are briefly reviewed.

The depositional sequences reflect decreasing glacial influence through the late Ordovician. Apart from probable glacial dropstones in the lower Melaz Shuqran Formation, no evidence has been found for glaciation in the Murzuq Basin, but fluctuations in the size and position of the ice sheets are thought to have had a degree of control on relative sea level at the time of deposition and thus on facies distribution and sequence architecture.

INTRODUCTION

This chapter summarises the principal results of a field study carried out on behalf of and in conjunction with Repsol Exploracion Murzuq and partners, TOTAL, OMV and SAGA. The main aims of the study were to:

- Develop a comprehensive facies scheme for outcrops of the Mamuniyat and Melaz Shuqran formations in order to identify the principal sedimentary environments,
- Re-examine and modify, as necessary, the lithostratigraphy of the Upper Ordovician,
- Develop sequence stratigraphic models summarising the relationships between the principal rock units,
- Create a database of directional data collected from the studied intervals.

The lowermost part of the Tanezzuft Formation and the uppermost Hawaz Formation were also studied at a number of localities in order to provide a stratigraphic context for the development of the Melaz Shuqran and Mamuniyat formations. This information will hopefully establish a

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reliable and practical geological model to better understand the results of seismic surveys and exploration wells in REMSA acreage in the Murzuq Basin.

LOGISTICS AND METHODOLOGY

The fieldwork phase of this study took place from February to April 1998 and lasted some 9 weeks. It focused principally on outcrops in the Ghat/Tikiumit and Gargaf areas although Jebel bin Ghanimah, and especially the Dur al Gussa area were also briefly reviewed (Fig. 1). Within these areas a total of 115 locations were visited. These were principally documented by means of outcrop logs drawn at a variety of scales ranging from 1:10 to 1:200 and supported by sampling for petrographical and palynological analyses. Palaeocurrent data were also recorded wherever possible from a variety of structures, mostly from trough cross-bedding, hummocky megaripples, primary current lineation, ripples and slump axes.

STRATIGRAPHY

It is apparent from a review of the available literature (Bellini and Massa, 1980; Grubic et al., 1991) that the stratigraphic nomenclature of the Murzuq Basin and adjacent outcrops is in a state of some confusion. During this study, however, there was no intention to formally redefine this stratigraphy. Instead an informal, practical, terminology is employed which may ultimately become accepted and formalised after extensive integration with subsurface datasets.

It is a principal conclusion of this study that the uppermost Ordovician succession can be subdivided into four unconformity-bound rock units herein termed the Melaz Shuqran, lower

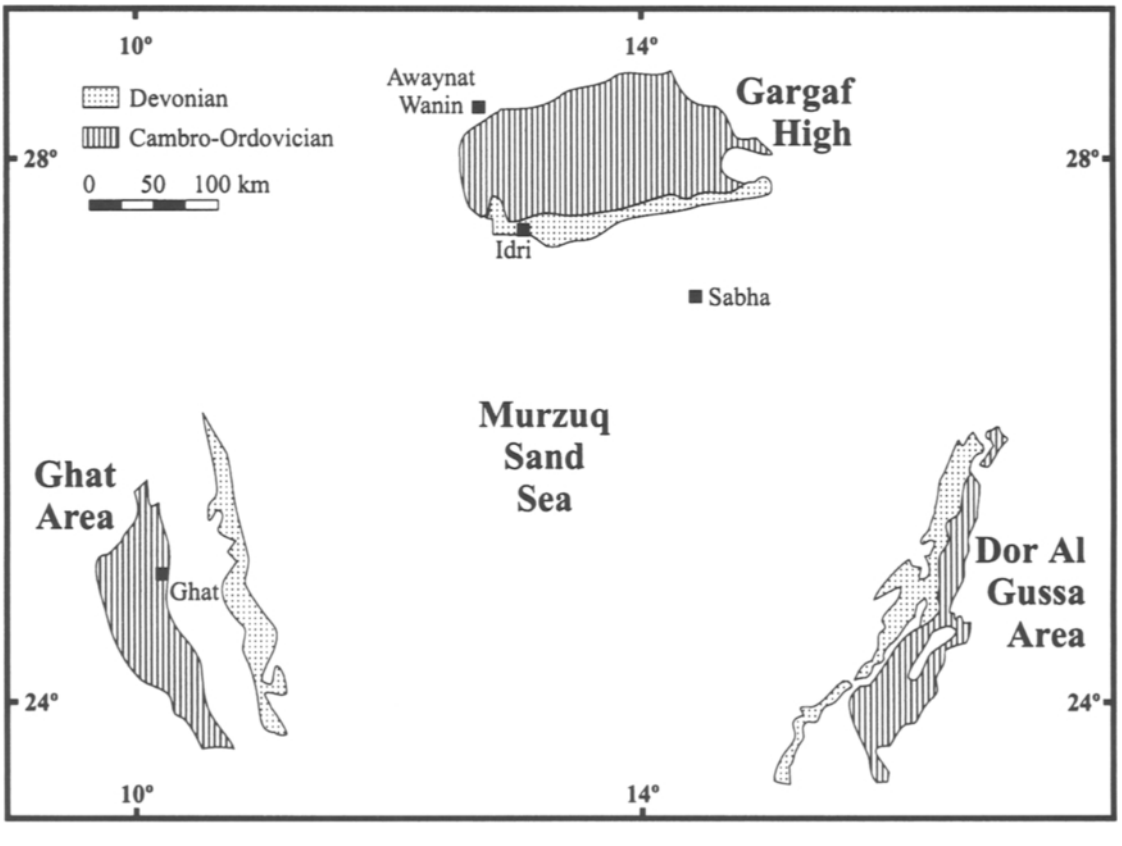

Figure 1. Geological sketch map of southwestern Libya highlighting the location of the study areas.

Mamuniyat, middle Mamuniyat and upper Mamuniyat formations. The fundamental characteristics of these units are summarised in Fig. 2 and in succeeding sections.

FACIES AND DEPOSITIONAL ENVIRONMENTS

The Melaz Shuqran and Mamuniyat formations comprise some 22 facies associations and a total of 60 lithofacies. The facies associations are grouped according to lithostratigraphic unit. The

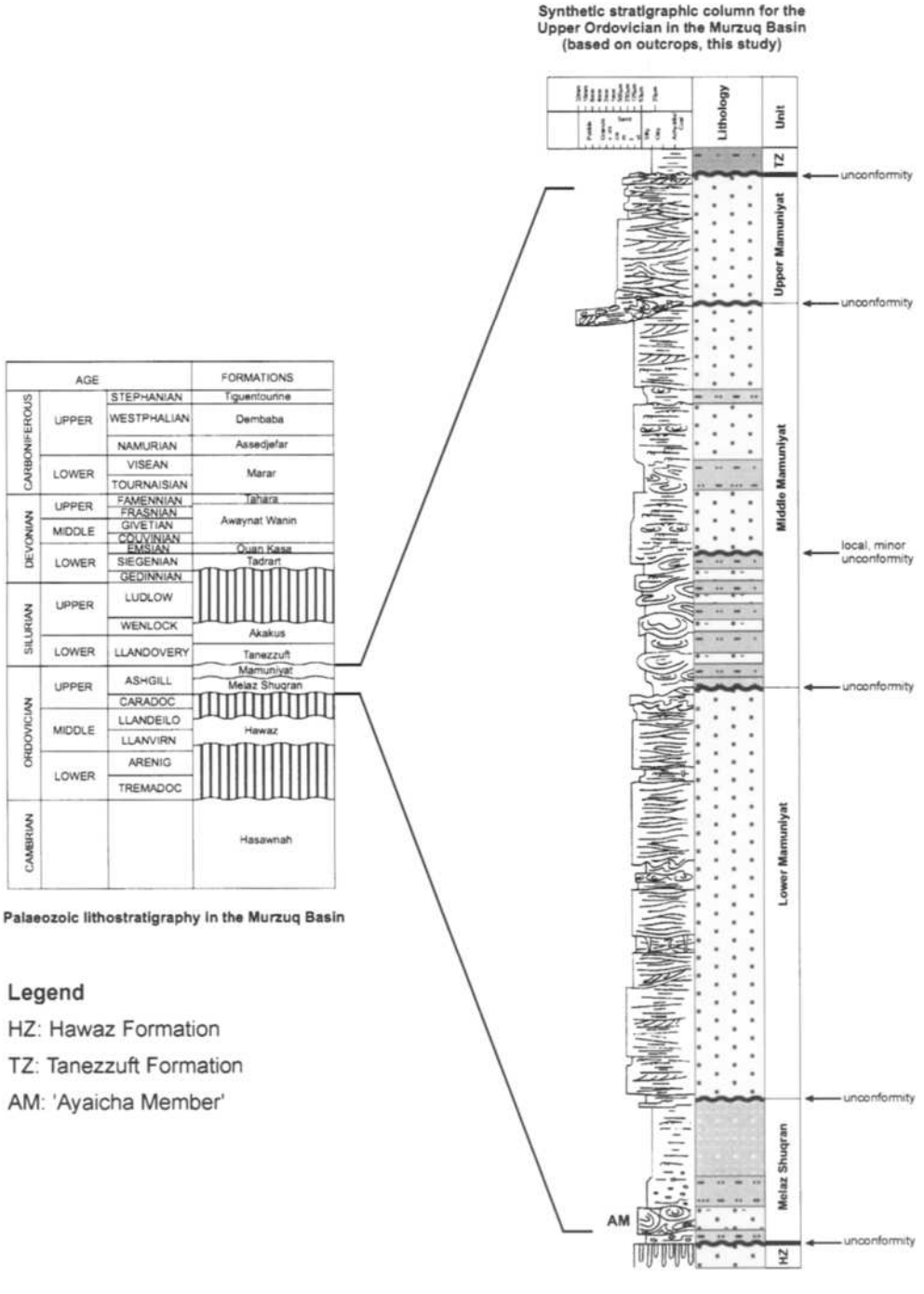

Figure 2. Summary of Upper Ordovician stratigraphy in SW Libya as used in this study.

details of this facies scheme remain confidential although the broad outlines of the facies framework are summarised in Table 1 and presented in the following sections. A summary of the sea-level fluctuatiuons interpreted to be represented in the succession is shown in Fig. 3.

Melaz Shuqran Formation

This is a predominantly shale-rich unit up to 70 m thick. It comprises argillaceous sediments assigned to four facies associations and a total of six lithofacies. At the most fundamental level sediments are differentiated into glacially influenced and non-glacial facies. The former are chiefly identified by the presence of probable dropstones within argillaceous siltstones (see Fig. 4) interpreted as rain-out diamictites (Benn and Evans, 1998) and/or ice margin density underflows. Non-glacial sediments are, in marked contrast, represented by heterolithic silty mudstones containing wave or current rippled sand lenses. In either case, the Melaz Shuqran Formation clearly represents the highest relative sea level attained during deposition of the Upper Ordovician succession.

Lower Mamuniyat Formation

This is the most aerially extensive of the Mamuniyat units, being present in most of the studied areas. It is largely synonymous, in the Tikiumit area, with the Tashgart Formation of Protic

Table 1. Summary of facies associations present in the succession studied

Formation	Facies Associations
	BR (Braided stream deposits)
	BRB (Bedrock-confined braided stream deposits)
	BC (Basal conglomerate)
Upper Mamuniyat	EC (Ephemeral channel/interchannel deposits)
	CL (Clinoform deposits)
	CG (Gilbert delta facies)
Unconformity	
	CS (Condensed sequence deposits)
	MSH (Muddy shelf deposits)
	SL (Slope)
	WB (Wave-influenced mouth bar)
Middle Mamuniyat	DF (Delta front)
	DP (Delta Plain deposits)
	FS (Foreshore to shoreface deposits)
Unconformity	
	SF (Storm-dominated sand-rich shelf)
	SS (Sandy shelf deposits)
Lower Mamuniyat	WS (Wave-dominated shelf/shoreface deposits)
	SN (slumped sandflat sandstones)
	AP (Alluvial plain deposits)
Unconformity	
	GS (Glacially-influenced shelf deposits)
	SD (Non-glacial shelf deposits)
Melaz Shuqran	GM (Subaqueous ice margin deposits, the 'Ayaicha' Member)
	TL (Transgressive lag deposits)

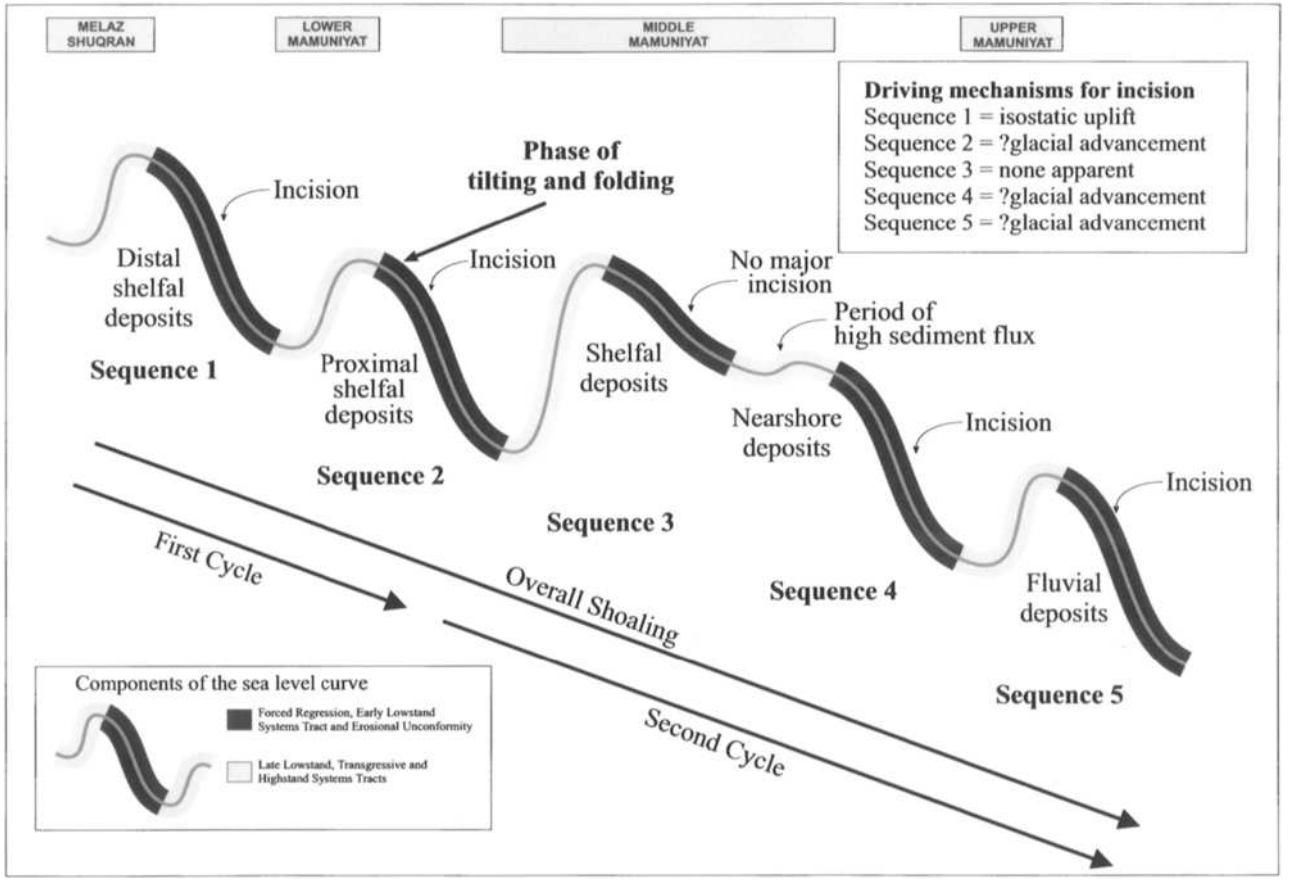

Figure 3. Relative sea-level fluctuations through the Late Ordovician.

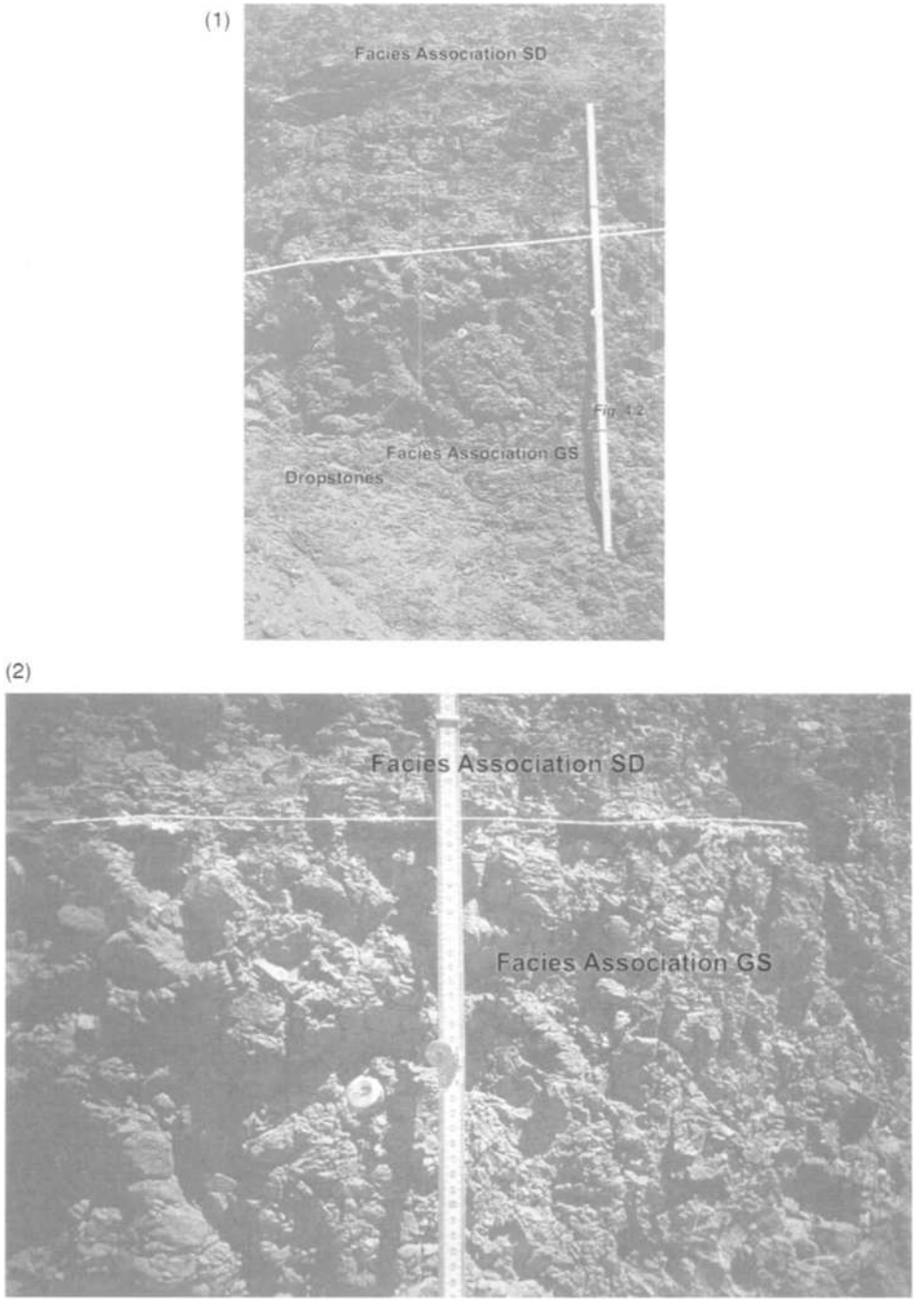

Figure 4. (1) Location 27°58.906′ N, 12°41.174′ E, Melaz Shuqran Formation, facies associations GS and SD: Over 1 m of section highlighting the contact between these facies associations. The lower unit contains rounded, pebble-sized (up to 6 mm in this view) vein-quartz and other extraformational clasts. These are interpreted as dropstones within a matrix of sandy/silty mudstone. A sharp, relatively planar break separates the dropstone unit from heterolithic mudstones containing thin ?wave cross-laminated fine-grained sandstone beds. (2) Location 27°58.906′ N, 12°41.174′ E, Melaz Shuqran Formation, facies associations GS and SD: A close-up view of the highlighted part of Fig. 4.1 mainly shows the dropstone facies, the principal feature of which is a small- to medium-sized rounded pebble in the centre of the image. This is typical of this facies in many parts of the study area.

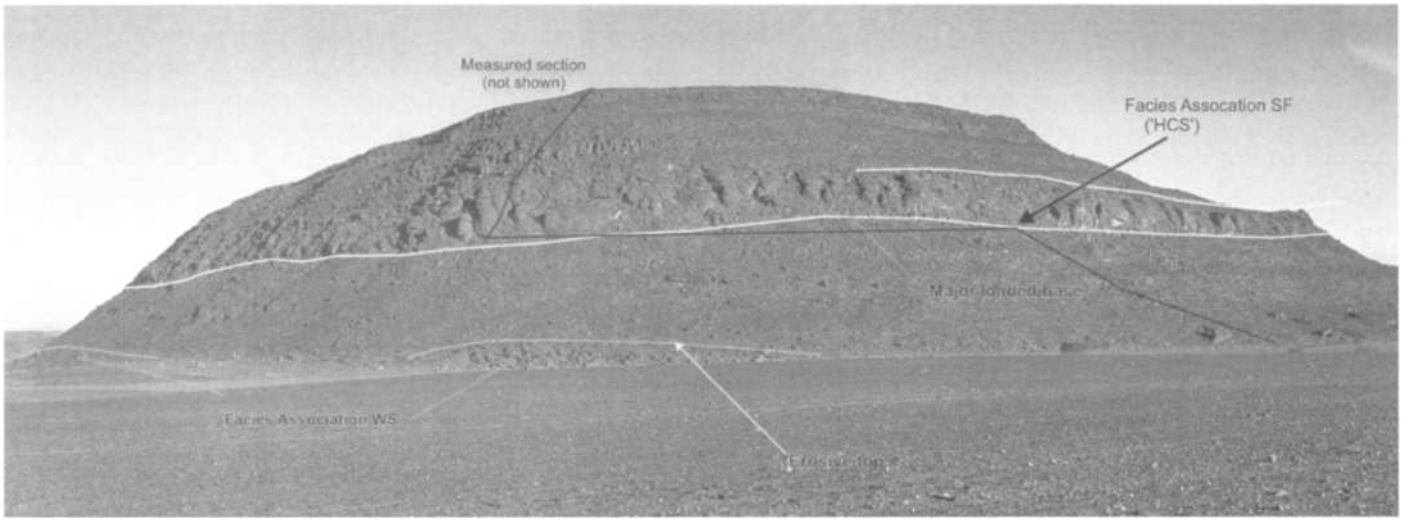

Figure 5. (1) Location 27°43.107′ N, 12°51.792′ E ('Gara Antelope'), lower Mamuniyat Formation, facies associations SF, SS and WS: Panoramic photomontage to the ESE of the southernmost hill at the Mamuniyat type section. The outcrop section is some 104 m thick. Principal features include the distinctive, (23 m thick) hummocky cross-bedded unit, which can be correlated across much of the SE part of the Gargaf study area, where it often represents the top of the lower Mamuniyat Formation (see also Fig. 6). This unit has a sheet to wedge-shaped geometry, apparently thinning southwards. Also shown are occurrences of Facies Association WS. These outcrop at the base of the hill and may have an elongate geometry with an erosional upper boundary.

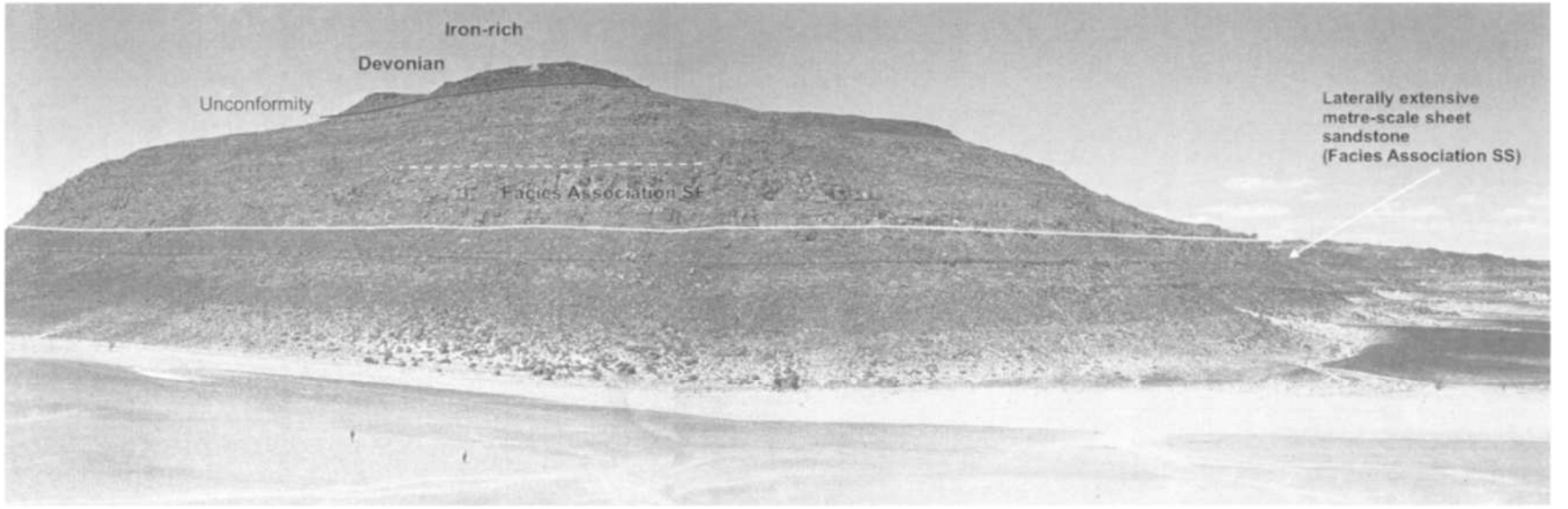

Figure 5. (2) Location 27°43.107′ N, 12°51.792′ E ('Gara Antelope'), lower Mamuniyat Formation, overlain by Devonian strata, facies associations SF and SS: Panoramic montage, looking NW, of the northernmost of the two distinctive hills comprising this locality. Outcrop quality is generally poorer than in the southern hill, although because of the slightly higher elevation a thin basal Devonian section has also been preserved. This directly overlies the lower Mamuniyat Formation, cutting out the Silurian and an indeterminate thickness of uppermost Ordovician section. The Devonian strata are iron-rich, resulting in a virtually black weathering colour – which usually distinguishes them from the Mamuniyat Formation in this area. This image, like Fig. 5.1, also highlights the laterally extensive character and sheet-like geometry of the Mamuniyat storm beds (facies associations SF and SS).

(1984) and Grubic et al. (1991) although elsewhere it has been included within the 'Memouniat Formation' (Parizek et al., 1984; Radulovic, 1984a, b). It is characterised by a predominantly fine-grained, sand-prone succession with a maximum thickness of at least 100 m (see Figs 5 and 6). Sediments are assigned to 5 facies associations and 25 lithofacies. These represent deposition in a variety of environments, principally storm-influenced shallow marine settings although locally, deposition appears to have occurred on sand flats and braid plains.

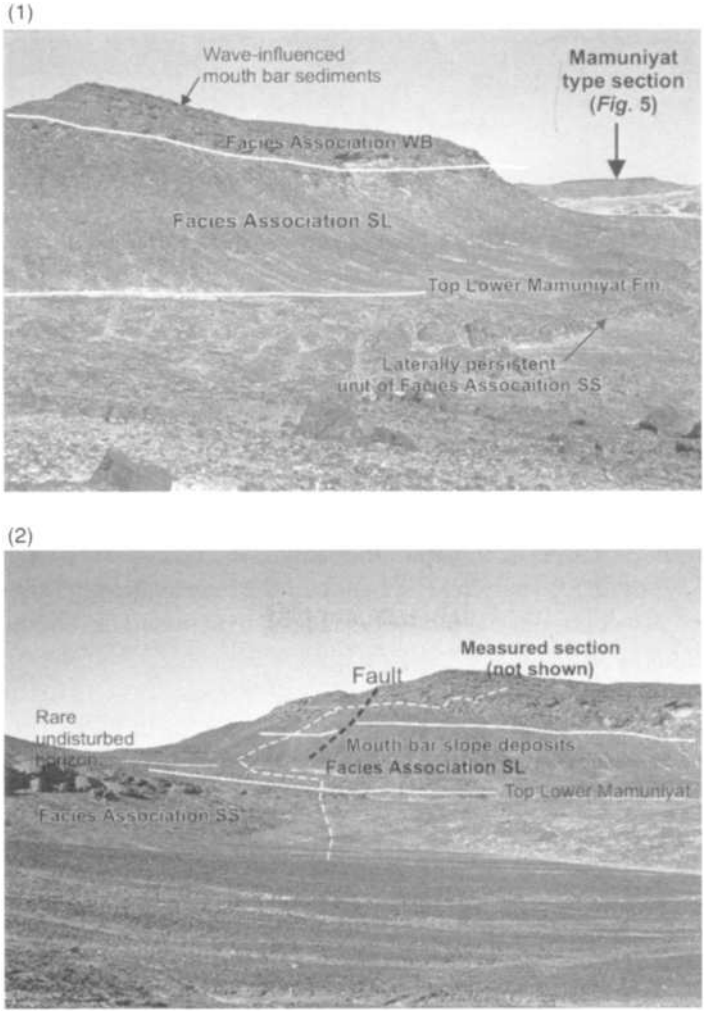

Figure 6. (1) Location 27°44.835′ N, 12°47.995′ E, lower and middle Mamuniyat Formation, facies associations SF, SL, WB and SS: This image, looking SE towards Gara Antelope, should be seen in conjunction with Fig. 6.2. The foreground is composed largely of hummocky sandstones assigned to Facies Association SF and the lower Mamuniyat Formation. A thin, but highly persistent silty bed <0.5 m thick (facies association SS) is also observed separating units of these sandstones. The hill covering much of the image is composed entirely of middle Mamuniyat Formation tilted toward the NE. (2) Location 27°44.835′ N, 12°47.995′ E, lower and middle Mamuniyat Formation, facies associations SF, SL, WB and SS: This image, looking eastwards, shows the northern end of the main outcrop in Fig. 6.1 and especially the location of the measured section. Again the low domal features outcropping in the foreground comprise lower Mamuniyat Formation sandstones. Relief on the unconformity separating the middle and lower Mamuniyat Formation is clearly visible, trending from top left to bottom right. Above the unconformity, there are largely scree-covered slope deposits with common slumps and slides. Occasionally, thin wave rippled and planar laminated beds appear to have avoided soft sediment deformation.

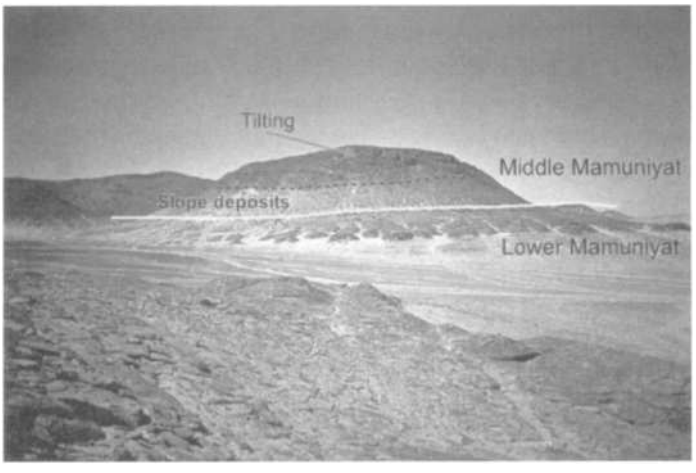

Figure 6. (3) Location 27°44.835′ N, 12°47.995′ E, lower and middle Mamuniyat Formation, facies associations SF, SL and WB: View looking NE from the summit of the hill shown in Fig. 6.1 and 6.2, showing a similar succession and structural style. Again relief is visible on the intra-Mamuniyat unconformity, dipping from right to left. Also highlighted is the middle Mamuniyat subdivision into silty slope (Facies Association SL) and wave-influenced mouth bar deposits (Facies Association WB). Both these units are clearly tilted, serving to emphasize the discordance between the lower and upper Mamuniyat formational units.

Middle Mamuniyat Formation

This informal unit is advanced as a new concept in the local Upper Ordovician stratigraphic succession. It principally occurs in the Gargaf area and is the most varied unit in terms of facies characteristics. In general terms, it is a variably argillaceous and generally fine-grained package up to at least 100 m thick, often characterised by large scale syndepositional deformation features such as slumps, metre-scale load balls, slides and growth faults (Fig. 6). Sediments of the middle Mamuniyat Formation can be assigned to a total of 7 facies associations and 18 lithofacies, mostly deposited in a linked complex of unstable delta front (mouth bar, distributary channels), slope and shelf environments. Deposition also occurred, locally, in destructive delta front (foreshore/shoreface) and braid delta plain environments.

Upper Mamuniyat Formation

This unit is present in all the studied areas, although it is most extensively developed in the Ghat and southern Tikiumit areas. In these areas upper Mamuniyat Formation thickness may exceed 100 m although elsewhere, such as in the SW Gargaf area, 20 m is more typical. It is typically coarse-grained, locally conglomeratic, and almost free of shaly horizons. Sediments are assigned to 6 facies associations and 13 lithofacies mainly deposited in braid plain, sand flat and bedrock-confined ?anastomosed high-energy fluvial systems (Fig. 7). Locally, the upper Mamuniyat Formation also comprises discrete bodies of inclined sediment interpreted as braid-delta clinoforms and Gilbert deltas.

SEQUENCE STRATIGRAPHY

During the late Ordovician the study area was subject to an intricate and dynamic interplay of tectonics, localised sediment supply and glacial eustasy associated with the advance and retreat

of ice sheets. This resulted in the development of complex superimposed relative sea level cycles, which due to localised tectonics during isostatic rebound cannot be followed over large areas, i.e. one area may have been undergoing glacial downwarping whilst another several tens to hundreds of kilometres away may have been experiencing isostatic uplift.

Five unconformity-bound sequences have been identified. With a single exception (the middle Mamuniyat) these sequences approximate to the previously outlined formations and all exhibit at least some incision at their base. They are summarised as follows:

Sequence 1 (Melaz Shuqran),
Sequence 2 (lower Mamuniyat),
Sequence 3 (middle Mamuniyat),

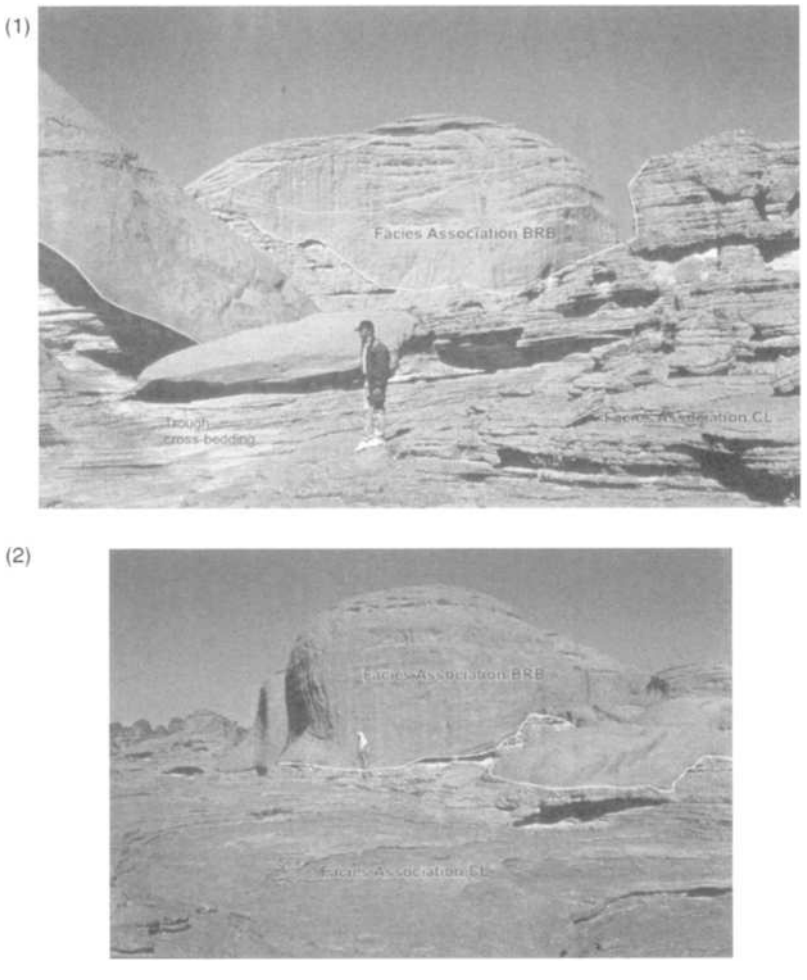

Figure 7. (1) Location 25°5.082′ N, 10°1.323′ E (Tahrmt), upper Mamuniyat Formation, facies associations CL and BRB: View to the WNW highlighting the characteristic erosional relationship between clinoform deposits and Facies Association BRB. Most noteworthy are the markedly 'stepped' and often steep erosional bases confining the coarse-grained sandstones of Facies Association BRB. Channel profiles are irregular and characterised by low width/thickness ratios. Also note multistage fill to channel body, metre-scale trough cross-bedding declining in scale up coset and the dip of the clinoform sediments from right to left. (2) Location 25°5.082′ N, 10°1.323′ E (Tahrmt), upper Mamuniyat Formation, facies associations CL and BRB: Another view looking NW also showing the highly irregular nature of the BRB channel bodies. Note the multistorey fill and large-scale of trough cross sets. Also apparent is the characteristic, rounded form typical of outcrops of this facies.

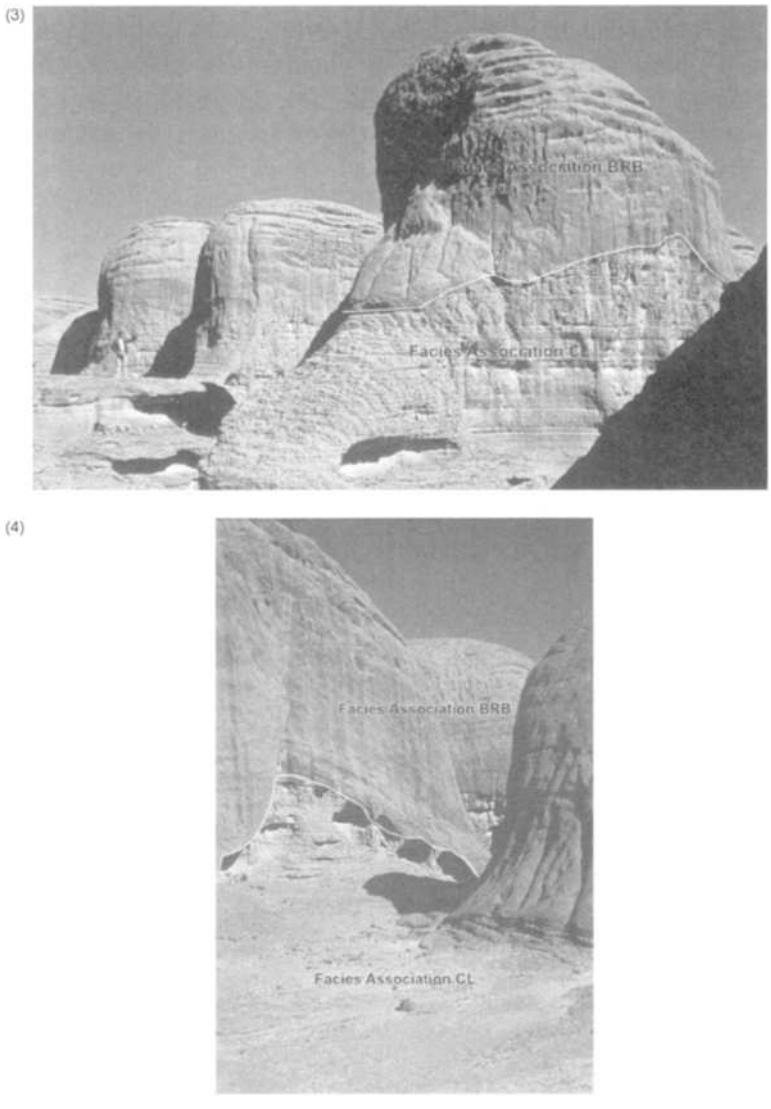

Figure 7. (3) Location 25°5.082′ N, 10°1.323′ E (Tahrmt), upper Mamuniyat Formation, facies associations CL and BRB: View looking NNW showing both clinoform deposits and Facies Association BRB. Note the well-bedded character typical of the former. No dip is apparent as this view shows a section roughly perpendicular to the direction of progradation. Also shown is the steep, irregular erosive base to Facies Association BRB and large-scale trough cross-bedding. Common mud chips are also observed in the basal part of the facies unit. (4) Location 25°5.082′ N, 10°1.323′ E (Tahrmt), upper Mamuniyat Formation, facies associations CL and BRB: another view showing the highly irregular nature of the facies contact suggesting that powerful erosive flows exploited any pre-existing weakness in the clinoform deposits.

Sequence 4 (middle Mamuniyat),
Sequence 5 (upper Mamuniyat).

Initial interpretations suggest that sequences 1, 2, 3 and 5 are of a similar order, whereas sequence 4 may be of a higher order. Thus sequences 3 and 4 together are present within the middle Mamuniyat Formation.

The lack of rigorous biostratigraphic control makes correlation of the sequences from one area to another problematic. There are, however, distinct marker horizons that can be traced

around the basin, such as a highly fossiliferous, but thin (< 1 m) unit thought to represent a period of condensation within the late Ordovician. In the absence of several such marker beds, facies unique to the various stratigraphic units must be used in sequence identification.

The sequences show an overall, progressive, if punctuated, shoaling (Fig. 3) such that Sequence 1 records proximal offshore, glaciomarine or shelfal deposition and Sequence 5 braided and anastomosed fluvial channels. This trend can be divided into two major cycles, the first comprising sequences 1 and 2 and the second sequences 3 to 5. These represent two phases of upwards shoaling. The sequences show increasing isolation through time (i.e. Sequence 1 is widespread and Sequence 5 is localised). In more proximal settings (to the south of the study area), the identification and regional correlation of the younger sequences can be problematic.

The architecture and relationship of the sequences is complex, with multiphase cut-and-fill of incised valleys. The geometries of the fills are highly dependent on the local accommodation space generation. It is thought that most of the Upper Ordovician sediments preserved in the Murzuq Basin represent either transgressive or highstand system tract deposits, with most of the lowstand phases of the sequences involving incision rather than deposition.

FIELD EVIDENCE FOR GLACIATION

In view of the widespread assumption that the Melaz Shuqran and Mamuniyat formations are closely associated with northern Gondwanan glaciation it is worthwhile to briefly review the field evidence. This indicates that direct evidence for glaciation in the Upper Ordovician succession is limited to the occurrence of dropstone textures in the lower part of the Melaz Shuqran Formation and rare subaqueous ice striations in the Mamuniyat Formation south of Ghat. Possible indirect indications of abnormal sedimentation include persistent high sediment flux during deposition of the lower Mamuniyat Formation, high energy discharge fluvial channels found in the upper Mamuniyat Formation and sequence-stratigraphic indications of rapid relative sea level fluctuations which probably relate to isostatic rebound and glacial eustasy interactions.

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Special thanks are due to Dr Ahmed El Hawat, Department of Geology, Garyhounis University, Mr Abdulla Khoja, NOC Exploration Department and finally Hassan S. El-Bargathi and Adel Ali Abdalla Obiedi for their assistance in the field. The authors would also like to acknowledge the support and assistance of Repsol Exploracion Murzuq S.A and partners (TOTAL, OMV, SAGA) in the production of this chapter. (Note: GPS coordinates provided in association with Figs 4 to 7 are WGS-84 system-based).

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CHAPTER 11

Ordovician and Silurian Arthrophycid Ichnostratigraphy

ADOLF SEILACHER[1]

ABSTRACT

Group-specific fingerprints (transverse corrugation) and distinctive behavioral programs make arthrophycids more suited for ichnostratigraphic correlation than other worm burrows. Arthrophycids comprise the ichnogenera *Arthrophycus*, *Daedalus* and *Phycodes*, whose ichnospecies evolved various behavioral programs for more efficient sediment feeding. In the Ordovician and Silurian, these trace fossils complement the scheme based on trilobite burrows (*Cruziana*) and at the same time have a more global distribution.

GENERAL CONSIDERATIONS

As stratigraphic lore has it, trace fossils are relatively useless in determining the age of the bedrock. This is certainly true for the majority of invertebrate burrows, particularly the 'non-descript' forms lacking diagnostic features, but nevertheless bearing Latin names. This common verdict also applies to more characteristic forms, such as *Rhizocorallium* and other spreiten burrows, because they reflect a certain behavior rather than taxonomic relationship and so may have been made by different animals at different times in geologic history. In order to be stratigraphically useful, trace fossils must be referable to certain groups of organisms: in this case it is irrelevant that we may never know the taxonomic positions of the makers, as long as the traces stand for a particular kind of animals in which body shapes and behavior underwent evolutionary transformation through time.

A prime example is given by trilobite burrows (*Cruziana*). Indeed, some *Cruziana* ichnospecies may have been made by arthropods other than trilobites. It is also true that much smaller, but otherwise similar, burrows (probably made by phyllopod crustaceans) occur in non-marine sandstones of Paleozoic through Mesozoic ages. Nevertheless it has been possible to establish a *Cruziana* stratigraphy, by which otherwise non-fossiliferous early Paleozoic sandstones can be recognized as marine and can be correlated in now widely separated parts of the world (Seilacher, 1970, 1991). The basis for this scheme has been: (1) a shared mode of burrowing (scraping sediment towards the midline instead of from under the body) and (2) scratch morphologies reflecting claw configurations that were the same in the many legs of one individual. Once general relationships have been established by these unifying fingerprints, one

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can then distinguish ichnospecies by distinguishing claw formulae and burrowing behaviors. The Silurian outcrops of the Murzuq Basin (Massa and Jaeger, 1971) play a crucial role in this effort.

This chapter deals with another group of trace fossils common in these Paleozoic sections, namely arthrophycids. These burrowing programs show an even greater variety, but the disparate trace morphologies are united by particular fingerprints: viz. (1) transverse backfill structures ('spreiten') and (2) a surface sculpture consisting of discontinuous rings, or knobs, that give the burrows a somewhat square cross section. In fact, these burrows may resemble a stem more than an ordinary cylindrical 'worm' burrow. Although originally coined for seaweed, the name *Arthrophycus* reflects this morphology.

Paleobiology

What do we know about the animals that produced arthrophycid burrows? The sculptures are certainly too blunt for scratches made by arthropod legs. In particularly well-preserved specimens one can also see sets of much finer transverse ridges that are reminiscent of wrinkles in a soft integument (Fig. 1b). This and the smooth curvature of the backfill lamellae point to a long, worm-like body that could reach a diameter of more than a centimeter – larger than a fat earthworm. On the other hand, these animals did not burrow merely by peristaltic waves passing along their bodies, because they must have been able to displace sediment from one flank of the body to the other to produce a lateral backfill. So, 'worm-like' means only a basic body construction found in burrowing members of many phyla – from sea cucumbers to annelids.

When considering the biological function of arthrophycid burrows we are on safer ground. Infaunal filter feeders commonly produce U-shaped burrows that provide protection and can be easily ventilated. However, the tube of arthrophycids is J-shaped with a blind end and its systematic translocation suggests sediment feeders. What kind of food they were looking for is another question. Arthrophycid burrows are commonly found in very clean sand, in which one would not expect much organic detritus. *Daedalus* in the Medina Sandstone also stops before reaching an underlying clay. Is it possible that the pore space of these sands housed enough minute animals (Mesopsammon) to warrant such an energy-consuming search effort?

The basic difference between arthrophycids and other spreite burrows (that the generating tube had the shape of a J rather than an U) can be seen from the asymmetry of the spreite in lateral view (arcs are more gently curved on the side where the shaft was) and tapering towards the tip. A blind-ended tunnel can also be inferred from the way in which the spiral turns of the *Daedalus* burrows intercut. This also suggests that the animal was exploring the sediment for food at the head end of the tunnel – in the same way that *Arenicola* does today.

We may never know how many weeks, or years, it took an arthrophycid animal to make its burrow. Nevertheless it must have been significantly less than a lifetime, as we never observe tunnel dimensions that become systematically larger within one system.

Biostratigraphy

Biostratigraphic correlation can only be as good as the taxonomic resolution of the index fossils on which it is based. Paleoichnological difficulties in distinguishing between preservational, behavioral and specific variation have led to the habit of using only ichnogeneric names (although systematic descriptions are required to be binomial). Such practice may be permissible in paleoecological studies. In ichnostratigraphy, however, taxonomic resolution has to be as close as possible to that of the unknown animal species and ichnospecific distinctions

must be made. Only after they have been identified can minor differences be tested for stratigraphical utility in the field. In this sense, the present study – as in my previous work describing behavioral modifications in *Cruziana acacensis* (Seilacher, 1996) – is only an initial step. The new tool can only be sharpened if used by field geologists. Even so, we can already say that the arthrophycid trace fossils reviewed herein have distinct ranges within the Ordovician and Silurian succession. To what degree these ranges can be narrowed down is a matter for future testing – particularly in areas in which better calibrated body fossils are also available.

Paleogeography

Along with a finer taxonomic resolution comes not only a stratigraphic, but also a geographic pattern of distribution. This has been particularly striking in trilobite burrows. Throughout the Paleozoic, most well known *Cruziana* ichnospecies are restricted to the now fragmented Gondwana paleocontinent and can be also used to identify exotic Gondwanan terranes in Newfoundland (Seilacher and Crimes, 1969), southern Urals (B. Erdtmann, pers. comm., 1998) and China (Seilacher, 1991). Arthrophycids were seemingly less provincial, as shown by their occurrence in the Laurentian part of present North America. Thus they can potentially be used for a more global correlation, but may prove less useful for terrane identification.

Paleoecology

Because of their strictly autochthonous nature, trace fossils are particularly good facies indicators – provided they are distinctive enough. Arthrophycid burrows, in particular, signal shallow marine conditions. This is demonstrated by their co-occurrence with trilobite burrows (*Cruziana acacensis*) in the western Murzuq Basin. Yet, the distribution of the two groups of trace fossils is not completely congruent. In Chad, for instance, similarly aged beds with abundant *Arthrophycus alleghaniensis* did not yield any *Cruziana*, which do however occur in adjacent horizons. Also, the Middle Ordovician Hawaz Formation at Al Barkat (south of Ghat) contains distinctive arthrophycid burrows; but intensive search produced not a single *Cruziana* that could have narrowed the geologic age. So we may assume that the arthrophycid animals had a wider tolerance than trilobites – for instance with regard to salinity.

There is also some preference to substrate. While *Arthrophycus* and *Daedalus* are usually found in rather pure and thick-bedded sandstones, the smaller *Phycodes* is restricted to dark shales with centimetre thick siltstone beds.

Preservation

All arthropycids are found in sandstones, but in different ways. *Arthrophycus* (= *Harlania*), as well as the smaller *Phycodes*, caught the eyes of early field geologists because they stick out in relief from the soles of sandstone beds. This does not mean that they were made on a muddy substrate: they lived in the overlying sand, but also penetrated into the mud layer underneath. Because they were cast by the animal's activity – rather than by a sedimentational event – the resulting undertraces preserve the sculptures best, but they represent only the bottom parts of burrow systems that may have extended well into the sand layer above. That arthrophycid burrows were deeper than appears from the preserved relief becomes clear in the sole faces of the Akakus Sandstone, where they are commonly associated with trilobite burrows (*Cruziana acacensis sandalina*). As in other such cases (Jensen, 1990) it is unlikely that the trilobites

hunted for the worm-like makers of the associated teichichnoid burrows. Rather the trilobite burrows were made earlier and became cross-cut by the deeper-tier worm burrows after more sand had been deposited. (This is also the reason why *Arthrophycus* is limited to relatively thick sands, while *Cruziana* may also occur on the soles of centimeter thick sand beds). In contrast, *Daedalus* burrows are rarely found in the form of sole casts (Delgado, 1885; Pl. X), but become visible on broken sandstone surfaces. The reason is that their makers stopped short before they touched an underlying mud layer. Therefore *Daedalus* provides a much more three-dimensional picture, which in softer sandstones (e.g. the Medina Sandstone of upstate New York) can be enhanced by chisel preparation. On the other hand, the submillimetric transverse sculpture (Fig. 1b) cannot be seen in *Daedalus*, because such details are not preserved inside the sand.

ICHNOTAXONOMY

N. ichnofam: Arthrophycidae

Diagnosis: Paleozoic worm burrows characterized:

- by regular transverse ridges, which are often discontinuous, giving the casts a squarish cross section,
- by teichichnoid backfill structures (spreiten) resulting from transverse or oblique dislocation of a J-shaped tunnel through the sediment. Depending on the behavioral programs, the backfill structures may have linear, palmate, fan-shaped, spiral,or multi-winged geometries. Also, their internal structures may be either protrusive or retrusive.

Typical ichnogenus: *Arthrophycus* Hall 1852

Range: (as presently known) Ordovician and Silurian shallow marine sand- and siltstones.

Remarks: Because trace morphology is variably controlled by anatomical and behavioral features of the trace maker, biologic purpose, and the original consistency and diagenetic history of the sediment, it is impossible to establish a hierarchy of ichnotaxobases (Bromley, 1996) that can be applied to all different kinds of trace fossils. Therefore alphabetic sequence has been used in the Treatise as ordering principle above the ichnogenus level (Häntzschel, 1962). While being practical, this solution neglects the fact that higher-order groupings of ichnogenera are made by every ichnologist – except that the unifying principles vary from group to group and from author to author. Given the extreme heterogeneity of the objects and the differences of opinions in this field, there will never be a 'Linnéan' system, in which every ichnogenus is uniformly nested into higher taxa. Nevertheless we should establish ichnofamilies in groups where this is possible – as in the present case. So far, Arthrophycidae n. ichnofam. comprise the ichnogenera *Arthrophycus*, *Daedalus* and *Phycodes* – each with several behaviorally defined ichnospecies.

Ichnogenus: Arthrophycus Hall, 1852

Synonym: *Harlania* Goeppert, 1852

Type species: *Arthrophycus alleghaniensis* (Harlan)

Emended diagnosis: Arthropycid burrows, 5–15 mm in diameter, which explore the sediment mainly in a horizontal fashion. Consequently, the teichichnoid structures are lower than their horizontal extensions and are mainly expressed as positive hyporeliefs.

Remarks: This ichnogenus is most familiar from the palmate form (*Arthrophycus alleghaniensis*; Harlan 1831, Conrad 1838) that occurs abundantly in Lower Silurian sandstones of the

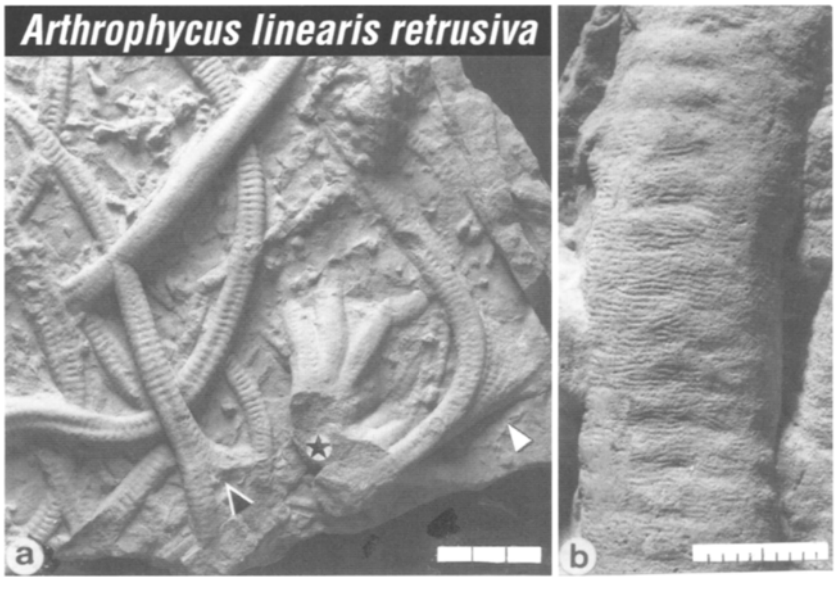

Figure 1. Arthrophycus linearis retrusiva n. ichnosp., n.subichnosp. – Medina Sandstone (Lower Silurian), Rochester, New York.

a: This soleface shows (1) transverse corrugation with a median furrow, which is a diagnostic feature of arthrophycid burrows, (2) intercutting relationships, indicating intrastratal backfill structures rather than mere casts of furrows on a mud surface; (3) swinging-out of the tail part in sharp curve (white arrow), (4) lateral branch produced by probing head end (black arrow) and (5) palmate bundle (star) transitional to *Arthrophycus alleghaniensis* (YPM.).

b: Enlarged portion of large burrow showing fine wrinkles (22/cm: probably reflecting wrinkled cuticle), in addition to coarser corrugation (GPIT 1858/9, plaster cast).

Gondwana province, but also in Eastern North America. Taken alone, palmate strip mining is a common strategy among sediment feeders of diverse affiliations and many of the resulting burrows also show teichichnoid backfill structures. Less striking, but taxonomically more important, is the regular 'segmentation' that led to the name *Arthrophycus*. Also typical is a shallow median depression that produces a square, rather than cylindrical, cross section of the burrow. In addition, exceptionally well-preserved specimens may show a minute transverse ornamentation reminiscent of a wrinkled worm integument (Fig. 1b).

Taking these sculptural fingerprints, the fairly large caliber (5–15 mm), and the tendency to produce transversal backfill structures as ichnogeneric attributes related to an unknown, but distinctive, group of worm-like (but not necessarily annelid) trace makers, we can use particular burrowing programs to distinguish biostratigraphically significant ichnospecies.

Arthrophycus linearis n.sp.
(Figs 1 and 2)

Diagnosis: Shallow *Arthrophycus* burrows with no or few side branches, running straight, or smoothly curving, along bedding planes. Depending on whether the animal burrowed with its head end up or down, the cross section of the low teichichnoid spreite is either protrusive (seleniform backfill lamellae convex-up) or retrusive (lamellae convex-down, in the same direction as in the longitudinal section).

Range: A. *linearis protrusiva*: Upper Ordovician, Benin and Jordan.
A. *linearis retrusiva*: Lower Silurian, U.S.A. and Argentina; Lower Ordovician, Libya and Algeria.

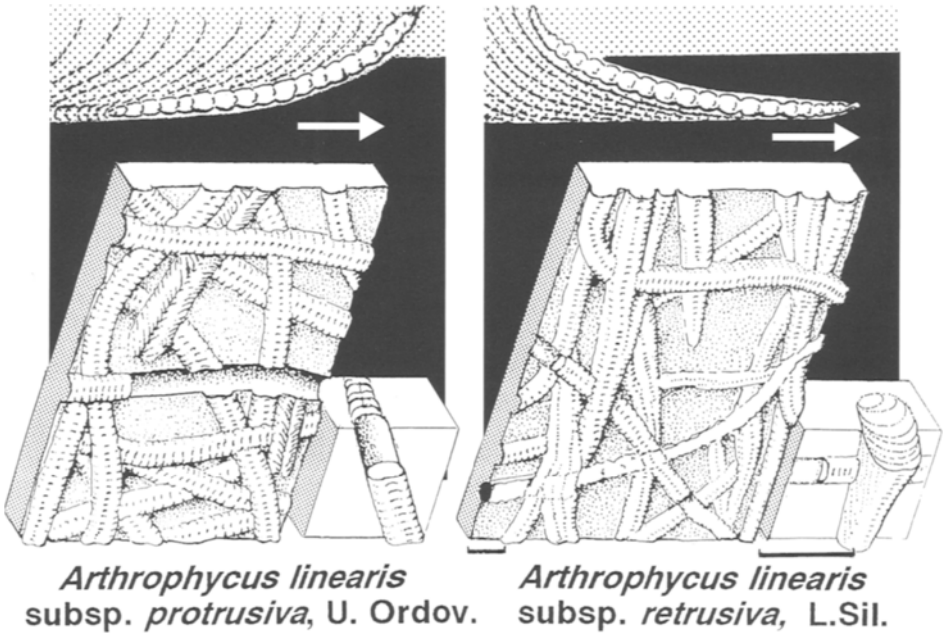

Figure 2. The otherwise similar forms of the Upper Ordovician (Kandi Group, northern Benin, GPIT 1858/2) and the Lower Silurian (Medina Sandstone, Rochester, YPM 50650) can be distinguished in cross-section by a protrusive versus a retrusive backfill in the low spreite. Therefore broken-away burrows leave a hemicylindrical groove only in the Ordovician subichnospecies. This difference is explained by head-up versus head-down modes of burrowing.

Remarks: If only hypichnial expressions are considered, the two specimens shown in Fig. 2 appear identical – except that there are a few narrow-angle branches in the Silurian form. One would also assume that the worm-like trace maker moved peristaltically along its body axis (transverse corrugation) and perhaps stuffed its burrow with a *Planolites*-like terminal backfill structure. Polished vertical cross sections, however, modify this simplistic model in important ways:

- the burrow is higher than wide – not cylindrical;
- seleniform backfill lamellae reflect a vertical component to the horizontal movement.

This means that locomotion within the sediment was at an angle to the body axis. While being energetically more expensive than axial locomotion, oblique burrowing has the advantage that it scans a larger volume of sediment in the search for food. This mode of burrowing is well known from the trace fossil *Gyrochorte* (Seilacher, 1955). More surprisingly, the gutter-shaped backfill lamellae of the two forms curve in opposite directions. In the U. Ordovician form they are convex-up, in the Silurian one convex-down. If we call the backfill body a spreite and assume that the worm-like animal had a convex-down bend, the Ordovician form produced a protrusive spreite, in which lamellae curve in opposite directions in lateral versus cross-sectional views. In contrast, the spreite of the Silurian form has a retrusive structure, with lamellae appearing convex-down in transverse as well as longitudinal sections.

Kinetically, this difference is best explained by head-up progression in the Ordovician and head-down burrowing (which facilitated the production of preservable exploratory side branches) in the Silurian form. Accordingly the trace of the swinging-out tail (Fig. 1a) lies at a higher level than the burrow floor shaped by the front end. If this difference proves to be stratigraphically consistent, it could be expressed at the subspecies level (*Arthrophycus linearis protrusiva* versus *A. linearis retrusiva*).

It should be noted that *Arthrophycus linearis* apparently also occurs in southern Algeria and in the Kufra Basin. It is there associated with Lower Ordovician (Arenig) trilobite burrows (*Cruziana furcifera*) and sometimes branches into small bundles. These have a retrusive backfill structure, but never reach the complexity of Silurian *Arthrophycus alleghaniensis* (specimens in Tübingen Museum GPIT 1858/2a and 2b).

Arthrophycus alleghaniensis (Harlan, 1831)
(Figs 3 and 4)

Emended diagnosis: *Arthrophycus* burrows forming 3-dimensional palmate bundles of tunnels with vertically retrusive backfill structures.

Range: Lower Silurian, U.S.A., Argentina, N-Africa.

Remarks: The relationship between *A. linearis* and *A. alleghaniensis* resembles that between a horizontally ploughed *Cruziana* and the tunnel of *Cr. ancora* (Lessertisseur, 1956). Rather than simply ploughing along, the animal had to produce a U-shaped tunnel and to retreat towards the stationary entrance before digging another branch. Since probings had to avoid each other (presumably to avoid double coverage in a feeding process), they laterally deviate on either side of the primary tunnel until a bush- or palm-like configuration is reached.

Cross sections show that this simple picture must be modified in two ways. Firstly, individual branches seen in hyporelief are not cylindrical, but represent the bases of teichichnoid spreite bodies with a retrusive backfill structure. Secondly, the distal ends of the branches often end abruptly, rather than merging gradually into the bedding plane. This suggests that the generating tunnel was not U-shaped with openings at both ends, but a dead-end J-burrow, as in *Daedalus*.

Developing this model further, we may assume that the rear end of the animal remained near the opening of the J-burrow. Meanwhile the front end did the probing by first digging a dead-end tunnel and then moving the bent part up through the sediment. Radial sections through adequately preserved specimens (spreite lamellae cannot be seen in most cases) will have to solve details of this process.

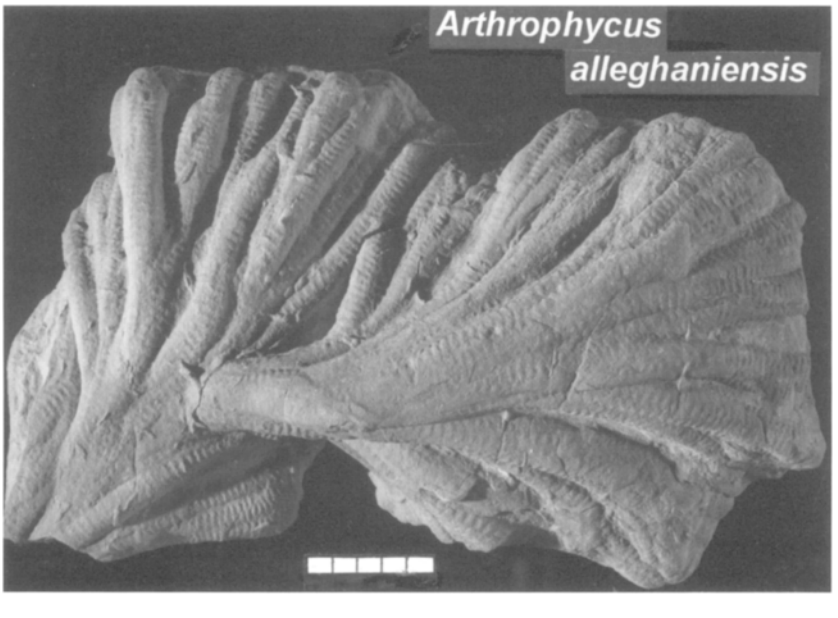

Figure 3. As shown by blunt tips, the burrow systems of *A. alleghaniensis* consist of dead-end probings extending from a central J-shaped shaft – Lower Silurian, Fada, Chad (GPIT 1858/3).

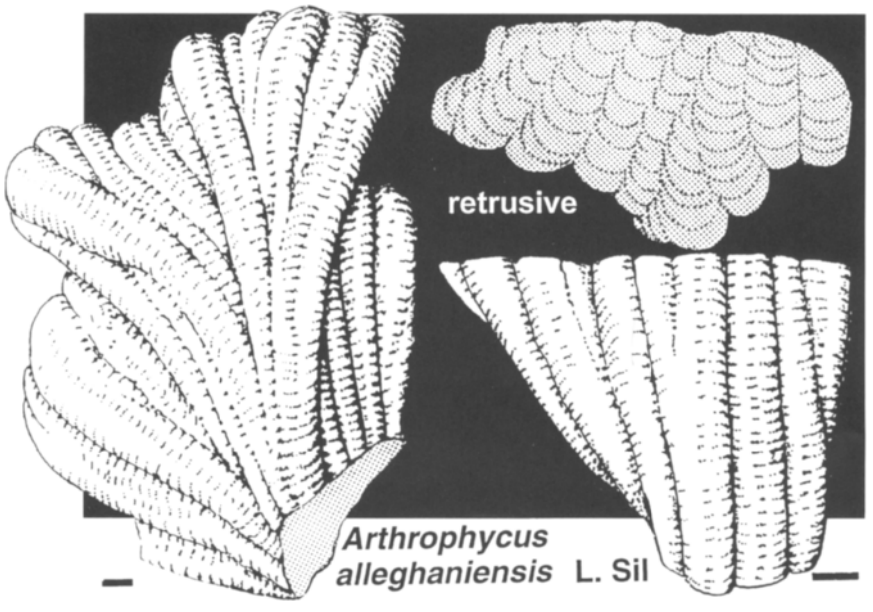

Figure 4. Cross-sections show that the branches seen in the hyporelief bundles of *A. alleghaniensis* are the bases of tightly packed retrusive spreite bodies. Since they consist of material derived from an overlying sand layer, the animal probably got its food from the dug-out mud, which was then flushed out to the surface and backfilled with sand from above. – Akakus Sandstone (Lower Silurian), Ghat, SW Libya (GPIT 1858/4 and GPIT 1858/5).

In any case, the animal did not simply shuffle the sediment from one side of the body to the other (as in *Gyrochorte*), because the spreite consists of sand, while the burrowed substrate was mud. Thus it is likely that the mud was reworked (or swallowed) for its food content and then flushed out, while sand became washed in by the respiration current from the sandy layer above. Stratigraphically it is interesting that *A. alleghaniensis* occurs in Gondwana as well as in Laurentia, in both cases in the Lower Silurian (Llandovery).

Arthrophycus lateralis n. ichnosp.
(Figs 5 and 6)

1969 *Arthrophycus* Seilacher, Plate 1.
1997 *Arthrophycus unilateralis* (nomen nullum) Seilacher, p 41.

Diagnosis: Fan shaped *Arthrophycus*, in which densely set branches bend only to one side. Internal structure reveals horizontal protrusive backfilling at tiers in ascending order.

Holotype: Fig. 6 (GPIT 1858/7)

Stratum typicum: Akakus Sandstone, Takharkhuri Pass south of Ghat, Libya.

Material: Several specimens, Tübingen collection (Fig. 5).

Remarks: At first glimpse this form appears little different from the bundles of *A.alleghaniensis* except for the one-sided curvature of the branches. Cross sections, however, reveal a totally different burrowing program. Instead of making new probings on both sides of an initial burrow and extending them vertically in a retrusive teichichnoid fashion, protrusive strip mining in this ichnospecies proceeds horizontally as in *Zoophycos* or *Rhizocorallium*, but with minor teichichnoid excursions between and in several tiers in upward succession.

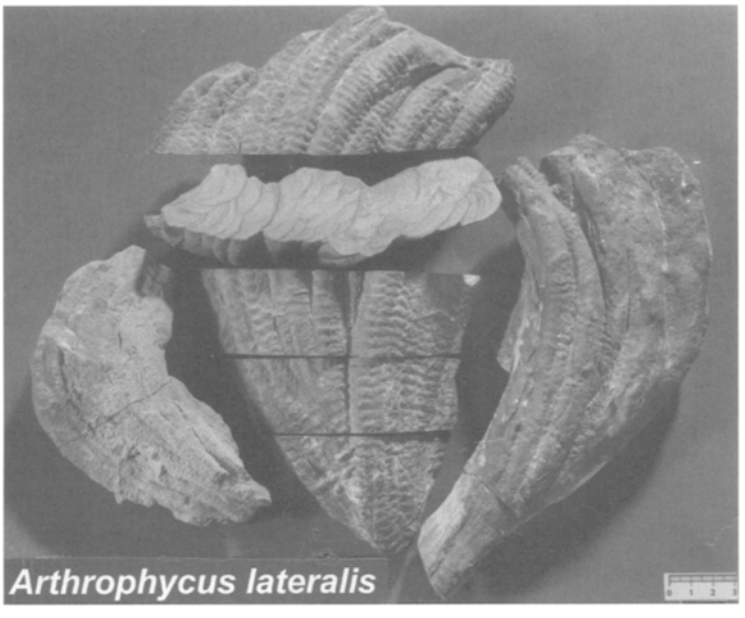

Figure 5. Although superficially similar to *A. alleghaniensis*, this ichnospecies reflects a completely different burrowing program (see Fig. 6) – Akakus Sandstone (Lower Silurian), Takharkhuri Pass, SW Libya (GPIT 1858/6–8).

Since this is the predominant form at the type locality, recognition of a separate ichnospecies with potential stratigraphic significance appears to be justified in the hope that its stratigraphic relationship to *A. alleghaniensis* can be defined in the future.

Ichnogenus *Daedalus* Rouault, 1850

Synonym: *Vexillum* Rouault, 1850 (preoccupied)

Emended diagnosis: Arthrophycid burrows that rework the sediment by dislocating a vertical or steeply inclined J-burrow, commonly in a spiral fashion.

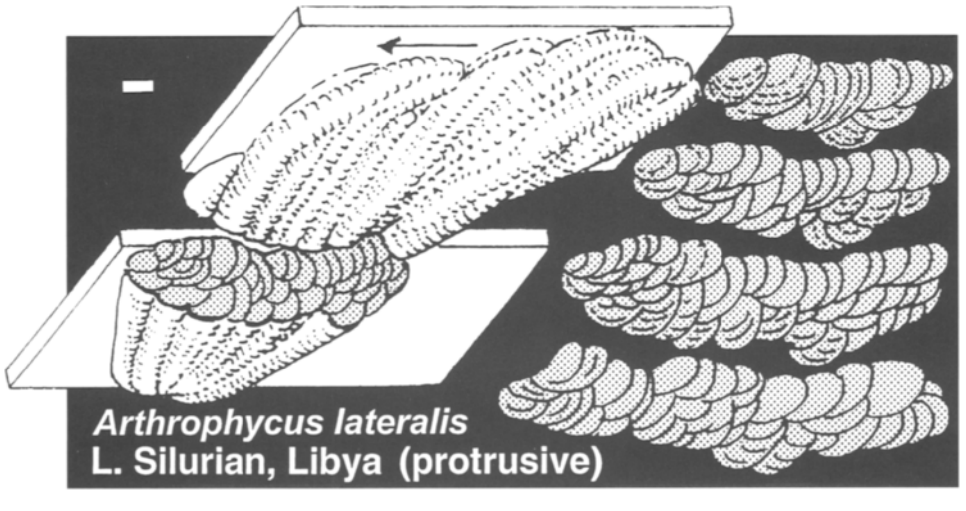

Figure 6. Serial cross sections reveal that the spreite of *A.lateralis* n. ichnosp. was formed by repeated protrusive dislocations of a J-tube parallel to bedding in ascending tiers – Akakus Sandstone (Lower Silurian), Takharkhuri Pass, SW Libya (holotype GPIT 1858/7).

Remarks: The name *Daedalus* was given, with reference to their wing-like sculpture, to conical 'algal' structures from the Lower Ordovician Armorican Sandstone of France. In our present interpretation as trace fossils they originated by the spiral displacement of a steeply inclined J-shaped burrow. Therefore one has to break the rock to see the typical spreite structure. Similar forms occur in the Lower Silurian (Medina Sandstone) of upstate New York (Sarle, 1906), where whole beds may be riddled by them. In spite of their very different appearance, these spiral burrows can now be shown to have been made by organisms closely related to the producers of *Arthrophycus*. In specimens of very large *Daedalus labechei* from Lower Ordovician (Arenig) quartzites (associated with *Cruziana rugosa* and its variants) of the Oman Mountains north of Muscat one can clearly recognize the typical transversal corrugations of *Arthrophycus*. The same can be observed in specimens of *Daedalus archimedes* (Figs. 12 and 13) and *D. verticalis* (Yale Peabody Collection, New Haven Nr. 35816) from the Lower Silurian Medina Sandstone of Rochester, New York.

This observation raises the old question as to whether trace fossils should be classified strictly by their geometry or with reference to the organisms that made them. In the present case I feel that the constructor should not be ignored. This is particularly true in an ichnostratigraphic context, where a trace fossil stands for the limited time range of the organism that made it. Therefore we unite *Daedalus* and *Arthrophycus* in the same ichnofamily, Arthrophycidae (see above).

As to be expected in a hybrid classification, this solution is not without problems. The lower Ordovician *Daedalus halli*, for example, will hardly ever show arthrophycoid fingerprints, because its tunnel diameter is too small relative to the grain size of the matrix. Yet, its conical shape and the contemporaneity with *Daedalus labechei* and *Daedalus desglandi* favor inclusion in the same ichnogenus.

On the other hand, similar burrowing strategies (spiral displacement of a J-shaped burrow) have been used by worm-like sediment feeders also at later times. '*Spirophyton*' *eifeliense* from the Lower Devonian and a similar form from a Miocene flysch community in Borneo (GPIT 1858/24), for instance, keep the shaft of the J stationary and spiral only the bent portion. There is also a homeomorph to *Daedalus desglandi* in pelagic Cretaceous limestones of southern France (GPIT 1858/25). By spiraling the whole shaft and bending the lower end of the J towards the rotational axis, it produces a structure resembling a high-spired gastropod shell, particularly since the whorls become wider at depth.

Spiral *Daedalus* burrows have also been recorded from Algeria (Beuf et al., 1971, Fig. 199). Their detailed structure and stratigraphic position remains to be studied.

Daedalus labechei (Rouault)
(Figs 7 and 8a)

1850 *Vexillum Labechei* Rouault, p. 734 (without illustration).

Emended diagnosis: Large ichnospecies of *Daedalus* with a protrusive spreite, whose inwardly spiraling base maintains about the same level.

Remarks: In spite of its very different behavior, this ichnospecies is closely related to *Arthrophycus* by having a similar tunnel diameter. It also has the typical transverse sculpture, which is seen on the spreite of specimens from Oman (Fig. 8a) and on the hypichnial base of a burrow from Portugal (Delgado, 1885; Pl. X).

More problematic is the mode in which these burrows were made. The protrusive spreite structure tells us that the animal first dug an inclined tunnel to the ultimate depth and then started to spiral with a wide turn, followed by only a few narrower turns on the inside of the first conical spreite. It is less clear, however, whether the head end of the animal was near the surface or at depth. Since the spiral is widest at the base, one would intuitively think the head was down and

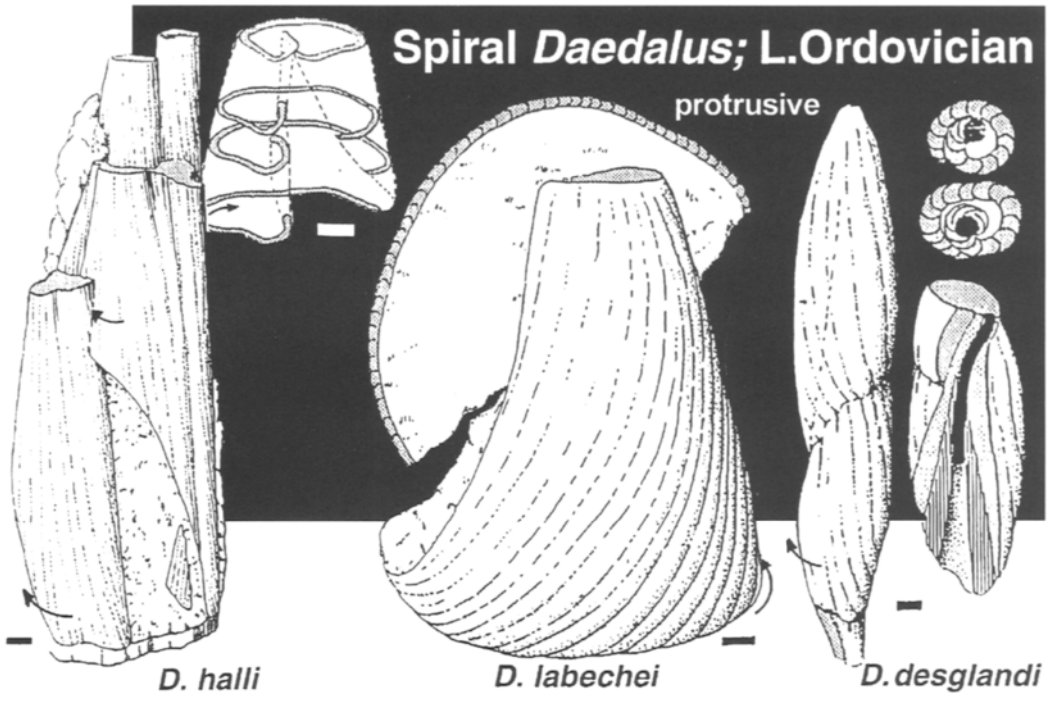

Figure 7. Three Arenig *Daedalus* ichnospecies differing in burrow diameter, convexity and orientation of the generating J-tube, as well as burrowing programs. Note that dislocation is protrusive (towards the convex side of the J) and that there is no unused sediment left between the helicoidal coils of *D. desglandi*. *D. halli* from Armorican Sandstone, France (GPIT 1858/9), *D. labechei* (GPIT 1858/10); *D. desglandi* (GPIT 1858/11).

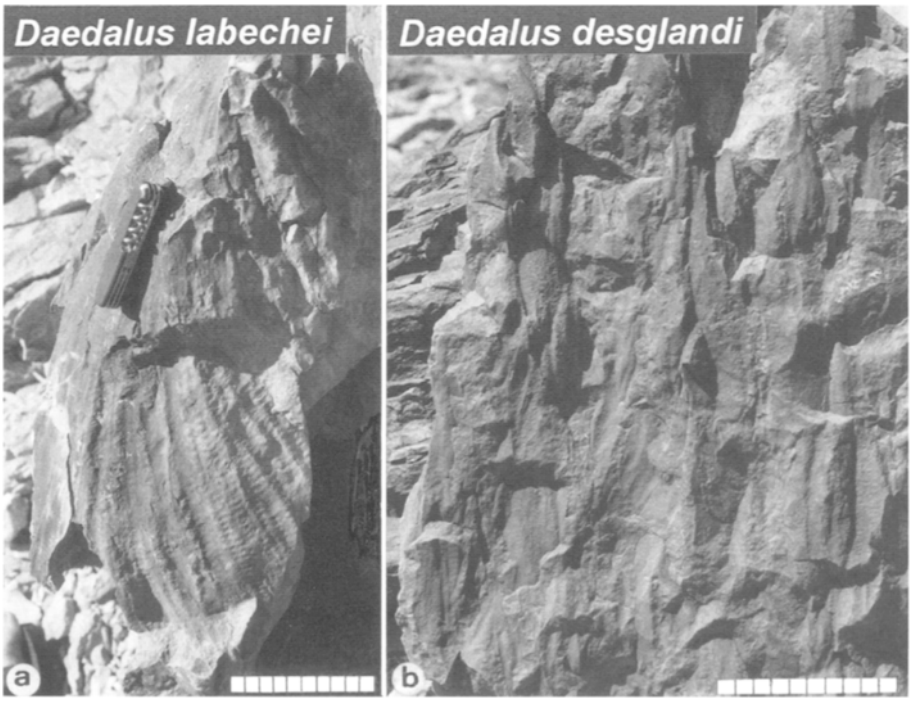

Figure 8. Daedalus in Lower Ordovician (Arenig) sandstones of the Oman Mountains. Fig. 8a: *D. labechei* with corrugations; Fig. 8b: dense population of *D. desglandi*. Individuals reach a depth of more than 40 cm – Field photographs.

dragged the tail behind – just as *Dictyodora* dragged its snorkel (Seilacher-Drexler and Seilacher, 1999). But near the base of the spreite, the contours of the former tubes bend asymptotically backwards instead of leading the way. This contradiction resolves when we remember that in the construction of an arthrophycid spreite, sediment was not simply shoveled transversely around the body, as in *Gychrochorte* or the *Dictyodora* snorkel. Rather, material from an overlying layer could be introduced as backfill. This implies that sediment was removed by the body rasping the front side of its tunnel. In such action the curvature of the tunnel was determined by contouring, so that its head end could bend backwards as the rasping action ran out. The asymptotic bend also explains why the hypichnial expression of the spiral base (Delgado, 1885; Pl. X) shows the typical arthrophycid corrugation.

Daedalus desglandi (Rouault)
(Figs 7 and 8b)

*1850 *Vexillum Desglandi* Rouault, p. 735
1883 *Vexillum Desglandi* Rouault, Pl. XVII–XVIII
1885 *Vexillum Desglandi* Rouault; Delgado, Pl. XLI, Fig. 1 and 2

Emended diagnosis: Large spiral *Daedalus* produced by descending dislocation of an inclined J-tube, whose distal end was turning back towards the center. Accordingly, turns of the protrusive spreite bulge out and their basal edges are cut away from below by the following turn. Whorls closely packed.

Range: Lower Ordovician (Arenig); France, Spain, Portugal, Oman, Antarctica.

Remarks: In spite of being similar to *Daedalus labechei* in size and spiral configuration, the present ichnospecies can be easily distinguished by its helicospiral geometry and bulging whorls. On vertical fracture surfaces, the burrows resemble giant gastropod shells, but with whorls maintaining the same diameter over a height of up to 50 cm (Fig. 7). They may co-occur with *D. labechei* in the same outcrop, but not in the same beds.

The constructional principle becomes clear from cross sections and vertical breaks (Fig. 7). The helicoidal coils of the spreite are very steep and so tight that no unused sediment is left between them. In fact, the lower edge of the previous coil is regularly cut away, which would have been detrimental had there been a marginal tunnel in the mode of *Zoophycos* or helicospiral *Rhizocorallium*. Arthrophycid corrugation has been observed.

Daedalus halli (Rouault)
(Figs 7 and 9)

*1850 *Vexillum Halli* Rouault,
1885 *Vexillum Halli* Rouault; Delgado, Pl. XL, Fig. 1, 3, 4 and 5

Emended diagnosis: Spiral *Daedalus* forming very slender cones with fine, straight lineation of the spreite. While burrows may penetrate several beds to a depth of more than 50 cm, the spreite is only 1–2 mm thick.

Range: Lower Ordovician (Arenig) sandstones of France, Spain, Portugal and northern Iraq.

Remarks: The interpretation of this trace fossil links on that of *Daedalus labechei* and *D. desglandi*, because its tube diameter was too small relative to grain size for arthrophycid corrugations to be preserved. Instead, the spreite surface is so smooth and finely lineated that one is reminded of inorganic sedimentary structures. Yet, bedding plane sections (originally described as *Humilis* Rouault, 1850) leave no doubt that we are here dealing with a very thin biologically produced backfill structure.

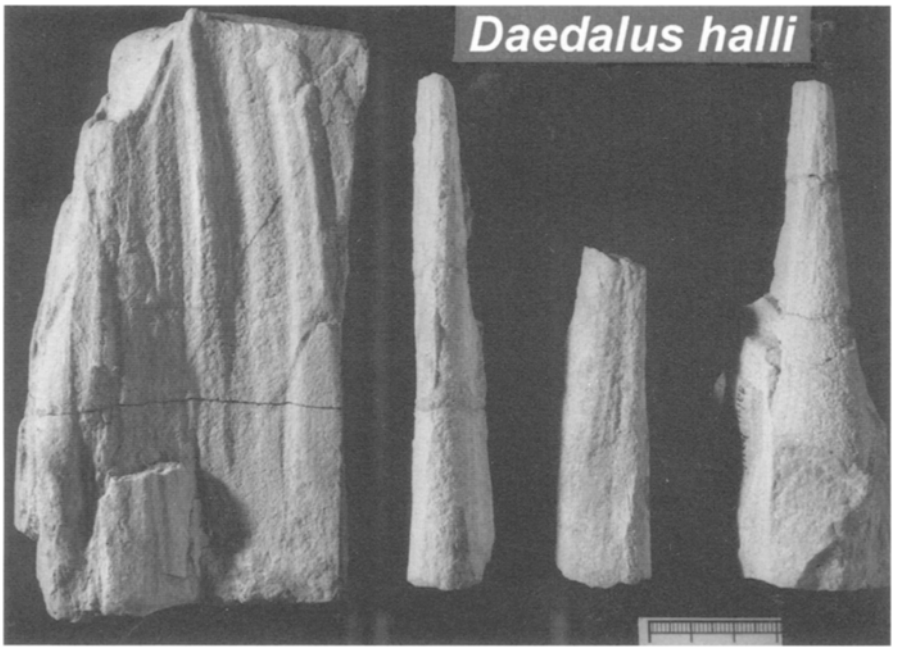

Figure 9. Spiral dislocation of a steeply inclined and almost straight tube produced the acute cones of *D. halli*. They may reach a depth of 90 cm – Armorican Sandstone, France (GPIT 1858/12–15).

Since the lineation of the spreite shows hardly any curvature, we must visualize a worm-like animal, whose body passed through the sediment like a straight stick stirring the sand, with the upper end being fixed at the surface. The balance between energy expenditure on burrowing and nutritional gain in such clean sands remains a problem.

Daedalus multiplex n. ichnosp.
(Fig. 10)

Diagnosis: Ichnospecies of spiral *Daedalus*, in which several protrusive spreite bodies radiate from a vertical shaft in a spiral fashion and spread at depth into vertical vanes, or wings.

Holotype: Fragmentary specimen from El Barkat, GPIT 1858/16. More complete specimens in the field (Fig. 10) are too large and fragile to be sampled.

Locus typicus: Hawaz Fm. (Middle Ordovician), El Barkat, south of Ghat (Libya)

Remarks: Because of their large size and the brittleness of the host rocks, complete specimens of this most complex *Daedalus* ichnospecies are difficult to prepare and to sample individually. Instead one has to reconstruct an idealized model (Fig. 10) from field data. In this effort, a photograph provided by Denis Vaslet (Orleans) has been of great help, because it shows a similar form from the Kahfah member of the Qasim formation (Llandeilo) of Uyun al Jiwa (Saudi Arabia) in horizontal section. From the combined observations it becomes clear that multiple (up to 6) protrusive spreite bodies radiate in the style of *Daedalus labechei* from a common shaft at the top and expand into large vertical vanes at a deeper level.

In an evolutionary sense, this ichnospecies appears to mark the peak of behavioral differentiation in Ordovician arthrophycids. Since no such forms have been found in the rich ichnofauna of the Upper Ordovician of Jordan (Seilacher, 1983), arthrophycid diversity may have been pruned during the Late Ordovician extinction, after which a new radiation occurred during the Early Silurian transgression.

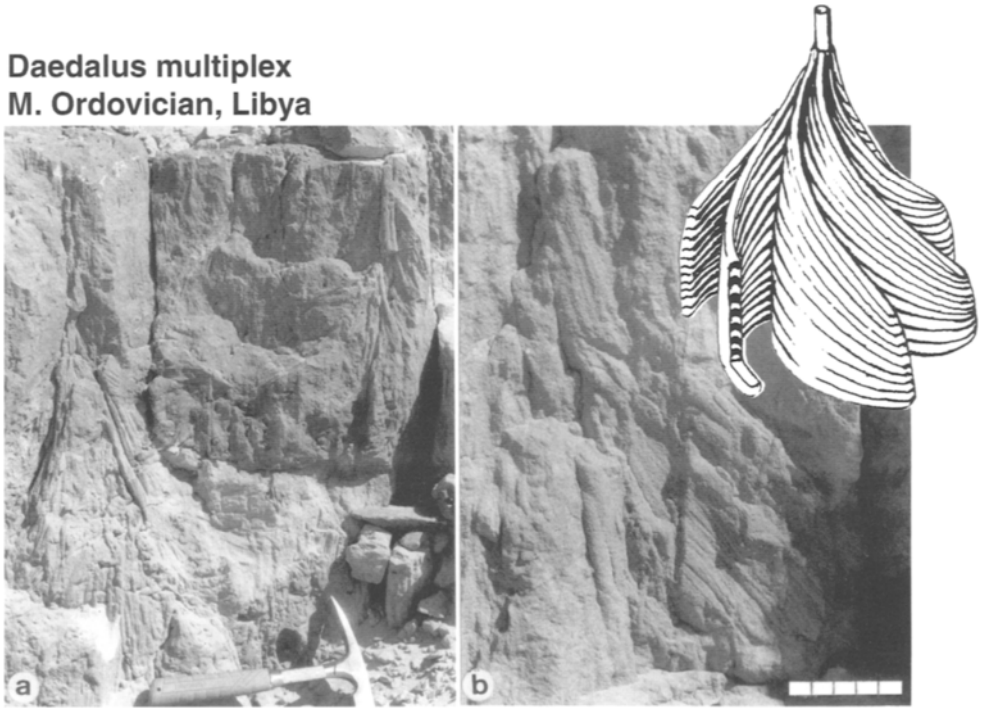

Figure 10. D. multiplex consists of several protrusive spreite wings that radiate from a vertical shaft like the arms of a spiral nebula or the petals of *Plumeria* flowers – Field photographs from the Hawaz Fm. (? Llandeilo), Al Barkat, near Ghat, SW Libya.

Daedalus verticalis n. ichnosp.
(Fig. 11)

Diagnosis: Deep arthrophycid burrow resembling *Diplocraterion*, but made by protrusive vertical dislocation of a slightly inclined dead-end J-tube without a spiral turn. Reaching a depth of more than 30 cm (YPM 38 254).

Holotype: YPM 38274 (Fig. 11).

Locus typicus: Medina Sandstone (Lower Silurian) of Rochester, NewYork.

Remarks: We begin the discussion of Silurian *Daedalus* morphologies with this form, because it lacks the spiral component that complicates the burrowing program of the more typical ichnospecies *D. archimedes*.

In spite of its superficial resemblance to *Diplocraterion*, the present form clearly belongs to the arthrophycids, because: (1) the diagnostic transverse corrugation is seen in many specimens and because (2) it originated by the vertical dislocation of a J rather than an U-tube. In spite of the lack of spirality this form is here affiliated with *Daedalus*, since its vertical extension is much larger than its width.

The asymmetry of the spreite can already be seen in vertical fractures (Fig. 11): the side of the shaft leans back and shows a more pronounced curvature of the former tubes, while the spreite is perfectly vertical in cross section. The geometry of the J-tube is even better expressed in horizontal sections made by Rachel Brakeman (Yale University). They show that individual burrows are neither clustered into radial arrays, nor arranged parallel to each other (which is the case in a much larger variant from the Sierra de la Ventana, Argentina: Buggisch, 1987). After polishing, horizontal sections are seen to taper away from the shaft. There may also be a ring

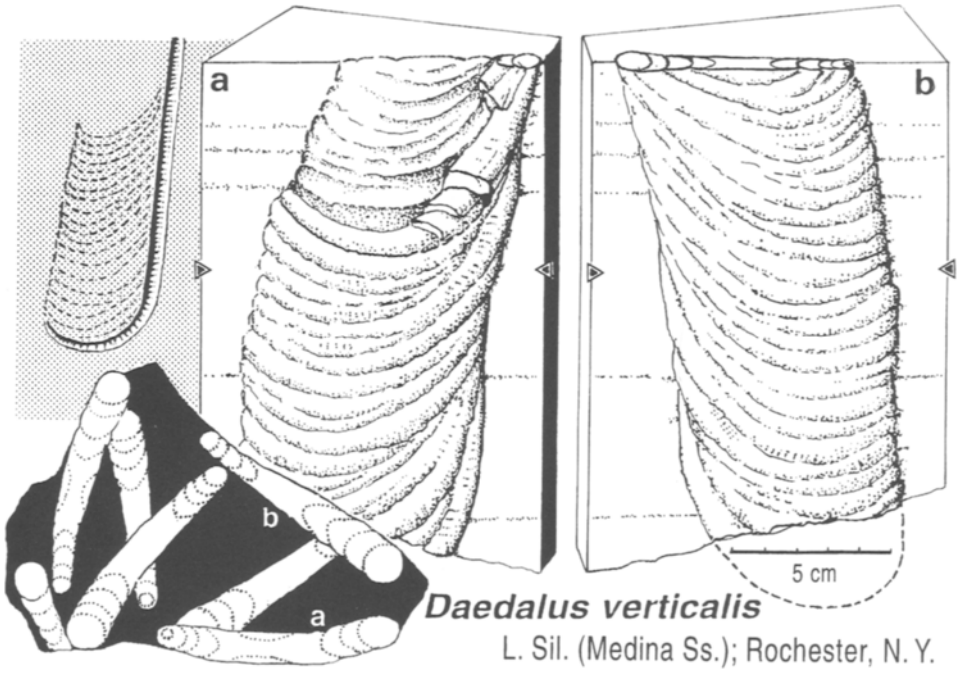

Figure 11. Unlike other *Daedalus* ichnospecies, *D. verticalis* lacks spirality. Instead, its spreite is vertical in section and slightly inclined in lateral view. The horizontal section shows that the spreite has a protrusive structure and narrows away from the shaft, indicating a tapering front end of the worm-like animal – Medina Sandstone (Lower Silurian), Rochester, New York (YPM 38274).

of disproportionately small diameter in the distal part of the spreite. This suggests that the head part of the animal was tapering and ended in a pointed proboscis. Since arthrophycid corrugations are present also in this ichnospecies, we may assume similar body shapes in the makers of other arthrophycid burrows.

Daedalus archimedes Sarle 1906
(Figs 12 and 13)

Emended diagnosis: Arthrophycid spreite burrows produced by protrusively helicospiral dislocation of a J-tube, whose lower end turned away from the rotational axis and was inclined into the plane of the spreite whorls. The coils of the spreite may either descend or ascend, depending on the rate of sedimentation.

Material: About a dozen specimens, including Fig. 13a and b, and YPM 35816 (collected under the guidance of Carlton Brett) and GPIT 1858/25.

Range: Medina Sandstone (Lower Silurian) near Rochester, New York.

Remarks: The return of arthrophycids to more complex burrowing programs in the early Silurian appears to have happened with a paleogeographic pattern. While no Silurian *Daedalus* has been found so far in the Gondwana realm (except for a giant version of *Daedalus verticalis* in the Sierra de la Ventana, Argentina), spiral burrowing programs seem to have evolved anew in Laurentia. *D. archimedes* from the Lower Silurian Medina Sandstone of upstate New York differs from Ordovician forms by an outward bend of the J-tube. The resulting cork-screw spreiten resemble helicospiral *Zoophycos*. Nevertheless the lack of a marginal tube, intersecting whorls and the occurrence of arthrophycid corrugation show that this similarity is mere convergence.

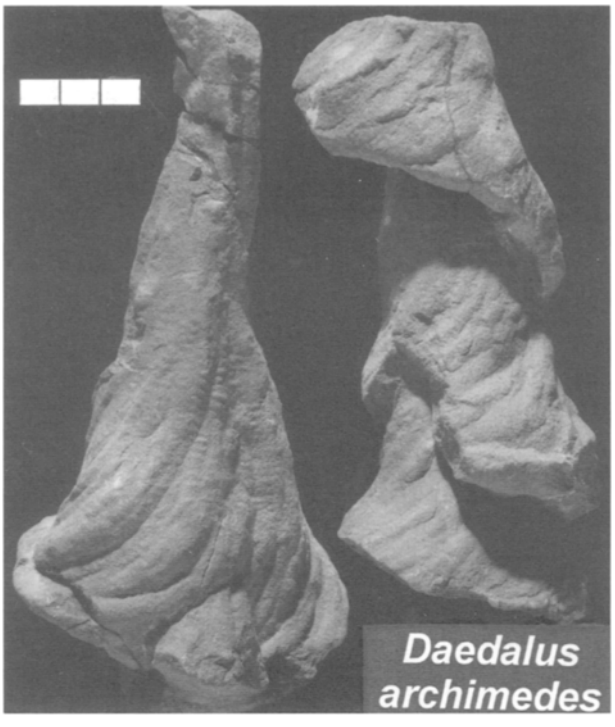

Figure 12. Descending spirals of *Daedalus archimedes* showing arthrophycid corrugation. Medina Sandstone (Lower Silurian), Rochester, New York (GPIT 1858/17–18).

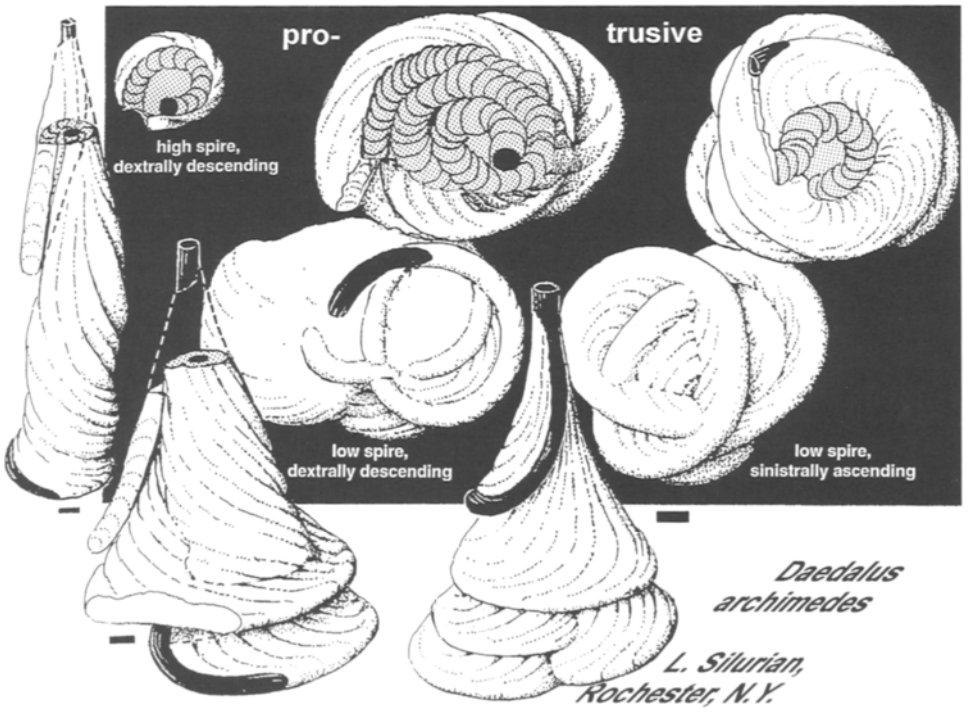

Figure 13. In contrast to Ordovician ichnospecies (Fig.7), the generating J-tube of *Daedalus archimedes* was bent away from the rotational axis and inclined. This allowed the protrusive spreite to vary steepness in descending (downward) spirals, or to progress upward – possibly in response to varying sedimentation rates. From left to right: YPM 38050; YPM 5925; GPIT 1858/19.

Ichnogenus *Phycodes* Richter

*1850 *Phycodes* Richter, Zeitschr. Deutsche Geol. Ges.
1865 *Licrophycus* Billings, Palaeozoic fossils

Remarks: While the close relationship between *Arthrophycus* and *Daedalus* is well established by shared characters (size; J-tube; transverse corrugation), the arthrophycid nature of *Phycodes* is less well founded. With diameters of only a few millimeters, these burrows are unlikely to preserve the diagnostic fingerprint, arthrophycid corrugation. It is also unclear whether the tubes were J- or U-shaped.

The main arguments in favor of an arthrophycid relationship are: (1) a similar stratigraphic range (Ordovician) and (2) behavioral convergences with *Arthrophycus*. Four Ordovician ichnospecies have so far been recognized. Stratigraphic correlation with other arthrophycids is complicated by the fact that they hardly ever co-ocur. While *Arthrophycus* and *Daedalus* are found in thick-bedded storm sands and delta deposits, in which *Cruziana* may also be common, *Phycodes* is restricted to alternations of thin siltstones with dark shales that were probably deposited below wave base.

Some confusion also arose by the inclusion (Seilacher, 1955) of '*Phycodes*' *pedum*, which has later gained importance in the definition of the Precambrian/Cambrian boundary. Because it lacks vertical spreite bodies, this ichnopecies is today attributed to the ichnogenus *Treptichnus* (Jensen, 1997).

Phycodes circinatum Richter
(Fig. 14)

*1850 *Phycodes circinatum* Rh. Richter (Thüringische Grauwacke)
1865 *Licrophycus ottawaensis* Billings (Trenton, Canada)
1884 *Vexillum rouvillei* De Saporta (Ordovician, Herault, France)
1934 *Phycodes circinatum* Richter; Mägdefrau p. 259 (Lower Ordovician, Germany)

Emended diagnosis: Type species, preserved as positive hyporelief on soles of thin silt beds. Tightly packed bundles of retrusive spreite bodies spread and curve back distally in a palmate fashion. Delicate transverse corrugation has been observed in a few specimens. Because distal ends merge into the overlying silt bed, it is not clear whether the generating tube (2–3mm in diameter) was J- or U-shaped.

Range: Lower Ordovician (Tremadoc) of France, Germany, Turkey, northern Iraq, U.S.A. The relationship to *Licrophycus* ichnospecies from the Middle and Upper Ordovician of Ontario (Billings, 1865; Osgood, 1970) remains to be studied.

Remarks: In basic structure, *P.circinatum* resembles *Arthrophycus alleghaniensis*, but branches spread out more readily and may lose contact in their distal parts.

Phycodes parallelum n. ichnosp.
(Figs 14, 15 and 16)

Diagnosis: Ichnospecies of *Phycodes* in which spreite bodies remain tightly packed throughout, without lateral fanning, and may proceed in the same direction to form long bodies with a rope-like appearance.

Holotype: Fig. 15, GPIT 1858/21.

Locus typicus: Stairways Formation (Upper Arenig/Lower Llanvirn), Ellery Creek near Alice Springs, Australia.

Other occurrence: Swan Peak Quartzite (Upper Arenig/Lower Llanvirn), Wasatch-Cache National Forest, 11 miles east of Logan (Utah, U.S.A.).

Remarks: The behavioral program of this ichnospecies contains the command not to change direction and not to give up close contact with the neighboring spreite. Unless we assume that many individuals were involved, there must have been branchings. It would be interesting to know whether they are in some way coordinated or occur randomly along the strand. Another open question is how the construction of a new spreite was initiated.

The apparently synchronous occurrence (uppermost Arenig/ lowermost Llanvirn) of this ichnospecies at distant places on different paleocontinents underlines its potential usefulness for stratigraphic correlation.

Phycodes fusiforme n. ichnosp.
(Figs 14 and 17)

1988 *Phycodes* aff. *palmatum* (Hall 1852); El-Kayal and Romano, Saq Formation, Fig. 5e–f.

Diagnosis: Ichnospecies of *Phycodes* in which spreite walls converge towards both ends of the bundle in bottom view and diverge at depth in cross section.

Holotype: Fig. 17, GPIT 1858/22).

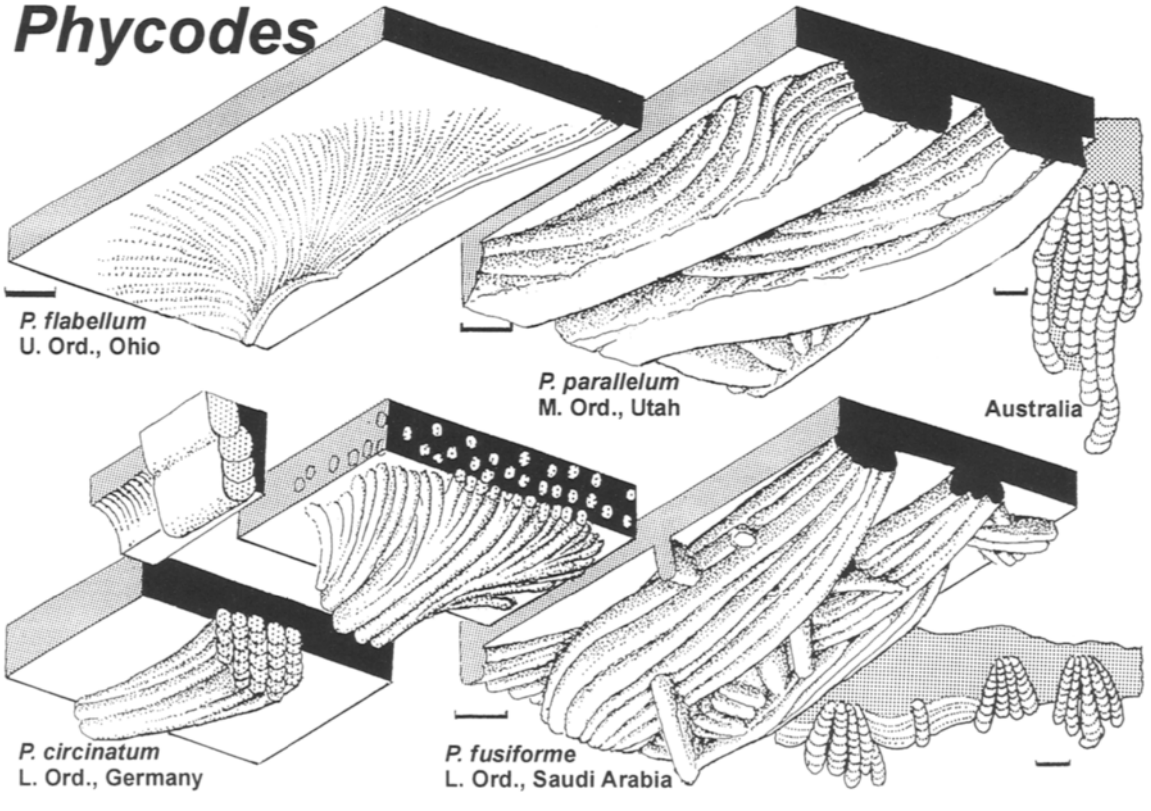

Figure 14. While *Phycodes* burrows are generally much smaller than other arthrophycids, the modifications of burrowing programs resemble those of *Arthrophycus*. In *P. circinatum* (from Seilacher, 1955), retrusive spreite bodies spread distally in a palmate fashion, while remaining closely packed in *P. parallelum* (GPIT 1858/20, section from GPIT 1858/21). In *P. fusiforme* (GPIT 1858/22, holotype) the spreite bodies diverge at depth and are bundled at both ends. This makes it difficult to distinguish the proximal from the distal side. *P. flabellum* (after Osgood, 1970) has horizontally protrusive spreite fans which are only on one side of a main shaft, along which they may alternate between right and left.

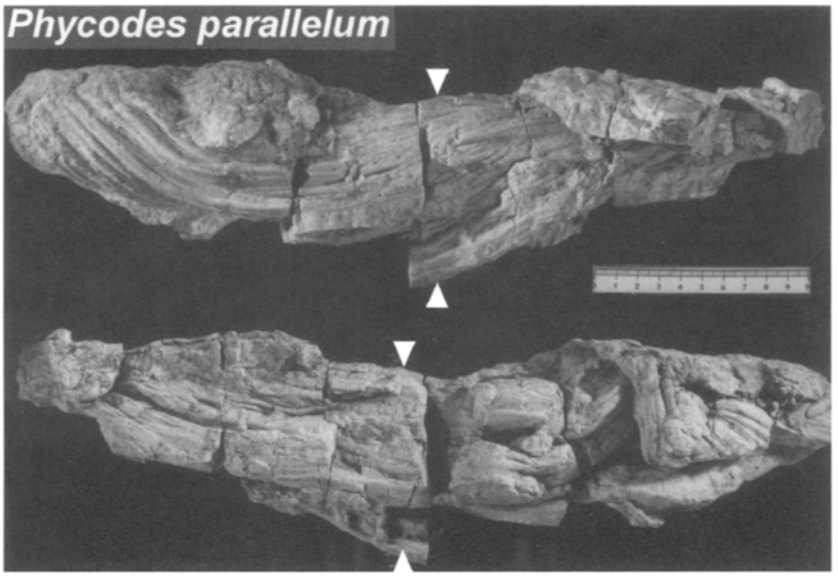

Figure 15. Individual system of *Phycodes parallelum* (holotype GPIT 1858/21) from the lower Ordovician Stairway Sandstone (latest Arenig/ earliest Llanvirn) of Ellery Creek near Alice Springs, Australia. Note that bundles are not clearly separated. Spreite bodies may rather change depth individually along the strand in a sinusoidal fashion. Cross-section at arrows shown in Fig. 14.

Locus typicus: Top of Saq Formation (uppermost Arenig) Al Hanadir, Saudi Arabia (El-Khayal and Romano, 1988).

Remarks: This spectacular trace fossil is so far known only from a few localities in Saudi Arabia, where it occurs in great abundance. Thus it can be stated that the spindle shape of these burrow

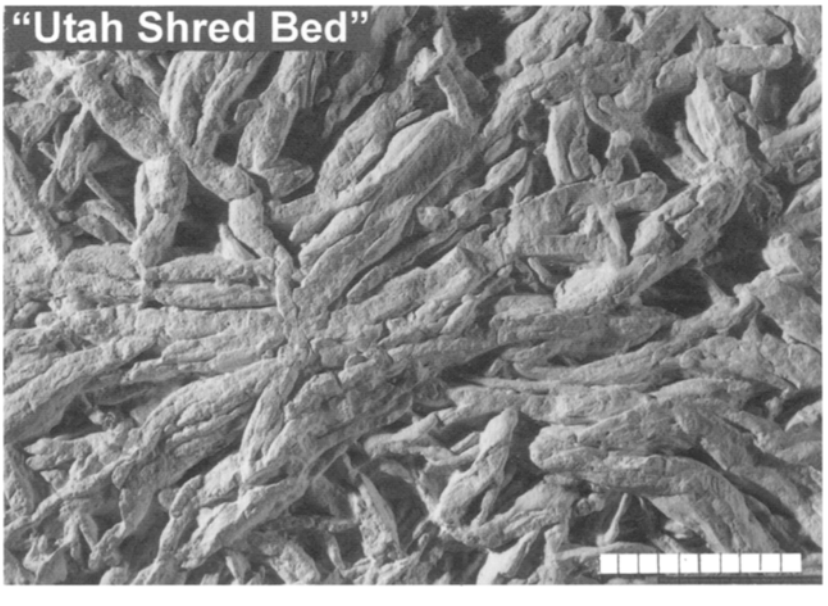

Figure 16. Part of a large surface exhibited along US Highway 89, 9 miles east of Logan, Utah. Although the bases of the burrow systems are corroded away, the strand-like appearance of *Phycodes parallelum* is still clearly expressed ('Utah Shred Bed'). Note that the stratigraphic level (uppermost Arenig, lowermost Llanvirn) is the same as in Australia (Fig.15) – GPIT 1858/23 (plaster cast).

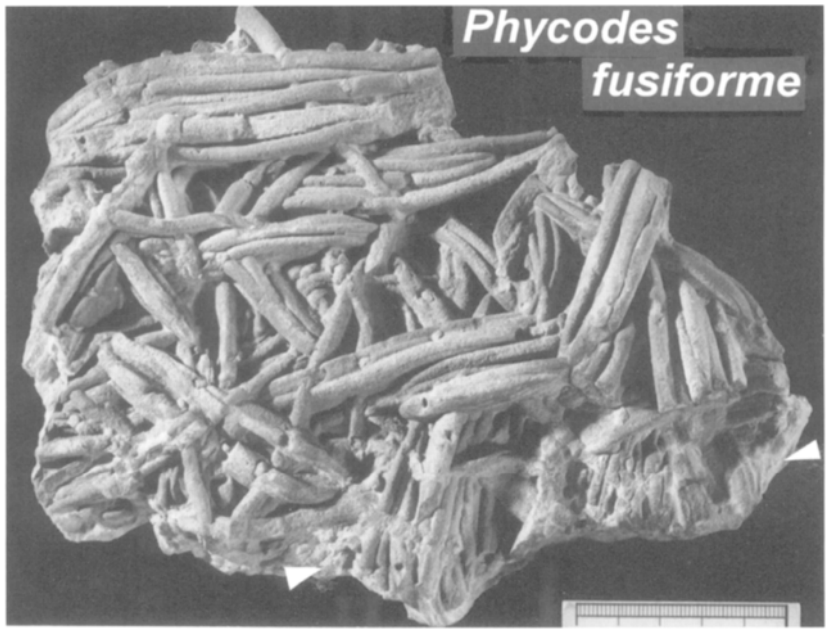

Figure 17. Holotype of *Phycodes fusiforme* from top of the Lower Ordovician Saq Sandstone (uppermost Arenig) at Uyun al Jiwa, Saudi Arabia. – GPIT 1858/22, courtesy of Denis Vaslet.

systems is a regular feature. It implies that during spreite formation the tube was fixed at both ends. This and the downward divergence of the spreite bodies would be easier to understand if the generating tube was U-shaped and became dislocated from top to bottom. The retrusive spreite structure (cross section in Fig. 14), however, shows that spreite bodies were produced from bottom to top, as in *P. circinatum* and *P. parallelum*.

Phycodes flabellum (Miller and Dyer)
(Fig. 14)

*1878 *Licrophycus flabellum* Miller and Dyer.
1884 *Inocaulis flabellum* (Miller and Dyer); James.
1970 *Phycodes flabellum* (Miller and Dyer); Osgood.

Emended diagnosis: Ichnospecies in which a finely corrugated J-tube was protrusively dislocated along the bedding plane and only on one side of the original burrow. After that, the animal moved on in the direction of the last spreite lamina to produce a similar fan on the opposite flank.

Range: Cincinnatian (Upper Ordovician), Cincinnati, Ohio, U.S.A.

Remarks: In *Phycodes circinatum*, radiating and recurving probes were made on either side of the fan towards the end of the cycle. In the present ichnospecies, however, the fan is one-sided and was probably constructed by horizontal dislocation of a J-tube in a protrusive mode. It could thus be interpreted as an analog to *Arthrophycus lateralis*, except that it has probably a one-tier spreite, that the tip of the tube was free to swing around, and that alternating fans could successively be produced along a horizontal axis (Osgood, 1970; Plate 65, Fig. 1).

CONCLUSIONS

By their unifying fingerprints and disparate behavior programs, arthrophycid burrows turn out to be excellent guide fossils in otherwise non-fossiliferous marine sandstones. They complement

the ichnostratigraphic scheme of *Cruziana* without being restricted to the realm of the ancient Gondwana continent. This reduces their value for identifying exotic terranes, but makes them potentially more useful for global correlation.

The present study is only a beginning. It had a stratigraphic goal, but ended up as a monograph with typological descriptions of an as yet scattered material. Hopefully this new tool will be used by field geologists in many countries and at the same time be refined with respect to stratigraphic and paleogeographic ranges.

On the other hand, one may also consider inclusion of well defined teichichnoid spreite burrows of somewhat similar Cambrian forms (e.g. *Syringomorpha*), in which the typical fingerprints have not yet been identified.

In summary, trace fossils are not altogether useless for stratigraphic purposes. In the absence of body fossils, distinctive invertebrate burrows may be used as time markers that can never fool us as ghost fossils in secondary deposits.

ACKNOWLEDGMENTS

For guidance in the field, thanks to Peter Haines (Australia), Henk Droste and Ingeborg Guba (Oman), Mukhtar Al-Ansari (Libya), Eberhard Klitzsch (Chad), Tony Ekdale (Utah), and Ulf Linnemann (Germany). Reuben Ross (Colorado School of Mines), Peter Haines (Univ. of Tasmania) and Tony Ekdale (Univ. of Utah) helped with stratigraphic information. Denis Vaslet (Orleans) made me aware of occurrences in Saudi Arabia and provided the specimen illustrated in Fig. 17. This was collected within the framework of an agreement between the Saudi Deputy Ministry for Mineral Resources (DMMR) and the French Bureau de Récherches Géologiques et Minières. Publication of these results was made possible thanks to the support and authorization of Dr. M.A. Tawfiq (Assistant Deputy Minister for Survey and Exploration, DMMR). Casting and preparation was made by Hans Luginsland (Tübingen), photography by Wolfgang Gerber (Tübingen) and Bill Sacco (Yale). Last but not least I am deeply indebted to my wife Edith for company in the field and everyday life (including tedious word processing) and to the organizers of the Murzuq Basin Symposium for inviting me to participate and produce this paper. Figured and cited specimens are deposited in the collections of the Geologisch-Paläontologisches Institut der Universität Tübingen, Germany (GPIT) and the Yale Peabody Museum (YPM) in New Haven, USA. Note that scale-bars in all figures denote 1 cm.

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CHAPTER 12

Seismic signature of the lower member of the Akakus Formation, Concession NC2, Ghadames Basin, Libya

ABDU-ELHAMED SHAHLOL[1]

ABSTRACT

The lower member of the Akakus Formation is the main reservoir in concession NC2. It comprises interbedded sandstone and shale in a deltaic sequence that was deposited during the late Silurian. Investigations of seismic reflections have shown changes in reflection characteristics such as configuration, continuity and external geometry that are associated with the reservoir system and can be interpreted as the channelling characteristics of the deltaic sequence. Synthetic modelling has been used to generate a seismic model and to confirm the seismic response of the geologic model, which is in many cases below seismic resolution. Mapping of the seismic facies can be used to better predict and map the distribution of these often hydrocarbon-bearing reservoirs.

INTRODUCTION

This chapter presents an example of how the integration of seismic and borehole data with synthetic modelling can be used to map the sandstone facies of the Akakus Formation in the evaluation of possible stratigraphic controls on hydrocarbon accumulations in NC2.

Oil exploration in NC2 historically has aimed at drilling the paleohighs as these structures were seen to control the distribution of Lower Akakus reservoir. Although this strategy has resulted in the discovery of numerous individual oil wells, significant volumes of hydrocarbons have not been found to date. The problem may be due to the small size of the structures or, alternatively, the traps may have a stratigraphic component. A better understanding of the distribution of the Lower Akakus sands is critical in this respect.

Individual sandstone beds of the Akakus Formation are typically 20 to 40 feet thick and can form multiple stacked pay zones. Their distribution has typically been mapped using well data, which is usually scattered and sparse. Until recently, no attempt has been made to map their distribution using both seismic and well data. This integrated approach to facies mapping could considerably improve the accuracy of the sand distribution maps and these could be used to identify the stratigraphic potential of these elusive but prolific reservoirs.

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GEOLOGICAL OVERVIEW

Concession NC2 lies on the northern truncated Palaeozoic flank of the Ghadames Basin (Fig. 1). This is an interior sag basin and is filled with clastic dominated Palaeozoic and Mesozoic sediments. The concession covers an area of about 4608 km^2 and contains a number of oil and gas discoveries, which are currently being exploited.

The Akakus Formation is middle to late Silurian in age (Fig. 2) and forms part of a regressive sedimentary wedge that thickens towards the south. The Akakus Formation overlies the Tanezzuft Formation and the transition between the two is gradational and often difficult to define (Bellini and Massa, 1980).

In concession NC2 the Akakus Formation is subdivided into three informal units, viz. the lower, middle and upper members. The sandstone of the lower regressive member forms the main reservoir in the area of NC2 and according to Cridland (1991) were deposited in response to basin tectonics and an eustatic sea level fall. The middle transgressive member is

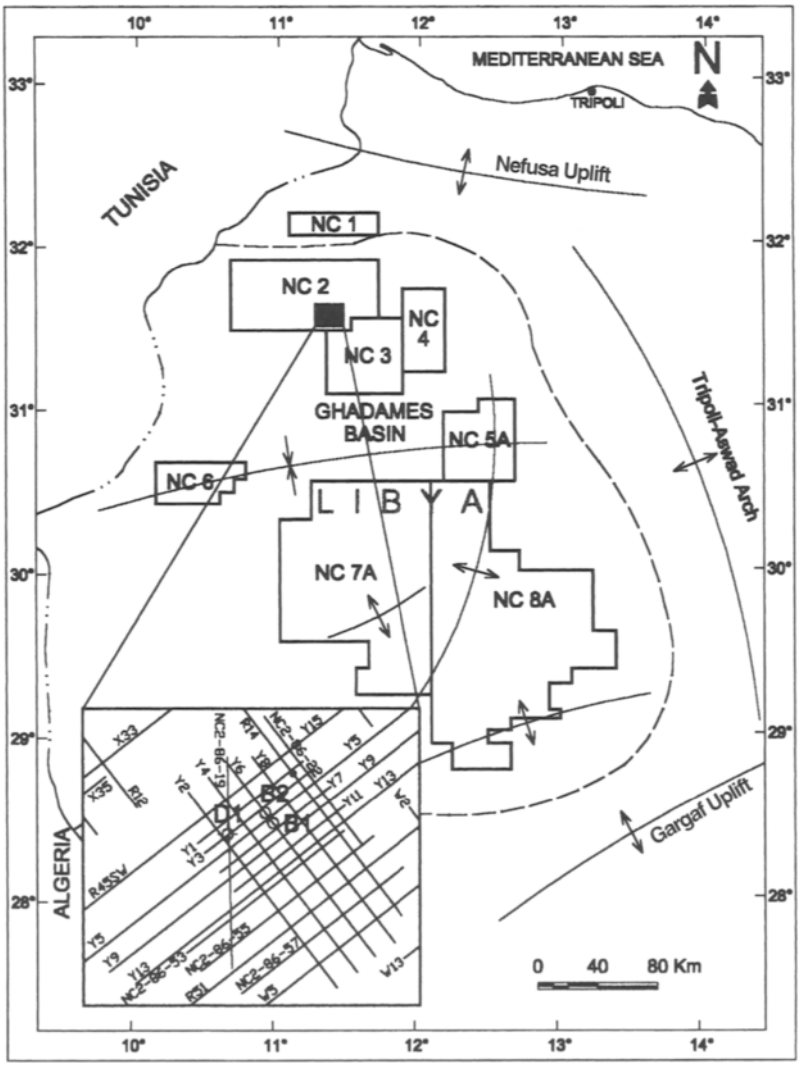

Figure 1. Index map of the study area showing major tectonic features. Individual oil pools and the seismic coverage are shown in inset.

characterised by a thin silty sandstone and the upper regressive member consists of marine shales that coarsen upward into shallow marine and continental sandstones and are unconformably overlain by the Tadrart Formation (Fig. 2).

Stratigraphic interpretations based on logs from NC2 wells (Cridland, 1991) and a sedimentological study of the lower Akakus cores from nearby wells (Dilekoz and Daniels, 1998) have indicated that the lower member was deposited in a deltaic environment, with sand content increasing to the south of the concession. This indicates that the delta system flowed in a generally northerly direction (Santa Maria, 1991) with the sands being deposited in an upper shelf position while the fine-grained sediments were deposited in the prodeltaic part of the system.

The Lower Akakus sands can be further divided into numerous transgressive and regressive rhythms, which are represented in electric logs as coarsening upward sequences. The thickness of the sandstones varies from rhythm to rhythm and well to well (Cridland, 1991). Local lithostratigraphic correlations across the 'B' and 'F' area, (Figs. 1 and 3) in concession NC2 have also been established by Teknica (1995). Four sand units have been recognised; the basal (A) unit that is the thickestsand and most easily correlatable across the study area. Its thickness ranges from 175′ to 240′. The overlying (B) sand unit ranges in thickness from 50′ to 100′; is not recognisable on seismic and is difficult to correlate. Unit (C) contains the main reservoir in the area and is easy to correlate seismically. This unit is about 100′ thick. Unit (D) is the uppermost sand package, overlain by massive middle Akakus shales. The thickness of this unit ranges between 140′ and 170′.

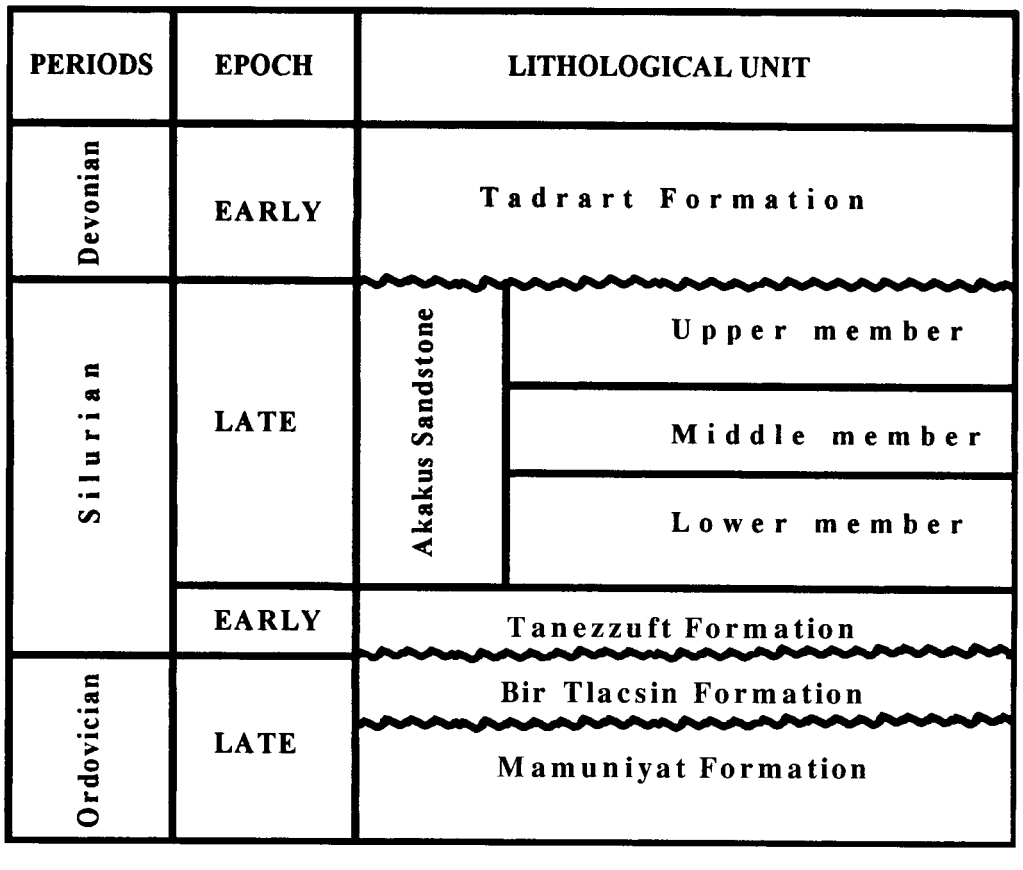

Figure 2. Idealized stratigraphic section for the study area.

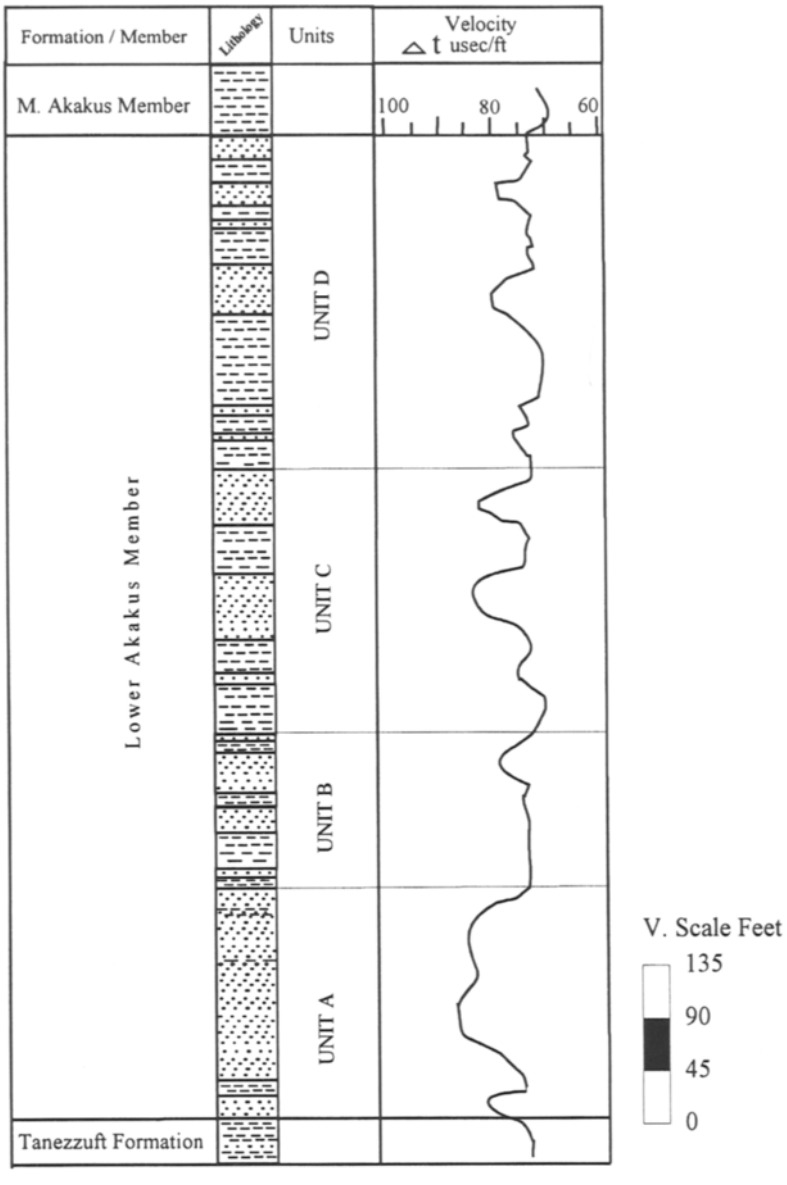

Figure 3. Stratigraphic column of the Lower Akakus Formation, NC2.

LOWER AKAKUS TRAPS

In the lower member of the Akakus Formation, hydrocarbons are trapped in multiple thin reservoirs with many of the reservoir zones being only 5 to 10 feet thick. Lateral continuity of gross sand packages is relatively good, but individual pay zones show marked changes over short distances (Fig. 4). Previous interpretations of seismic data across the area have indicated that oil entrapment in the Lower Akakus is structurally controlled, with the trap being provided by drape closure over anticlinal structures. The top Cambro-Ordovician surface gives the best map to determine the crest of the structures and resultant prospect locations, (Shah et al., 1989; Shahlol, 1989). However, the apex of the top Tanezzuft and the top of the Lower Akakus are often offset from that of the top of Cambro-Ordovician and this might suggest the overprint of a stratigraphic component. The idea of drilling structural highs was ruled out after drilling the D1-NC2 well. This well lies in a crestal position as defined by the Cambro-Ordovician and

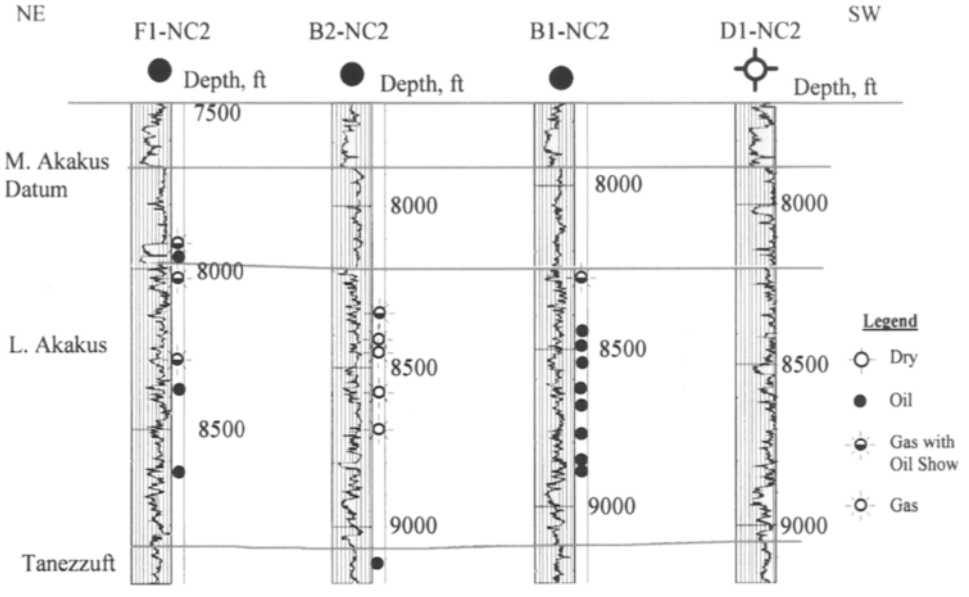

Figure 4. Gamma ray cross-section showing the stratigraphic relations of the various sandstone units across the study area. For location refer to Fig. 12.

Tanezzuft maps and is separated from the B and F structures by a saddle. However, a weak closure similar to that of the B and F structures defines the structure at the lower Akakus level. Well D1-NC2 was classified as dry and abandoned with minor oil shows. Careful investigations of the seismic reflection character across the 'B' and 'D' structures shows a rather different

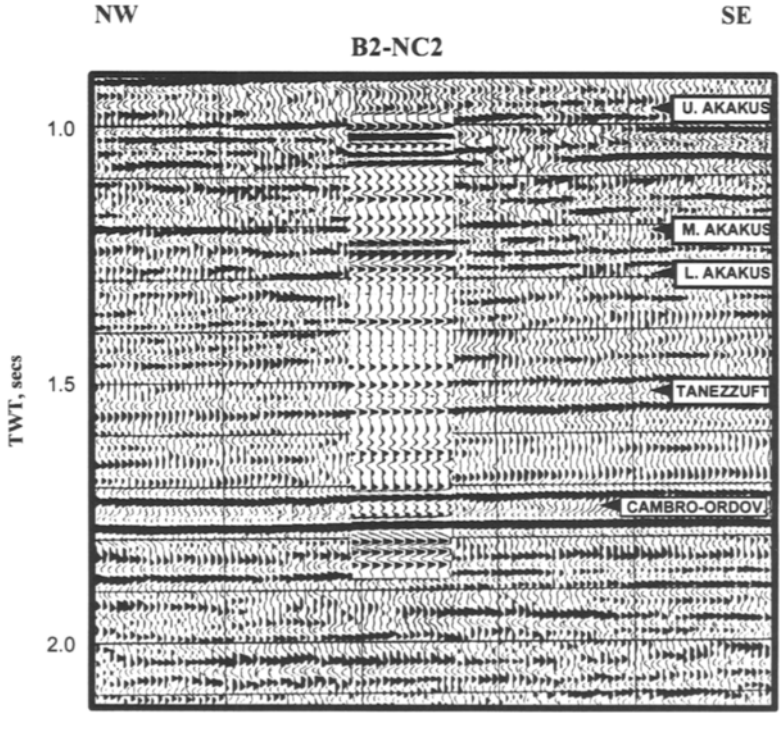

Figure 5. Synthetic tie to seismic line Y6 at well B2-NC2.

picture. Continuous, parallel and strong amplitude reflections are clearly seen across the 'D' structure and this reflection pattern is interpreted to be associated with the more shaly facies of a prodeltaic sequence. These observations highlight the importance of the seismic stratigraphic investigation and its possible applications in the search for subtle stratigraphic changes.

GEOPHYSICAL DATA: FIELD SEISMIC AND REFLECTION CHARACTER

The first seismic survey acquired in the area was of 6-fold dynamite data shot in 1975. The quality of this data is poor and severe static problems created great difficulties in its interpretation. Additional seismic data were acquired in 1980, 1986 and 1994 using dynamite and vibrator sources. These seismic programs were planned to record some regional lines and to provide more detailed seismic information at some selected areas across the entire area. The quality of this seismic data is reasonably good, although the 1980 dynamite data provides better overall quality for interpretation. Most of the seismic interpretation in the study area is therefore based on the 1980 data. The seismic grid is 1 km by 2 km, which is sufficient for detecting the subtle and small structures typical of this part of the Ghadames Basin.

SYNTHETIC MODELLING

Reflection amplitudes are normalised prior to their final presentation on seismic sections so that original distinctions between weak and strong reflections are suppressed. This practise tends to

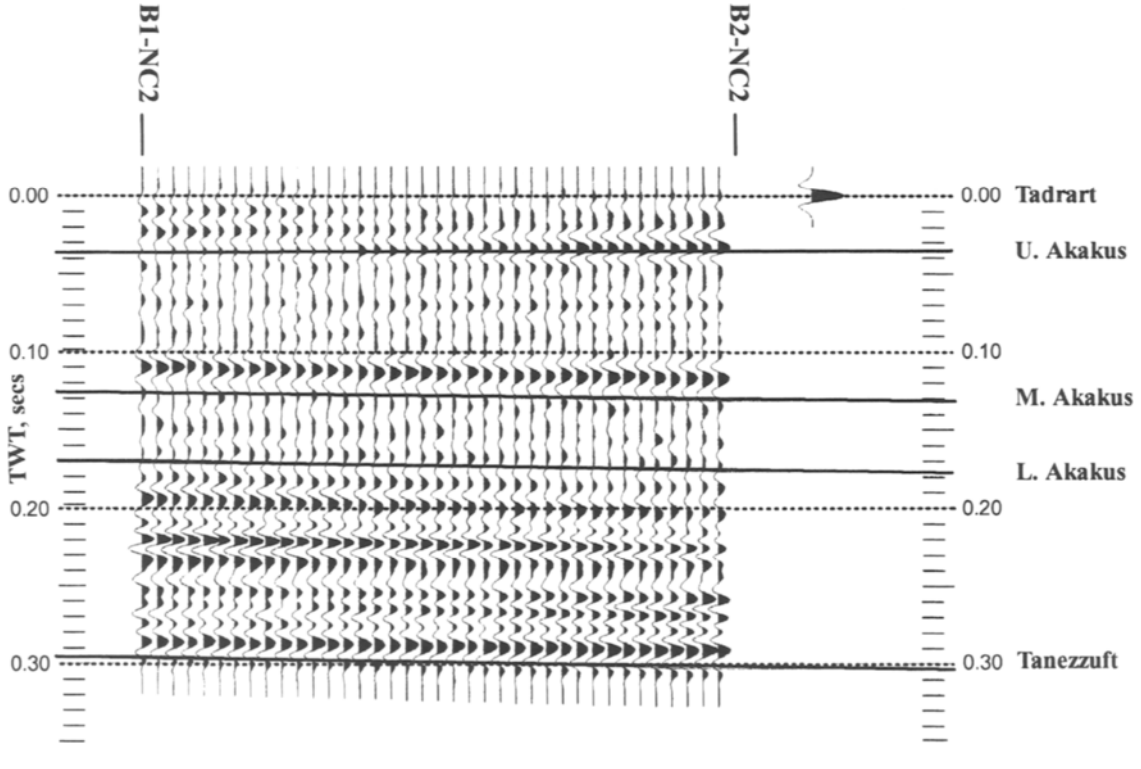

Figure 6. Two-dimensional seismic model of the Akakus Formation across wells B1-NC2, B2-NC2. 10% noise added. The section is flattened at the top Tadrart Formation horizon. See text for interpretation. Two-way time is in seconds.

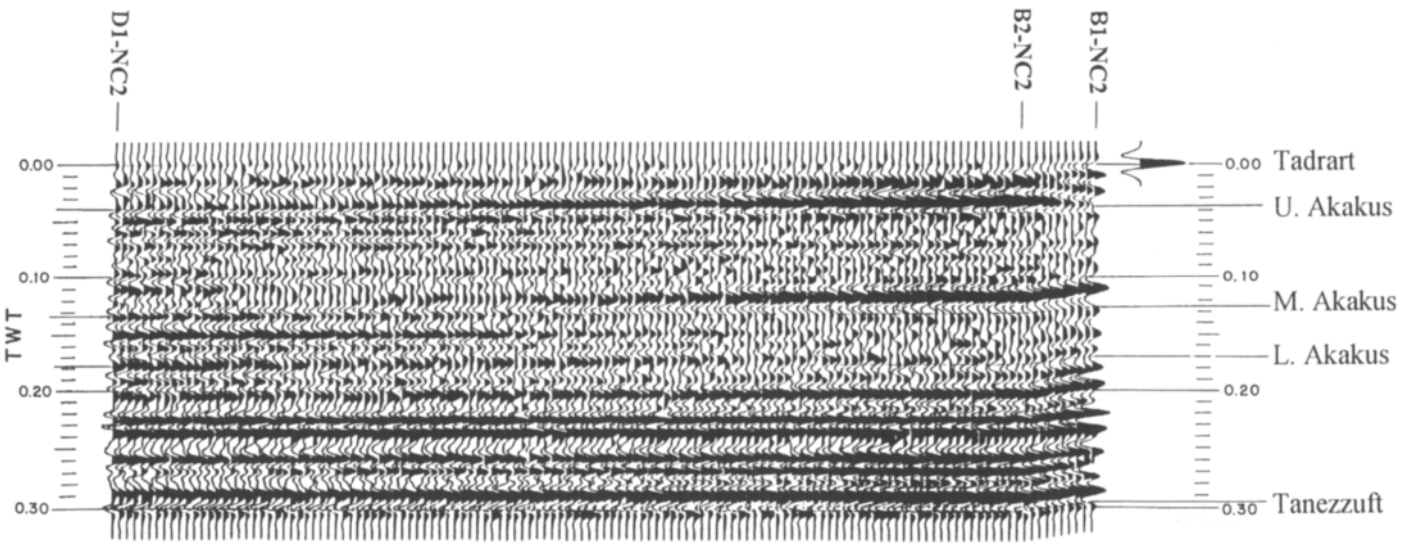

Figure 7. Two-dimensional seismic model of the Akakus Formation across wells D1, B2, and B1-NC2. 10% noise added. The section is flattened at the top Tadrart Formation horizon. See text for interpretation. Two way time is in seconds.

increase the continuity of reflection events across a section and therefore aids their structural identification and mapping. However, much valuable geological information is contained in the true amplitude of the reflection events and this can be recovered from suitably calibrated field recordings. Any lateral variation of reflection amplitude reflects lateral changes in lithology of a rock unit or in its pore fluid content. In addition to amplitude, the shape and polarity of a reflection event also contain important geological information (Meckel and Nath, 1977). Analysis of the significance of lateral changes of shape, polarity and amplitude observed in the true-amplitude seismic section is carried out by seismic modelling, often referred to in this context as stratigraphic modelling. Seismic modelling involves the production of synthetic seismograms for layered sequences to investigate the effects of varying the model parameters on the form of the resulting seismograms. Synthetic seismograms and synthetic seismic sections can be compared with real data, and models can be manipulated to in order to simulate the real data.

The seismic modelling carried out here is designed to establish the precise seismic signature associated with the Akakus Formation. The models were generated using LOGM[2] software. Since the modelling was designed to test stratigraphic concepts, a Ricker wavelet was considered to be ideal for generating the seismic response (Neidell and Poggiagliolmi, 1977). A zero phase wavelet with 55 Hz central frequency was chosen and convolved with the reflectivity series generated from sonic log.

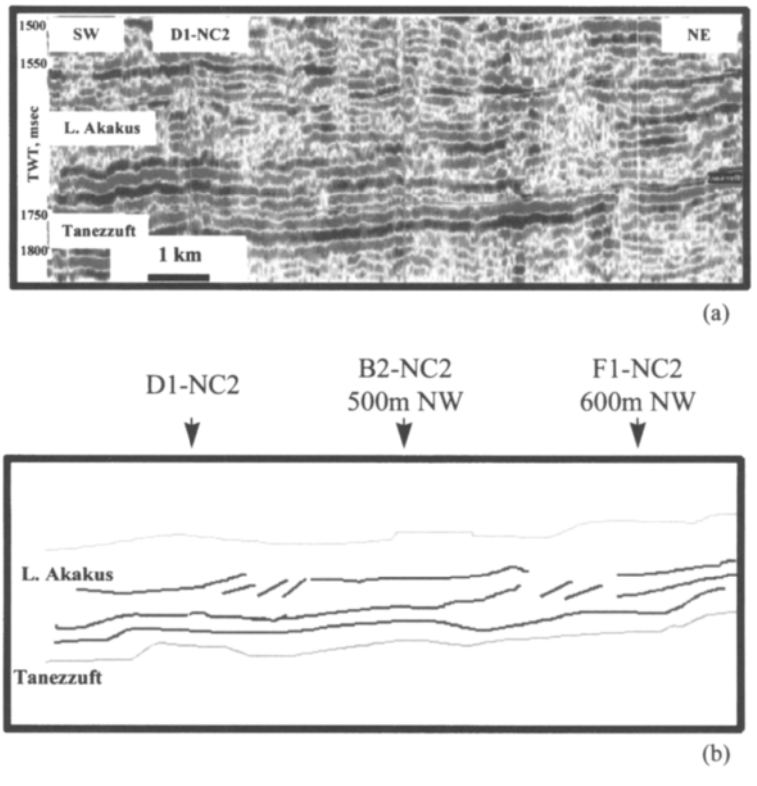

Figure 8. (a). Segment of seismic section; line Y3, showing the seismic reflection character. (b) Geoseismic interpretation of the reflection geometry shown on (a). Note that the locations of 'B' and 'F' structures are projected into the line. For location see Fig. 12.

[2] LOGM Trade mark of Geophysical Microcomputer Applications (International) Ltd., Calgary, Canada T2P 3T7.

WELL TO SEISMIC TIE

Figure 5 shows the synthetic traces inserted into seismic line Y6 over the 'B' structure. The synthetic traces correlate well with the seismic data. The tops of the Lower Akakus and Tanezzuft formations are at 1.385 and 1.55 sec respectively.

TWO-DIMENSIONAL MODELLING

The 2D model was constructed by linearly interpolating the sonic logs between wells. A Ricker wavelet of 55 Hz was used to generate the seismic model. To simulate the real seismic data and to demonstrate the limitation imposed by noise on the recognition of the subtle sand units, random noise was added. The 2D modelling across the B1 and B2 wells shows the following results (Figs 6 and 7):

- Strong and relatively prominent amplitude reflection associated with the top Tanezzuft horizon (Fig. 7),
- A relatively stable interval of weak amplitude events from 2.65 to 2.8 secs. The reflections broaden out towards B1-NC2, (Fig. 6),
- The broad amplitude event shown at about 2.6 sec in the B1-NC2 well is split into two relatively strong amplitude well-separated events in B2-NC2 (Fig. 6),

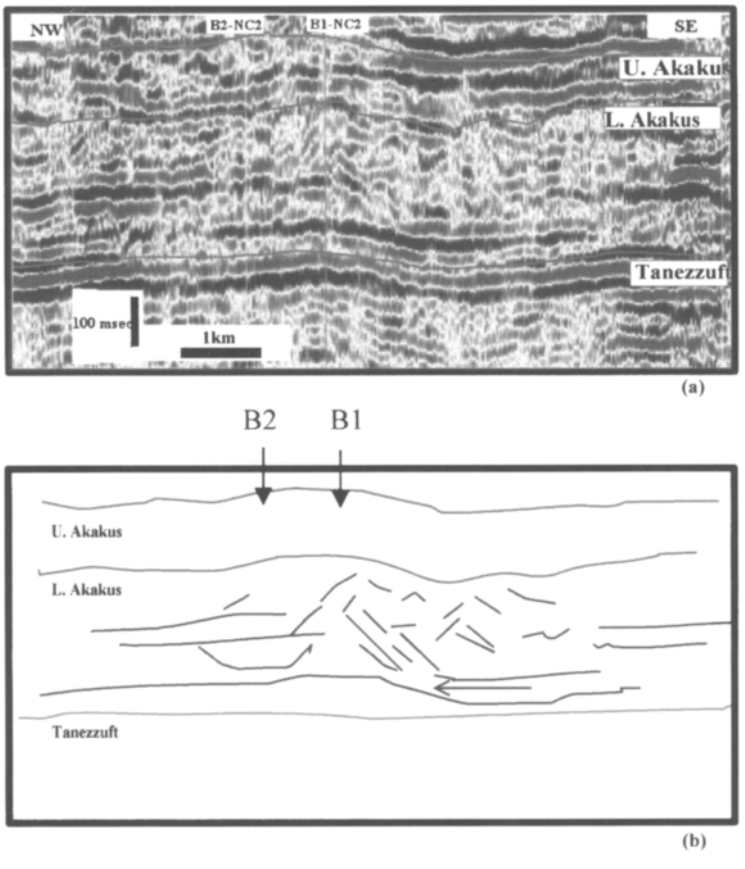

Figure 9. (a) Segment of seismic section; line Y6, showing the seismic reflection character across the 'B' structure. (b) Geoseismic interpretation of the reflection geometry shown on (a). For location see Fig. 12.

- Lateral amplitude variations at about 2.3 sec may indicate the abruptness of vertical contact (Meckel and Nath, 1977; Clark, 1987),
- The sharp amplitude response at about 2.2 sec at B1-NC2 is dimming out towards B2-NC2. This may coincide with the changes in net sand content (Fig. 4). Large amplitudes define areas of thick sand (Khattri and Gir, 1975).

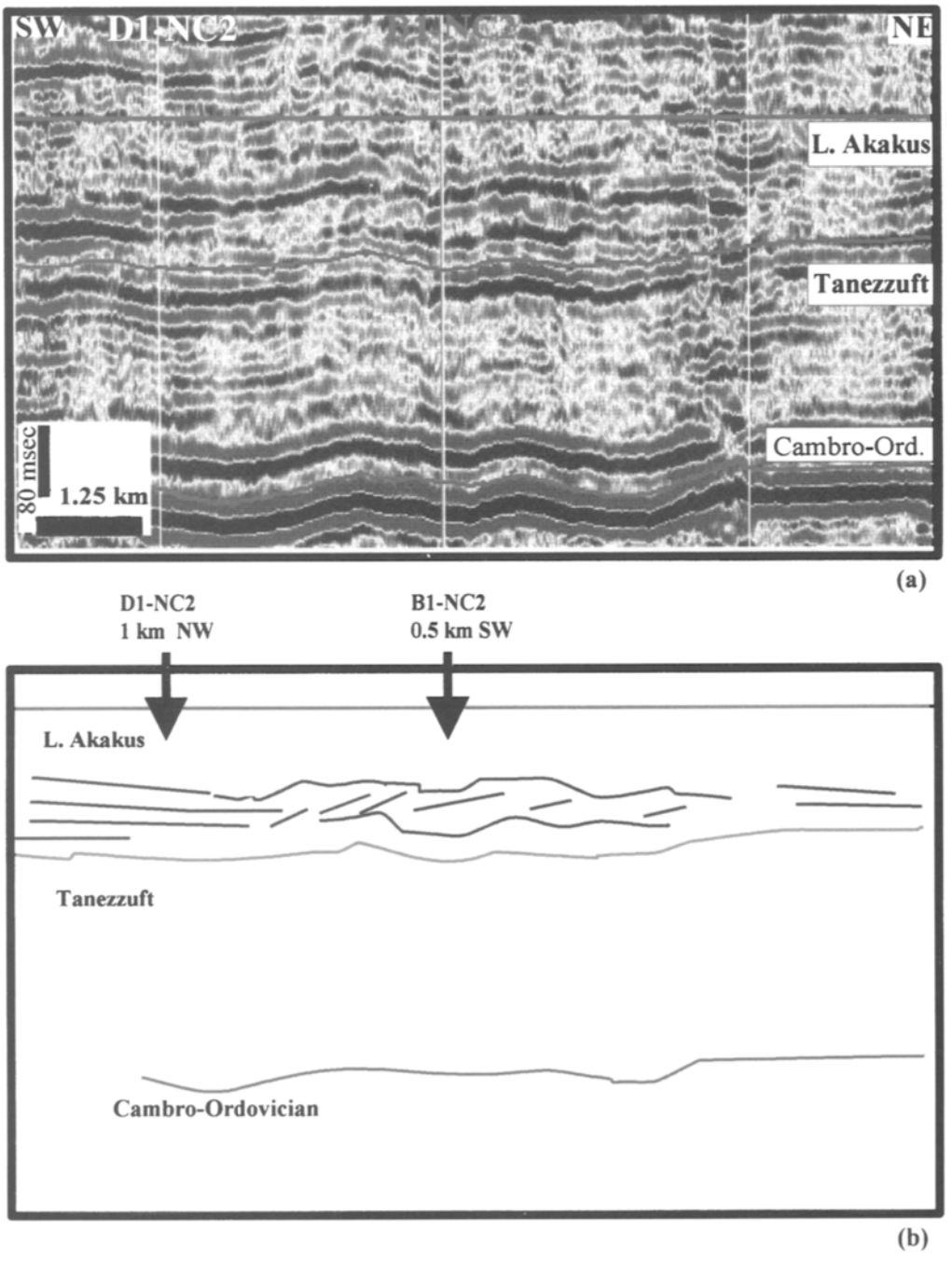

Figure 10. (a) Segment of seismic section; line Y5, showing the seismic reflection character across the 'D' and 'B' structures. Note the section is flattened at the top of Lower Akakus horizon. (b) Geoseismic interpretation of the reflection geometry shown on (a). For location see Fig. 12.

SEISMIC REFLECTION PATTERNS

The interpretation of the seismic data was carried out on Schlumberger's Charisma[3] workstation. The reflection patterns recognized on the seismic data are discussed below. The seismic data are displayed on variable area with dark blue colour representing peak and dark brown representing trough. Geoseismic interpretations of reflection patterns are shown below each portion of seismic section. Some seismic sections across the study area are interpreted as follows:

Seismic line Y3 (Fig. 8) runs across the D structure in the southwest, and over the structural margins of the B and F structures. The seismic reflection patterns at the lower Akakus level show

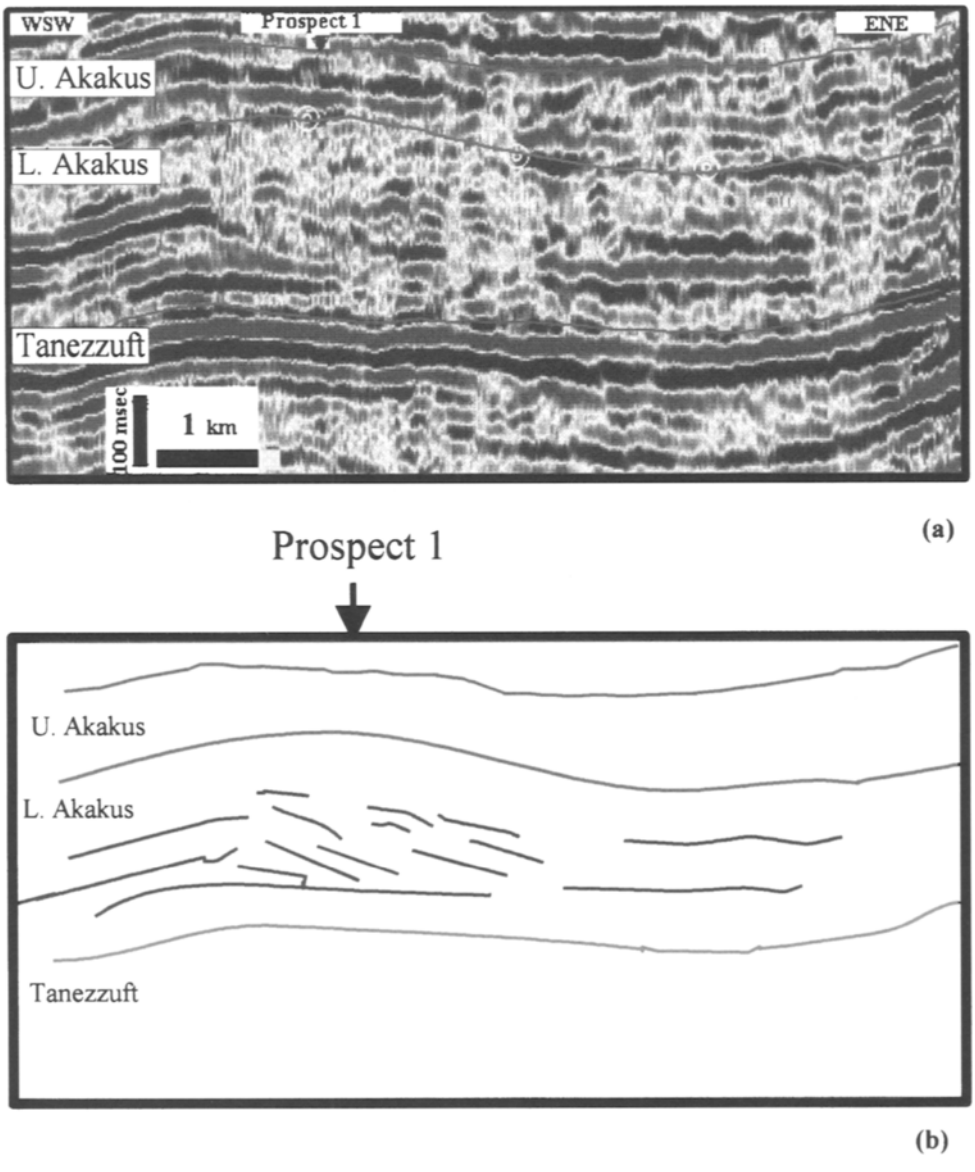

Figure 11. (a) Segment of seismic section; line Y13, showing the seismic reflection character across prospect 1. (b) Geoseismic interpretation of the reflection geometry shown above. For location see Fig. 12.

[3] Charisma: trade mark of Schlumberger Data Services.

rather parallel strong amplitudes at 1.7–1.75 secs across the D structure. Northeast of the D well and toward the B structure, reflection strength decreases and clinoform patterns can be seen.

Seismic line Y6 (Fig. 9) is a NW–SE profile passing through the B structure. This line shows erratic changes of reflection patterns when compared to those of the D structure. The changes are also noticeable even across the location of the B1 and B2 wells themselves. A chaotic reflection pattern and polarity reversal due to truncation of some reflection events is indicated at the location of B1, which may be interpreted as a cut-and-fill channel complex (Mitchum et al., 1977). These patterns may explain the distinct lithological facies changes and hence, the variable hydrocarbon occurrences in the above mentioned two wells, which are only one-kilometer apart (Fig. 4).

Seismic line Y5 (Fig. 10) runs over the southern flank of the D structure and bisects the B structure. This line shows a lenticular shaped reflection geometry. This pattern is characterised by a combination of sigmoid and oblique clinoform patterns known as a 'complex sigmoid-oblique pattern' (Mitchum et al., 1977) and is associated with deltaic facies. The upper segments of the delta are characterized by an alternation of parallel reflections in sigmoidal pattern and oblique configuration with top lap terminations. This implies those alternating episodes of aggredation and progradation occurred within a single seismic sequence.

Seismic line Y13 (Fig. 11). This line shows a similar reflection pattern to that observed on line Y6, (Fig. 9), where parallel reflections are cut by inclined clinoforms but with a regular pattern.

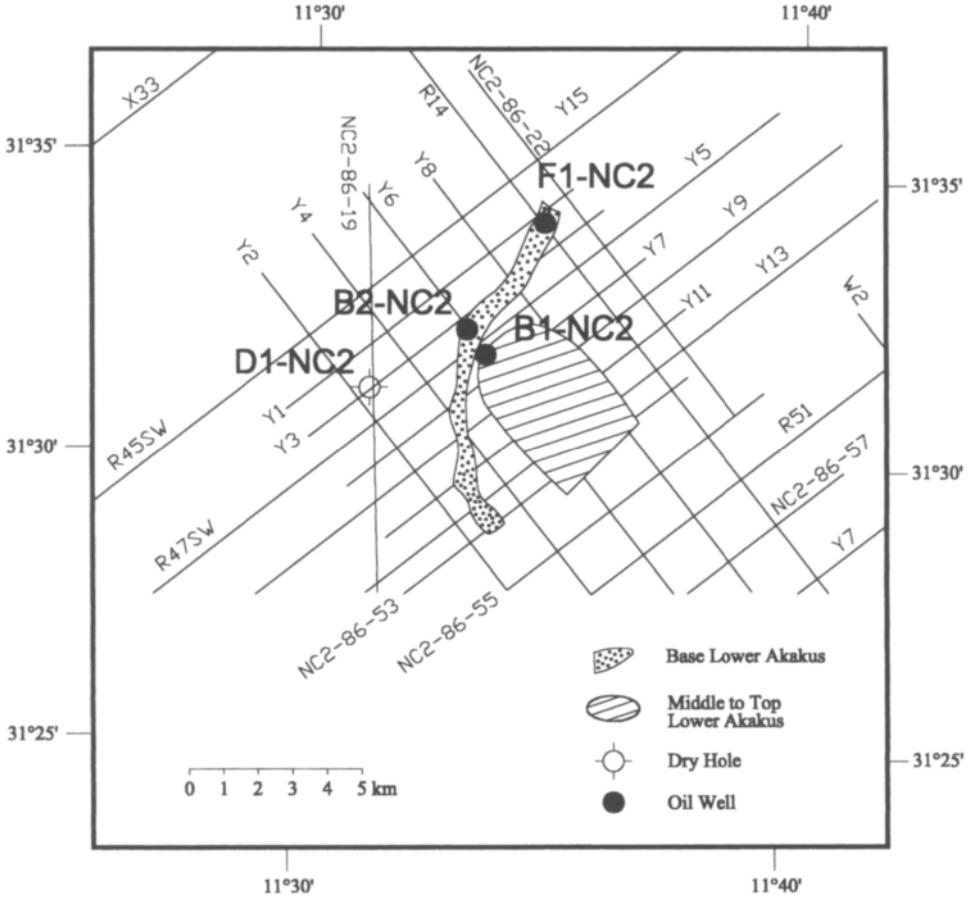

Figure 12. Location map showing areal extent of the Lower Akakus character changes across the study area as interpreted from seismic. See text for explanations.

A map summarizing the areal extent of the various lower Akakus reflection character changes is shown in Fig. 12.

CONCLUSIONS

Individual sandstone beds within the lower member of the Akakus Formation are too thin to be resolved seismically. However, a series of thin sandstones interbedded with shale produces an (overall) distinct seismic reflection pattern. This pattern is regionally mappable, and its occurrence in areas where well control is sparse suggests that sandstone beds are present. Stratigraphic trapping of hydrocarbons occurs in fluvial and/or deltaic systems where lateral and vertical seals are provided. Consequently, analyses and mapping of the seismic reflection character of the Akakus and Tanezzuft formations have been used successfully to highgrade areas for prospect generation and to map the trend of potential stratigraphic traps. Synthetic modelling has also provided good control for well to seismic ties and description of seismic character.

The method presented in this study demonstrates the benefits of integrating well and seismic facies information when interpreting stratigraphic sequences. Detailed analyses of other seismic facies indicators such as the seismic interval velocities coupled with seismic inversion may also help in detecting and mapping subtle stratigraphic traps over large areas.

ACKNOWLEDGMENTS

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CHAPTER 13

Palynology of the upper Tahara Formation in Concession NC7A, Ghadames Basin

ALI DAW EL-MEHDAWI[1]

ABSTRACT

Core samples from the upper part of the Tahara Formation in four wells from concession NC7A have yielded very rich, diverse and well preserved palynomorphs. Terrestrial taxa (spores) represent up to 95% of the total palynomorph content, and marine taxa (acritarchs, prasinophytes and scolecodonts) represent 5% or less of the total palynomorph content. Based on presence of index spore species such as *Retispora lepidophyta*, *Leiotriletes struniensis* and acritarch species such as *Horologinella quadrispina* and *Stellinium micropolygonale*, the studied intervals are assigned a Late Devonian (Late Famennian-Strunian) age.

The palynological organic debris of the Tahara Formation is characterised by a predominance of herbaceous organic matter. Black/opaque debris is also present but less abundant, while amorphous debris is rare to absent. The predominance of terrestrial over marine taxa and vascular debris over amorphous debris would suggest deposition in a marginal marine environment, very close to land and under fluvial – probably deltaic – influence. The dominance of herbaceous debris suggests oil potential for the formation's shales, but the SCI places the formation in the upper part of the oil window (immature to early mature).

INTRODUCTION

The Tahara Formation was introduced by Massa et al. (1974) and Massa and Moreau-Benoit (1976) for a clastic sequence underlying marine Carboniferous deposits and this unit marks the transition between the Devonian and Carboniferous systems in the Ghadames Basin. The type section of the formation is from Well B1–49 drilled in 1958 (Massa and Moreau-Benoit, 1976; Mamgain, 1980). This formation was known previously as 'Grès Tahara' by Burollet and Manderscheid (1967).

The formation consists of a 50 to 70 metre thick sequence of intercalated sandstones and shales, with frequent lateral variation (Fig. 1). The upper boundary of the Tahara Formation is marked by a clear hiatus. It is represented by a marine basal transgressive sandstone and shale unit that was deposited during a period of sea level rise. The sandstone is characterised by several sedimentary structures such as low-angle cross-stratification indicative of tidal action.

[1] Arabian Gulf Oil Co., Exploration Division, Geological Laboratory, PB 263, Benghazi, Libya, Fax: 00 218 61 222 9006

The presence of oolitic chamosite indicates wave activity, which – together with bioturbation and burrowing – indicate normal marine conditions (Saenz de Santa Maria, 1991). The formation contains a sparse microfauna and a rich microfloral association. The formation was assigned to Palynozone 11 of the Late Devonian (Late Famennian-Strunian) by Massa and Moreau-Benoit (1976), and to the Strunian by Collomb (1962) and Mamgain (1980). The former age has been documented by El-Mehdawi (1997 and this chapter). Saen de Santa Maria (1991) and other workers have usually assigned the formation to the early Carboniferous.

This study is concerned with the palynomorph identification of the Tahara Formation in Concession NC7A in order to clarify its age, depositional environment and petroleum potential. Sixteen conventional core samples were selected from five cores cut through the upper part of the unit in four wells in Concession NC7A in the Ghadàmes Basin. These are the AA5, AA6, AA10 and II1 wells (Fig. 1).

The crushed and cleaned samples were treated using standard palynological techniques, including treatment with HCL (35%), HF (40%) and oxidation with Schultze solution. Overoxidation was necessary to liberate the palynomorphs inside the organic material and to make them more visible under transmitted light microscope. All slides are housed in the Geological Laboratory of the Arabian Gulf Oil Company, Benghazi, Libya.

The following samples were processed and examined for their palynological organic matter (P.O.M.) content. Figs 2 to 6 show lithological descriptions of the cores and locations of the studied samples. Lithological descriptions of the selected samples are as follows.

Well AA5-NC7A

Core no. 2:

5705′	Shaly sandstone
5707′	Shaly sandstone
5720′ 6″	Shale
5724′ 2″	Shale

Well AA6-NC7A

Core no. 3:

5718′ 6″	Sandstone
5721′ 4″	Sandy shale
5724′	Shaly sandstone

Core no. 4

5736′ 6″	Sandy shale
5752′	Shale

Well AA10-NC7A

Core no. 1:

5757′	Silty micaceous shale
5758′ 8″	Shaly sandstone
5767′ 2″	Shale

Well II1-NC7A

Core no. 1:

5513′ 5″	Sandstone with silty shale interbeds
5519′	Silty shale
5527′ 7″	Oolitic-chamositic sandstone
5733′	Burrowed sandstone with silty clay.

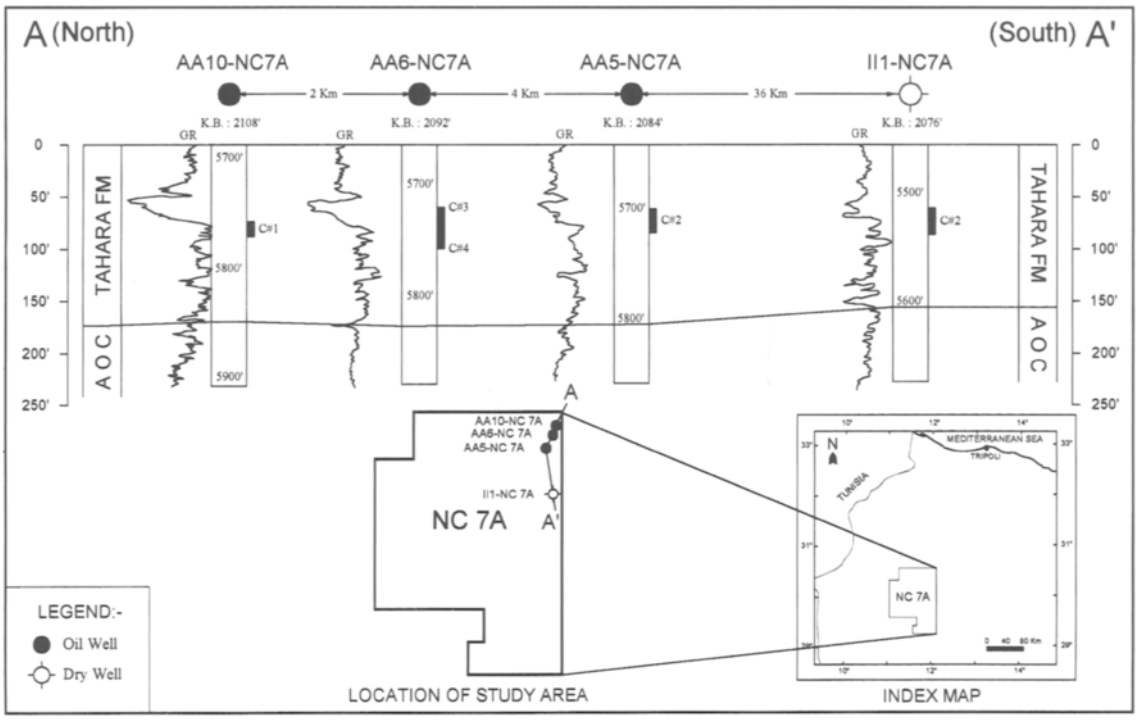

Figure 1. Stratigraphic cross section of the Tahara Formation in the studied wells and location map.

PALYNOSTRATIGRAPHY

The studied samples yielded well preserved, very rich and diverse palynological organic matter (P.O.M.). The P.O.M. is dominated by vascular debris (including plant tissues and wood fragments) and terrestrial taxa, and a low percentage of black/opaque debris (black debris has no internal structure). Amorphous debris (colloidal or aggregates) is very rare to absent.

The predominant sporomorphs comprise up to 95% of the total palynomorph content. They are dominated by microspores, but some types of megaspores and megaspore fragments are also present. Marine taxa are rare (up to 5%) in comparison to terrestrial taxa and are represented by acritarchs, prasinophytes and scolecodonts. Marine chitinozoa were not recognised in the studied samples.

The sporomorph assemblage reported from the studied intervals is very similar to those reported by Massa and Moreau-Benoit (1976) from the Ghadàmes Basin and by Grignani et al. (1991) from the Al Kufra Basin. The only difference is that the studied intervals are barren of chitinozoans, which are reported in the above references. Microphotographs of some of the stratigraphically important taxa are displayed in Plates 1 to 4 and their stratigraphic distribution in the studied samples are shown in Figs 7 to 10.

The most characteristic palynomorphs in the studied samples are listed in Table 1. The recorded assemblage is indicative of a Late Devonian (Late Famennian-Strunian) age. The stratigraphically most important species are *Retispora lepidophyta* and *Leiotriletes struniensis*. The former species is the dominant miospores and was observed in samples from all the studied cores. These taxa are known to be restricted to the Late Devonian (Late Famennian-Strunian) from different parts of the world (see Tables 1 and 2).

Other stratigraphically important miospores include *Acinosporites acanthomammillatus, Asperispora* sp., *Auroraspora hyalina, Convolutispora mellita, C.* cf. *flexuosa, Cristatisporites* spp., *Cyrtospora cristifer, Dibolisporites eifeliensis, D. verrucatus, Dictyotriletes fimbriatus,*

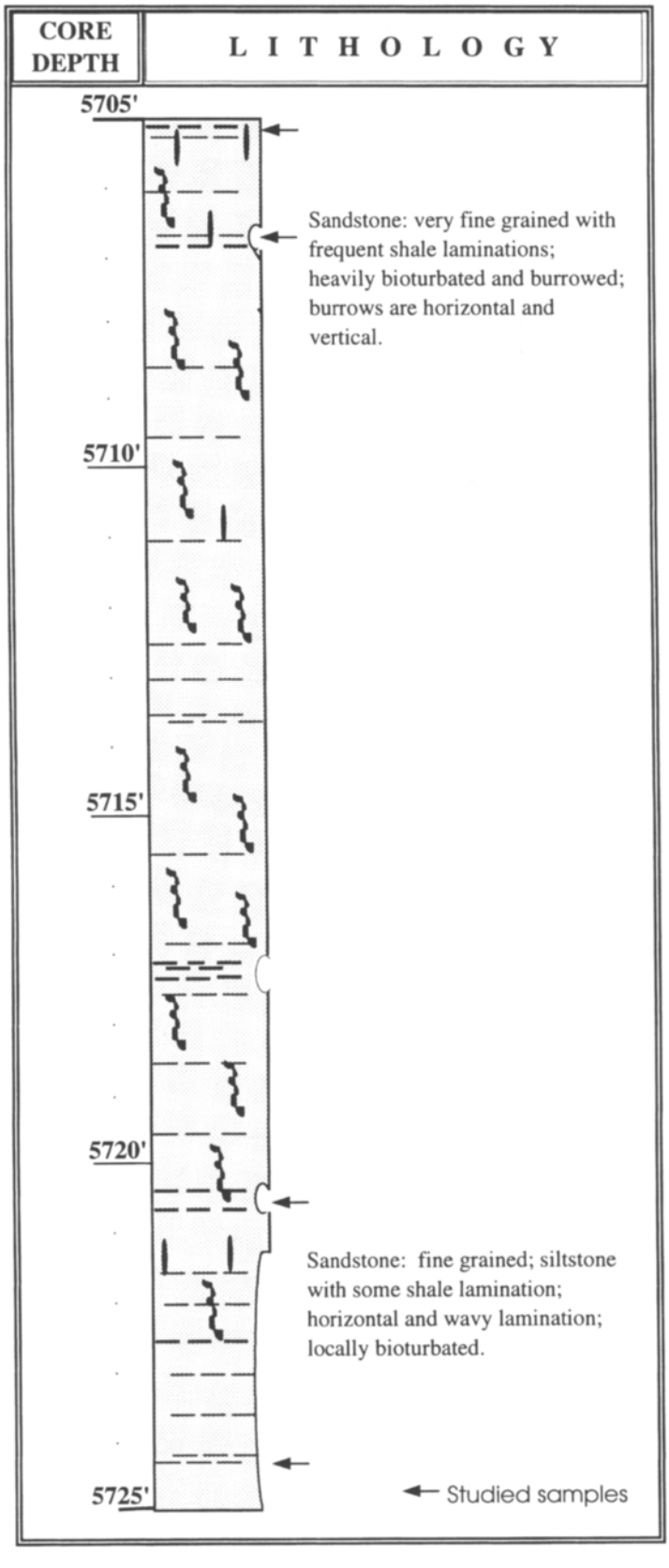

Figure 2. Lithofacies summary of the upper Tahara Formation, Core no. 2, Well AA5-NC7A.

Emphanisporites erricatus, Endosporites micromanifestus, Geminospora lemurata, Grandispora cornuta, G. gabesensis, G. uncata, Hystrichosporites spp., *Knoxisporites literatus, Knoxisporites* spp., *Lophozonotriletes rarituberculatus, L. varituberculatus, Lophozonotriletes* spp., *Pustulatisporites gibberous, P.* cf. *glabrimarginatus, Raistrickia baculosa, R. clavata, Spelaeotriletes crustatus, S. granulatus, Vallatisporites verrucosus, Vallatisporites* spp. and *Verrucosisporites nitidus*. Other indeterminate microspores with tetrad form are also recorded.

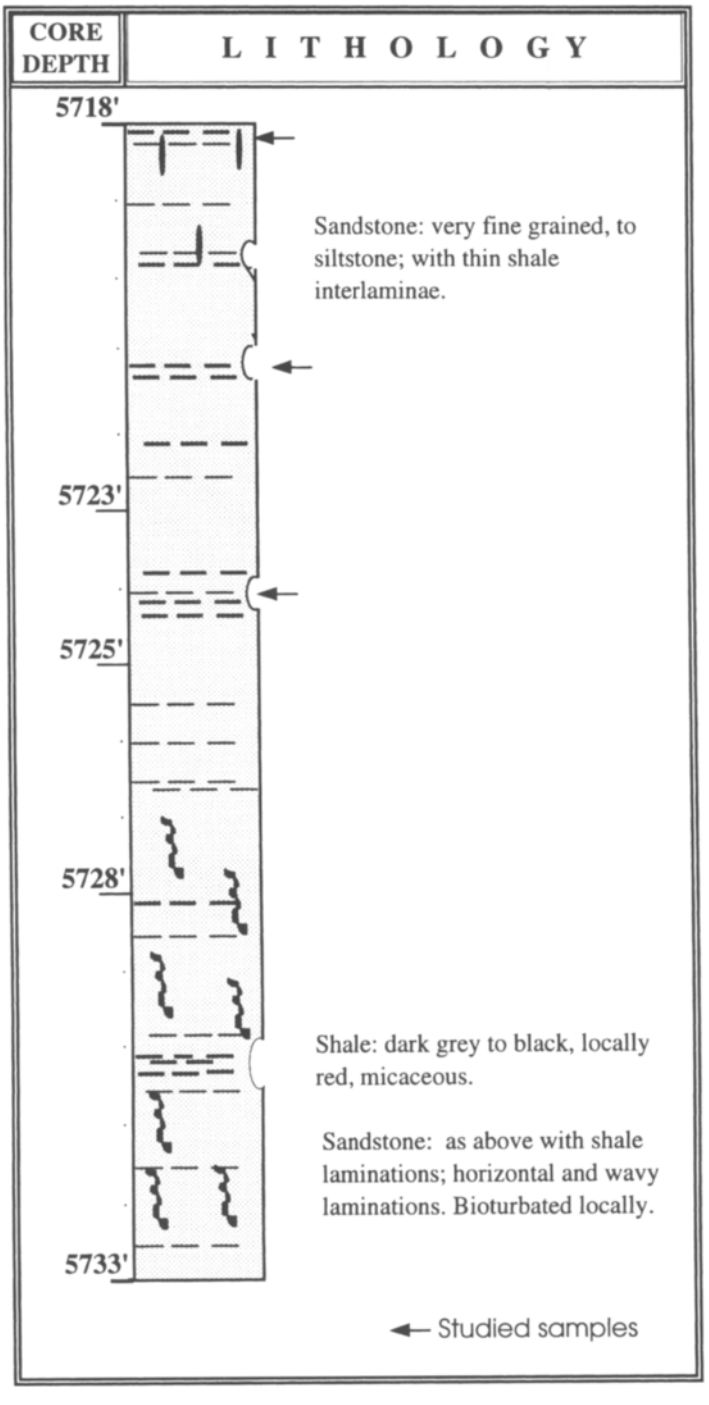

Figure 3. Lithofacies summary of the upper Tahara Formation, Core no. 3, Well AA6-NC7A.

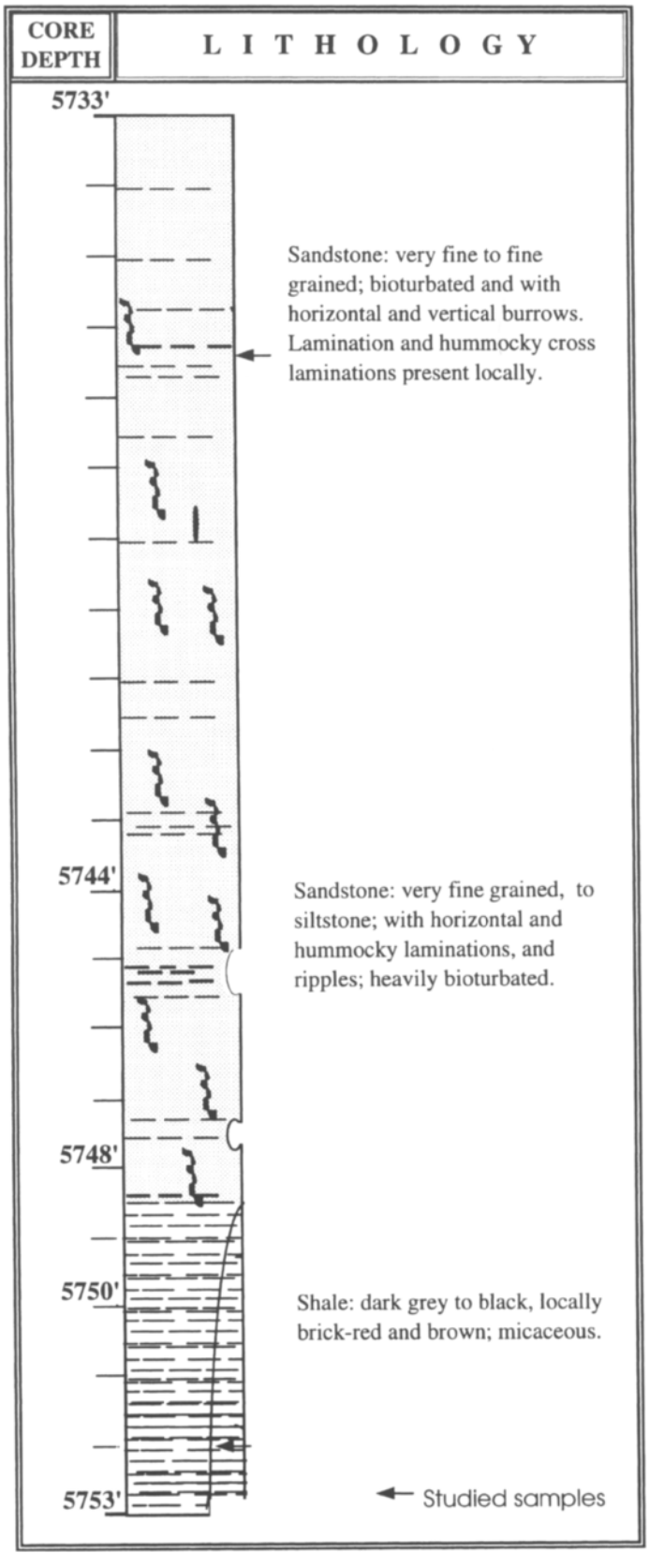

Figure 4. Lithofacies summary of the upper Tahara Formation, Core no. 4 Well AA6-NC7A.

Marine taxa are represented by rare acritarchs, prasinophytes and scolecodonts (jaw of polychaete annelid worms) only. Acritarchs include stratigraphically important species such as *Horoginella quadrisina*, which is known from Upper Devonian (Upper Famennian-Strunian) sediments of North Africa, and *Stellinium micropolygonale*, which is known from the Late Famennian-Strunian of several parts of the world (see Tables 3 and 4). Other acritarch species include *Horoginella horologia*, *Horoginella* sp., *Grogonisphaeridium* sp., *Micrhystridium stellatum*, *?Tornacia stela*, *Unellium winslonae, Veryhachium downiei, V. roscidum* and *V. trispinosum*. Other palynomorphs include very rare *Pterospermella* sp. (prasinophyte) and *Botryococcus braunii* (chlorophyte).

The palynomorph assemblages from the studied wells are all comparable, except that the studied samples from Well II1-NC7A are characterised by either absence, or rare presence of *C. cristifer*, *Convolutispora* spp., *Cristatisporites* spp., *Vallatisporites* spp. and *Raistrickia* spp.

The reported palynomorph assemblage is very comparable to that reported from NE Libya by Paris et al. (1985), to Palynozone 11 of Massa & Moreau-Benoit (1976) from the Ghadàmes Basin, and to Palynozone 11 of Grignani et al. (1991) from the Al Kufra Basin. In Algeria, the assemblage is correlatable to Palynozone L in the Grand Erg Occidental (Lanzoni and Magloire, 1969), and to Palynozone 11 in the Illizi Basin (Attar et al., 1980). As a result of these comparisons the studied section of the Tahara Formation is assigned to the Late Devonian (Late Famennian-Strunian).

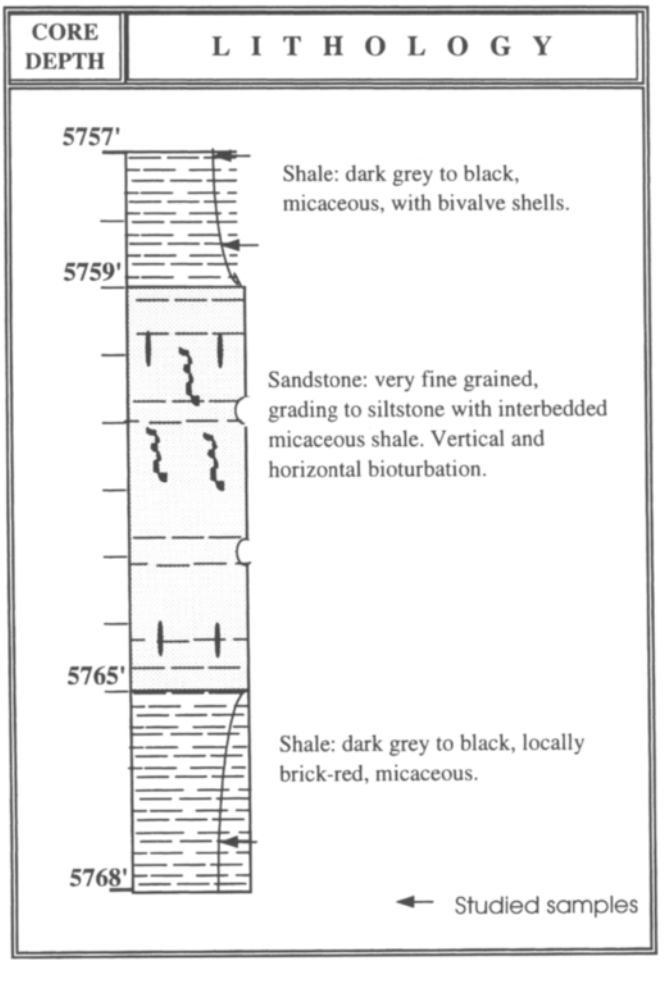

Figure 5. Lithofacies summary of the upper Tahara Formation, Core no. 1, Well AA10-NC7A.

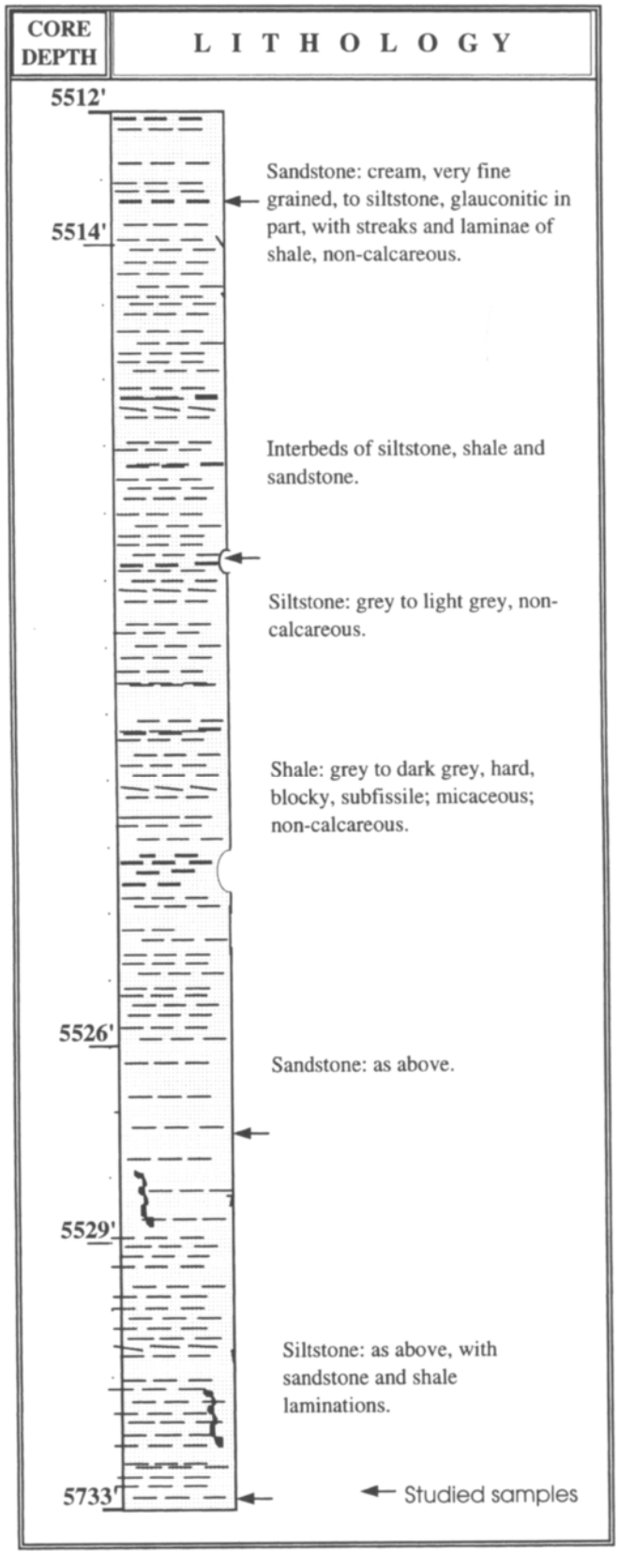

Figure 6. Lithofacies summary of the upper Tahara Formation, Core no. 1, Well II1-NC7A.

LATE FAMENNIAN-STRUNIAN				AGE	
T A H A R A				FORMATION	
5724'2"	5720'6"	5707'	5705'	DEPTH IN FT	LIST OF PALYNOMORPHS
●					*Acinosporites* cf. *acanthomammillatus*
●					*Asperispora numova*
		●			*Asperispora* sp.
			●		*Auroraspora asperella*
●			●		*Auroraspora hyalina*
		●			*Calamospora* sp.
●	●	●	●		Cyrtospora cristifer
●	●				*Convolutispora mellita*
●					*Convolutispora* cf. *flexuosa*
	●				*Convolutispora* cf. *superficialis*
●					*Convolutispora vermiformis*
●	●	●	●		*Convolutispora* spp.
	●		●		*Cristatisporites* sp.
●					*Cristatitriletes* sp.
			●		*Clivesispora* sp.
		●	●		*Densosporites* spp.
			●		*Dibolisporites eifeliensis*
		●			*Dibolisporites verrrucatus*
●	●	●	●		*Dictyotriletes fimbriatus*
	●				*Dictyotriletes* sp.
●	●	●	●		*Dictyotriletes* spp.
	●				*Endosporites micromanifestus*
●	●		●		*Grandispora uncata*
●					*Grandispora* sp.
●			●		*Hystrichosporites* spp.
	●				*Knoxisporites literatus*
●	●	●	●		*Knoxisporites* spp.
			●		*Laevigatosporites vagularis*
			●		*Lophozonotriletes rarituberculatus*
			●		*Lophozonotriletes varituberculatus*
●					*Lophozonotriletes* spp.
●					*Pustulatisporites gibberosus*
		●			*Pustulatisporites* cf. *glabrimarginatus*
	●				*Pustulatisporites* sp.
	●				*Raistrickia clavata*
●	●	●	●		*Retispora lepidophyta*
			●		*Retusotriletes* sp.
●					*Spelaeotriletes* cf. *crustatus*
●					*Spelaeotriletes granulatus*
			●		*Spelaeotriletes* spp.
			●		*Vallatisporites verrucosus*
			●		*Verrucosisporites nitidus*
		●			*Verrucosisporites scurrus*
●	●	●	●		*Verrucosisporites* spp.
●					Trilete spores indet. (Tetrad forms)
●	●	●	●		Trilete spores undiff.
●	●	●	●		Other trilete spores undiff.
	●				*Grogonisphaeridium* ? sp.
●					*Horologinella horologia*
●					*Horologinella quadrispina*
●					*Horologinella* sp.
	●				*Micrhystridium stellatum*
			●		*Micrhystridium* sp.
	●	●	●		*Stellinium micropolygonale*
		●			?*Tornacia stela*
	●				*Unellium winslonae*
●					*Veryhachium downiei*
			●		*Veryhachium roscidum* ?
			●		*Veryhachium trispinosum*
●					*Veryhachium* sp.
	●		●		*Petrospermella* sp.
	●				*Maranhites mosesii*
●	●				Scolecodonts

MIOSPORES

ACRITARCHS

OTHERS

Figure 7. Stratigraphic distribution of recorded palynomorphs in Core no. 2, Well AA5-NC7A.

LATE FAMENNIAN-STRUNIAN					AGE		
T A H A R A					FORMATION		
C # 4		C # 3			CORE NO.		
5752'	5736'6"	5724'	5721' 4"	5718 6'	DEPTH IN FT	LIST OF PALYNOMORPHS	
●		–				*Acinosporites acanthomammillatus*	MIOSPORES
●	●	●	●	●		*Auroraspora hyalina*	
	●					*Auroraspora macra*	
●						*Calamospora* sp.	
		●	●	●		*Cyrtospora cristifer*	
		●	●	●		*Convolutispora mellita*	
		●	●			*Convolutispora* cf. *flexuosa*	
		●		●		*Convolutispora* cf. *superficially*	
		●	●			*Convolutispora vermiformis*	
●						*Convolutispora* spp.	
●	●	●	●			*Cristatisporites* sp.	
●						*Densosporites variomarginatu* s	
●						*Densosporites* spp.	
				●		*Dibolisporites verrrucatus*	
●	●	●	●	●		*Dictyotriletes fimbriatus*	
		●	●	●		*Dictyotriletes* sp.	
				●		*Dictyotriletes* spp.	
			●			*Emphanisporites erricatus*	
●				●		*Endosporites micromanifestus*	
		●		●		*Geminospora lemurata*	
		●				*Geminospora* sp.	
				●		*Grandispora gabesensis*	
	●	●	●	●		*Grandispora uncata*	
	●	●		●		*Grandispora* sp.	
●	●			●		*Hystrichosporites* spp.	
●	●	–		–		*Knoxisporites literatus*	
			●			*Knoxisporites* spp.	
	●					*Lagenicula* sp. (megaspore)	
●						*Leiotriletes struniensis*	
		●				*Lophozonotriletes rarituberculatus*	
●	●	–		–		*Lophozonotriletes varituberculatus*	
				●		*Raistrickia clavata*	
●	●	●	●	●		*Retispora lepidophyta*	
●		–		–		*Spelaeotriletes* cf. *crustatus*	
●		●	●			*Spelaeotriletes granulatus*	
			●	●		*Vallatisporites verrucosus*	
		●		●		*Vallatisporites* sp.	
●	●			●		*Verrucosisporites nitidus*	
●				●		*Verrucosisporites* spp.	
●		●				Megaspores indet.	
		●				Monolete spore indet.	
		●				Trilete spore type 1	
		●		●		Trilete spores indet. (Tetrad forms)	
		●	●	●		Trilete spores undiff.	
		●	●			*Grogonisphaeridium* ? sp.	ACRITARCHS
			●			*Grogonisphaeridium* cf. *ohioense*	
●						*Horologinella quadrispina*	
●						*Micrhystridium stellatum*	
			●			*Micrhystridium* sp.	
	●					*Solisphaeridium* sp.	
			●			*Stellinium micropolygonale*	
●						*Veryhachium roscidum* ?	
●			●			*Veryhachium trispinosum*	
						Indet. acritarch (cavate form)	
	●	●	●	●		Scolecodonts	OTHERS

Figure 8. Stratigraphic distribution of recorded palynomorphs in cores no. 3 & 4, Well AA6-NC7A.

PALYNOFACIES AND SOURCE ROCK POTENTIAL

The studied samples are characterised by the predominance of terrestrial organic matter, including vascular debris (plant tissues and wood fragments) and black/opaque debris. The black/opaque debris has no internal structure, while amorphous debris (colloidal or aggregates) is rare to absent.

The samples are characterised by a high percentage of terrestrial palynomorphs. The cores from wells AA5, AA6, AA10 and II1-NC7A (except the intervals 5519′ and 5527′ 7′ from the

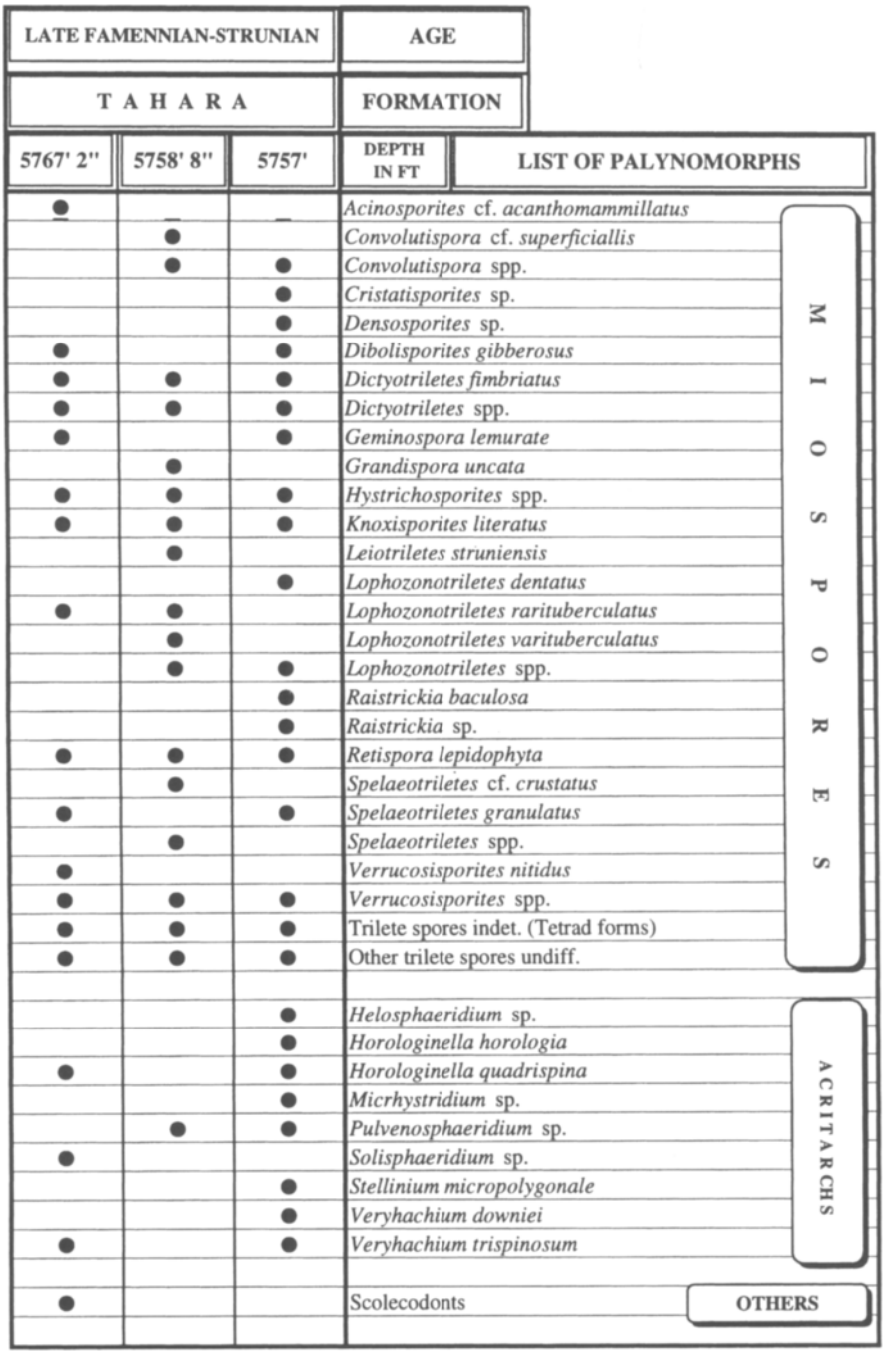

Figure 9. Stratigraphic distribution of recorded palynomorphs in Core no. 1, Well AA10-NC7A.

latter well), are distinguished by a predominance of large plant tissues, wood fragments and a high percentage (more than 95% of the total palynomorph content) of heavily sculptured microspores, megaspores, megaspore fragments, and only rare acritarchs. The high abundance of the vascular debris in the study section, especially the presence of large plant tissues, suggests close proximity to the parent flora and an active fluviodeltaic source (Tyson, 1993). The predominance of terrestrial content and presence of megaspores and megaspore fragments (in wells AA5, AA6 and AA10-NC7A) and tetrad spores (not seen from the lower three samples of

LATE FAMENNIAN-STRUNIAN				AGE	
T A H A R A				FORMATION	
5533'	5527'7"	5519'8"	5513'5"	DEPTH IN FT	LIST OF PALYNOMORPHS
●	●				*Auroraspora hyalina*
	●				*Auroraspora* sp.
			●		*Cyrtospora cristifer*
			●		*Convolutispora mellita*
	●				*Convolutispora* spp.
●		●	●		*Dictyotriletes fimbriatus*
		●			*Dictyotriletes* sp.
●					*Grandispora cornuta*
		●	●		*Grandispora uncata*
			●		*Grandispora* sp.
●		●			*Hystrichosporites* spp.
		●			*Knoxisporites literatus*
		●			*Laevigatosporites vagularis*
		●			*Leiotriletes struniensis*
		●	●		*Lophozonotriletes rarituberculatus*
			●		*Raistrickia baculosa*
●					*Raistrickia* sp.
●	●	●	●		*Retispora lepidophyta*
●	●				*Spelaeotriletes* cf. *crustatus*
●			●		*Spelaeotriletes granulatus*
		●			*Spelaeotriletes obtusus* ?
●		●			*Spelaeotriletes resolutus*
		●			*Vallatisporites splendens*
			●		*Vallatisporites verrucosus*
		●			*Vallatisporites* sp.
		●			*Verrucosisporites* spp.
			●		Trilete spores indet. (Tetrad forms)
			●		Trilete spore type A
●	●	●	●		Trilete spores undiff.
			●		*Amonidium* sp.
			●		*Grogonisphaeridium* ? sp.
		●			*Horologinella horologia*
●					*Horologinella quadrispina*
●					*Micrhystridium* sp.
●		●			*Veryhachium trispinosum*
●					Acritarchs undiff.
			●		*Botryococcus braunii*
			●		Scolecodonts

MIOSPORES

ACRITARCHS

OTHERS

Figure 10. Stratigraphic distribution of recorded palynomorphs in Core no. 1 Well II1-NC7A.

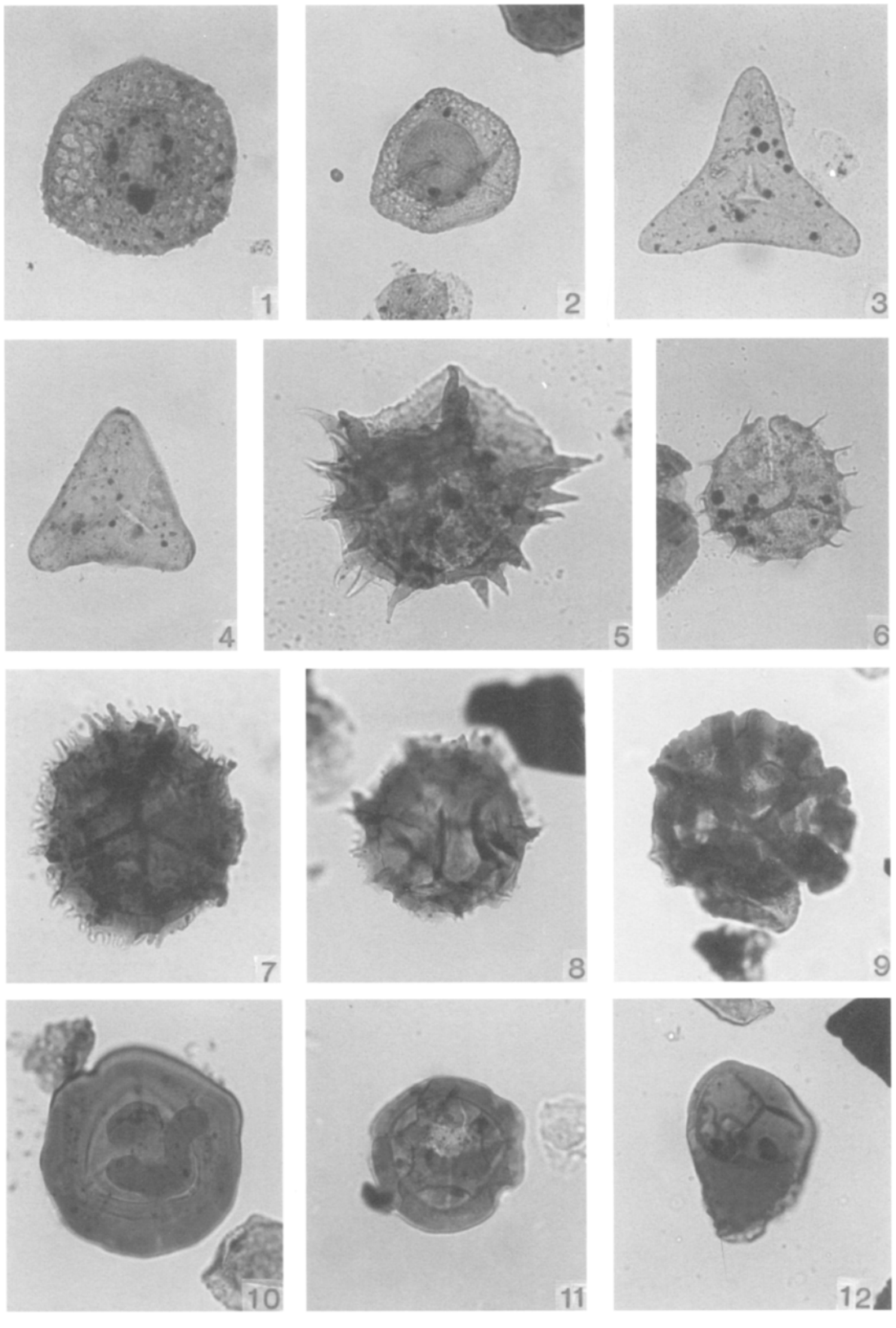

Plate 1. (*for description see end of chapter*)

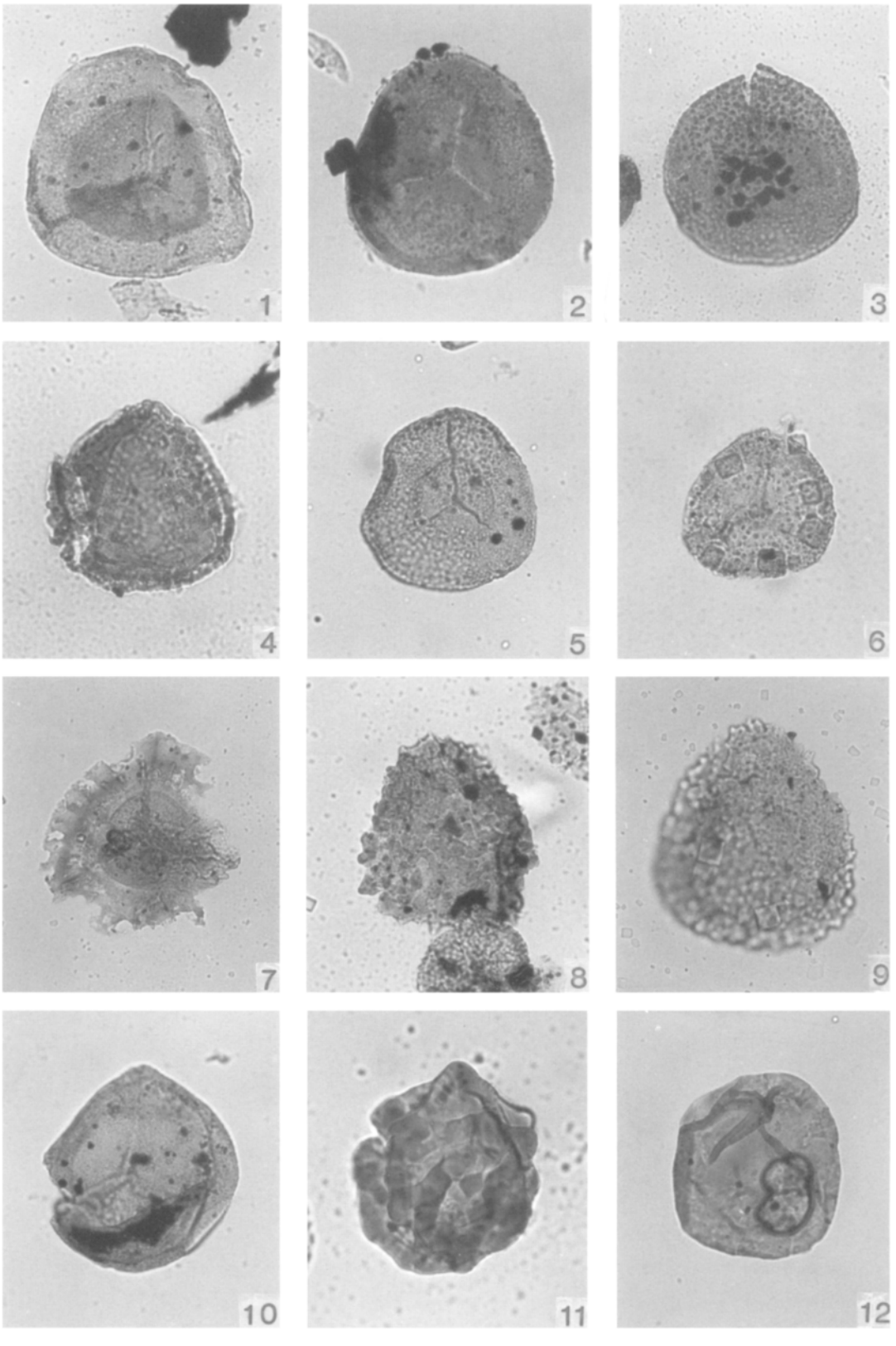

Plate 2.

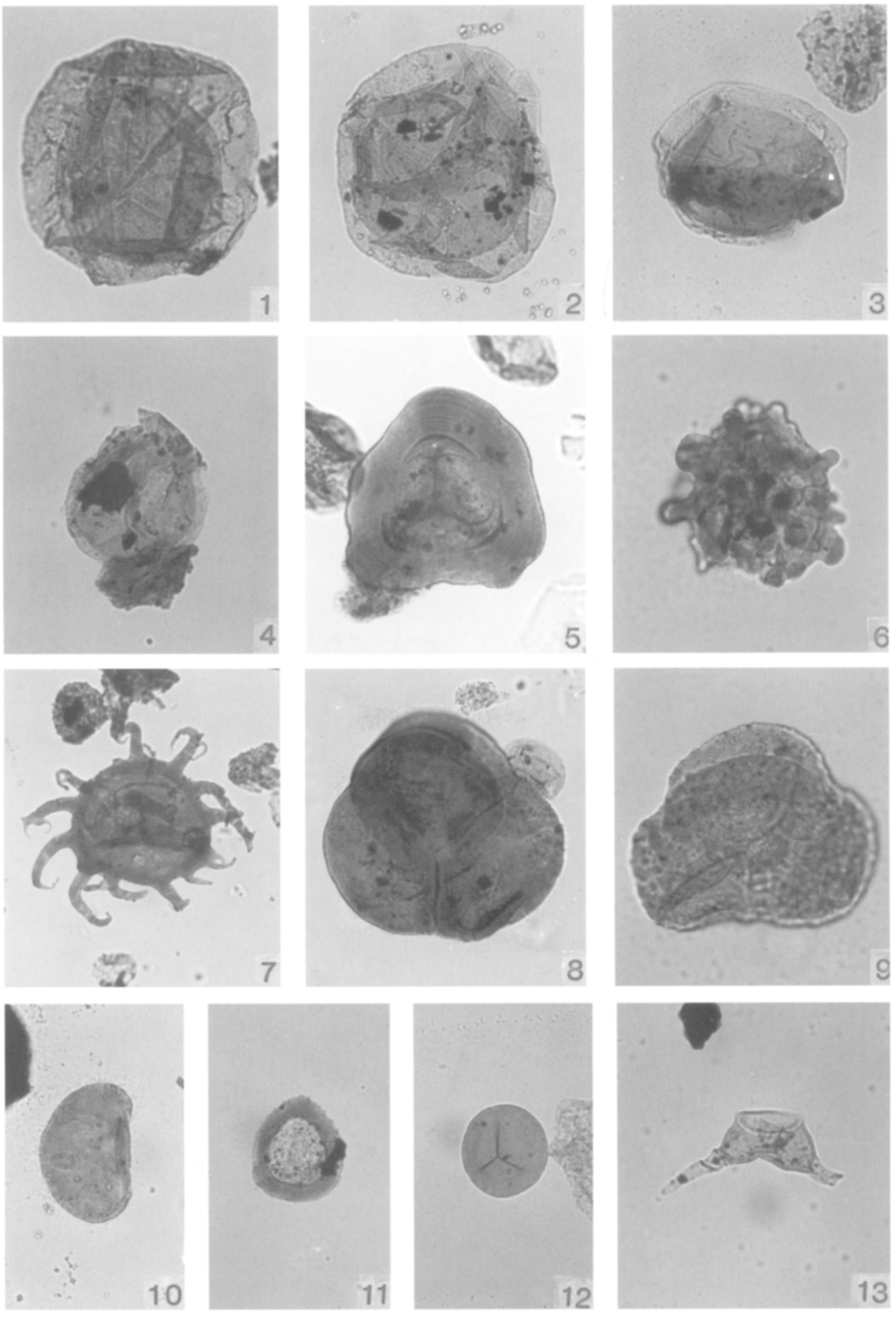

Plate 3.

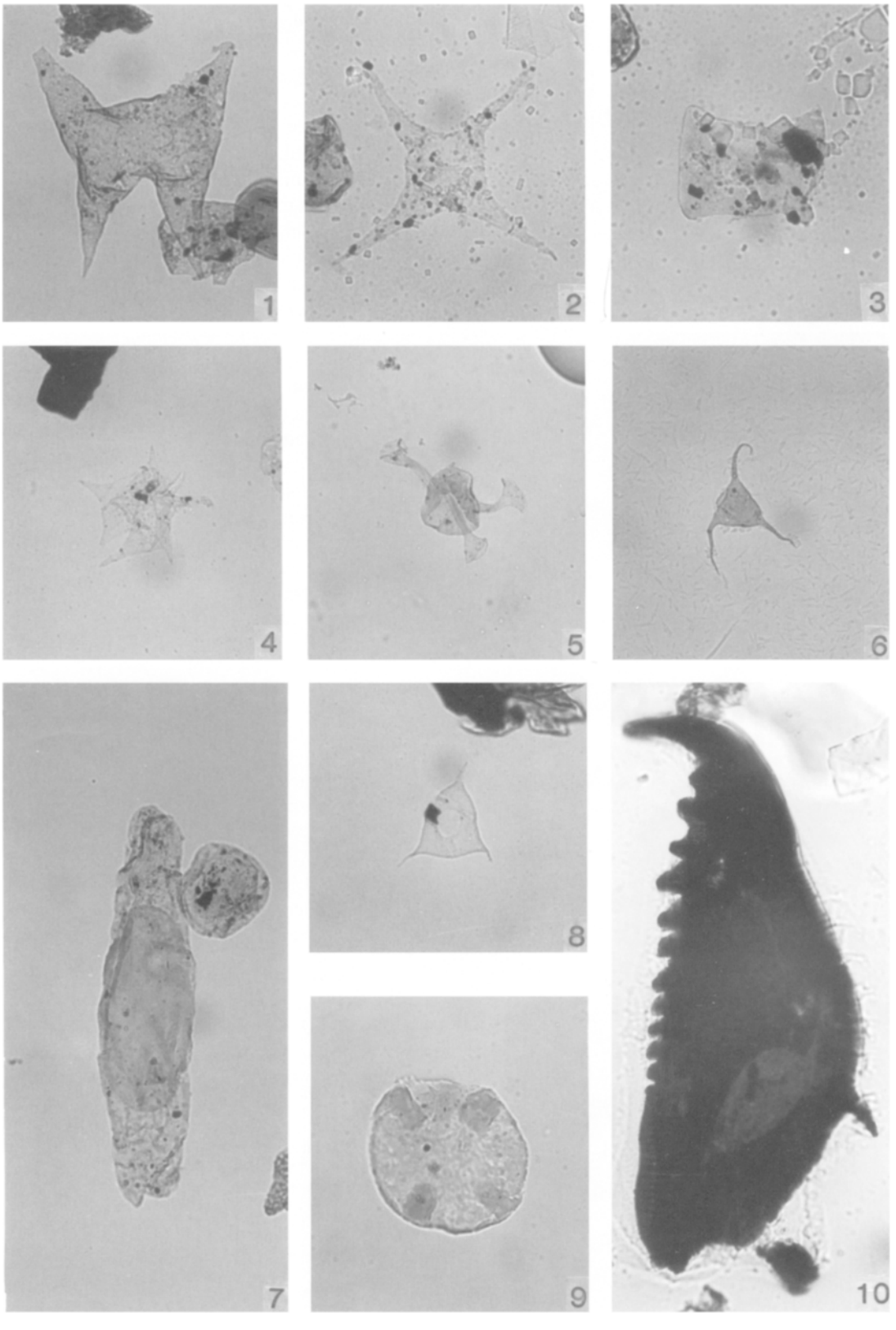

Plate 4.

Table 1. Some known stratigraphic occurrences of *Retispora lepidophyta* (Kedo) Playford

Author	Country	Age
Attar et al., 1980	Algeria	Strunian
Avchimovitch, 1992	Belarus	Famennian
Balme & Hassell, 1962	W. Australia	Famennian
Bouckaert et al., 1969	Belgium	Late Famennian-Strunian
Byvscheva et al., 1984	USSR-Germany	Famennian-Strunian
Clayton et al., 1974	W. Europe	Famennian-Lower Tournaisian
Coquel & Deunff, 1977	France	Strunian
Coqule et al., 1977	Iran	Late Famennian-Strunian
Grignani et al., 1991	Al Kufrah Basin	Late Famennian-Strunian
Higgs, 1975	SE Ireland	Late Famennian
Lanzoni & Magloire, 1969	Algeria	Strunian
Loboziak et al., 1991	Brazil	Late Famennian-? Late Tournaisian
Massa & Moreau-Benoit, 1976	Libya	Late Famennian-Strunian
Neves & Dolby, 1967	Britain	Late Devonian
Playford, 1990	Australia	Famennian
Rahmani-Antari, 1990	Morocco	Late Famennian-Late Tournaisian
Sandberg et al., 1972	U.S.A.	Late Famennian
Streel, in Paris et al., 1985	NE Libya	Late Famennian
Wray, 1964	Libya	Late Devonian

Table 2. Some known stratigraphic occurrences of *Leiotriletes struniensis* Moreau-Benoit

Author	Country	Age
Coquel & Latreche, 1989	Algeria	Strunian
Massa & Moreau-Benoit, 1976	Libya	Late Famennian-Strunian
Massa & Moreau-Benoit, 1979	Libya	Late Famennian-Strunian
Streel, in Paris et al., 1985	NE Libya	Late Famennian

Table 3. Some known stratigraphic occurrences of *Horologinella quadrispina* Jardine et al.

Author	Country	Age
Coquel & Latreche, 1989	Algeria	Strunian
Grignani et al., 1991	Al Kufrah Basin	Late Famennian-Strunian
Jardine et al., 1972	Algeria	Famennian-Strunian
Massa & Moreau-Benoit, 1985	Libya	Late Famennian-Strunian
Moreau-Benoit, 1984	Libya	Late Famennian-Strunian
Vanguestaine, in Streel et al., 1988	NE Libya	Frasnian-Strunian

Table 4. Some known stratigraphic occurrences of *Stellinium micopolygonale* (Stockmans & Williere) Playford

Author	Country	Age
Coquel & Latreche, 1989	E. Algeria	Strunian
Cunha & Oliveria, 1989	Portugal	Famennian
Giese et al., 1988	SW Spain	Strunian
Grignani et al., 1991	Al Kufrah Basin	Late Famennian-Strunian
Lanzoni & Magloire, 1969	Algeria	Late Famennian-Strunian
Massa & Moreau-Benoit, 1985	Libya	Late Famennian-Strunian
Playford, 1976	W. Australia	Late Devonian
Rahmani-Antari, 1990	Morocco	Frasnian-Famennian
Vanguestaine, in Paris et al., 1985	NE Libya	Emsian-Famennian
Wicander & Loeblich, 1977	Indiana	Late Frasnian-Early Famennian

Well II1-NC7A) would suggest deposition in a very restricted marginal marine, nearshore environment very close to land under fluviodeltaic conditions.

The palynological organic matter recorded from samples 5519′ (silty shale) and 5527′ 7′ (oolitic-chamositic sandstone) in Well II1-NC7A are characterised by a greater abundance of lath-shaped and equidimensional black/opaque debris, a finer size of vascular debris, an absence of (latter sample) to rare (former sample) marine acritarchs and a low abundance and diversity of sporomorphs. The miospores are generally small sized. These components would indicate a high energy depositional environment far from the source of the terrestrial supply.

The visual kerogen study of samples from Core no. 4 of Well AA6-NC7A and Core no.1 of Well AA10-NC7A shows that the samples are characterised by high contents of herbaceous material (including spores) and a low percentage of amorphous debris. The herbaceous debris content ranges from 85 to 95%, while the amorphous debris content ranges from 5 to 15%. The oil generating organic matter content (herbaceous and amorphous) varies from 90 to 97%.

The maturity level of the Tahara Formation has been determined by the colour of the organic matter, particularly spores. The colour of the organic matter in the studied samples is golden yellow to yellowish brown, which corresponds to the SCI (spore colour index) 3 to 4. This is an indication that the Tahara Formation lies within the immature to early mature zone of hydrocarbon generation. A study carried by Savic and Ojaley (1995) shows that the studied samples from Core no. 4 of Well AA6-NC7A and Core no. 1 of Well AA10-NC7A are characterised by high pyrolysis indicating good to very good source rock potential, and with a Tmax range from 427–434°C. The visual kerogen analysis and the available Rock-Eval data (Savic and Ojaley, 1995) would suggest that the Tahara Formation in the studied wells is capable of generating mainly oil, but it has not been subjected to high enough temperatures to generate hydrocarbons.

CONCLUSIONS

The studied sections of the upper part of the Tahara Formation in wells AA5, AA6, AA10 and II1-NC7A are assigned a Late Devonian (Late Famennian-Strunian) age and are characterised by a palynomorph assemblage correlatable to those reported from the Ghadàmes Basin, Al Kufrah Basin, Libya and from the Grand Erg Occidental and Illizi Basin, Algeria.

The palynomorph assemblages of the studied wells are very similar and show minor variations in abundance from one well to another. This similarity supports log and lithofacies correlations in these wells.

The predominance of terrestrial over marine taxa suggests deposition in a marginal marine, nearshore environment, and under fluviatile – probably deltaic – influence.

The studied sections of the Tahara Formation are dominated by herbaceous debris suggesting oil generating potential, but the SCI puts the formation into the upper part of the oil widow (immature to early mature).

ACKNOWLEDGMENTS

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DESCRIPTION OF PLATES 1–4 (pp. 283-286)

The well number, core number, sample depth in feet, slide designation (ox) for oxidised samples and (unox) for unoxidised samples, and England Finder reference are all given sequentially for each illustrated specimen. A Leitz 2 Orthplan microscope was used. The magnification of the taxa is X757.

PLATE 1. (p. 285)

1. *Retispora lepidophyta* (Kedo) Playford; Well II1-NC7A, Core no. 1, 5519″8′, sl.1 (unox), T49/2.
2. *Retispora lepidophyta* (Kedo) Playford; Well AA6-NC7A, Core no. 4, 5752′, sl.2 (ox), F48/1.
3. *Leiotriletes struniensis* Moreau-Benoit; Well II1-NC7A, Core no. 1, 5519′8′, sl.1 (unox), L51/0.
4. *Leiotriletes struniensis* Moreau-Benoit; Well AA6-NC7A, Core no. 4, 5752′, sl.1 (ox), N32/0.
5. *Grandispora uncata* (Hacquebard) Playford; Well AA5-NC7A, Core no. 2, 5720′6′, sl.1 (unox), E41/0.
6. *Grandispora cornuta* Higgs; Well II1-NC7A, Core no. 1, 5519′8′, sl.1 (unox), G32/2.
7 *Dictyotriletes fimbriatus* (Winslow) Kaiser; Well AA5-NC7A, Core no. 2, 5705′, sl.1 (ox), L45/0.
8. *Dictyotriletes fimbriatus* (Winslow) Kaiser; Well AA5-NC7A, Core no. 5, 5705′, sl.2 (ox), P56/0.
9. *Dictyotriletes* sp.; Well AA5-NC7A, Core no. 2, 5720′6′, sl.1 (unox), U37/1.
10. *Lophozonotriletes rarituberculatus* (Luber) Kedo; Well AA6-NC7A, Core no. 1, 5736′6′, sl.1 (ox), G35/4.
11. *Knoxisporites literatus* (Waltz) Playford; Well II1-NC7A, Core no. 1, 5519′8′, sl.1 (unox), D46/2.
12. *Cyrtospora cristifer* (Luber) Van Der Zwan; Well AA5-NC7A, Core no. 2, 5705′, sl.3 (ox), H50/0.

PLATE 2. (p. 286)

1. *Endosporites micromanifestus* Haquebard; Well AA5-NC7A, Core no. 2, 5720′6′, sl.2 (ox), N41/0.
2. *Geminospora* sp.; Well AA5-NC7A, Core no. 2, 5705′, sl.1 (unox), S56/4.
3. *Spelaeotriletes pretosus* (Playford) Neves & Belt; Well II1-NC7A, Core no. 1, 5519′8′, sl.1 (unox), G42/3.
4. *Vallatisporites verrucosus* Haquebard; Well II1-NC7A, Core no. 1, 5513′5′, sl.1 (unox), T44/2.
5. *Spelaeotriletes granulatus* (Kedo) Moreau-Bennoit; Well AA5-NC7A, Core no. 2, 5705′, sl.1 (ox), F41/1.
6. *Spelaeotriletes crustatus* Higgs; Well AA5-NC7A, Core no. 2, 5724′ 2′, sl.2 (ox), E52/4.
7. *Vallatisporites* sp.; Well AA5-NC7A, Core no. 2, 5720′ 6′, sl.2(ox), J58/0.
8. *Acinosporites* cf. *acanthomammillatus* Richardson; Well AA5-NC7A, Core no. 2, 5724′2′, sl.2 (ox), L48/1.

9. *Asperispora* cf. *numova* Staplin & Jansonius; Well AA5-NC7A, Core no. 2, 5724′2′, sl.2 (ox), D34/0.
10. *Retusotriletes* sp; Well AA5-NC7A, Core no. 2, 5724′2′, sl.2 (ox), O34/2.
11. *Convolutispora* cf. *superficialis* Flix & Burbridge; Well AA5-NC7A, Core no. 2, 5720′6′, sl.2 (ox), D57/4.
12. *Calamospora* sp.; Well AA6-NC7A, Core no. 1, 5752′, sl.1 (ox), H 46/4.

PLATE 3. (p. 287)

1. *Auroraspora macra* Sullivan; Well AA6-NC7A, Core no. 4, 5736′6′, sl.1 (ox), T41/0.
2. *Auroraspora macra* Sullivan; Well AA6-NC7A, Core no. 4, 5736′6′, sl.1 (ox), H33/0.
3. *Auroraspora asperella* (Kedo) Van Der Zwan; Well AA5-NC7A, Core no. 2, 5705′, sl.1 (unox), N48/1.
4. *Auroraspora* sp.; Well II1-NC7A, Core no. 1, 5527′7′, sl.3 (ox), K45/0.
5. *Densosporites varimarginatus* Playford; Well AA6-NC7A, Core no. 4, 5752′, sl.2 (ox), L49/0.
6. *Raistrickia clavata* Hacquebard emend. Playford; Well AA5-NC7A, Core no. 2, 5720′ 6′, sl.2 (ox), X55/1.
7. *Hystrichosporites* sp.; Well AA5-NC7A, Core no. 2, 5724′2′, sl.1 (ox), V43/1.
8. Trilete spores indet. (tetrad form); Well AA5-NC7A, Core no. 2, 5720′6′, sl.1(unox), Q51/2.
9. Trilete spores indet. (tetrad form); Well AA5-NC7A, Core no. 2, 5724′, sl.1 (ox), V54/2.
10. *Laevigatosporites vagularis* (Ibrahim) Potonie & Kremp emend. Alpern & Doubinger; Well AA5-NC7A, Core no. 2, 5705′, sl.4 (ox), L34/0.
11. *Densosporites* sp.; Well AA10-NC7A, Core no. 1, 5757′, sl.1 (ox), R49/3.
12. *Puncatatosporites* sp.;Well AA5-NC7A, Core no. 2, 5720′6′, sl.1 (unox), K24/3.
13. *Schizocystia bicornuta* Jardine *et al.*; Well AA5-NC7A, Core no. 2, 5720′6′, sl.3 (ox), E47/3.

PLATE 4. (p. 288)

1. *Horologinella quadrispina* Jardine *et al.*; Well II1-NC7A, Core no. 1, 5733′, sl.1 (unox), U39/3.
2. *Horologinella* sp.; Well AA5-NC7A, Core no. 2, 5720′6′, sl.2 (ox), J48/1.
3. *Horologinella horologia* (Staplin) Jardine *et al*; Well AA5-NC7A, Core no. 2, 5724′ 2′, sl.2 (ox), T42/3.
4. *Stellinium micropolygonale* (Stockmans & Williere) Playford; Well AA5-NC7A, core no. 2, 5720′ 6′, sl.2 (ox), K61/3.
5. *Umbellasphaeridium saharicum* Jardine *et al.*; Well AA5-NC7A, Core no. 2, 5705′, sl.1 (ox), L35/2.
6. *Veryhachium trispinosum* (Eisenack) Playford; Well II1-NC7A, Core no. 1, 5733′, sl.1 (unox), K45/4.
7. Indet. acritarch (cavate form); Well AA6-NC7A, Core no. 4, 5752′, sl.2 (ox), F47/2.
8. Indet. acritarch; Well AA5-NC7A, Core no. 2, 5720′6′, sl.1 (unox), U34/1.
9. *Maranhites mosesii* (Sommer) Brito; Well AA5-NC7A, Core no. 2, 5720′ 6′, sl.1 (unox), Y52/0.
10. Scolecodont; Well AA6-NC7A, Core no. 4, 5736′6′, sl.1 (ox), H42/0.

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Geological Exploration in Murzuq Basin
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CHAPTER 14

The structure, stratigraphy and petroleum geology of the Murzuq Basin, southwest Libya

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ABSTRACT

The Murzuq Basin covers an area of over 350 000 km^2, and is one of several intracratonic basins located on the North African Platform. The present-day borders of the basin are defined by tectonic uplifts, each of multi-phase generation, and the present basin geometry bears little relation to the much broader North African sedimentary basin which existed during the early Palaeozoic. Several generations of fault movement are recognised in the basin, but the resultant degree of deformation is relatively minor. The basin contains a sedimentary fill that reaches a maximum thickness of about 4000 m in the basin centre and comprises a predominantly marine Palaeozoic section and a continental Mesozoic section.

The principal hydrocarbon play in the basin consists of a periglacial sandstone reservoir of Ordovician age sourced and sealed by overlying Silurian shales. This play has proved very successful and accounts for approximately 1500 million barrels of recoverable oil discovered to date. Thermal modelling presented in this chapter suggests that the main phase of oil generation may have taken place during the Cretaceous, but further work is required to better define the timing of oil charge. Subsequent regional uplift and erosion has resulted in cooling of the source rocks, which are no longer generating oil over large parts of the basin At the present day the Silurian source rock remains within the oil generating window only in a limited area of the basin centre. The key to better understanding of this play is the relative timing of oil generation compared to Cretaceous and Tertiary inversion tectonics which influenced burial depth of the source rock, reactivated faults on the trapping structures and reorganised migration pathways.

Many of the discovered fields and exploration prospects identified in the Murzuq Basin involve high angle reverse faults, and are typically found in the hanging wall or in tip-line folds above the faults. Fault orientations in the basin show considerable variation, but a dominant clustering around a north-south trend suggests the influence of a late

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Precambrian Pan-African grain in the underlying basement. Initial Palaeozoic fault movements are recognised in the Cambro-Ordovician, with significant growth occurring across steeply dipping faults. Subsequent reactivation during late Silurian to early Devonian compression resulted in reverse displacement on many of the larger faults, creating the presently observed trapping structures. Further reverse fault movements and transpression also occurred during the mid-Carboniferous, mid-Cretaceous (Austrian) and early Tertiary (Alpine) compressive tectonic phases, all of which were associated with regional uplift and erosion.

EXPLORATION HISTORY

Exploration activity began in the Murzuq Basin in the 1950s and has carried on sporadically since. The B1–1 well drilled in 1957 on the Atshan Arch to the northwest of the Murzuq Basin was the first exploration well to discover hydrocarbons in Libya, but appraisals of this gas-condensate discovery proved to be disappointing. Subsequent success in the Sirt Basin in the 1960s diverted attention away from the more remote Murzuq areas and it was not until the 1980s that exploration activity picked up once again with Braspetro, Rompetrol and BOCO taking exploration licenses in the basin.

Braspetro drilled eight wells in NC58 (Meister et al., 1991; Pierobon, 1991) without encountering any commercial accumulations, although their first well, A1-NC58, was a small discovery. BOCO made several oil discoveries in NC101, but these have not been developed to date and are relatively small. Rompetrol was extremely successful in block NC115, with their twelve well exploration programme resulting in the discovery of three large fields, 'A', 'B' and 'H'. Operatorship of this block was subsequently transferred to Repsol who initiated a development programme for these fields, with production beginning in 1997. The oil is transported through a newly constructed pipeline to the Hamada field, from which an existing pipeline takes it to the oil terminal at Zawiyah on the coast west of Tripoli.

In 1990, a consortium of companies led by Pedco (now KNOC) was awarded the NC174 license, located between the NC101 and NC115 blocks. LASMO Grand Maghreb Ltd. subsequently joined Pedco to act as operator for exploration of the acreage. Four wells drilled during 1993 and 1994 resulted in two small oil discoveries in Mamuniyat sandstone reservoirs. One of the discoveries also encountered a small oil column in Devonian sandstone. Agip North Africa BV joined the NC174 group in 1996 and a new exploration programme began in the block during 1997. The second well in this campaign, F1-NC174, drilled on the 'Elephant' prospect, encountered a significant oil accumulation, which has subsequently been successfully appraised. The Elephant discovery is currently estimated to contain over 500 million barrels of recoverable oil and at the time of drilling was the largest oil discovery in Libya for fourteen years.

REGIONAL TECTONIC SETTING

The Murzuq Basin is one of several intracratonic basins located on the North African Platform. The basin covers an area of over 350 000 km^2, and has a roughly triangular shape, narrowing towards the south from Libya into Niger (Fig. 1). It is not a sedimentary basin in the normally accepted sense, and could more accurately be described as an erosional remnant of a much larger Palaeozoic and Mesozoic sedimentary basin which originally extended over much of North Africa, as described by many authors (e.g. Boote et al., 1998). The present-day borders of the

Murzuq Basin are defined by erosion resulting from multiphased tectonic uplifts, the flanks comprising the Tihemboka High to the west, the Tibesti High to the east and the Gargaf/Atshan Uplift to the north. These uplifts were generated by various tectonic events ranging from mid Palaeozoic through to Tertiary times, but the main periods of uplift took place during mid-Cretaceous (Austrian) and early Tertiary (Alpine) movements.

There is little evidence that these present basin-bounding uplifts were active during the early Palaeozoic, when upper Ordovician sandstone reservoirs and lower Silurian source rocks of the primary play system were deposited. The main influence on sedimentation at that time was probably exerted by the NW–SE trending Tripoli-Tibesti Uplift (Klitzsch, 1971), which extended across the northeastern part of the present-day basin. The influence of this palaeohigh is demonstrated by a progressive thinning of the Silurian Tanezzuft Formation shale towards the

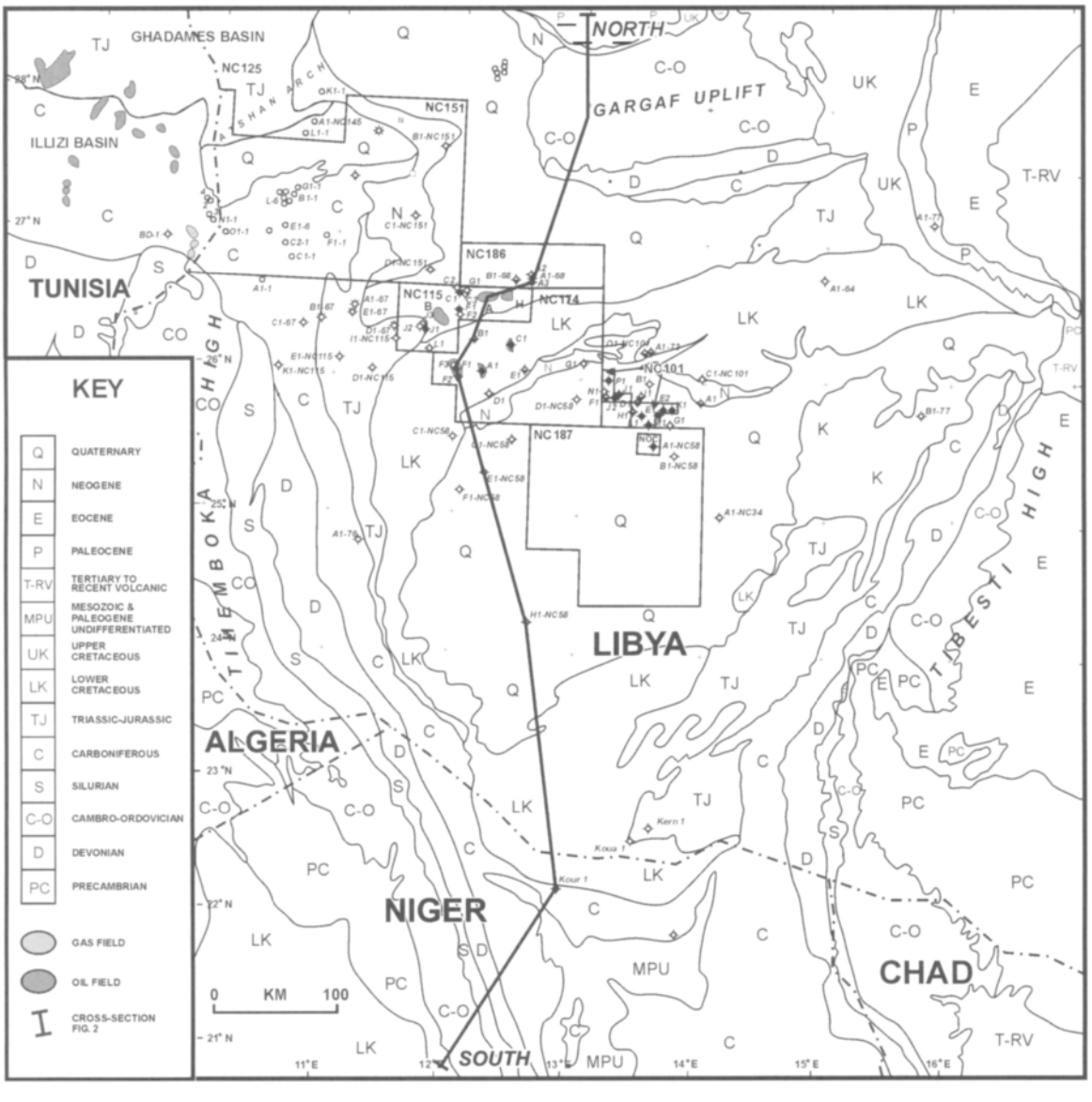

Figure 1. Simplified map of the surface geology of the Murzuq Basin, showing current exploration and production license areas. Source: Geological map of Libya, Industrial Research Centre, 1985. International borders from NOC Concession Map, 1994.

northeast of the basin, mainly as a result of erosion, with the unit being demonstrably absent along the exposed southern margin of the Gargaf Uplift.

The erosional nature of the basin margins and the partial erosion of the Tanezzuft shale are illustrated in the N–S cross-section shown in Fig. 2. The current state of preservation of the basin probably relates to the underlying lithosphere, which is inferred to be relatively competent and less susceptible to compressive stress compared to that beneath the surrounding highs, which have been preferentially uplifted and eroded.

The present-day basin centre contains a maximum sedimentary fill of about 4000 m. In addition to this a cumulative total of 1000 to 2000 m of section may have been stripped off during several phases of uplift and erosion throughout the history of the basin, but the maximum sedimentary thickness probably never exceeded 5000 m at any single point in time. Overall, this is a relatively modest sedimentary accumulation for a basin of some 500 million years in age. The principal reason for this is that accommodation space in the Murzuq Basin has been created primarily by sag processes, and the basin has never been subjected to any significant phase of extensional rifting, in marked contrast to the Sirte Basin which lies only some 400 km to the northeast. Several generations of structuring, mainly compressional and transpressional in nature, are recognised within the Murzuq Basin, but the cumulative structural deformation is relatively minor. No quantitative estimates of regional strain have been published for this area, but it is probable that overall crustal shortening across the basin is less than 1% in any orientation. It is this crustal and lithospheric stability which has preserved the lower Palaeozoic source and reservoir rocks from excessive burial, while also resisting trap-destroying uplift and erosion. This has allowed the development and retention of a productive hydrocarbon system in rocks considerably older than the average for successful petroleum provinces.

Seismic evidence shows only one possible phase of extensional fault movement within the basin, during Ordovician times, but these faults are widely spaced and of relatively small displacement, usually < 100 m. Other phases of extensional movement may have taken place, but if so, these were never of major significance and their effects are now obscured by subsequent compressional and/or transpressional faulting and fault reactivation. The depositional history of the basin has been punctuated by various phases of uplift and erosion, principally during the Cambro-Ordovician, the late Silurian/early Devonian, middle and late Carboniferous, mid-Cretaceous and early Tertiary, as detailed below.

Evidence from apatite fission track work, fluid inclusion data and shale velocity studies (Glover, 1999) indicate that the early Palaeozoic rocks encountered in wells in the basin are not presently at their maximum burial depths, but have been subjected to moderate but significant uplift and cooling since these maximum depths were reached. A cross-section (Fig. 2) shows present-day surface elevations to be 500 to 900 m above sea level, while there is clear evidence of ongoing active erosion, most noticeably at the scarp of the Jurassic to lower Cretaceous Mesak Formation. The current aeolian depocentres (sand seas) within the basin can be regarded as temporary ponded sub-basins which are unlikely to be preserved in the future geological record. These will themselves be removed by erosion once the threshold barriers of the Gargaf Uplift and the Mesak scarp are progressively worn down and sediment transport routes become re-established towards the north.

BASIN STRATIGRAPHY

A stratigraphic column for the Murzuq Basin is shown in Fig. 3. Previous syntheses of available outcrop data from the margins of the basin have been published by Mamgain (1980), Bellini and Massa (1980) and Abugares and Ramaekers (1993), among others. The stratigraphic schemes

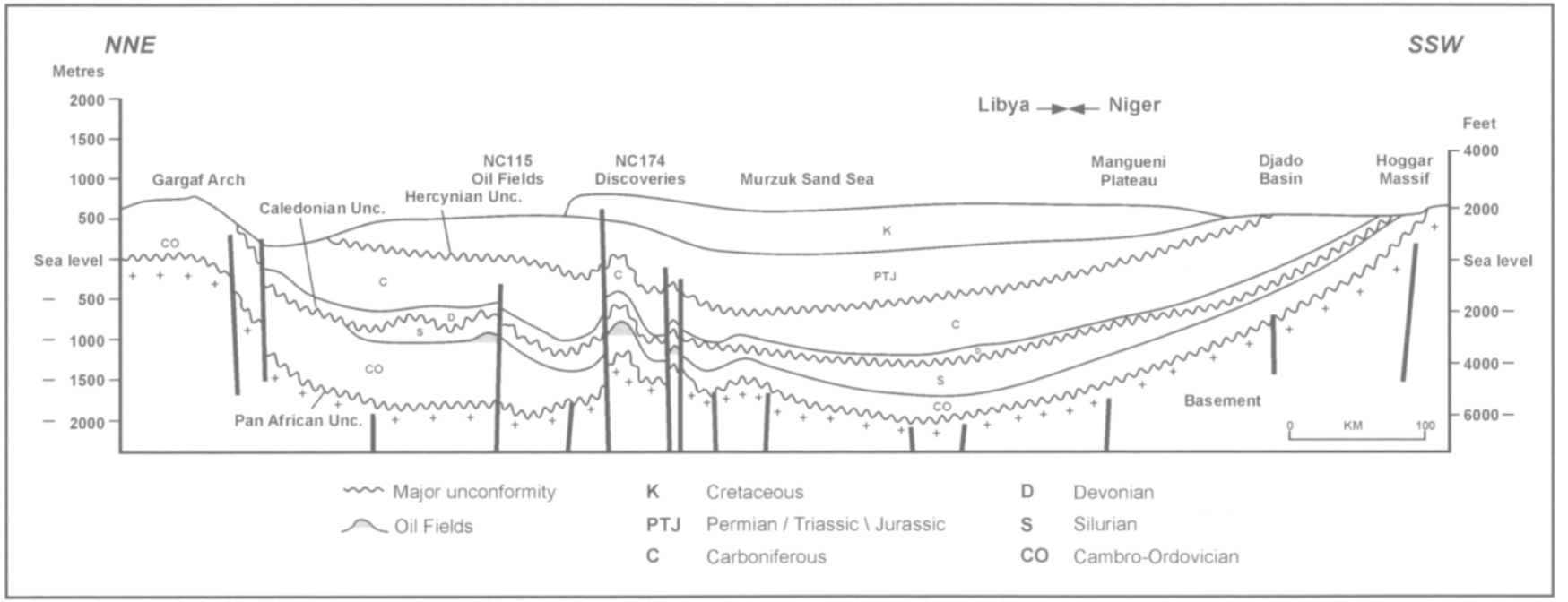

Figure 2. NNE–SSW trending geological cross-section through the Murzuq Basin, constructed from outcrop, well and seismic information. See Fig. 1 for location.

established by these authors have been slightly modified in Fig. 3 to incorporate additional information from the subsurface of the present basin centre.

The sedimentary deposits in the Murzuq Basin range from Cambrian to Cretaceous in age, and can be divided into four major sedimentary units.

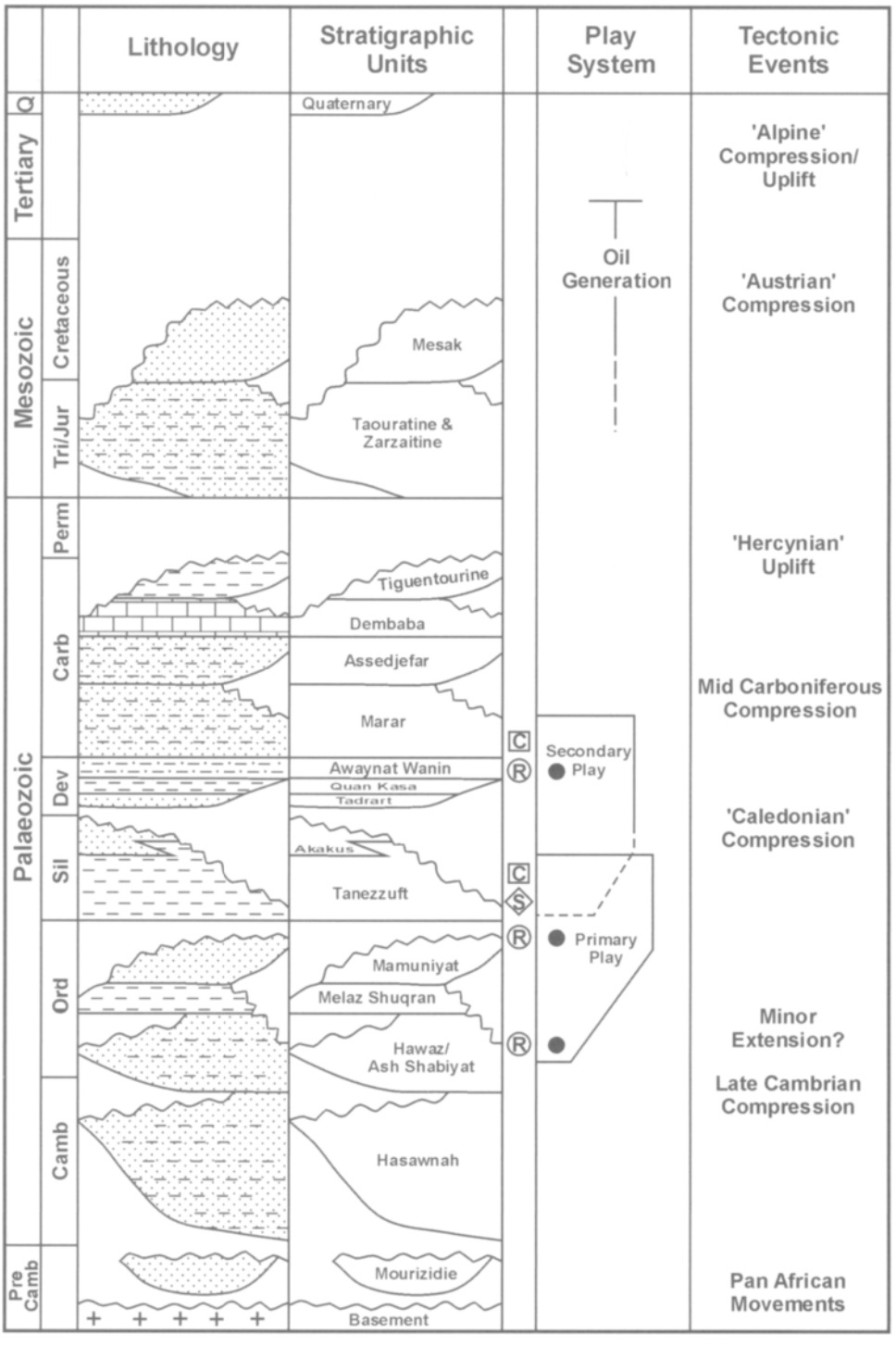

Figure 3. Summary of the stratigraphy, hydrocarbon play systems and chronology of tectonic events in the central part of the Murzuq Basin.

Cambro-Ordovician

A generalised stratigraphy of the Cambro-Ordovician is shown in Fig. 4. The first sediments to be deposited throughout the basin belong to the Cambrian Hasawnah Formation. A basal conglomerate has been recorded, but most of the formation comprises medium to very coarse-grained, quartzitic sandstone. The environment of deposition passed from fluvial at the base of the formation to shallow marine at the top. Sediment supply was from the south, with the sea transgressing from the north.

An unconformity separates the Hasawnah Formation from the overlying Ordovician Hawaz Formation. The type section of the Hawaz Formation on the Gargaf Uplift consists of fine to medium-grained sandstone, with subordinate siltstone and shale. This section has been described by Vos (1981), who suggested that the sediments were deposited in a fan delta complex which prograded across the Gargaf Uplift in a northerly direction. The Ash Shabiyat Formation is probably the lateral equivalent of the Hawaz Formation on the Tihemboka High.

In the northwestern part of the basin, the Hawaz Formation is overlain by shales of the upper Ordovician Melaz Shuqran Formation. This fairly distinctive unit, with uniform wireline log

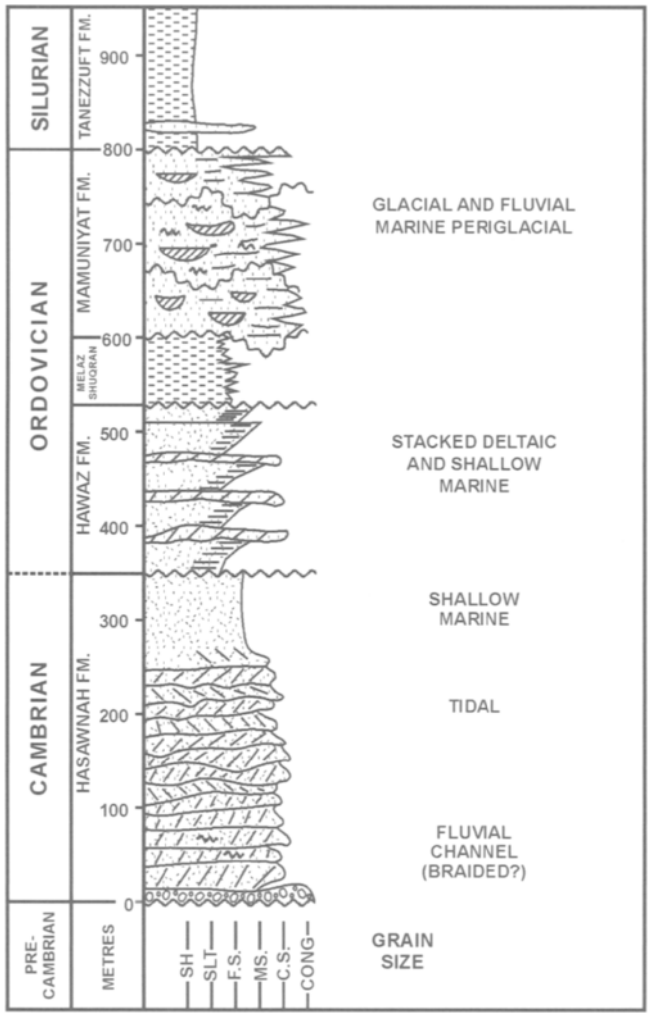

Figure 4. A summary of the Cambro-Ordovician stratigraphy, lithology and depositional settings in the Murzuq Basin. The section represents an idealised column with approximate maximum thicknesses of the constituent formations. In NC174 the Cambro-Ordovician is generally thinner than illustrated here; parts of the succession are often missing, either because of erosion or non-deposition.

responses, has been dated to the Ashgill (Abugares and Ramaekers, 1993). The shales were probably deposited in a relatively shallow marine environment, and a predominantly green colour might indicate reducing conditions, suggesting restricted marine circulation. On the Tihemboka High, the presence in the upper few metres of the formation of siltstone and very fine grained sandstone beds which show soft sediment deformation, suggests that the contact with the overlying Mamuniyat Formation is transitional in nature, with no major break in sedimentation (Beswetherick et al., 1996). The Melaz Shuqran Formation is frequently absent in wells drilled in the centre of the basin, but it is not clear whether this is a result of non-deposition or of subsequent erosion.

The uppermost Ordovician sediments of the Mamuniyat Formation form the primary hydrocarbon reservoir in the basin, and the reservoir properties and characteristics of this formation are described below in more detail. The Mamuniyat Formation consists mainly of sandstone with subordinate siltstone and shale beds, also dated to the Ashgill (S.P.T., 1994). The sandstone is typically quartzitic, fine to medium-grained, and fairly well sorted. Several different facies can be recognised in the Mamuniyat Formation, although most can be assigned to a high energy, deltaic to marine environment of deposition.

The Mamuniyat Formation and underlying Melaz Shuqran Formation were deposited at a time of glaciation over North Africa, which lay along the margin of Gondwanaland. It is probable that the ice sheet periodically extended as far north as the Murzuq Basin. In the Ghat area on the western flank of the basin the authors have observed some direct evidence for glaciation in the presence of small dropstones in the Melaz Shuqran shale and the occurrence of interpreted ice striations on bedding planes within the Mamuniyat Formation.

The action of glaciation in the hinterland to the south was important in releasing vast quantities of sediment, which were initially transported into the area of the Murzuq Basin by high energy braided or sub-glacial fluvial systems, and then reworked in a marine environment, often as gravity flow deposits. Seismic evidence from the subsurface in NC174 suggests that the upper part of the Mamuniyat Formation may contain a series of deeply incised erosional channels filled with fluvioglacial sediments (Smart, 2000). The late Ordovician glacial period would also have resulted in repeated short lived sea level changes, connected with the growth and retreat of the ice cap (Hadley, 1992), providing the alternating marine and fluvial influences observed in deposits of the Mamuniyat Formation.

One general comment regarding the stratigraphy of the Cambro-Ordovician in the Murzuq Basin is that the sand-rich facies that dominate this section tend to provide very poor biostratigraphic data and age dating is therefore very poorly constrained. Formational identifications in the subsurface are usually based on lithostratigraphic or log criteria, often quite unreliable for regional correlation.

Silurian to Devonian

The Silurian began with a major marine transgression which spread from the north, and reached across much of the North African margin. An unconformity separates the Mamuniyat Formation from the overlying shale of the Silurian Tanezzuft Formation. An organic and uranium rich 'hot shale' with patchy areal distribution within the basal part of the Tanezzuft Formation forms the main hydrocarbon source rock within the basin. The hot shale seldom exceeds 50 m in thickness, although the overall thickness of the whole Tanezzuft Formation may be more than 800 m. The lower parts of the Tanezzuft Formation have been dated to the early Llandovery. The nature and distribution of this hot shale is discussed in more detail below.

The Tanezzuft shales thin and become more arenaceous towards the northeast of the basin in the direction of the Tripoli-Tibesti palaeohigh, which clearly exerted an influence on early

Silurian deposition. The sandy, shallow marine mid- to upper Silurian Akakus Formation, which outcrops along the western basin margin, is apparently absent in wells at the present-day basin centre, probably as a result of early Devonian erosion.

The Tanezzuft Formation is unconformably overlain by the mid- to upper Devonian Awaynat Wanin Formation. Sediments of early Devonian age appear to be absent in the basin centre. The Awaynat Wanin Formation comprises shale and subordinate sandstone, often rich in iron, deposited in a littoral to shallow marine environment. The sandstones of this formation constitute the reservoirs for a secondary hydrocarbon play in the basin.

Lower to Mid-Carboniferous

The early to mid-Carboniferous was also marked by a significant marine transgression. The Awaynat Wanin Formation is overlain by the Marar Formation, which is in turn overlain by the Assedjefar Formation. Both of these formations are early Carboniferous in age and consist of shale with subordinate sandstone. Several minor coarsening-up cycles can be traced across the basin, suggesting deposition in a relatively low energy shallow marine environment with periodic shoaling. The overlying mid-Carboniferous Dembaba Formation comprises shallow marine limestone, sandstone and grey shale in the northern part of the basin, and lagoonal limestone and red shale in the southern part. This formation represents a transition from the marine conditions typical of much of the Palaeozoic, to the continental conditions which have prevailed since.

Red lacustrine mudstone of the upper Carboniferous Tiguentourine Formation may be found in parts of the basin but this unit is often absent, either because of non-deposition or as a result of uplift and erosion during the late Carboniferous – which produced the so-called Hercynian unconformity. Permian sediments are not present in the basin, probably due to non-deposition following this late Carboniferous regional uplift.

Triassic to Lower Cretaceous

Triassic to lower Cretaceous sediments were deposited in continental conditions. This section can be divided into the fluvial sandstone and red mudstone of the Triassic to Jurassic Zarzaitine/ Taouratine formations and the fluvial sandstone, conglomerate and mudstone of the Jurassic/lower Cretaceous Mesak Formation. These formations appear to be conformable but their contact may represent a significant period of non-deposition. Approximately 1700 m of Mesozoic section are preserved in the basin centre, but it remains uncertain how much Cretaceous and Tertiary succession has been removed by erosion following the mid-Cretaceous (Austrian) and early Tertiary (Alpine) uplifts.

TIMING OF BASIN STRUCTURING – IMPLICATIONS FOR PETROLEUM EXPLORATION

A chronostratigraphic chart (Fig. 3) shows the principal stratigraphic units and hydrocarbon plays in the Murzuq Basin. Also indicated is the timing of tectonic events which influenced the basin's development and which were responsible for the major erosive unconformities which we now observe. Numerous minor unconformities and disconformities are also present within the stratigraphic section.

Cambro-Ordovician Faulting

The earliest recognised structures to affect the sedimentary section of the basin are faults of Cambro-Ordovician age. Many of these were subsequently reactivated by later movements and this can lead to some difficulties in interpretation of Cambro-Ordovician kinematics. A few small displacement features that have not undergone post-Ordovician reactivation can be interpreted as extensional normal faults with thickening of the hanging wall Cambro-Ordovician section, as illustrated in Figs 5 and 6. If this interpretation is correct, these are the only purely extensional faults yet recognised in the basin, but with typical minor displacements of less than 100 m.

More commonly, however, thickening of the Cambro-Ordovician section is observed in the footwall of steeply dipping reverse faults, implying synsedimentary movement of compressional or transpressional origin, as seen in the main block-bounding faults in Fig. 6. Displacements are significant, often with over 100 m thickening across the larger faults. Well D1-NC174 (Fig. 6) suggests that these fault movements predated deposition of the upper Ordovician Mamuniyat Formation, the main reservoir rock in the basin, which is present on the crest of the horst block despite severe thinning of the overall Cambro-Ordovician section.

Silurian to Devonian (Caledonian) Tectonics

A major unconformity in the basin reflects late Silurian to early Devonian tectonic movements, which were mainly of a compressional nature. Bellini and Massa (1980) state that these

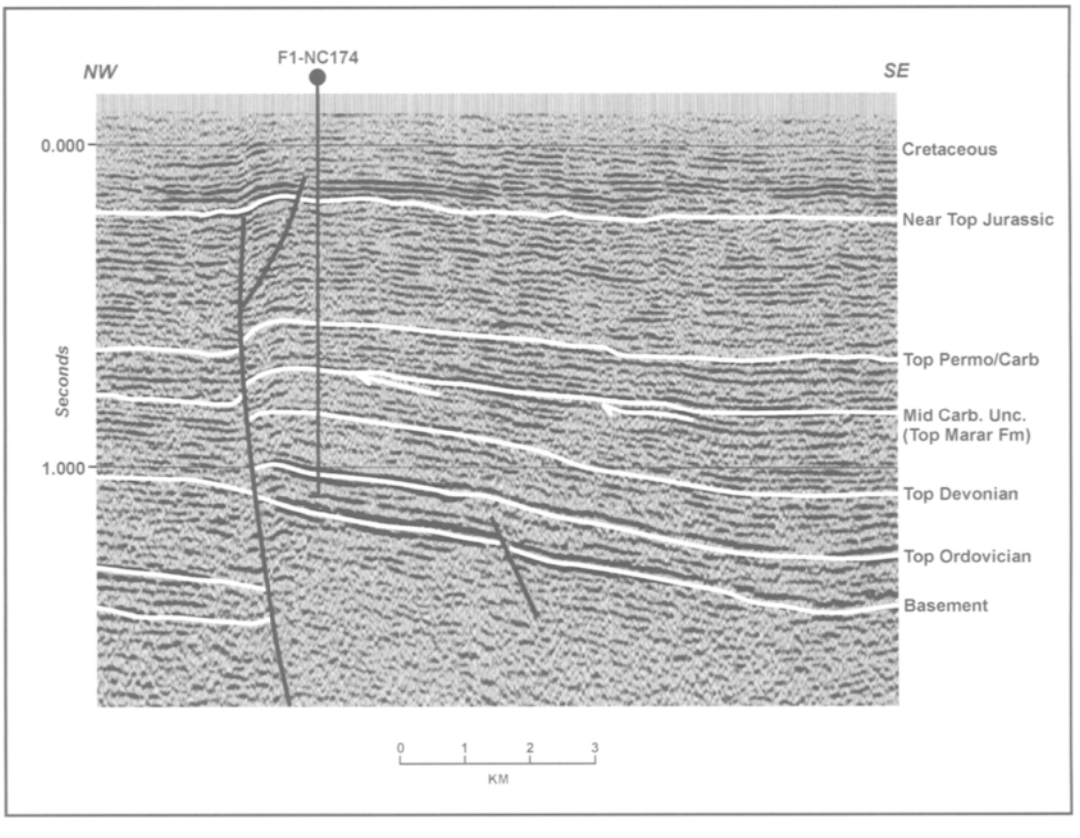

Figure 5. Seismic section trending NW–SE and passing through the Elephant Field discovery well, F1-NC174.

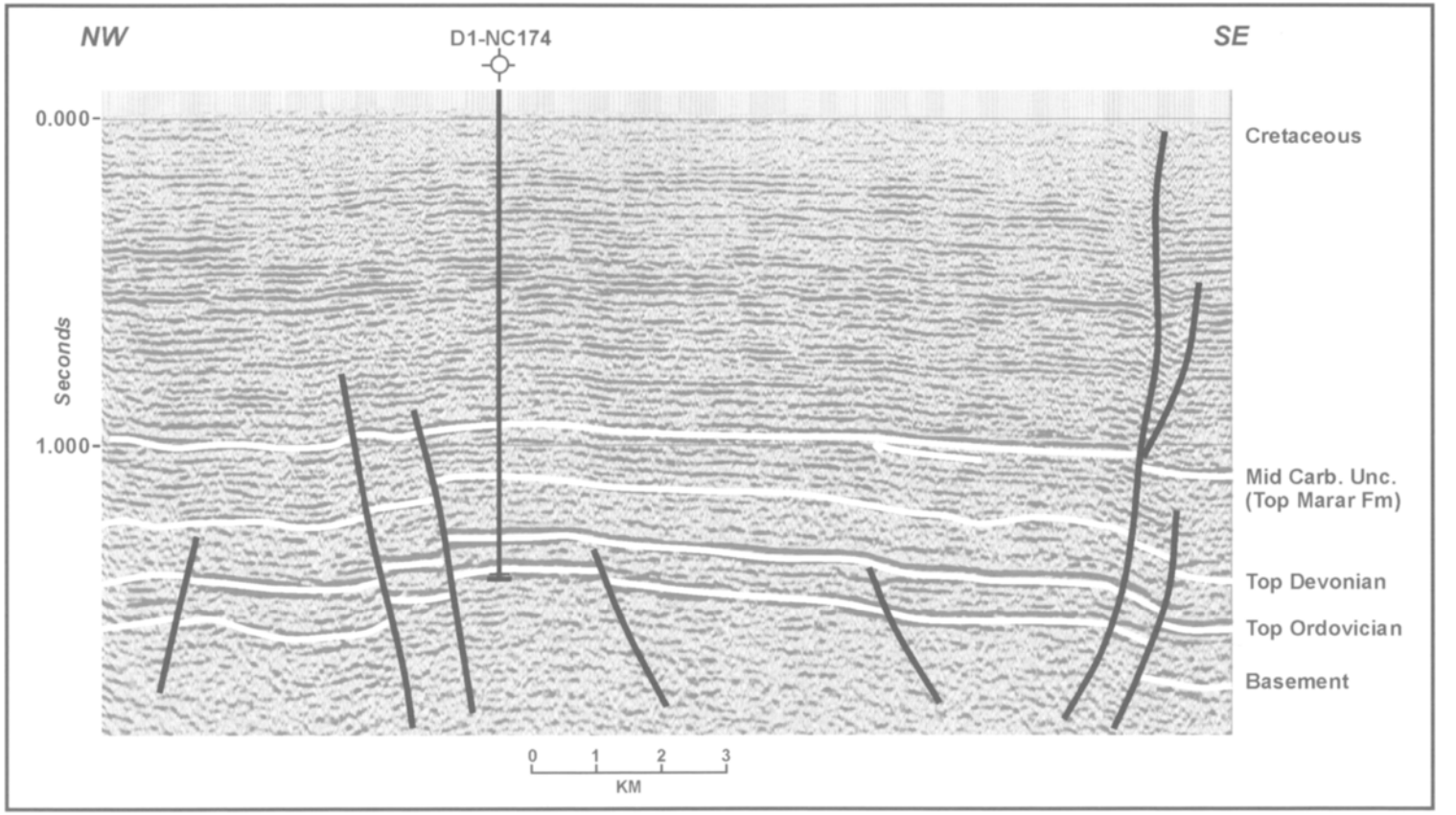

Figure 6. Seismic section trending NW–SE and passing through the D1-NC174 dry hole.

movements persisted from mid- to late Silurian times, and in some outcrops an angular unconformity of up to 5° can be observed between Silurian and overlying Devonian strata. Chronostratigraphic sections published by Boote et al. (1998) and Abugares and Ramaekers (1993) show much of the upper Silurian and lower Devonian section to be missing through erosion at this unconformity.

The thick upper Silurian sandstones of the Akakus Formation, which outcrop on the western flank of the basin, are apparently absent in wells in the basin centre, probably due to erosion. In the adjacent Ghadames Basin, Echikh (1998) shows evidence of basinwide partial erosion of the Akakus Formation at the late Silurian to early Devonian unconformity.

Many of the structures which form present-day hydrocarbon traps in the basin were initiated by late Silurian to early Devonian compression. The seismic line in Fig. 5 illustrates the trapping structure of the F1-NC174 discovery that was created by a high-angle reverse fault. The Silurian/Devonian section shows significant thickening across this trap-forming fault, indicating synsedimentary fault movement at this time. Later reactivation of this fault occurred during mid-Carboniferous and Cretaceous/Tertiary movements. More precise dating of the movements on this fault require drilling and detailed biostratigraphic analysis of the thickened footwall sedimentary section, but such data are not available at the present time due to a lack of well penetrations. The available seismic evidence does, however, indicate that every period of movement on this fault appears to have been compressional or transpressional in origin.

The late Silurian to early Devonian faults in the Murzuq Basin vary in trend from NW–SE through N–S to NE–SW, probably following pre-existing Pan-African trends. Underlying the northeastern flank of the basin is the Silurian age NW–SE trending Tripoli-Tibesti Uplift (Klitzsch, 1971), also termed the Bin Ghanimah High (Bellini and Massa, 1980). This uplift had some expression prior to the main late Silurian to early Devonian tectonics but underwent renewed growth during this time. An important consequence of the movements on this palaeohigh is that the Silurian section, including the hot shale source rock, is absent from the northeastern part of the Murzuq Basin, probably due to a combination of non-deposition and erosion following late Silurian to early Devonian reactivation (see Fig. 2 of this paper, Pallas 1980: Fig. 3, and Boote et al., 1998: Fig. 18b). The geological map of the Murzuq Basin in Fig. 1 shows the Silurian section to be absent from the southern margin of the Gargaf Uplift and also between latitudes 24° to 25° (approximately) on the eastern (Tibesti) flank of the basin.

Mid- to Late Carboniferous Tectonics

Mid-Carboniferous compression resulted in reactivation of earlier high angle reverse/transpressional faults, with the development of localised erosional unconformities that can be observed on seismic sections on the crests of uplifted fault blocks (e.g. Fig. 5 and 6) and by thickening of the Carboniferous sediments in the footwall sections. In the drilled hanging wall sections this unconformity approximates to the top of the Marar Formation. There is presently a lack of evidence from drilling results of any change in sedimentary facies where the Carboniferous section thickens across faults in the basin, there being no well penetrations on the footwall side of such faults. These mid Carboniferous fault movements resulted in significant modification and amplification of late Silurian to early Devonian compressional structures that later became hydrocarbon traps in the Murzuq Basin.

Late Carboniferous 'Hercynian' compression, uplift and erosion played a significant role in the structural development of many of the North African petroleum producing basins (Boote et al., 1998), but available evidence indicates that this period of tectonism was less important in the development of the Murzuq Basin. No significant regional tilting occurred at this time in Murzuq, in marked contrast to the Illizi and Ghadames basins where a major angular

unconformity is observed. However, despite the absence of demonstrable angular erosion, a significant stratigraphic section does appear to be missing at the 'Hercynian' unconformity in the Murzuq Basin, with several authors in agreement that all or most of the Permian section is not present (e.g. Mamgain, 1980; Abugares and Ramaekers, 1993; Boote et al., 1998). It is concluded herein that the basin was probably subject to significant regional uplift during late Carboniferous time, resulting in relatively uniform erosion of the Carboniferous succession and non-deposition of Permian sediments.

Mid-Cretaceous (Austrian) and Early Tertiary (Alpine) Tectonics

In the centre of the Murzuq Basin there is a major unconformity between the Jurassic/early Cretaceous Mesak Formation sandstones and overlying Quaternary aeolian/fluvial deposits (Fig. 3). At the present time it is unclear whether this stratigraphic break is due to uplift during the early-mid Cretaceous 'Austrian' movements, the early-mid Tertiary 'Alpine' movements or a combination of both. Boote et al. (1998, Fig. 18b) suggest that both of these tectonic pulses caused uplift and erosion of the margins of the Murzuq Basin, but that the mid-Cretaceous pulse was responsible for the more significant movements. Compressional or transpressional fault reactivation is evident in NC174, affecting the outcropping Mesak Formation (Figs 5 and 6), and dating this movement as post mid-Cretaceous.

The geological map of Libya (IRC, 1985), as shown in simplified form in Fig. 1, shows that upper Cretaceous deposits in the northeast of the Murzuq Basin overstep earlier strata from the lower Cretaceous all the way down to the Cambrian on the Gargaf Uplift, demonstrating the effects of a major phase of uplift and erosion of approximately mid-Cretaceous age, probably associated with the Austrian tectonic phase. These vertical movements were regionally variable in nature, with the Gargaf Uplift being subject to significant uplift and exhumation while the basin centre was affected to a much lesser extent. This mid-Cretaceous event was demonstrably an important period of structural growth on the Gargaf Uplift and may also have played a significant role in the development of the Tihemboka High and the Tibesti High, which respectively form the western and eastern margins of the present-day basin. It remains enigmatic that the only identified tectonic movements in the Murzuq Basin during the Cretaceous were apparently compressional or transpressional in nature while the Sirte Basin, some 400 km to the northeast, was subjected to a major Cretaceous extensional rifting event.

The upper Cretaceous sediments to the northeast of the Murzuq Basin comprise mixed carbonates and clastics of marine origin, which are dated as Maastrichtian in age (Woller, 1984). These sediments and the thin overlying Paleogene marine deposits now occur some 500 m above present-day sea level, clearly demonstrating the effects of renewed post-Paleogene uplift. It is inferred that this uplift is a consequence of the Alpine tectonic movements responsible for the growth of the Atlas Mountains in Morocco and Algeria. However, at the present time it is unclear whether this Tertiary uplift was uniform over the entire region or whether there was differential uplift of certain areas relative to others.

Cretaceous and Tertiary tectonics were of prime importance in the development and modification of the hydrocarbon system in the Murzuq Basin. Differential uplift of the source rocks had a major effect on oil generation, with some areas possibly remaining within the oil window while oil generation in other areas ceased as the source rocks cooled. Existing oil traps were modified by fault reactivation, enhancing closure on some but promoting spillage or fault plane leakage on others. Migration pathways were also fundamentally altered by changes of regional dip direction. Unfortunately the timing and magnitude of the uplift events are not well documented at the present time, largely due to the absence of upper Cretaceous and Tertiary sediments over most of the basin. However the oil industry is currently attempting to address this

question with apatite fission track, fluid inclusion and other related studies which might eventually provide data to resolve questions on the relative timing of tectonics, oil generation and trapping formation, and also allow reconstruction of palaeomigration routes.

THE MAMUNIYAT FORMATION RESERVOIR

Sandstone of the upper Ordovician Mamuniyat Formation forms the reservoir for the primary play in the Murzuq Basin, although in some wells the underlying Hawaz sandstone is also a productive reservoir where the Mamuniyat Formation is thin or absent. The Mamuniyat and the underlying Melaz Shuqran Formation were deposited at a time of glaciation over North Africa, which then lay along the margin of Gondwanaland. It is possible that at its maximum extent, the ice sheet extended across the whole of the Murzuq Basin.

The depositional model for the Mamuniyat Formation is based on a combination of outcrop and well data. Field observations on the eastern and western margins of the basin (the Tibesti High and Tihemboka High respectively) indicate that the sediments appear to have been deposited in high-energy glacial outwash fans and channels, which spread out from the edge of the ice sheet (Beswetherick, 1992). The proximal parts of these fans include matrix-supported conglomerates containing boulder-sized clasts, whereas the distal parts are dominated by poorly sorted, coarse-grained sandstones deposited in braided fluvial conditions. Other sandstones were deposited as gravity driven flow deposits in a marine environment. All the outcrop evidence points to very rapid, high energy deposition and it is likely that the periods of deposition coincided with times of glacial retreat when large quantities of meltwater would be released to transport the glacially derived sediments towards the ocean to the north.

On the northern margin of the basin (the Gargaf Uplift), the Mamuniyat Formation is dominated by moderate to well sorted, fine to medium grained, quartzitic sandstone, which tends to be both texturally and mineralogically mature. The bulk of the sandstone in this area appears to have been deposited in shallow marine conditions, although there is also some evidence for braided fluvial deposits, particularly near the base of the formation.

Sedimentological analyses of cores taken from the early NC174 wells suggest that the Mamuniyat Formation was probably deposited in the broad setting of a sand rich, regionally extensive braid delta with alternating fluvial and marine influences controlled by glacially induced sea level changes. Sediment supply was from the south, with the shoreline trending roughly east to west. A range of facies can be identified. Thick sequences of clean sandstones occur in some wells and appear to have been deposited during marine destructive phases, involving reworking of the braid delta sediments in a high-energy marine environment. Sedimentation rates would have increased during times of glacial retreat when meltwater flow reached a maximum of volume and energy. This naturally coincided with periods of eustatic sea level rise, with the result that large volumes of sand were deposited as gravity flow deposits in a marine setting in front of the ice sheet. The upper part of the Ordovician section is occasionally seen in a facies association dominated by shale with thin sandstone beds. These thin sandstones were probably deposited in isolated channels and associated overbank environments on a relatively steep, unstable, mud-dominated slope that locally formed the delta front. Braided fluvial deposits appear to be relatively scarce in NC174.

Correlation between drilled sections of the Mamuniyat Formation is severely hampered by two factors:

- the lack of preserved biostratigraphic markers in the sand rich, high energy sediments, possibly masking diachroneity in the subcrop to the base Silurian unconformity, and
- the highly heterogeneous, channelised nature of deposition, which resulted in wide variations in unit thickness (either due to original depositional controls or differential erosion) and rapid

lateral changes of facies. Even in wells located only a few kilometres apart there can be a remarkable dissimilarity between well log patterns from the drilled sections of the Mamuniyat Formation.

An obvious consequence of the heterogeneous nature of the Mamuniyat Formation is that reservoir simulation modelling is fraught with uncertainty. It may be the exception to find continuous reservoir units across any large field; more commonly the sand units are probably elongated in a channelised geometry, with older channels cut into by younger bodies, possibly in a complex anastamosing pattern (Smart, 2000). Channel orientation is an important factor and might best be determined through interpretation of 3D seismic data. However prediction of relative permeabilities in three dimensions, e.g. for design of a water flood, will require careful analysis of early production data. The expectation is that large scale permeability might be significantly different in the cross and along-channel orientations, but this fact will not be apparent from small-scale measurements taken from core samples. However the sand:shale ratio in the Mamuniyat Formation is generally high, averaging 0.8 (ignoring the reservoir potential of the sand), and where this ratio is high it is possible that good permeability might be present in all orientations.

ORDOVICIAN SANDSTONE PETROGRAPHY AND RESERVOIR QUALITY

Petrographic studies indicate that the Ordovician sandstones cored in the NC174 wells are mainly fine to medium grained quartz arenites (S.P.T., 1994). The detrital mineralogy is dominated by monocrystalline quartz grains, with minor amounts of polycrystalline quartz grains, lithic fragments, feldspar grains and mica. The petrographic studies allow the following diagenetic sequence to be proposed for the NC174 sandstones:

1. Precipitation of early grain coating clays, which are replaced by anatase, leucoxene and hematite,
2. The onset of quartz overgrowth development,
3. The main feldspar dissolution phase, and associated onset of kaolinite authigenesis, with continued quartz overgrowth,
4. The development of platy and fibrous illite, continued feldspar dissolution and kaolinite authigenesis, and
5. The precipitation of siderite and dolomite.

Although the quartz overgrowths result in a reduction of porosity, they can also reduce the degree of compaction, preserving a well connected pore system and good permeability. Feldspar dissolution results in secondary porosity, which is in part offset by associated kaolinite authigenesis. Most of the sandstones contain at least small amounts of illite, which can block pore throats and reduce permeability. A few of the sandstones contain late-stage cements such as dolomite or siderite, which could be indicative of a marine depositional setting.

There is no simple overall relationship between the porosity and permeability of the Ordovician sandstones in the NC174 wells, although a relationship may exist in individual wells as illustrated in Fig. 7. The lack of a unique poroperm trend is probably a reflection of several factors:

- Poor biostratigraphic control, leading to comparisons of sections of different ages,
- Facies variations either within the fluvial system or between fluvial and marine units,
- Wide variations in initial energy of deposition resulting in large differences in percentage of original clay content within the sands,
- Different depths of maximum burial in different wells.

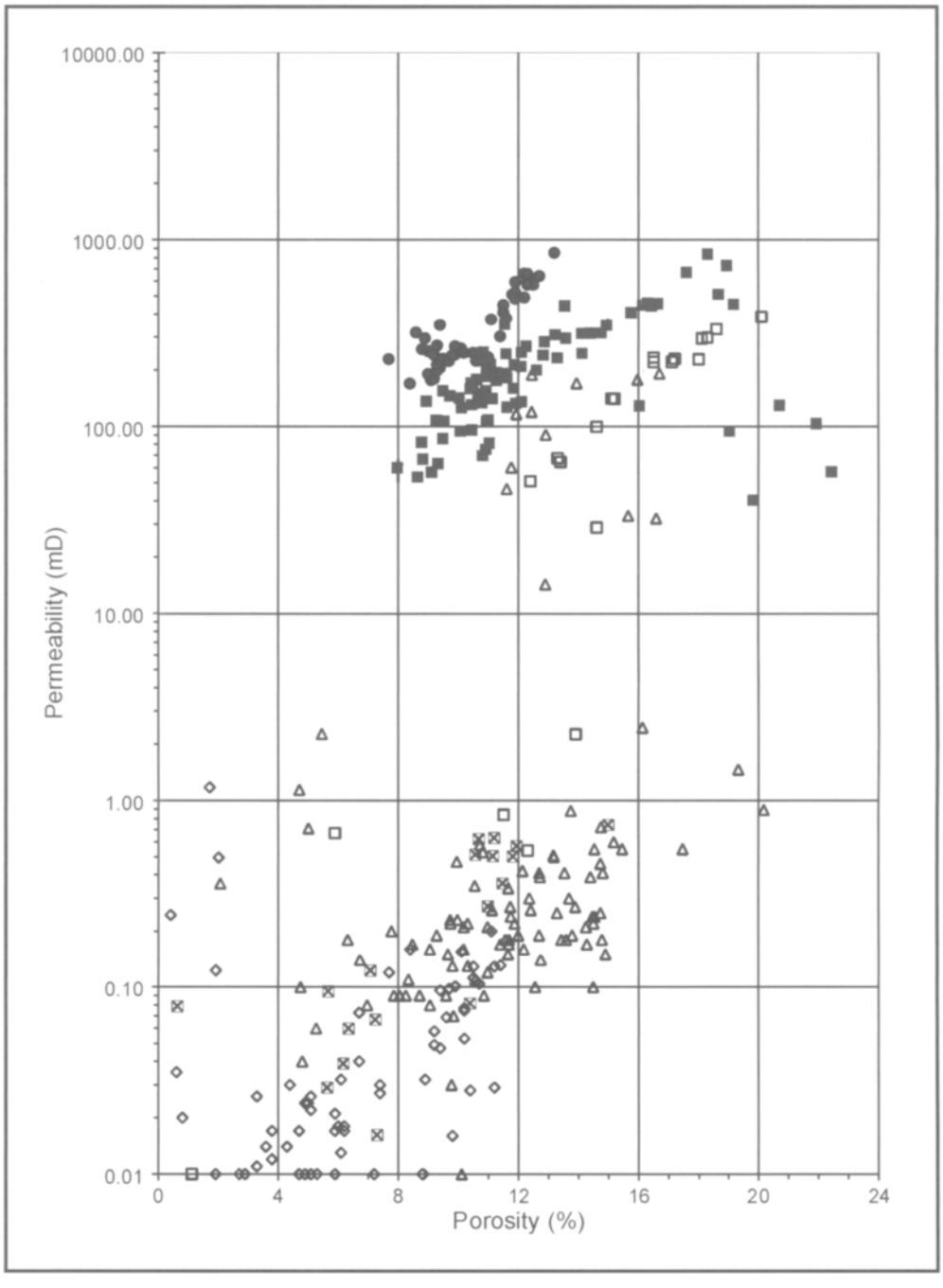

Figure 7. Porosity-permeability crossplot from analyses of Ordovician cored sections of exploration wells A1 to F1-NC174. Two distinct groupings are apparent, one with very good reservoir characteristics of moderate porosity and moderate to high permeability, the other with poor reservoir quality due to very low permeabilities. The primary differentiating factor seems to be percentage of original clay content, but other factors are also important. See text for discussion. The cored sections are interpreted as belonging to the Mamuniyat Formation, with the exception of C1-NC174 (upright triangles), interpreted as belonging to the Hawaz Formation.

The best reservoir quality sandstones in NC174 have measured porosities ranging from 12 to 20% combined with permeabilities of 100 to 1000 mD. The relatively low porosities, even in the clean sandstones, result from the abundant quartz overgrowths, but this has a less detrimental effect on permeability.

Other wells in NC174 show significantly poorer reservoir quality, with low to moderate porosity (1 to 11%), and low permeability (less than 0.2 mD). The low porosity mainly results from the presence of late siderite, dolomite, and ferroan dolomite cements, whereas the low permeability results from the relative sparsity of macropores, and the presence of illite. Petrographic analyses indicate that the sandstones with the best reservoir quality are those in which the porosity mainly occurs in macropores, rather than micropores. These sandstones tend to contain relatively low amounts of kaolinite, and no or very little illite.

The reservoir quality of the Mamuniyat sandstone depends on a combination of primary compositional and textural factors combined with secondary compactional and diagenetic factors. Reservoir quality tends to increase with increasing grain size and sorting, and decreasing detrital clay content (depositional fabric and the abundance of detrital feldspar, lithic fragments and mica are also important). These primary factors can be strongly overprinted by the secondary factors, which tend to reduce the porosity and permeability of the sandstone (for example, through compaction, precipitation of authigenic cement, and clay mineral authigenesis). One exception to this reduction in reservoir quality is that of feldspar dissolution, which can increase the porosity and permeability.

Successful future prediction of the reservoir potential in the Mamuniyat Formation will only result from a detailed understanding of the environment of deposition and original facies distribution, together with better estimates of the subsequent degree of reworking and/or erosion that has occurred in the particular locations in question. These levels of predictive understanding have not been achieved to date. However it is anticipated that field development datasets of closely spaced wells and 3D seismic, which are now becoming available, should provide adequately constrained local models of reservoir quality distribution that might be extrapolated to the wider area of reservoir prediction in future exploration.

EARLY SILURIAN TANEZZUFT FORMATION 'HOT SHALE' SOURCE ROCK

Hot Shale Depositional Setting and Source Properties

Oil-prone source rocks at the base of the Silurian section occur throughout much of North Africa. These source rocks have generated and expelled significant volumes of hydrocarbons, not only in the Murzuq Basin, but also in the nearby Illizi and Ghadames basins and in the Triassic basins of Algeria. Geochemical data in the Murzuq Basin indicate that the best source potential is provided by an irregularly distributed organic rich hot shale unit occurring within the lowermost part of the Silurian section.

In the NC174 block, reliable biostratigraphic age determinations for the upper part of the Ordovician section are essentially limited to the early Ashgill dates obtained from the shale rich B1-NC174 well (S.P.T., 1994). The lower Tanezzuft shale in the NC174 wells is dated as early Silurian (early Llandovery). The major Silurian transgression initially resulted in a relatively shallow anoxic sea and the deposition of a thin transgressive sequence tract overlain by organic rich, lower Silurian hot shales with excellent source rock qualities. The anoxic conditions of deposition of the hot shales probably developed as a result of restricted marine circulation in shallow seas broken by numerous islands and peninsulas, the natural result of a low energy marine transgression over an irregular post-glacial topography. The early Silurian bottom waters were dense and very anoxic which, coupled with very low sedimentation rates, allowed the preservation of very high concentrations of organic matter.

Well logs through the lower part of the Tanezzuft section can be set alongside measured TOC percentage (Fig. 8), demonstrating the well known relationship between increasing TOC and gamma ray values (Rider, 1996). Resistivity also increases with rising TOC due to unexpelled hydrocarbons within the pore spaces. It is also apparent that as TOC increases there is a corresponding decrease in both sonic velocity and density, giving the useful relationship that increasing TOC in the Tanezzuft shale is associated with decreasing acoustic impedance. This relationship can be used for the prediction of the presence of hot shale through analysis of seismic reflection amplitude.

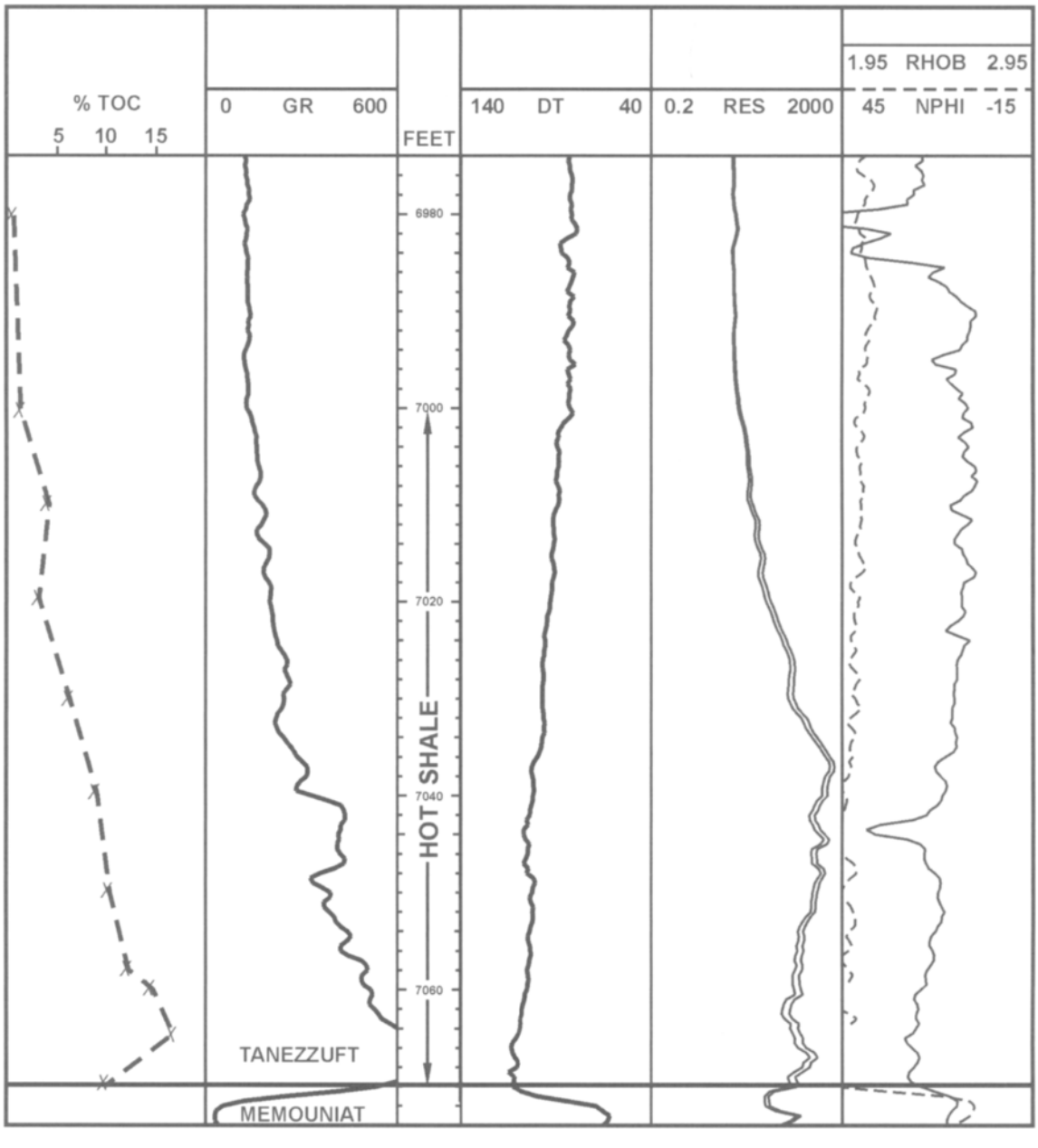

Figure 8. Logs from a typical NC174 well through the lower part of the Silurian Tanezzuft shale, including the hot shale interval. Measured TOC values are plotted alongside the logs to illustrate the relationship between log response and TOC. Note the strong positive correlations between TOC, GR and DT response, while TOC and density (RHOB) show a negative correlation. The high TOC hot shale source facies has significantly lower acoustic impedance than the low TOC shales.

In most wells in the Murzuq Basin the transition downwards from normal to highly radioactive 'hot' Tanezzuft shale is gradual, as shown in Fig. 8, and therefore the top of the hot shale does not tend to produce a strong seismic reflector. However, the acoustic impedance of the hot shale is also significantly lower than the underlying Mamuniyat sandstones, and this sharp interface generates a large positive reflection coefficient, which produces a strong reflector on seismic data. In areas where the hot shale is not present and the normal shale rests directly on the Mamuniyat Formation sandstones, this reflector is significantly reduced in amplitude. This relationship allows the areal distribution of hot shale to be mapped using the seismic amplitudes of the base Silurian reflector calibrated to well control (Fig. 9).

From the map of hot shale distribution (Fig. 9) it can be seen that this facies within the Tanezzuft Formation has a highly irregular distribution in NC174, probably as a result of the uneven topography of the transgressed surface. One implication of this observation is that no simple assumptions can be made regarding source rock distribution elsewhere in the basin. This uncertainty is further highlighted by Meister et al. (1991) who quote only one occurrence of the Silurian hot shale from a sample of twelve logged and geochemically analysed wells in the Murzuq Basin. Another implication is that the early Silurian transgression was diachronous on a local scale, with the oldest marine sediments (including the hot shale) being deposited only in topographic depressions, while the adjacent higher areas remained above sea level for some significant period of time, as illustrated by Lüning et al. (1999). The absence of hydrocarbon discoveries in large areas of the Murzuq Basin may be due to the source rock being absent or ineffective. The transition from deposition of hot to normal Silurian shale occurred as continued subsidence in the Murzuq Basin allowed deeper water conditions to become established and the circulation of open oceanic water destroyed the anoxic seabed conditions.

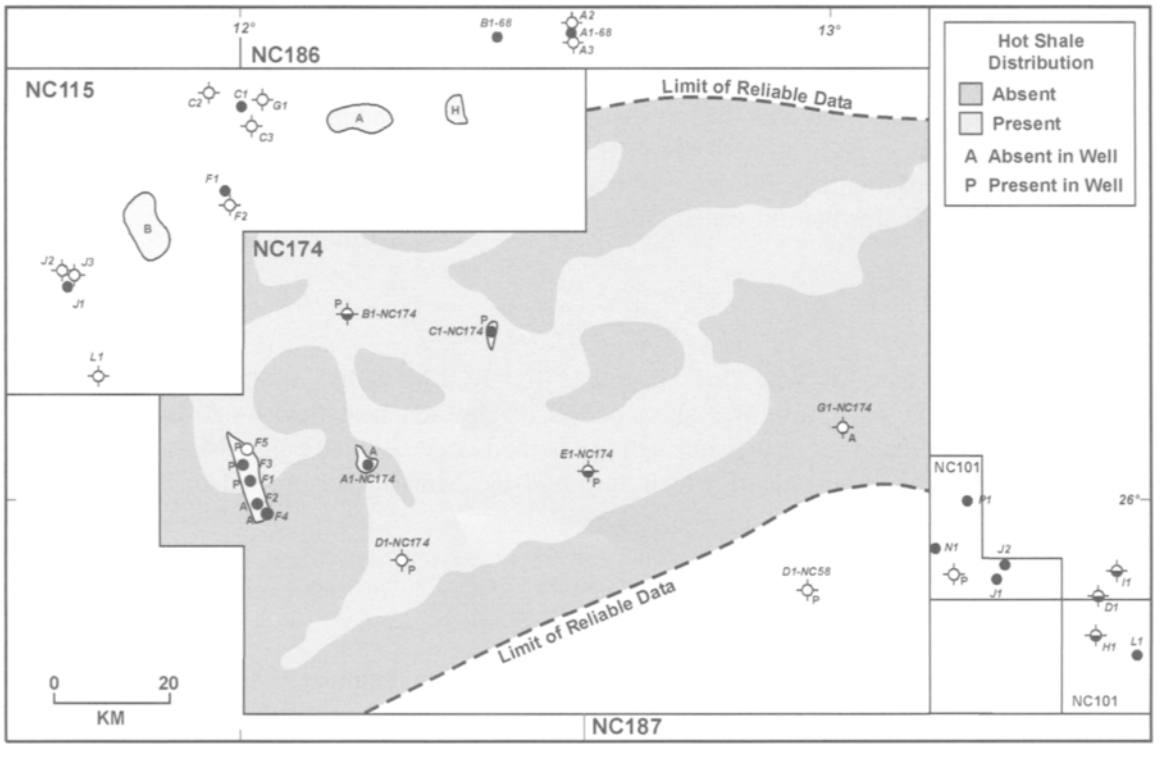

Figure 9. Distribution of the hot shale source rock within the Tanezzuft Formation in NC174. The map is based on well control, interpolated with mapping of variations in seismic amplitude. The base Tanezzuft reflector shows higher amplitude where the hot shale is present and lower amplitude where it is absent.

The hot shale unit is well developed in several of the NC174 wells, where it varies in thickness from 18 to 24 m, and gives gamma ray readings of up to 705 API units. Evidence of hydrocarbon generation is provided by high gas readings (C1 to C4) and crush cut fluorescence during drilling.

A comprehensive series of geochemical analyses have been conducted on cuttings and sidewall cores from the Silurian and Cambro-Ordovician sections and on oil samples from NC174 wells. These analyses confirm the organic rich nature of the hot shale unit, with measured TOC values of up to 17% and pyrolysis yields (S2) of up to 64 kg/tonne. Visual kerogen analyses indicate that the organic matter is sapropelic and the samples plot on a Van Krevelen diagram as Type I/II (oil-prone). The remainder of the Silurian section, and the shales in the Cambro-Ordovician section tend to have little or no source potential and to be dominated by Type III, gas-prone kerogen. GC-MS analyses of an extract from core samples of the hot shale, and of the NC174 and NC115 oils indicate that the hot shale is a suitable source rock for having generated the oils (Geochem, 1993, 1994a, 1994b).

MATURITY MODELLING

A programme of thermal modelling of the basal Tanezzuft hot shale source rock in the NC174 wells is currently being carried out by LGML using the BasinMod programme. Some early results of the models on the B1-NC174 well are illustrated in Figs. 10, 11 and 12, but it is recognised that more controls are required to constrain the inputs to these models. In particular, the thermal history is poorly constrained, and this is currently being addressed by fluid inclusion and apatite fission track studies. The timing and amount of uplift during phases of compressional tectonics are also key inputs to the model, and these parameters are being refined by studies on basin tectonics combined with shale velocity work.

A number of T Max calibration points derived from sample pyrolysis are available from within the Tanezzuft shale of the analysed well and these are used as calibration for the maturity model. The TMax data imply that the hot shale in the well reached mid-maturity ($R_o = 0.9\%$) for oil generation at some point in geological time (Fig. 11). Work is currently being carried out with a view to improving the calibration of maturity modelling in the Murzuq Basin.

Assumptions made for the illustrated model are:

Heat Flow

The measured present-day heat flow, averaged for NC174 wells, of 45 mWm^2 was used throughout, with the exception of a short period of elevated heat flow (+20%) in the early Tertiary relating to the onset of volcanic activity in the Eocene in the Hoggar Massif, the Tibesti Massif and Jebel Al Haruj, all of which surround the Murzuq Basin (Wilson and Guiraud, 1998).

Uplift and Erosion

Approximately 300 m (1000 ft) of uplift and erosion has been assumed to have taken place both during the Carboniferous and Cretaceous/Tertiary compressive movements. Preliminary results from shale velocity studies support the assumption that maximum burial in the area of NC174 was at least 300 m deeper than present-day. It is recognised that the timing and magnitude of these uplifts are not well constrained, and work is currently in progress to provide more reliable quantitative estimates for these critical input parameters.

It is apparent from Fig. 10 that the assumed amount of Carboniferous uplift and erosion would have had relatively little effect on source maturity, since the hot shale had only just entered the early mature window at the end Carboniferous.

The results of the maturity model show that the hot shale in the B1-NC174 well might have entered the mid-mature window and started to generate significant quantities of oil at about mid-Cretaceous times, approximately 100 Ma BP, and continued to do so until early Tertiary, about 50 Ma BP, when uplift and erosion caused sufficient cooling of the source rock to remove it from the oil window (Fig 12). The hot shale in the modelled well is not generating any oil at present and will remain in this 'frozen' state unless its temperature is elevated by further burial or increased heat flow.

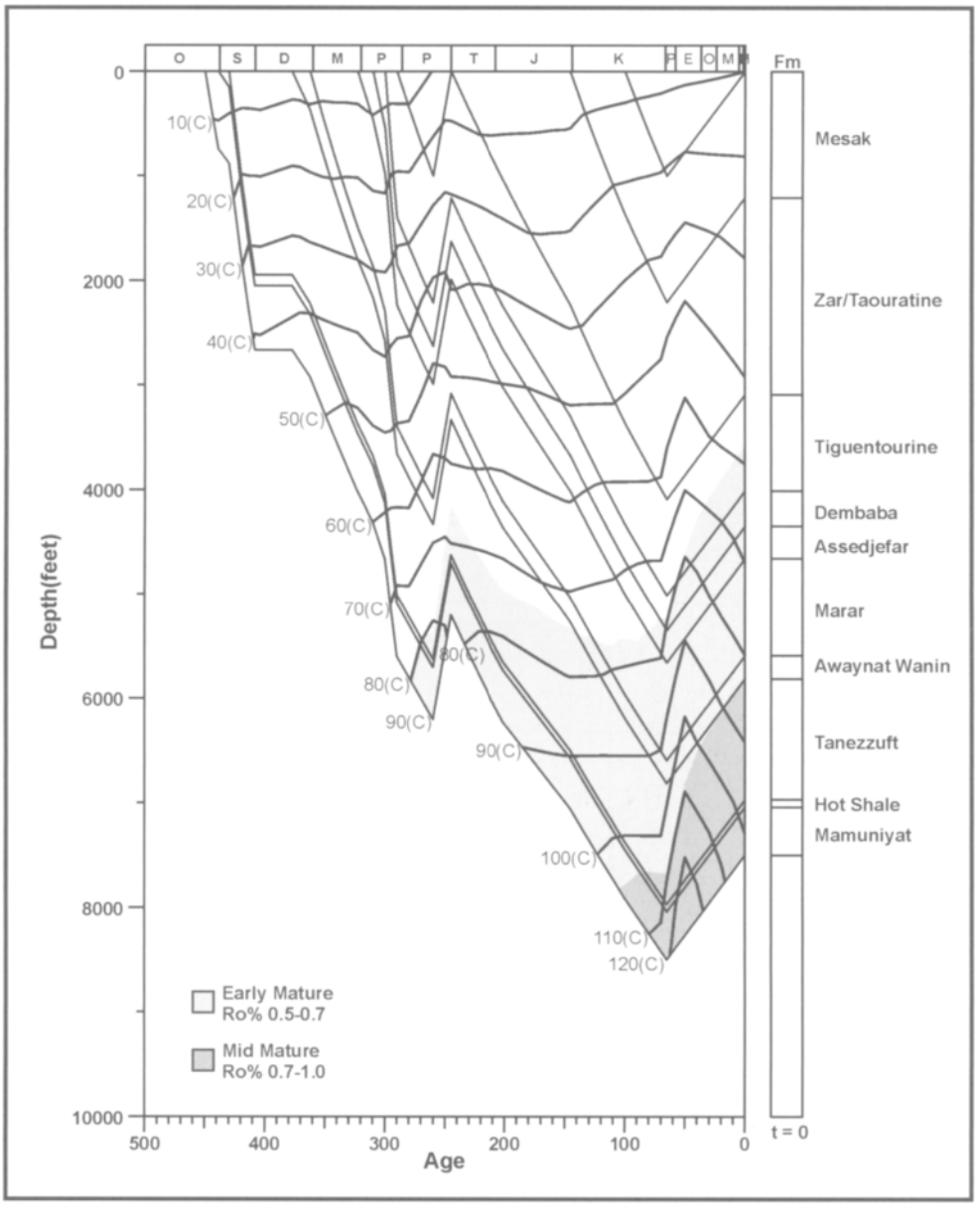

Figure 10. Burial history plot from preliminary maturity modelling of well B1-NC174 using the BasinMod programme. See text for assumptions and input data for this model.

It should be noted that the conclusions reached here do not agree with those of some other authors. Meister et al. (1991) took the view that the Murzuq Basin has not been subjected to significant post-Carboniferous erosion, that only the deepest parts of the present-day basin generated oil and that long distance migration is responsible for the oils trapped in shallower parts of the basin, e.g. in NC115. In contrast, Aziz (2000) proposes that the basin was subject to significantly more Permo/Carboniferous (Hercynian) and Tertiary (Alpine) uplift and erosion than suggested in this paper. The resulting maturity model for the Tanezzuft source rock

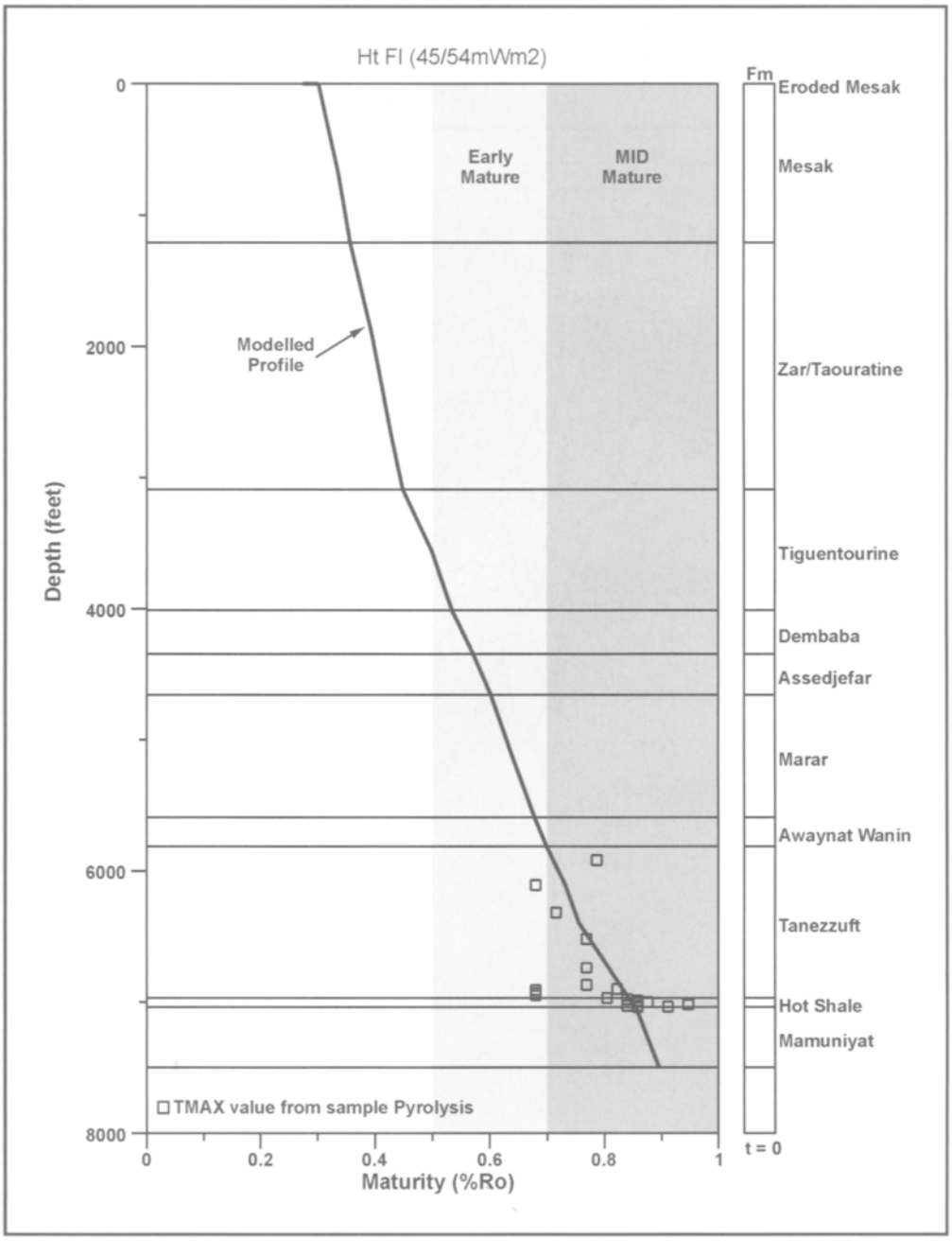

Figure 11. Calibration of the preliminary maturity model of the B1-NC174 well modelled in Fig. 10. The TMax values used as calibration points were derived from pyrolysis results from samples of Tanezzuft shale. No calibration points are available to constrain the model in the section younger than the Silurian.

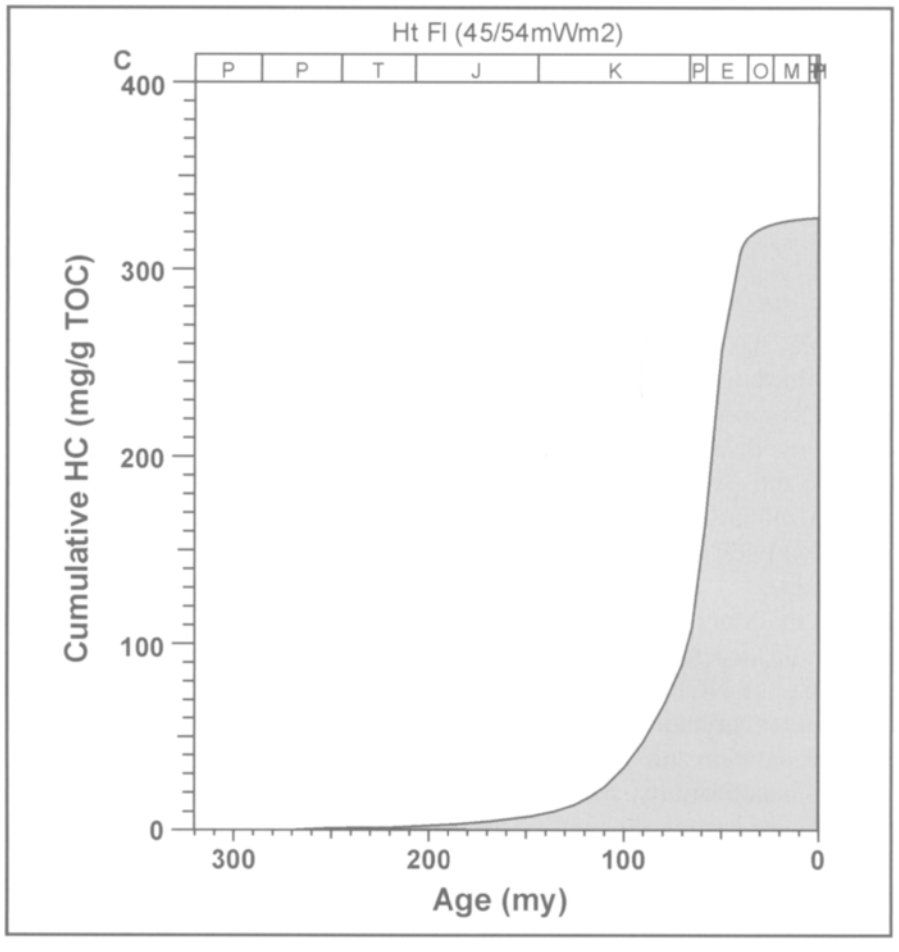

Figure 12. Calculated oil generation from well B1-NC174 modelled in Fig. 10. The model indicates that significant oil generation began approximately 100 million years ago, but generation ceased at about 40 Ma due to uplift and cooling of the hot shale source rock. Note that the model does not distinguish between migrated oil and that retained within the source rock.

presented by Aziz (2000) indicates that oil generation began in the Carboniferous (pre-Hercynian).

PRESERVATION OF TRAPPED OIL

Although the Murzuq Basin oils show no obvious evidence of biodegradation, they all are characterised by a low to very low GOR and very low aromatic contents in the gasoline range fractions. This could be a primary effect caused by source rock composition, but is more likely to be a secondary effect produced by the removal of these lighter elements probably through the process of water washing. Tectonic uplift and erosion of the margins of the Murzuq Basin during the Cretaceous and/or Tertiary had the effect of exposing the basin aquifers to fresh water flushing, with the result that the Cambro-Ordovician sandstones are now charged with fresh water throughout the basin. Despite present arid conditions in the area, the Cambro-Ordovician aquifer is probably still full to its current structural spill point into the deeper younger basins to the north. Although this may be a relatively static condition at present, it is probable that significant hydrodynamic flow took place within this aquifer during the documented wet

climatic periods of 3000 to 12 000 years ago (Lutz and Lutz, 1995) and other undocumented wet periods before that, when the exposed aquifers to the east and west of the basin were continuously recharged with fresh meteoric water. Persistent exposure to this flowing fresh water could have resulted in dissolution of gas and the lighter liquid hydrocarbon elements from the trapped hydrocarbon accumulations within the Murzuq Basin.

THE ORDOVICIAN PLAY STATISTICS

The Ordovician play has proved very successful in the Murzuq Basin. Approximately fifty-seven exploration wells have been drilled in the basin between 1958 and 1997, and nearly all of these were drilled with the primary objective of testing the Ordovician play. This exploration work has resulted in four large discoveries, with combined reserves of about 1000 to 1500 million barrels of recoverable oil, and sixteen smaller discoveries. The size of many of the discoveries is mainly a function of trap volume, although underfilling of traps may also be a factor. Of the remaining thirty-seven wells, twelve encountered hydrocarbon shows in Ordovician sandstones, and twenty-five were dry.

One enigma of the Murzuq Basin involves several wells that have been drilled near the centre of the basin on valid structural closures at base Silurian level, but have failed to encounter any hydrocarbons. The D1-NC174 well (Fig. 6) is a good example. This well drilled a clearly defined fault-bounded structural closure, encountered a good hot shale source rock at the base of the Tanezzuft Formation and found excellent reservoir quality Mamuniyat sandstones beneath the base Silurian unconformity, but proved to be a dry hole with no shows in the reservoir section. At the time of writing the preferred explanation for failure of this well is that sandstone to sandstone juxtaposition across the main bounding fault resulted in cross-fault leakage, but a number of alternative explanations are also possible. Some other drilled structures in the basin have been found to contain only residual oil, perhaps implying leakage, and yet others appear to be underfilled. These examples serve to illustrate that the hydrocarbon system in the Murzuq Basin is not as simple as it may appear on initial analysis, and that significant work remains to be done to achieve a full understanding of the processes that controlled the initial accumulation and subsequent preservation of the major oilfields discovered to date.

The drilling results for the Cambro-Ordovician play give an overall technical success rate of approximately 35% in the basin as a whole and 38% in NC174.

CONCLUSIONS

The Murzuq Basin is a relatively underexplored basin in which reserves of approximately 1.5 billion barrels of recoverable oil have already been discovered. The primary play in the basin comprises an Ordovician periglacial sandstone reservoir, sourced with oil from and sealed by overlying Silurian shales. Oil was generated from an extremely rich source rock at the base of a thick Silurian shale section, and migrated directly into the underlying sandstone-rich Ordovician reservoir section. The timing of the main phase of oil generation is not well constrained but it is believed to have taken place from the mid-Cretaceous to early Tertiary. The relatively simple structure of the basin might have allowed long distance migration within the Ordovician sandstones, but late Cretaceous and early Tertiary tectonic movements have affected the basin subsequent to the main phase of oil generation, leading to obvious difficulties in prediction of original oil migration routes.

Drilling results in the basin provide evidence that the play is not yet fully understood. In addition to the main discoveries there are also some drilled structures that appear never to have

been charged with oil, while others contain only residual oil, perhaps implying leakage, and yet others are underfilled. These inconsistent results may be the result of the timing of oil generation predating at least one, and probably two phases of regional tectonic movements which may have caused spillage of oil from existing traps, re-migration from one trap to another and leakage of oil due to reactivation of trap-bounding faults. The uplift and erosion associated with these tectonic movements resulted in cooling of the source rocks which probably froze hydrocarbon generation in the basin from the early to mid-Tertiary. There is also uncertainty surrounding the areal distribution of the Silurian source rocks, which provided the bulk of the oil generated within the basin; the known distribution of the Tanezzuft hot shale is very irregular and it may be absent over large parts of the basin.

The Ordovician play has met with only a limited amount of success elsewhere along the North African margin. In some basins, this lack of success can be attributed to the distribution of the source rock. However, in other cases, such as the neighbouring Illizi Basin of Algeria, the limited success of the play is mainly the result of a different tectonic history resulting in excessive burial of both the Ordovician reservoir and Silurian source. In contrast, the Murzuq Basin lies on a stable craton and has had a relatively gentle tectonic evolution, with the consequence that the Ordovician sandstone reservoir has not been buried to great depths and has retained good reservoir properties. Over large parts of the basin the Silurian source rock probably did not enter the oil window until Mesozoic times. The extent of late Cretaceous to early Tertiary uplift and associated erosion in the Murzuq Basin requires further quantification, but it is likely that the source rock in the centre of the basin is presently at least 300 m shallower than its maximum burial depth. However the properties of the trapped hydrocarbons indicate that pressure/temperature conditions of the mid to upper oil generation window were not exceeded.

Two areas of study are currently being pursued in order to obtain a better understanding of the Ordovician play. Firstly, work is progressing to unravel the complex relationships between the generation/migration of oil and the various phases of tectonic movements that affected the area. Secondly, a better model of the Ordovician reservoir distribution and quality is being developed by analysis of recent wells drilled in the basin, coupled with seismic stratigraphic interpretation. The conclusions from these studies should greatly assist future exploration in the basin.

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CHAPTER 15

Sedimentology and sequence stratigraphy of the Devonian to lowermost Carboniferous succession on the Gargaf Uplift (Murzuq Basin, Libya)

JEAN-LOUP RUBINO[1] and CHRISTIAN BLANPIED[1]

ABSTRACT

In the Murzuq Basin of Libya, the Devonian succession diachronously overlies the Caledonian unconformity. The Lower Devonian second order transgressive-regressive sequence, which includes the fluvial to shallow marine Tadrart Formation and the prograding shallow marine Ouan Kasa Formation, is restricted to the western margins of the basin. The only preserved exposures of this succession on the Gargaf Uplift are found in this structure's western corner, in the Awaynat Wanin area. The whole Gargaf Uplift was probably only submerged during the Middle Devonian. The Middle Devonian to Lower Carboniferous succession outcropping on the southern flanks of the uplift, in the Wadi ash Shati area, has been reviewed and subdivided into nine depositional sequences. The transgressive systems tracts of most of these sequences are characterised by tidal dominated facies, whilst the highstand systems tracts are storm and wave dominated. This relatively common pattern of development seems to be related to changes in shelf physiography as a response to sea level variations.

There seems good agreement between outcrops in the Wadi ash Shati area and the subsurface formations in the Ghadames Basin when interpreted in terms of sequence stratigraphy. Although at present only poorly constrained by datings essentially based on macrofauna, these depositional sequences of the Gondwanan realm may be compared with the eustatic cycles and the relative coastal onlap curve for Euramerica proposed by Johnson et al. (1985). Therefore, a refined stratigraphy of the Devonian to lowermost Carboniferous succession of Libya should permit integration of these depositional sequences into a larger, worldwide framework. This will facilitate regional correlation and help better understanding of the Devonian geological evolution of western Libya.

INTRODUCTION

The Murzuq Basin is separated from the Ghadames Basin by the Gargaf Uplift and is one of a series of northern Gondwana Palaeozoic intracratonic basins (Fig. 1). Palaeozoic outcrops occur all around the Murzuq Basin: along the western edge of the Tibesti Arch to the southeast, in the Jabal Tadrart to the southwest, and in the Gargaf Uplift to the north. Generally, the Devonian

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succession is bracketed by two main unconformities, each representing a significant hiatus: the Caledonian unconformity at the base, and the pre-Middle Tournaisian unconformity at the top.

The Devonian succession usually rests unconformably on the Silurian Tanezzuft shale or the Akakus Formation sandstones (Fürst and Klitzsch, 1963; Fig. 2 herein). However, in the Gargaf area erosion can reach down to the Cambrian Hasawnah Formation. On a regional scale, this Caledonian unconformity is then diachronously sealed by the Devonian succession following an apparently progressive eastward trending onlap (Fig. 3).

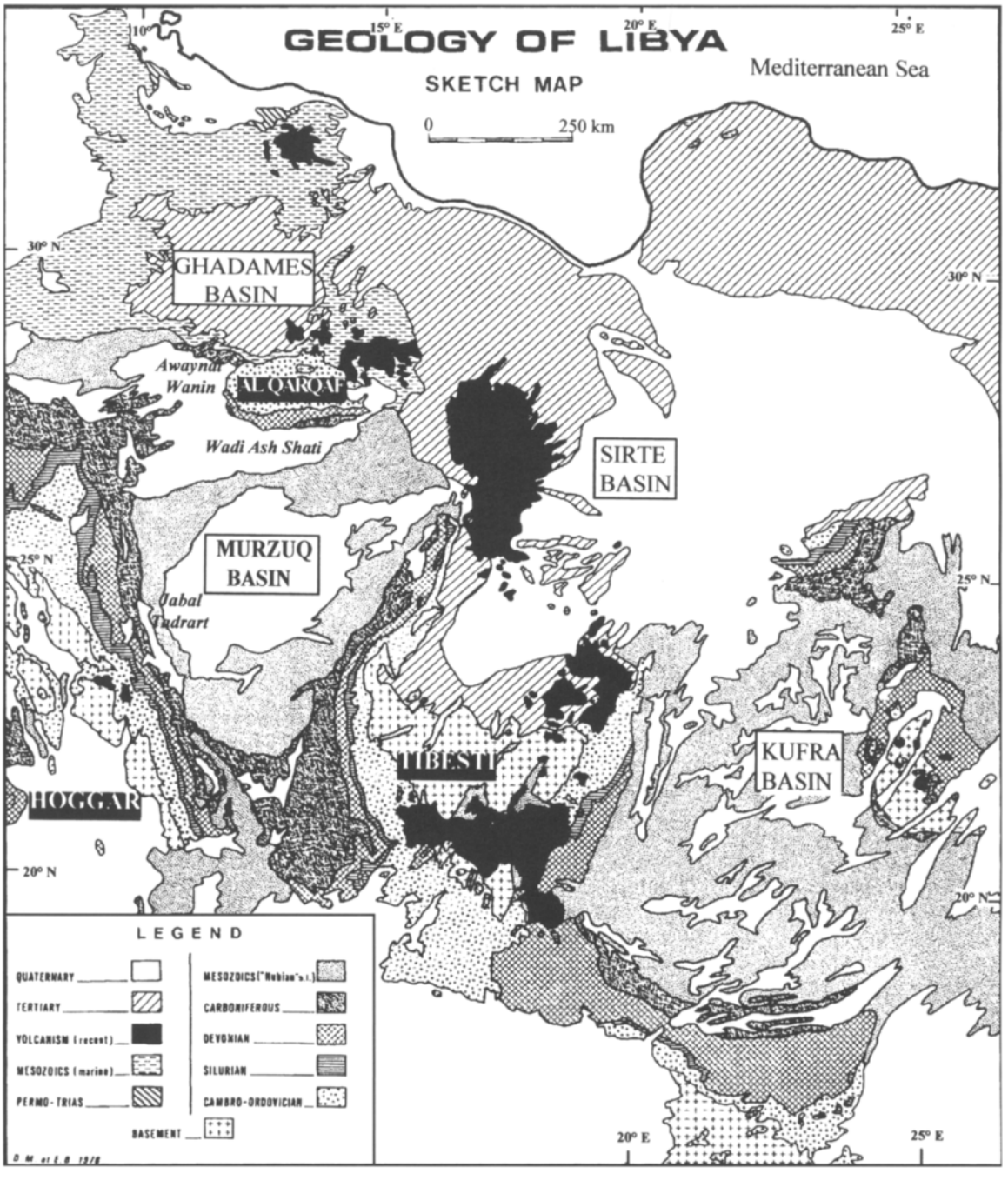

Figure 1. Geological sketch map of Libya: modified after Bellini and Massa (1980).

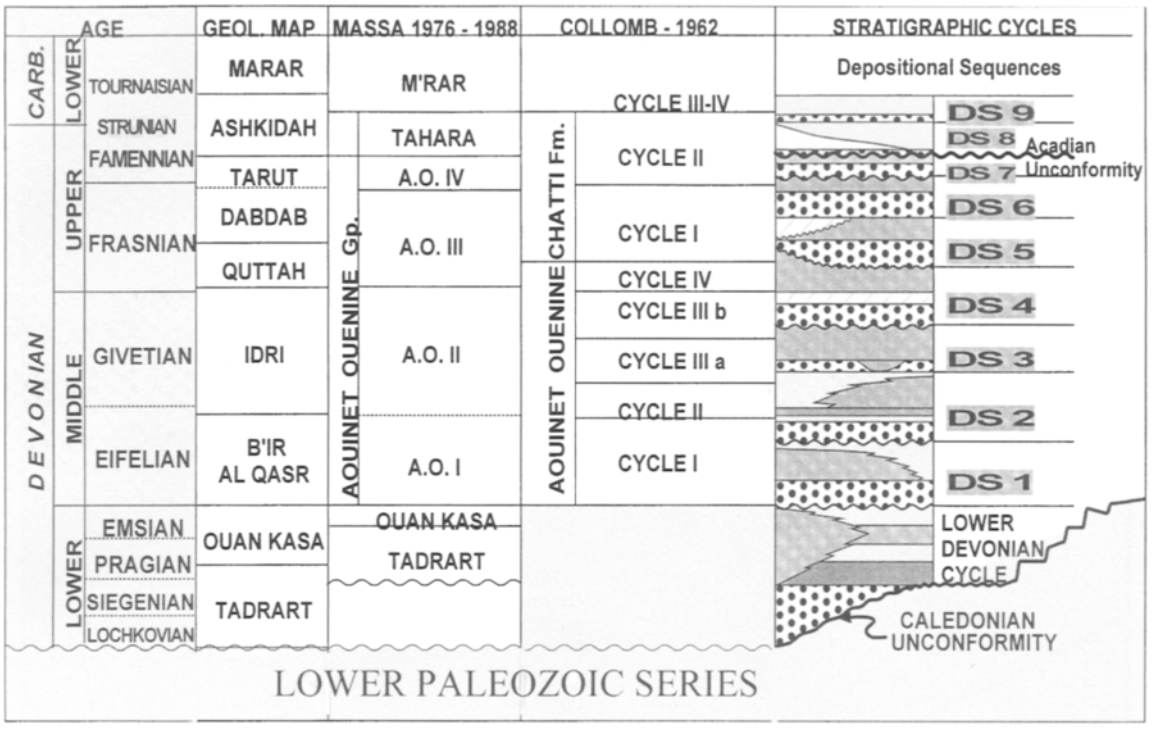

Figure 2. Stratigraphic correlation of the Devonian to Lower Carboniferous formations.

The Lower Devonian Tadrart and Emsian Ouan Kasa formations are only present in the northwestern corner of the Gargaf Uplift, near to Awaynat Wanin itself (Bellini and Massa, 1980). The geometrical relationships between this Lower Devonian cycle and the underlying Lower Palaeozoic series cannot be directly inferred from the outcrops. However topographic reconstruction (Massa, personal communication, 1999) tends to support onlap rather than truncation related to late Early Devonian tectonics. This is also supported by the lack of such an unconformity in subsurface data from both the Ghadames and Murzuq basins. This suggests that most of the Gargaf area was subaerially exposed and eroded during the Caledonian tectonic event (i.e. during the late Silurian and early Devonian) and only flooded during the Middle Devonian, resulting in deposition of the B'ir Al Qasr Formation of probable Eifelian age (Parizek et al., 1984). Predominantly clastic sedimentation then continued until the earliest Carboniferous over the Wadi ash Shati area (Fig. 1).

The upper unconformity corresponds to a time gap spanning the early to late Tournaisian. The geometrical relationships of units across this unconformity are less well documented in the southern Gargaf area than those related to the Caledonian unconformity. However this major break also occurs in the southwestern corner of the Murzuq Basin, where the Upper Tournaisian rests on the Tadrart Formation with a marked angular unconformity (Mergl and Massa, 1998).

This chapter focuses on the outcrops of the Middle Devonian and lowermost Carboniferous formations extending in the Wadi ash Shati area from the westernmost locality of B'ir Al Qasr to Wadi Dabdab in the east (Fig. 3). This succession was primarily analysed in terms of sedimentology, including analyses of facies and depositional systems, and subsequently interpreted in terms of sequence stratigraphy following established Exxon terminology (Posamentier et al., 1988a, b; Van Wagoner et al., 1988) and the concepts of coastal stratigraphy developed by Swift (1968) and Kraft and Chrzastowski (1985). A tentative correlation of these depositional sequences with the Devonian eustatic cycles proposed by Johnson et al. (1985) and Dennison (1985), in addition to a correlation between the Wadi ash Shati outcrops and a well

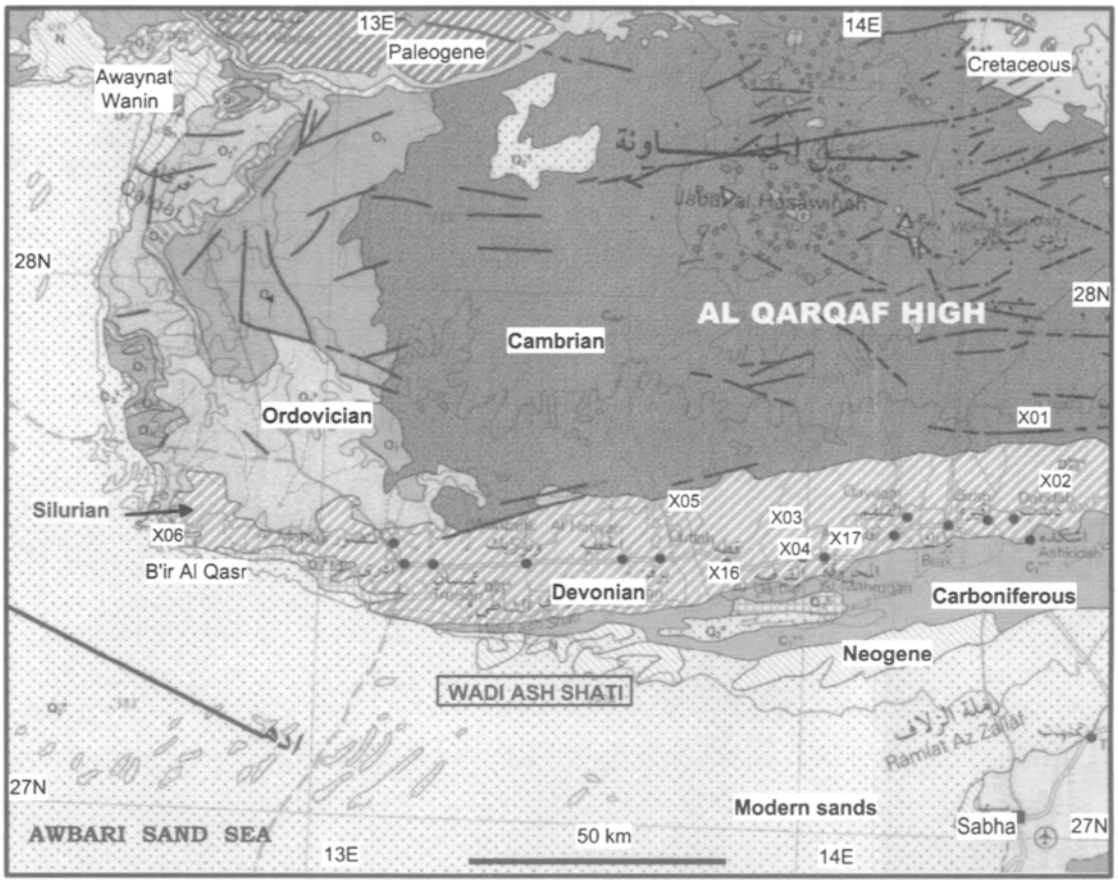

Figure 3. Location of measured Devonian sections. See text and Fig. 4 for detailed description. Modified after I.R.C. Geological Map of Libya, 1: 1 000 000, 1985 edition.

located in the Ghadames Basin, will also be presented. Finally, a brief comment regarding the significance of the Gargaf Uplift in terms of palaeogeography will address the major direction of progradation indicated by the succession.

SEQUENCE STRATIGRAPHY VERSUS LITHOSTRATIGRAPHY

Depositional sequence boundaries do not always coincide with formation boundaries. In the Murzuq Basin, the Devonian succession comprises several lithostratigraphic formations as summarised in Fig. 2. The depositional sequences discussed below are compared either to the previous lithostratigraphic units still commonly used (Massa and Collomb, 1960; Collomb, 1962; Massa and Moreau-Benoit, 1976; Bellini and Massa, 1980; Massa, 1988), or to the formation names utilised in the geological map of Libya 1: 250 000 mapsheet series (Parizek et al., 1984; Seidl and Röhlich, 1984).

AGES OF FORMATIONS

The biostratigraphic data available in the literature have been used to constrain the ages of the various depositional sequences. Present status will be briefly reviewed below in order to evaluate the degree of uncertainty regarding the ages of each sequence.

Lower Devonian

Even though the Lower Devonian is missing in the study area, elsewhere it defines a large scale second order transgressive-regressive cycle (Fig. 2). This cycle comprises the basal Tadrart Formation's fluvial and marginal marine sandstones grading upward into the shallow marine Ouan Kasa Formation. The basal part of the Tadrart Formation in the Murzuq Basin was dated to the Upper Siegenian/Pragian by Bellini and Massa (1980) whilst in the Ghadames Basin the marine part has an older, Lower Lochkovian, aspect (Massa, 1988; Weyant and Massa, 1991; Mergl and Massa, 1992). This suggests that just after Caledonian uplift and erosion, deposition of marine sandstones started first in the Ghadames Basin, with the fluvial series bypassing the Murzuq area and then, at the end of the progradation, the fluvial series started to retrograde to the south, and onlapped the Caledonian unconformity in the Murzuq Basin. Consequently, only the upper part of the Tadrart Formation of the Ghadames Basin is time equivalent with the Tadrart Formation of the Murzuq Basin.

The overlying Ouan Kasa Formation, comprising marine carbonates and mudstones interbedded with thin sandstones, is dated to the late Emsian by a rich macrofauna including brachiopods, bivalves, pteropods and bryozoans (Collomb and Heller, 1959; Bellini and Massa, 1980). This early Devonian cycle is common in most north Gondwanan basins; in particular it has been described in Saudi Arabia (Razin et al., 1993).

Middle Devonian

The B'ir al Qasr Formation is poorly dated; it apparently corresponds to Cycle I of the Aouinet Ouenine Formation of Collomb (1962), or to Aouinet Ouenine I of Massa and Moreau-Benoit (1976). Although attributed to the Couvinian (probably Eifelian) based on brachiopods and bivalves, some palynomorphs could indicate a wider age range, spanning from the late Emsian to Givetian (Massa and Moreau-Benoit, 1976). To the north, in the Ghadames Basin, Hajlasz et al. (1978) have documented an upper Eifelian age. Taking into account the well-documented Givetian age of the overlying Idri Formation, an Eifelian age is therefore assumed for the B'ir al Qasr Formation in the Gargaf area.

The Idri Formation may include the Aouinet Ouenine cycles II, IIIa and IIIb of Collomb (1962). However, it may be more confidently compared with Aouinet Ouenine II of Massa and Moreau-Benoit (1976). The Givetian age of the Idri Formation based on brachiopods is well established, at least for its upper part (Parizek et al., 1984).

Upper Devonian to Lower Carboniferous

The Quttah Formation corresponds to Aouinet Ouenine cycle IV of Collomb (1962), and to the base of Aouinet Ouenine III of Massa and Moreau-Benoit (1976). This formation contains the characteristic trace fossil *Bifungites fezzanensis* in its lower parts, and its age may be definitely assigned to the Frasnian (Collomb, 1962; Seidl and Röhlich, 1984).

The two overlying formations are best exposed and preserved in the easternmost area, around the town of Brak. The Dabdab Formation is also dated to the Frasnian on the basis of pre-Famennian atrypid brachiopods (*Spinatrypina* sp.). However its precise age cannot be ascertained, as diagnostic fossils are extremely rare (Seidl and Röhlich, 1984). The Dabdab Formation corresponds to cycle I of the Chatti Formation of Collomb (1962), and to the upper part of Aouinet Ouenine III of Massa and Moreau-Benoit (1976). Both this and the overlying Tarut Formation are well-known for their thick iron-ore beds, for a time considered as possibly

of commercial interest and extensively studied by the French Study Group (1972, 1976) and reviewed by Turk et al. (1980).

The Tarut Formation corresponds to the lower part of the Chatti cycle II of Collomb (1962), and to Aouinet Ouenine IV of Massa and Moreau-Benoit (1976). Its lower part contains the regionally developed 'Bivalve key bed', a possible lateral equivalent of the so-called 'Cues Limestone horizon' of Said (1974). The Tarut Formation contains endemic brachiopods that are only poorly dated. It also contains relatively abundant plant remains and spectacular stems of lycophytes (Hlustik, 1991), although these also have little stratigraphic value. The most recent conodont analyses of samples collected from Awaynat Wanin outcrops and from the subsurface indicate a late Frasnian/early Famennian age (Weyant and Massa, 1980). This agrees with datings in the Ghadames Basin cited by Seidl and Röhlich (1984). More recent datings have been given by palynostratigraphic analyses in the Al Wafa field where the 'Cues Limestone Horizon' is assigned to the late Frasnian (Elzaroug and Lashhab, 1998).

The Ashkidah Formation corresponds to cycle II of the Chatti Formation of Collomb (1962), and to the 'Strunian' Tahara Formation of Massa and Moreau-Benoit (1976).* Recent work suggests that the transition from the Devonian to the Carboniferous occurs within this formation. Palynological assemblages suggest that the basal part of the Ashkidah Formation may be assigned to the uppermost Devonian Famennian stage (Vavrdova, 1991). On the other hand, a characteristic Tournaisian brachiopod assemblage occurs in the uppermost part of this formation in the central part of the Wadi ash Shati area (Massa, 1988; Mergl and Massa, 1992). However in the absence of a regional biostratigraphic reappraisal the precise boundary cannot be confidently identified and the entire formation is correlated to the Tahara Formation of the Awaynat Wanin area (French Study Group, 1972 cited in Seidl and Röhlich, 1984; Massa and Moreau-Benoit, 1976).

DESCRIPTION OF THE DEPOSITIONAL SEQUENCES

A series of eight measured sections (X1 to X6, X16 and X17) in the Wadi ash Shati area (Fig. 3) serve as the basis for this study and are tentatively correlated in terms of sequence stratigraphy. Nine Devonian to Lower Carboniferous depositional sequences (DS-1 to DS-9) are identified between the Caledonian unconformity and the Lower Carboniferous Marar Formation. These depositional sequences have been reviewed in the western or central regions, either in the type localities described in the Explanatory booklets of the 1: 250 000 Idri and Sabha Geological Sheets (Parizek et al., 1984; Seidl and Röhlich, 1984), or along transects permitting a better lateral understanding of the transition between formations. However, DS–6 and DS-7 (Dabdab and Tarut formations), which are thinner to the west, were visited in their type locality to the east of Brak. The correlation of these various sections is illustrated in Fig. 4.

Depositional Sequence 1 (Eifelian)

In the southern Gargaf area, the Devonian succession starts with the Middle Devonian (Eifelian-Givetian) B'ir Al Qasr Formation, the type locality of which constitutes the southwesternmost outcrop of the Gargaf Uplift, bordering the Awbari Sand Sea (Fig. 3). The B'ir Al Qasr Formation overlies the Caledonian unconformity and from west to east gradually oversteps underlying units, namely: the Lower Silurian Tanezzuft Formation, the Upper Ordovician Mamuniyat Formation, and finally the clastics of the lower Ordovician to Cambrian Hawaz and Hasawnah formations, to the north of the town of Brak.

* Eds note: see also paper by El-Mehdawi (this volume)

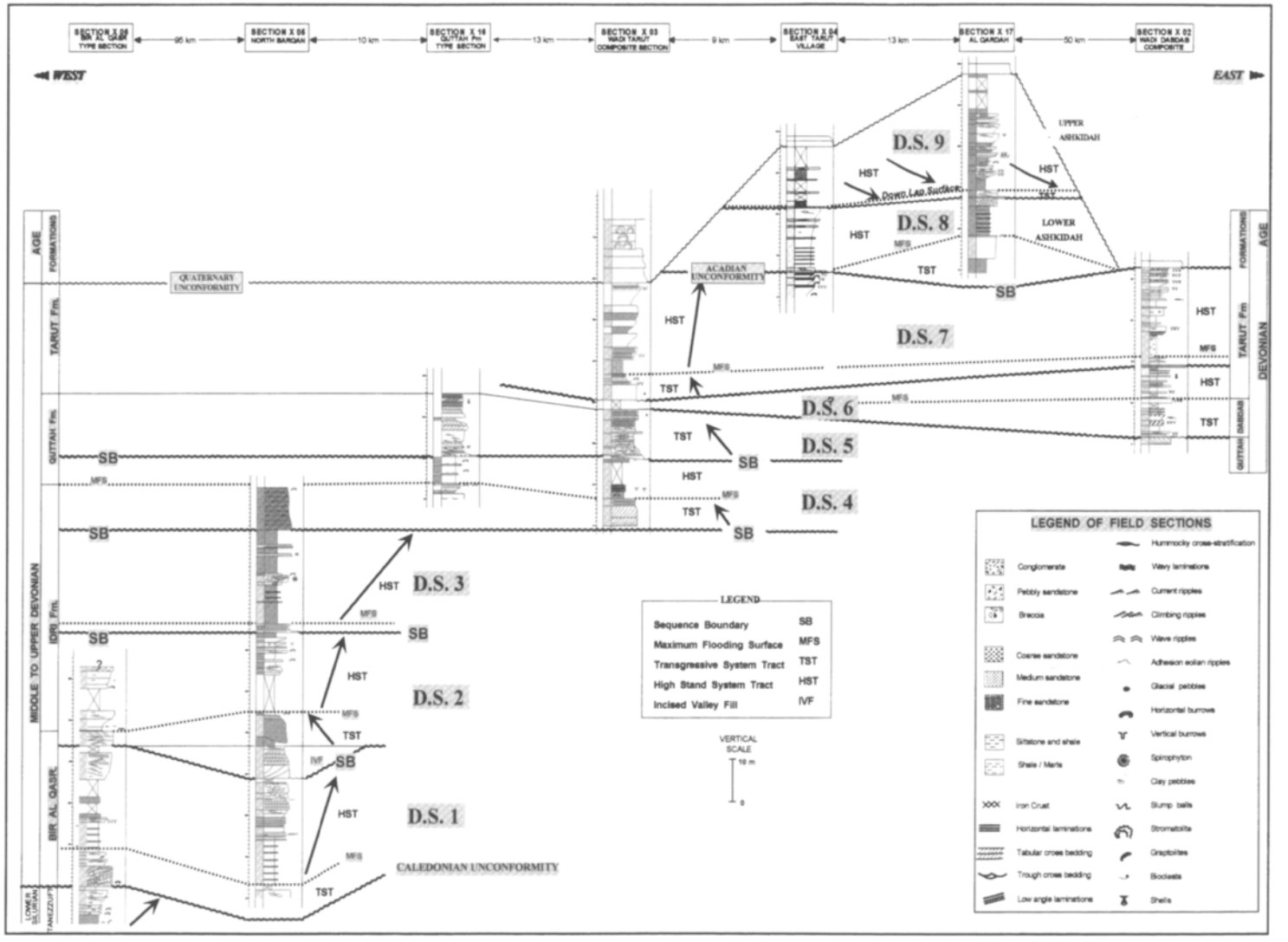

Figure 4. Wadi ash Shati: Correlation of Devonian to Lower Carboniferous depositional sequences (for locations see Fig. 3).

In the type locality (X6 on Fig. 3), the B'ir Al Qasr Formation rests unconformably on the Tanezzuft Formation and is about 35 m thick (Fig. 4 and Plate 1, fig. 1). It is interesting to note that the uppermost preserved Tanezzuft succession includes wave dominated fine-grained sandstones. The Devonian succession starts with an 8 m thick transgressive shelf tidal bar (Plate 1, fig. 2) migrating locally to the southwest; in the vicinity, tidal regimes seem also to be suggested by a bimodal pattern of bar migration (D. Worsley, personal communication, 1999). This bar is made up of superimposed small-scale bidirectional megaripples. The upper part of the transgressive systems tract (TST) consists of two superimposed small-scale parasequences grading from silty shales to storm-dominated sandstones with hummocky cross-stratification. The change from a tide to wave dominated system within the TST suggests that a double ravinement surface occurs, the first at the base of the transgression being tide-related and the second created by wave action. This change is probably linked to local evolution of the basin physiography during the sea level rise. During the early stages of transgression, the basin was somewhat confined, but with time the shelf became wider and wave action became predominant.

The highstand systems tract (HST) of the sequence shows a shallowing-up parasequence set, with basal very thin storm-graded layers interbedded with silty shales deposited in an outer shelf setting. These pass upwards into a prograding sandy littoral complex grading from shoreface with wave ripples (Plate 1, fig. 3) and hummocky cross-stratification (Plate 1, fig. 4), to beach face with swaley cross-stratification and low angle parallel lamination. The southward progradation of this coastal system can be observed on a semiregional scale in the surrounding scattered hills (Plate 1, fig. 5).

One hundred kilometres further to the east, north of the town of Barqan, the B'ir Al Qasr Formation unconformably overlies the Mamuniyat Formation (section X5). There, the transgressive systems tract is either missing, or it cannot be distinguished from the underlying Mamuniyat sandstones, and this interpretation is depicted in Fig. 4. Consequently the studied section starts in a shaly interval more or less coincident with the maximum flooding surface. The overlying HST corresponds to the lower part of the B'ir Al Qasr exposures and defines a 30 m thick overall coarsening-up and thickening-up cycle including from base to top:

- Varicoloured to pale grey shelf shales interbedded with thin storm levels containing marine trace fossils,
- Thicker sandstone horizons (0.5 m) with wave ripples, some climbing ripple units and hummocky cross-stratification, all features suggesting a littoral setting (beach to shoreface),
- Thicker (2.5 m) and coarser-grained cross-stratified sandstones, probably fluvial in origin, which in turn are overlain by very clean sandstones with festoons. The occurrence of some adhesion ripples suggests an aeolian environment (littoral dune). Dewatering has subsequently deformed the uppermost bed.

The transition from the B'ir Al Qasr Formation to the Idri Formation can be seen in localities X5 and X6. However, the Idri Formation is best preserved to the north of the town of Barqan in locality X5 and the transition to the overlying Quttah Formation is also best developed in the same area. There, the Idri Formation can be subdivided into two well-defined third-order depositional sequences (DS-2 and DS-3), and the base of a third one (incised valley fill – IVF of DS-4) is also preserved on the hilltop.

Depositional Sequence 2 (Givetian)

This sequence is about 35 m thick in section X5 (Fig. 4), and begins with an incised valley fill of limited extent, composed of 8 m thick medium-grained cross-stratified sandstones. The

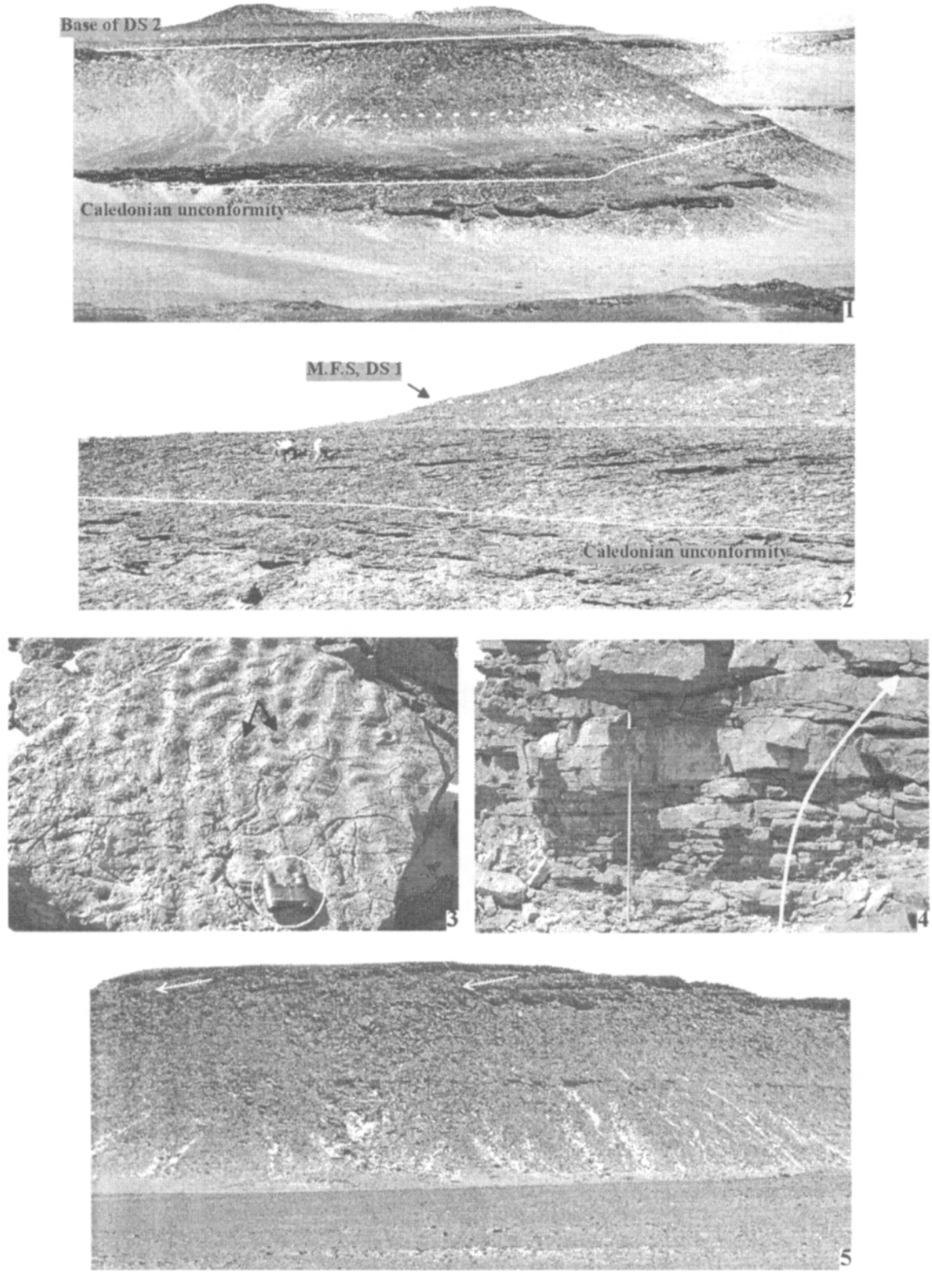

Plate 1. (*for description see end of chapter*)

bidirectional palaeocurrent pattern (N 110°–N 230°) indicates tidal influence and suggests an estuarine complex rather than a fluvial setting (Plate 2, fig. 1). This valley infill could either represent the lowstand phase or the TST stage. Although the tidal currents are locally E-W oriented, this does not necessarily imply that the whole valley has the same trend since estuarine complexes can be very sinuous, especially when the channel is narrow. Storm processes have reworked the sandstones on top of this first unit, suggesting an abrupt change in depositional setting. Overlying shales contain marine trace fossils, and then a new 5 m thick narrow tidal channel is capped by bioturbated siltstones. This superposition of two tidal channels separated by a unit made up of more marine deposits within the TST is tentatively interpreted as the result of high frequency relative sea level changes.

The maximum flooding surface (mfs) of depositional sequence DS-2 is probably located within an unexposed presumably more silty unit. This mfs appears to correspond to the base of the Idri Formation as described for the Sabha geological mapsheet by Seidl and Röhlich (1984).

The highstand, 18 m thick in section X5, comprises stacked, metre-thick small-scale parasequences (Plate 2, fig. 3) with storm and wave-dominated sandstones interbedded with burrowed siltstones/sandstones (Plate 2, fig. 4). The absence of the most regressive facies, in the form of beach or deltaic to fluvial deposits, suggests erosion related to the ensuing sequence boundary.

The basal valley fill of section X5 has not been found in the B'ir Al Qasr locality (X6) and the estuarine complex characterising the TST to the north of Barqan (X5) has changed to a beach deposit, suggesting an interfluve setting. The maximum flooding surface in X6 is well defined by a condensed interval characterised by the occurrence of shells and glauconite. Also in this locality, the lower part of the HST is sandier than eastwards in X5, suggesting a more proximal setting, or at least the proximity of a sediment source. The upper part of the highstand series of DS-2 is perhaps not developed in the B'ir Al Qasr locality.

Depositional Sequence 3 (Givetian)

This sequence belongs entirely to the Idri Formation and has only been observed in outcrops to the north of Barqan (X5). A sharp and erosional contact separates the underlying marine shales of the upper part of DS-2 from a 3 m thick unit composed of medium to coarse-grained sandstones (Plate 2, fig. 3). This sharp contact makes these sandstones – interpreted as the late fluvial HST of DS-2 – very conspicuous. This interpretation is supported by the presence of a pink to whitish horizon below these sandstones, here interpreted as a weathering horizon. In a nearby locality, this basal clastic unit shows large-scale accretionary surfaces suggesting a meandering, fluvial to deltaic system. However, sedimentary features are concealed along-section and a reliable differentiation between fluvial and deltaic settings is therefore not possible. Consequently, these basal sandstones may either belong to an incised valley filled during the lowstand stage with a thin retrograding fluvial series, or to a transgressive deltaic unit.

The main flooding surface occurs within the overlying shales at a marker bed characterised by an enriched Fe-Mn crust. The overlying 23 m thick highstand systems tract then consists of thin storm sands grading upwards into marine silty shales with interbedded metre-thick lower shoreface sandstones. Red shales in the upper part of this HST, possibly deposited in a coastal plain environment, are interbedded with well-defined tidal bundles within isolated channels. These sedimentary facies indicate the most proximal setting identified in the Devonian succession in this study.

Depositional Sequence 4 (Givetian-Frasnian)

The basal part of this sequence terminates the X5 measured section (Fig. 4) and coincides with the top of the Idri Formation as defined by Seidl and Röhlich (1984). This unit shows a sharp erosional contact to the underlying red shales. It comprises a 10 m thick unit of coarse-grained

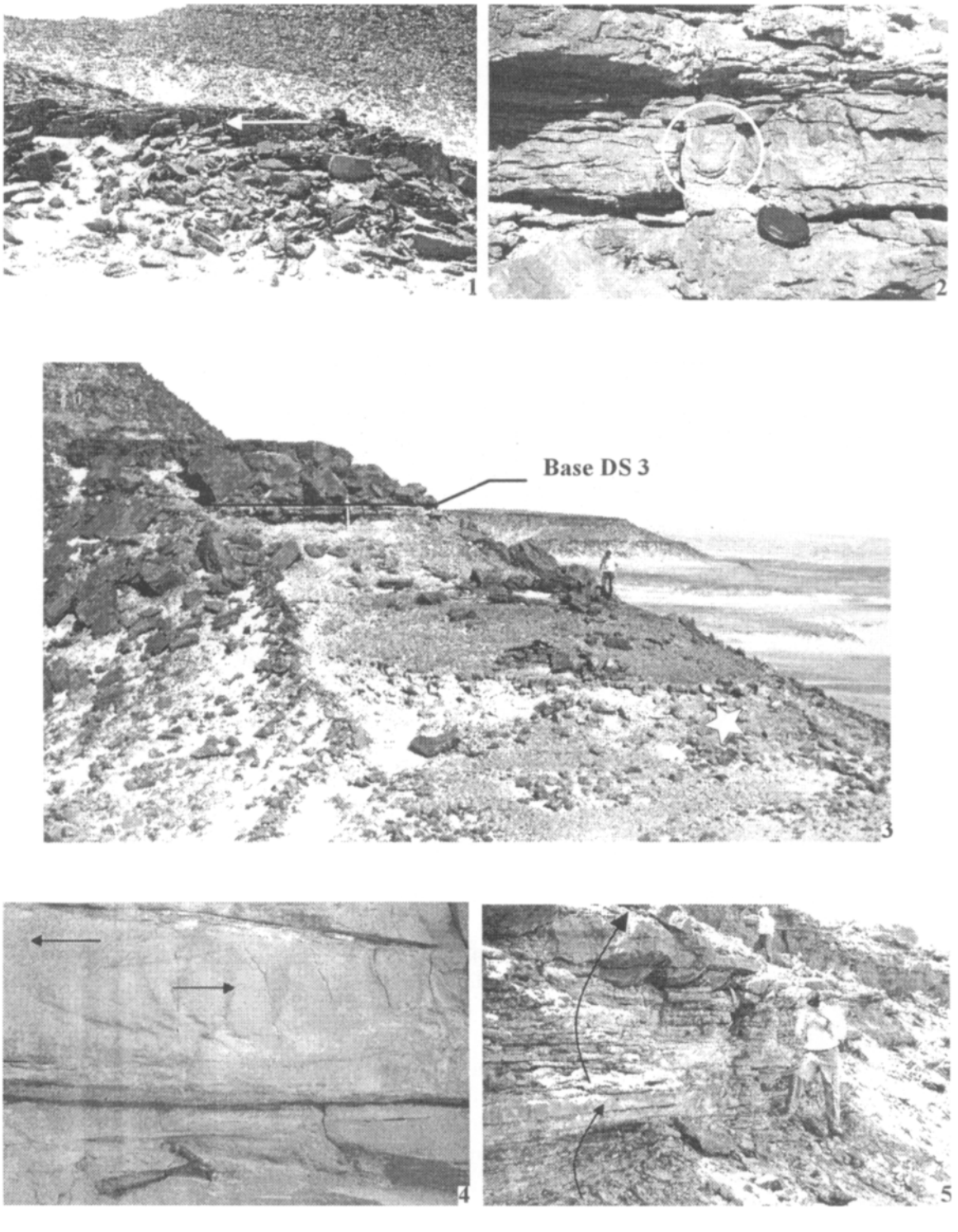

Plate 2.

cross-bedded sandstones showing an overall fining upward development, with some bioturbation uppermost. A unidirectional palaeocurrent pattern has been measured (N 330°) in this locality. In this case, the equivocal interpretation of such sandstones as an incised valley filled either during the lowstand or the transgressive phase is similar to the problematic development previously discussed in DS-3. However, according to our correlation, the uppermost Idri Formation exposed along Wadi Tarut (X3 on Fig. 4), which is clearly tidally dominated with bimodal palaeocurrent patterns (Plate 2, fig. 4), strongly supports the interpretation of this horizon as a transgressive sandstone unit deposited in an estuarine environment. In such an environment, lateral separation of ebb and flood channels is common, probably explaining the apparent unidirectional current pattern in any single place (Allen, 1972; Fenies and Tastet, 1998).

The upper part of this transgressive systems tract also occurs in the type section of the Quttah Formation further to the southwest (X16 on Fig. 4) where it also is assigned to the Idri Formation. The base of the succession there is slightly more diversified than in X5. A basal cross-stratified sandstone unit is overlain by fine-grained sandstones with wave ripples and cross-stratification, which appear to represent a retrograding facies sequence. The main flooding surface is marked by a heavily bioturbated and condensed interval with typical *Bifungites fezzanensis* ichnofacies.

The highstand part of this succession belongs to the lower part of the Quttah Formation. In both sections X3 and X16 (Fig. 4) this systems tract is less than 10 metres thick and includes thin storm-graded beds with wave ripples interbedded with siltstones. This development is well exposed in Wadi Tarut where small-scale facies sequences (Plate 2, fig. 5) include storm-deposited beds with many reworked calcareous bivalves.

Compared to the other sequences already described, it is difficult to define a sedimentological trend because the two sections where depositional sequence 4 has been reviewed are relatively close to each other (X 3 and X 16) and display the same type of facies.

Depositional Sequence 5 (Frasnian)

This depositional sequence has been studied in two areas:

- On the transect along Wadi Tarut terminating with outcrops near Tarut village, constituting part of the X3 composite section,
- In the type locality of the Quttah Formation (X16), about 4 km to the SW of X3 (Fig. 4).

In Wadi Tarut the transgressive systems tract of this sequence is 11 m thick, and represents a sandy development of the Quttah Formation. This TST overlies a polygenic breccia that could be subaerial scree and may record the subaerial phase coeval to the seaward development of the lowstand. This basal unit is then overlain by cross-stratified coarse-grained sandstones, including beds with climbing ripples, in turn overlain by hummocky cross-stratification passing upward into small-scale superimposed megaripples. The top of the sandy unit consists of well sorted and clean coarse-grained sandstone that may possibly represent a horizon with a wide and semi-regional development. This transgressive unit is interpreted as a littoral complex with tidal inlets incised into the shoreface and beach.

The upper part of the section has been measured immediately to the north of Tarut village, and there is some uncertainty regarding the vertical continuity of this sequence. In particular, a possible ravinement surface may account for the erosion of the apparently missing HST of this sequence. Alternatively, this HST may correspond to the lowermost shale beds of the covered Dabdab Formation, which is very thin in this area.

Most of the Quttah Formation type section (locality X16 in Fig. 4) is also sand-rich. An erosional surface at its base deeply incises the underlying siltstones that correspond to the HST

of DS-4. This surface is a sequence boundary and the overlying sandy unit is therefore interpreted as a valley fill complex probably deposited during the transgression. The 15 m thick preserved transgressive unit includes a basal pebble lag passing upward into shoreface fine-grained sandstones with hummocky cross-stratification and topped by a coarser sandstone unit showing tidal influence (currents oriented to N140°, probably in tidal channels). This sandstone is overlain by a thin shale that in turn is covered by a uniform and thin coarse-grained sandstone passing upward into tidally influenced medium-grained sandstones (currents oriented to N250°). Finally, the section terminates with a white and very clean sandstone containing bivalves. This uppermost sandy unit displays low angle parallel laminations and swaley cross-stratification.

All the sedimentary features identified in DS–5 indicate a littoral environment. The uppermost sandy unit in outcrop X16 may possibly be correlated to the upper part of the DS-5 TST in the Wadi Tarut section (X3, see above). Some tidal influence is noted in the TST of both localities. The bidirectional current patterns in sequence DS–5 are generally similar to those in underlying DS-4, indicating the persistence of similar physiographic conditions.

The next two depositional sequences are best exposed in the eastern part of the area. They have been studied to the east of Brak, near to the type localities of the Dabdab and Tarut formations, along a transect in Wadi Dabdab (X2 composite section, Fig. 4).

Depositional Sequence 6 (Frasnian)

The sequence in Wadi Dabdab starts with the uppermost part of the Quttah Formation represented by pale grey, highly weathered medium-grained cross-stratified sandstones possibly representing the HST of DS-5 not observed in sections X3 and X16 (Fig. 4).

The transgressive systems tract of depositional sequence DS-6 is about 10 m thick and generally corresponds to the oolite-rich Dabdab Formation. However, the basal first stage of the transgression is represented by a siliciclastic parasequence which consists of intensely bioturbated fine-grained sandstones with wave ripples and hummocky cross-stratification. All features indicate a storm- and wave-dominated system. Most of the TST consists of superimposed parasequences with iron-rich horizons. An ironstone bed with abundant vertical burrows (*Tigillites*) on top of this TST corresponds to the ore-bearing member 'L' of the French Study Group cited in Seidl and Röhlich (1984). This intensively bioturbated bed could represent a condensed interval. Iron enrichment may be related to syndepositional condensation or it could reflect post-depositional weathering preferentially affecting specific beds. A silcrete horizon of subaerial origin on top on the ironstone at the maximum flooding surface could indicate secondary weathering rather than primary condensation. The 7 m thick highstand systems tract of this sequence is claystone-rich, but some thin and fine-grained sandy interbeds show wave and storm-generated sedimentary structures. Among these sandy beds, in the upper part of this HST, there is an unusual limestone bed referred to as the 'Bivalve key bed' by Seidl and Röhlich (1984). This bed, in the HST of depositional sequence DS-6, represents the base of the Tarut Formation.

Depositional Sequence 7 (Frasnian)

This sequence corresponds to the upper and main part of the Tarut Formation exposed in sections X2 and X3 (Fig. 4). In section X2, the transgressive systems tract is only 2 m thick and is marked by a transgressive lag composed of pebbly sandstones and conglomerates, interpreted as a beach lag characterising the ravinement surface. It is overlain by two superimposed isolated trends of sandy megaripples that could correspond, in the absence of tidal features, to possible lunate megaripples typical of a high-energy shoreface setting (Clifton et al., 1971).

Because of poor exposure, the maximum flooding surface can only be inferred to occur somewhere within an 8 m thick grey marl interval overlying this TST, (Plate 3, fig. 3). However these grey marls represent the deepest facies observed in the whole Gargaf area. The occurrence of a slumped horizon immediately below the first sandstones and the total lack of sedimentary structures suggest that these marls were probably deposited below storm wave base in an outer shelf setting. They are therefore thought to represent a marked transgressive event during the late Frasnian. This mfs is better expressed in section X4 at the base of the cliff (Plate 4, fig. 1). This event could represent the local expression of a global transgressive event occurring just before the Frasnian/Famennian boundary and commonly leading to black shale deposition (Johnson et al., 1985). The lower part of the prograding highstand systems tract again consists of storm-dominated parasequences grading from shales to bioturbated shoreface sandstones. The upper part of the highstand, immediately below the Quaternary unconformity, includes three oolitic ironstone beds that terminate the depositional sequence in the X2 outcrop (Fig. 4). The same problem as previously discussed for depositional sequence 6 arises, but in this particular case the haematitic concentration just below the unconformity suggests a secondary origin.

The lithofacies of the upper part of the highstand systems tract seem to have a regional extent, because three iron rich parasequences made up of bioturbated sandstones occur 70 km to the west in the Tarut section X3 (Fig. 4; Plate 3, fig. 2). There, the Tarut Formation is 30 m thick, but it is erosively overlain by the Quaternary, so that the uppermost beds are not preserved. As in section X2 the mfs occurs within a pale marly horizon. The TST, which was quite thin in section 2, is thicker and shows a deepening upward facies succession (Plate 3, fig. 1) with a *Skolithos* ichnofacies association. The whole sequence is also well exposed at the base of the cliffline east of Tarut (Plate 4, fig. 1.)

The next two depositional sequences, which belong to the Ashkidah Formation, have been studied in a hill about 1 km to the east of Tarut village and in an outcrop close to the village of Al Qardah, along the main road.

Depositional Sequence 8 (Famennian)

Because of Quaternary erosion, the transition from sequence 7 to DS-8 is not exposed in the two localities X2 and X3. This transition is best observed to the east of Tarut village in section X4, where the Ashkidah Formation is exposed.

The section starts with units that are equivalent to the underlying DS-7 and finishes uppermost with a series of coarsening-upward sandstones topped by ironstone beds showing strong bioturbation characterised by *Tigillites* (*Skolithos* ichnofacies association), indicating a very shallow, shoreface setting. The Ashkidah Formation then unconformably overlies these ironstones. The boundary between the Tarut Formation and the overlying Ashkidah Formation is marked by a pronounced angular unconformity (Plate 3, fig. 5). This is interpreted as a sequence boundary enhanced by tectonic movements possibly related to the pre-Hercynian Acadian phase. In addition, this major unconformity more or less coincides with the Frasnian/Famennian boundary – where several authors have suggested short lived and high amplitude sea level variations related to a glacial event (Johnson, 1974; Caputo and Crowell, 1985). In this locality, the Ashkidah Formation is subdivided into two depositional sequences, each with an approximate thickness of 15 m. The transgressive systems tract of the first depositional sequence (DS-8) is only 1 m thick and includes a pebble lag overlain by medium-grained sandstones with planar to low angle cross-stratification, indicating deposition in a foreshore setting. This grades upwards into wave-rippled sandstones deposited in an upper shoreface regime (Plate 3, fig. 4). The pebble lag represents the transgressive ravinement surface and the beach residues. The regressive highstand systems tract of this sequence consists of thin storm-graded sandy beds and

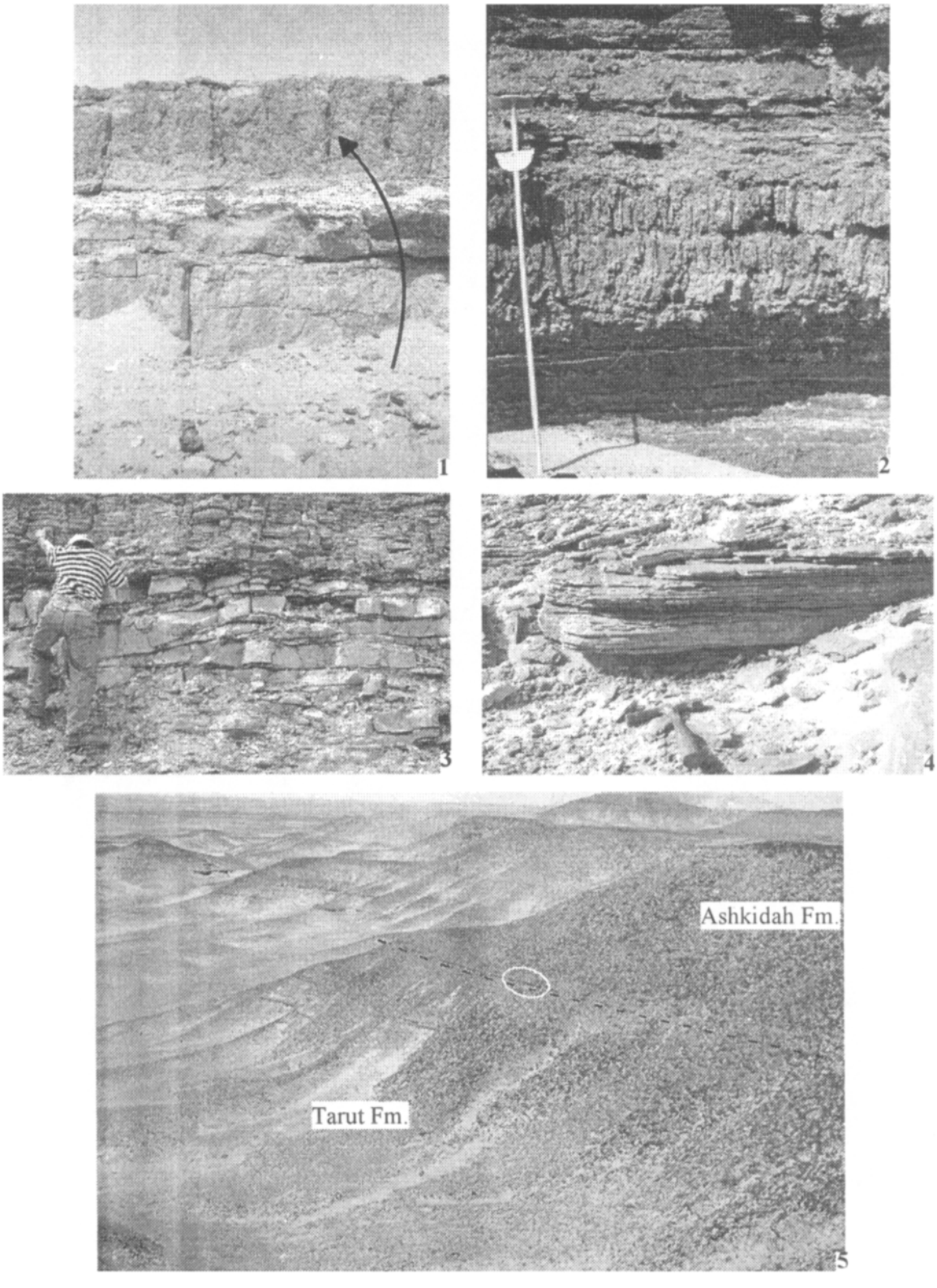

Plate 3.

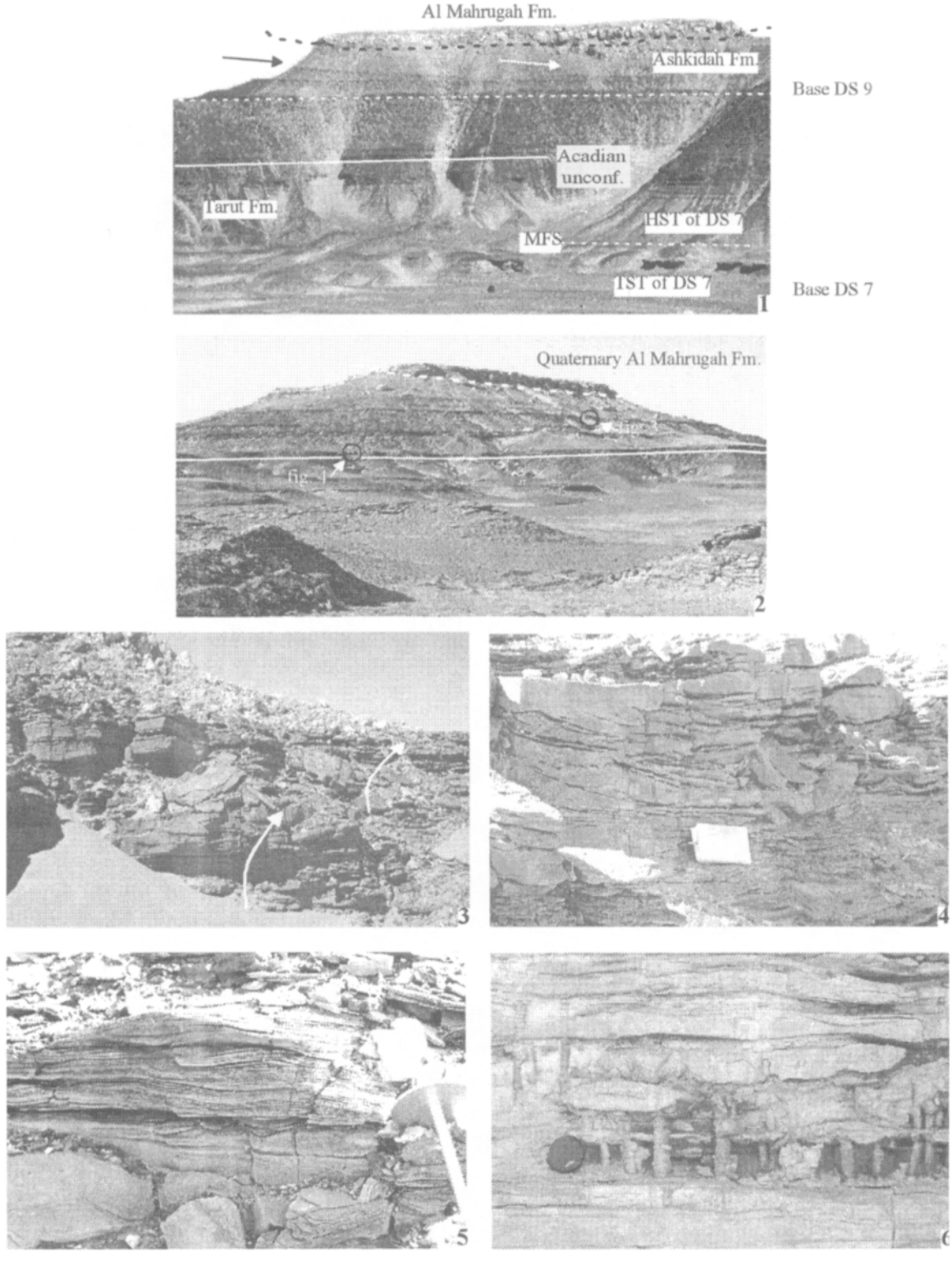
Al Mahrugah Fm.
Ashkidah Fm.
Base DS 9
Acadian unconf.
Tarut Fm.
HST of DS 7
MFS
TST of DS 7
Base DS 7
1
Quaternary Al Mahrugah Fm.
fig. 1
2
3
4
5
6

Plate 4.

wave-rippled horizons with siltstones deposited in an inner shelf environment. These grade upward into coarser sandstones showing wave ripples and hummocky cross-stratification, suggesting deposition in a shoreface setting. Storm-dominated deposits in this sequence have been previously described by Carneiro et al. (1991).

Thirteen kilometres to the east of this outcrop, and near to Al Qardah village, a hillock along the main road (X17 in Fig. 4) shows a particularly good exposure of the upper Ashkidah Formation (Plate 4, fig. 2). The base of the section is covered by scree and the exposure starts with a 5 m thick sandstone unit showing rhythmic beds that may be interpreted as the bottomsets of large-scale tidal bars. This basal part of the section is tentatively interpreted as the TST of DS-8. This indicates that a depositional change occurred within the transgressive systems tract of DS-8, which is littoral and wave-dominated in section X4, and eastwards evolves into a shelf tidal environment in section X17. The highstand is wave and storm-dominated in both localities, but in X17 it appears slightly more distal than in X4 as it comprises siltstones with thin sandy interbeds showing only distal storm-graded features.

Depositional Sequence 9 (Famennian)

In the hill to the east of Tarut (X4), DS-9 – which is only 15 m thick – and its large-scale geometrical relationships can be analysed. The sequence includes a thin TST characterised by a basal transgressive beach facies overlain by a one-metre thick shelf parasequence. The particularly well-exposed overlying HST defines a prograding series with a marked downlap surface. This relationship is clear in the landscape (Plate 4, fig. 1) and major clinoforms consist of covered shales with interbedded thin sandstones showing hummocky cross-stratification. The entire development is interpreted as a storm-dominated ramp. Finally the Quaternary Al-Mahruqah Formation, made up of continental conglomerates and lacustrine deposits (Thiedig et al., 2000), unconformably overlie the Devonian Ashkidah Formation at this locality.

Along strike near Al Qardah village (X17), the same depositional sequence is also well exposed, permitting a detailed facies analysis (Plate 4, fig. 2). The sequence boundary is defined by a sharp contact between distal shelf shales of underlying DS-8 and a metre-thick sand unit belonging to the transgressive systems tract of DS-9. This transgressive systems tract is of particular interest, because it is clearly subdivided into two units separated by a wave ravinement surface with a pebble lag. A tidal dominated channel at the base with tidal bundles and subtidal couplets (Plate 4, fig. 4) is overlain by a shoreface sandstone unit with hummocky cross-stratification.

The highstand systems tract is at least 28 m thick, and consists of numerous small scale and well-defined parasequences (Pl. 4, fig. 3). Their bases usually consist of shales interbedded with thin wave-rippled sandstones containing vertical burrows (*Tigillites-Skolithos* type, Plate 4, fig. 6) and these grade upwards into medium-grained sandstones showing either hummocky (HCS: Plate 4, fig. 5) or swaley cross-stratification and low angle parallel cross-lamination.

These sedimentary structures, together with the *Skolithos* ichnofacies association, are typical of a shallow storm and wave-dominated system, ranging from inner shelf to beach environments. Recurrent examples of *Tigillites* truncated by wave-rippled beds (Plate 4, fig. 6) or by HCS, suggest episodic sedimentation characterised by a succession of high energy events with intervening quiet periods during which marine fauna reworked the sandstones.

The Ashkidah Formation is truncated by an unconformity and directly overlain by the Quaternary Al Mahruqah Formation.

DISCUSSION

Sedimentology and Depositional Environment

Detailed facies analyses of the Devonian to lowermost Carboniferous formations show a greater variability of depositional environments than previously suggested (c.f. Parizek et al., 1984; Massa, 1988). Important facies changes suggest the evolution of the general depositional environment within the same depositional sequence. Consequently, major sedimentary system changes can be recognised within a given formation. For example, local fluvially dominated series interbedded with distal shelf shales have been described in the Idri Formation. Such a change in facies is associated with relative sea-level variations and the resultant fluvial systems may either correspond to a braided stream environment in an incised valley or they may represent more sinuous (meandering?) systems, as is the case at the base of sequence DS-3.

The storm dominated facies described by Carneiro et al. (1991), and Pierobon (1991) are, in fact, present in every depositional sequence. They never represent a really distal setting, because they are commonly associated with lower shoreface wave ripples and also occur in the upper parts of regressive intervals containing beach laminations. The shallow water depth is also indirectly confirmed by the thicknesses of the two different prograding littoral complexes (DS–1 and DS-9) – both approximately 20 m thick, as shown by the size of their low angle clinoforms.

Tidal dominated systems are described herein for the first time in the Gargaf area. They are particularly well-defined at the bases of sequences DS-1, DS-2, DS-4 and DS-8. They show a relatively great variability of setting within every sequence – for instance in the basal B'ir al Qasr and the lower Ashkidah formations they are interpreted as shelf tidal bar complexes. Similar sand-wave complexes have often been described in a transgressive context (Nio, 1976), or in transgressive systems tracts (Rubino et al., 1994). Other tidal systems such as estuarine complexes or smaller scale tidal inlets, occur within sequences DS-2 (upper B'ir al Qasr Formation), and DS-4 (top Idri Formation).

We should note that most of these middle Devonian to lower Carboniferous depositional sequences are characterised by tidally dominated facies during their transgressive systems tracts, whilst the highstand systems tracts are storm and wave-dominated. Such sedimentological differences have been noted in many other settings and seem often to be related to changes in shelf physiography in response to sea level variations. During the early stage of transgression, pre-existing basin topography controlled the distribution of the tidally dominated systems. These were best developed in the incised valleys transformed into estuarine complexes by the sea level rise, or in confined settings where tidal currents were funnelled and enhanced by resonance. Later, as the sea transgressed landwards to reach a maximum, the basin became wider and wave and storm processes predominated. This occurred together with the onset of coastal progradation, which produced a more regular coastline.

In some cases, no tidal influence has been noted within the TST, as e.g. in sequences DS-6, DS-7 and DS-9, and storm-dominated systems are found immediately above the sequence boundary. This could suggest that those particular transgressions occurred in an interfluve setting or that the basin physiography had not been significantly modified during the preceding lowstand period by fluvial processes. It is also interesting to note that such cases coincide with an extreme reduction of the thickness of the transgressive systems tract and are probably linked to a marked landward shift of the coastal onlap over a flat-lying area.

Gargaf Devonian Depositional Sequences and Eustatic Fluctuations

The six Devonian formations outcropping in the Wadi ash Shati area have been subdivided into nine depositional sequences and a synthetic composite vertical succession is illustrated in

Fig. 5. The overall thickness of these individual depositional sequences amounts to about 200 m, grouped into two larger second order transgressive-regressive cycles each about 100 m thick.

The first cycle includes DS-1 to DS-5 – viz. the B'ir al Qasr, Idri and Quttah formations – and is mainly middle Devonian in age. The second cycle, comprising 4 depositional sequences from DS-6 to DS-9, corresponds to the Dabdab, Tarut and Ashkidah formations and is essentially late Devonian. Each individual depositional sequence in both cycles shows varying thicknesses. Upwards in the succession individual transgressive systems tracts tend to thicken, while their regressive parts become thinner. Taking into account that no drastic changes in depositional environment occur, this is most likely related to a variation of accommodation space in connection with eustatic variation or with tectonic subsidence.

Except for sequence DS-8, which has a tectonically enhanced base, there seems to be only limited local tectonic control on facies distributions and variations in subsidence. Consequently, as a working hypothesis, it is assumed that eustasy is the main driving force controlling the deposition of the sequences identified in the Gargaf area.

In order to validate this hypothesis these Gondwanan depositional sequences should be compared to the global transgressive-regressive cycles and the relative coastal onlap curve proposed by Johnson et al. (1985). These authors subdivided the Devonian System of Euramerica into depophases I and II, each of these consisting of six transgressive-regressive cycles, respectively labelled 'a' to 'f' from bottom to top (Pragian to Famennian). However, Dennison (1985), and Ross and Ross (1988) added two more cycles in the Lower Devonian starting in the Lochkovian to basal Pragian. Each transgressive-regressive cycle corresponds to rocks deposited between two successive deepening events, and sedimentologically the cycle boundaries then coincide with main flooding surfaces. That is to say that there is an interdigitation between depositional sequences and the Johnson et al. cycles. Moreover, transgressive-regressive cycles often begin within stages and straddle stage boundaries.

Uncertainties on the Ages of the Depositional Sequences

To achieve the necessary refined correlations, a more precise dating of the depositional sequences defined in the Wadi ash Shati area is required. However the very shallow depositional setting and the relative faunal paucity of the studied formations preclude a direct comparison between the ages published and those obtained from the high-resolution conodont zonation used elsewhere. Although some horizons in the Devonian formations of Wadi ash Shati are relatively well dated, the precise relationship between these datings and the depositional sequences defined in this paper are uncertain. For instance, the upper part of the Ashkidah Formation is dated to the basal Carboniferous (Tournaisian) and may possibly correspond to the upper part of DS-9, while the argillaceous lower part of the Quttah Formation is Frasnian and may in part correspond to DS-4; it also appears that the Givetian age assigned to the Idri Formation covers DS-2, 3 and 4.

The tentative correlation proposed herein is therefore primarily based on sedimentological analyses and on the sequence-stacking pattern, while it also integrates the few published datings in an overall time frame. This leads to a possible shift of the cycles relative to the depositional sequences, and this is illustrated by the two subcolumns on the right-hand side of Fig. 5, the first one representing a possible best fit with the sedimentological criteria, and the second a suggested best fit with the biostratigraphic data available at present.

As discussed in the introduction, the Lower Devonian is not preserved in the southern Gargaf area, and this succession has not yet been interpreted in terms of sequence stratigraphy elsewhere in Libya. This succession has long been interpreted as a single stratigraphic cycle

(Massa, 1988), and can be compared with the second order transgressive – regressive cycle already identified on the Arabian plate by Razin et al. (1993). Our tentative correlation of the Middle to Upper Devonian series is based on the identification of a major deepening event termed the Taghanic onlap in Euramerica that occurs during the Givetian and separates depophases I and II of Johnson et al. (1985).

Tentative Correlation of the Upper Depositional Sequences

The Taghanic major onlap corresponds to the transition between cycle 'If' and 'IIa' of Johnson et al. (1985). Cycle If was characterised by these workers as containing an upper regressive unit: "the regression was great enough to offlap some cratonic areas" and this series contains the "highest near-shore rocks below the Famennian." The overlying IIa cycle has "the appearance

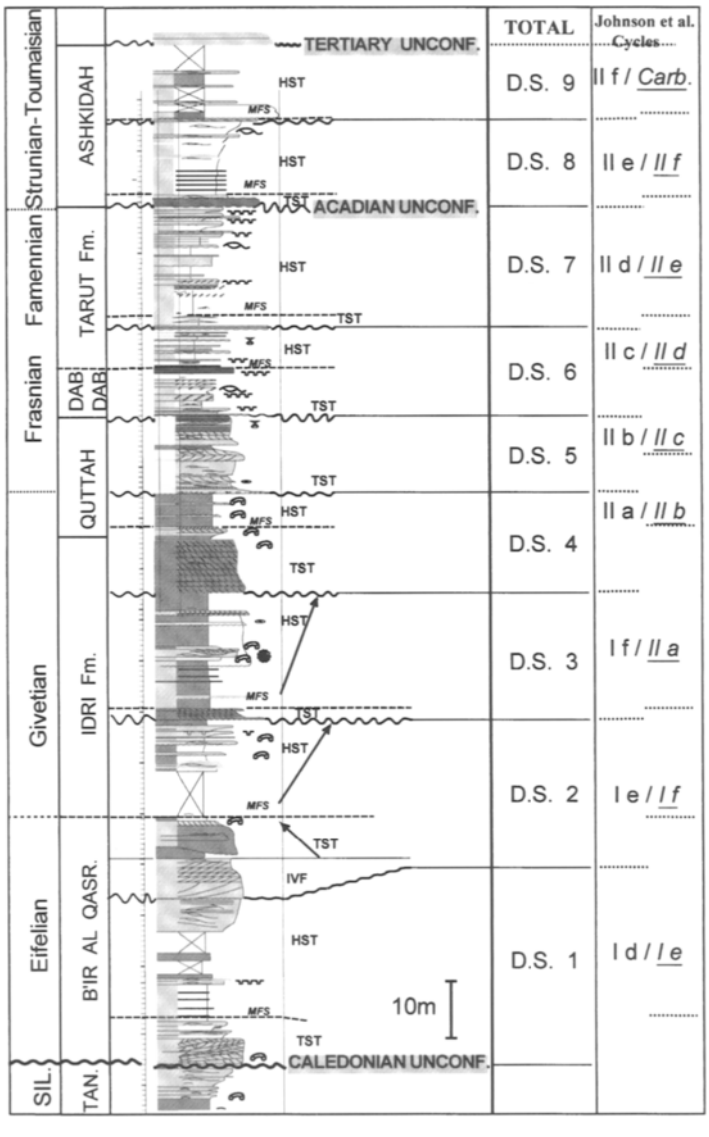

Figure 5. South Gargaf Uplift. Devonian-Lower Carboniferous composite section: depositional sequences and correlation to cycles of Johnson et al. (1985). By sedimentology/by biostratigraphy.

of a long sustained transgression." Sedimentologically, such characteristics fit well with the transition from the HST of DS-3, the facies of which we have interpreted as being the most proximal setting of the Devonian (see above), to the TST of DS-4, which is the thickest clastic transgressive tract (15 m) seen to date in the Gargaf area.

If ages are taken into consideration, the first Frasnian dated series corresponds to the lower argillaceous part of the Quttah Formation that contains the mfs and HST of DS-4. In this case, DS-4 correlates well with cycle 'IIb' of Johnson et al., (1985).

The overlying two cycles of Johnson et al. (1985), that is IIb and IIc, are characterised by a relatively continuous deepening event, and find their respective equivalents in DS-5 and DS-6, which have similar thicknesses.

Cycle IId corresponds to the 'greatest Devonian transgression' and sedimentologically correlates well with DS-7, which is characterised by a thin TST (2 m), and the thick grey marls in the HST are herein interpreted as representing the deepest facies seen to date in the southern Gargaf area. According to the accurate conodont zonation on which Johnson et al. (1985) based their cycles, the Frasnian/Famennian boundary would then occur within depositional sequence DS-7, i.e. within the Tarut Formation, and this fits with published datings.

However, if the biostratigraphic data are considered, and following the proposed correlation between DS-4 and IIb, sequence DS-7 should logically be purely Famennian in age and should therefore correspond to cycle IIe. On the other hand, cycle IId in fact comprises two successive deepening events of unusual magnitude and an alternative solution is that this corresponds to DS-6 and DS-7, that is the whole Dabdab and the base of the Tarut Formation.

The overlying composite cycles IIe and IIf show a rapid deepening event followed by an overall long and prominent regression, which sedimentologically fit with DS-8 and DS-9 respectively. However, if the unequivocal Tournaisian faunas identified in the upper part of the Ashkidah Formation fall in the upper part of DS-9, then this depositional sequence clearly belongs to the Carboniferous.

Thus although there are still some apparent discrepancies, this upper part of the Devonian succession apparently fits well with the cycles of Johnson et al. (1985). It is then necessary to review the basal transition towards the Ouan Kasa and Tadrart formations that are not represented in the southern Gargaf area.

The Middle to Lower Devonian Transition

In descending order, cycles Ie and Id of Johnson et al. (1985) should correspond to depositional sequences DS-2 and DS-1 respectively. One of the characteristics of cycle Id is that it is "the most distinct deepening event of the pre-Taghanic major coastal onlap," that is prior to cycle IIa. This corresponds well with the first widespread marine transgression of the Gargaf Uplift and is represented by the B'ir Al Qasr Formation. This interpretation implies that the B'ir Al Qasr Formation is intra-Eifelian and this appears to agree with published datings. Moreover, and according to the correlation suggested herein with the cycles of Johnson et al. (op cit.), at least one depositional sequence (Ic) is missing between the Ouan Kasa Formation (which is dated as upper Emsian and therefore correlated to cycle Ib) and the B'ir Al Qasr Formation. Finally, the Tadrart Formation would correspond to cycle Ia dated as Pragian, while the earliest Devonian (Lochkovian) will only been represented in the deepest parts of the Ghadames Basin.

The above discussion indicates that although the depositional sequences identified in Gargaf appear to match the supposedly global eustatic cycles proposed by Johnson et al. (1985), the absence of a more precise stratigraphy makes these relationships hypothetical at the present time. This underlines the need to refine the biostratigraphic framework of the Wadi ash Shati area and to integrate with subsurface data in Libyan basinal areas to eventually establish a

coherent sequence stratigraphic framework more easily correlatable with possible worldwide Devonian cycles.

CORRELATION OF DEPOSITIONAL SEQUENCES WITH SUBSURFACE DATA

In this section, a comparison is presented between the Devonian to Lower Carboniferous depositional sequences identified in the Gargaf area and relatively close-lying subsurface data. Well D1–66 (Fig. 6) is located approximately 250 km to the northwest of Wadi ash Shati in the Ghadames Basin and this well's Devonian succession has already been discussed by Massa (1988). The comparison is based on the combined use of the stratigraphic nomenclature of Massa (1988) and the well logs analysed in terms of stacking patterns following the Exxon approach (c.f. Van Wagoner et al., 1988).

Firstly, the Devonian-Lower Carboniferous succession in the Ghadames Basin is twice as thick as that in the Wadi ash Shati area. This thickening primarily results from the differing developments of the Lower Devonian Tadrart and Ouan Kasa formations, but also from the occurrence of aggrading lowstand wedges at the bases of DS-3, 6, and 7. Surprisingly, these three lowstand systems tracts are apparently not coeval with the outcrop occurrences of the incised valley fills developed at the bases of DS-2, 4 and 5. This means either that the shelfal erosion related to these lowstand wedges in the Ghadames Basin did not reach the southern Gargaf area or that the Wadi ash Shati outcrops are all located in an interfluve setting. In the first case this would imply that DS–3 corresponds to an important drop in sea level and indirectly corroborates the present correlation of this depositional sequence with cycle If of Johnson et al. (1985) (see above). Following the same logic a similar interpretation of DS-6 and DS-7 again fits well with the proposed correlation of these depositional sequences with cycles IIe and IIf of Johnson et al. (1985).

Secondly, the succession in well D1–66 can be subdivided into three second-order transgressive-regressive cycles. The first, as already recognised by Massa (1988), includes the Lower Devonian Tadrart and Ouan Kasa formations that are missing in the southern Wadi ash Shati outcrops. In common with the outcrops, the second cycle includes DS-1 to 5 plus the base of DS-6 (that is the regressive lowstand), and corresponds to Aouinet Ouenine units I, II and III of Bellini and Massa (1980). The third cycle comprising DS-6, 7, 8 and 9 corresponds to Aouinet Ouenine IV and the Tahara Formation.

Differences and Similarities

Middle Devonian depositional sequences 1 and 2 show marked similarities in outcrop and the subsurface, both with a well-developed transgressive systems tract at their bases (Fig. 6).

In well D1–66, depositional sequence 3 shows a 30 m thick lowstand wedge (LSW), whilst in the upper part of this sequence it is not easy to distinguish the TST from the HST. The overlying depositional sequence 4 is characterised in the well by a thin development essentially represented by the HST and by a marked maximum flooding surface which fits very well with the condensed section identified at the base of the Quttah Formation in its Wadi ash Shati type section. This would also support our correlation of this depositional sequence with cycle IIa, which Johnson et al. (1985) characterised by major coastal onlap.

Depositional sequence 5 shows the biggest difference in thickness between outcrop and subsurface: it is the thickest subsurface sequence and the thinnest in the outcrops. In outcrop only the TST seems to be preserved, while in the well the TST is very thin and the HST is about

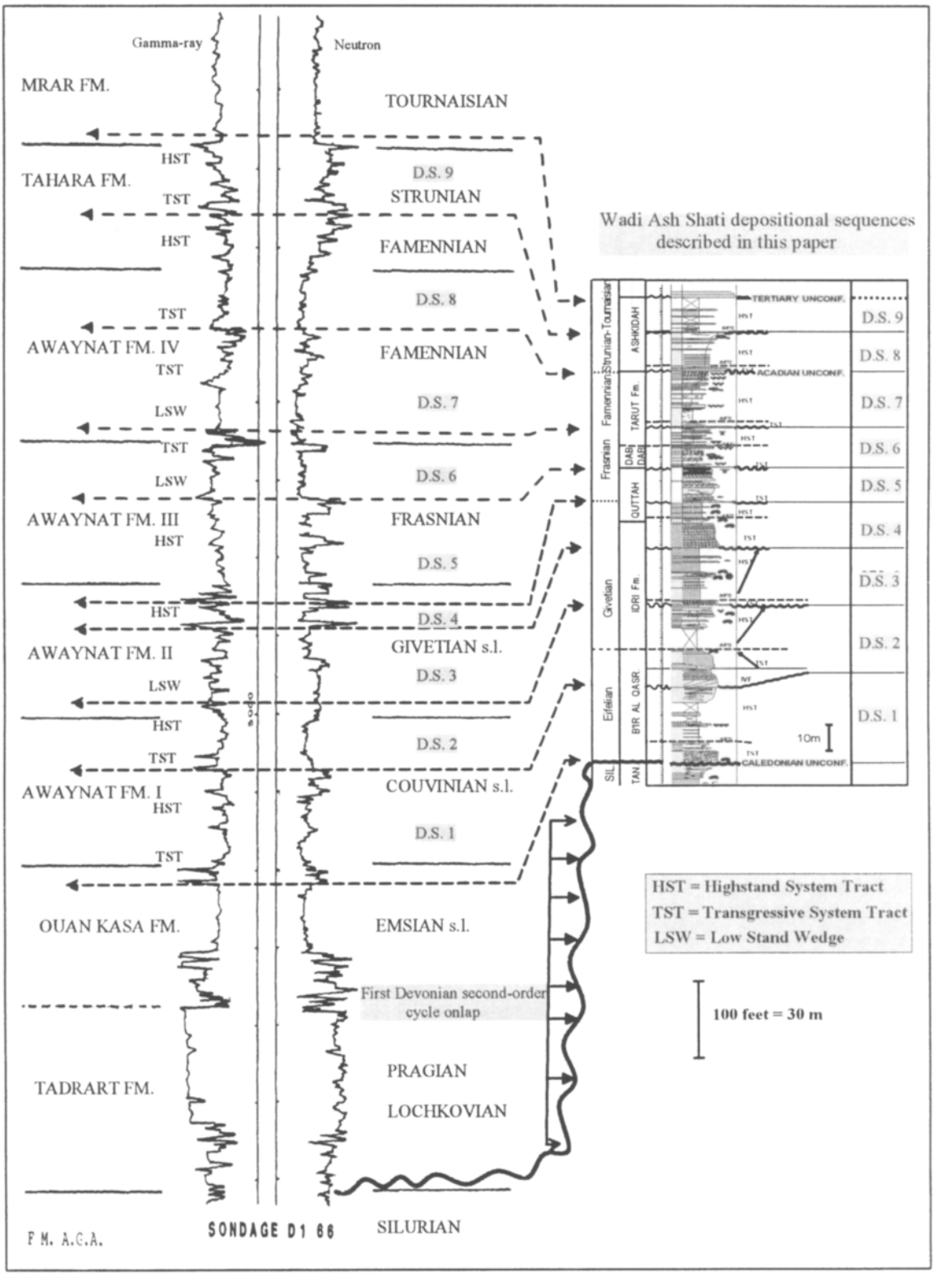

Figure 6. Tentative correlation between the Wadi ash Shati depositional sequences and well D1–66 in the Ghadames Basin (stratigraphy and formation names in the well after Massa, 1988).

50 m thick. This represents a continuous transgressive event and once more fits with cycle IIb of Johnson et al. (1985).

The subsurface development of depositional sequence 6, as mentioned above, includes a thick LSW. This is overlain by a thin TST, on top of which a Frasnian high gamma-ray peak occurs (equivalent to the Cues Limestone horizon of Elzaroug and Lashhab, 1998), indicating a major flooding surface probably correlative to the top of the Dabdab Formation.

Depositional sequence 7 in the well starts with an aggrading lowstand wedge: the marked GR shift towards the left which occurs at the top of this LSW sequence may suggest the development of a ravinement surface at the base of the TST. It is difficult to differentiate between the TST and the HST in the upper part of the sequence in the absence of any core control or of a more regional approach. This difficulty could be related to the influence of the Acadian unconformity, which cannot be identified without a dipmeter analysis.

Finally, sequences 8 and 9, both assigned to the Ashkidah Formation in outcrop and to Aouinet Ouenine IV and the Tahara Formation in the well, are significantly different in the sense that in subsurface both have a well-defined TST, whilst in outcrop the sequence boundary more or less coincides with the maximum flooding surface.

This tentative sequence stratigraphic correlation of the Devonian to lower Carboniferous formations in the outcrops of Wadi ash Shati with well D1–66 in the Ghadames Basin demonstrates an overall pattern which, if applied on a regional basis, may help build a reliable sequence stratigraphy framework – hopefully leading to a better understanding of the geological evolution of the entire area.

Palaeogeographic Implications

Palaeocurrent patterns measured in Cambro-Ordovician exposures from many places in the Murzuq Basin indicate an overall northwestward direction of sediment transport across the entire Gargaf area, suggesting that it did not then act as a topographic high. On the contrary, and particularly during the early Devonian following the Caledonian tectonic phase, the Gargaf area was a positive feature and served as a source of clastic supply. This is indicated by the absence of Lower Devonian strata in the southern part of the Gargaf area, while they do occur in the western corner of Gargaf in the Awaynat Wanin area. In this latter region, the palaeocurrents measured in the Lower Devonian Tadrart fluvial sandstones, are directed to the NW, (Clark-Lowes, 1985), suggesting derivation from emergent areas to the SE.

From the middle Devonian to the earliest Carboniferous, continental encroachment increased markedly, at least on the southern flanks of the Gargaf Uplift. However, the littoral complexes in the highstand systems tracts of DS-1, DS-8 and DS-9 were clearly prograding towards the south. This implies that part of the Gargaf area to the north of Wadi ash Shati was not entirely flooded and formed an island able to provide clastics towards the south. In the other depositional sequences the pattern is less pronounced, but the regular occurrence of fluvial sandstones infilling incised valleys, as well as the development of estuarine complexes, also suggests the potential development of a larger land area during lowstand phases. At these times reworking of Lower Palaeozoic sandstones produced the coarse clastics seen in the Devonian succession. This hypothesis could be validated on a regional basis by integrating the palaeocurrent measurements of Karasek (1981) with supplementary work.

CONCLUSIONS

This sedimentological study of the Middle Devonian to Lower Carboniferous succession of Wadi ash Shati on the southern flanks of the Gargaf Uplift shows that sequence stratigraphy is

a useful complementary tool which increases our understanding of the area's established lithostratigraphical framework. Although the depositional sequences do not always coincide with formational boundaries, they may help to better understand vertical and lateral variations in depositional environments. More detailed work – including systematic sampling and integrated biostratigraphical analyses leading to a more thorough constraint on the ages of the depositional sequences – is needed to test the hypotheses presented herein. In addition, detailed mapping of these depositional sequences in the Wadi ash Shati area should be integrated with subsurface data to give a better understanding of the Devonian evolution of the Gargaf Uplift and the surrounding Murzuq and Ghadames basins. Although only based on a few selected outcrops, this study will hopefully provide a useful preliminary framework for future work.

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PLATE CAPTIONS

PLATE 1. B'ir Al Qasr type section (X 6). (p. 329)

1. Contact between the Silurian Tanezzuft Formation and the Middle Devonian B'ir Al Qasr Formation over the Caledonian unconformity (straight line). Depositional sequence 1 about 35 m thick (dashed line: maximum flooding surface, mfs). The top of the outcrop corresponds to base DS-2.
2. Prograding low-angle tidal bar constituting the TST of DS-1, and overlain by the HST of DS-1. Dashed line: mfs.
3. Wave ripples and horizontal burrows at the base of the shoreface parasequence. Binoculars circled for scale. Note the occurrence in plan view of *Diplocraterion* (double arrow).
4. Thickening up and coarsening up facies sequence with hummocky cross-stratification on top of the HST of DS-1. Jacobs staff is 1.5 m high for scale.
5. Landscape view showing the southwards directed low-angle progradation of the littoral complex during the late HST of DS-1 (arrow).

PLATE 2. (p. 331)

1. North of Barqan (X 5). Estuarine channel (incised valley fill) in the basal Idri Formation (arrow), DS-2.
2. North of Barqan (X 5). U-shaped burrows (*Diplocraterion*-type) in the wave-dominated facies of the regressive part of DS-2.
3. North of Barqan (X 5). General view showing the transition from small scale parasequences constituting the HST of DS-2 (star) to the basal fluvial (estuarine ?) sand of DS-3 (arrow).
4. Wadi Tarut (X 3). Topmost sand of the Idri Formation. Large-scale bidirectional cross-stratification of tidal origin in DS-4, interpreted as a transgressive estuarine complex.
5. Wadi Tarut (X 3). Metre-scale superimposed wave and storm-dominated parasequences in the upper part of the HST of DS-4.

PLATE 3. (p. 335)

1. Tarut village (X 3). Detail of the TST of DS-7 showing a deepening upwards facies succession with shoreface deposits at the base, grading into highly bioturbated condensed horizons (*Tigillites*).
2. Tarut village (X 3). Top of the HST of DS-7, with heavily bioturbated (*Tigillites* type burrows) shallow water iron-bearing facies (Jacobs' staff = 1.5 m).
3. Tarut type section (X 16). Outer shelf mudstones developed at the base of the prograding HST of DS-7.
4. East Tarut village (X 4). Basal transgressive beach and wave rippled shoreface

deposits unconformably overlying the Acadian unconformity: base of the Ashkidah Formation (DS-8).

5. East Tarut village (X 4). Angular unconformity (Acadian ?) between the Tarut Formation (DS-7) and the Ashkidah Formation (DS-8). The white oval shows the approximate location of the beach deposits of Plate 3, fig. 4.

PLATE 4. (p. 336)

1. East Tarut village (X 4). Low-angle clinoforms prograding southwards, representing the HST of DS-9 (arrows). The top of the Devonian succession is truncated by the Quaternary unconformity and overlain by the Al Mahruqah Formation. Note also the development of DS-7 and 8.
2. East of Al Qardah (X 17). General view of DS-9 (upper Ashkidah Formation) truncated by the Quaternary. DS-8 is poorly exposed in the foreground.
3. East of Al Qardah (X 17). Well-defined thickening upwards wave and storm-dominated parasequences in the HST of DS-9.
4. East of Al Qardah (X 17). Detail of the TST of DS-9 showing tidal bundles.
5. East of Al Qarqah (X 17). Hummocky cross-stratification in the upper Ashkidah Formation.
6. East of Al Qarqah (X 17). *Tigillites* horizons truncated by wave-rippled levels indicating episodic storm-dominated sedimentation.

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CHAPTER 16

Stratigraphy and hydrocarbon potential of the Lower Palaeozoic succession of License NC-115, Murzuq Basin, SW Libya

A. AZIZ[1]

ABSTRACT

The Murzuq Basin (Fezzan) is one of several intracratonic North African basins that has a predominantly marine Palaeozoic clastic infill, although with recurrent continental influence. The maximum depth to Precambrian basement reaches about 3500 m in the basin depocentre. The Palaeozoic succession is unconformably overlain by up to 1500 m of mainly Mesozoic continental deposits. Present-day tectonic elements delimiting the basin are the Tibesti-Haruj, the Tihemboka and the Gargaf uplifts on the eastern, western and northern flanks respectively, while to the south the basin narrows and terminates in the Djado sub-basin of northern Niger.

The geology displayed in the NC-115 license area is generally representative for the basin. Several wells have penetrated Precambrian and 'Infracambrian' units with varying kinds of greywacke. The eleven defined Palaeozoic formations are herein informally assigned to two groups: The *Lower Paleozoic group* with the Hasawnah (Cambrian), Hawaz (Lower to Middle Ordovician), Melaz-Shuqran (Caradoc) Mamuniyat (Ashgill) Tanezzuft (Llandovery) and Akakus (Wenlock to Ludlow). The *Upper Paleozoic group* comprises five formations, the 'Basal Devonian Sandstone' (BDS–Middle to lowermost Upper Devonian, Awaynat Wanin (Upper Devonian), Marar (Lower Carboniferous), Assedjefar (Upper Carboniferous) and Dembaba (Upper Carboniferous) formations. The Mesozoic is represented by continental deposits previously termed the 'Post-Tassilian' and 'Nubian' formations, but now assigned to the Zarzaitine and Taouratine formations respectively. These are directly overlain by Quaternary deposits.

The sandstones of the Mamuniyat Formation provide the primary reservoir, with the fluvial and shallow marine sandstones of the Hawaz Formation as a secondary target. The regressive deposits of the 'BDS' are also thought to have some reservoir potential in the central parts of the block. The lower part of the Tanezzuft Formation (the 'Hot Shale interval') is the main source rock. Stratigraphic changes appear to reflect regional tectonic events and changes in relative sea level. The main tectonic episodes affecting the study area have generally been assigned to the Caledonian, Hercynian and Alpine orogenies.

The main objective of this chapter is to describe the distribution and hydrocarbon potential of the lower Palaeozoic rocks, with an additional brief overview of the other formations deposited within NC-115.

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INTRODUCTION

Several hydrocarbon discoveries made over the last fifteen years have made the Murzuq Basin an attractive site for further hydrocarbon exploration. The NC-115 concession is located in the northwestern part of the basin (Fig. 1), with an area of about 25 000 km^2. Activity in this area has passed through three stages: in the first exploration phase from 1956 to 1980, 17 wells were drilled, with an oil discovery in B2–1 (Atshan) and hydrocarbon shows in several other wells. The second 'Rompetrol' phase from 1980 to 1992 resulted in wells drilled on twelve structures, with commercial discoveries in six of these (ROMPETROL, 1987). The third 'Repsol' phase, where kept only the central part of the block (Fig. 1), with an area about 5000 km^2 for development stage, which started in 1993, has been characterized by development of the three main fields discovered to date (A, B and H). A pipeline has now been constructed to Zawia port and production started in December 1997, giving infrastructure and support for further exploration activity.

The stratigraphic column ranges from the Precambrian to the Quaternary. Most Palaeozoic formations have a wide lateral distribution through the area. In this chapter the Palaeozoic deposits are informally placed in two groups: viz. the Lower Palaeozoic group (Cambrian-Silurian) with the Hasawnah, Hawaz, Melaz Shuqran, Mamuniyat, Tanezzuft and Akakus formations and the Upper Palaeozoic group (Devonian-Carboniferous) with the 'Basal Devonian sandstone' (BDS), Awaynat Wanin, Marar, Assedjefar and Dembaba formations.

The basin has been molded by many tectonic events, the main ones being related to the Caledonian (late Silurian–middle Devonian), Hercynian (end Carboniferous–Permian) and Alpine (early Tertiary) orogenies. Several burial history models have been constructed for selected wells in the license and surrounding area; these have been calibrated with the available data (well temperatures, vitrinite reflectance, spore color index and apatite fission tracks). The resultant burial diagrams indicate the main subsidence and uplift episodes, the estimated amount of missing sections and the timing of oil generation.

The general age of the whole succession has been established by earlier regional studies of the Murzuq Basin; Repsol and other license partners have refined these datings on the basis of several geological studies (Aziz, 1992; Herzog, 1997a, b), recently confirmed by palynological analyses. This work has resulted in some correlational changes: most notably strata previously believed to belong to the Silurian Akakus Formation have now been assigned to the Basal Devonian sandstone. Mesozoic units have also been redefined and parts of what were earlier thought of as representing the lower Quaternary succession are now assigned to the Taouratine Formation.

The main reservoir rock is provided by the Mamuniyat Formation, with overlying Tanezzuft Formation shale giving the cap rock. The main reservoir sandstones represent shoreface deposits with good reservoir quality. The secondary target is provided by the sandstones of the Hawaz Formation, which are important where the Mamuniyat Formation is thin or even totally absent; Hawaz sandstones are shallow marine deposits with fair reservoir quality. The third target is provided by the Basal Devonian sandstone, which may have an attractive potential in the central part of the license area, with fair reservoir quality. The Tanezzuft Formation shale is considered to be the main source rock; present geochemical data indicate that the Lower Tanezzuft 'Hot Shale' interval represents the main source unit with huge amounts of generated hydrocarbons.

BASEMENT AND MOURIZIDIE FORMATIONS

Basement rocks exposed along the basinal margins are generally divided into two groups:

- A high-grade metamorphic suite comprising mica-schist, gneiss and amphibolites, associated with granite and granodiorite,

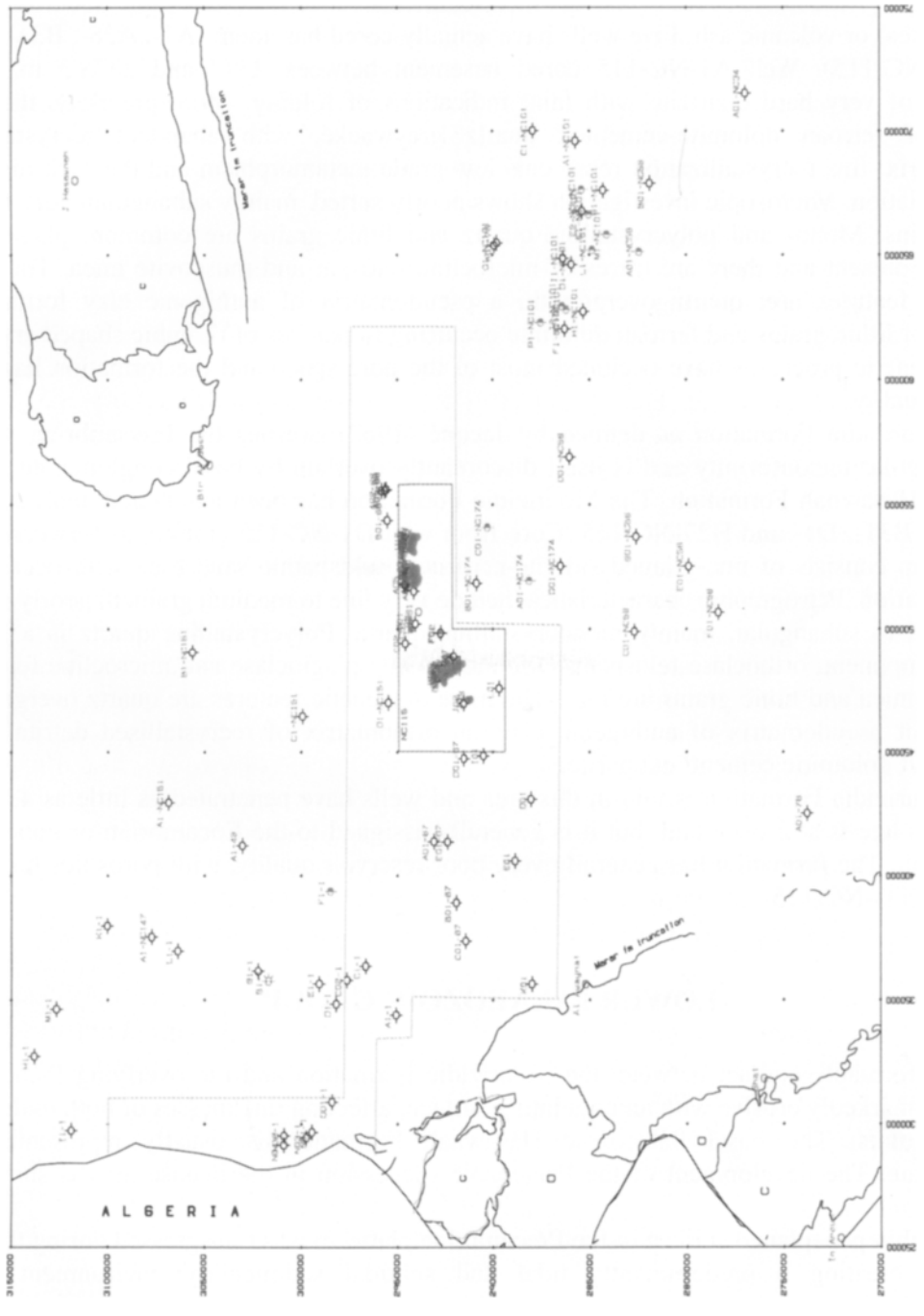

Figure 1. Location of license NC-115 and drilled wells.

- A low-grade metamorphic suite of quartzite, phyllite, schist and arkose, including locally preserved unmetamorphosed deposits of the so-called Mourizidie Formation (Burollet, 1963).

Several wells drilled by Esso and Gulf in the western part of the NC-115 license area reached TD in highly indurated sediments or metasediments, locally even with metavolcanics (serpentinites) or volcanic ash. Five wells have actually cored basement (A1-, A28-, B31-, D1-, and H27-NC-115). Well A1-NC-115 cored basement between 2377 and 2378.3 m, there consisting of very hard quartzite with faint indications of folding. More precisely, the core consists of ferroan dolomite-cemented quartz greywacké, with abundant recrystallized pseudomatrix; this recrystallization represents low-grade metamorphism and the rock displays distinct foliation. Microsopic investigation shows poorly sorted, mainly subangular, very fine to coarse grains. Mono- and polycrystalline quartz and lithic grains are common, plagioclase feldspar is present and there are traces of microcline feldspar and muscovite mica. The main diagenetic features are: quartz overgrowth, a pseudomatrix of authigenic clay formed by alteration of lithic grains and ferroan dolomite occurring in patches of rhombic shaped crystals; these diagenetic processes have occluded most of the pore space and the formation has poor reservoir quality.

The Mourizidie Formation as defined by Jacqué (1962) overlies the Precambrian with a distinct angular unconformity and is itself discordantly overlain by basal conglomerate of the Cambrian Hasawnah Formation. The Mourizidie Formation has been penetrated and cored by wells A1-, B31-, D1- and H27-NC-115. Core from well D1-NC-115 at a depth between 1502 and 1507 m consists of fine-grained siderite-cemented feldspathic sandstone with occasional faint lamination. Petrographic characteristics include very fine to medium grained, poorly sorted subrounded to subangular, mainly monocrystalline quartz. Polycrystalline quartz is a minor detrital component, orthoclase feldspar is common, while plagioclase and microcline feldspar, muscovite mica and lithic grains are rare. The main diagenetic features are quartz overgrowth, an abundant pseudomatrix of authigenic clay, an orthomatrix of recrystallised detrital clay, sideritic and dolomitic cement and pyrite.

The Mourizidie Formation is thin in this area and wells have penetrated as little as 43 m of the unit. Its age is still uncertain, but it is generally assigned to the Eocambrian or uppermost Precambrian. The formation has generally very poor reservoir quality, with porosities less than 5% in well D1-NC-115.

LOWER PALAEOZOIC GROUP

The unconformable contact between the Mourizidie Formation and the overlying Palaeozoic deposits is markedly erosive with an undulating surface, affecting thicknesses of both under-and overlying units. The basal Palaeozoic Hasawnah Formation is usually represented by conglomerate. The development of the Palaeozoic succession in the license area is shown in Fig. 2.

The roughly peneplaned surface of the Precambrian platform was transgressed during the late Cambrian, creating a predominantly tidal and subtidal sedimentary environment, with occasional fluviodeltaic incursions. Similar conditions were also present in the early Ordovician, while towards the end of the Ordovician, glacial influence was widespread throughout the central Sahara, with periglacial deposition in the NC-115 area immediately prior to end glaciation. This was followed by large-scale transgression in the early Silurian. Several workers have assigned the lower four Cambro-Ordovician formations in this succession to the Gargaf Group (Burollet, 1960; Collomb, 1962; Jacqué, 1962).

Hasawnah Formation (Cambrian)

The Hasawnah Formation is preserved over vast areas of the Murzuq Basin; this unit was first described by Jacqué (1962) and then by Klitzsch (1966). It is typically developed as medium-

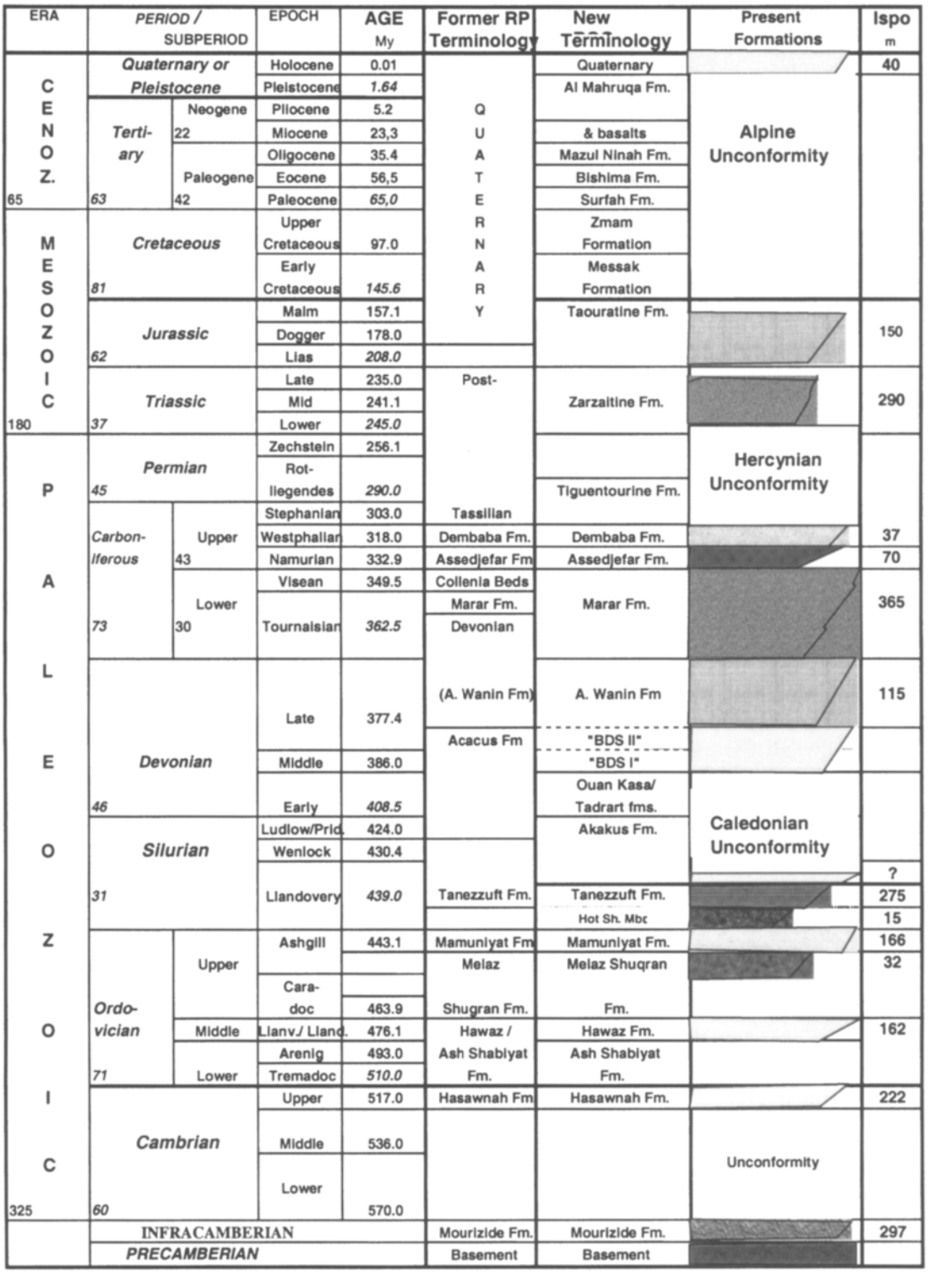

Figure 2. Stratigraphic column in NC-115.

to coarse-grained, cross-bedded sandstone with conglomeratic interbeds. Silica and kaolinite are the main cementing agents. A similar development is seen in outcrops on the western margin of the basin in the Ghat area.

Seven wells have penetrated the Hasawnah Formation in NC-115 (A1-, A28-, B1-, B31-, H27-, H28- and D1-NC-115), but few of these have been cored. The upper part of the formation is characterized by light grey, greenish to brownish, fine to medium grained sandstone with occasional interbeds of mudstones and siltstones, while the lower part is dominated by medium to coarse-grained sandstone, sometimes with conglomeratic intercalations. A1-NC-115 well cored the Hasawnah Formation in the interval between 2301 and 2308 m. Three sedimentary lithofacies were identified in this interval:

- A cross-bedded sandstone lithofacies consisting of kaolinitic quartzarenite, gray to white, hard, medium- to coarse-grained (locally very coarse to granular) poorly sorted quartzitic sandstone, with some clay partings. Monocrystalline quartz is the main detrital component, polycrystalline quartz is very common, lithic grains and heavy minerals occur rarely. Diagenetic kaolinite is commonly pore-filling, illite has also been noted and quartz overgrowth is common. Some thicker beds show trough cross bedding.
- A fractured, fine-grained sandstone lithofacies comprising argillaceous quartz wacke, pale green to white, hard, fine grained quartzitic sandstone; argillaceous laminae are present and deformed in many places. This facies contains abundant pseudomatrix and detrital clays, monocrystalline quartz is present, polycrystalline quartz and lithic grains are rare.
- A siltstone lithofacies comprising dark grey, very hard, tightly cemented siltstone, often occuring as rubble as a result of abundant brittle fracturing.

Several depositional models have been suggested for the Hasawnah Formation. Collomb (1962) interpreted the unit as representing marine deposits, while Klitzsch (1970, 1981) and Cepek (1980) suggested an origin as fluvial deposits. Cores from A1-NC-115 contain medium- to coarse-grained cross-stratified sandstones, fining upward with local siltstone intercalations, perhaps suggesting a series of fluvially derived sediments. No age- or environmentally distinctive fossils have yet been identified, apart from trace fossils generally referred to as *Tigillites* (Klitzsch, 1966).

The Hasawnah Formation has moderate to poor reservoir quality; the diagenetic growth of clay material has had an evident negative effect on pore space, as also has quartz overgrowth, both of these diagenetic processes reducing the reservoir quality. In A28-NC-115 (interval 5807–5837 ft) the formation has moderate reservoir quality, with porosity ranging from 11–13.5% and permeability varying from 2 to a few hundred mD (max. recorded 750 mD). However, the abundant fractures in the core indicate the potential for enhanced reservoir potential as a result of fracturing.

Hawaz Formation (Lower to Middle Ordovician)

The Hawaz Formation was first named by Massa and Collomb (1960); it consists of fine- to medium-grained, coarsening upward, well-cemented, hard sandstone, with siltstone, mudstone and fine sandy interbeds. The Hawaz Formation is very similar to the upper parts of the Hasawnah Formation and the contact between the two units can be difficult to establish; in several wells the two units are therefore combined, with a total thickness varying between 699 m (A1-NC-115) and 246 m (A1–1).

The uppermost Ordovician Mamuniyat Formation is normally considered to be the primary reservoir interval in NC-115. However this formation is not preserved in the eastern part of the H-field where the Hawaz Formation directly underlies the lowermost Silurian Tanezzuft shale

and there constitutes the main reservoir. The cross-section through the H-field (Fig. 3) shows the Hawaz Formation in the east, juxtaposed along an escarpment with the western part of the field where an infill of Mamuniyat deposits provides the reservoir. The Hawaz Formation has also given promising results in the F-structure, where the Mamuniyat Formation is very thin. However, only a limited number of wells in the area have been drilled deep enough to penetrate the Hawaz Formation.

Four wells in the H-field and six scattered wells elsewhere (C2-, E1-, F1-, F2-, J1- and L1-NC-115) have cored the Hawaz Formation, Sedimentological studies have recognized several sedimentary facies ranging from bioturbated, cross-stratified or heterolithic sandstones to mudstones. The alternations of these lithofacies indicate that regularly fluctuating sea-level conditions prevailed on the shelf during deposition of the formation.

Petrographically, the Hawaz Formation consists of very fine to coarse-grained quartzarenite which is moderately to well-sorted. Detrital components are dominated by monocrystalline quartz, but some lithic grains also occur. The common diagenetic components are quartz overgrowth, pore-filling recrystallized detrital clay, and crystallized clay. The quality of the formation as a reservoir rock varies from poor to good; within the H-field the upper parts display very poor reservoir quality with high shale content and sandstone porosity and permeability ranging from 6 to 12% and 0.2 to 2.5 mD respectively, while the lower part has better quality and forms the main reservoir zone, with average porosity and permeability from 10 to 16% and 6 to 900 mD respectively (Fig. 3). The poorest quality within the block is found in the C and F structures, with diagenetic silica cement overgrowth and recrystallized detrital clay which is dominated by illite. The porosity and permeability in F1 and F2 generally range from 3.6 to 14.6% and 0.02 to 0.32 mD respectively, with maximum permeability of about 50 mD in F1-NC-115. In contrast, the E and L structures show better reservoir quality (e.g. average porosity of 15 to 19% in L1-NC-115), perhaps due to increased marine influence to the north in the area.

Acritarch assemblages within the formation indicate a lower to middle Ordovician age (COREX, 1998). The depositional environment is probably transitional from fluvial to shallow marine, with increasing marine influence upwards. The Hawaz Formation varies in thickness in the license area, ranging between 0 and 280 m; well A1-NC-115 shows a 70 m thick development of the formation.

Melaz Shuqran Formation (Upper Ordovician–Caradoc)

The Melaz Shuqran Formation immediately overlies the Hawaz Formation. The Melaz Shuqran Formation generally displays a pelitic to fine clastic sequence, consisting of varicolored, chloritic, thinly bedded shales and siltstones intercalated with fine-grained sandstone. The formation outcrops to the northwest of Ghat and is there over 15 m thick, consisting of grey-greenish to reddish compact shales with silty interbeds. In the section north of Dur al Qussah on the eastern flanks of the basin, the <20 m thick development of the formation is characterized by shales with ferruginous oolites.

Within NC-115 the formation consists predominantly of dark gray to blackish shales, with thin interbeds of siltstones and fine-grained, gray to dark gray, micaceous sandstones. Palynological analyses indicate that the Melaz Shuqran Formation is late Ordovician (Caradoc) in age. It appears to have been deposited in a quiet marine setting, reflecting a widespread marine transgression that took place in the early late Ordovician. The formation is generally considered to have poor source potential. Thicknesses seen in NC-115 range between 21 m (D1-NC-115) and 70 m (B1–67), although in some areas the formation is completely missing.

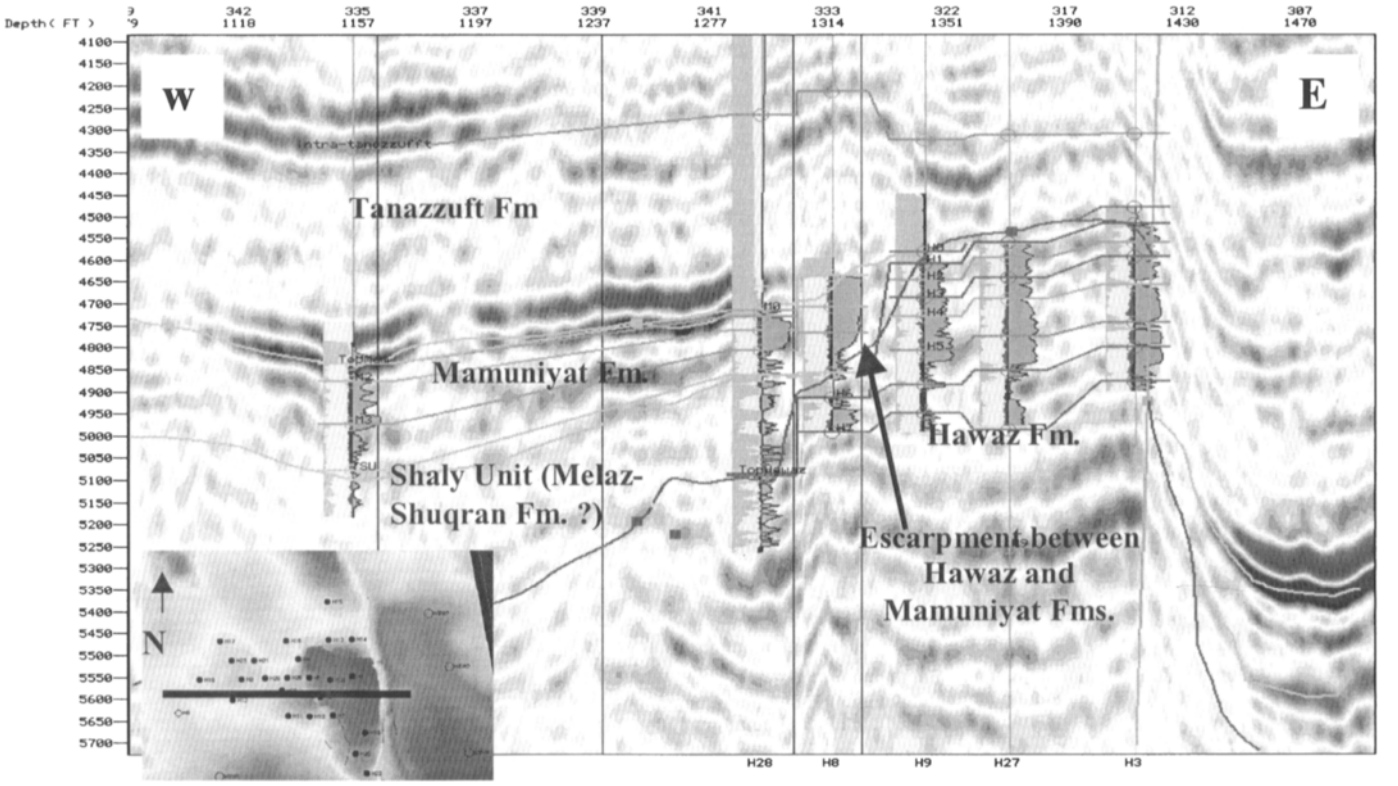

Figure 3. An example of the buried escarpment between the Hawaz and Mamuniyat formations in NC-115.

Mamuniyat Formation (Upper Ordovician – Ashgill)

The Mamuniyat Formation represents the primary reservoir target in the Murzuq Basin and most particularly in the fields of the NC-115 license area. It consists of regressive coarse clastics provenanced from emergent areas and generally comprises massive, cross-bedded, fine to coarse-grained to conglomeratic sandstones, with siliceous and sometimes mixed cements. The thickness of the Mamuniyat Formation is highly variable.

The formation has a widespread distribution in the subsurface of the Murzuq Basin and it has been penetrated by all Repsol (Rompetrol), Gulf, Sirte (Esso), Boco, Lasmo and Braspetrol wells (Fig. 4). The base of the formation is easily identified in wells where the shales of the Melaz Shuqran Formation are present; in eastern parts of the basin, Klitzsch (1966) found a basal highly ferruginous sandstone bed which passes laterally into almost pure hematite, indicating the presence of a major hiatus; indeed, in some localities the formation directly overlies Cambrian strata with a marked angular unconformity. The upper unconformable contact to the shales of the Tanezzuft Formation is also well defined, locally marked by a hematite-rich horizon (Klitzsch, 1966) or by a conglomerate as in the B Field of NC-115.

The Mamuniyat Formation is present over the whole NC-115 Concession area, where it is developed as shoreface to deltaic deposits (Fig. 5) in complex facies variations – both vertically and laterally. The formation's generally well-consolidated sandstones are grey, light grey to whitish, sometimes yellowish in colour. Grain size varies from fine to coarse, occasionally conglomeratic (Fig. 6a), with subangular to rounded grains and variable sorting. The sandstones contain some clasts and thin interbeds of shales and siltstones. Microfracturing is common, as in A2-NC-115 (Fig. 6b); this is especially the case in the A and B fields where the fracture patterns have been extensively interpreted by the use of FMI logs.

The Mamuniyat sandstones generally contain 80 to 97% quartz, 2 to 4% lithic fragments (quartzites and cherts), 2 to 3% micaceous minerals (sericite, muscovite and chlorite) and 1 to 5% opaque minerals, including pyrite. Silica and sometimes mixed silica and kaolinitic cements are common. The silica cement displays various textures (porous-pellicular cement, as overgrowth and as mixed cement) and was itself affected by secondary diagenetic processes. The

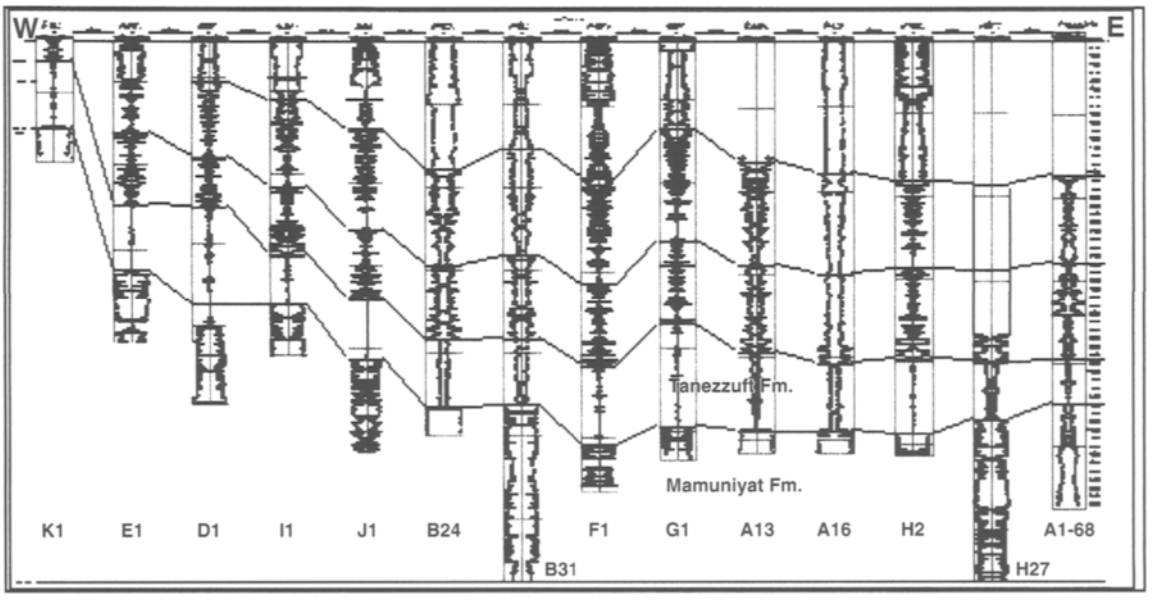

Figure 4. East –West log correlation, NC-115 (GR & revedrse GR log).

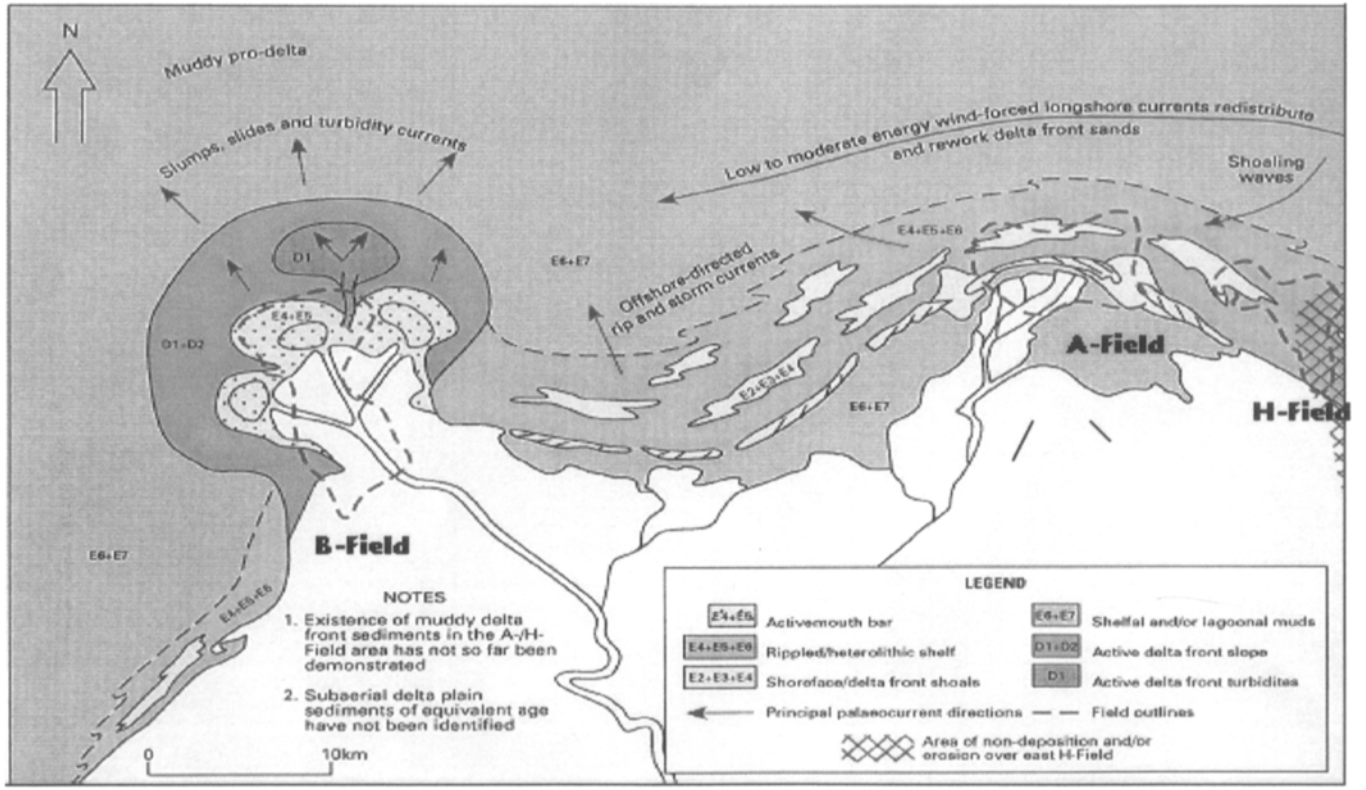

Figure 5. Sedimentological model for deposition of the Mamuniyat Fm, (R.R.I., 1996).

Mamuniyat Formation displays better reservoir quality in the A-field than elsewhere, although there is much variation within the field. Northern segments show somewhat reduced quality, perhaps because of increased marine influence, with average porosity and permeability 5 to 12% and 7 to 160 mD respectively (A2-NC-115). Reservoir quality increases in the central and southern parts of the field to values of 9 to 16% and 115 to 1850 mD respectively (A1-NC-115). Sandstones in the H-field show fair to good quality, with average porosity and permeability of 13 to 15% and 84 to 1017 mD (H2-NC-115), with general upwards coarsening grain size accompanied by increasing reservoir quality. The central and northern parts of the B-field show moderate to poor porosity and permeability in the range from 9 to 12% and 1 to 11 mD respectively (B31-NC-115), while southern segments, where the periglacial unit is missing (see below), show better quality, with an average of 9 to 13.5% and 18 to 700 mD (B3-NC-115).

Outcrops around the flanks of the Murzuq Basin show thicknesses generally between 100 and 150 m, up to a maximum of 220 m in the type area of Jabal Al-Mamuniyat, while wells in NC-115 show a generally thinner development in the range between 40 (C1–67) and 175 m (A1-NC-115); the formation is occasionally completely missing, as in the eastern part of the H Field (Fig. 3). The age of the formation has been established by palynological studies to be late Ordovician (Ashgill); all assemblages studied are dominated by sphaeromorph, polygonomorph and acanthomorph acritarchs (COREX 1998).

The B-structure in the western part of NC-115 contains a unit of granular and conglomeratic sandstone directly underlying the Silurian Tanezzuft Formation shales and separated from typical Mamuniyat sandstones by a shale horizon that varies in thickness from 2 to 15 m. This coarse clastic unit, here called the 'Periglacial horizon', consists of gray-yellowish to whitish, sometimes brown, sandstone, medium to coarse grained, with granular and conglomeratic clasts, poorly to well cemented, slightly micaceous, (Fig. 6C), with thin interbeds or lenses of dark grey shales. The sandstone consists of 85 to 95% unequigranular quartz, with poor sorting and a higher content of lithic fragments (quartzite and chert) than 'typical' Mamuniyat, but lesser opaque minerals. The underlying shale, which consists of alternations of shales and very fine sandstone gives a high gamma response on wireline logs, but must not be confused with the Tanezzuft Formation's basal radioactive shale.

The Periglacial unit appears to represent a transitional stage between the upper Ordovician to lower Silurian, with an unconformable relationship to both. In the B-Field it ranges between 15 and 45 m thick (B3- and B4-NC-115 respectively) and is completely missing in the southern part of the structure. The lithofacies development suggests a high energy coastal environment. The model suggested by Robertson Research (1996) shown in Fig 5, suggesting the presence of Gilbert delta fans.

Palynologically, the Periglacial unit horizon contains acritarch species typical of the Upper Ordovician and chitinozoans which appear more Silurian in character; low numbers of the marker species *Veryhachium subglobosum* and *Veryhachium longispinosum* and terrestrially derived spores (B21-NC-115 in the interval 4825–4892′) are dated as Late Ordovician (Caradoc-Ashgill).

Silurian

Silurian strata are widespread over most of the Murzuq Basin, including the concession area, and outcrop along the basin's western margins in Jebel Akakus. Deposition started immediately following the late Ordovician glaciation and the lowermost Silurian succession reflects the first major post-glacial marine transgression, the results of which are preserved over much of the North African platform. The early Silurian sea is thought to have invaded the Murzuq Basin from the NNW. The resultant marine shales covered the whole central Sahara, with prevailing

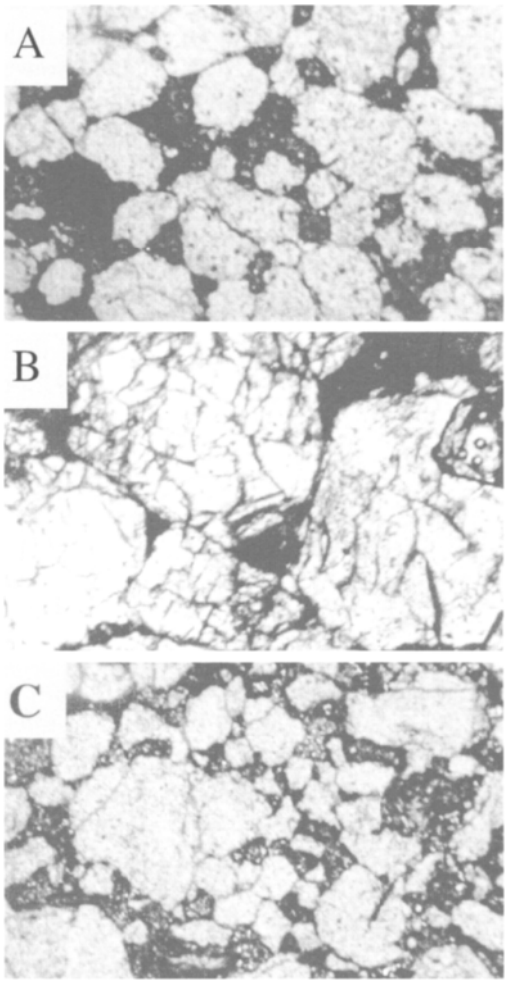

Figure 6. Microphotographs of Mamuniyat Fm sandstones

quiet water fine clastic deposition and high concentrations of radioactive elements suggesting a very low sedimentation rate, especially in structurally low areas.

This transgressive shale passes gradually up into prograding siltstones and sandstones. The Silurian deposits are therefore regionally assigned to two depositional cycles – the transgressive lower Silurian Tanezzuft Shale Formation and the mid- to upper Silurian regressive Akakus Sandstone Formation. The first of these is preserved in the NC-115 concession area, while the Akakus Formation is missing from most of the block.

Tanezzuft Formation (Silurian – Llandovery)

Tanezzuft Formation shales have been penetrated in all wells in NC-115 (Fig. 4), and a total of 146 m of core has been taken from 22 wells. The thick basal Tanezzuft shale overlies and seals the main reservoir interval and therefore functions as a good cap rock, while the radioactive 'hot shales' in the same interval represent the main hydrocarbon source rock, both regionally and locally. This hot shale is best developed in wells located in the middle to eastern parts of the block. The Tanezzuft Formation consists of dark gray claystone usually with shaly lamination, very compact, frequently micaceous and pyritic, sometimes with silty and sandy interlaminae and beds, which become increasingly common upward. Three main lithofacies are recognized:

(1) Dark grey, fissile, carbonaceous mudstone, with rare siltstone laminae and well preserved graptolites (commonly *Climacograptus* sp.); this facies has a limited distribution in NC-115,

(2) The most common mud-prone heterolithic facies, consisting of interbedded mudstone (more than 50%, similar to above) and siltstone or very fine-grained sandstone,

(3) Basal poorly sorted sandstone facies, observed in only one well (H6), fine to very coarse grained, poorly sorted sandstone occurring lowermost in the formation.

Detailed studies to establish the age of the Tanezzuft Formation have been made by several authors, both in outcrop and the subsurface. The formation is very rich in graptolites and these indicate an Early to Middle Llandovery age. Recent palynological studies (COREX, 1998) confirm this dating: samples collected from 11 scattered wells contain rich, diverse and well preserved early Silurian acritarch assemblages, which include *Veryhachium trispinosum*, *Veryhachium lairdii*, *Baltisphaeridium* spp. and the marker species *Neoveryhachium carminae*, together with chitinozoans, including *Sphaerochitina* and *Angochitina*, and miospores. The lithofacies and paleontology of the Tanezzuft shale clearly indicate the development of a marine offshore shelf environment.

The Tanezzuft Formation is up to 475 m thick in outcrop in the southwestern Murzuq Basin, while subsurface thicknesses in concessions 1, 67, 68, and NC151 range from 102 to 256 m. In NC-115 wells the thickness varies between 117 and 368 m, with thickest development in the structural low in the central part of the block, decreasing both east- and westwards (Fig. 4). The Tanezzuft shale is generally regarded as the main source rock in the Murzuq Basin (Meister et al, 1991). Recent detailed geochemical studies (Robertson 1998) have shown the base Tanezzuft hot shale to have most attractive source potential. Our own studies suggest that this source interval entered the oil window in the Carboniferous to Permian, the burial history diagram in Fig. 7 showing the location of the oil window. The hot shale has very high total organic carbon

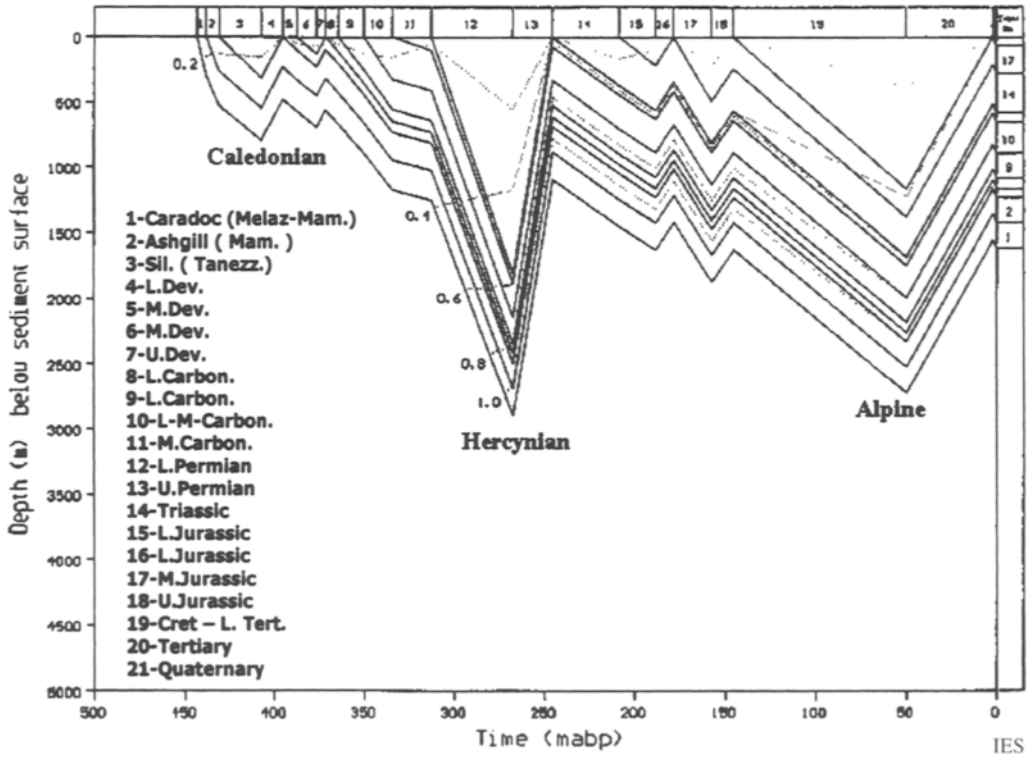

Figure 7. Burial history diagram of well H1-NC-115.

contents (TOC) generally ranging from 5.7 to 16.7%, the average vitrinite reflectance (Ro) is 0.54 to 0.83%, and average spore color index (SCI) is between 7 and 8.5, while the Tanezzuft shale otherwise has a somewhat poorer source rock quality, with average TOC 0.5 to 1.34%.

The hot shale extends in a north to south belt with a limited width, ranging in thickness up to 35 m; thickest developments are seen in the southeastern parts of the block. The unit is at present at the late oil maturity stage but has not yet entered the gas window. It is predicted to be more mature both to the north and southeast of the NC-115 concession area. Oil to source correlations indicate that the oil entrapped in NC-115 has migrated from more mature source rock areas, and our models suggest migration into the block from the NNW. The geochemical results indicate that the hot shale in the Murzuq Basin has generated huge quantities of hydrocarbons; within NC-115 alone the hot shale interval may have generated approximately 8.3 to 19.4 mmbbl/km^2, giving the potential for approximate amounts of entrapped hydrocarbons in the Murzuq Basin of around 40 billion barrels.

Akakus Formation (Middle – Upper Silurian)

Klitzsch (1969) described the 345 m thick type section of this formation on the southwestern margins of the basin. It there shows a regressive coarsening upward development of thin to thickly bedded light gray sandstone, sometimes cross stratified, with some more silty and shaly interbeds. The base is gradational to the Tanezzuft shales, while the top is marked by the sharp and erosive contact to the fluvial sandstones of the Tadrart Formation.

Revised correlations in NC-115 have shown that units previously assigned to the Akakus Formation in fact erosively overlie various levels of the truncated Tanezzuft Formation. These units have proven to have a middle to possibly late Devonian age and have therefore been reassigned to the informal Basal Devonian sandstone (BDS). Late Silurian Caledonian uplift has removed the Akakus sandstones from most of the license area and only thin remnants have been encountered in the southwestern wells D1- and E1-NC-115.

Caledonian Unconformity

Caledonian tectonism had clear effects on the study area, resulting in long term uplift and erosion from the late Silurian to middle Devonian. Several burial history models have been tested in an attempt to fit the available calibration data (downhole temperature, Ro, spore color index and apatite fission track analyses, Fig. 7) and the estimated missing section over most of the basin is around 250 m. The Tanezzuft Hot Shale was then still at such shallow depths that it was immature and this erosion has had no effect on source maturity. The Basal Devonian sandstone (BDS) infilled the irregular topography created by this uplift within the NC-115 area.

THE UPPER PALEOZOIC GROUP

Devonian and Carboniferous rocks occur over the whole basin and in NC-115. The early Devonian was still affected by uplift and deposition probably did not start until the middle Devonian. Devonian strata are characterized by an upwards gradation from continental to marginal marine thickly bedded, cross stratified sandstone into thinly bedded marine sandstone, passing into fully marine finer clastics as a result of a major transgressive cycle which reached a maximum during the Carboniferous. Parts of the Devonian succession may represent an

attractive target for hydrocarbon exploration in terms of reservoir quality. Within NC-115 the Devonian seems to be an attractive target only in the C structure in the central part of the block, while in other parts of the block the Devonian is considered to form the main aquifer. (Garea and Zwawi, 1998). The Devonian succession is divided into two formations, the informal Basal Devonian sandstone (BDS) and the Awaynat Wanin Formation.

The Carboniferous succession represents the culmination of the Devonian transgression and also the last phase of Palaeozoic marine deposition over the Murzuq Basin. The Carboniferous strata were deposited on a stable shelf, in coastal to shallow marine settings, affected by slight changes in subsidence and by eustatic sea level changes, resulting in rhythmic depositional patterns.

The Carboniferous is more than 1000 m thick in the basin center, gradually thinning to the N and W. Carboniferous strata are widespread in NC-115, and form extensive outcrop areas to the west of the block. Three formations are represented, viz. the Marar, Assedjefar and Dembaba formations of early to late (Moscovian) Carboniferous age. The youngest Carboniferous epochs have not been preserved or were already a time of Hercynian uplift.

Basal Devonian sandstone (BDS) (Middle–Early upper Devonian)

This unit is quite thinly developed throughout the block. For operative purposes it is divided into two sandstone members (BDS-I and BDS-II), separated by a shaly unit (BDSh). The two sandstone members are best developed eastwards, and the entire formation becomes more shaly and thins westwards; this thinning is most marked in the upper sandstone member BDS II.

Lithologically, this sand-dominated unit contains varying interbeds of shale and siltstone; sandstones occur as thick massive beds banks or as thin beds in the finer clastic horizons. The sandstone is fine to medium-grained; it contains some minor mica and is well cemented by silica. Shale beds can be up to a metre thick or occur as thin interbeds with the sandstones. Reservoir quality shows rapid lateral variation, e.g. in the C-structure there are significant variations between nearby wells, but quality generally improves from poor in the west to moderate to good in the east.

Palynological studies have given identifiable assemblages in well H5; a sample from 3967 ft yielded mainly acritarchs, with the marker species *Tyligmasoma alargadum* and *Onondagaella asymmetrica*. Miospores include *Emphanisporites rotatus*, *E. obscurus*, *E. spinaeformis*, *Retusotriletes* spp., *Ambitisporites* spp., and *Leiotriletes* spp., this association of taxa suggesting an early Devonian age. Another assemblage rather indicates an early middle Devonian dating, as in A6 (3779.8, 3795, 3874 ft.), B1 (3774 ft.) and H5 (3747, 3751, 3773, 3810.5, 3827, 3858.7 and 3871 ft.). Acritarchs and associated miospores there seem typical of the middle Devonian and there are no taxa diagnostic of the early Devonian. On the other hand some acritarchs, including the diagnostic species *Unellium winslowae*, together with *Gorgonisphaeridium* spp., *Duvernayspharea tenuicingulata* spp., *Retusotriletes* spp., *Geminospora tuberculata*, *Ambitisporites* spp. and *Grandispora* spp., suggest a middle to late Devonian age. From this palynologically wide range it is impossible to establish the unit's exact age, but it is believed to be middle to early Late Devonian.

The BDS has a thin and irregular development throughout the block, clearly filling Caledonian erosional relief. BDS I covers the whole of the block, with an average thickness of 7 to 27 m, thinning northwestward. The BDSh shale covers the entire block, with an average range of 5 to 20 m. The upper package of sandstone BDS II shows various thicknesses from zero to 23 m, covering the southern and southwestern parts of the block and thinning to the northeast.

Awaynat Wanin Formation (Upper Devonian- Givetian – Famennian)

The Awaynat Wanin Formation was first described by Lelubre (1946) for a succession displaying rhythmic alternations of thick or thin units of sandstones, siltstone and shale. The formation has been cored in four wells in NC-115; these show a mud-dominated development and sandstones encountered are very fine to fine-grained, argillaceous and strongly bioturbated. The formation is considered to have a generally very poor reservoir quality. Geochemical analyses of the shales show poor source rock potential. Lithological variations indicate fluctuating sea level affecting shallow marine to coastal or lagoonal depositional environments

Previous studies of the Awaynat Wanin Formation have suggested a generally middle to late Devonian age (Eifelian to Famennian) in its type area. Samples from several wells in NC-115 contain the diagnostic acritarch species *Veryhachium pannuceum* and/or *Unellium winslowae*, together with the miospore marker species *Spelaeotriletes lepidophytus* and/or *Dictyotriletes fimbriatus* (A1 at 1059 m, A4 at 1125 m, H1 at 1063 and 1070m and J1 at 939 m), all indicating a Late Devonian age for the development of the formation in this area.

Acadian Unconformity

Late Devonian to early Carboniferous uplift had only limited effects in the NC-115 block; although there may be a slight erosional break between the upper Awaynat Wanin and lower Marar formations, this had no significant effect on the burial history (Fig. 7).

Marar Formation (Lower Carboniferous–Viséan)

The Marar Formation outcrops along the western borders of NC-115 and is penetrated by all wells drilled in the block. The formation unconformably overlies Devonian deposits and is represented by rhythmic alternations of marine shales and sandstones. The shales are frequently silty, micaceous and pyritic, compact, dark gray to blackish in color, while the sandstone is light gray, fine to very fine-grained, and poorly consolidated by siliceous, clay or sometimes carbonate cement. Occasional thin shaly limestone beds also occur. The formation becomes increasingly sandy upwards. The formation thickens southwards, ranging between 154 and 226 m in the licence area (as compared to about 400 m in its type section further north).

Core data for the Marar Formation have been collected from five wells (A1-, B1-, C1-, C3- and F1-NC-115); several sedimentary facies have been identified in the interbedded mud- and sandstones, which display a generally coarsening upward regressive aspect. The complex interrelationship between the individual facies suggests a depositional environment that fluctuated between fluvial channel to delta front and upper to lower prodelta deposits.

The formation is rich in fossils and palynological studies have found assemblages of taxa typical of the early Carboniferous Viséan stage. These assemblages are dominated by miospores with only sparse marine acritarchs. This age as suggested by palynology agrees with previous studies largely based on macrofaunas.

The sandstone facies of the Marar Formation can be classified as having poor to good reservoir potential. Geochemical studies show the shale facies to have high TOC, but they have not entered the oil window in NC-115; these shales may be more attractive as a potential source rock in the center of the basin.

Assedjefar Formation (Lower Carboniferous – Viséan/Namurian)

This formational name was introduced by Lelubre (1952) and the type section to the north of the Awbari Sand Sea was described by Collomb (1962). The Assedjefar Fm is characterized by alternations of siltstone, shale and sandstone, with a thickness of about 120 m in its type area, increasing to the north towards the Ghadamès Basin. The formation outcrops on the northwestern and western margins of the Murzuq Basin, and in some spots around the NC-115 block's western limits, with varying thicknesses. The subsurface thickness within the block ranges between 25 and 136 m. The formation consists of non-marine siltstones to fine sandstones in the H Field, while the A Field displays shoreface sandstone deposits passing into more shaly facies westwards.

The Assedjefar Formation contains an abundant and rich assemblage of fossils, all suggesting a Viséan to Namurian age.

Dembaba Formation (Upper Carboniferous)

The Dembaba Formation was introduced by Lelubre (1952) based on the Hasy Dembaba exploration well C1–49 on the northern edge of the Awbari Sand Sea and the type section was described by Collomb (1962). These represent the youngest Carboniferous marine deposits in the basin and are composed mainly of carbonates, but with common shale interbeds; the formation is approximately 60 m thick in its type area.

Within NC-115 the Dembaba Formation shows an alternation of shales and limestone with minor fine-grained sandstone and siltstone. The formation ranges in thickness between 10 and 65 m. Its age is suggested to be Bashkirian to early Moscovian.

Hercynian Unconformity

Hercynian tectonic movements affected the Murzuq Basin from the late Carboniferous to the Permian and sediments of this age are generally missing. The general thickness of preserved Carboniferous strata increases northwestwards in the Murzuq Basin and into the southern Ghadames Basin, while effects were much stronger to the center and SE of the Murzuq Basin, where the preserved Carboniferous section is much thinner.

The Hercynian tectonic phase in the Murzuq Basin is considered a key event as regards timing of hydrocarbon generation, but estimates of missing section have a very wide range. Minimum uplift in NC-115 has been thought to affect the western part of the B Field, with estimates of around 1000 m missing section, increasing to the east to a maximum of approximately 1700 to 1800 m in the H Field. Maximum uplift in the order of as much as 2500 m is estimated for the SE of the basin, i.e. in the area around well A1-NC58.

MESOZOIC AND CENOZOIC COVER

Zarzaitine Formation (Post-Tassilian)

This formation was introduced by Burollet (1960). It outcrops over many parts of the Murzuq Basin and particularly in the west of the NC-115 area, unconformably overlying the Dembaba Formation across the Hercynian unconformity. Reddish-brown clays and siltstones alternate

with continental cross-bedded sandstones, these alternations becoming more frequent upwards, where gypsum horizons also occur. Rompetrol staff considered this unit as Triassic to Jurassic in age, but Jakovljevic (1984) dated it purely to the Triassic. The formation's thickness in the A and B fields varies from 190 to 220 m, increasing up to 320 m in the H field; maximum thicknesses of up to 350 m are seen to the east of the H Field.

Taouratine Formation

This formation outcrops in the center of NC-115 and unconformably overlies the Zarzaitine Formation. It consists of pale red quartzitic conglomerates, with alternating interbeds of sandstone, siltstone and claystone, deposited in a braided river system. The formation has been penetrated by most wells in NC-115, with a thickness of around 400 m in L1-NC-115. Early correlations by Rompetrol thought these strata to represent Quaternary deposits, but the Jurassic age is clearly indicated by palynological analysis (see e.g. Jakovljevic, 1984). This formation is the main fresh water source for agricultural and human use in the area.

Messak Formation

The Messak Formation forms a prominent escarpment and represents the natural southern border of the block. The formation is late Jurassic to early Cretaceous in age, and is usually divided into a lower Jarmah Member and an upper Awbari Member, both consisting of continental clastics deposited in a predominantly braided stream environment, but with interbedded lake and swamp deposits.

Alpine tectonism

Uplift is thought to have started in the early Tertiary, and had widespread effects throughout the Murzuq Basin, although these were limited from a hydrocarbon generation point of view in the NC-115 area, where the main source interval is thought to have entered the oil window already in Carboniferous time. The missing section resulting from this uplift in NC-115 has been estimated to around 1200 to 1300 m, increasing to the north (A1–48) to around 2000 m missing section and decreasing to the south and southeast (A1-NC58) to only about 500 m. The burial history diagram in Fig. 7 shows the estimated effect of this tectonic event for the H1-NC-115 well.

Quaternary Deposits

Quaternary deposits cover most of the surface of the block, in its northern part forming an extensive dune system separated by deflation valleys. Recent eolian deposits are medium to coarse-grained, well-rounded and sorted, unconsolidated, quartizitic sands. Other Quaternary sediments include old and Recent wadi fill, sabkha, and fluvio-eolian deposits.

CONCLUSIONS

The Paleozoic succession consists of predominantly clastic sediments with widespread distribution and good lateral correlation. Marine deposits dominate, but with recurrent

continental influences. Some correlational changes have been made in the NC-115 license: units earlier correlated to the Silurian Akakus formation are now assigned to the informal Basal Devonian sandstone (BDS), and deposits once thought to be of Quaternary age are now assigned to the Mesozoic Taouratine Formation. The area has been affected by three main periods of tectonic uplift; the end-Silurian Caledonian orogeny produced missing section of around 250 m over Murzuq Basin, while the end-Carboniferous Hercynian orogeny resulted in missing section of 1000 in the eastern part of block, reaching 1800m in the western parts. Maximum uplift of 2500 m is suggested in the southeast of the basin. Tertiary Alpine uplift is estimated to have resulted in average erosion of 1200 to 1300 m. The Mamuniyat Formation has a widespread distribution and is considered to show good reservoir quality, particularly in the A Field. The Hawaz Formation is considered normally to be the second reservoir target, but is primary target when the Mamuniyat sandstones are completely missing. The Basal Devonian sandstone is considered a potentially attractive target in the middle part of the block. The main diagenetic processes are quartz overgrowth, authigenic clay precipitation and carbonate cementation. The Lower Silurian hot shale is the main source rock and seal, and modelling indicates approximately 8.3–19.4 mmbbl/km^2 of generated oil, to produce a total of 40 billion bbls. Main oil generation is believed to have taken place in the Carboniferous immediately prior to Hercynian uplift. Oil is expected to have migrated from the NNW into NC-115. These results show that Murzuq Basin is still a highly attractive area for further hydrocarbon exploration.

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CHAPTER 17

Sedimentology and Cu-U mineralisation of the Upper Cretaceous Bin Affin Member, Dur Waddan, Southwestern El Haruj, Murzuq Basin, Libya

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ABSTRACT

The Upper Cretaceous Bin Affin Member of the Zimam Formation is widely distributed on the east and southeast margins of the Murzuq Basin. It passes laterally into the Lower Tar Member. Preliminary sedimentological investigations reveal that this member consists of four lithofacies as follows:

- Cross-bedded sandstone consisting of calcareous pebbly sandstone rich in tree logs and roots and believed to be deposited on the point bars of fluvial channels,
- Sand sheet facies composed of structureless poorly sorted sandstone beds rich in root-like bodies where Cu-U mineralisation is restricted. The depositional environment of this facies seems to be fluvial channels of low sinuosity,
- Sandstone and siltstone rich in the trace fossil Ophiomorpha characteristic of shallow subtidal environments,
- Pebbly sand facies uppermost in the Bin Affin Member, composed of friable sandstone rich in poorly preserved vertebrate bones and deposited in tidal channels.

Widespread Cu-U mineralisation characterizes the sediments of the Bin Affin Member. The mineralised zone extends over a hundred kilometres from Dur Waddan to Dur El Messad. Preliminary chemical analyses show that the mineralised sandstone contains up to 0.5% copper and up to 0.1% uranium. X-ray diffraction analyses indicate that copper bearing minerals are represented by azurite, bornite, malachite and cuprite, whereas uranium is present in the form of uraninite. The source of Cu and U seems to be related to the Tibesti Massif and the granitoid rocks of the neighbouring basement outcrop.

INTRODUCTION

This study goes back to the year 1994, when a teaching staff and graduate student team from the Earth Science Dept. of Sebha University carried out a field study on the Precambrian basement granites and metasediments of Dur Waddan, SW El Haruj. In the course of this work they also visited the Cretaceous Zimam Formation outcrops. The authors were intrigued by the peculiar sedimentary structures and features shown by these outcrops and decided to revisit the area to

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investigate these sediments in more detail. These later studies found Cu mineralisation zones restricted to horizons that are full of branching vertical bodies interpreted as root-traces. The Cu mineralisation is associated with iron that gives a distinctive red colour and appearance, making it easy to follow throughout the whole area of Dur Waddan, extending laterally over about 120 km (Fig. 1).

GEOLOGICAL SETTING AND GEOGRAPHIC DISTRIBUTION

The stratigraphic section in Dur Waddan is represented by the Bin Affin and Upper Tar members of the Zimam Formation, but the lower contact of the Bin Affin Member to the underlying Messak Formation is not exposed. The sediments of the upper Tar Member conformably overlie the Bin Affin Member. This sequence is developed through the whole area and extends beyond it with a characteristically regular thickness and lithology (Fig. 2).

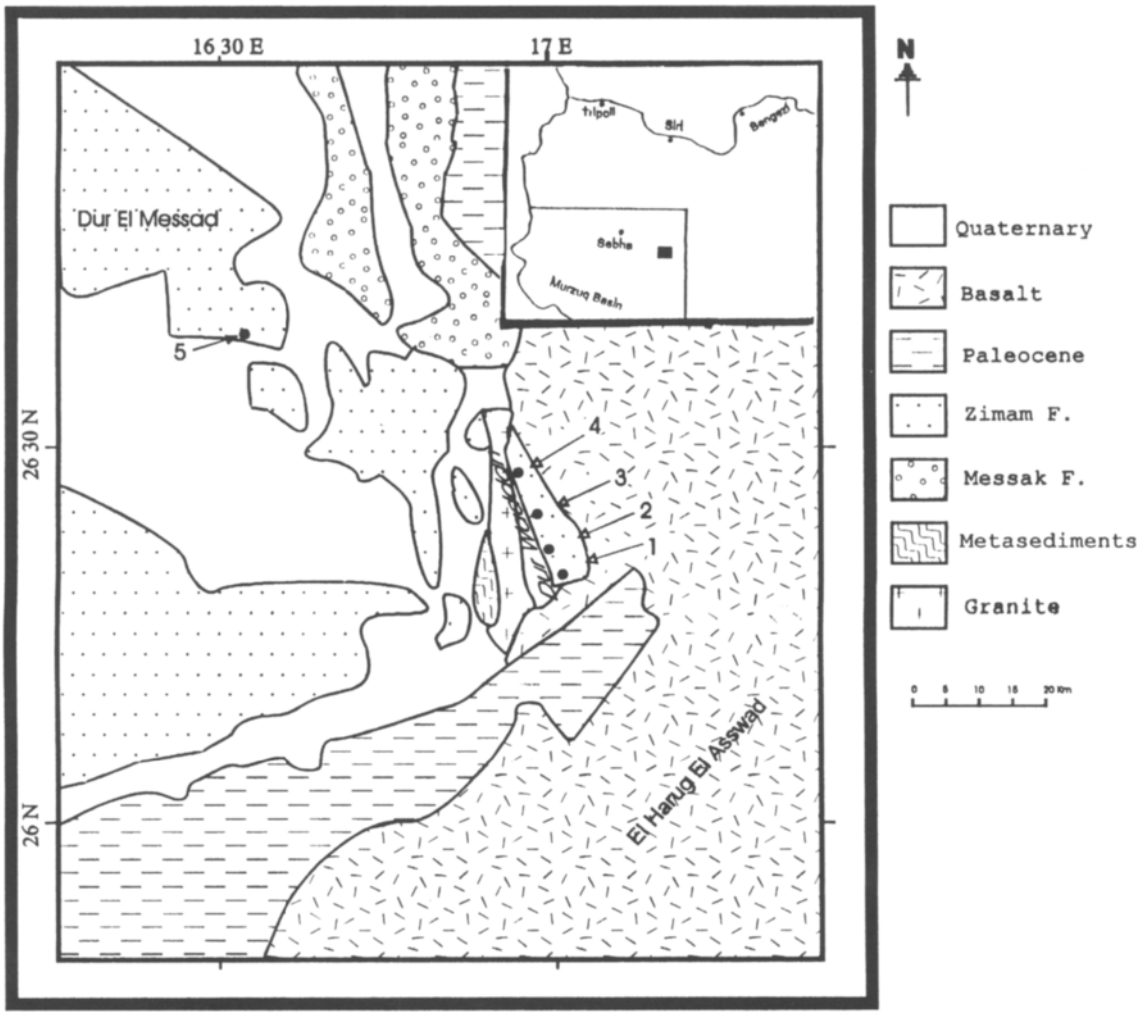

Figure 1. Simplified geological map of the Dur Waddan – Dur El Messad area, southwest El Haruj, Libya.

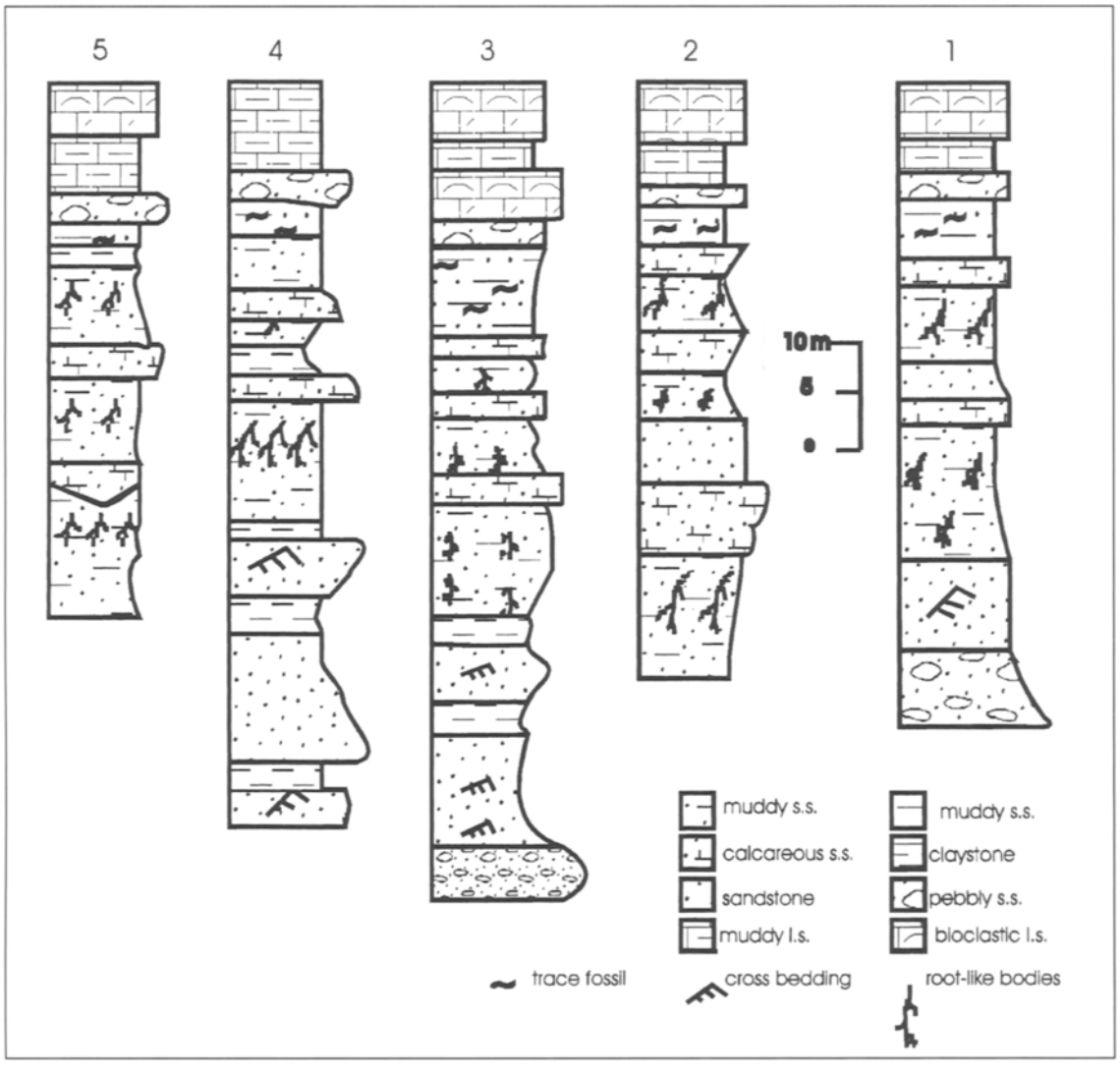

Figure 2. Measured sections of the Bin Affin Member, Dur Waddan area.

LITHOLOGY AND DEPOSITIONAL ENVIRONMENTS

The Bin Affin Member in the study area is represented by a classic sequence which can be divided into three units .The lowermost unit is composed of several fining upward rhythms (Fig. 2). Each rhythm begins with conglomeratic sandstones with microconglomerate lenses and grades upwards into cross-bedded calcareous sandstones and finally into siltstones or claystones uppermost. The middle unit consists of muddy poorly cemented and poorly sorted sandstone beds with no sedimentary structures apart from abundant root-like bodies. The upper unit consists of a silty sandstone bed with Ophiomorpha burrows representing the start of a transgressive phase and this is overlain by a pebbly sandstone bed rich in vertebrate bone fragments. The two beds have a wide lateral extent, generally with no significant changes in thickness or lithology. The bone bed directly underlies the bioclastic limestones of the upper Tar Member. The writers followed the outcrops of this member from Dur Waddan in the south to Dur El-Messad in the north over a distance of 120 km and noted the consistency in the type and sequence of rock units – particularly the persistent occurrence of thick mineralised root-like

horizons. These bodies are easily recognized from a distance by virtue of their characteristic shape and smothered tops through the study area. Nevertheless, they sometimes tend to become somewhat less abundant upward in the section.

FACIES AND ENVIRONMENTAL INTERPRETATION

Four lithofacies can be recognized in the Bin Affin Member:

Cross-Bedded Sandstones

Widely distributed cross-bedded sandstones represent the lower part of the fining upward rhythms with erosional bases. These consist of coarse poorly sorted hard sandstone with conglomeratic bases. The sandstones are composed mainly of quartz (90% of the grains) cemented by calcareous matter and grade laterally and vertically into arenaceous limestone. Planar and trough cross-bedding and planar lamination are the most common sedimentary structures. In the Dur Waddan area this facies is rich in tree logs and roots that are preserved today as sandy moulds. The sandstone usually grades upwards into mudstone beds 0.5 to 1 metre thick. The cross-bedded sandstone facies is characterized by a high coarse/fine ratio (up to 90% coarse) and by its multistory nature (Fig. 2) .The depositional environment here is believed to be a braided channel system (c.f. Miall, 1977 and Selley, 1982).

The Sand Sheet Facies

The sand sheet facies dominates the middle part of the Bin Affin Member. It is widely distributed through the study area and is repeated vertically several times and is usually eroded into by overlying cross-bedded sandstone beds (Fig. 2). This facies is composed mainly of muddy, poorly sorted and poorly cemented light grey to greenish grey sandstones, characterized by their structureless nature and the abundance of branching root-like bodies of variable size that vertically penetrate it. These bodies range in length from 0.5 to 7 m, with diameters ranging from several centimetres to half a meter.

It should be noted that the copper-uranium mineralisation is restricted to these bodies and has not been found elsewhere. Therefore, the widespread nature of these root-like bodies is the main characteristic feature of this facies. The coarse-grained development with no silt or clay beds indicates deposition in stream channels (Lattman, 1960; Reineck and Singh, 1980 and others). However, stream channel deposits usually have linear geometry, which is not the case here. According to Reineck and Singh (1986) the sheet geometry may result from lateral migration of stream channels. Schumm (1977) also suggested that any type of lateral migration of river channels can produce sheet or blanket sand. Visser (1980) added that structureless sand sheets can be produced by the lateral migration of low sinuosity channels.

The Ophiomorpha *Sand Facies*

The *Ophiomorpha* sand facies is found lowermost in the upper part of the Bin Affin Member. It also has a wide geographic distribution and a uniform thickness and composition. It consists of fine sand and silt of brownish-yellow colour and is heavily bioturbated by *Ophiomorpha* burrows characteristic of shallow subtidal conditions (5 to 6 metres water depth). The forms of

Ophiomorpha burrows include vertical or straight shafts up to 10 cm long forming 50% of the burrows; other forms either branch perpendicularly to the main shaft or form J-shaped burrows. The burrows are up to 1.0 cm in diameter but some are slightly thicker at their distal ends. The walls are characteristically knobbly and are probably built of cemented faecal pellets. The sediments of this facies were presumably deposited in an agitated subtidal to intertidal environment (Kanes, 1963; Weimer and Hoyt, 1974). Extensive burrowing probably destroyed cross-lamination and other sedimentary structures.

The Pebbly Sand Facies

The pebbly sand facies is found uppermost in the Bin Affin Member. It consists of 50 cm of coarse pebbly friable poorly-sorted sandstone, with quartz pebbles, mud clasts and bone fragments as the main coarse components. The bones represent the poor preservation of vertebrate and small fragments of ribs that possibly belonged to small land vertebrates. These features, together with the well-rounded nature of the quartz pebbles, suggest terrestrial deposits that were probably reworked by tidal channels.

RHYTHMIC SEDIMENTATION OF THE BIN AFFIN MEMBER

As previously mentioned, the Bin Affin Member consists of three units. The lower and the middle units exhibit a clear rhythmicity (Fig. 2). The lower unit consists of several fining-upward rhythms (Fig. 2). The middle unit shows repeated sand sheets with abundant root-like bodies and a cross-bedded sandstone erosively overlies every sand sheet. Such rhythmic development is a common phenomenon in fluvial sediments (Turnbull et al., 1950; Allen, 1964; Allen and Friend, 1968; Miall, 1977) and may be attributed to many agents. The rhythms may reflect local causes (lateral migration of river channels coupled with isostatic adjustment of basin floor) or may be due to external agents (climatic changes and tectonic activity). Beerbower (1964) classified fluvial cycles as being autocyclic or allocyclic according to the cause of cyclicity. The allocyclothem is basinwide in contrast to the autocyclic cyclothem (Selley, 1982). Since the rhythms of the Bin Affin Member can be followed for more than 100 km, it seems likely that they should be assigned to the allocyclic type of Beerbower (1964).

ENVIRONMENTAL EVOLUTION

The sedimentary facies of the Bin Affin Member indicate deposition in a predominantly fluvial environment, commencing with a braided channel system (Fig. 3A) and gradually changing to a high sinuosity channel system (Fig. 3B) interrupted by occasional braided episodes. By the end of the Cretaceous (the uppermost part of the Bin Affin Member) ongoing transgression led to the replacement of fluvial by marginal marine (coastal, intertidal and subtidal) conditions (Fig. 3C).

COPPER-IRON-URANIUM MINERALISATION

Iron mineralisation has been recorded from many places in Libya. The largest and most famous iron ore occurrence is that of Wadi ash Shati. Copper, however, has not been described previously. As mentioned earlier, the mineralisation is restricted only to the root-like bodies of

the sand sheet facies, and has not been seen elsewhere. It has a wide areal distribution, covering an area at least 120 km long and 15 km wide (from Dur Waddan to Dur Al Messed) and may extend far beyond that. The mineralised zone can be easily distinguished in the field by its distinctive shape and reddish brown colour due to the associated iron minerals.

X-ray diffraction analyses (Fig. 4) have shown that iron is present in the form of hematite, copper in the form of azurite, malachite, bornite and cuprite and uranium in the form of uraninite. Reconnaissance X-ray dispersion analyses (Fig. 5 and Table 1) reveal that the copper content in the mineralised sandstone may be as much as 5% and that of iron is up to 25%. It was also a surprise that some of the analysed samples (1, 2, 3, 4 and 9) also contain a moderate concentration of uranium that may reach up to 0.1% in the form of the mineral uraninite, and this needs more detailed study.

MODE OF OCCURRENCE AND ORIGIN OF CU MINERALISATION

The copper minerals are found in the muddy sandstone in the form of speckles and blebs disseminated in the mineralised root-like bodies. Occasionally they are found to fill some small cavities or occur as thin films around quartz grains. Such modes of occurrence of the sediments

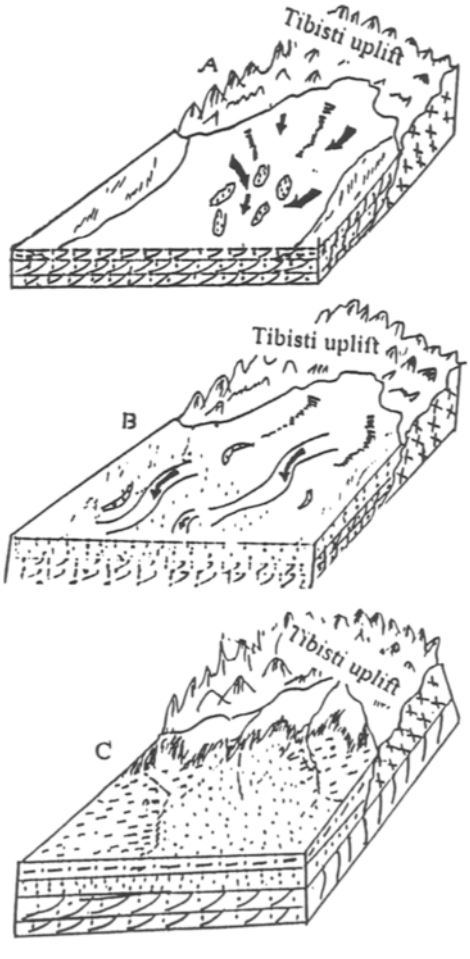

Figure 3. Simplified block-diagrams showing the sedimentological evolution of the Dur Waddan area during the deposition of the Bin Affin Member. A: Fluvial braided channel systems dominated the area, B: Low sinuosity channels became more dominant, C: Tidal conditions prevailed in the area.

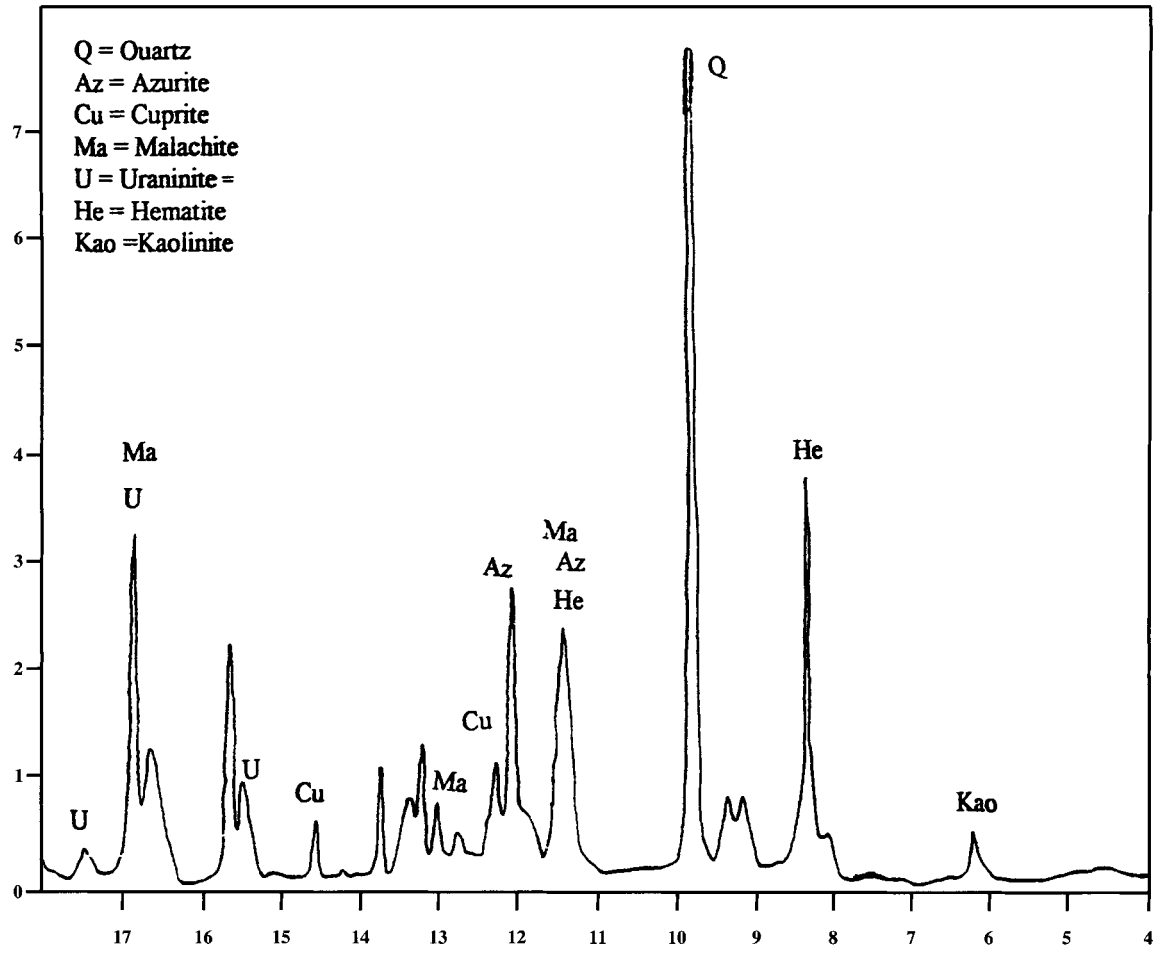

Figure 4. X-ray diffraction pattern of the mineralised sandstone of the Bin Affin Member, Dur Waddan area.

filling the sites of decaying roots and by the presence of organic materials that served as a reducing nucleus for iron and copper precipitation during very early stages of diagenesis. This is supported by the penecontemporaneous erosion and smothering of copper bearing units by cross-bedded sandstones that lack any sign of mineralisation. The selective distribution of the mineralisation in addition to the disseminated nature of iron-copper minerals indicates replacement processes (Jensen and Bateman, 1979). Many writers have established some sort of relation between the organic carbon clearly represent a preferential distribution, presumably enhanced by the higher porosity content and sedimentary copper ore (e.g. Haranczyk, 1961; Rentzsch, 1974; Annels, 1979). Edwards and Atkinson (1986) during their study of Zambian copper ore referred to a diagenetic origin of the ore involving the reduction of copper-bearing solutions by carbonaceous material. This may explain why the copper mineralisation of the Bin Affin Member is restricted only to the root-like bodies.

SOURCE OF COPPER

At the present time the sources of copper and the nature of possible ore bearing fluids are poorly understood (Edwards and Atkinson, 1986). Many writers favour a thick sequence of tholeiitic

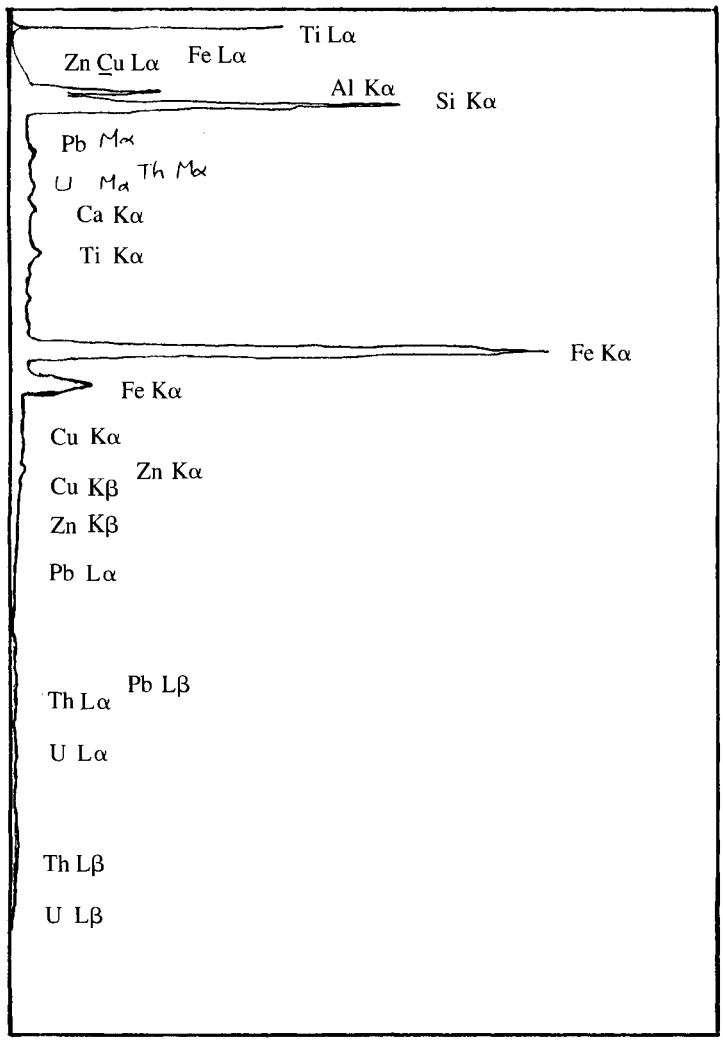

Figure 5. Energy dispersion pattern of x-ray analysis (EDAX) of the mineralised sandstone of the Bin Affin Member (sample 3).

Table 1. The chemical composition of the mineralised sandstone (%)

Element	Sample No.									
	1	2	3	4	5	6	7	8	9	10
Fe	28.92	22.62	30.62	24.44	31.36	25.89	33.21	32.21	50.41	29.92
Si	51.09	47.50	45.12	32.45	46.60	40.43	42.35	45.83	25.27	42.44
Al	17.43	6.79	20.78	12.78	20.14	7.88	21.30	20.49	21.36	20.29
Cu	0.60	0.17	0.42	0.34	0.48	0.17	1.17	0.46	0.65	0.89
Th	0.09	0.04	0.00	0.00	—	0.00	—	0.19	0.23	—
Zn	0.30	0.03	0.33	0.21	—	0.00	0.98	0.11	0.61	0.69
U	0.08	0.12	0.15	0.07	—	0.00	0.17	—	0.31	—
Ti	0.33	0.13	0.52	0.13	0.58	0.24	0.62	0.42	0.59	0.29
Ca	0.31	0.11	0.37	0.13	0.32	0.12	0.20	0.46	0.49	0.54

basalts beneath the sedimentary pile as a source of copper deposits while others suggest that the sediments themselves may be a possible source for the sediment-hosted copper ore. The Bin Affin copper mineralisation of the Dur Waddan area is surrounded by a large basaltic plateau (El Haruj) covering an area of about 40,000 square kilometres. At first glance one may think of El Haruj as a source of copper for the Bin Affin mineralised zones. However, El Haruj basalt (?mid-Eocene to Quaternary) is much younger than the Bin Affin sediments (Upper Cretaceous). Therefore, El Haruj basalt – as a source of copper for the Bin Affin mineralisation- does not fit with the early diagenetic evidence mentioned earlier. The sediments of the Bin Affin Member are in contact with a basement outcrop composed largely of granitoid rocks (granites, granodiorites, diorites). It is more likely that these granitoid rocks are the source of copper for the Bin Affin mineralisation.

SOURCE OF URANIUM

As mentioned above, the Bin Affin Member in the study area is in contact with a basement outcrop composed largely of granitoid rocks (granites, granodiorites and diorites). Goodell (1991) pointed to the Tibesti massif as a main source of uranium for the adjacent sedimentary basins (e.g. the Murzuq Basin and the Kufrah Basin). The Tibesti massif and the granitoid rocks of Dur Waddan are the most probable sources for the uranium content of the Bin Affin Member. Since the mineralisation is restricted to the root-like bodies described above, the organic material that resulted from the decay of the plant roots may also have played a role in the stabilisation of the uranium from uranium-bearing fluids. Edwards and Atkinson (1986) pointed out that humic materials, formed by the breakdown of plant debris, are the most common type of organic adsorbents that can remove uranium from solution. Nash et al. (1981) suggested that the main role of organic matter is to adsorb the uranium and experiments by Giblin (1980) showed that uranium is adsorbed on kaolinite.

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CHAPTER 18

The rubidium-strontium geochronology of the Pan-African post-orogenic granites of the eastern Tibisti orogenic belt, Tibisti Massif, South-central Libya: Application to origin and tectonic evolution

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ABSTRACT

Post-orogenic granites give clear evidence for the last phase of the Pan-African orogeny that led to the stabilization of the accreted Eastern Tibisti orogenic belt. This type of granite is widespread in the Jabal Eghei (Nugay) area and along the Eastern Tibisti orogenic belt (eastern and southern parts of the Tibisti massif).

The Addaba Mohamed Salah, Kangara, and Kangara-Tushidi plutons are generally mesozonal (7–16 km), discordant, zoned, and have outward dipping contacts. The granites range in composition from hornblende-biotite, two-feldspar, and quartz granites through biotite to two-mica granites.

The post-orogenic Cambrian granites and cogenetic rhyolites of the Jabal Eghei area are the Eghei Magmatic Series ranging in age from 554 to 528 Ma. The range of initial $^{87}Sr/^{86}Sr$ of 0.7044 to 0.7079 for these rocks suggests that they were derived from a middle crustal source. Upper crustal materials did not significantly contaminate the Addaba Mohamed Salah and Kangara granites. Some upper crustal contamination has affected the Kangara rhyolites and the Kangara-Tushidi pluton.

The post-orogenic magmatism associated with the stabilization and cratonization of the Tibisti massif was followed by an extensional tectonic regime, which prevailed in the Pan-African orogenic belts during a period of 50 Ma, from 500 to 450 Ma, in northern Africa.

INTRODUCTION

The study area is in south-central Libya (The Great Socialist Peoples Libyan Arab Jamahiriya) on the northeastern fringe of the Tibisti massif (19°00′00″ to 19°46′10″ E,22°49′38″ to 23°45′ N). This northeastern part of the Tibisti is called Jabal Eghei (Nugay) (Fig. 1). The geology of Jabal Eghei and the Tibisti massif is discussed in a separate paper about the tectonics of the Tibisti massif (El-Makhrouf, 1988). Also, the tectonics of the Tibisti massif and its application to regional tectonics has been discussed in a paper about the Tibisti-Sirt orogenic belt (El-

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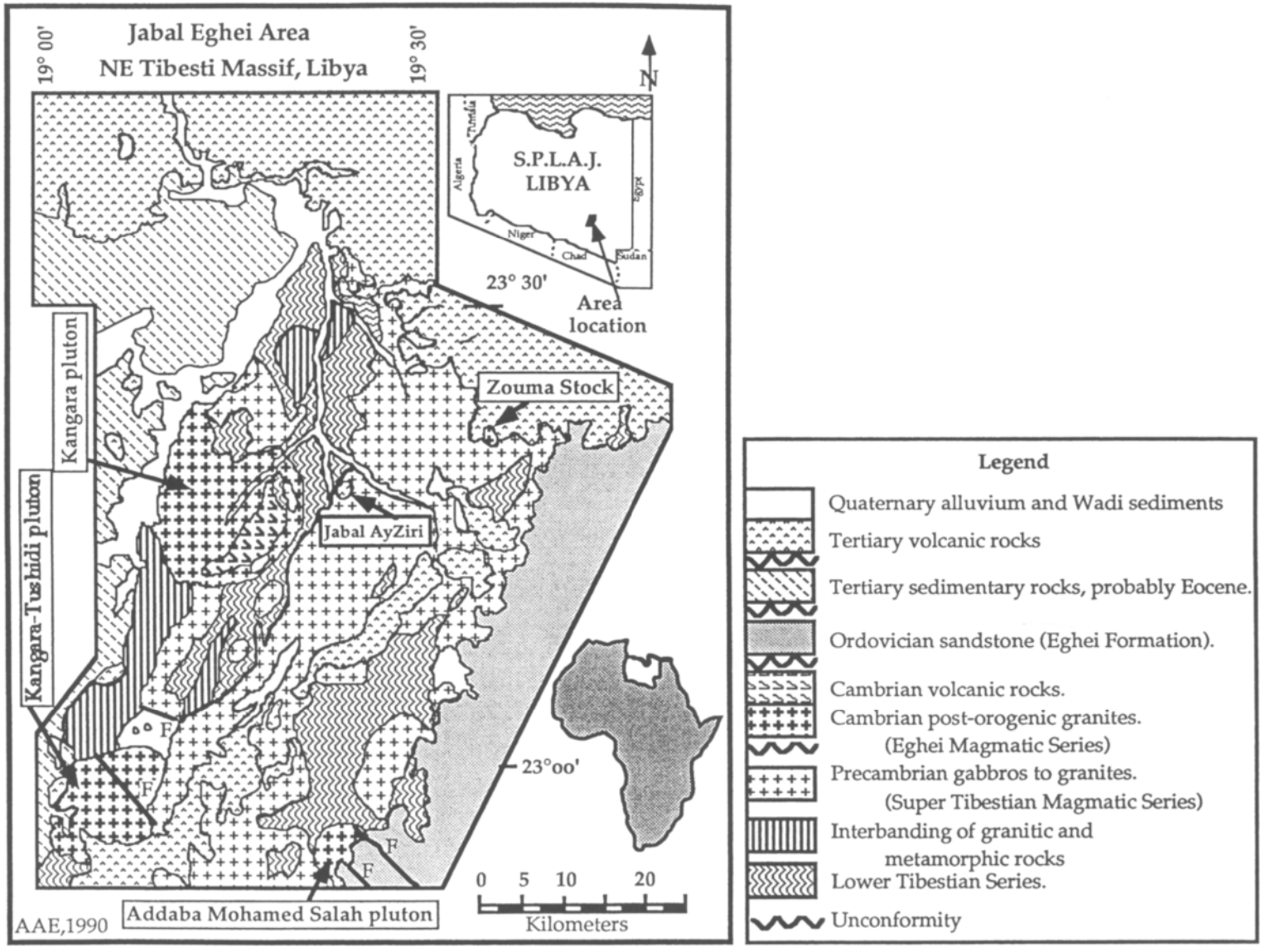

Figure 1. Location map of the post-orogenic plutons in Jabal Eghei area, NE Tibisti massif, after El-Makhrouf (1991), with inset showing location of study area.

Makhrouf, 1996). The best exposures are in the Jabal Eghei area, the southern-central portion of the massif, and the Bin Ghanimah (Ben Ghnema) batholith in the northwestern part of the massif.

The oldest rocks exposed in the eastern Tibisti massif are the Lower Tibestian and Upper Tibestian series of Middle to Late Proterozoic age (El-Makhrouf, 1988). These sedimentary and volcanic rocks have been metamorphosed to upper greenschist and almandine amphibolite facies. These rocks were deformed and metamorphosed in late Proterozoic time and are cut by syntectonic granitoids of late Proterozoic age and by Cambrian post-orogenic granitic plutons and related rhyolitic volcanics. These plutons and associated extrusive rocks are referred to as the Eghei Magmatic Series (El-Makhrouf, 1984).

El-Makhrouf (1984, 1988) used the term 'alkali granites' for the Cambrian post-orogenic granites according to Rogers et al. (1978). However, this terminology is not consistent with IUGS recommendations for the classification of felsic plutonic rocks (Streckeisen, 1976), which defined 'alkali granites' as granites containing alkali amphibole and/or pyroxene. According to the IUGS scheme the modal compositions of the post-orogenic Cambrian granites of the Jabal Eghei area (Tibisti massif) plot within the monzogranite and part of the syenogranite fields. Only the amazonite granite of the Zouma stock (El-Makhrouf and Feiss, 1997) plots within the alkali feldspar granite field of Streckeisen (1976).

This chapter describes the geology, field relations, and Sr isotope geochronology of the Eghei Magmatic Series. We also compare the Sr isotopic compositions of the Upper Tibistian and Eghei Magmatic Series of this area to those for the Wadi Yebigue pluton and the Bin Ghanimah batholith. The Eghei Magmatic Series is significant in understanding the evolution of the Eastern Tibisti Orogenic belt (eastern part of the Tibisti massif) during the Pan-African (1200 – 500 Ma; Fleck et al., 1980; Hashad, 1980; Stoeser and Camp, 1985; Kröner et al., 1987). Also, this chapter compares the style of evolution of the eastern Tibisti Orogenic belt to that of the Arabian, Nubian, and the Hoggar shields.

PREVIOUS WORK

Previous studies in the Tibisti massif have concentrated on the northern and southern portions of this province. Existing geological maps include those of Desio (1940), Conant and Goudarzi (1967, 1977), Klitzsch (1966) and Goudarzi (1980). A geological map (1:250 000) of the Jabal Eghei area was prepared by Hunting Geology and Geophysics (1974) for the Industrial Research Centre, Tripoli, Department of Geological Research and Mining. This map is used as a base map for this study. A total intensity aeromagnetic map of the Jabal Eghei (Nugay) area was published by the Industrial Research Centre (1978). Missallati et al. (1979) used geological, geophysical and Landsat data for the Wadi Kemeha area (5 km south of the Jabal Eghei area) in a uranium exploration program.

Ghuma (1975) studied the geology and geochemistry of the Pan-African calc-alkalic granitoids of the Bin Ghanimah batholith on the northwestern fringe of the Tibisti massif. Nagy et al. (1976), Pegram et al. (1976), Ghuma and Rogers (1978), and Rogers et al. (1978 and 1980) carried out more detailed geochemical studies on the same samples. Fullagar (1980) compared the initial 87Sr/86Sr values for the Bin Ghanimah batholith to values obtained for similar age granites from Egypt. Suayah (1984) and Suayah and Rogers (1986) studied the Wadi Yebigue pluton, south-central Tibisti.

El-Makhrouf (1984, 1988) studied the Jabal Eghei area and suggested that the Tibisti massif formed by accretion of two orogenic belts (Eastern Tibisti and Western Tibisti) during the late middle to late Proterozoic. El-Makhrouf (1996) concluded that the late Proterozoic and early

Phanerozoic subsurface basement of the Sirt Basin and southward to the Tibisti Mountains were formed as one orogenic belt called the 'Tibisti-Sirt Orogenic belt'.

GEOLOGY OF JABAL EGHEI AREA

The Jabal Eghei area contains six major rock sequences as summarized by El-Makhrouf (1988) (Table 1):

- Late Proterozoic metamorphic rocks – Lower Tibistian and Upper Tibistian series according to the classification of Wacrenier et al. (1958),
- Super Tibistian Magmatic Series (calc-alkalic rocks, El-Makhrouf, 1988),
- Eghei Magmatic Series (El-Makhrouf, 1988),
- Palaeozoic sedimentary rocks,
- Tertiary sedimentary rocks,
- Tertiary volcanics.

The three granitic plutons (Fig. 1) described herein form part of the Eghei Magmatic Series. They are zoned from hornblende-biotite two-feldspar granite to biotite granites and minor intrusions of two-mica granites at the pluton center. The plutons have contacts that dip outwards and are mesozonal (7 to 16 km, Hughes, 1982), (Table 1) and discordant. Intrusion of post-orogenic granites was followed by emplacement of pegmatites, aplites, quartz veins, and finally, diabase dikes.

INDIVIDUAL UNITS

Addaba Mohamed Salah Pluton (AMS)

The semicircular AMS pluton (Fig. 1) is reversibly zoned and located on the southeastern margin of the study area. The AMS pluton consists of medium-grained sphene-biotite at the margin to coarse-grained sphene-hornblende-biotite granite in its interior.

The northern margin of the AMS is in contact with calc-silicates, mica schist, and quartzite. On the western side, the contact is covered by Cenozoic sediments. At the southern end, the contact is sharp, dipping outwards against mica schist, calc-silicates, and the Super Tibestian magmatic rocks.

Kangara Pluton (KAN)

The KAN pluton (Fig. 1) is the largest of the post-orogenic granitic plutons. This pluton is gradationally zoned from hornblende-biotite granite on the outside, to biotite granite and minor intrusions of two-mica granites at the pluton center. Pink granites with two-micas and cataclastic hornblende-biotite granite occur in the northeastern part of the pluton. Contacts at the western edge are obscured by Cenozoic sediments. Abundant felsic dikes of quartz and feldspar porphyry, rhyolite, and granophyre are probably late magmatic differentiates. Some dikes may have been feeders for felsic lava flows.

Kangara Volcanics (KANV)

The dacitic to rhyolitic extrusive rocks form a crescent-shaped body overlying the eastern side of the KAN pluton (Fig. 1). This exposure includes a roof pendant of the Super Tibestian

Table 1. Rb-Sr Isotopic data, Jabal Eghei area. Measured Sr isotopic ratios are fractionation corrected to $^{86}Sr/^{88}Sr = 0.1194$ and reported to $^{87}Sr/^{86}Sr = 0.708$ for E & A standard. Lower Tibestian Series* and Super Tibestian Magmatic Series* are data from El-Makhrouf (1988).

Sample	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	ppm Rb	ppm Sr
I. Eghei Magmatic Series				
1. Addaba Mohamed Salah pluton				
62	0.74571	5.221	206	115
173	0.75872	6.864	207	88
174	1.76865	135.7	379	9
178	0.83386	16.84	263	46
179	0.78105	9.779	216	64
181	0.76318	7.524	221	85
186	2.02104	165.2	391	8
187	0.8343	16.51	235	42
191	0.81973	14.46	227	46
194	2.7055	254.5	483	7
2. Kangara pluton				
2-A. Granites				
54A	0.73115	3.236	207	186
102	0.78737	10.63	263	72
103	0.75974	6.946	225	94
109	0.75042	5.705	195	99
113	0.77366	8.427	219	76
236	0.72172	2.114	150	205
2-B. High-K rhyolites				
71	0.77683	9.238	222	70
74B	0.71395	0.933	70	218
77	0.72097	1.869	156	242
2-C. High-K dacite				
59	0.72189	2.176	150	200
60	0.73257	3.118	169	157
79	0.72720	2.758	141	148
54B	0.72952	3.035	169	161
54BXen	0.73429	3.599	167	134
2-D. Rhyolite dike				
239	0.84579	17.93	253	41
239B	0.83761	16.98	257	44
239C	0.83719	16.64	245	43
239CA	0.84428	17.79	237	39
239D	0.85063	18.40	251	40
3. Kangara-Tushidi pluton				
3-A. Granite				
120(a)	0.75191	5.843	233	116
120(b)	0.75140	5.774	230	116
133	0.76229	7.285	238	95
143	0.77000	8.208	244	87
160	0.72265	1.960	165	244
211	0.74806	5.330	211	121
214	0.76105	7.069	236	97
3-B. Silicified breccia Dike				
134	0.78196	10.50	142	39
145	0.79708	12.51	176	41
212	0.73698	4.114	136	96
213	0.78795	11.28	165	43

granodiorites and granites and metamorphic rocks of the Lower Tibestian Series above the KAN pluton. The volcanics include rhyolitic ash flow tuffs (ignimbrites), rhyolite tuffs, and lava flows of rhyolite porphyry, rhyolite, rhyodacite, and dacite.

Kangara Dike (KAND)

The dike is located within the eastern margin of the KAN pluton. The dike ranges in composition from dacite to rhyolite and is composed of quartz, K-feldspar, plagioclase, and biotite. The dike has granitic xenocrystic material in it. There are several dacitic to rhyolitic dikes throughout the pluton.

Kangara-Tushidi Pluton (K-T)

The elliptical K-T pluton (Fig. 1) consists of coarse-grained to porphyritic, leucocratic granite. The K-T pluton varies inwards from hornblende-biotite to biotite granite and minor intrusions of two-mica granites at its center. The pluton contains xenoliths of gneiss, diorite and granodiorite, ranging in size from a few centimeters to one meter long.

The K-T pluton is cut by minor intrusions of hornblende-biotite granite, biotite granite and two-mica granite as well as quartz, aplitic and pegmatitic veins. Dikes of cataclastic pink granite and silicified breccia cross the pluton. Small volcanic plugs, possibly of Tertiary age, also intrude the pluton.

Silicified Breccia (Fault zone, SBK-T)

The silicified breccia dike occupies a NW-SE fault zone that cuts the K-T pluton. This fault zone is about 9 km long and about 5 to 15 meters wide. The fault zone trend N50°W to N40°W and dip varies from 85°SW to vertical. The fault zone bifurcates at its western end to a stockwork of pegmatitic veins.

The fault zone is composed of a breccia and is affected by hydrothermal fluids. Cataclastic pink granites occur on both sides of the fault zone.

ANALYTICAL PROCEDURES

Rb and Sr analyses were made with a high resolution Nuclide Corporation Solid source, 30 cm radius-curvature, 90° direction-focusing mass spectrometer at the Geology Department of the University of North Carolina at Chapel Hill, U.S.A. Techniques of sample preparation and isotope dilution analysis were described by Kish (1983). Rb and Sr data are given in Table 1.

All measured Sr isotopic ratios were fractionation-corrected to $^{86}Sr/^{88}Sr = 0.1194$ and reported relative to $^{87}Sr/^{86}Sr = 0.708$ for the Eimer & Amend $SrCO_3$ standard. All isochron ages and initial $^{87}Sr/^{86}Sr$ ratios were calculated using York's model II cubic least squares linear regression (York, 1969), with a decay constant of $^{87}Rb = 1.42 \times 10^{-11}$ yr^{-1}. Uncertainties of one standard deviation are reported for all Rb-Sr ages and initial $^{87}Sr/^{86}Sr$ ratios (Table 2). The regression data were evaluated according to the recommended values of Mean Square of Weighted Deviates (MSWD) of Brooks et al. (1972). If MSWD < 2.5, the regressed Rb/Sr isotopic data are considered to define an isochron, but, if MSWD > 2.5, the regressed data result in an errorchron.

Table 2. Whole rock Rb-Sr data of Eghei Magmatic Series, the Super Tibestian Magmatic and Lower Tibestian Series of the Tibisti Massif (1 – this study; 2 – Fullagar, 1980; 3 – El-Makhrouf, 1988; 4 – El-Makhrouf, 1984; 5 – Pegram et al., 1976; 6 – Suayah and Rogers, 1986). NA = number of samples analyzed, *Ref = Reference, (C) = the data are recalculated, **MSWD = Mean Square of Weighted Deviates, MD = model date.

Pluton	NA	Age Ma	*Ref	$(^{87}Sr/^{86}Sr)_i \pm ISD$	**MSWD
1. Jabal Eghei Area					
1-A. Eghei Magmatic Series (Unit 1):					
Addaba Mohamed	10	552 ± 3	(1)	0.70436 ± 0.00047	1.1
Salah pluton	7	547 ± 6	(1)	0.70497 ± 0.00076	1.3
Kangara pluton	6	554 ± 6	(1)	0.70530 ± 0.00046	2.7
Kangara-Tushidi pluton	7	528 ± 7	(1)	0.70791 ± 0.00054	0.1
Zouma Stock	8	532 ± 7	(4)	1.24265 ± 0.19032	2.1
1-B. Eghei Magmatic Series (Unit 2):					
Kangara rhyolite	4	530 ± 7	(1)	0.70680 ± 0.00033	0.20
	7	537 ± 7	(1)	0.70650 ± 0.00030	5.36
KAN rhyolitic dike	5	559 ± 35	(1)	0.70330 ± 0.00882	2.56
SB dike (K-T)	4	499 ± 7	(1)	0.70767 ± 0.00079	0.22
1-C. Super Tibestian Magmatic Series: Raft exposure in					
Kangara pluton	3	560 ± 4	(3)	0.70529 ± 0.00009	0.04
1-D. Lower Tibestian Series:					
Calc-silicate	4	873 ± 12	(3)	0.70736 ± 0.00023	30.0
Metavolcanics	6	939 ± 52	(3)	0.70304 ± 0.00029	21.3
2. Wadi Yebigue pluton: Eghei Magmatic Series (Unit 1):					
2-A. Hornblende-Biotite Granite and					
Biotite Granite	6	558 ± 5	(6)	0.70640 ± 0.00039	2.06
2-B. Biotite Granite	4	548 ± 12	(6)	0.70690 ± 0.00218	0.56
3. Bin Ghanimah batholith: A. Super Tibestian Magmatic Series:					
Granite	9	537 ± 9	(2,5)	0.70617 ± 0.00033	2.16
Gabbro and	3	545 ± 7	(2,5)	0.70490 ± 0.00010	
granodiorite		575 ± 12	(C)	0.70511 ± 0.00024	5.44
Pegmatites	3	522 ± 5	(2,5)	0.70650 ± 0.00040	
	4	531 ± 4	(C)	0.70614 ± 0.00038	4.87
Aplite	1	545 ± 5	(2,5)	MD; 0.7065	
3-B. Whole-rock and biotite pair					
	15	529 ± 5 – 446 ± 5	(2,5)		

ISOTOPIC AGES

Rb-Sr isotopic compositions of three rock suites from the Jabal Eghei area are available:

- Lower Tibestian Series, metamorphic rocks,
- Super Tibestian Magmatic Series, and
- Eghei Magmatic Series.

Data for the first two rock series were reported by El-Makhrouf (1988) and will only be discussed briefly herein. The analyzed Eghei Magmatic Series samples are from the Kangara (KAN), Kangara-Tushidi (K-T), and Addaba Mohamed Salah (AMS) plutons, and the Kangara volcanics (KANV), Kangara dike (KAND), and the Silicified breccia (SBK-T):

Lower Tibestian Series

A six point whole-rock errorchron of the Lower Tibestian metavolcanic yields a date of 939 ± 52 Ma and Sr initial ratio of 0.70304 ± 0.00029 (El-Makhrouf, 1988). The Sr initial ratio of these volcanics plots above the upper mantle growth curve of Moorbath (1977). As the date obtained (939 Ma) probably is the time of metamorphism, then the extrusion and crystallization of these metavolcanics must clearly have occurred much earlier (El-Makhrouf, 1988).

Four calc-silicate samples yield an errorchron with a date of 837 ± 12 Ma and initial ratio of 0.70736 ± 0.00023 (Table 2) (El-Makhrouf, 1988). Based on available data and the Wilson tectonic cycle, El-Makhrouf (1988) suggested that the Lower Tibestian Series has a maximum age of 1314 Ma and a minimum age of 609 Ma, which is consistent with Middle to Late Proterozoic evolution of the Eastern Tibesti orogenic belt.

Super Tibestian Magmatic Series

Based on a whole-rock isochron age of 560 ± 4 Ma (with a Sr initial ratio of 0.70529 ± 0.00009) for a granodioritic roof pendant in the KAN pluton, El-Makhrouf (1988) suggested that the Super Tibestian Series rocks were formed during the late Proterozoic (Table 2).

Eghei Tibestian Magmatic Series

Addaba Mohamed Salah (AMS) Pluton. The whole-rock isochron age for 10 samples is 552 ± 3 Ma (Table 2, Fig. 2), with a Sr initial ratio of 0.70436 ± 0.00047. The 552 ± 3 Ma age is considered to be the age of emplacement.

Kangara Pluton. A six-point whole rock isochron (Table 2 and Fig. 2) gives an age of 554 ± 6 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70530 ± 0.00046. This age is considered to be the age of emplacement.

Kangara Volcanics (KANV). The Kangara rhyolites yield a four-point whole-rock isochron (Table 2 and Fig. 2) with an age of 530 ± 7 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70680 ± 0.00033 (El-Makhrouf, 1984). Three more samples with lower potassium contents were analyzed plus one mafic xenolith (Table 1). A whole-rock errorchron obtained for seven samples (Fig. 2, Table 2) gives an age of 537 ± 7 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70650 ± 0.00030.

Kangara Dike (KAND). A five-point isochron (Fig. 2, Table 2) gives an age of 559 ± 35Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.70330 ± 0.00882. The age obtained is indistinguishable from the KAN pluton age. Thus, the dike was formed relatively soon after the granite crystallized. The high $^{87}Rb/^{86}Sr$ values for the dike suggest that it could

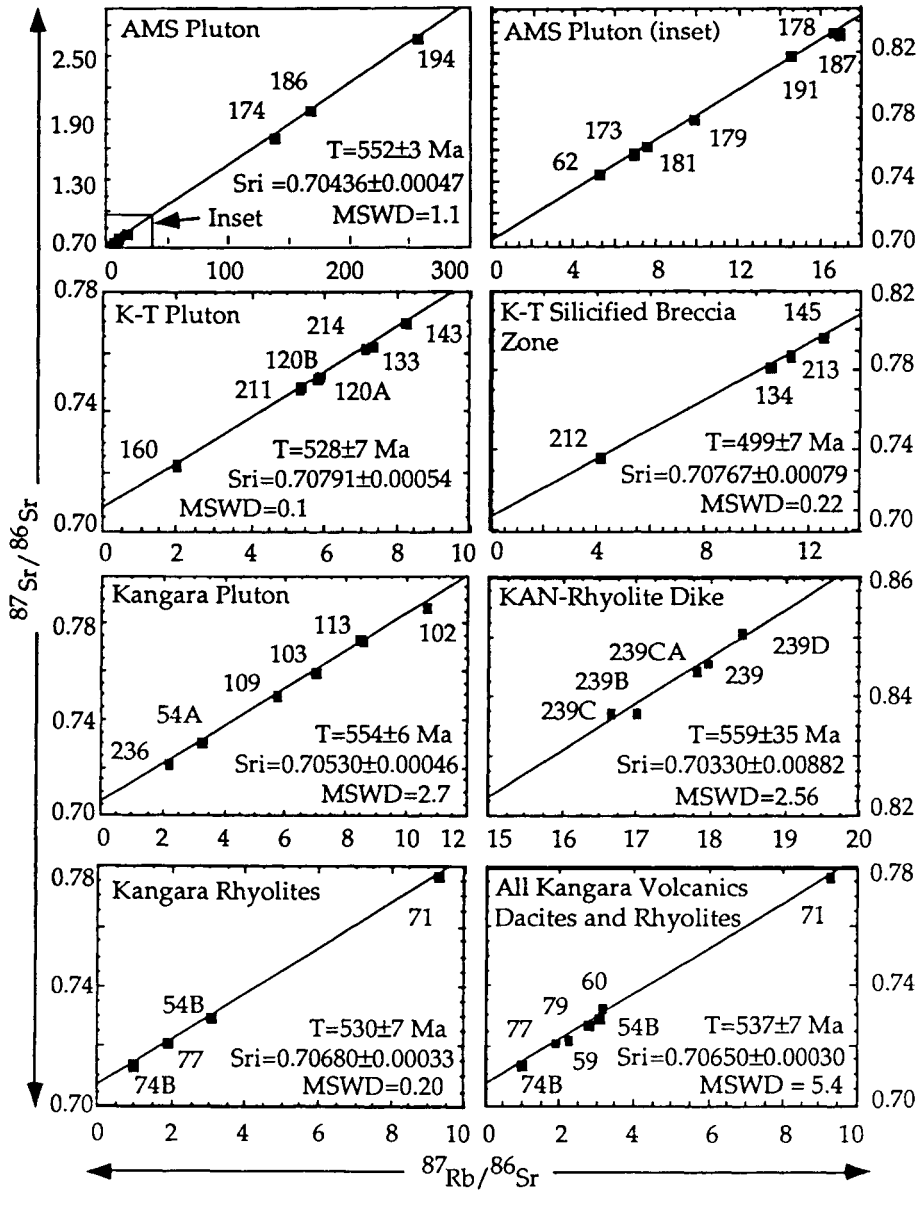

Figure 2. Isochrons and errorchrons for samples from the eastern Tibisti orogenic belt. AMS, Addaba Mohamed Salah; K-T, Kangara-Tushidi; KAN, Kangara; MSWD, Mean Square of Weighted Deviates; Sr_i, Strontium initial ratio; and T, Age or date.

have formed as a late stage differentiation product from the same magma source that produced the granite.

Kangara-Tushidi Pluton (K-T). A seven-point whole-rock isochron (Fig. 2, Table 2) gives an age of 528 ± 7 Ma, with a Sr initial ratio of 0.70791 ± 0.00054. This age is considered to be the age of emplacement.

Kangara-Tushidi Silicified Breccia Dike (K-T-SBD). A four-point whole-rock isochron (Fig. 2, Table 2) yields an age of 499 ± 7 Ma and a Sr initial ratio of

0.707671 ± 0.00079. This age suggests that an extensional event occurred no more than about 30 Ma after the emplacement of the K-T pluton.

IMPLICATIONS OF INITIAL $^{87}Sr/^{86}Sr$ RATIOS

Ages and initial $^{87}Sr/^{86}Sr$ ratios with one standard deviation errors for whole-rock samples of AMS, KAN, and K-T plutons of the Jabal Eghei area plus values for the KANV, KAND, and K-T-SBD are listed in Table 2. The ages range from 556 to 528 Ma. The youngest plutons (K-T and Zouma stock) have the highest initial ratios. The initial $^{87}Sr/^{86}Sr$ ratios for the AMS and KAN plutons and KANV are low and fall close to values expected if their magmas were derived from the upper mantle (Moorbath, 1977). Sr isotopes cannot discriminate between magmatic source regions in the lower crust and the upper mantle (Moorbath and Taylor, 1986).

Generation of large amounts of granitic melts from the upper mantle is not petrologically reasonable (Brown and Hennessy, 1978; Pitcher, 1982; Jackson, 1986a, b). The most plausible source for the generation of these granites is lower crustal parental rocks. El-Makhrouf (1984, 1988) suggested that the granites of the Eghei Magmatic Series of the Jabal Eghei area were derived from a parent in the lower crust of calc-alkaline composition. The initial $^{87}Sr/^{86}Sr$ ratios of the K-T pluton and the KANV are sufficiently high to suggest the influence of Late to Middle Proterozoic sialic crust (i.e. high Rb/Sr).

Figure 3 is a variation diagram of initial $^{87}Sr/^{86}Sr$ ratios and corresponding Rb/Sr ages for the Super Tibestian and Eghei Magmatic Series rocks. All initial Sr ratios for post-orogenic granites plot between the strontium growth curves for the metavolcanics of the Lower Tibestian Series. This suggests that the granitic magmas of the Eghei Magmatic Series of the Tibesti massif were generated by partial melting of lower crustal source rocks of similar chemical and isotopic composition to the metavolcanics of the Lower Tibestian Series which are about 1000 Ma old.

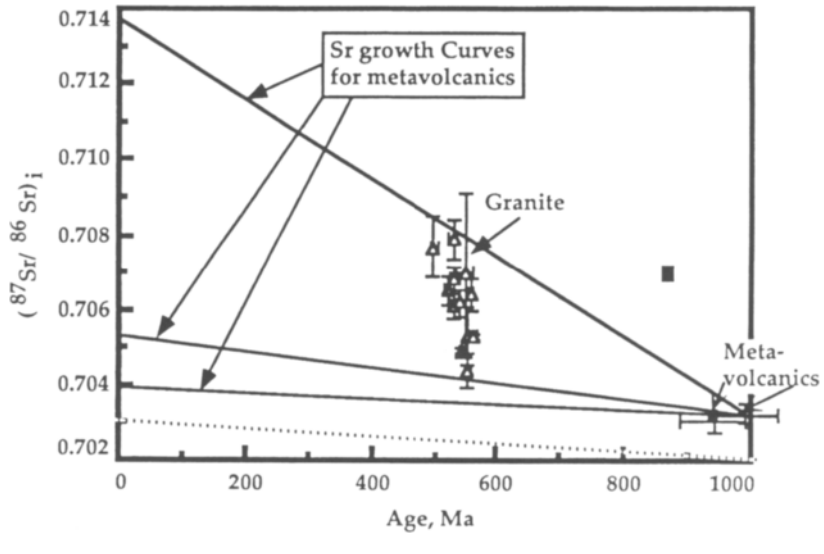

Figure 3. Sr isotopic evolution diagram plus data for the Eghei Magmatic Series (post-orogenic granites) of the Tibisti massif, with Sr growth curves for the metavolcanics of the Lower Tibestian Series in the Eastern Tibisti orogenic belt (El-Makhrouf, 1988). The closed rectangle symbol is for calc-silicates of the Lower Tibestian Series (Eghei area). The dotted line is a hypothetical linear upper mantle Sr growth line drawn according to Moorbath (1977). The solid lines imply a constant Rb/Sr ratio.

The lower crustal source had $^{87}Sr/^{86}Sr$ of 0.70304–0.70324 with a range of Rb/Sr of 0.0144 to 0.253 (El-Makhrouf and Fullagar, 1988).

This model is consistent with the models of Jackson et al. (1984) and Jackson (1986: Fig. 8) for the generation of Arabian Shield post-orogenic granites. These models propose that the post-orogenic granites are the products of simple fusion of either an island arc calc-alkaline crust with a small degree of partial melting, or continental crust with a large degree of partial melting.

A plot (Fig. 4) of initial Sr ratios versus ages for the AMS, KAN, and K-T plutons, the KANV, the Jabal Bin Ghanimah batholith (Pegram et al., 1976; Fullagar, 1980), and the Wadi Yebigue pluton (Suayah and Rogers, 1986) show that the Sr initial ratios increase with decreasing age. This suggests that the Tibisti massif evolved to a thicker sialic crust with time during the Pan-African orogeny.

EXTENSIONAL TECTONICS

The widespread occurrence of post-orogenic extensional tectonics in the Pan-African belts is indicated by dike swarms (mafic to felsic composition) and peralkaline granites. The presence of rhyolitic and diabase dikes in the eastern part of the Tibisti massif is indicative of the predominance of extensional stresses in the region. El-Makhrouf (1988) reported the intrusion of diabase dikes (500 Ma?) through the Lower Tibestian, Super Tibestian and Eghei Magmatic Series in the Jabal Eghei area.

Rhyolitic, microgranitic, granophyric, pegmatitic, and aplitic dikes are also present in the area. The K-T silicified breccia dike occupies a NW–SE fault zone that cuts the K-T pluton. Also, a fault with the same trend cuts through the northernmost part of the AMS pluton. Other faults of similar trend are present in the region, but have not been studied in detail. These

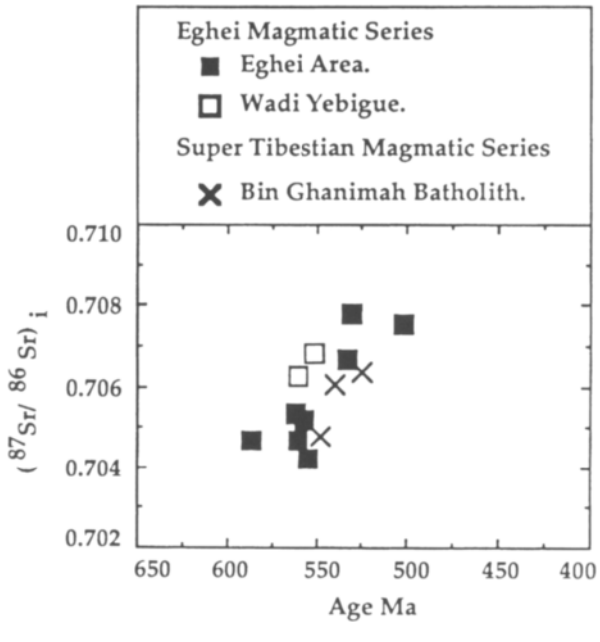

Figure 4. Initial $^{87}Sr/^{86}Sr$ ratios versus Rb/Sr ages for the post-orogenic granites (this study) of the Jabal Eghei area, Bin Ghanimah batholith (Fullagar, 1980) and two data points for the Wadi Yebigue pluton (Suayah and Rogers, 1986).

features are related to the aborted rifting stage (500 Ma) suggested by El-Makhrouf (1988), which is associated with the intrusion of diabase dikes.

The end of the Pan-African event in northern Africa was marked by extensional tectonism. The timing of this event has been estimated to be 450 Ma (Kennedy, 1964), 500 Ma (Gass, 1977; Harris et al., 1984), and 493 ± 7 Ma to 476 ± 2 Ma (Abdel Rahman and Doig, 1987), and 500 to 400 Ma (Ajibade and Woakes, 1987).

CRATONIZATION OF THE TIBISTI OROGENIC BELTS AND THEIR RELATION TO THE PAN-AFRICAN OROGENIC BELTS OF N AFRICA AND ARABIA

Kennedy (1964) defined the Pan-African event as a thermo-tectonic episode dated to 500 ± 100 Ma based on K-Ar ages. Kröner (1984) redefined the Pan-African as a series of orogenic processes that included all tectonic, magmatic and metamorphic events that were associated with the differentiation of the African continent into cratons and mobile belts towards the end Precambrian. The time span of the Pan-African as Kennedy (1964) had defined it has been a matter of debate. Al-Shanti (1979) adopted a time span of 1200 to 450 Ma BP for the Pan-African events that dominated the evolution of the Arabian-Nubian shield. Kröner (1984) suggested a time period from 950 to 450 Ma for the Pan-African events that led to the evolution of Africa as a stable continent through accretion and cratonization. This time span includes the Arabian-Nubian shield. Most authors now agree that northeastern Africa and Arabia developed typical continental crust over a period of 700 Ma (1200–500 Ma; Fleck et al., 1980; Hashad, 1980; Gass, 1982). Rogers and Greenberg (1981) suggested that the post-orogenic granites represent part of the process that leads to development of stable cratons by addition of new sialic material that thickens the continental crust.

A comparative study of the evolution of the Tibisti orogenic belts, the Arabian-Nubian shield, and the Touareg shield is important (Fig. 5). This discussion is vital to understanding the accretion processes that led to the evolution and stabilization of the African continent during the Pan-African orogeny.

El-Makhrouf (1988) concluded that the Tibisti massif was formed during the Pan-African from two accreted orogenic belts: the eastern Tibisti orogenic belt (Jabal Eghei area and southward) and the western Tibisti orogenic belt (Bin Ghanimah batholith). The two orogenic belts were amalgamated during the Early to Middle Cambrian. During the stress relaxation period (570 to 500 Ma) the Eghei Magmatic Series magmas were generated at depths of 24 to 25 km and intruded to depths of 11 to 13 km into the upper crust (El-Makhrouf, 1992). These post-orogenic granites and their cogenetic volcanics are 'crustal nails' (Anderson, 1987) that led to the stabilization of the Tibesti massif (Rogers and Greenberg, 1981, Brown, 1981).

The evolutionary phases of the Tibisti orogenic belt (Ghuma and Rogers, 1978; El-Makhrouf, 1988), the Arabian (Greenwood et al., 1976, 1982; Al-Shanti, 1978; Deflour, 1979, Schmidt et al., 1979; Fleck et al., 1980; Gass, 1981, 1982; Camp, 1984; Stoeser et al., 1984; Stoeser, 1986), the Nubian (Ries et al., 1983; Kröner et al., 1987), and the Touareg (Hoggar massif) shields (Bertrand and Caby, 1978; Bertrand et al., 1978; Caby et al., 1981; Caby, 1987) during the Pan-African orogeny are illustrated graphically in Figs. 5 and 6. These demonstrate that these orogenic belts, in general, have evolved through two stages: Rifting and opening of small ocean basins (1200–800 Ma), followed by subduction and magmatism (600–450 Ma) (Ghuma and Rogers, 1978; Stoeser et al., 1984; Stoeser, 1986; Kröner et al., 1987; Stern, 1985; Stern and Hedge, 1985; El-Makhrouf, 1988; 1996). The accretion of the Tibisti plates took a longer period of time than that of the Nubian and Arabian plates (Fig. 6). However, the Tibisti collision magmatic stage took the same time span as that of the Touareg shield. Thus, the continental crust

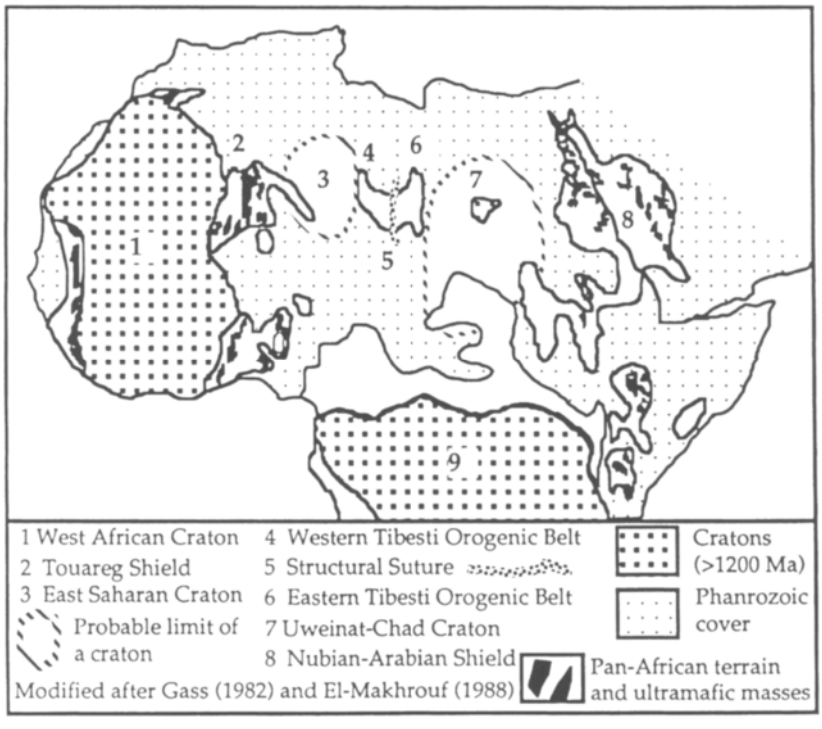

Figure 5. A Pre-Phanerozoic tectonic map of northern Africa and Arabia, modified after Gass (1982) and El-Makhrouf (1988).

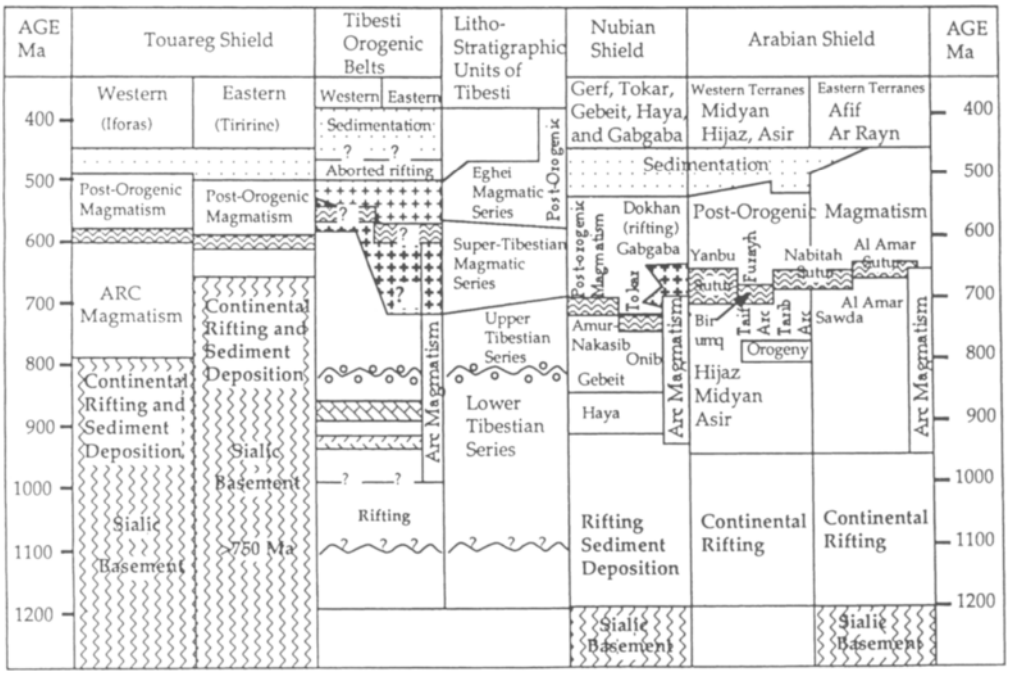

Figure 6. A comparative diagram of the tectonic evolution of the Tibisti orogenic belts (this study and El-Makhrouf, 1988), the Arabian Shield (Stoeser and Camp, 1985), the Nubian Shield (Ries et al., 1983; Stern and Hedge, 1985; Kröner et al., 1987), and the Touareg shield (Hoggar massif) (Caby, 1987). The horizontal wavy pattern show the sutures, the vertical wavy pattern show the presence of older Proterozoic continental crust, the bold plusses show syn-orogenic granitoids, the light plusses show post-orogenic granites and the dotted pattern shows the distribution of Paleozoic sediments.

of the Eastern Tibisti Pan-African orogenic belt evolved from the late Proterozoic to early Palaeozoic, as did the Nubian-Arabian shield.

CONCLUSIONS

We conclude that:

1. The post-orogenic granites and rhyolites formed as a result of differing degrees of partial melting of a middle to lower crustal source. This crustal source has a similar isotopic composition to the supracrustal metavolcanics of the Lower Tibestian Series.
2. These granitic products of partial melts were emplaced into upper crust between 554 Ma and 528 Ma.
3. The $^{87}Sr/^{86}Sr$ initial ratios for all the plutons and their cogenetic volcanics are within a range of 0.7033 to 0.70791, suggesting the influence of the assimilated upper crustal rocks.
4. The Tibisti orogenic belts evolved during the same time period as those of the African and Arabian Pan-African belts.

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Geological Exploration in Murzuq Basin
M.A. Sola and D. Worsley, editors.

CHAPTER 19

Seismic expressions of depositional processes in the upper Ordovician succession of the Murzuq Basin, SW Libya

JERRY SMART[1]

ABSTRACT

The Mamuniyat Formation is the principal reservoir in the upper Ordovician succession of the Murzuq Basin. It has hitherto been assumed to have a ubiquitous occurrence beneath the base Silurian subcrop. Previous depositional models for the Mamuniyat Formation describe outwash alluvial fans at the southern margins of the basin passing into a northwesterly trending braided fluvial system. Towards the northwest, marginal marine facies are noted as alternating with the dominantly fluvial lithofacies. Detailed investigation of 2D seismic data in block NC174 has resulted in a more complex depositional model. An intra-Ordovician unconformity surface has been mapped as a major sequence boundary dividing the Ordovician into 'pre-glacial' and 'glacial' megasequences. The latter comprises the Mamuniyat Formation, which was deposited above the unconformity during a period of late Ordovician glaciation.

The intra-Ordovician unconformity surface exhibits significant morphological relief. Seismic event onlap, truncation and termination are observed and associated with discrete incised valley fairways. Within these incised valleys, the Mamuniyat Formation comprises either fluvial or sub-ice channel deposits. Continued deposition filled in most of the erosional topography and widespread channel systems developed. At least two anastomised channel systems are interpreted to have developed across the block. A number of discrete mounded features are mapped which are interpreted as glacial landforms of one kind or another.

In areas not markedly affected by local end-Ordovician fault activity and erosion, the early Silurian transgressive event (associated with the cessation of regional glacial conditions) resulted in the deposition of organic rich 'hot shales' of the Tanezzuft Formation across the block. This flooding surface is a major unconformity separating the upper Ordovician glacial sequence from the lower Silurian marine transgressive sequence.

INTRODUCTION

The Murzuq Basin, located in southwestern Libya, is one of a number of intracratonic basins located on the Saharan Platform of North Africa (Fig. 1). The basin contains a sedimentary fill

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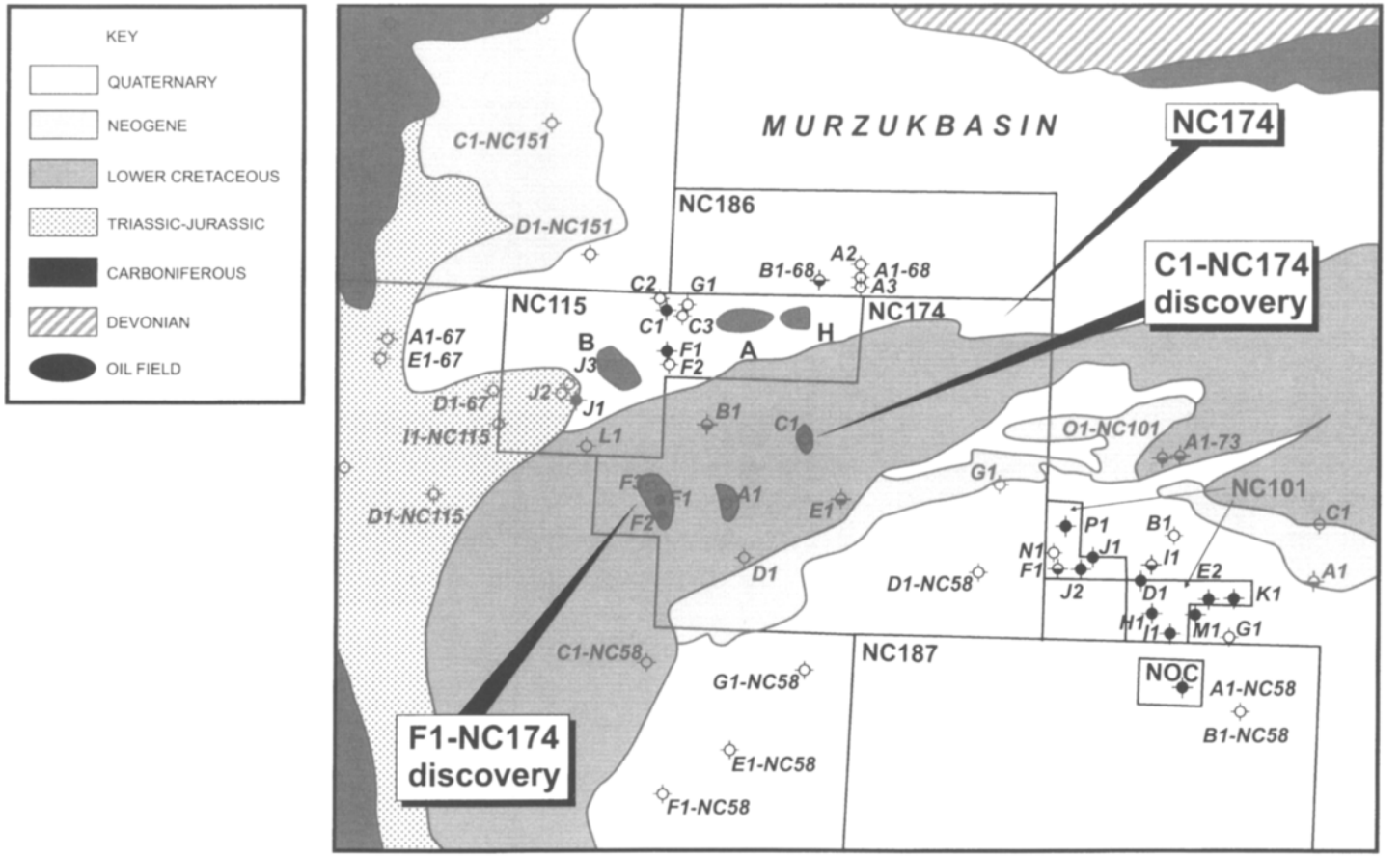

From: Geological map of Libya, Industrial Research Centre, 1985 and other sources.

Figure 1. NC174 Location Map.

with a thickness of about 4 km in the basin centre and consists of a fluvial to marine Palaeozoic succession overlain by continental Mesozoic strata. The principal reservoirs in the Murzuq Basin are the sandstones of the upper Ordovician Mamuniyat Formation, which are generally capped and charged by shales of the lower Silurian Tanezzuft Formation (Fig. 2). Successful exploration in the Murzuq Basin is to a large extent governed by the presence of good quality and productive Mamuniyat sandstones. To date this has proved difficult to predict.

The interpretation of the processes responsible for the deposition of the Ordovician succession in the Murzuq Basin has largely been based on outcrop studies together with scattered exploration well data. Latterly, 2D and more recently 3D seismic data have been acquired, some of which are of sufficient quality to give further insight into depositional processes. However fundamental data constraints, such as poor biostratigraphic resolution, have hindered the development of a robust predictive depositional model for the Ordovician that is consistent with both local and regional observations.

Detailed mapping of 2D seismic data across the Lasmo Grand Maghreb Limited (LGML) operated NC174 concession has resulted in a revised depositional model dividing the Ordovician into 'pre'- and 'glacial' megasequences. Within the glacial megasequence, which essentially comprises the Mamuniyat Formation, two distinct channel fairways have been interpreted which may be the product of conventional and/or sub-glacial fluvial processes. These channel fairways can be used as a framework for detailed facies modelling and thus for reservoir quality prediction within the basin.

For the purposes of clarity, 'glacial' and 'fluvio-glacial' deposits are defined here as sediments deposited in an environment where ice sheets and/or glaciers were developed and locally,

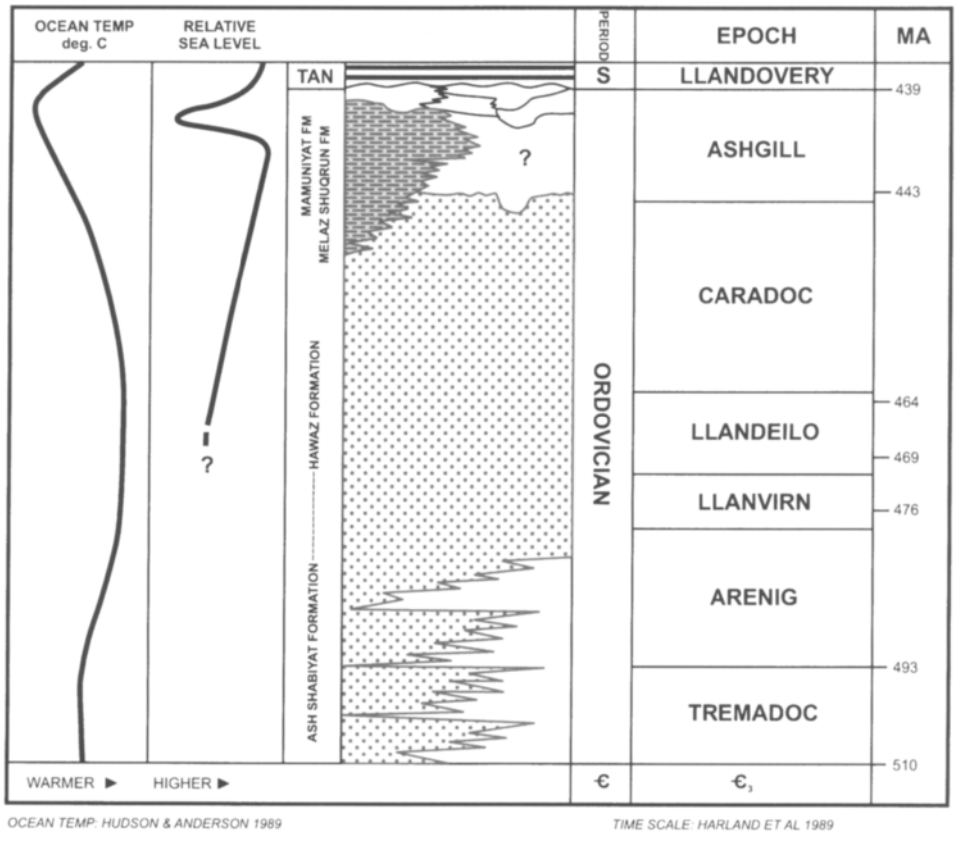

Figure 2. Generalised stratigraphy of the Ordovician of the Murzuq Basin.

directly or indirectly, influenced depositional processes, the resultant landforms and sedimentary body morphology.

SEISMIC INTERPRETATION

Previous interpretations of 2D seismic data in NC174 have concentrated on structural mapping. These data were seen to contain some geological/facies information, but this was not systematically interpreted. The interpretation presented herein is based on LGML's proprietary and traded 2D seismic database, comprising some 6355 km in total. The resultant seismic coverage approximates to a 4 by 4 km grid across much of the block, although this becomes coarser in places. The interpretation has been performed using the Schlumberger Geoquest© IESX platform, with all seismic data normalised with respect to amplitude.

Within the Cambro-Ordovician seismic interval, between the interpreted picks for the base Silurian (light blue on the seismic figures) and basement (red on the seismic figures), numerous local packages of reflectors and seismic 'anomalies' have been identified and mapped. The majority of these packages onlap and terminate against a surface that also appears to incise and truncate the underlying section (Figs 3 and 4). The few well penetrations of this surface generally correlate to a stratigraphic position at or near the base of the upper Ordovician (the Melaz Shuqran Formation). Notwithstanding that well-to-seismic ties are difficult to establish owing to poor biostratigraphic control and relatively low seismic resolution, this reflector is interpreted to be an intra-Ordovician unconformity (black dashes on the seismic figures). This records the transition from the fluvial to marginal marine sediments of Cambrian to earliest late Ordovician (Caradoc to early Ashgill) age to fluvio-glacial deposits of the late Ordovician (middle to late Ashgill). This occurred following a major fall in relative sea level and subsequent base level rejuvenation associated with the onset of the well-documented late Ordovician Gondwanan glaciation event (Brenchley et al. 1994).

Seismic reflectors in the glacial megasequence above the intra-Ordovician unconformity generally have a coherent character, often forming packages of reflectors which onlap and terminate onto the unconformity surface. The seismic package beneath the unconformity – which exhibits significant topography interpreted to be the result of incision – have mostly weak and discontinuous seismic reflectivity, although occasional angular truncation is observed. This package is interpreted to represent the pre-glacial megasequence.

A simplified time thickness map of the sediments between the intra-Ordovician unconformity and the base Silurian reflector illustrates the distribution and thickness trends of the glacial megasequence (Fig. 5). This reveals several northwest-southeast trending time thicks which, when constrained by the termination and onlap of shallower reflectors onto the intra-Ordovician unconformity, define a number of discrete depositional fairways within the block. Seismic profiles reveal that the time thicks are located within steeply sided valleys forms incised into the underlying strata (Fig. 6). These valleys probably formed during the initial phase of late Ordovician glaciation and are flanked by bypassed zones comprising middle Ordovician or older strata. Within the valleys, and restricted to them, are the initial deposits of the glacial megasequence. However, elsewhere in NC174, apparently also within the initial valley fairways, are discrete areas where the glacial megasequence is absent and it is believed that this reflects local fault activity during the late Ordovician (Fig. 5). An example of this is the structure that was tested by well C1-NC174 (Fig. 7). Here, the glacial megasequence appears to onlap the intra-Ordovician unconformity down-dip to the southwest of the well location. The age of the Ordovician succession penetrated in this well is equivocal as the age of the cored interval at the top of the section is indeterminate. However, the section comprises marine sediments intensely bioturbated with pervasive vertical burrows (*Skolithos*), a facies often associated with the lower

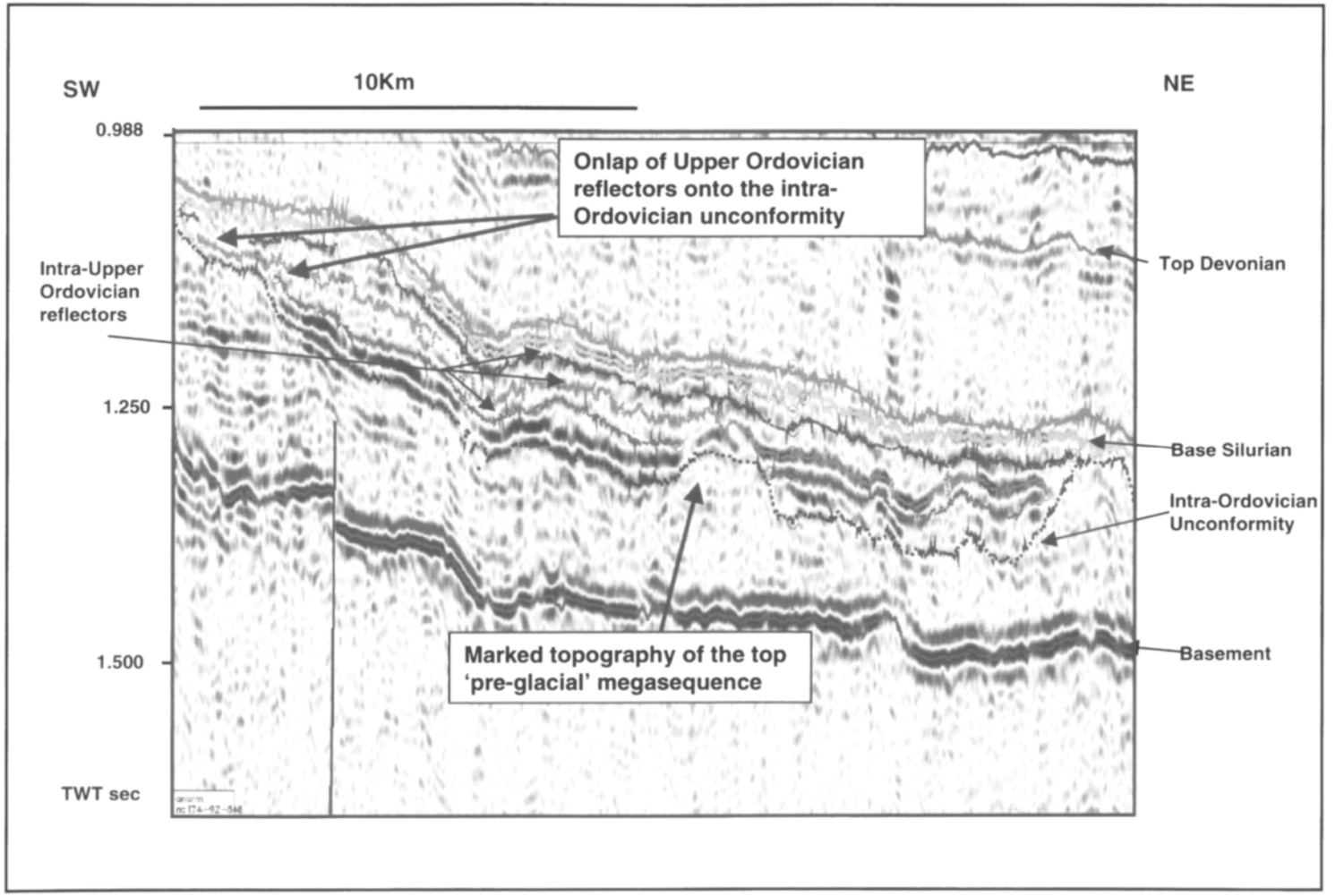

Figure 3. Example of the intra-Ordovician unconformity: southwestern limit of major incised channel fairway.

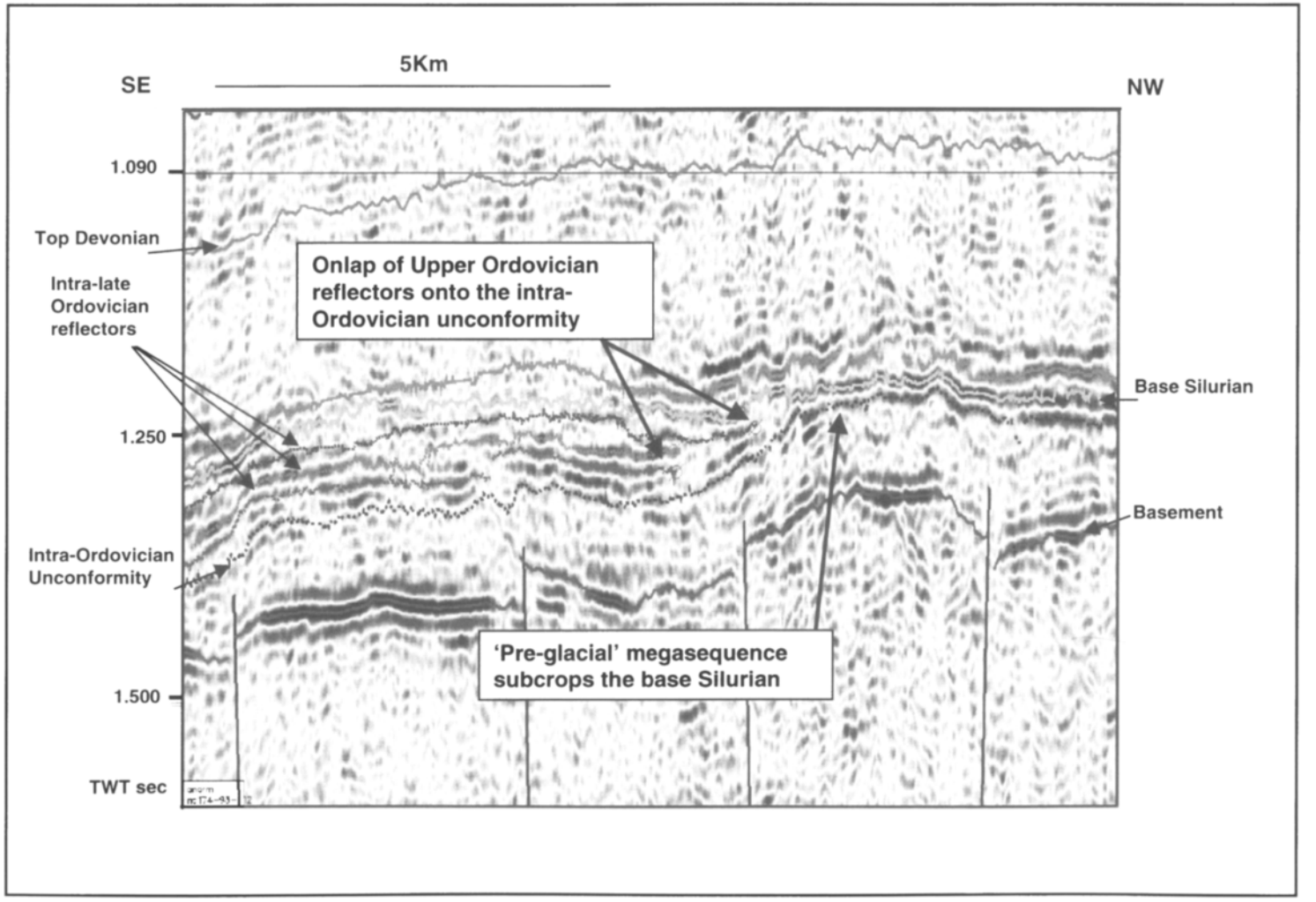

Figure 4. Example of the intra-Ordovician unconformity: north-eastern limit of major incised channel fairway.

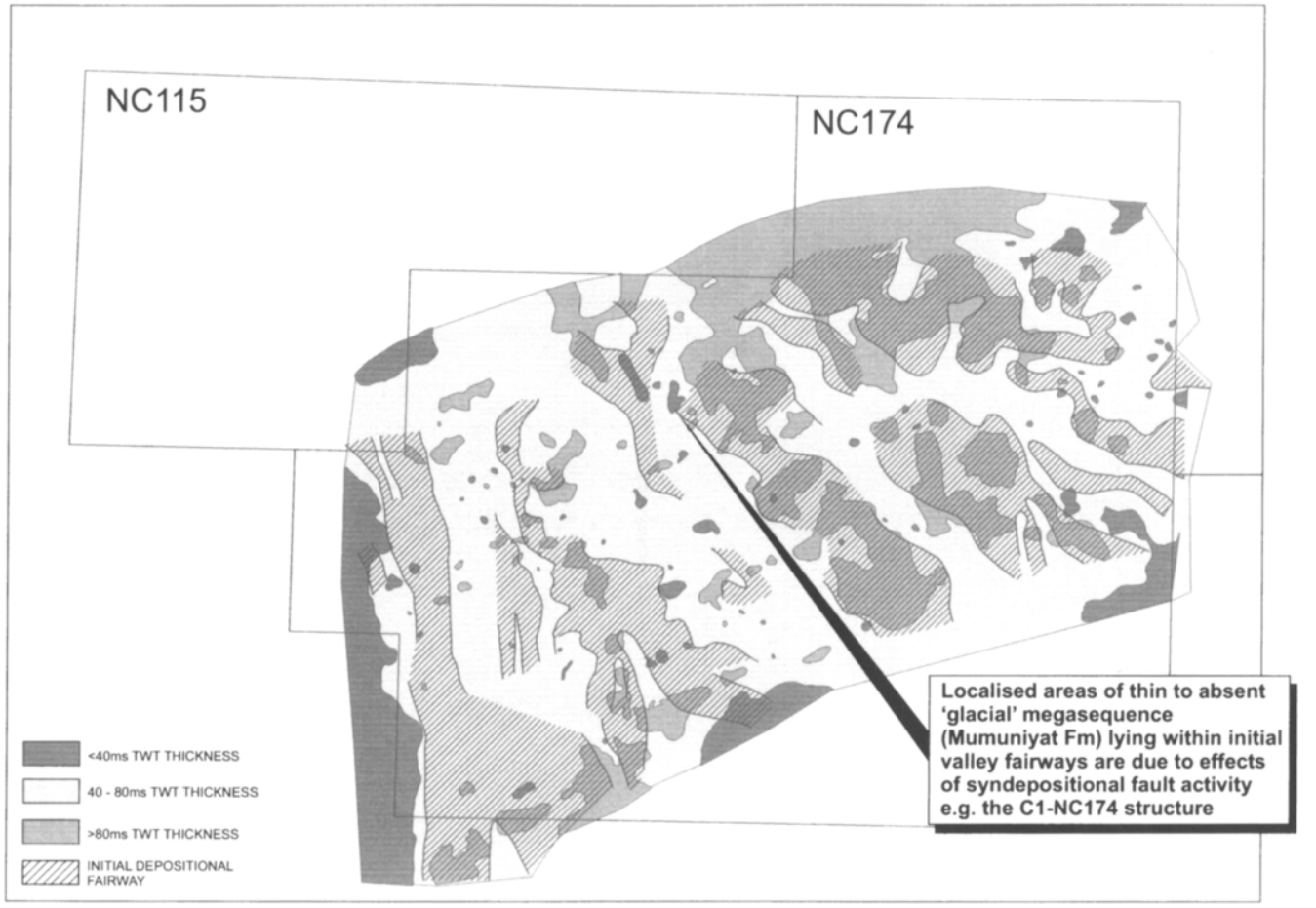

Figure 5. Interpreted incised valley fairways superimposed on a simplified glacial megasequence time thickness map.

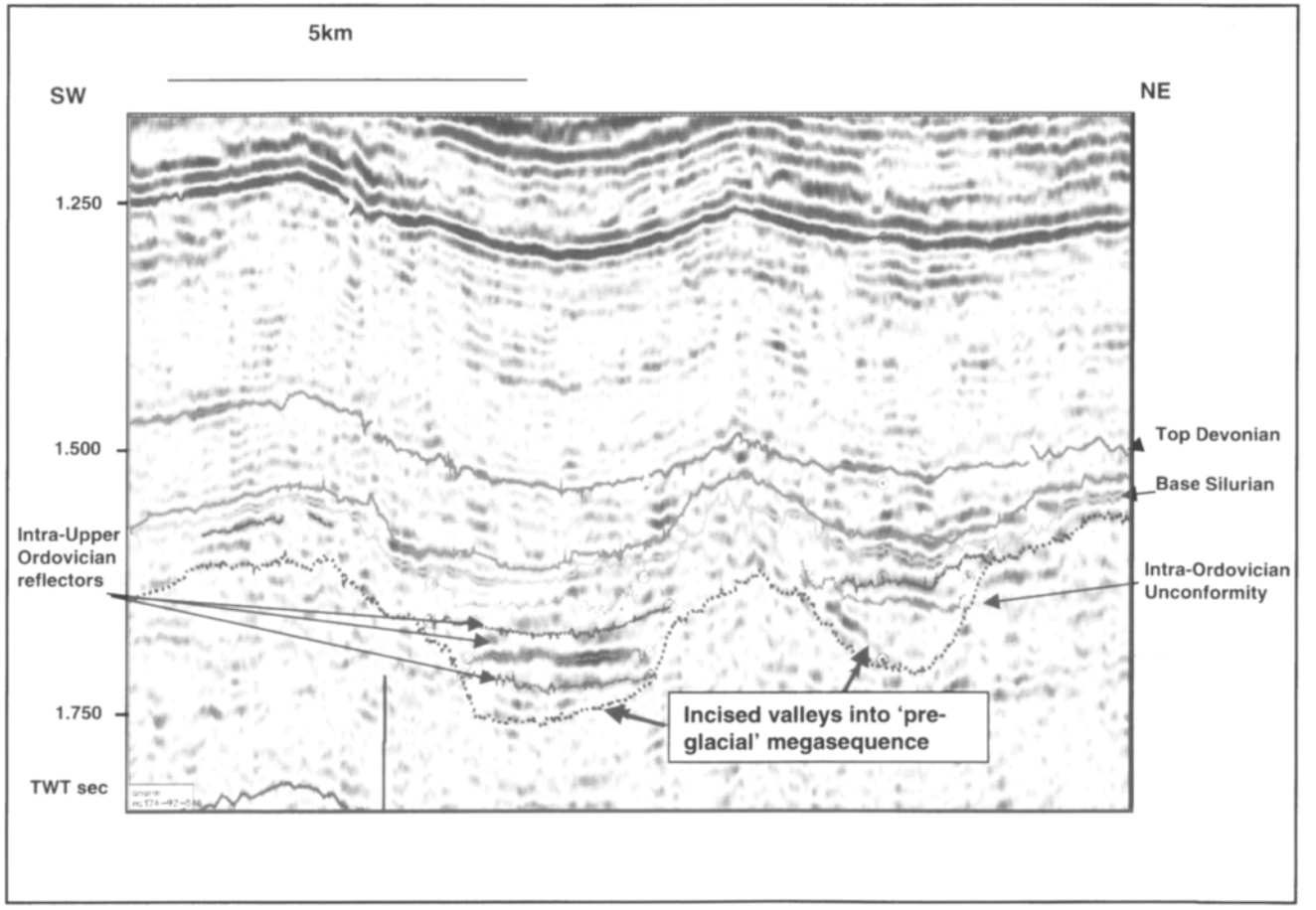

Figure 6. Examples of channel valleys incised into the pre-glacial megasequence.

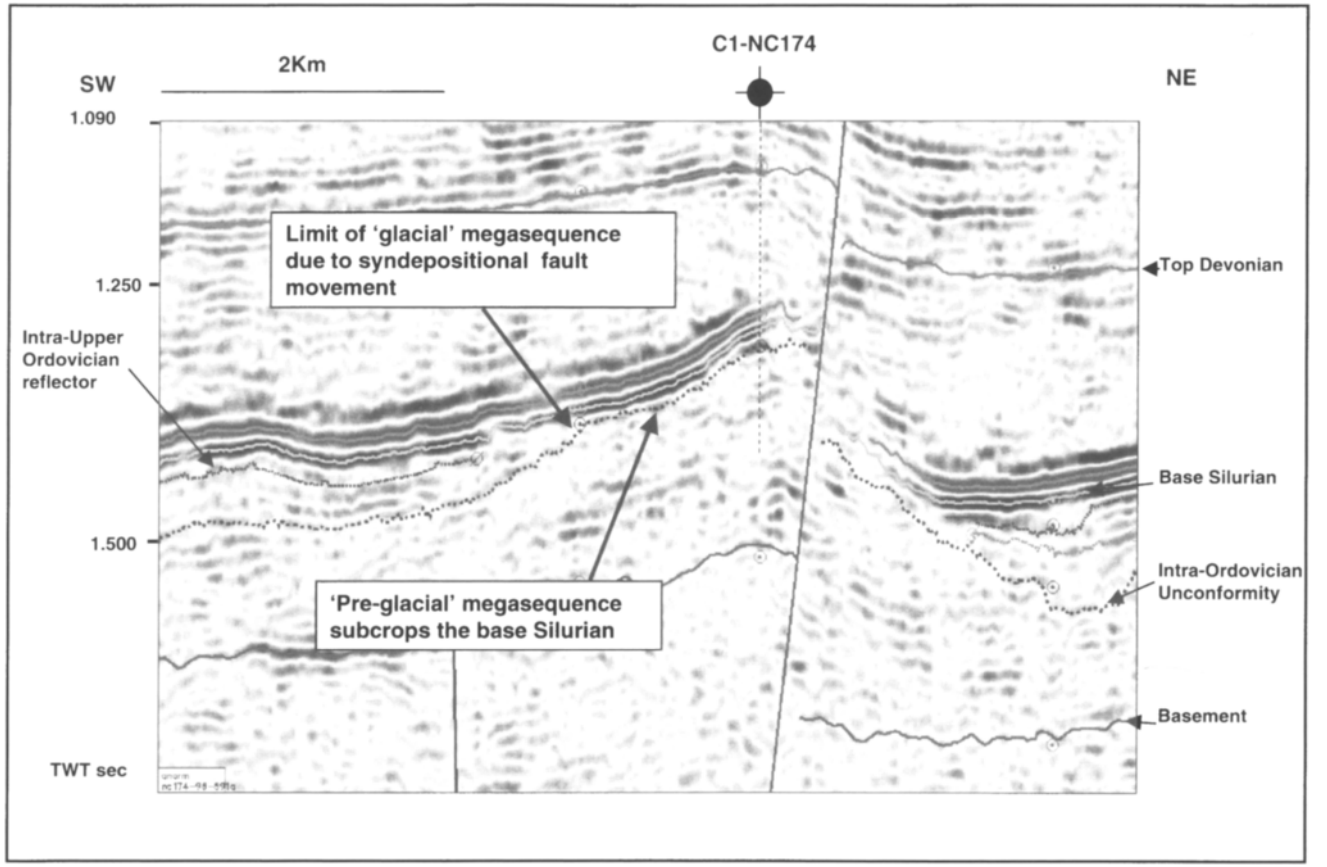

Figure 7. Example of the intra-Ordovician unconformity subcropping the base Silurian.

to middle Ordovician Hawaz Formation. This feature, coupled with the evidence from seismic, indicates that the glacial megasequence (Mamuniyat Formation) is absent because of syndepositional fault movement and that the sediments of the pre-glacial megasequence (here likely to be the Hawaz Formation) subcrop the base Silurian.

As noted above, the glacial megasequence comprises packages of seismic reflectors, which although they cannot be continuously interpreted across the block, in part due to the coarse seismic grid, have sufficient character to enable them to be mapped with some confidence as correlative units. Two discrete channel systems have been interpreted within the glacial megasequence, systems 'A' and 'B', in addition to a number of the morphological features described below.

The oldest channel system 'A' comprises packages of laterally discontinuous, high amplitude seismic reflectors, often exhibiting convex-upward profiles, which locally 'onlap' the intra-Ordovician unconformity. They occur as thin to moderately thick packages (up to 50 milliseconds TWT) and vary in width from a hundred metres to several kilometres (Fig. 8). These are thought to have been deposited in a high-energy environment and they appear to have eroded into the underlying pre-glacial megasequence. This channel system appears most widespread in the western part of the block, as shown by the channel system A interpolated distribution map (Fig. 9). The channels in the southwest part of the block are anastomosing and have a dominant north-south orientation, in contrast to channels observed in the southeast which have general westerly orientation and appear to be restricted to the initial steep-sided valley fairways.

A younger set of channels, system 'B', is interpreted to occur immediately beneath the base Silurian. They are defined by a localised broadening of the base Silurian reflector (decrease in frequency and increase in amplitude), coupled with seismic reflector termination associated with subtle changes of dip within the underlying section. These anomalies generally occur as thin (10–20 milliseconds TWT), but up to 1 km wide features, often with flattened saucer-shaped cross-sectional profiles (Figs 10 and 11). These seismic features, which are interpreted as a younger second channel system, have been mapped across the block and have a general southeast-to-northwest orientation (Fig. 12). These channels are more restricted than the underlying system A, perhaps indicating a reduction in sediment input and depositional energy towards the end of the Ordovician. The slight change in channel orientation and direction between the channel systems, becoming more westerly with time, may reflect the increasing influence that uplift of the eastern margin of the basin (the Brak-Ghenemah Arch) had on depositional processes towards the end Ordovician.

Several seismically defined thicks within the glacial megasequence have been mapped throughout the data set. These comprise irregularly shaped but closed bodies varying in width from 1 to 10 km and with up to 150 ms TWT (c. 800 ft) relief (Fig. 12). These are characterised by sharply eroded edges and are often associated with a dimming of the base Silurian seismic marker across their tops. The best example of these features is shown in Fig. 13.

Interpretation of these particular features is equivocal. Either they comprise preserved, discrete sedimentary landforms (see Reading, 1986 and Boulton and Deynoux, 1981 for examples) or are erosional remnants following an end Ordovician to early Silurian erosive event. The dimming of the base Silurian reflector against the flanks, sometimes with apparent onlap, and across the top of these features suggests that the lowermost Silurian (the 'hot shale') is absent due to non-deposition.

It seems unlikely that these features are erosional remnants however. Their relatively rare occurrence would necessitate that most of the section was removed by a major end Ordovician to early Silurian erosive event – for which there is no substantive evidence. A preferred interpretation is that they are depositional features which, given late Ordovician glaciation, could be preserved glacial landforms.

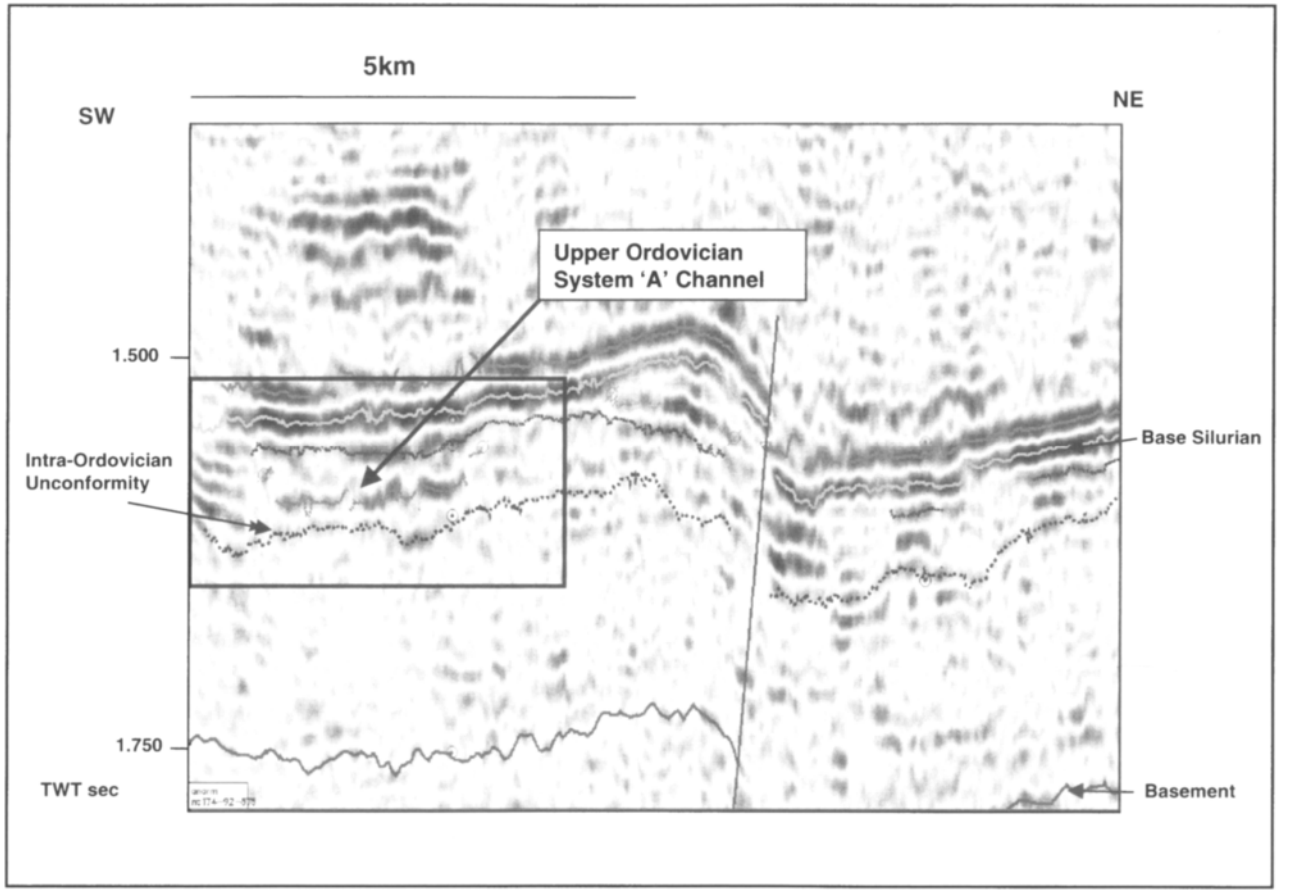

Figure 8. Example of a system 'A' channel within the glacial megasequence of the Upper Ordovician.

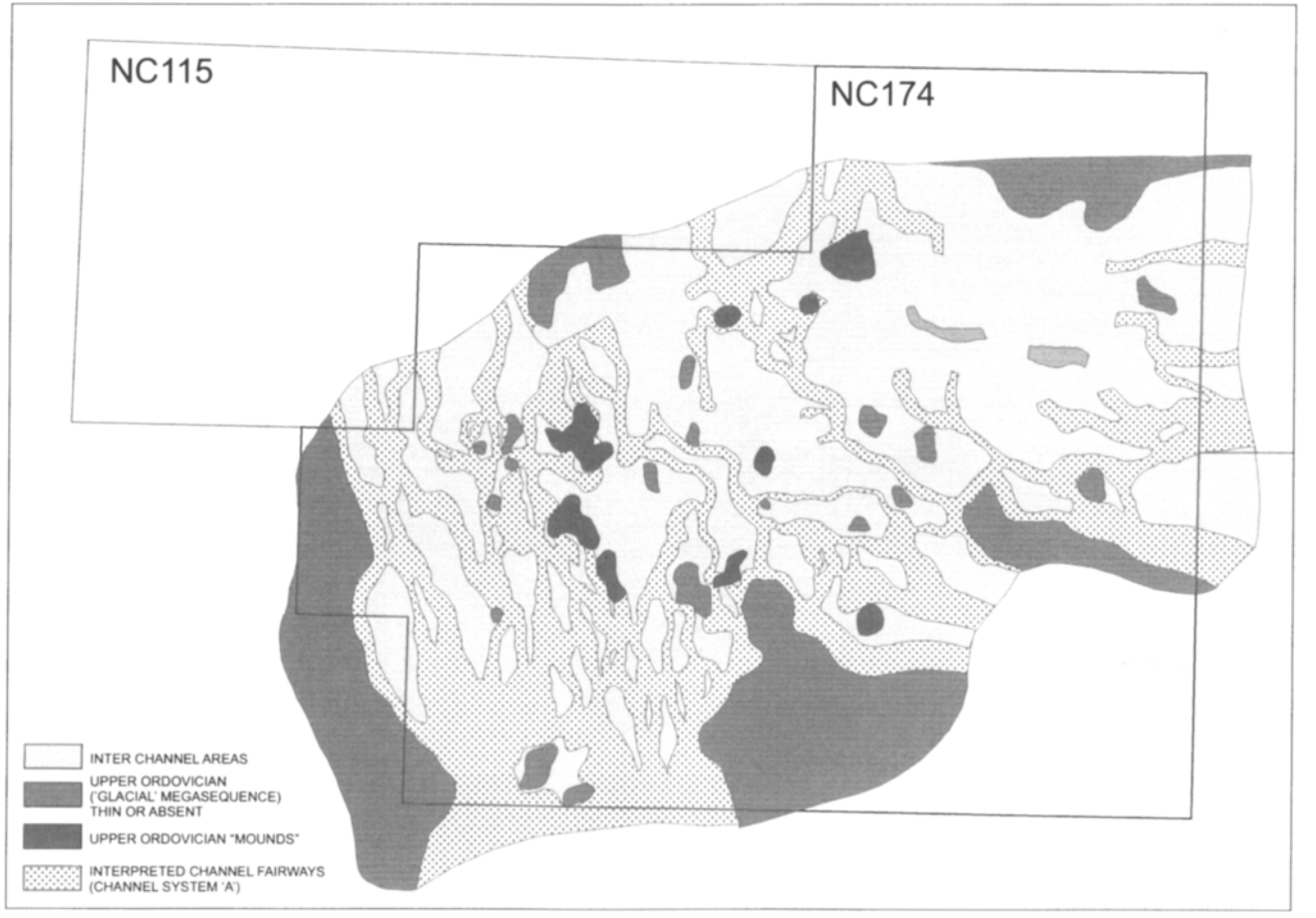

Figure 9. Interpreted distribution of system 'A' channels within the glacial megasequence.

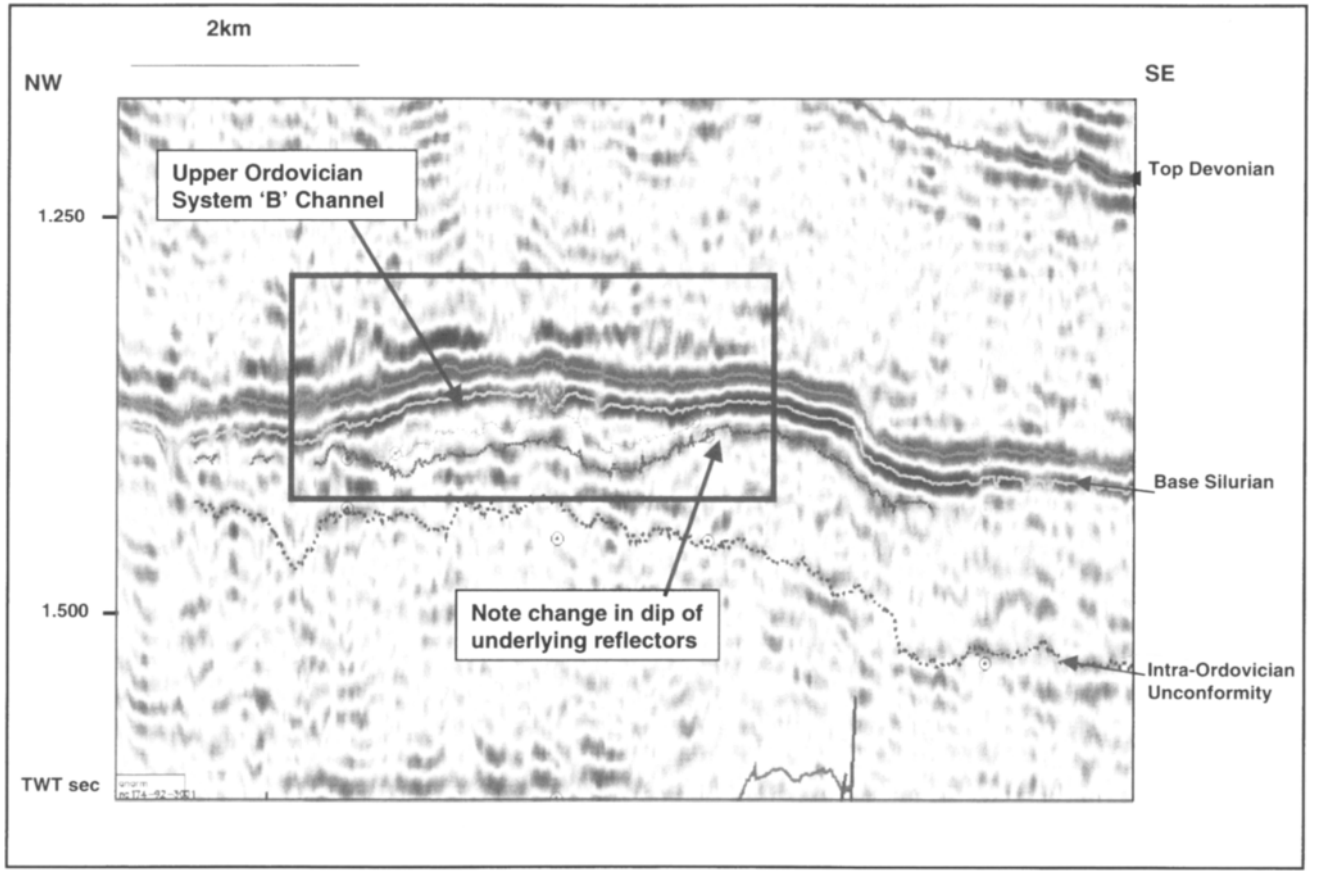

Figure 10. Example of a system 'B' channel within the glacial megasequence.

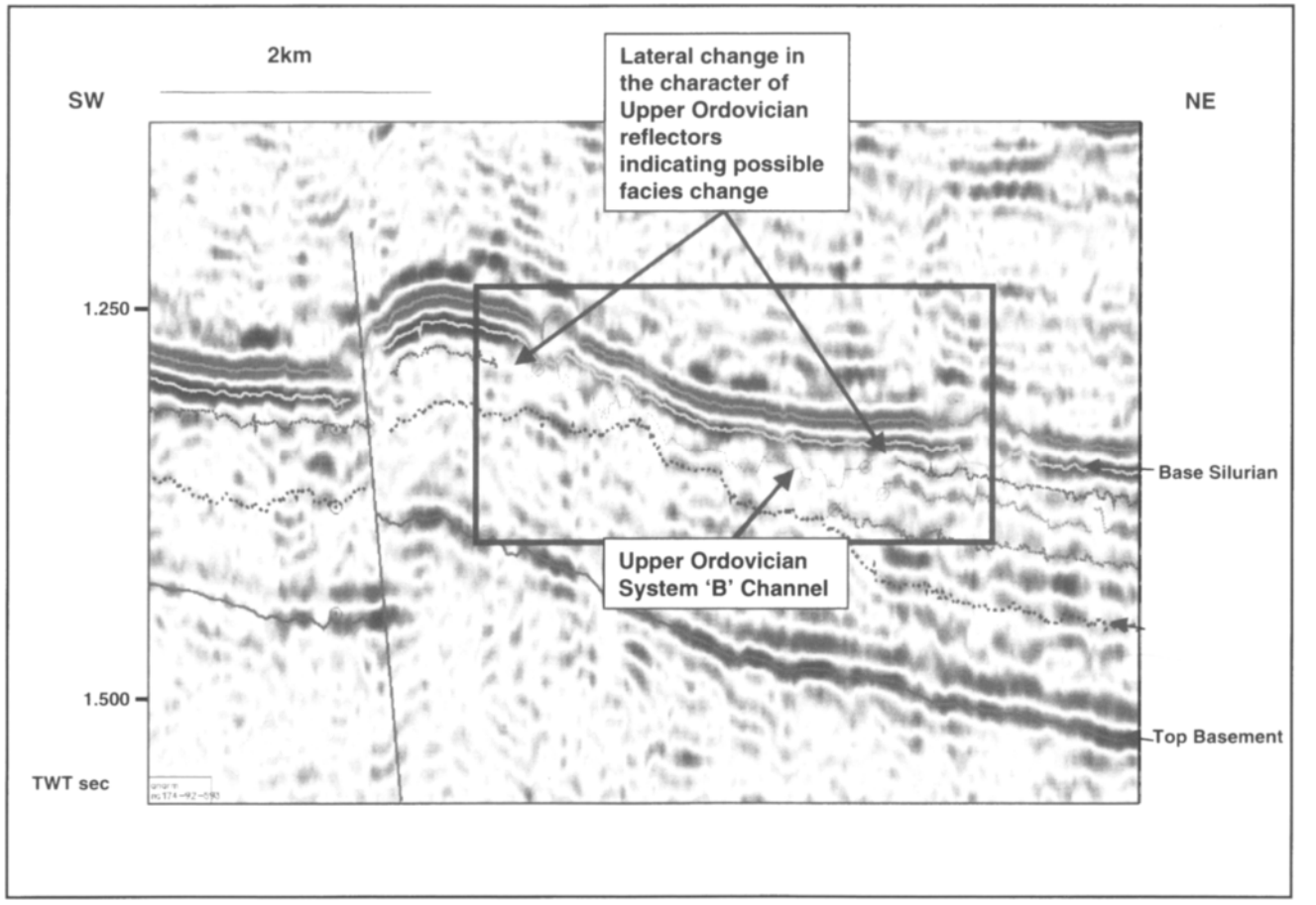

Figure 11. Example of a system 'B' channel within the glacial megasequence.

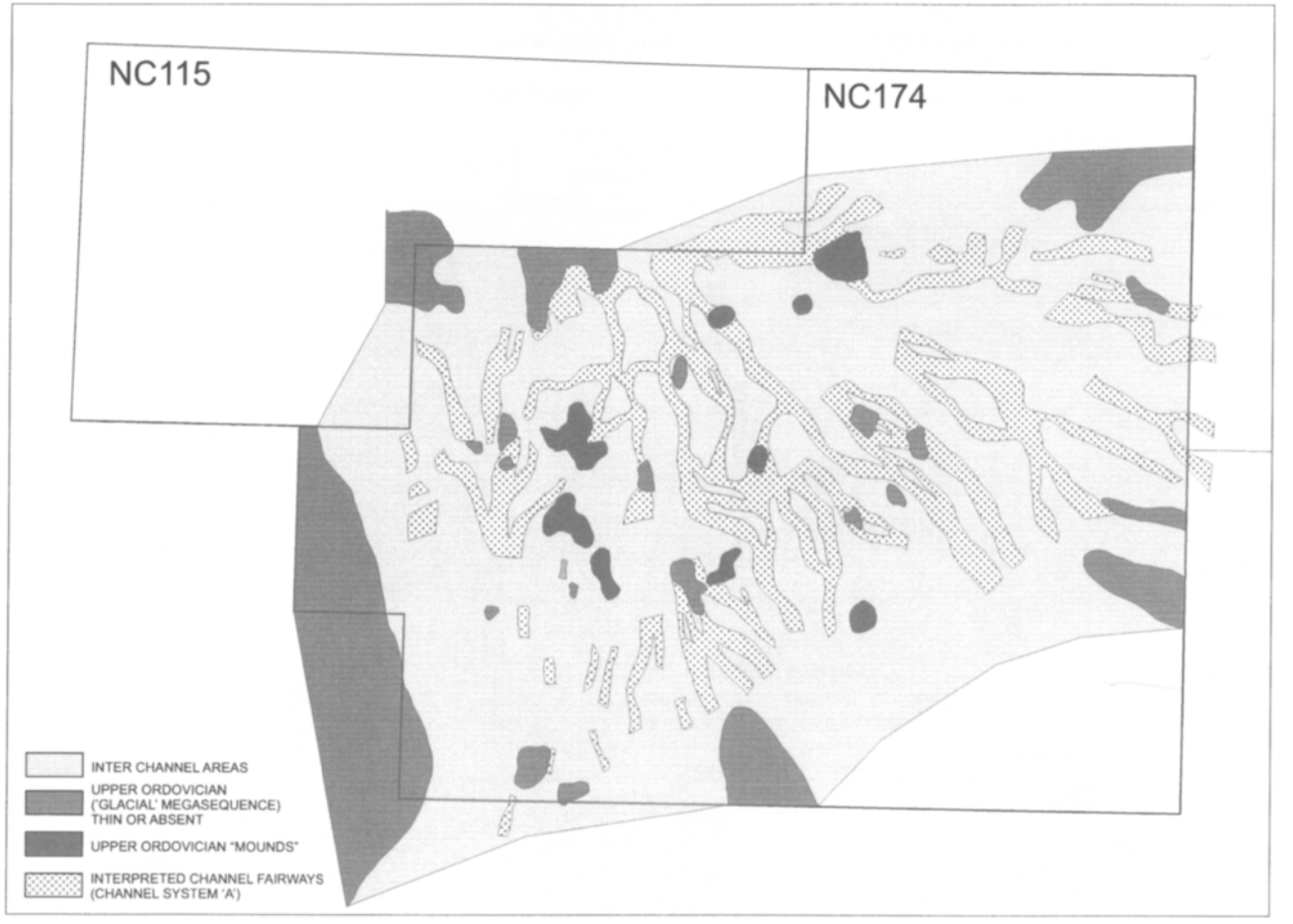

Figure 12. Interpreted distribution of the system 'B' channels.

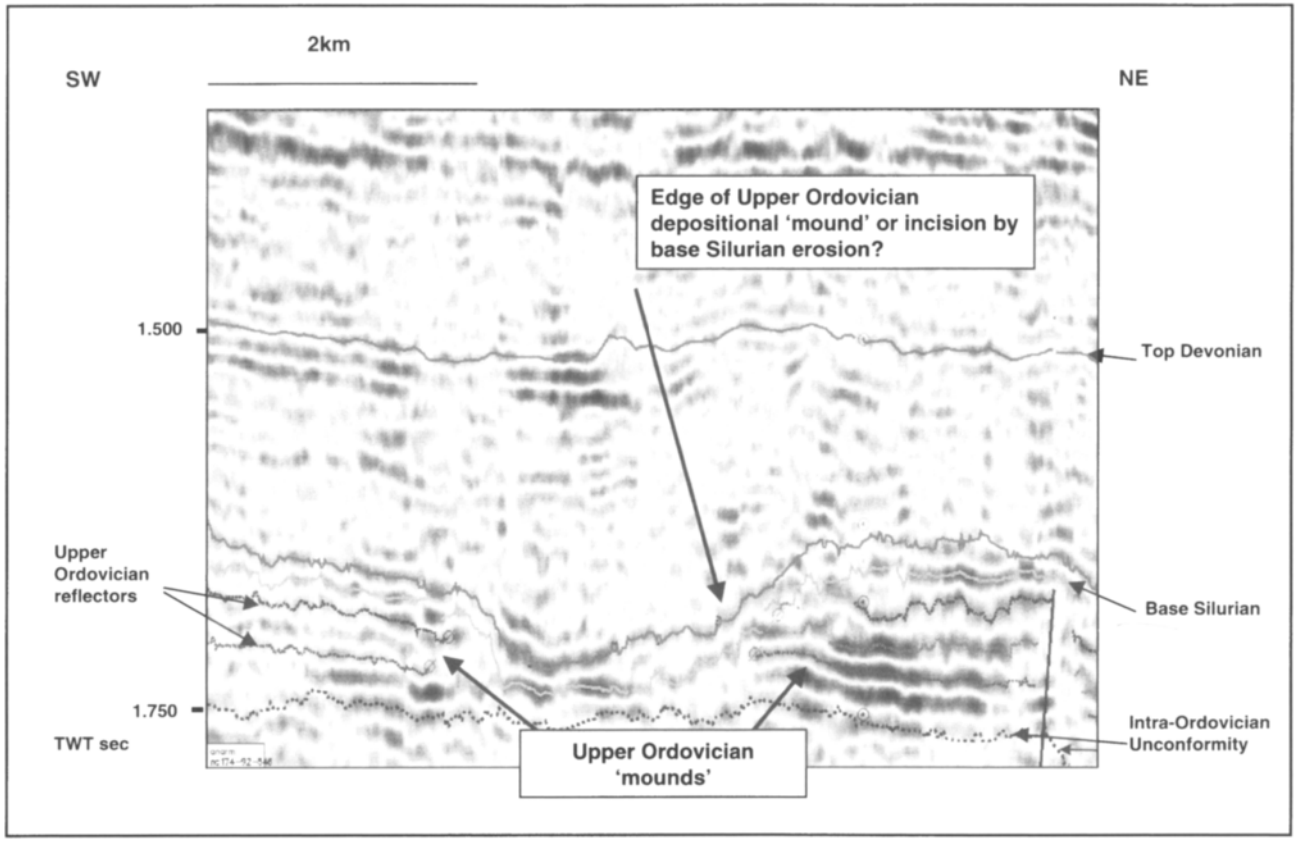

Figure 13. Example of a depositional 'mound' within the glacial megasequence.

DISCUSSION

The seismic interpretation of the Ordovician succession in NC174 has identified two megasequences separated by an intra-Ordovician unconformity. This interpretation does not propose any amendment to the depositional model generally found in the literature for the older pre-glacial megasequence, which comprises Cambrian to lowermost Upper Ordovician sediments (Bellini and Massa, 1980; Cepek, 1980; Vos, 1981). However, the seismic data clearly show that the top of the pre-glacial megasequence has significant topography due to erosion. Sediments comprising this megasequence are locally interpreted to occur immediately beneath the base Silurian shale, implying that the base Silurian subcrop is markedly diachronous in places.

The latter observation has significant implications for our understanding of the distribution, facies and depositional environment of the glacial megasequence, which is interpreted to be late Ordovician in age. As clearly shown by the seismic data within NC174 this megasequence is not always found beneath the base Silurian shales. In some wells there is evidence to suggest that sediments earlier interpreted as upper Ordovician (Mamuniyat Formation) because they subcrop the base Silurian in fact belong to the older pre-glacial megasequence. Consequently, the upper Ordovician depositional environment and sediment distribution was certainly more complex than perhaps generally envisaged, at least in the NC174 concession area.

Initial deposition of the glacial megasequence occurred within steep-sided and restricted incised fairways. Similar features have been observed in adjacent basins where they have been described as palaeovalleys of glacial origin. The Upper Ordovician successions of these basins are characterised by periglacial and glacial depositional processes (Beuf et al., 1971; McClure, 1978; Young, 1981; Destombes et al., 1985; Deynoux, 1985; Vaslet, 1990; McGillivray and Husseini, 1992; Powell et al., 1994). The change in depositional environment from dominantly marine to periglacial or glacial occurred as the Gondwana continent moved into southerly polar latitudes (Scotese et al., 1979; Cromwell, 1981; Smith et al., 1981) and the establishment of the late Ordovician ice cap resulted in a relative sea level fall. Late Ordovician reconstructions of Gondwana place the Murzuq Basin near the centre of this ice cap.

As far as the author is aware, there are no unequivocal periglacial or glacial sediments yet identified from either outcrop or the subsurface of the Murzuq Basin. From a regional perspective, this is anomalous. The apparent absence of these types of sediments could be a function of insufficient sampling as, at the time of writing, there have been no complete penetrations of the glacial megasequence by exploration wells in NC174. Also, identification of sediments of this type is more difficult within a very sand rich system where sediment reworking has also occurred. This process would have been especially significant on the local highs where thorough marine reworking is thought to have occurred. Most exploration wells are located on these highs. Furthermore, it is debatable whether a distinction between conventional fluvial and sub-ice meltwater sediments – ice tunnel channels for example –can be easily made.

The depositional processes responsible for the two identified channel systems and for the sedimentary 'mounds' are unclear. These seismically defined features could easily be interpreted as the products of glacial depositional processes. The channels have cross-sectional profiles and apparent distributions similar to those of sub-ice tunnel channel systems (Woodland, 1970; Pugin et al., 1996; Praeg, 1997). These are characterised by anastomising and bifurcating channels, which can be open-ended or closed. Formed by the flow of sub-ice meltwater during periods of glacial retreat they can be highly erosive, forming extensive incised channel systems beneath the ice sheet/glacier. Channels often terminate with sediment bodies as a result of the tendency of these systems to back-fill. Such could be the origin of some of the mapped upper Ordovician 'mounds'.

DEPOSITIONAL MODEL

The onset of glaciation during the late Ordovician resulted in a major relative sea level fall and a marked change in depositional processes across the Murzuq Basin. During this phase, sediment deposition reduced significantly as water was captured in ice sheet formation. Migration of these ice sheets across the basin and perhaps the localised development of glaciers in pre-existing fluvial fairways led to a marked change in the pre-glacial megasequence landscape which is recorded by the topography of the intra-Ordovician unconformity.

Significant sediment deposition occurred during periods of thaw when meltwater flow reached a maximum. Initial deposits during this period were restricted to well-defined fairways where meltwater fluvial systems and/or sub-ice channels systems developed, perhaps exploiting pre-existing fluvial fairways or topographic lows (Fig. 5). More basinwide deposition occurred as initial fairways became infilled. Extensive anatomised channel systems developed, of which at least two have been identified within NC174 (Figs. 10 and 12). What appear in the seismic data to be 'depositional mounds' are tentatively interpreted as glacial landforms of one kind or another.

Late Ordovician glaciation waned with a corresponding relative sea-level rise, which resulted in much of the Murzuq Basin being covered shallow seas by the early Silurian. During this transgressive phase, sediment reworking on topographic highs occurred, with perhaps local resedimentation of sand. Organic rich 'hot shales' of the basal Tanezzuft Formation were preferentially deposited in topographic lows. Continued relative sea-level rise led to the deposition of the Tanezzuft marine shales across much of the basin.

CONCLUSIONS

Detailed geological mapping of seismic data has led to the development of a new depositional model for the late Ordovician. Above the intra-Ordovician unconformity, a number of incised valleys, channel fairways, depositional 'mounds' and areas where the glacial megasequence is absent have been identified. From these observations, a subjective prediction on reservoir age, facies and thus quality can be attempted. Incorporation of the most recent seismic and well data from NC174 will help further amend and refine the model. A reduction in the uncertainty regarding reservoir quality of the Mamuniyat Formation for subsequent drilling campaigns should thus be achievable.

ACKNOWLEDGMENTS

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Geological Exploration in Murzuq Basin
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CHAPTER 20

Evidence for soft-sediment deformation – the Duwaysah Slide of the Gargaf Arch, central Libya

TIM GLOVER,[1,2] KEITH ADAMSON,[1,2] ROBERT WHITTINGTON,[1] BILL FITCHES[3] and JONATHAN CRAIG[4]

ABSTRACT

Soft-sediment deformation features associated with shallow marine Ordovician sediments of the Gargaf Arch are described and related to three main styles of deformation. Various types of structures resulted from gravity induced sliding down the eastern flank of a northerly trending palaeo-topographic high. They include: (i) extensional zones dominated by listric growth faults and abundant microfaults, (ii) compressional zones characterised by leading-edge folds generated by movement on internal thrust faults, (iii) sheath folds produced by internal shear between different parts of the slide, and (iv) small-scale water-escape structures. The whole complex is herein referred to as the Duwaysah Slide. Initial failure of this slide was promoted by over-pressuring resulting from continuous, rapid deposition of shallow marine sandstones of the Mumuniyat. Formation on an inherently unstable substrate comprising transgressive shales of the Melaz Shuqran Formation.

REGIONAL GEOLOGICAL SETTING

Initial subsidence in the area of the present day Murzuq Basin (Fig. 1) was caused by Cambro-Ordovician transtensional movements along pre-existing, NW- to N-striking pre-Pan-African and Pan-African basement structures. During the Early Palaeozoic, the North African area formed an extensive, northerly dipping, depositional platform extending from Morocco to Saudi Arabia. This platform was locally modified by early extensional movements that created a series of northerly trending grabens and horsts (Klitzsch, 1970). These structures effectively channelised local depositional systems from south to north. The present-day basinal structure is a result of a combination of Palaeozoic, Hercynian and Alpine deformation and does not reflect the depositional basin which developed during Cambro-Ordovician times.

During Early Palaeozoic times, sediment was derived from a sub-Saharan source and transported in a north to north-westerly direction across the Saharan platform. As a result, there is a marked contrast between the facies developed in the more proximal southern areas, which

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were dominated by coarse continental clastic deposits, and those of the distal northern areas where deep marine shales were deposited over the northern extension of the platform (in the present-day northern Ghadames Basin).

Lithostratigraphically, the Palaeozoic deposits of this part of Libya can be divided into three major groups: (i) predominantly sandy deposits of the Cambro-Ordovician Gargaf Group (Fig. 2a & b), (ii) predominantly shaly deposits of the lower Silurian Tanezzuft Formation, and (iii) interbedded, often repetitive, sandstones, shales and carbonates of the mid to upper Silurian to Carboniferous Akakus to Marar formations.

GEOGRAPHICAL LOCATION

The type sections of both the Mamuniyat and Melaz Shuqran formations can be found in the Duwaysah region of the western Gargaf Arch (Fig. 3). This is an ENE-trending, westward

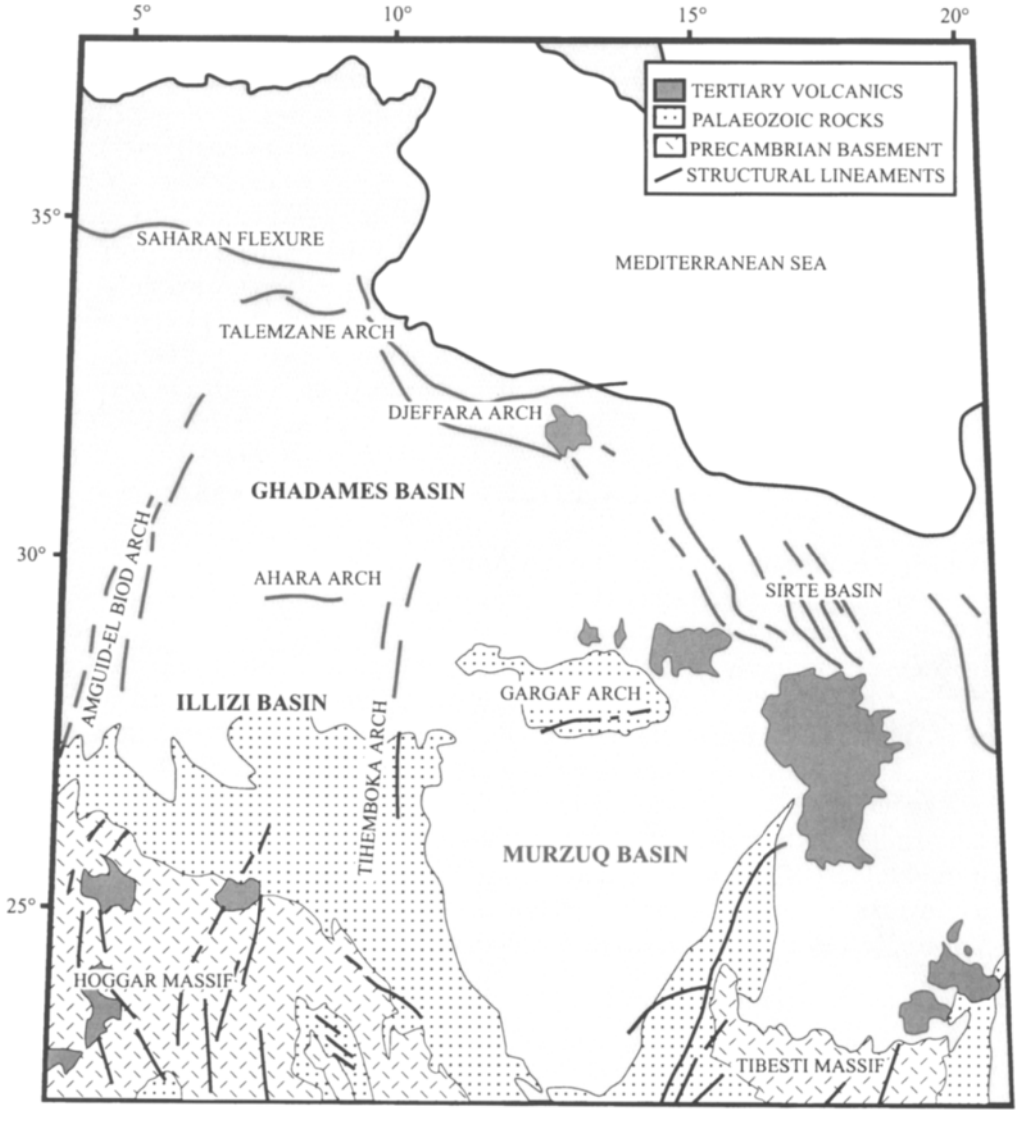

Figure 1. Regional tectonic framework of the Murzuq Basin.

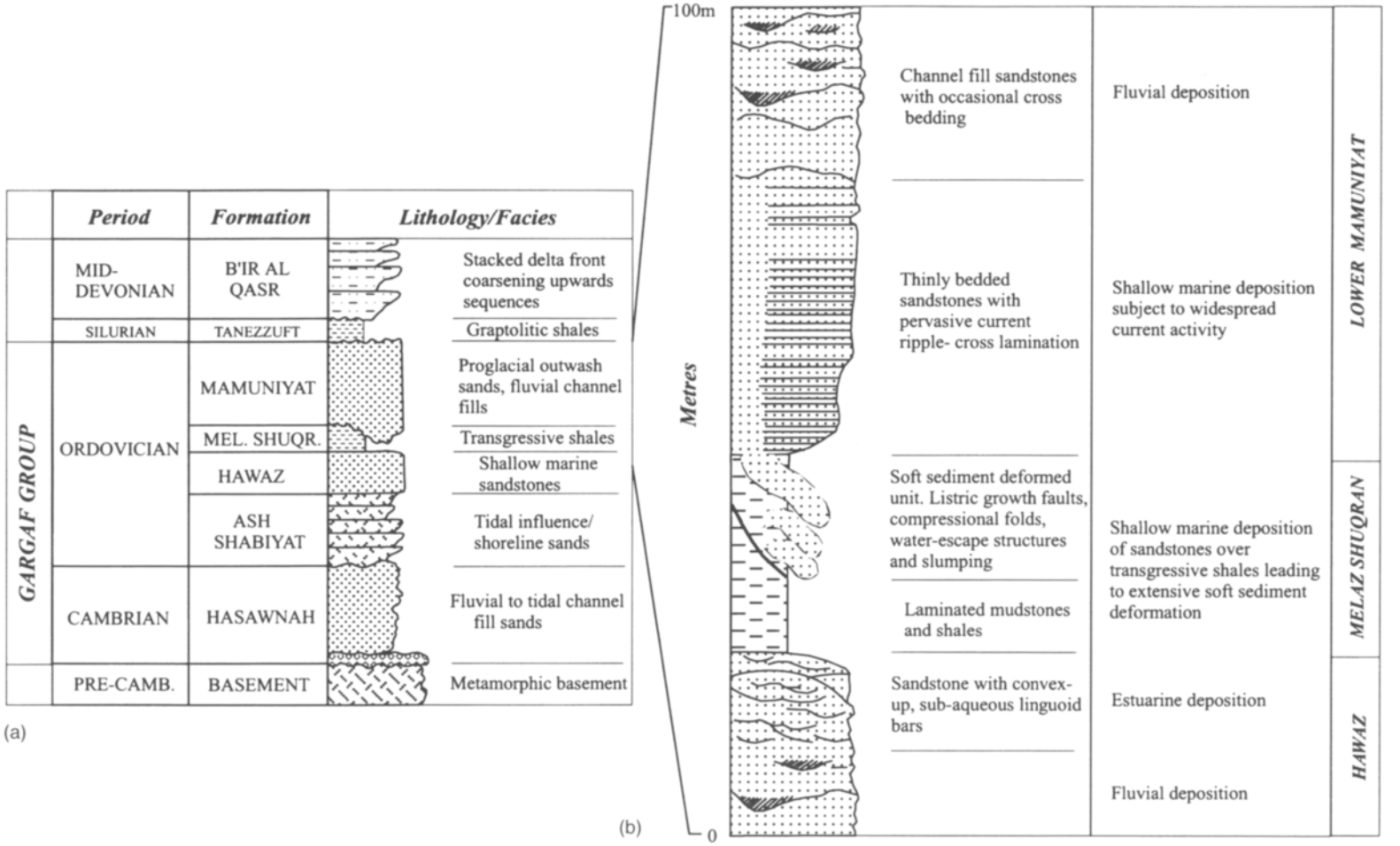

Figure 2. (a) Composite stratigraphic succession through the Gargaf Group of central Libya. (b) Composite log depicting the sedimentology of the Mamuniyat and Melaz Shuqran formations in the Duwaysah area (27°43′08″ N, 12°51′45″ E to 27°42′03″ N, 12°45′93″ E).

plunging Hercynian–Mesozoic uplift, separating the Murzuq Basin in the south from the Ghadames Basin in the north. The Duwaysah area comprises a gently westward dipping succession of Cambro-Ordovician siliciclastics directly overlain in many places by ferruginous sandstones of the Middle Devonian B'ir Al Qasr Formation. Graptolitic shales of the Silurian Tanezzuft Formation, which form thick sequences in the subsurface of the Murzuq and Ghadames basins, are very thin (> 10 m) and are only locally preserved.

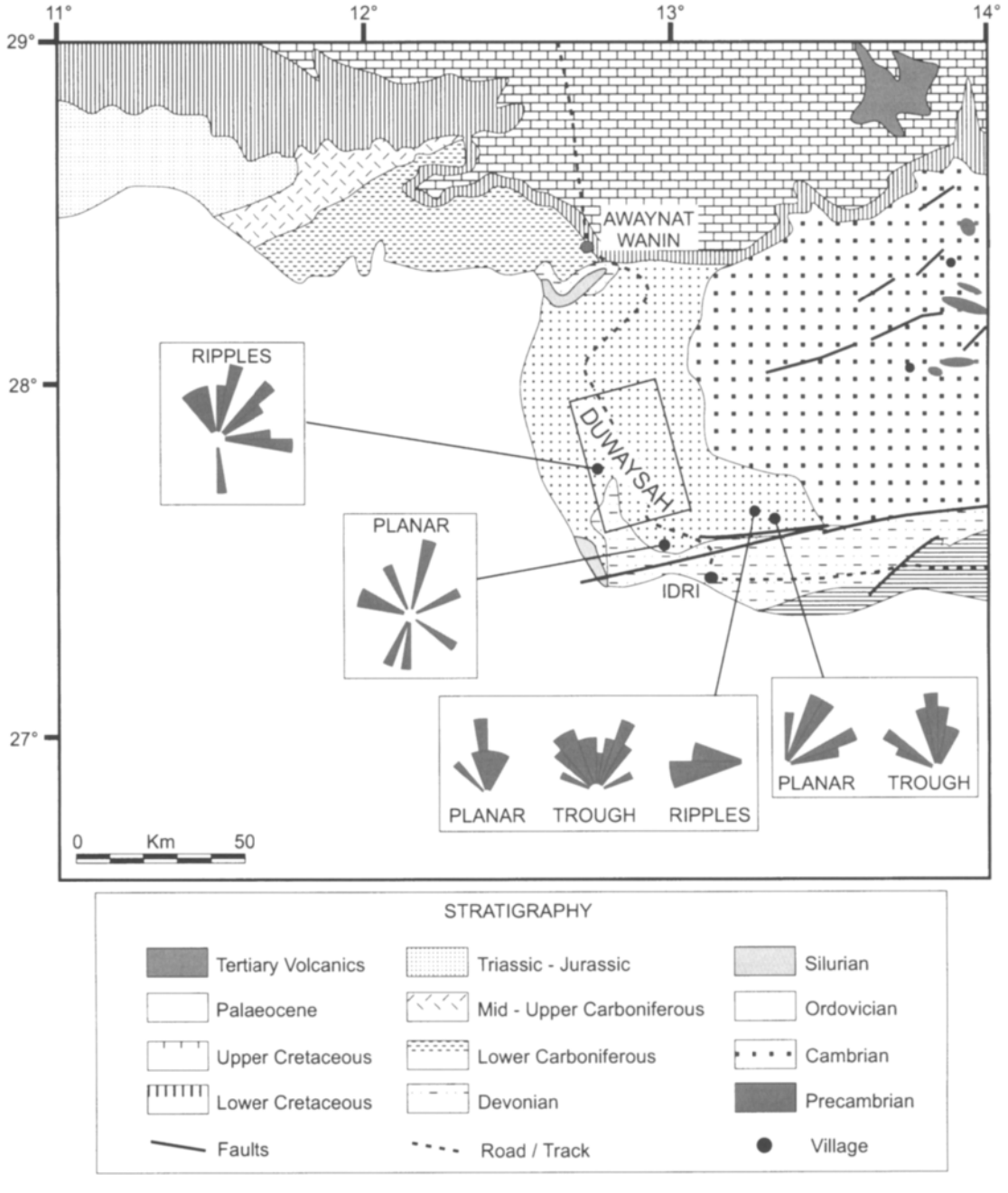

Figure 3. Geological map of the Gargaf Arch showing the location of the soft-sediment deformation identified by this study. Palaeocurrent rose diagrams showing planar and trough cross bedding foresets, together with flow direction from asymmetrical ripple crest are also given.

SEDIMENTOLOGY OF THE MELAZ SHUQRAN AND MAMUNIYAT FORMATIONS

The deformation recorded in this chapter is confined to sediments belonging to the uppermost part of the Gargaf Group, namely the Melaz Shuqran and Mamuniyat formations. The Melaz Shuqran Formation forms a predominantly argillaceous succession with interbedded silts and sandstones. Havlicek and Massa (1973) assigned a Caradoc age to the formation, which was deposited during a marine transgression.

The Mamuniyat Formation comprises dominant sandstones with minor siltstone and shale beds which have been dated as Ashgill in age (Havlicek and Massa, 1973; Paleoservices, 1994). The Ashgill was a time of widespread glaciation in North Africa, which at that time lay along the northern margin of Gondwanaland. Late Ordovician plate reconstructions of Gondwana (McKerrow and Scotese, 1990) have been constrained by the recognition, at outcrop, of possible upper Ordovician 'glacial' deposits in Algeria (Beuf et al., 1971), Saudi Arabia (McClure, 1978; Clark-Lowes, 1985), Jordan (Powell et al., 1974), West Africa (Deynoux et al., 1985) and Morocco (Destombes et al., 1985).

Although examples of what have been interpreted as striated pavements, patterned ground and ice-folding have been identified in Algeria (Beuf et al., 1971) there has been discussion as to whether these features are necessarily indicative of a glacial origin (Abugares and Ramaekers, 1993). Dropstone conglomeratic intervals in the Melaz Shuqran Formation at outcrop and also in wells in the NC-115 concession (J. Smart, personal communication, 1998) support the idea the Murzuq Basin area was subjected to a glacial event during the late Ordovician. However, use of the term 'glacial' does not imply that the area was covered by an ice sheet analogous to the present-day Antarctic ice sheet. A number of these features, particularly patterned ground, may develop under periglacial conditions, far away from ice sheets. It is significant that there is no indisputable evidence for the direct action of ice on the sediments preserved in the Murzuq Basin.

Figure 3 shows palaeocurrent data collected from the Mamuniyat Formation in the Duwaysah region. The data reflect planar and trough cross bedding showing a pronounced N–NE distribution. Asymmetrical ripple crests were recorded along steeply dipping beds involved in the deformation; in order to reconstruct the accurate palaeocurrent azimuths, the ripple crest orientations were restored to palaeo-horizontal with the help of stereographic projection. Restored ripple-crests strike in a WNW–ESE direction, perpendicular to the N–NE directed flow. Trough cross bedding also indicates flow towards the north whereas planar cross bedding is more widely scattered, indicating current flow to the N, NE and SW. Recognition of northerly flowing palaeocurrents supports earlier ideas that the palaeo-shoreline was oriented roughly ENE–WSW and that overall sediment supply was from south to north.

Several different facies have been encountered in the Mamuniyat Formation at outcrop and in subsurface core data (SPT, 1994; McDougall and Martin, 1998). The facies have been assigned to two main depositional environments: (i) coarse grained, erosional braided channel sandstones that were subject to destructive marine reworking, and (ii) more abundant, parallel bedded, bioturbated, shallow marine sandstones with minor distributory channels and mouth bars (Worden, 1997; McDougall and Martin, 1998). Sparse palynological data from wells drilled within the NC-174 concession consistently support a marine environment of deposition at least for the finer grained lithologies (Worden, 1997). The wide scatter of forest dips and ripple crest orientations illustrated in Fig. 3 is consistent with a nearshore, shallow marine environment, with the asymmetrical ripples indicating current flow.

The facies of the Mamuniyat Formation are interpreted to have been deposited during periods of ice sheet advance and retreat. Ice-sheet advance and associated sea-level fall promoted deposition of the coarse grained braided fluvial deposits. These deposits were reworked by the

marine transgression that accompanied subsequent sea-level rise during ice-sheet retreat. Cycles of ice advance and retreat could have resulted in the aggradation or progradation of several phases of glacial to fluvio-glacial deposition and associated erosion. However, the entire period is likely to have been brief (>500 Ka) as global sea level curves indicate that the greatest excursion occurred during the Hirnantian stage (Brenchley et al., 1994).

Ice retreat releases huge volumes of sediment and water and resultant high energy depositional systems exploit any pre-existing topographic lows. Erosion and incision into underlying units is not therefore restricted to true glacial down-cutting but may also be the result of depositional processes associated with deglaciation and ice-sheet retreat.

SOFT SEDIMENT DEFORMATION

The soft-sediment deformation features recorded in the following section are found at the junction between shales of the Melaz Shuqran Formation and the basal sandstones of the Mamuniyat Formation. Minor soft sediment deformation is common at this stratigraphic level throughout much of SW and central Libya, although the diverse structures recorded in this paper are exceptional and have not been documented previously in the Ordovician succession of the region.

Extensional Structures

By far the largest structures recorded in the Duwaysah region comprise a family of normal listric growth faults (Figs 4a to 4d), which offset the basal sandstones of the Mamuniyat Formation. The largest faults are N–NNW trending (Fig. 5), exhibit opposing dips and appear to sole out at the same stratigraphic level within the underlying shale-dominated Melaq Shuqran Formation. The exact level of the detachment within this shale succession is unknown because it is not exposed. It is most probably located in the lower part of the sequence as fault disruption of the uppermost shale succession is observed in the field. Fault throw is variable, only rarely exceeding 5m, and the spacing of the individual listric faults can be up to 100 m.

Rotation of the bedding is commonplace between the major faults. Rollover anticlines are well developed and there is also subtle drag or flexure of bedding along the fault planes (Fig. 6a). Considerable thickening of some early sandstone beds occurs into some of the larger faults (maximum throw 5 m), whilst smaller, synthetic and antithetic faults do not exhibit thickening and are probably slightly later structures. These small conjugate faults are represented by poles in Fig. 5 and are oriented parallel to the major listric growth faults. The upper parts of the listric faults are truncated by overlying sediment, thereby proving their early origin. Late-stage extensional faults which offset early slump folds are also common in the slide unit, although displacement on them is only a few centimetres.

Arrays of microfaults are common within the slide unit. Their spacing is in the order of centimetres and displacements of the order of millimetres (Fig. 6b). They are found through the slide unit and indicate zones that have undergone extensional strain (around listric faults, around folds and zones of bedding parallel slip). Fig. 5 illustrates that the microfaults contained within the growth sequence are parallel to the major listric bounding fault. These faults strike N–NW and dip toward the SW. Thin sections through microfaults indicate that they result from frictional grain boundary sliding and repacking, as opposed to grain breakage, and are therefore early 'soft-sediment' features.

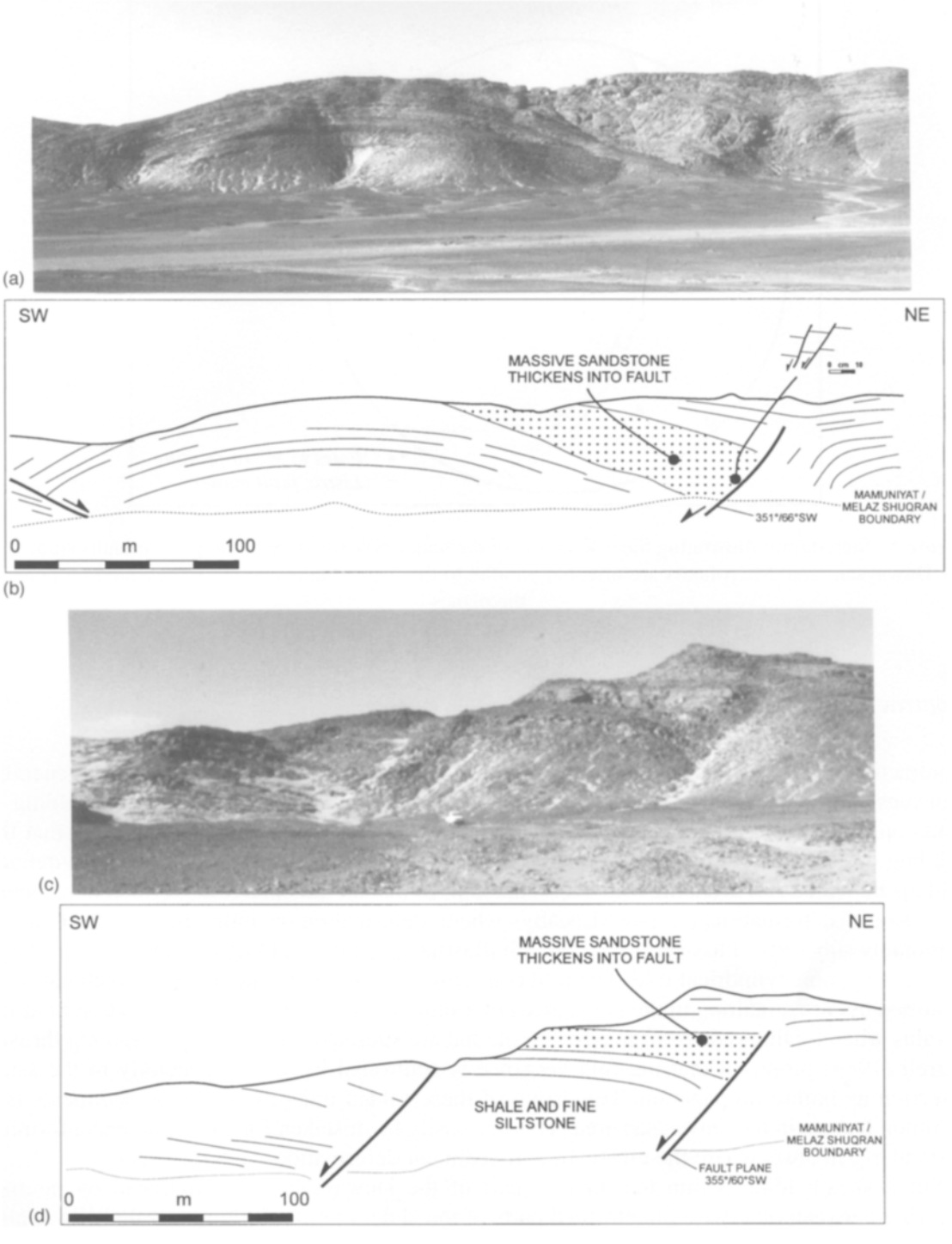

Figure 4. (a) Large listric growth fault and associated low angle, antithetic fault developed in basal sands of the Mamuniyat Formation (27°42′03″ N, 12°45′93″ E). Note the 5–10m thick growth sequence and rollover anticline developed in the hangingwall of the fault. Note that the slide is overlain by relatively flat-lying beds, (b) Field sketch of Fig. 4a, (c) Syndepositional thickening of Mamuniyat Formation sandstone along a sub-parallel listric fault (27°41′80″ N, 12°45′10″ E), (d) Field sketch of Fig. 4c.

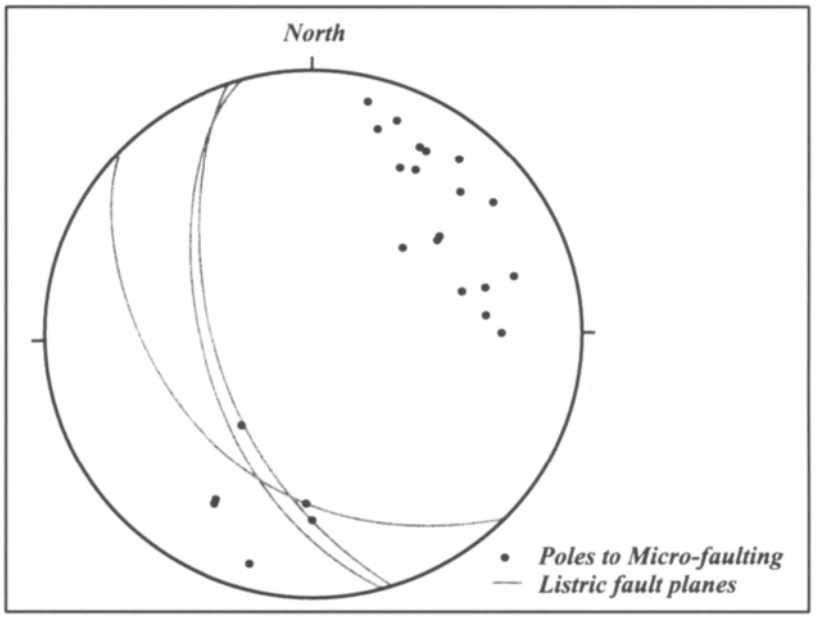

Figure 5. Stereogram illustrating the orientation of the major NW-trending listric growth faults studied in the Duwaysah area. Microfaults are oriented parallel to the major faults and are represented by poles to the planes.

Contractional Structures

Contractional strain is manifested by folding and thrusting of the sediments and generally indicates the downdip 'toe' of the slide unit. In the Duwaysah area, broad open folding is common, with dips rarely exceeding 25°. The stereogram shown in Fig. 7a illustrates that the bedding orientations from all the open folds studied in the Duwaysah area form a well-defined fold girdle with a NW-trending fold axis. This implies that all the open folds formed in response to a single deformational phase. Locally, where deformation is more intense, bedding is commonly sub-vertical to overturned. Fig. 7b illustrates that the bedding is disposed into a large NE-verging, non-cylindrical fold. The fold consists of an anticline-syncline pair which has been modified by thrust faulting in the hinge areas in a similar way to ductile-bead formation in thrust terrains whereby the folds form in advance of, and are subsequently cut by propagating thrusts. Farrell (1984) proposed that the fold vergence is controlled by, and is generally in the same direction as failure propagation. Truncation of these folded units by overlying sediments is a common feature in the Duwaysah area. This can easily be mistaken for a tectonic unconformity, particularly in areas where the effects of soft-sediment deformation are not clear.

Small sheath folds within the internal part of the Duwaysah slide originated by internal shearing between otherwise undeformed parts of the slide. Internal bedding parallel slip is also indicated by zones of microfaults which have formed in response to simple shearing between internal slide masses. A notable feature from the subsurface data is the abundance of soft-sediment deformation features, particularly small-scale slump folds. Slump bedding is common in the more agrillaceous lithologies of the Mamuniyat Formation in the subsurface, where it is present as minor convolutions and slump folds which are inclined towards the NW (S. Beswetherick, personal communication, 1998). The orientation of these slump folds is consistent with the orientation of the listric growth faults and the broad open folding recorded at outcrop.

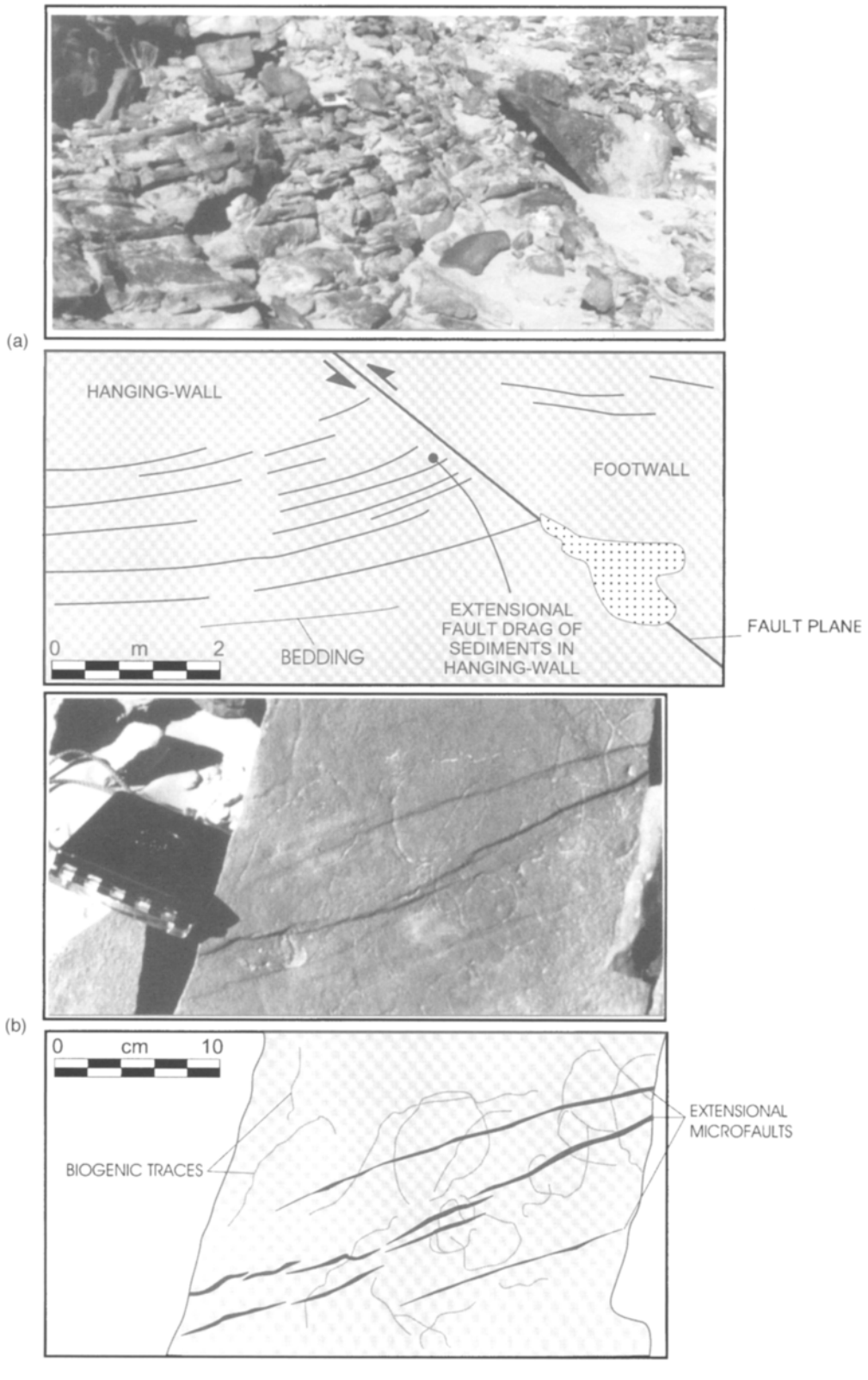

Figure 6. (a) Gentle extensional fault drag effects recorded in the hangingwall of an early formed listric fault (27°42′03″ N, 12°45′93″ E), (b) Plan view of linked extensional microfaults (27°43′07″ N, 12°46′20″ E). The faults are cut by small trace fossils, indicating how early the extensional fractures are.

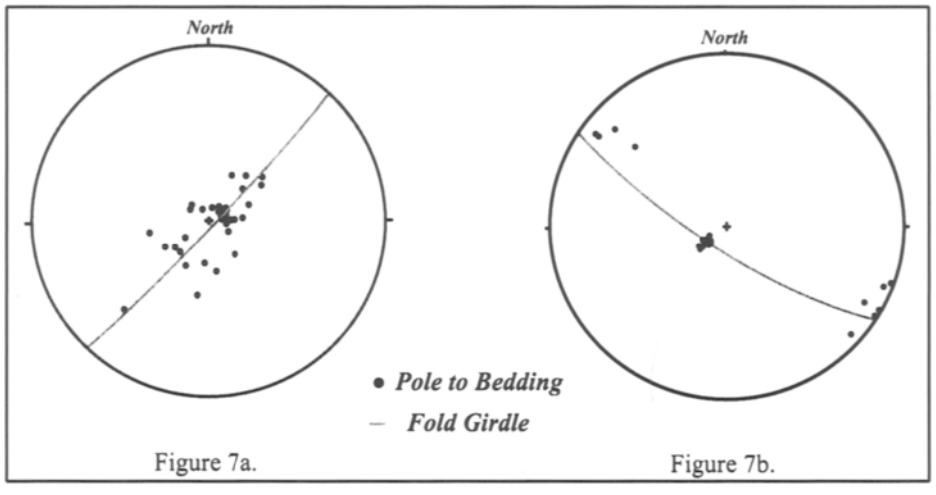

Figure 7. (a) Poles to bedding in Mamuniyat Formation in the Duwaysah area, NE-oriented fold-girdle delineates a NW-trending fold axis formed during a single deformational episode. The orientation of the fold axes is parallel with the major listric faults shown in Fig. 5b, (b) Poles to bedding in a NE-trending slump fold in the northern part of the study area (27°43′07″ N, 12°46′20″ E).

Water-Escape Structures

The structures associated with dewatering of the sediment column can be related to the movement of water (ball and pillow structures shown in Fig. 8a) or to the sinking of sediment (load features). The best examples are found around 27°43′ N, 12°45′ E and along the junction between the Mamuniyat and Melaz Shuqran formations.

The most common structures are load features which are up to 1 m across and sometimes reach the same vertical dimensions (Fig. 8b). These are connected at the junction between the two formations and indicate the foundering of the sandstone units into the underlying shales through pore-water escape. Fig. 8c illustrates the microfault arrays that develop around the outside of these load features.

Loading of sandstones of the Mamuniyat Formation into the underlying shales may have been enhanced by activity along the listric faults. Increasing displacement along these faults would have favoured movement of the pressurised shales into the immediate footwall areas of the faults in an analogous fashion to the formation of salt rollers through halokinesis. Similar processes are thought to have operated in a Namurian delta slope succession in SW Ireland where mud diapirs have developed along soft-sediment faults (Martinsen and Bakken, 1990). No diapiric features have yet been recorded in the Duwaysah area.

DISCUSSION

The high degree of internal coherence between the beds involved in the deformation, together with the presence of listric growth fault families and the absence of contorted and/or rotated bedding, suggests that the large scale structures recorded in the Duwaysah region are more likely the product of sliding than slumping.

The abundance of soft-sediment deformation at the junction between the agrillaceous Melaz Shuqran Formation and the arenaceous Mamuniyat Formation suggests that the shales of the Melaz Shuqran Formation formed an inherently unstable substrate, which promoted sediment failure. Similar conditions exist today along the Nova Scotian margin and along the delta slopes

of the Mississippi, where soft-sediment deformation is promoted by rapid sedimentation and the production of biogenic methane in the sediment column (Coleman et al., 1983).

Progressive, yet rapid deposition of coarser sediment over fine-grained incohesive sediments can lead to the development of over-pressuring and promotes instability. This process is a common cause of ancient slides and slumps (Martinsen, 1989). The initial influx of basal sands

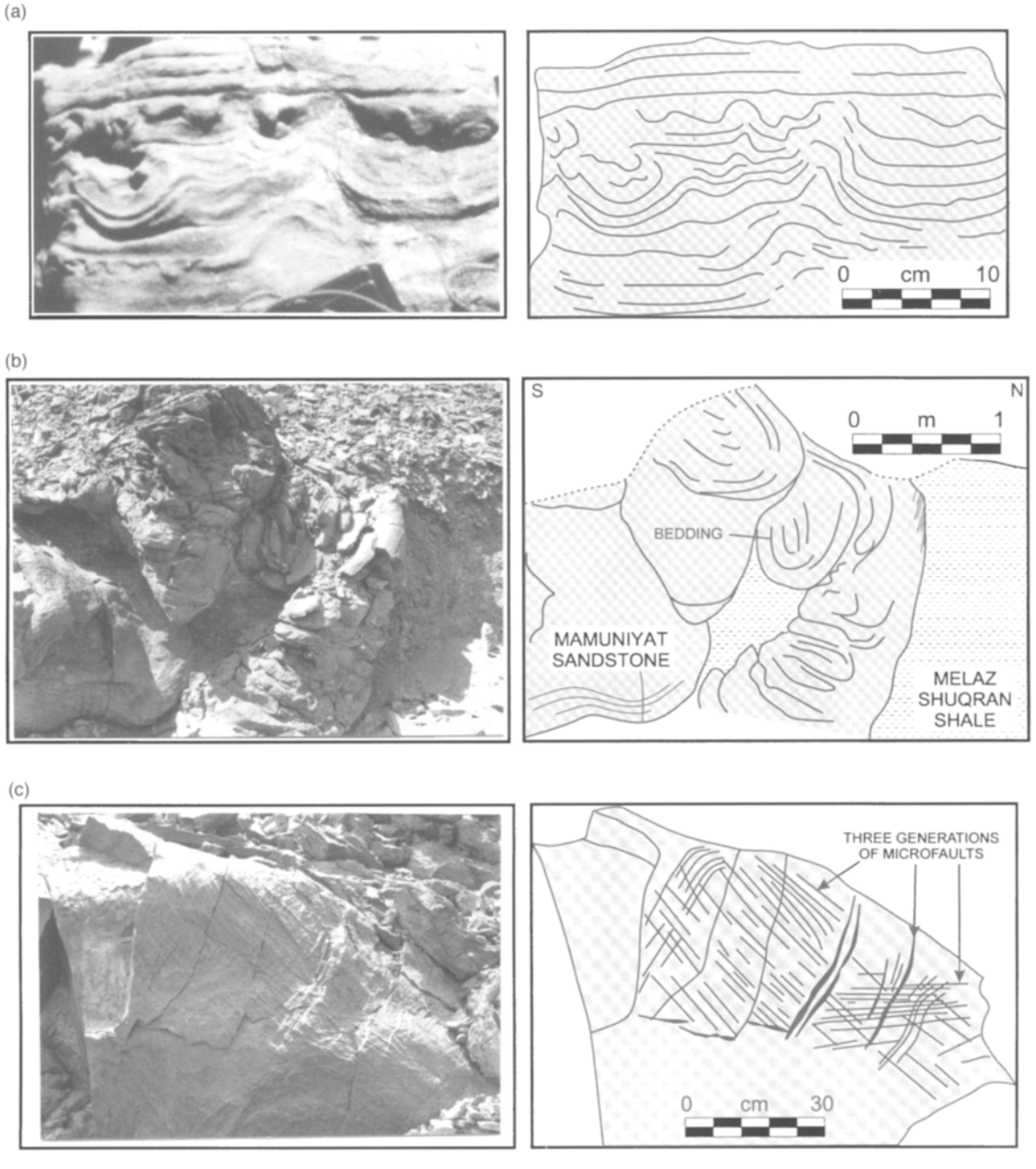

Figure 8. (a) Small scale dewatering structures developed within the internal part of the slide (27°43′07″ N, 12°46′20″ E), (b) Load features preserved along the contact between the Mamuniyat and Melaz Shuqran formations (27°45′04″ N, 12°47′69″ E), (c) Different generations of microfaults developed around the limbs of load structures, formed by the sliding of grains with little or no cataclasis (27°45′04″ N, 12°47′69″ E). This type of faulting is typical in weakly lithified or highly pressured sediment.

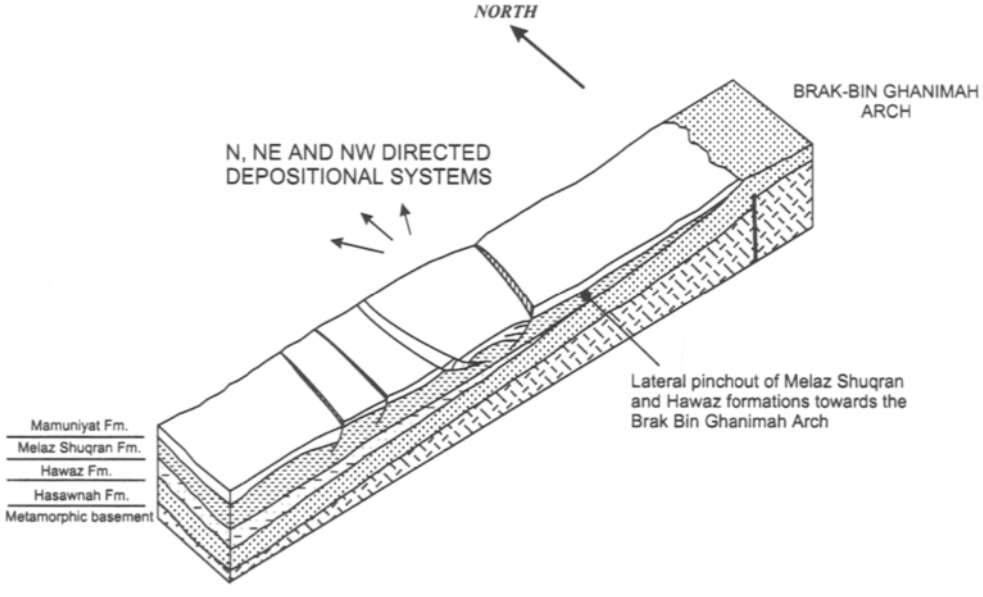

Figure 9. Schematic diagram illustrating sliding of Mamuniyat Formation sandstones off the western flank of the Brak-Ben Ghenemah Arch.

of the Mamuniyat Formation appears to have played a major role in the soft-sediment deformation recorded in the Duwaysah Slide. Emplacement of these sands onto an unstable substrate was probably one of the main internal causes of sliding.

Late Ordovician fault activity could have triggered the soft sediment deformation, although the effectivity of this mechanism is difficult to quantify. Seismic sections through the NC–174 concession reveal Cambro-Ordovician across-fault thickness changes and thinning of the interval across fault block crests indicating that faults in the Murzuq Basin were active at this time. Tectonism created a series of northerly trending highs (Tumarolin and Brak-Ben Ghenemah arches) and intervening sub-basins (Klitzsch, 1970). Uplift and erosion is also recognised at this level in southwesternmost Libya where basal sands of the Mamuniyat Formation directly overlie the Tremadoc sandstones of the Ash Shabiyat Formation.

The occurrence of water-escape structures, particularly load structures, is probably the result of density contrasts resulting from the rapid influx of sand and resulting overpressure, leading to lateral and vertical pore-water flow. Contractional deformation brought about by the downslope sliding of sediment promoted rapid pore-water escape in the toe region of the slide.

The soft sediment deformation features described above are thought to represent a slide unit initiated by the rapid deposition of coarse sandstone on a muddy substrate. Although the regional palaeoslope dipped northwards, the orientation of the listic growth faults and the slump folds indicates that the overall movement of the slide was controlled by the Brak-Ben Ghenemah Arch, a NW-striking uplift passing through the centre of the present-day Gargaf Arch and first described by Klitzsch (1970). As previously stated, the northerly dipping palaeoslope was locally modified by these NW- and NE-striking uplifts. It is proposed that the deformed sediments in the Duwaysah region slid off the western edge of this uplift (Fig. 9).

CONCLUSIONS

The soft-sediment deformation recorded in the Duwaysah Slide along the western Gargaf Arch in Libya is characterised by both extensional and contractional structures. The extensional zones

recorded are dominated by families of early listric, normal faults which commonly reveal syn-depositional growth and sole-out at the same level. Conversely, compressional structures include sheath folds resulting from internal shearing of the slide unit and more open upright folds together with thrusts. Although the location and orientation of the slide was controlled by the presence of the Brak-Ben Ghenemah Arch, sliding was triggered by the rapid deposition of basal sandstones of the Mamuniyat Formation across an already unstable substrate of transgressive marine shales of the Melaz Shuqran Formation.

ACKNOWLEDGEMENTS

This chapter has benefited greatly from discussions with LASMO Grand Maghreb Ltd employees and with colleagues at the University of Wales Aberystwyth, particularly Simon Beswetherick, Jerry Smart, Mike Buck and Andy Fisher. Particular thanks are extended to Messrs. Mukhtar, Hassan and Habib of Fezzan Tours in Sebha for their assistance with fieldwork logistics. The main author would like to thank LASMO Grand Maghreb Ltd. for their continuous support and assistance throughout the duration of this research project. The study was undertaken during the tenure of a University of Wales studentship, which is gratefully acknowledged.

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CHAPTER 21

The Lower Devonian succession of the Murzuq Basin – possible indicators of eustatic and tectonic controls on sedimentation

K. ADAMSON,[1,2] T. GLOVER,[1,2] R. WHITTINGTON[1] and J. CRAIG[3]

ABSTRACT

During the Devonian the Murzuq Basin was situated on the northern margin of Gondwanaland and formed part of an extensive ramp margin that gently deepened to the northwest with no marked shelf slope break. The Lower Devonian Tadrart and Ouan Kasa formations have been studied in outcrop on the southwest flank of the basin and also by the use of subsurface data from the centre of the basin. These formations comprise seven facies associations, representing initial deposition by coarse-clastic braided fluvial systems, followed by paralic and finally ferruginous oolitic deposits. The intercalation of these facies associations suggests a number of base-level fluctuations during the early Devonian that juxtaposed alluvial and marine facies. Several phases of tectonism are also interpreted to have occurred, resulting in lateral variations in subsidence rate and also in the uplift and erosion of early and Pre-Devonian deposits near to a number of large structural features.

INTRODUCTION

The Murzuq Basin is bounded to the east by the Tibesti basement massif, to the south and west by the Hoggar basement massif and to the north by the Gargaf Arch (Fig. 1). The present day basin is believed to have formed as a result of late Palaeozoic to Mesozoic tectonism; the basement massifs were reactivated and uplifted during the Tertiary and the Gargaf Arch was last uplifted during the late Cretaceous to Tertiary. The Murzuq Basin did not exist as a separate depositional entity during the Devonian, but was part of the northern margin of the Gondwana continent. Therefore, in this paper the term 'Murzuq Basin' refers to the area's present-day configuration and not the Palaeozoic depositional basin. During the Palaeozoic the entire area formed a ramp type margin that dipped gently towards the northwest, although localised tectonic modifications occurred several times during that era.

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During the early Devonian, this part of northern Gondwana was situated in low southern latitudes with the pole position over or near present-day southern Africa (Scotese et al., 1979; Van Houten and Hargraves, 1987; Kent and Van der Voo, 1990; Scotese and McKerrow, 1990). The pre-Devonian fill of the basin is dominated by a siliciclastic succession with numerous unconformities. The late Silurian was characterised by widespread subaerial exposure, erosion and localised tectonism over the entire area (Bellini and Massa, 1980; Clarke-Lowes, 1985; Khoja et al., 1998; Echikh, 1998; Logan and Duddy, 1998; Boote et al., 1998; Adamson, 1999).

The Lower Devonian Tadrart and Ouan Kasa formations have been studied in outcrop on the southwestern margin of the basin, using a GPS satellite navigation system to locate the study areas and logged sections. These outcrop data were evaluated together with wireline log data from 39 wells and 2D seismic reflection data from the central part of the basin (Fig. 1), as well as oil company reports and previously published data from other areas of the basin. The main outcrops studied are in Jabal Tadrart on the southwest margin of the basin between Ramlat Takharkhuri and the settlement of Al Awaynat (Fig. 1). Over 165 m of section were logged through the Tadrart and Ouan Kasa formations, and additional studies were also made in a number of other areas (Fig. 2). These formations generally dip at a low angle (1 to 4°) towards the east with the outcrop pattern broadly oriented N-S, tapering northward before pinching out completely around 25°48′ N, 10°30′ E (Fig. 2).

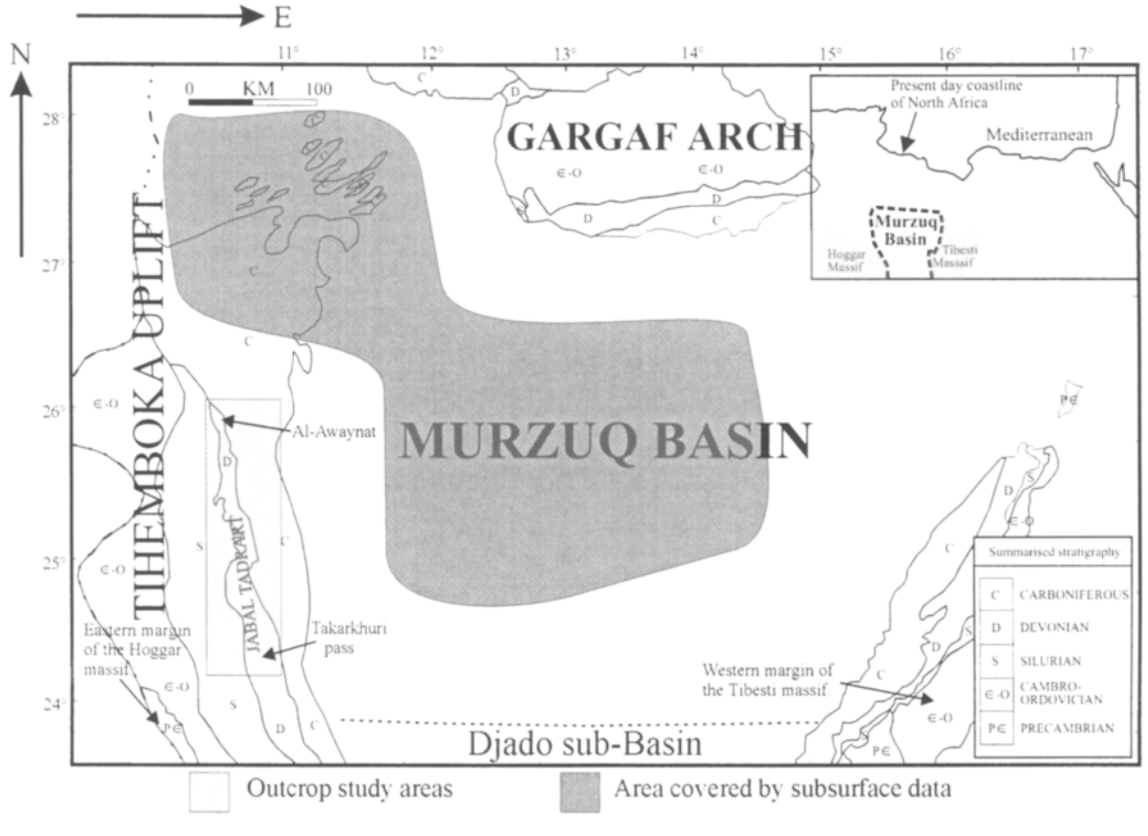

Figure 1. Location map of the Murzuq Basin showing the main geological subdivisions, the position of the outcrop study area on the western margin of the basin and the area covered by subsurface data. The insert (top right) shows the outline of the Murzuq Basin relative to the present day coastline of North Africa.

REGIONAL STRATIGRAPHY

Previous work on the Lower Devonian succession in this area by Klitzsch (1969) recorded over 350 m of the Tadrart and Ouan Kasa formations. Several authors (Galecic, 1984; Jakovljevic, 1984; Protic, 1984; Radulovic, 1984a, b; Clarke-Lowes, 1985; Selley, 1997a) have noted that the Tadrart Formation sandstones are predominantly texturally and compositionally mature quartzites or orthoquartzites, usually comprising 95–100% quartz. However, rare interbeds of micaceous siltstones, mudstones and claystones are also seen. The age of the Tadrart Formation is still poorly constrained; palynological data indicate a general 'early Devonian' age. The early Emsian to Givetian age assigned to the Tadrart Formation by Selley (1997b) is used herein (Fig. 2).

The Tadrart Formation is overlain by the Ouan Kasa Formation throughout much of the study area, although in the NW of the Murzuq Basin the Ouan Kasa Formation apparently directly overlies various levels of the Akakus Formation (Bellini and Massa, 1980; Protic, 1984; Selley,

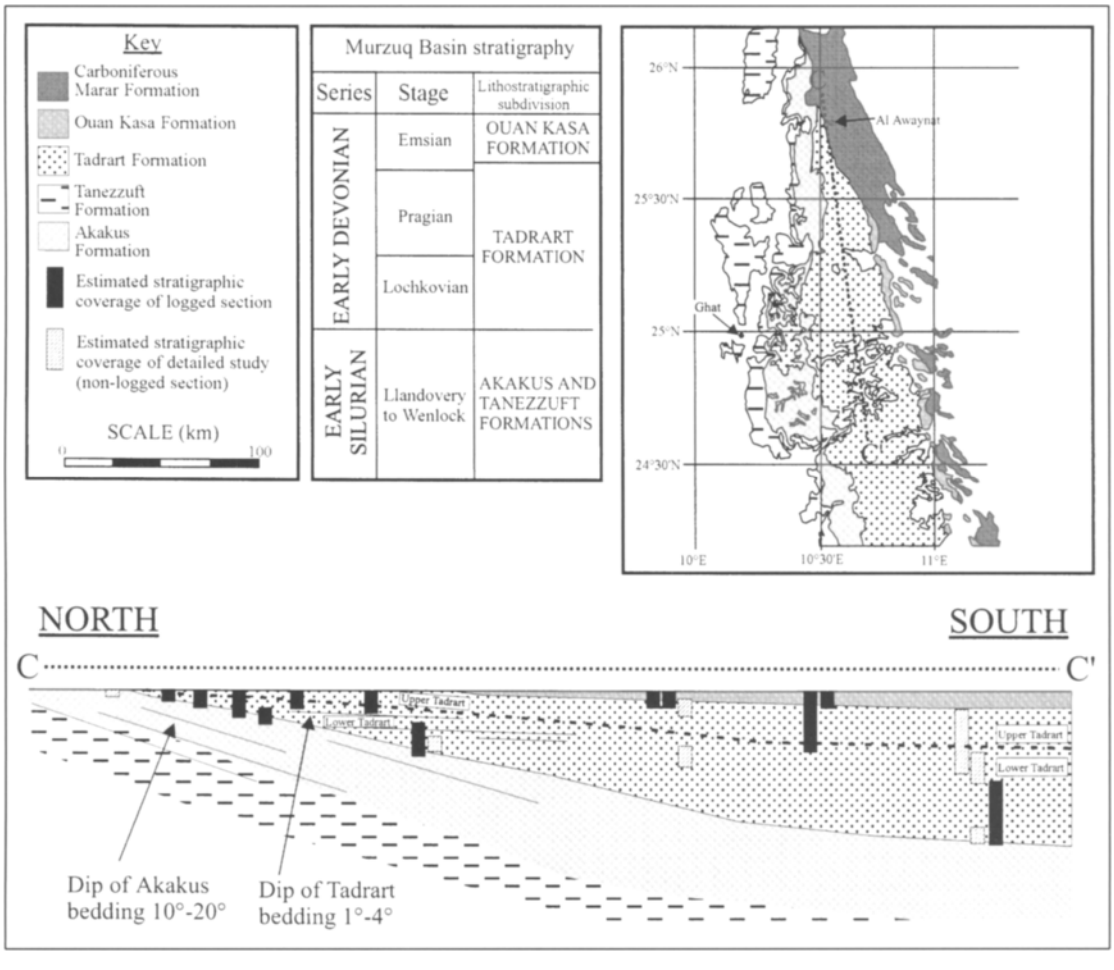

Figure 2. Stratigraphic column and coverage of logged sections and detailed study areas of the Lower Devonian succession on the southwest flank of the Murzuq Basin. The North-South oriented schematic cross-section is hung from the base Carboniferous surface and clearly illustrates the pinch out of the Lower Devonian formations from south to north. Data used in this figure are taken from Klitzsch (1969), Bellini and Massa (1980), Galecic (1984), Jakovljevic (1984), Protic (1984), Radulovic (1984a, b) and Massa (personal communication, 1998).

1997a). This juxtaposition of the Ouan Kasa and Akakus formations is disputed by Massa (personal communication, 1998) who considers that the Ouan Kasa Formation is missing from the central and northern part of the western flank of the Murzuq Basin (Fig. 2). The Ouan Kasa Formation comprises claystones, siltstones, sandstones, and ferruginous oolites, and is generally regarded as Emsian to early Eifelian in age (Galecic, 1984; Jakovljevic, 1984; Protic, 1984).

Seven facies associations have been recognised in the Lower Devonian succession, based on systematic variations in lithology, sedimentary structures and ichnofabric (Fig. 3). Although earlier workers have presented general environmental interpretations for this succession, the

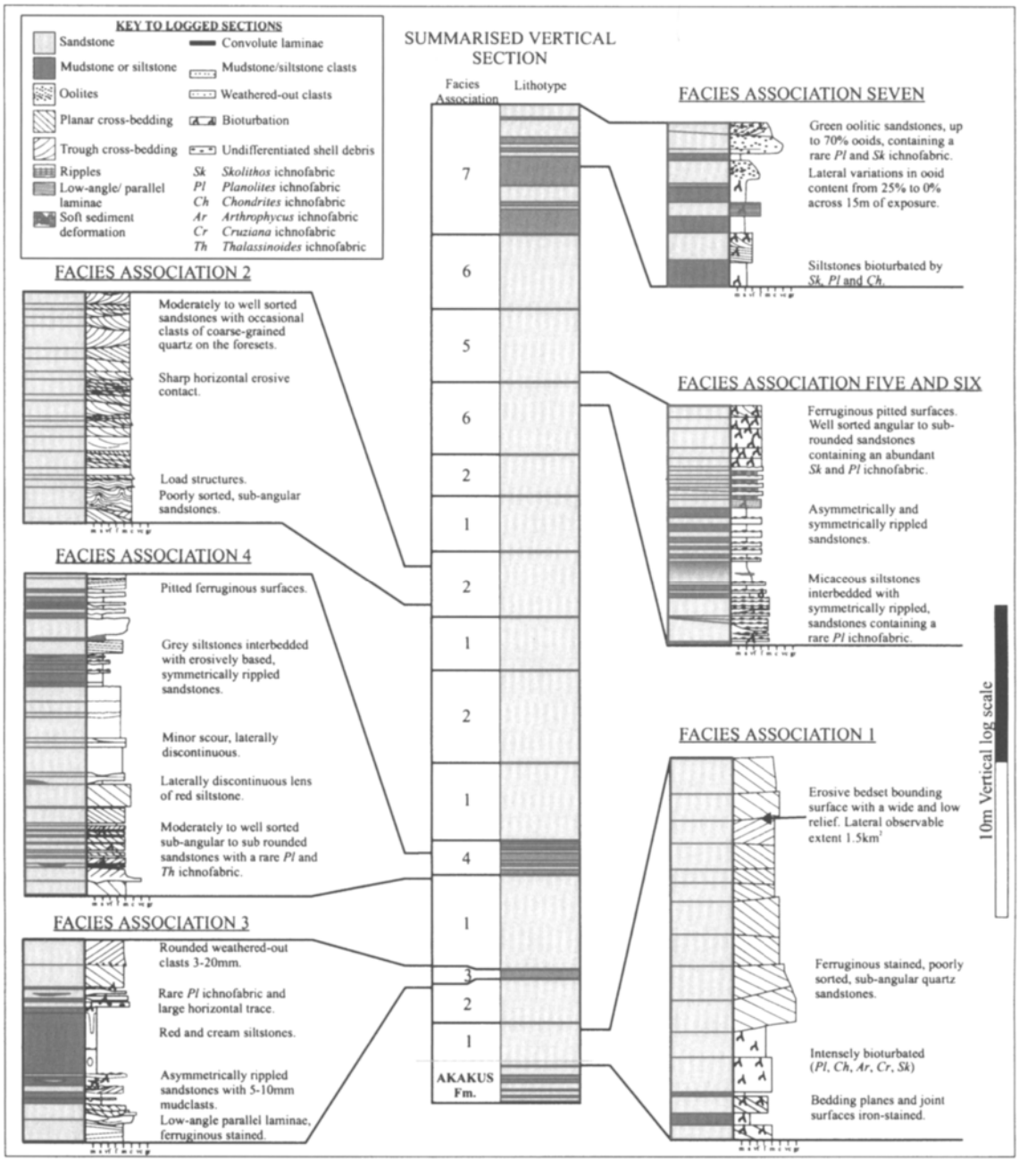

Figure 3. Illustrations of the typical features of facies associations 1 to 7 on the southwest flank of the Murzuq Basin, with reference to the summarised vertical section through the Lower Devonian interval.

facies associations defined and discussed herein give a much more detailed breakdown of these formations' development. The Tadrart Formation comprises facies associations 1 to 6, while the Ouan Kasa Formation comprises Facies Association 7. The transition from one facies association to another is usually abrupt, the exceptions being the contacts between facies associations 5 and 6, which can be transitional. The internal architecture, juxtaposition and regional distribution of these units within the Murzuq Basin has been examined for indications of base-level fluctuations in the area during the early Devonian.

Facies Association 1

This facies association comprises massively bedded, laterally extensive single-storey sheet sandstones (Fig. 3). The sandstones are medium to very coarse-grained, moderately sorted and are planar tabular and trough cross-bedded. The planar tabular cross-bedded units are up to 15 m wide and 1.2 m thick while the trough cross-bedded units are up to 20 m wide and 2 m thick. Rare *Thalassinoides* burrow forms occur. The cross-bedded sandstones occur above kilometre-scale scour surfaces which commonly have coarse-grained, clast-rich lags. Soft sediment deformation structures are generally rare, but some laterally continuous horizons showing fluid escape structures and recumbent foresets (Fig. 3) are common in the northern part of the outcrop study area near Al Awaynat (Fig. 2). At 25°37′19″ N, 10°31′09″ E the units of Facies Association 1 immediately overlying the Early Devonian/ Silurian unconformity comprise moderately to poorly sorted, very coarse-grained to granular conglomeratic iron-stained sandstones. The sandstones at this locality also contain iron concretions, and iron-stained foresets and joint surfaces. The sandstones within this facies association also contain low-angle truncation surfaces that can be traced many tens of metres laterally, as well as laterally discontinuous minor erosional scour surfaces. The truncation surfaces are sub-horizontal and appear to parallel the regional dip.

Facies Association 2

Facies Association 2 comprises thinly to medium bedded, laterally discontinuous, multi-storey channel sandstones with rare siltstones (Fig. 3). The sandstones are fine to very coarse-grained, poorly to moderately sorted and contain minor scour surfaces and rare *Planolites* burrow forms. The sandstones are also planar tabular and trough cross-bedded, as in Facies Association 1, but the bedforms are smaller, laterally discontinuous and occur within discrete channels. Facies Association 2 also contains subordinate 5–10 cm thick packages of low-angle planar laminated sandstones. As in Facies Association 1, this association also shows increasing soft sediment deformation in the north of the outcrop study area (Fig. 2), with recumbent foresets (overturned towards the west), fluid escape structures, and massive 'fluidised' sandstones. At a number of localities the sandstones contain low-angle scour/truncation surfaces that can be traced many tens of metres laterally. These truncation surfaces are repeated vertically to produce a succession of cross-bedded sandstones cut every 50–100 cm by truncation surfaces. Bed thickness and grain-size commonly decrease away from these truncation surfaces.

The rare siltstones in Facies Association 2 are micaceous and occur in laterally discontinuous lenses that are incised by the sandstones. The siltstones also contain rare *Tigillites* burrow forms.

Interpretation of Facies Associations 1 and 2

Facies associations 1 and 2 display broadly similar features and are interpreted to have been deposited in braided fluvial deposystems (Fig. 4). The distinction between these two associations is made because of the distinct and systematic variations in bedform size and channel geometry between them. Units in Facies Association 1 are interpreted to have been deposited in large, relatively deep braid channels that contained large bedforms, while units in Association 2 were deposited in smaller and shallower channel systems (Fig. 4). Both associations contain evidence of frequent erosional reworking of previously deposited bedforms.

Braided rivers are characterised by wide, shallow, low sinuosity channels (Cant, 1982; Selley, 1985) containing multiple thalwegs (Miall, 1996) that form as a result of differential flow in the channel systems. The differential flow regime leads to the formation of composite braid bars separated by interbar channels (Cant, 1982; Miall, 1996). The sedimentary structures and alluvial architecture of the present associations are similar to those observed in the Platte-type braided river of Miall (1977), and the shallow, perennial, sand-bed braided river of Miall (1996). Both of Miall's braidplain models are characterised by large planar, tabular cross-bed sets and subordinate trough cross-bed sets, although the latter cross-bed type is more common in the Tadrart associations than in either of Miall's models, possibly suggesting highly mobile channel margins. These cross-bedded, sand-dominated successions comprise most of the deposits of the Platte-type braided river, with fine-grained lithofacies subordinate or entirely absent (Miall, 1977; 1996). It is difficult to further subdivide the various bedforms observed in facies associations 1 and 2 because of limited data regarding their three-dimensional geometry and relationships to the channel margins.

The absence of complete waning-flow accretion successions, usually capped by small 2D and 3D bedforms and ripples (Miall, 1996), is thought to indicate the frequent erosional reworking of the channel fill units to form complex coalesced bar forms. There is also little evidence of unconfined flow and sheet flood conditions, although the numerous low angle truncation surfaces observed in Facies Association 2 may represent scour surfaces which formed during repeated periods of relatively high stage flow (Miall, 1996).

The channel systems of braided rivers are laterally unstable because of the lack of cohesive floodplain sediments and generally high discharge peaks result in the lateral incision and migration of channels (Miall, 1996). This lateral migration can result in the preservation of an apparently laterally continuous sand body that may contain a number of diachronous and coeval facies associations filling clearly or poorly defined channels. According to Coleman (1969) lateral migration rates of several thousand metres in a single flood are not uncommon in the present-day Brahmaputra River. Campbell (1976) identified palaeo-braided fluvial channel complexes up to 11 kilometres across containing several coalesced, smaller channels in the Jurassic Morrison Formation of New Mexico. The bounding surfaces of such large channels can be very low-angle, sloping at a few degrees or less (Miall, 1996). Channel scour can result in juxtaposition of sandstones (Miall, 1996), and consequently the bounding surfaces can be difficult to identify in the field. Laterally migrating channels generally produce successions dominated by cross-bedded units, rather than the massive sandstones resulting from upper flow regime sedimentary structures formed by unconfined sheet floods (Allen and Allen, 1990).

The laterally continuous, thinly to thickly bedded sheet sandstones of facies associations 1 and 2 are therefore interpreted to reflect laterally migrating mobile channel belts rather than unchannelised sheet floods. The overall dimensions of the braid channels in these facies associations were not determined during the course of this study, partly due to the limited availability of sections oriented perpendicular to the flow direction. However, the increased frequency of erosion surfaces and smaller bedforms in Facies Association 2 (Fig. 3) is thought

to indicate a greater degree of topographic differentiation within the alluvial system, with more numerous, relatively narrow and smaller channels with steeper sides.

The recumbent foresets observed in these facies associations are interpreted to have formed as a result of liquefaction and subsequent deformation by simple shear. The concentration of these deformed intervals in the north of the outcrop study areas strongly suggests an external mechanism to cause the liquefaction such as earthquake(s). This deformation process is common in fluvial deposits with the deformation occurring soon after deposition in unconsolidated sediment (Collinson and Thompson, 1989).

The presence of a rare, monotypic *Thalassinoides* ichnofabric in Facies Association 1, and rare examples of a monotypic *Planolites* or *Tigillites* ichnofabric in Facies Associations 2 may indicate the periodic establishment of paralic environmental conditions. However, present data is too limited to understand the significance and regional distribution of this ichnofabric.

Palaeocurrent data from planar tabular cross-bedding in these facies associations generally have a bimodal distribution towards the WSW and N, bisected by the northwesterly directed vector mean from the trough cross-beds (Fig. 4). These variations in cross-bed migration direction probably indicate the migration of straight crested bars and sandflats in directions transverse to the in-channel primary flow direction, while sinuous crested and lunate bars migrated downstream within the channels (Fig. 4). The overall distribution of palaeocurrent data suggests that bedforms were migrating in low sinuosity channels that were generally oriented towards the N and NW (Fig. 4). The drainage direction identified in this study generally corresponds to that inferred by Beuf et al. (1971), Jakolovljevic (1984), Clarke-Lowes (1985), and Selley (1997a).

Facies Association 3

This association comprises laterally discontinuous thinly to massively bedded siltstones and mudstones with thin sandstone interbeds (Fig. 3). The siltstones and mudstones generally weather to a cream colour although the uppermost mudstones sometimes weather red. The siltstones and mudstones contain sub-angular to sub-rounded clasts of fine to very coarse-grained quartz sandstone. The thinly bedded sandstones are laterally discontinuous, fine to very coarse-grained, poorly to well sorted and contain mudstone flakes, rounded clasts, and plastically deformed clasts of siltstone or mudstone (Fig. 3). The sandstones also contain an ichnofabric of low to medium abundance and low diversity, comprising *Planolites* and an unidentified, large horizontal trace. The sandstones are planar tabular and trough cross-bedded, the upper beds of which contain symmetrical ripples. Units comprising Facies Association 3 are very uncommon in lateral and vertical profiles through the Lower Devonian succession and are wholly encased in units of facies associations 1 and 2 (Fig. 3).

At 24°40′52″ N, 10°36′61″ E, Facies Association 3 comprises a 4 metre thick lenticular body of massive mudstones and subordinate current rippled sandstones that pinches out laterally across 20 m of exposure. This lenticular geometry is controlled by a concave-upward basal scour surface that incises into the underlying sandstones.

Interpretation of Facies Association 3

This association is interpreted to comprise abandoned channel fill and laterally discontinuous flood plain deposits (Fig. 4). The red/cream colouration of the mudstones is thought to be the result of the variable weathering, oxidation and/or organic content of the sedimentary rocks, produced by a range of pedogenic processes as outlined by Miall (1996). The lenticular feature

described above is interpreted as a braid channel that was scoured during high-flow conditions and subsequently filled following abandonment by fine-grained lithofacies (Fig. 4). This abandoned channel may be positioned laterally to the active channel complex, or may have been filled by the process of reverse eddy transport (c.f. Selley 1985).

The ichnofabric in Facies Association 3 indicates more favourable conditions for colonisation by burrowing organisms than in facies associations 1 and 2, possibly reflecting the transition from a braidplain to a paralic setting (Fig. 4). The fine-grained nature of Facies Association 3 results in a low preservation potential because of the otherwise generally high energy, sandy, braidplain environment and the few cases where this facies association is preserved may represent isolated examples of what was a more common association in the primary depositional system.

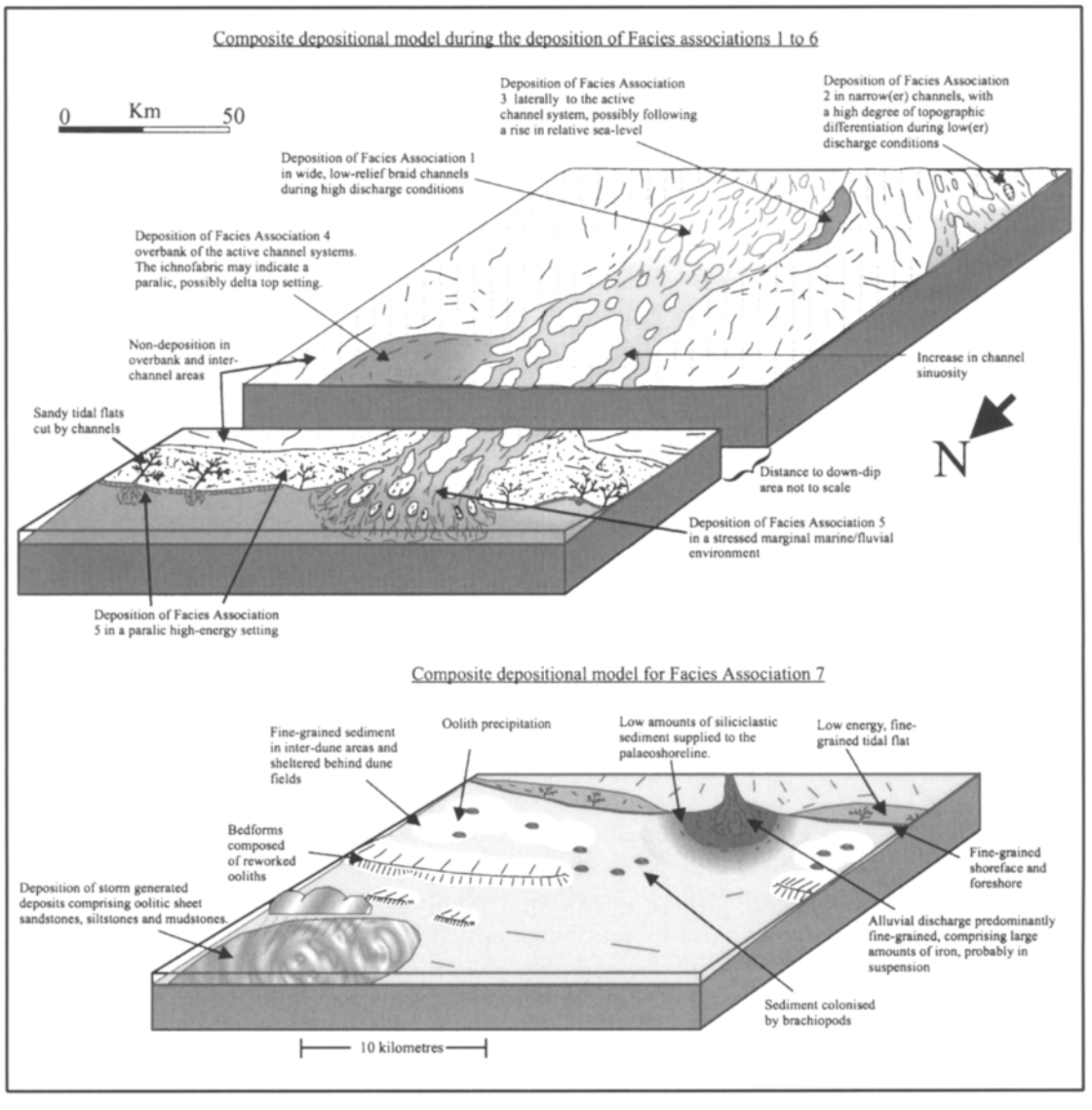

Figure 4. Summarised depositional models for facies associations 1 to 7 on the southwest flank of the Murzuq Basin. Note the dramatic change in depositional processes active during the deposition of facies associations 1 to 6 relative to facies association 7.

Facies Association 4

This facies association comprises laterally continuous, erosively-based, thinly to medium bedded mudstones, siltstones and sandstones (Fig. 3). The mudstones and siltstones contain sub-angular and sub-rounded clasts of fine to very coarse-grained sandstone. The mudstone and siltstone beds show laterally variable thicknesses, as they are often erosively overlain by sandstones. The sandstones are fine to coarse, rarely very coarse-grained, and are moderately to well sorted; they are commonly structureless although rare symmetrical ripples, planar tabular and trough cross-bedding, low-angle planar laminae and soft sediment deformation also occur (Fig. 3). The upper surfaces of many of the sandstones are irregular and iron-stained. The sandstones also contain an ichnofabric of low to medium diversity comprising *Planolites* and *Thalassinoides*.

Interpretation of Facies Association 4

The sediments of this facies association are interpreted as alluvial flood plain and/or coastal plain facies, deposited laterally to or down-dip of areas within which facies associations 1 to 3 were deposited (Fig. 4). The increased amounts of fine-grained sediment in Facies Association 4 indicates an overall decrease in depositional energy, perhaps reflecting a change in alluvial style, e.g. from braided to anastomosing channels, or deposition in areas distal to active channels (Fig. 4). The sedimentary structures suggest deposition in overbank areas, with the ichnofabric possibly indicating a mixed fluvial/paralic environment. However, as these overbank units could not be directly correlated to in-channel facies the regional depositional setting is poorly constrained.

Facies Association 5

This association comprises laterally continuous, thinly to medium bedded sandstones with rare siltstones (Fig. 3). The sandstones are very fine to very coarse-grained and poorly to moderately sorted, with the finer grained sandstones being micaceous. The sandstones have erosive bases and contain weathered-out rounded clasts and siltstone/mudstone flakes; internally they display planar and trough cross-bedding with subordinate low-angle planar lamination (Fig. 3). These sandstone dominated successions contain laterally continuous planar and convex-up coset bounding surfaces, scour surfaces and re-activation surfaces, with cross-bed cosets up to 1.5 metres high that can be traced laterally over tens of metres. The thinly bedded sandstones contain asymmetrical ripples, ripple cross-laminae, symmetrical ripples, rare fluid escape structures and rare iron-stained upper surfaces. The sandstones also contain an ichnofabric of high abundance comprising *Planolites*, *Tigillites*, *Skolithos*, *Cruziana*, *Arthrophycus*, and possibly *Ophiomorpha*. Lateral variations in the diversity and abundance of the ichnofabrics are observed, commonly with single beds dominated by *Skolithos* or *Cruziana* ichnofabrics. At 25°48′37″ N, 10°30′62″ E *Skolithos* burrows are noted to penetrate though a 40 cm thick sandstone bed into the underlying siltstone across a low-angle scour surface, a feature that can be traced over 150 metres of lateral exposure.

Facies Association 6

Facies Association 6 comprises thinly to massively bedded sandstones, siltstones and mudstones (Fig. 3). The sandstones are fine to medium-grained, occasionally granular, poorly to well

sorted, and contain an ichnofabric of low to high abundance comprising *Planolites*, *Tigillites*, *Skolithos* and *Chondrites* with monotypic *Skolithos* ichnofabrics dominant. The sandstones are commonly devoid of sedimentary structures but rare ripple cross-laminae, laterally discontinuous planar tabular and trough cross-bedding, low-angle planar laminae, and fluid escape structures are observed. The upper beds of many of the sandstones are also iron-stained and contain asymmetrical ripples overlain by symmetrical ripples. The sandstones commonly incise into the siltstones and mudstones with laterally discontinuous lenses of siltstones and mudstones interbedded with the sandstones.

Interpretation of Facies Associations 5 and 6

Facies Association 5 is interpreted as marine-influenced braidplain and braid delta deposits while Facies Association 6 comprises marine influenced braid delta, interdistributary bay, tidal flat, tidal channel, and shoreface deposits (Fig. 4).

The sand dominated succession and clast-lined scour surfaces indicate high depositional energy levels, with erosional reworking of fine-grained material. The diverse and abundant ichnofacies in both facies associations indicate favourable conditions for colonisation within the sediment and above the sediment/water interface, although variations in the abundance and diversity of the ichnofabric are observed, indicating subtle changes in the physical and chemical conditions within the sub-environments outlined above. An example of this was seen at 25°48′84″ N, 10°30′91″ E, where bioturbated sandstones and siltstones deposited on a tidal flat are incised by tidal channels with planar tabular and trough cross-bedded sandstones. The laterally discontinuous iron-stained upper surfaces observed on some of the sandstones are interpreted to have formed during short periods of subaerial exposure, resulting from variations in the rate of deposition and changing patterns of active fluvial, deltaic, and shallow marine depositional conditions.

Palaeocurrent data from planar tabular and trough cross-bedding in these facies associations generally indicate the migration of bedforms towards the WSW to NNW (Fig. 4). These bedforms generally migrate in a downstream direction within proximal fluvial, deltaic and tidal channels. These orientations are broadly comparable to the data from facies associations 1 and 2 (towards the WSW to N; Fig. 4), indicating generally similar bedform migration and channel orientation. The current ripples overlain by symmetrical ripples in Facies Association 5 are interpreted to have formed initially by unidirectional current activity, later modified by oscillatory flow conditions. Flow conditions of this type can occur within fluvial and deltaic channels that are subject to marine processes, often within the tidal range. The inland limit of sedimentary structures influenced by marine processes can be many kilometres inland of the limit of saline intrusion (Dalrymple et al., 1992; Allen and Posamentier, 1993), with low-angle basin dips, such as in the Murzuq Basin, promoting such marine incursions (Wright and Coleman, 1973).

There is limited evidence in this area of marine currents driving bedform migration, probably indicating that wave action was minimal. This situation may have occurred as a result of the low angle basin profile, although high rates of fluvial discharge can also subdue wave action, leading to the formation of fluvially dominated deltas (Wright and Coleman, 1973). The WSW to northerly directed palaeocurrents may also reflect ebb tidal currents of marine origin.

Facies Association 7

This facies association, which corresponds to the Ouan Kasa Fm, comprises laterally discontinuous thinly to medium bedded claystones and ferruginous oolitic siltstones and

sandstones (Fig. 3). The oolitic sandstone bars have a lenticular form, often passing laterally into siltstones and mudstones before being replaced by successive oolitic bar forms. The siltstones contain between 5 and 20% oolitic material while the sandstones contain between 0 and 70% oolites, the latter being fine to medium-grained, sub-rounded and ferruginous. The sandstones are fine-grained and contain rounded siltstone clasts, shell debris, shell moulds, and an ichnofabric of low to medium diversity comprising *Planolites*, *Tigillites* and *Chondrites*. The sandstones form erosively-based beds within which the grain-size fines or coarsens upward and they display rare planar tabular and trough cross-bedding, low-angle planar or parallel laminae, soft sediment deformation or are structureless. The upper surfaces of many of the oolitic sandstones are iron-stained and irregular.

Geochemical analysis of the claystones in this facies association (Galecic, 1984; Jakovljevic, 1984; Protic, 1984) suggest that they mainly comprise kaolinite with subordinate illite-montmorillonite, alunite, jarosite, gypsum, goethite and quartz.

Interpretation of Facies Association 7

This association is interpreted to have been deposited within shallow marine and lagoonal palaeoenvironments (Fig. 3). The lithofacies variations observed are thought to be the result of transitions between offshore bar, shoreface, tidal flat, and lagoonal depositional environments. According to Galecic (1984), Jakolovljevic (1984) and Protic (1984) the geochemical analyses of claystones in the association suggest deposition within the quiet brackish waters of a closed basin, probably a lagoon with acidic water, pH ranging from 2 to 6.

The ooliths in the facies association occur in variable amounts within the cross-bedded sandstones and are interpreted as offshore bar deposits that migrated in a shallow marine setting, while the oolith prone siltstones are interpreted to have been deposited in lower energy areas between and behind the oolite bars (Fig. 4). The fining-upward grain-size noted in several of the sandy oolite beds is thought to reflect the migration of sandy/oolitic bedforms that were separated by finer grained interbar areas.

The thinly bedded quartz sandstones, which are interbedded with siltstones and mudstones, may be the result of occasional storms or strong tidal activity (Fig. 4). The mud and siltstone clasts and shell debris in these sandstones also indicate a high depositional energy level. The pitted upper surfaces of many of the thinly bedded sandstones are interpreted to be the result of bioturbation during low-energy conditions and/or the result of oxidation and/or subaerial exposure. Similar iron-stained surfaces were observed by Clarke-Lowes (1985) together with desiccation cracks and he therefore interpreted these features to be the product of subaerial exposure.

Previous studies of Palaeozoic to Recent ferruginous oolites in the Murzuq Basin and worldwide have proposed a variety of models to explain their formation and occurrence (Bennacef et al., 1971; Guerrak, 1989, 1991; Pierobon, 1991; Selley, 1985, 1988; Van Houten and Karasek, 1981). The general consensus is that oolites form by the bonding of aragonite crystals around an often bioclastic nucleus, with blue-green algae being thought to play a role in aragonite precipitation (Selley, 1985, 1988). Ferruginous oolites have been interpreted to accrete in quiet conditions, forming within iron rich muds (Chauvel and Guerrak, 1988; Guerrak 1989; 1991). The ferruginous oolites in Facies Association 7 generally occur in a quartz rich matrix (silt to medium-grained sand), in beds of limited thickness and geographic distribution, thus falling within the definition of the Local Ironstone Deposition (LOID) and Ferruginous Oolite Detrital (FOD) ironstone facies of Guerrak (1989, 1991). The source of iron within LOID type ferruginous oolites may be localised, but Guerrak (1991) proposed a remote source of iron for the ferruginous oolites in Facies Association 7 – possibly the West African craton, the

Nigerian Pan-African chain, or the Congo shield. Palaeogeographic reconstructions for the pre-Devonian generally suggest a southeasterly clastic source, indicating that the iron was transported down rivers from weathered basement rocks or from eroded, iron-rich, pre-Devonian sedimentary rocks uplifted to the south and east of the Murzuq Basin during the late Silurian.

The absence of Facies Association 7 from the northern part of the outcrop belt on the SW flank of the basin is thought to be the result of post-depositional erosion (D. Massa 1998, personal communication; Adamson, 1999).

EARLY DEVONIAN FACIES EVOLUTION

The different levels within the Lower Devonian succession appear to be dominated by one or more of the facies associations outlined above. The lower part of the Tadrart Formation is primarily made up of 'Platte type' braided fluvial deposits comprising facies associations 1 and 2, but with rare examples of Facies Association 3 (Fig. 5). However, this interval also contains a succession of alluvial flood plain and/or coastal plain deposits assigned to Facies Association 4 (Fig. 5). This development may simply record the avulsion of the active braid channels away from this region or a discharge-related change in channel sinuosity and bedload character. However the abrupt change in facies and alluvial architecture may also reflect a rise in relative sea-level, juxtaposing relatively up-dip alluvial and down-dip alluvial to paralic facies. Previous studies of what are thought to be coeval deposits in this area of the Murzuq Basin (Clarke-Lowes, 1985), and in the Kufra Basin (Turner, 1987, 1998) have also identified a rise in relative sea level within the alluvially dominated Lower Devonian succession. Although the lack of detailed biostratigraphic data prevents the definitive correlation of these events, these interpretations suggest that relative sea level fluctuations did occur during this time, influencing

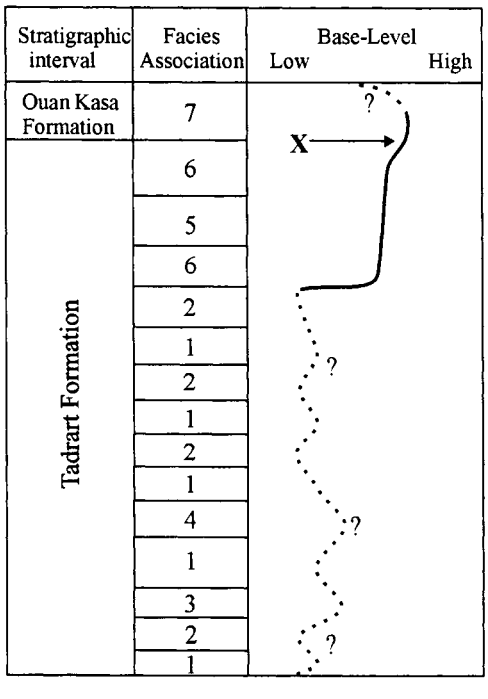

Figure 5. Schematic base-level variations during the deposition of facies associations 1 to 7. The decrease in base-level in the upper part of facies association 7 (Ouan Kasa Formation) is in accordance with the interpretations of Clarke-Lowes (1985). Point **X** represents the approximate position of the abrupt transition from coarse-grained siliciclastic to fine-grained oolitic lithotypes.

alluvial style, and/or juxtaposing fluvial and paralic facies. It is also possible that the abrupt transitions between intervals comprising facies associations 1 and 2 record changes in fluvial channel style and discharge character that are driven by variations in base-level or climate, although the driving mechanisms, in this instance, are poorly constrained.

The vertical transition from predominantly fluvial to marine influenced facies in the upper part of the Tadrart Formation and in the Ouan Kasa Formation indicates a rise in relative sea level in this region (Fig. 5), corresponding with the observations and interpretations of previous workers (Klitzsch, 1969; Bellini and Massa, 1980; Clarke-Lowes, 1985). Analysis of regional data and interpretations from elsewhere in Libya (Bellini and Massa, 1980; Clarke-Lowes, 1985; Turner, 1998), Algeria and Morocco (Dubois et al., 1969; Bekkouche, 1992; Daoudi, 1995) and Iberia (Keller, 1997), suggest that this rise in relative sea level may be of regional importance, possibly corresponding to the eustatic transgression at the end of the Early Devonian in Euramerica as summarised by Johnson et al. (1985). The limited amounts of coarse siliciclastic sediment in the Ouan Kasa Formation may also be explained by a late Early Devonian transgressive event which flooded clastic source areas and resulted in a change in sediment supply processes to shallow marine areas (Fig. 4).

REGIONAL VARIATION IN FORMATIONAL DISTRIBUTION

Outcrop data from the western and northern margins of the basin and subsurface data from the present-day basin centre highlight a number of variations in the distribution and thickness of the Tadrart and Ouan Kasa formations (Fig. 6). Most notably, well logs suggest that both formations

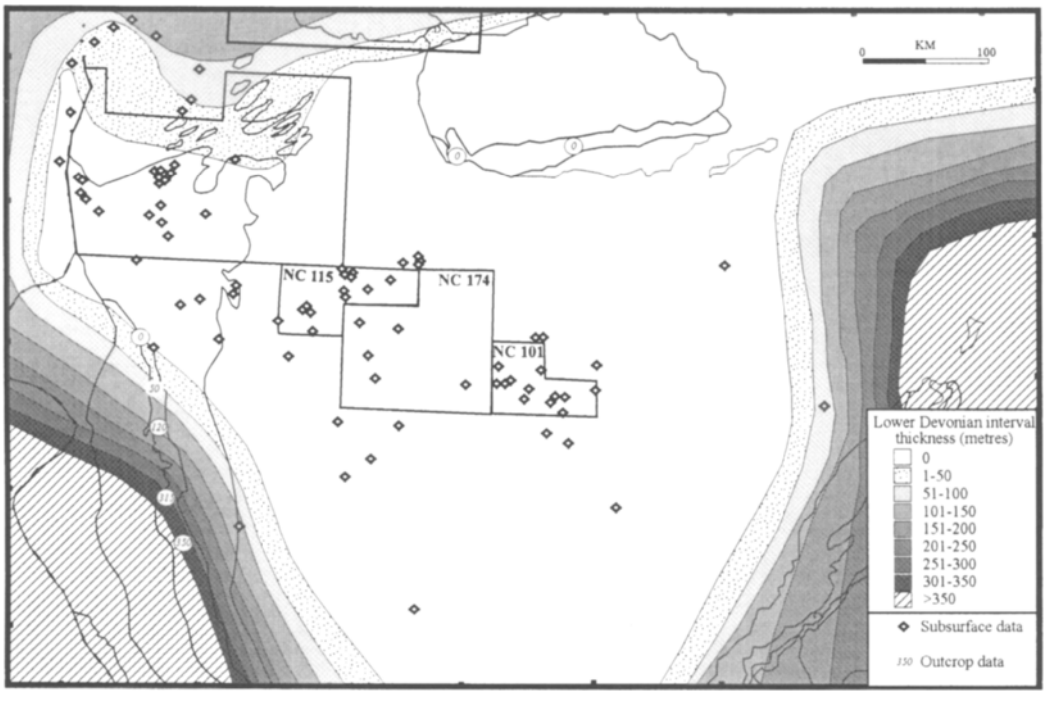

Figure 6. Isopach of the Lower Devonian succession within the Murzuq Basin illustrating the rapid pinch-out of the interval on the western margin towards the N and E, and a number of other, abrupt thickness variations. Data utilised include outcrop, wireline log and previous studies by Klitzsch (1969), Bellini and Massa (1980), Galecic (1984), Jakovljevic (1984), Protic (1984), Radulovic (1984a, b), Clarke-Lowes (1985), Massa (1988) and Adamson (1999).

are absent from the basin centre . In part this may reflect the late Silurian tectonism outlined by many authors (Bellini and Massa, 1980; Clarke-Lowes, 1985; Boote et al., 1998; Echikh, 1998; Khoja et al., 1998, Logan and Duddy, 1998; Adamson, 1999; Glover, 1999) that created a complex palaeotopography across the basin. However, on the western margin of the basin both the fluvial and marine influenced parts of the Tadrart Formation appear to thin towards the north (Fig. 2), possibly indicating syndepositional differential subsidence in this area of the basin. The absence of the Lower Devonian succession from the present day basin centre may also have a similar, subsidence driven controlling mechanism.

While the exact location and nature of the structure(s) that may have caused these thickness variations are difficult to accurately constrain, a number of large structural elements have previously been identified within the basin (Klitzsch, 1981). The western margin of the Murzuq Basin abuts the Tihemboka Uplift (Fig. 7), and it may be that the northern part of this structure, near the settlement of Al Awaynat, was active during the early Devonian. The present day basin centre also contains a number of large, seismically resolvable faults, although it is difficult to accurately identify which of these structures were active at this time to cause differential subsidence and/or erosion. The intervals containing widespread and continuous soft sediment deformation structures in facies associations 1 and 2 may also have been triggered by the movement of faults associated with the Tihemboka Uplift during the early Devonian. The erosion of the Ouan Kasa Formation from this part of the basin also highlights another phase of

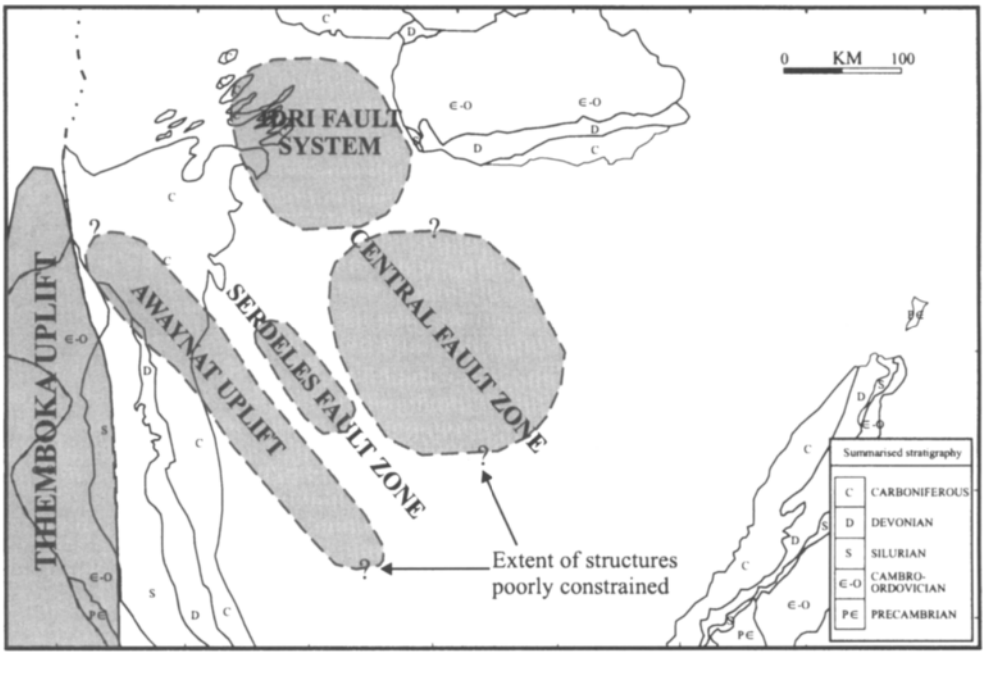

Figure 7. Outline map of the Murzuq Basin illustrating the positions of a number of major structures that influenced the distribution and nature of the Lower Devonian succession. The Tihemboka Arch is recognised to have become active during the late Emsian (Adamson, 1999), while the Awaynat Uplift, Serdeles fault zone and Central fault zone, probably linked in terms of their genesis and movement history, influenced the thickness of the Lower Devonian succession in the central area of the basin (Adamson, 1999). The effects of the Idri fault system, and Serdeles fault zone/Awaynat uplift can be recognised on gravity profiles across the region, while the position of the Central fault Zone is indicated by thickness variations in the Palaeozoic succession, including the Lower Devonian (Glover, 1999). Note that the areal extent of these structures is poorly delimited due to widely spaced or low resolution seismic data.

tectonism during the latter part of the early Devonian (D. Massa, personal communication, 1998)

CONCLUSIONS

Deposition of the Tadrart Formation in the early Devonian Murzuq Basin occurred within a braided alluvial plain setting, with palaeoflow from the southeast to the northwest. Down-dip of this region the braided fluvial systems fed a series of large braid deltas and associated clastic shorelines, palaeoenvironments which impinged upon the study area during periods of relative sea level rise. One such period of relative sea level rise occurred during deposition of the upper part of the Tadrart Formation, when marginal marine conditions prevailed on the southwest margin of the basin. This late Early Devonian rise in relative sea level may be coeval with a similar phase recognised throughout North Africa and in other Palaeozoic basins, possibly indicating a eustatic origin. The alluvial architecture of the Lower Devonian succession may also have been directly controlled by raising or lowering the graded profile during eustatic fluctuations, with a number of potential events recognised during this time. Early Devonian tectonism interpreted in the Murzuq Basin region may also have influenced the nature of sedimentary facies, modifying the character, as well as the thickness and distribution of these depositional facies.

ACKNOWLEDGMENTS

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CHAPTER 22

Palaeostress reconstruction and tectonic evolution of the Tataouine Basin (southern Tunisia)

SAMIR BOUAZIZ[1]

ABSTRACT

Southern Tunisia displays the transition from the northern edge of the Saharan Platform to the southern part of the folded Atlas region. Two domains have been distinguished on a morphotectonic basis: (1) the Dahar subtabular plateau and (2) the Jeffara coastal plain, which represents a collapsed block. These domains extend eastwards into Libya and the offshore Pelagian Basin. The Dahar Plateau is underlain by a major sedimentary basin – the Tataouine Basin. This basin's stratigraphic succession is almost complete and ranges from the Upper Permian to the Upper Cretaceous, providing a good opportunity to analyse brittle tectonic deformation as expressed by numerous small fractures (minor faults and joints).

Fracturing has affected the whole succession and has been systematically analysed in numerous sites. The geometrical characteristics of the different fault systems and the relationships of the different joint sets (nature, relationship with bedding, geometrical distribution and mechanisms related to regional paleostress) allow reconstruction of the tectonic evolution of the Tataouine Basin. Analyses of tensor determination and of tectonic chronology between faulting regimes have been also conducted.

The successive main stress regimes affecting the region were: (1) Late Permian NE–SW synsedimentary extension affecting the Permo-Carboniferous Jeffara Basin; (2) Early to mid-Triassic NNW-SSE synsedimentary extension related to Early Tethyan rifting; (3) Middle Carnian N 150° compression, with strike-slip regimes, (4) Dominantly N–S extension from the Late Triassic to Early Aptian, reflecting the development of a subsiding basin in the Tataouine area and (5) ENE–WSW and NNW–SSE Late Cretaceous multidirectional extension, followed by ongoing E–W Campanian-Maastrichtian extension. Other compressional and extensional trends recorded in the Tataouine Basin are attributed to Cenozoic events.

INTRODUCTION

Geological and stratigraphical knowledge of southern Tunisia (Fig. 1) has improved considerably since the beginning of this century (Pervinquière, 1912; Mathieu, 1949; Busson,

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1967; Ben Ismail et al., 1989). In addition, geological mapping (1:100 000) undertaken in the last decade by the National Office of Mines has allowed more precise definition of the region's major unconformities and of lateral facies and thickness changes. This region has usually been considered to be a stable platform by previous authors.

The study of brittle deformation in such stable platform areas provides a key to the reconstruction of regional tectonic evolution (Letouzey and Trémolières, 1980; Bergerat, 1987). This is because these domains record the major tectonic events that have occurred along neighbouring plate boundaries.

Because of its particular location in western Tethys and on the northern margin of the African plate and because of its complete stratigraphic section, southern Tunisia provides a good opportunity to reconstruct regional paleostress evolution on the basis of the analysis of fault slip data and joint populations. The first tectonic studies by Bouaziz (1986), Barrier et al. (1993), Bouaziz (1995) and Bouaziz et al. (1998) have covered the most explored parts of southern Tunisia (Fig. 1). In reality, this domain contains several major depocentres, viz. the Tataouine Basin (pertinent to this study), the Jeffara Basin and the Chott Basin. Tectonic data (minor fault-slip data and joint sets) have been collected from numerous sites distributed in all formations in the exposed succession (Fig. 1).

In this chapter, I aim to present a calendar of tectonic evolution where tectonic events are considered in terms of stress. The results of tectonic analyses in the Tataouine Basin are discussed within the tectonic framework of Tunisia (Turki, 1985; Zargouni, 1986; Ben Ayed, 1986; Zouari, 1995) and are related to new data on the break-up of Pangaea (Aubouin et al., 1980), the opening of the East Mediterranean basin (Biju-Duval, 1980; Dercourt et al., 1993; Ricou, 1994) and the convergence between Eurasia and Africa (Bousquet and Philip, 1981).

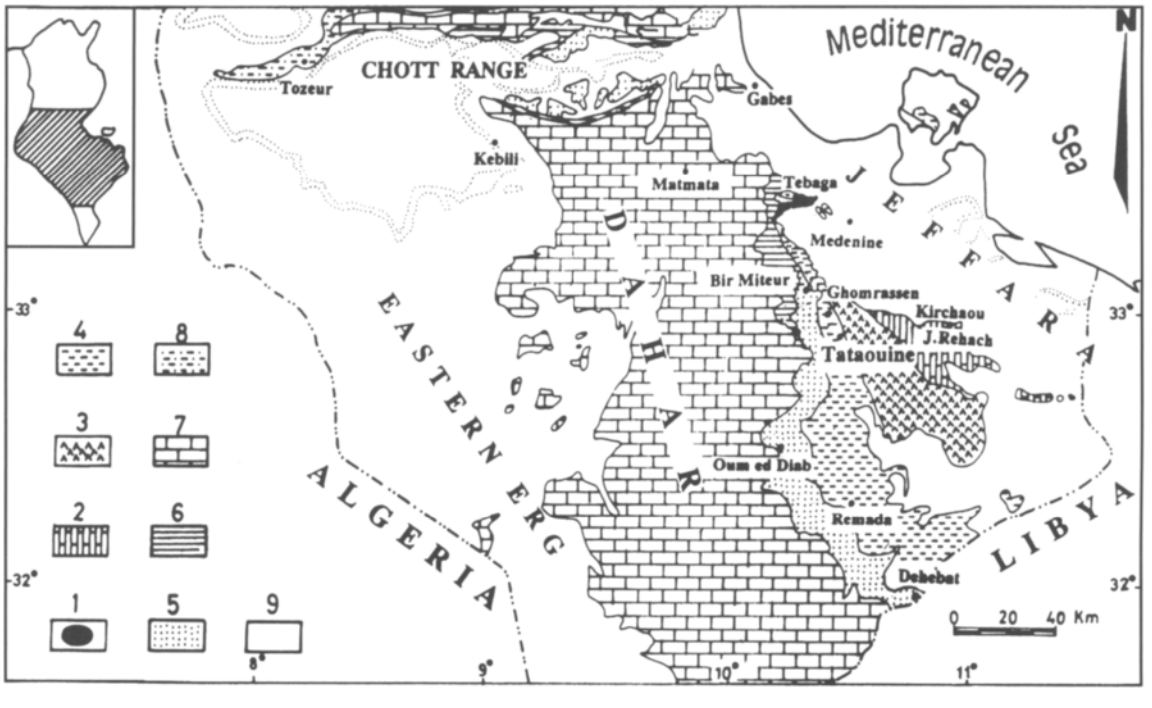


Figure 1. Geological map of southern Tunisia: 1: Late Permian.; 2: Triassic.; 3: Rhaetian-Liassic; 4: Dogger; 5: Malm-Neocomian; 6: Late Albian; 7: Cenomanian-Maastrichtian; 8: Mio-Pliocene; 9: Pliocene-Quaternary.

GEOLOGICAL SETTING

The investigated area is located in southern Tunisia and northwestern Libya (Fig. 1). The Tataouine Basin is one of the major depositional basins of southern Tunisia and generally corresponds to the morphotectonic domain of the Dahar Plateau. The basin has an E–W axis and is bounded to the north by the Tebaga of Medenine Uplift and to the south by the Gharyan Uplift (northwestern Libya). The basin is mostly filled by Mesozoic strata overlying upper Palaeozoic rocks (Fig. 2). Sedimentation in a generally subsiding regime was controlled by major E–W trending faults.

Lithostratigraphical Summary

The composite stratigraphic section shows a complete succession of late Permian to late Cretaceous age (Fig. 2). Special attention will be paid to important facies and thickness variations as well as to precise dating of the major unconformities.

The upper Permian deposits of the Tebaga of Medenine represent the only Palaeozoic rocks exposed in Tunisia. These comprise a very thick marine sequence (800 m) with common biohermal complexes interbedded with red sandstones and marls with fossils (fusulinids). This unit constitutes the upper part of the very thick (>3,000 m) Permo-Carboniferous sequence of the Jeffara Basin (Newell et al., 1976; Termier et al., 1977; Khessibi, 1985; Chaouachi, 1988; Razgallah et al., 1989).

Triassic outcrops have been studied along the Dahar scarp and in the Jabal Rehach section (Busson, 1967; Bouaziz, 1995; Bouaziz et al., 1987). They include three units separated by major unconformities:

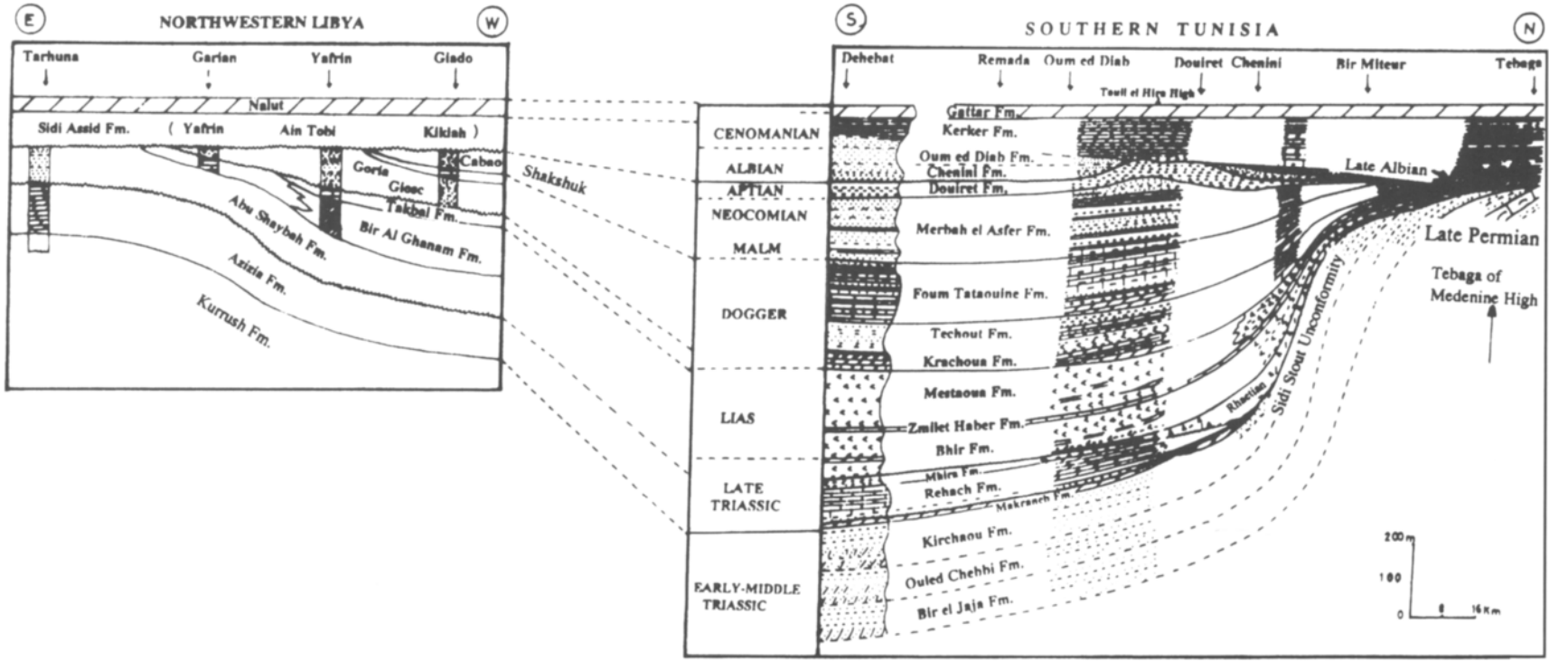
- The lower to middle Triassic comprises red sandstones and shales mostly deposited in continental environments (800 m). This succession represents the continuation of the Permian depositional phase, with rapid subsidence in the Jeffara Basin and development of a southerly dipping tilted block as in the upper Permian outcrop (Fig. 2). From south to the north the deposits are truncated by an early Carnian unconformity,
- A marine transgression then initiated deposition of the first carbonate beds (8–10 m) with fossils of early Carnian age, overlain by red sandstones and clay (15 m). Upper Carnian dolomites and clay, 100 m thick, outcrop only in the Jabal Rehach area (Mock et al., 1987),
- The third unit rests unconformably on all older Triassic formations; deposition started in the Norian-Rhaetian and is characterized by conglomerates, breccias and gypsum.

In Jurassic to early Cretaceous times, sedimentation was marked by deposition of a thick evaporitic succession during the Liassic, while marine facies dominate the middle and upper Jurassic; the upper Jurassic to lower Cretaceous succession shows a varied clastic character. There are important variations in facies and thickness from south to north throughout this succession. The Tataouine Basin constituted the main depocentre during this period.

The overlying upper Cretaceous deposits comprise monotonous carbonate sequences which are well exposed along continuous cliffs bordering the northeastern Dahar Plateau. Albian carbonates unconformably overlie all older formations from the upper Permian to the Aptian. Thickness and facies changes were considerable, particularly in Cenomanian time, but the depocentre was located in the Tebaga of Medenine area.

General structure

The Dahar Plateau is a gentle large-scale subtabular monocline, dipping westwards at 1° to 2° and it may be considered as tabular in form on a regional scale. However, its northern border is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marked by a single structural element, 13 km wide, formed by the 20°–25° southerly dipping Jabal Tebaga (Plate 1, fig. 1).

Southwards, over the upper Permian, the dip of lower to middle Triassic beds decreases from 20° to 8° from the Tebaga of Medenine area to Jabal Rehach. This tilted block, sealed successively by the middle Carnian, Norian and Albian unconformities, is related to folding and fracturing.

The dominant fault trend runs in an E–W direction, including the Chott fault, the Tebaga of Medenine fault, the Zemlet el Ghar fault, the Remada fault and the Azizia fault. The NW–SE trending Jeffara fault and the NE–SW trending Remada-Bahiret El Biban fault are also dominant features. The regional deformation pattern is shown in Fig. 4.

By integrating stratigraphic data, thickness and facies variations and the age of major unconformities with similar data from northwestern Libya, the Tataouine area is shown to be a megabasin separated by two uplift zones: the Tebaga of Medenine Uplift in the north and the Nefusah Uplift in the south. The area represents a major zone of subsidence bounded by major faults trending E–W (Fig. 3).

STRUCTURAL ANALYSIS

Methods of Study

This study is mainly based on brittle tectonic analysis. It was conducted using the analysis of minor fault slip data, slickenside lineations and joint sets. The procedures for data collection and analysis and the limits of these methods have been described by Angelier (1984).

The mesoscopic structural analysis approach, utilising the stereoscopic projection (Schmidt's projection, lower hemisphere), was taken in an attempt to compute the palaeostress: maximum stress $\sigma 1$, intermediate $\sigma 2$ and minimum $\sigma 3$ and the ratio $\Phi = \sigma 2 - \sigma 3/\sigma 1 - \sigma 3$, between principal stress magnitude (Angelier, 1990).

In the Tataouine Basin an extensive brittle tectonic analysis has been carried out at several sites representing all formations ranging in age from the Late Permian to Late Cretaceous (Barrier et al., 1993). Further, more sites have also been studied in the Jeffara Plain and in the Chott range (southern Atlas fold belt) in order to correlate the Cenozoic compressive events (Bouaziz, 1995; Bouaziz et al., 1998).

Synsedimentary features (slumps, breccias), thickness and facies changes, together with the significance of jointing and pretilting fracturing have also been considered in order to characterise the relationships between sedimentation and tectonic development.

Chronologic Succession of Events

Fracturing is the most common tectonic feature in the area of investigation. The results of the paleostress determination allow us to reconstruct the main tectonic events that governed sedimentation in the Tataouine Basin (Fig. 4).

The upper Permian outcrops show minor synsedimentary normal faults trending NNW-SSE, which suggest a N 44° extensional event (Fig. 4: S1). Most normal faults display characteristic brecciation and are accompanied by slumping (Plate 1, fig. 2). This regime is also demonstrated by joint sets, which show four systems: a NNW-SSE trend corresponds to normal shear joints; two sets of subperpendicular tension joints trending roughly N-S and E-W may be related to a tilting of the Tebaga of Medenine High and a NW-SE normal shear joint trend may reflect a later event (Fig. 4: S1a).

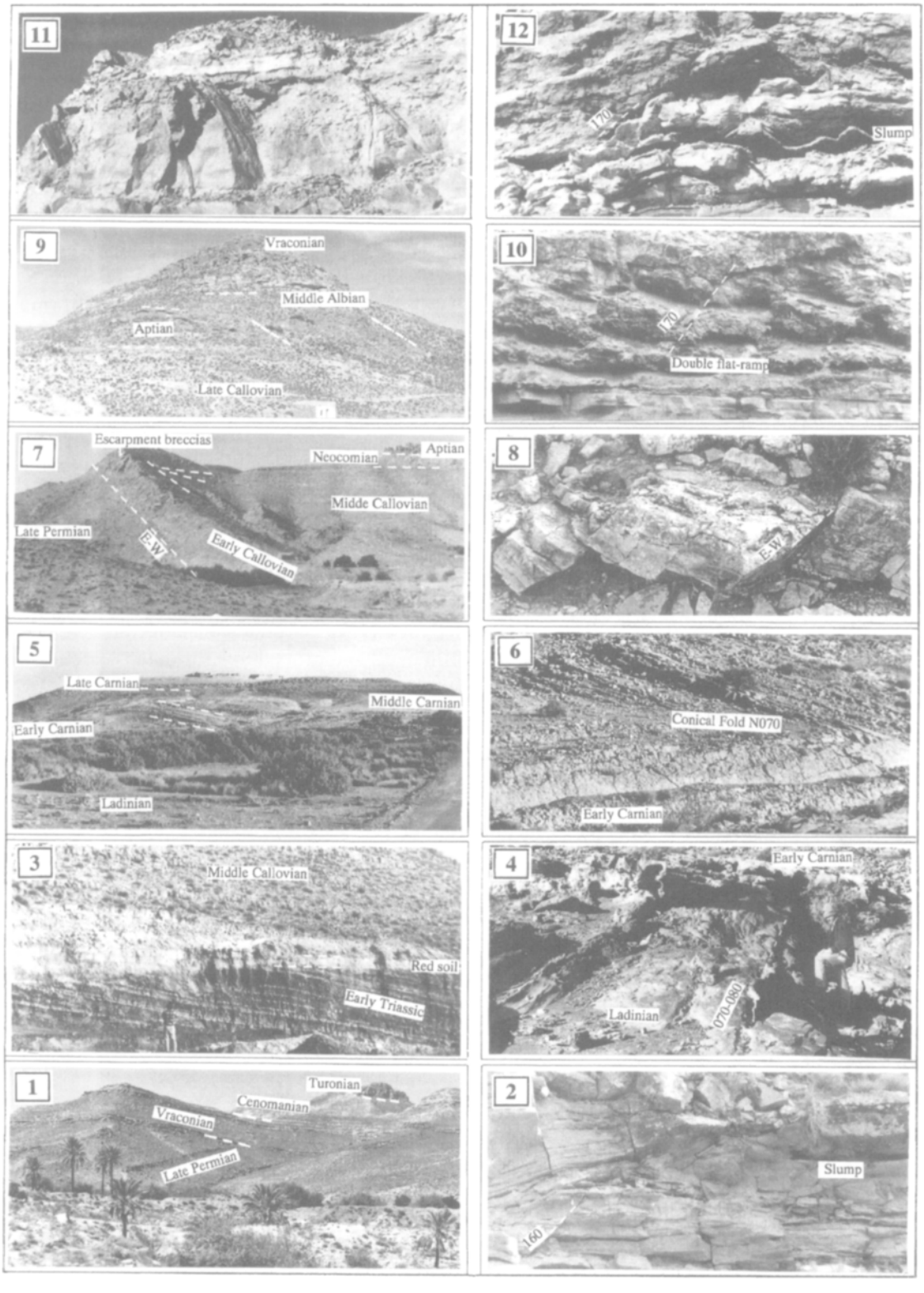

Plate 1. General overview of main tectonic features and brittle tectonic deformation in Tataouine Basin and its surroundings. (*for description see end of chapter*)

The early to middle Triassic was characterised by southward block tilting (Plate 1, figs. 1, 3). The underlying angular unconformity reaches 25° in the Jabal Tebaga area, but the angle decreases southwards. The Jabal Rehach section shows a normal fault that trends ENE–WSW and is sealed by early Carnian carbonates (Plate 1, Fig. 4). The fault system is expressed in the form of N 070° to 080° conjugate normal faults which predominate in the Tataouine Basin and form horst and graben structures on the basin's northern margin. Normal shear joints with the same trend are also common. These features indicate an extensional regime trending N 160°

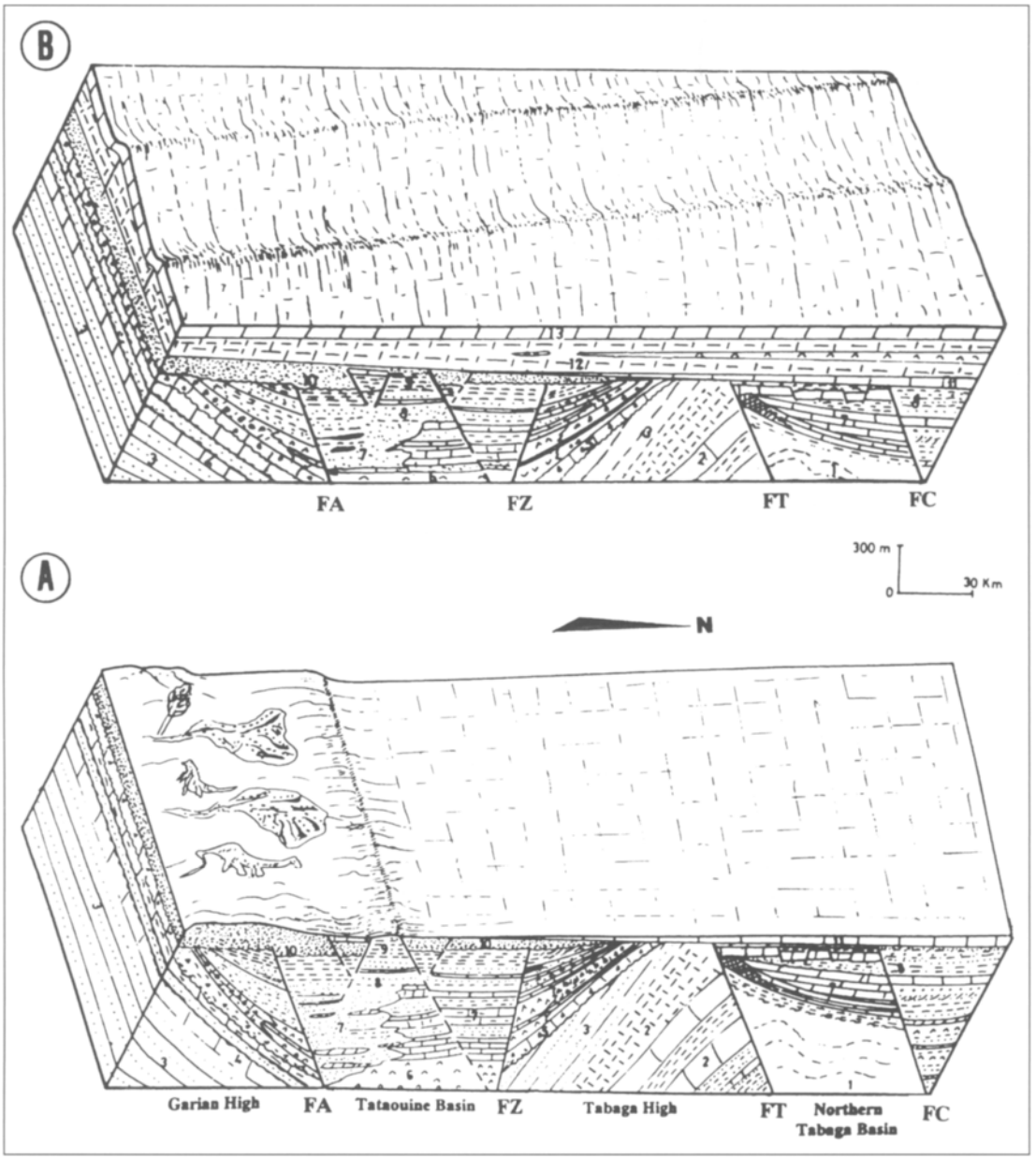

Figure 3. Schematic block diagrams of southern Tunisia: tectono-sedimentary evolution, structure in basin separated by uplift zones: A – At Vraconian; B – At Turonian; 1: Undifferentiated Permian; 2: Late Permian; 3: Early Triassic; 4: Carnian-Norian.; 5: Rhaetian pp.; 6: Rhaetian-Liassic; 7: Bajocian-Callovian; 8: Malm-Neocomian; 9: Aptian; 10: Early Albian; 11: Albian; 12: Cenomanian; 13: Turonian; FA: Azizia Fault; FZ: Zemlet el Ghar Fault; FT: Tebaga of Medenine Fault; FC: Chott Fault.

(Fig. 4: S2, S3). Within this sequence, the study of pretilting populations shows conjugate strike-slip faults associated with conical folds, suggesting transcurrent movement characterised by $\sigma 1$ oriented N 150° (Fig. 4, S3a). This event is related to folding of the Permo-Triassic block. All of these structures are sealed by the late Carnian transgression (Plate 1, figs 4, 5, 6).

Above the Norian unconformity, Rhaetian to Aptian sedimentation was clearly controlled by major fault lineaments trending E–W (Fig. 4: F1 to F4, Plate 1, figs. 7, 8, 9,). Both brittle deformation and synsedimentary features at several morphotectonic levels (Liassic, Bathonian, Callovian and Neocomian) indicate a N 170° to N 007° extensional phase (Fig. 4C). This may suggest that N–S extension represented the major tectonic regime during this period.

Upper Cretaceous deposits overlying the regional Albian unconformity are dominated by carbonate sequences showing evidence of synsedimentary deformation in Cenomanian, Coniacian-Santonian and early Campanian times (Fig. 4D):

The Cenomanian sequence shows clearly distensive synsedimentary features. Most are NNW–SSE normal faults and joints associated with intraformational breccias and slumps (Plate 1, fig. 10). The tectonic pattern was controlled by a major N 070°–080° extensional trend (Fig. 4: S9). The joint population comprises two subperpendicular sets trending roughly N–S and E–W (Fig. 4: S9a),

Intraformational brecciation and slumping were frequent phenomena in Turonian-Santonian times. Normal faults with a predominant NNW–SSE and a secondary ENE–WSW trend suggest multidirectional extension (Fig. 4: S10). The data from joint sets confirm the principal character of the NNW–SSE trend (Fig. 4: S10a),

Lower Campanian carbonates show a group of roughly N–S conjugate normal faults, almost exclusively expressed in the Matmata area (Fig. 4: S11). Tectonic analysis suggests that the tectonic regime reflected E–W extension.

Deformation observed in the sedimentary cover of the Jeffara Basin and in the Cenozoic of the Chott range and the southern Atlas domain implies the development of very different stress regimes. Comparison between data from tabular and folded regions permit the assembly of a precise tectonic calendar for southern Tunisia (Bouaziz, 1995; Bouaziz et al., 1998).

GEODYNAMIC CONCLUSIONS

The integration of new stratigraphic and structural information from southern Tunisia, considered a stable platform by previous authors, permits a reinterpretation of this area's tectonic evolution (Fig. 5). The different stress regimes from the end Palaeozoic to the late Mesozoic show the differentiated development of the Tataouine Basin in terms both of structure and of paleogeography. This tentative reconstruction should allow a better understanding of the geodynamic framework of the southwestern Tethyan margin. The main results emphasize the following tectonic stages:

The phases of late Permian NE oriented and early to middle Triassic SSE oriented extension reflect rift systems associated with high subsidence rates, particularly in the Jeffara Basin (Busson, 1970; M'Rabet et al., 1989; Bouaziz, 1995). The effects are clearly demonstrated in Algeria (Boudjema, 1987) and in Libya (Del Ben and Finetti, 1980). These events are generally related to the Permo-Triassic rifting of western Pangaea (Stampfli et al., 1991).

Transcurrent movements in the middle Carnian are demonstrated by N 150° trending compression. This event, which may reflect movement along dextral transcurrent faults that separated Gondwana and Laurasia, is also documented in Morocco (Arthaud and Matte, 1977; Mattauer et al., 1977; Ricou, 1992).

N–S extension dominated the whole southern Tunisian platform from the late Carnian to Aptian. An extensional context has also been described from central and northern Tunisia (Turki,

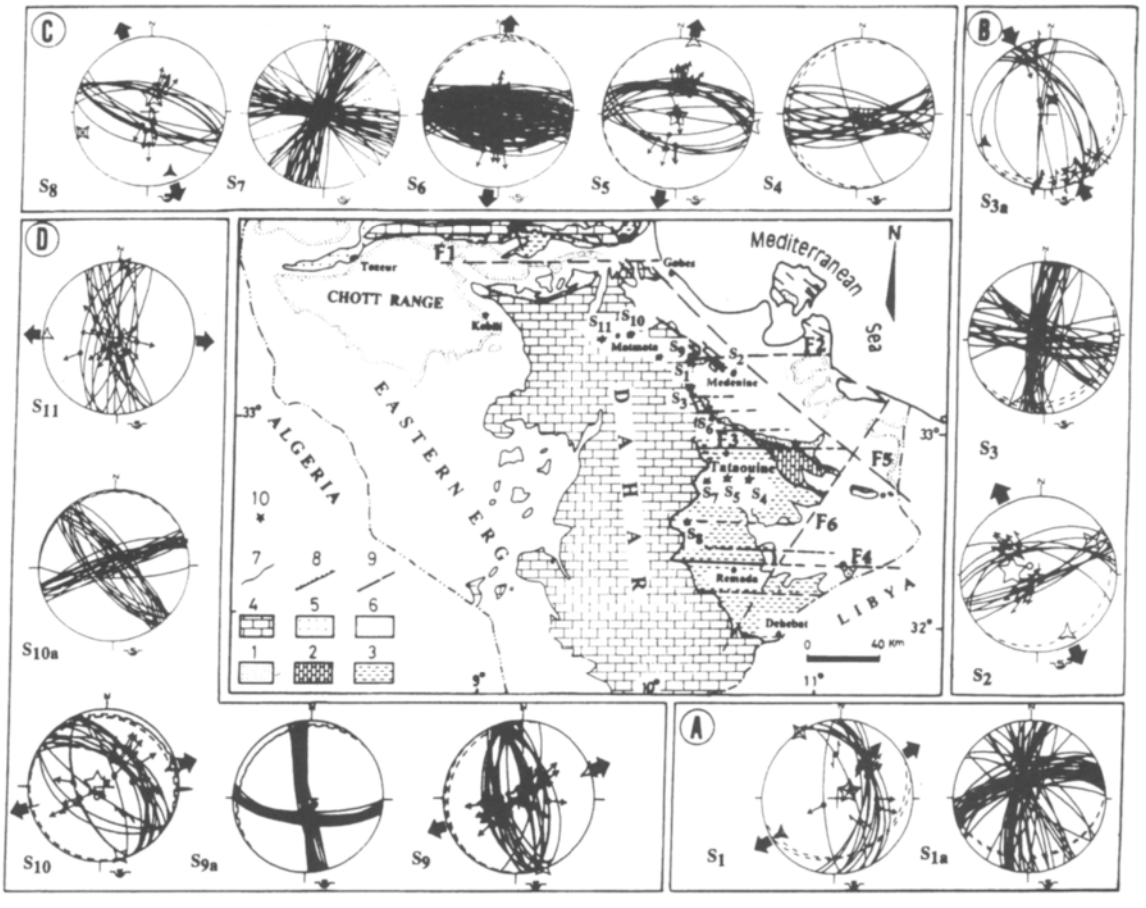

Figure 4. Structural map of southern Tunisia and main sites of fracture analyses: 1: Late Permian-Middle Triassic; 2: Late Triassic; 3: Liassic-Aptian; 4: Vraconian-Maastrichtian; 5: Mio-Pliocene; 6: Pliocene-Quaternary; 7: Geological limit; 8: Unconformity; 9: Major faults; 10: Sites of tectonic analyses. A: in late Permian; B: in early-middle Triassic; C: in Liassic to Aptian; D: in Late Cretaceous. S1-S11: Fault diagrams; Schmidt's projection, lower hemisphere, joints: planes as continuous lines, faults: planes with slickenside lineations as dots with arrows (divergent for normal slip, convergent for reverse slip, double for strike-slip); main axes of paleostress as stars (5, 4 and 3 branches For $\sigma 1$, $\sigma 2$ and $\sigma 3$); main directions of extension and compression as large black arrows.

1985; Ben Ayed, 1986; Soussi, 1990; Alouani et al., 1992), from Libya (Del Ben and Finetti, 1980) and from Morocco (Mattauer et al., 1977, Laville, 1981). This general extension is considered as resulting from Tethyan rifting in response to African-Eurasian divergence (Dercourt et al., 1993);

NNW–SSE to N–S fault systems were particularly evident during the late Cretaceous. In contrast, a change in orientation of the maximum principal stress from N-S to roughly E–W in the latest Cretaceous reflects inversion of the Tataouine Basin. The effects of this change have been noted elsewhere in Tunisia (Boltenhagen, 1981; Ellouze, 1984) and especially in the Sirt Basin (Westaway, 1996) and east of Cyrenaica (Anketell, 1996). This important regional extensional event has been linked to the opening of the South Atlantic Ocean (Olivet et al., 1984).

Better understanding of the tectonic evolution of the northern African plate requires further studies that integrate brittle deformation and high-resolution stratigraphic analyses. Such studies should be extended throughout the Saharan Platform and along the plate boundaries between Africa, Eurasia and Arabia.

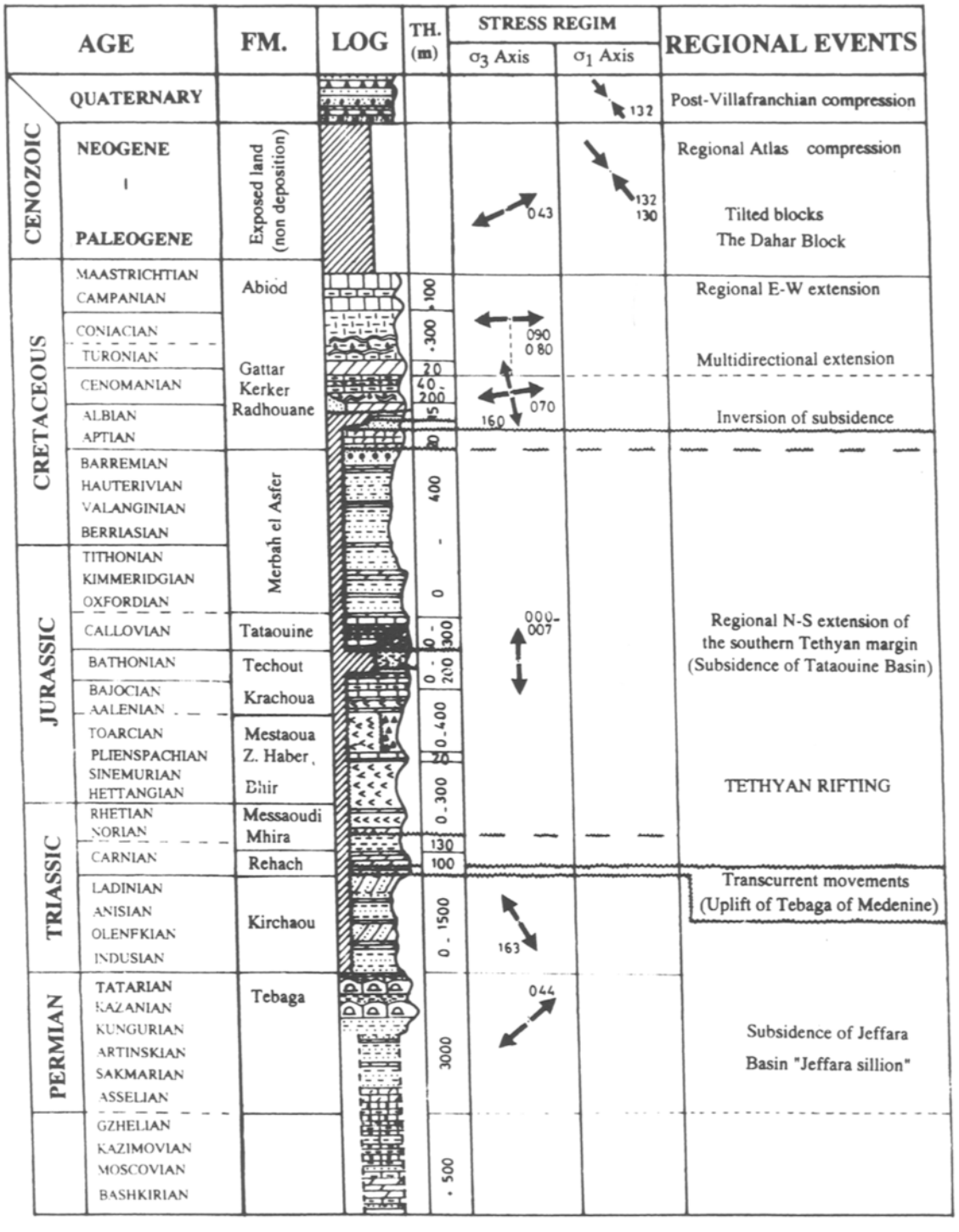

Figure 5. Tectonic evolution of southern Tunisia and geodynamic implications.

ACKNOWLEDGMENTS

This study was financially supported by the Peri-Tethys programme (France). I thank Dr. M. Sola and the Organising Committee of the Geological Conference on Exploration in the Murzuq Basin for their help and encouragement to participate in the meeting. I would also like to thank Dr. D. Worsley (Saga Petroleum Mabruk, Libya) for reviewing the manuscript and for valuable comments

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CAPTIONS, PLATE 1

1. Angular unconformity (25°) of upper Albian carbonate on upper biohermal complex of Late Permian age. Large Cenomanian-Turonian cliff at the top. Location: The western end of Jabal Tebaga of Medenine (33°25′ N, 10°00′ E).
2. A detail of synsedimentary submeridian conjugate normal fault with slumps in upper Permian sandstone-carbonate sequences of the Jabal Tebaga of Medenine. Location: The western end of Jabal Tebaga of Medenine (33°25′ N, 10°10′ E).
3. Angular unconformity (12°) of Callovian strata on lower Triassic units, separated by red soil. Location: Jabal Tajera (33°22′ N, 10°25′ E).
4. N 070°–090° conjugate normal fault populations which cut Ladinian sandstones and are sealed by lower Carnian carbonates. Location: Jabal Rehach section (32°55′ N, 10°55′ E).
5. Unconformity between Late Carnian transgressive strata and deformed lower-midde Carnian carbonate and sandstone. Location: Jabal Rehach section (32°55′ N, 10°55′ E).
6. A detailed view of conical folds of early-midde Carnian age trending N 070°–080°. Location: Jabal Rehach section (32°55′ N, 10°55′ E).
7. Unconformity of lower Callovian escarpment breccias on upper Permian deposits. Breccias sealed by the middle Callovian sequences marked by onlap structures. At the top the Aptian masks the Neocomian conglomerates. Location: The eastern end of Tebaga of Medenine (33°25′ N, 10°20′ E).
8. A detail of E–W synsedimentary conjugate normal fault populations associated with breccias and slumps within Bajocian limestones. Location: Zemlet el Ghar-Tataouine (32°58' N, 10°35' E).
9. N 100°–110° normal faults affecting the Aptian carbonates and sealed by Albian-Vraconian transgression. Location: Jabal Oujh el Gabel, northern part of Tebaga of Medenine (33°27′ N, 10°15′ E).
10. A submeridional normal mesofault with breccias developed in extensional zones caused by sliding along a double flat-ramp topography within Cenomanian sequences. Location: Toujane, northern part of Tebaga of Medenine (33°28′ N, 10°10′ E).
11. N 170° and N 080° synsedimentary conjugate normal fault populations indicating multidirectional extension within Coniacian-Santonian sequences. Location: Matmata (33°35′ N, 10°00′ E).
12. N 160°–170° synsedimentary conjugate normal faults associated with slumps within the Coniacian-Santonian sequence. Location: Matmata (33°35′ N, 10°00′ E).

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CHAPTER 23

Mud-mounds on divergent extensional and transform margins: Devonian and Cretaceous examples from southern France.

ROBERT BOURROUILH[1]

ABSTRACT

Like reefs, carbonate mud-mounds can provide reservoirs for water, ore and/or oil. As they are sensitive to ecosystem variations and record sea-level changes as well as subsidence, tectonic and/or hydrothermal activity, they are also good basinal margin evolutionary markers. To illustrate their formation and growth, two examples are analysed here:

- A Devonian sedimentary succession, exposed on the southern flank of the Montagne Noire comprises a transgressive and deepening upward sequence deposited along a divergent extensional-type margin. Biogenic mud-rich mounds with stromatactis developed during the latest Emsian at the platform margin in a deepening environment, when the sea floor passed below the photic zone and the lower limit of storm wave base. Instability of this margin is reflected by seismotectonic gravitational events. Extension and faulting also affected the mounds, creating cracks and crevices which were quickly filled with sedimentary material and cements to produce Neptunian dykes and veins. Manganese enriched fluids also entered the dyke system.
- A Lower Cretaceous sedimentary succession deposited on the North Pyrenean margin first underwent extensional-type divergence, rapidly followed by transform-type divergence. Reefs and mud-mounds developed during the transition between the two margin types. Mud-mounds situated on tilted rollover blocks were first exposed to karstic erosion; the karstified mud-mounds then slid into the deep anoxic basin and karstic caves were later partly filled by hydrocarbons.

A brief comparison with other selected mud-mounds is given, including particularly those found to date in Libya. Because they may be recognizable on seismic profiles, mud-mounds provide useful tools for basinal and basin margin analysis.

INTRODUCTION

Reefs and mud-mounds are biogenic buildups (James and Bourque, 1992) whose development is controlled by physiochemical and biological factors. Reefs and mud-mounds therefore accurately record the environmental factors controlling the evolution of sedimentary basins and

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continental margins. Mud-mounds occur from the Precambrian to the present day and can be formed by bacteria and cyanobacteria and/or, during Phanerozoic times, by other organisms, for example bryozoans, sponges, or even seagrass (Monty, 1995). Reefs and mud-mounds are of considerable interest in economic geology, and can contain important reserves of water, ore and/or oil (Elloy, 1973). Although reefs and mounds can be easily distinguished from one another in the field, they look very similar on seismic profiles, both generally appearing as dome-shaped features. Subsurface prediction for wells or prospects may therefore be difficult.

The purpose of this chapter is to direct particular attention to mud-mounds to emphasize their importance for sedimentary basin and continental margin analysis, and to identify some characteristics of the development and evolution of such buildups and their possible relationship with structural types of basin or margin.

Two types of divergent margins and their associated mud-mounds are presented herein:

The first type is developed on the Devonian divergent continental margin of the Montagne Noire, in southern France, which then constituted an extensional-type margin of Palaeozoic Panthalassa (Fig.1),

The second continental margin type is exemplified by the Lower Cretaceous Iberian-North Pyrenean margin, which developed first as a passive rift and then as a transform margin during the Mesozoic opening of the Bay of Biscay.

Because of their complex geological history, the Devonian mounds were favoured sites for ore mineralisation, while the Cretaceous mounds were partially filled by oil.

In conclusion a brief comparison is made with other selected mud-mounds, particularly the Late Ordovician bryozoan mounds developed on the cratonic margin of Tripolitania (Djeffara Formation) and Paleogene mounds developed on the rift margins of the Sirt Basin in Libya.

THE MONTAGNE NOIRE DEVONIAN MARGIN: SUB-PHOTIC TO APHOTIC MUD-MOUNDS

The Montagne Noire (Figs 1 and 2) Precambrian to Palaeozoic rock sequence was involved in both the Caledonian and Variscan orogenies. The Caledonian orogeny led to the formation of a continental emergent area until the late Silurian. Subsequent Variscan divergence produced an extensional-type margin in the Montagne Noire and southern Europe generally (Bourrouilh, 1981) during the Devonian and the Carboniferous (Fig. 1). The Variscan orogeny was severe throughout the Montagne Noire, producing large thrust nappes, folds and faults (Fig. 2). The southern flank of the Montagne Noire comprises four main Variscan tectonic elements: the Faugères, Pardailhan, Mont Peyroux and Minervois nappes, the two latter being thought to be equivalent. Palaeozoic sedimentary rocks compose most of the nappes and Devonian sequences are present in the four nappes with facies variations (Fig. 2).

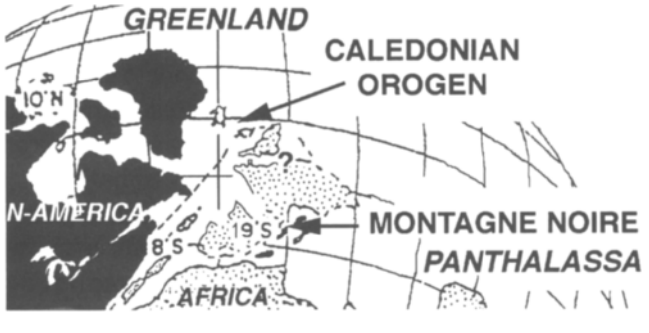

Figure 1. Simplified palaeogeographical map of continents during the Devonian, ca 395 Ma (modified from Van der Voo, 1988). Note location of future Montagne Noire.

The overall framework for the evolution of the Montagne Noire Devonian platform margin was given by Bourrouilh (1981), with emphasis on the sedimentology of stromatactis mounds and the Palaeozoic equivalent of 'Ammonitico-Rosso facies', called the 'Goniatitico-Rosso' and 'Orthoceratitico-Rosso' facies. These facies, also known as 'Griotte facies', are deep water pelagic sediments deposited in water depths of several tens to hundreds of metres (Tucker, 1974). The stratigraphy of the Devonian sequence of the Mont Peyroux nappe has been described by Feist (1985), Feist and Klapper (1985) and by Blieck et al. (1988).

Boyer (1964) described the general stratigraphy of the Devonian succession of the Minervois nappe. Boyer et al. (1968) presented a consistent conodont-based biostratigraphy for the Upper Devonian succession. However, they did not study the stromatactis-bearing formation, which they also assigned to the Upper Devonian. Lower Devonian (Emsian) conodonts have since been found in the stromatactis limestones in the Mont Peyroux (Feist, 1985) and Minervois nappes (Flajs and Hüssner, 1993; Bourrouilh and Bourque, 1995; Bourrouilh et al. 1997). Also, Bourrouilh and Bourque (1995) considered new depth indicators from the Montagne Noire Devonian margin, particularly with regard to the stromatactis mounds.

The Devonian Mud-Mounds of the Minervois Nappe.

In the Minervois nappe, the upper Silurian(?)-lowermost Devonian rests unconformably on the Cambrian (Fig. 3). The whole nappe (Cambrian to Carboniferous) forms a large fold, thrusted to the south over Ordovician shales (Fig. 3).

The Devonian comprises a several hundred metres thick carbonate sequence. In the studied area, several mud-mounds outcrop along a line trending approximately N 65° E (Fig. 3). The

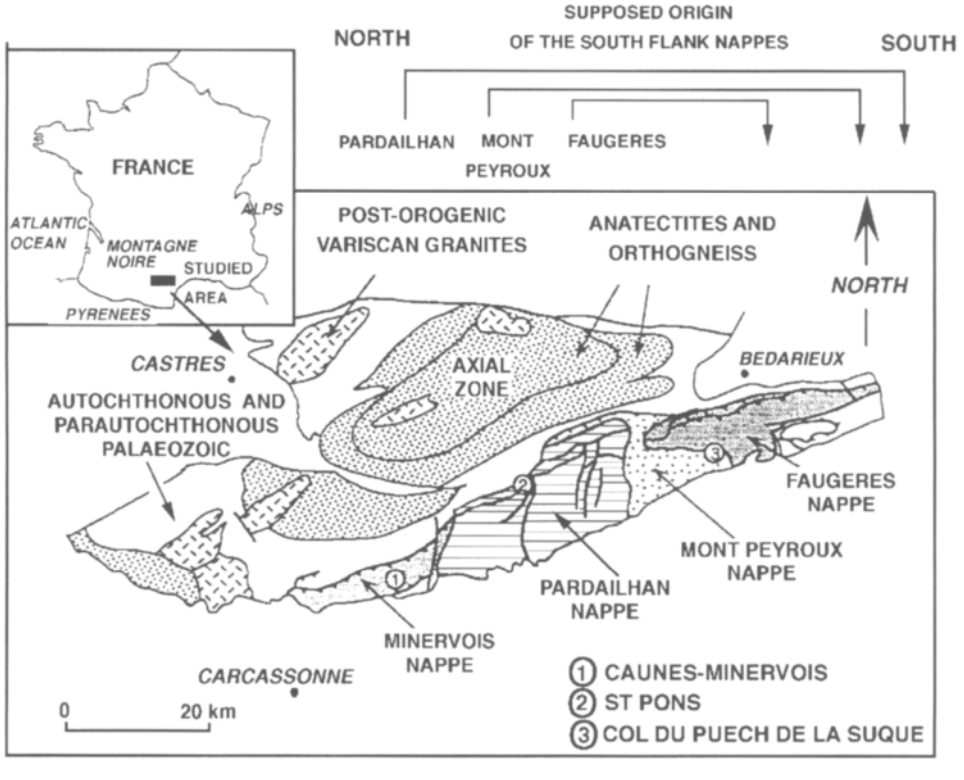

Figure 2. Location map showing Variscan nappes on southern flank of Montagne Noire, and three localities where stromatactis mounds can be observed in the nappes (modified from Bourrouilh and Bourque, 1995).

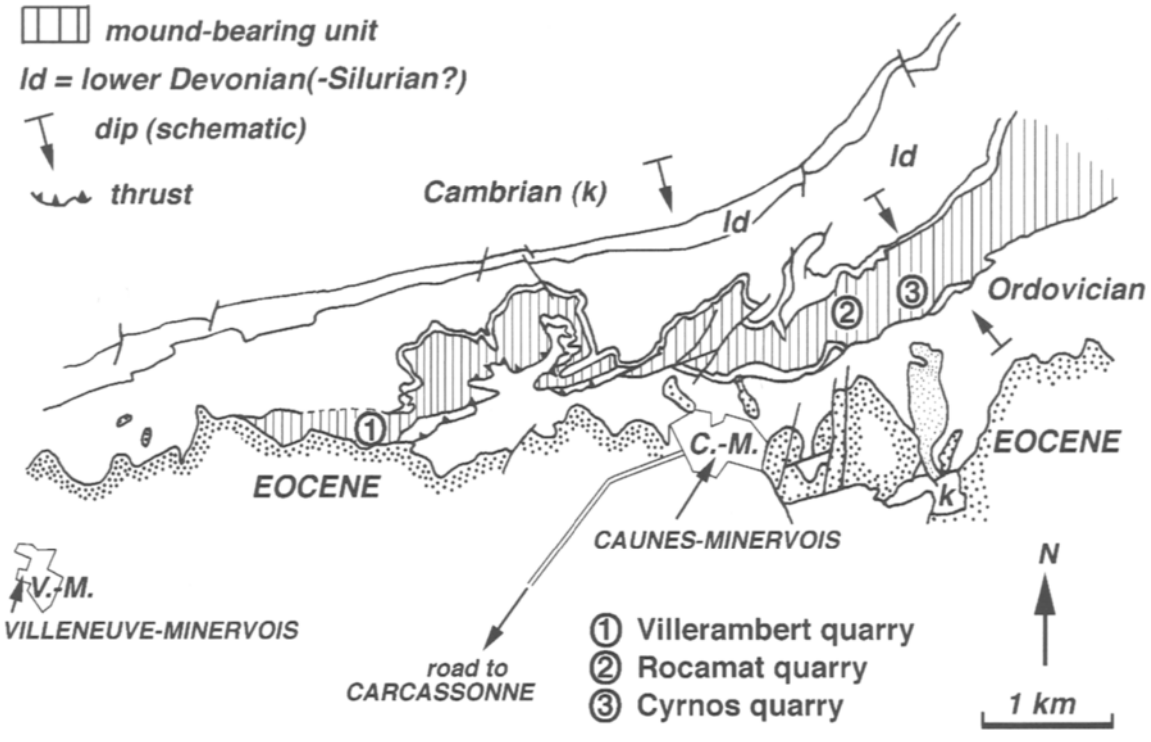

Figure 3. Schematic geological map of the Villerambert-Caunes-Minervois area with location of the studied quarries (based on Berger et al., 1990; 1993 and on personal mapping). The mound-bearing unit is part of a recumbent fold locally overthrusting the Ordovician.

mounds have been quarried for marble since Roman times (the term 'marble' is taken here in a quarryman's sense, viz. any limestone which can be polished and utilized like a true metamorphic limestone or marble). These mounds were intensively exploited especially during the 17th and 18th centuries and provided columns and marbles for King Louis XIV's Trianon Palace at Versailles (Bourrouilh and Bourque, 1999). Three main quarries exposing the mounds have been studied (Fig. 3).

The Villerambert Quarry

This quarry (Figs 3 and 4) shows a mound that was identified by Boyer (1964) as a reef and assigned to the Lower to Upper Devonian. Boyer further identified the stromatactis as algae, in accordance with what was then accepted by the geological community. Bourrouilh and Bourque (1995), among others, pointed out the 'algal reef' of Boyer (1964) is in fact a mud-mound with stromatactis representing substitutes for sponges. Quarry faces show tabular stromatactid red marbles, about 50 m thick, obliquely cut by two kinds of neptunian dykes that have not previously been reported from this area:

A pink dyke fills cavities that sharply cut the red stromatactis mound (Figs 4 and 5a). The dyke comprises pink stratified sediment formed by successive beds, sometimes graded, of bioclastic grainstones containing fragments of crinoid ossicles, brachiopods and bryozoans, together with some ooids. Other similar dykes appear on the quarry wall to the north. In common with similar dykes in the Rocamat quarry (below), these are thought to represent the filling of tidally and karstic eroded cavities.

A thin (50 to 80 cm thick) dark red neptunian dyke obliquely cuts the mound (Figs 3, 4 and Fig. 5b). This dyke is multifilled by several generations of sediment and calcitic cement. The

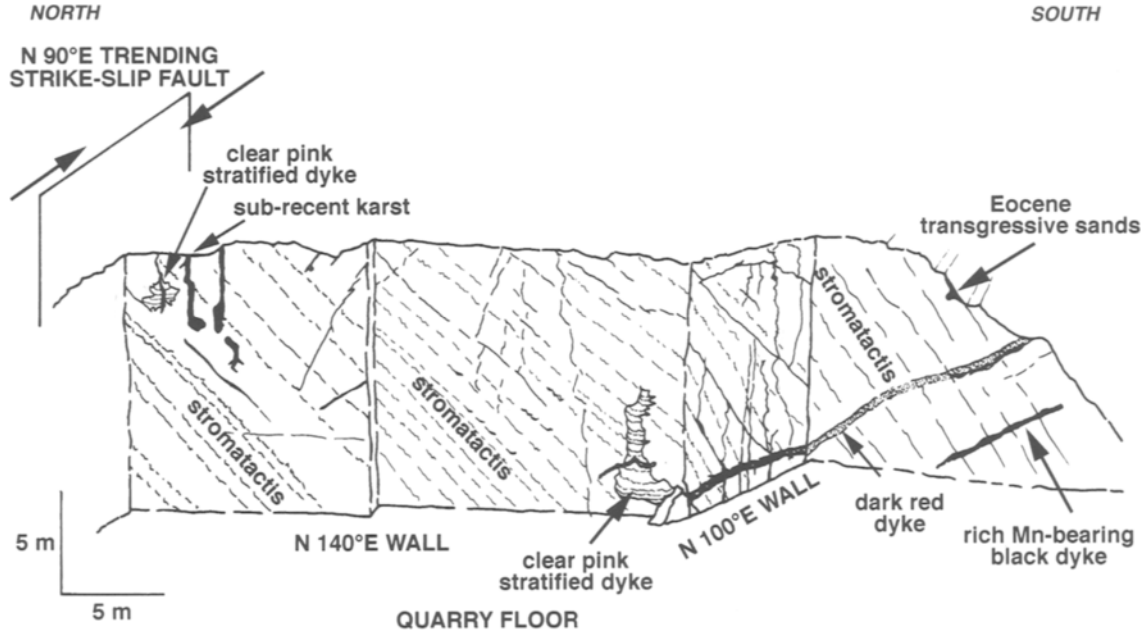

Figure 4. Sketch of walls of Villerambert quarry as visible in 1998. Note the regular stratified beds of white stromatactis in a bulk of fine red sediment and the two kinds of neptunian dykes, both cross-cutting the mound: a submarine erosional dyke (clear pink), multifilling an erosional cavity and showing successive graded beds, and a seismotectonic red distensional dyke, multifilling a progressively opening active fissure. Medium to high energy deposits and Mn entered these latter dykes, some of which have black Mn-rich portions (south side of quarry, to the right).

sediments consist mainly of grainstones and packstones with fragmented tentaculitids. One of the sedimentary filling phases of the dyke contains an Upper Givetian conodont fauna with *Icriodus* sp., *Polygnathus dubius*, *P. foliformis*, *P. linguiformis* ssp. and *P. pennatus* (C. Cygan, personal communication 1998). This dyke represents the filling of a tectonically active fissure that cut the mound. The fissure opened and was filled several times, one of the fillings being of late Givetian age. The dyke has later been intruded by veins of manganese oxide and hydroxide. Other Mn-bearing dykes occur in the southern part of the quarry (Fig. 4). Manganese ore has been worked from a large mine immediately east of the marble quarry. Although Mn mineralisation of this area has yet to be satisfactorily explained and seems to have several causes (Ballery, 1975), our observations in the Cyrnos quarry (below) suggest clear linkage of at least one type of Mn-mineralisation with the tectonic opening of fissures and the filling of these to form dykes in the mud-mounds.

The Rocamat Quarry

This quarry, northeast of the village of Caunes-Minervois, shows a large stromatactis mud-mound, which is about 150 m thick, and several hundred metres in diameter (Fig. 3). The mound has been described in detail by Bourrouilh and Bourque (1995) and Bourrouilh et al. (1997) and has the following main features:

The mound began growing as a dome-shaped structure, but during growth the mound flanks were affected by sliding and slumping. These gravity movements, which reflect both mound growth and tectonism, facilitated the development of veins and crevices.

Veins and crevices are mainly filled by white, pink and grey cements, forming neptunian dykes. Some crevices are also filled by pisoids (Fig. 5c), reflecting calcite precipitation from

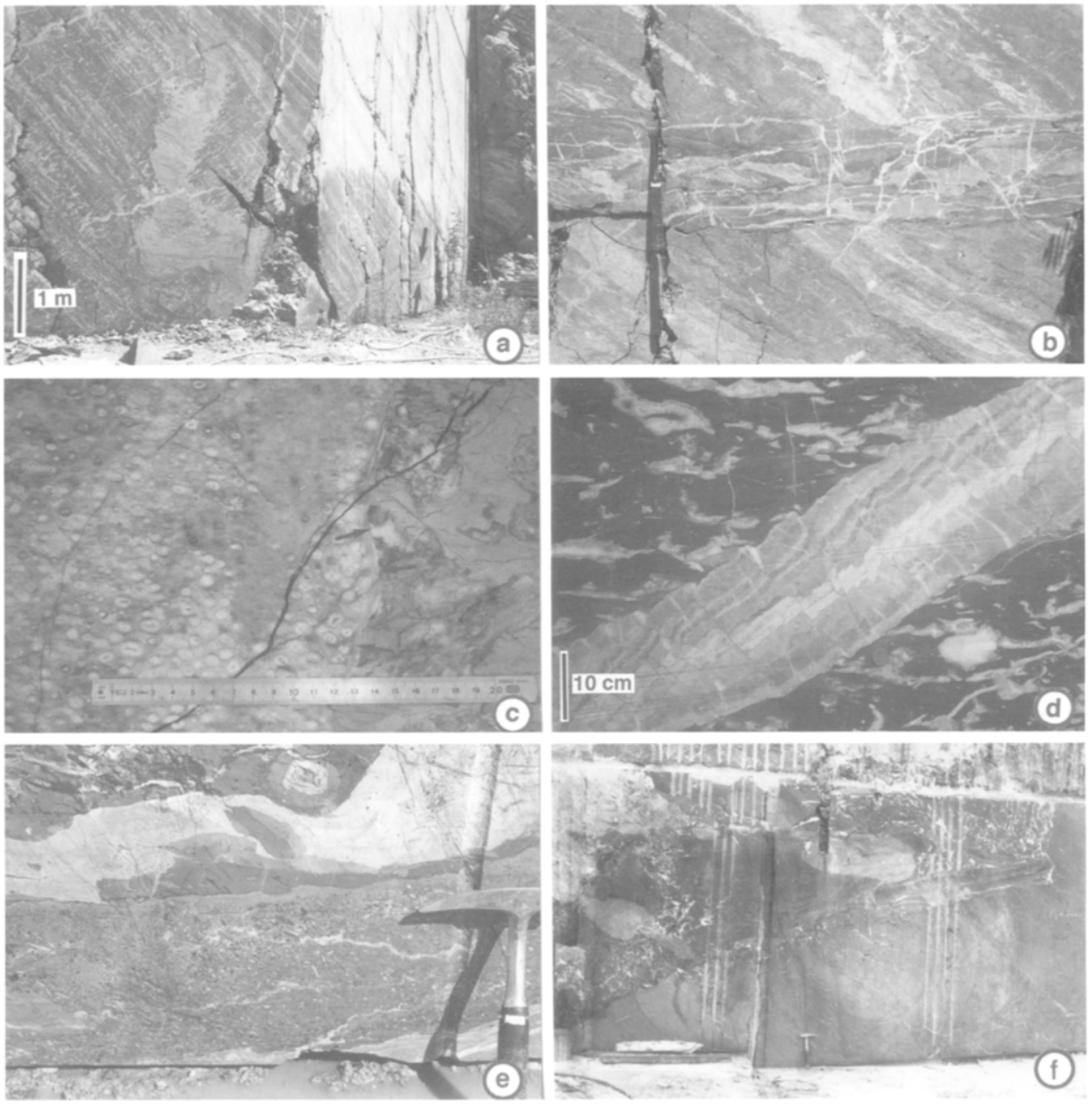

Figure 5. *(a)* Villerambert quarry in 1998: submarine erosional clear pink dyke. Note that the walls are erosional and that the multifill is stratified. A dark red seismo-tectonic dyke is observable on the right, near the base of the sunny wall, between the black arrows. *(b)* Villerambert quarry in 1998: seismo-tectonic dark red dyke, with its successive fissures highlighted by calcite cements, by multifilling of dark red sediments (containing conodonts, including an Upper Givetian fauna), and by Mn (black filling). Hammer (31 cm long) for scale, see also Fig. 4. *(c)* Rocamat quarry in 1998: pisoid-rich erosional dyke, arrows point to dyke margin. Pisoids are up to 15 mm in diameter. *(d)* Dark red neptunian multifilled sedimentary dyke affected by systematic short wavelength fracturing interpreted as seismic in origin. Note Mn filling (dark stripes), which is dated in the Cyrnos quarry to the syn- or post-late Frasnian. *(e)* Cyrnos quarry in 1998: closeup view of the dark red neptunian dyke showing corals with epigenetic Mn. Sediment filling of the dyke contains Upper Givetian and Upper Frasnian conodonts fauna. Hammer for scale. *(f)* Bois du Bager quarry in 1997, lower Cretaceous, Pyrenees.: Close-up view of features 2b and 3 in Fig.11, showing flatlying multidepositional storm-graded beds, overlain by perpendicular hydrothermically delaminated parts of the cave wall and cemented by probably hydrothermic white calcite cement.

seawater circulating through the crevices. Some pisoids developed around crinoid ossicles. Considering their shape, filling and occurrence, the large crevices are interpreted as pathways for seawater currents, which eroded the crevice walls. Compared with modern analogues, they appear similar to karstic Bahamian blueholes, affected by tidal currents.

Isotope geochemistry shows that the mud-mounds have been subject to marine diagenesis (cements of stromatactid cavities and of veins, crevices and pisoids). Subsequently, the red lime mud matrix, forming the bulk of the mound, has undergone hydrothermal or meteoric diagenesis, probably related to a relative sea level fall.

The measured section of the exposed part of the mud-mound is 121 m across; the total thickness is perhaps 150 m or more, but the lower part of the mound is not exposed. Immediately to the south, near the southern edge of the mountain, the mound is overlain by light grey crinoidal grainstones and packstones followed by mudstones. These crinoidal grainstones and packstones were deposited in a shallower water high-energy environment and are related to a relative sea level fall.

As noted above, crinoidal bioclasts have been observed as nuclei of the pisoids in the large neptunian dykes. It is possible that these crinoid clasts were contemporaneous with the crinoidal limestones, so that submarine erosion of the crevices of the mud-mound occurred during lowstand deposition of the crinoidal limestones.

Neptunian dykes filled by dark red sediment also cut the mud-mound; some of these are Mn-bearing and have been fractured by tectonic activity (Fig. 5d).

The Cyrnos or La Boriette Quarry

This quarry lies on the opposite bank of the Cros River and also exploits a stromatactis mound (Figs 3 and 6). The quarried part of the mound is about 30 m thick, but its lower parts disappear below the quarry floor so that the total thickness is not known. This build-up exhibits a mound-shaped morphology in its lower parts and becomes more tabular upwards (Figs 4, 9a and b).

This mound is also cut by a dark red neptunian dyke, 80 cm thick, which is filled by grainstones and packstones containing corals and brachiopods (Figs 4 and 5e). As in the Villerambert quarry, the dyke shows multiple filling. One sample has given a Givetian conodont fauna with *Polygnathus varcus*, and another sample an upper Frasnian fauna with *Ancyrodella curvata*, *Ancyrognathus triangularis*, *Palmatolepis semichattovae, Polygnathus pacificus*, *P. pennatus* and *Schmidtognathus sp.* (C. Cygan, personal communication 1998). This dark red dyke is Mn-bearing, as are the similar dykes in Villerambert and Rocamat quarries. The eastern part of the Cyrnos quarry (Fig. 6) also shows a swarm of thinner similar Mn-bearing dykes. Manganese mineralisation has also affected the stromatactid cavities, which were evidently not completely cemented by the late Frasnian (Fig. 6).

In the upper part of the mound, the stromatactid facies is affected by gravity sliding, with sedimentary folds overturned towards the south. This facies is overlain (as in the Rocamat quarry) by a 35 m thick unit of light grey crinoidal cross-bedded grainstones, packstones and mudstones, indicating a high-energy cap, and a decrease of the water depth on the top of the mound. These beds contain Middle Devonian conodonts.

Neptunian dykes

These features are characteristic of the three studied Minervois mud-mounds. Two main kinds of neptunian dykes and crevices affect the mounds (Fig. 7):

- The first form large distensional crevices, which vary from a few centimetres to 2 to 3 metres wide. The walls of the largest dykes cannot be matched and thus do not represent simple

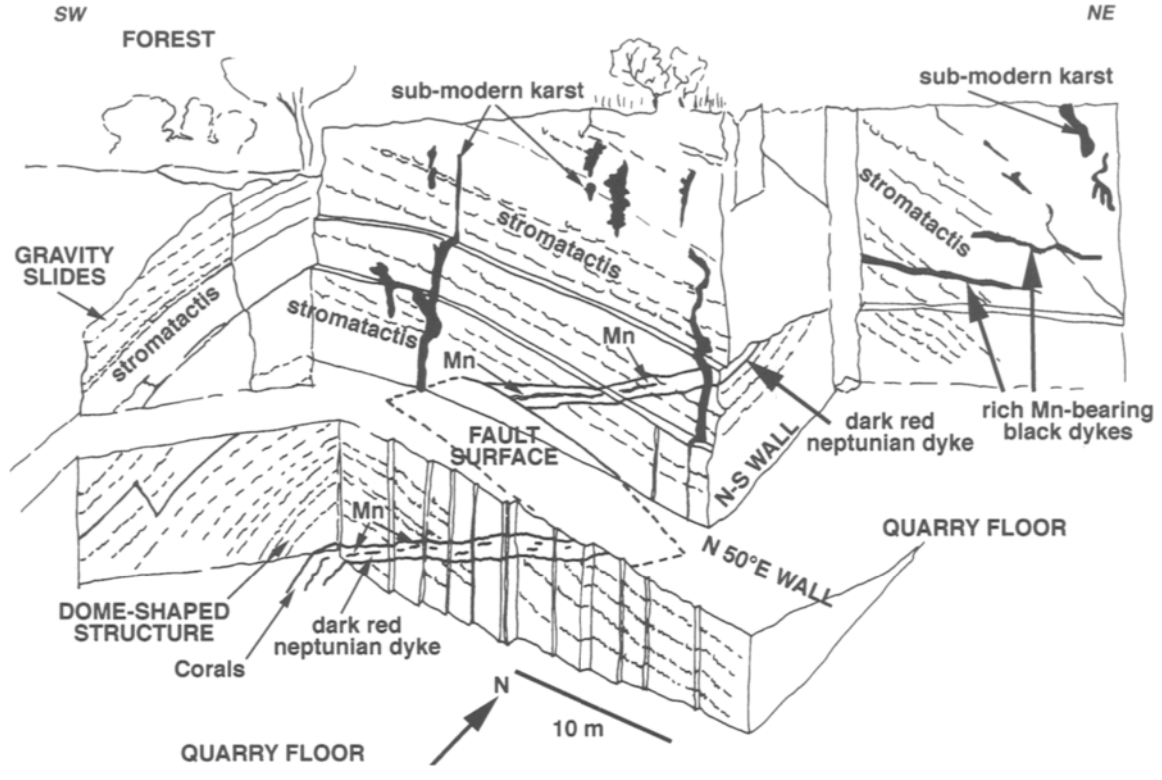

Figure 6. Sketch of walls of Cyrnos (La Boriette) quarry as visible in 1998: general perspective view of the two exploitation levels. In its deeper visible part (lower level), the stromatactis mound exhibits a dome-shaped morphology. A dark red multifilled distensional neptunian dyke, containing medium and high energy sediments with corals and a late Devonian conodont fauna, crosscuts the stromatactis mound. This dyke is in turn cut by an apparent inverse fault. The dyke is Mn-bearing and accompanied by a swarm of other Mn-rich thinner black dykes (wall on the right).

opening; multiphase opening and erosion of the walls is suggested. Their filling is mainly composed of pisoids (radial microspar crystallized around crinoid bioclast nuclei). Such pisoids normally form as a result of current action. These features suggest that the dykes are the result of submarine erosional currents that used the open dykes as passageways, allowing the formation of the pisoid filling. These dykes (Fig. 5c) are well developed in the Rocamat and Villerambert quarries (Fig. 4). Dyke formation reflects both growth and periodic seismic activity provoking slumping of the mound flanks: the stromatactis fabric and some of the crevices show features that could reflect slumping deformation related to growth. However, some veins and crevices also have zigzag traces with a presumed seismo-tectonic origin. Subsequent erosion of the already open crevices, and filling of these by pisoids is attributed to a sea level fall (see above).

- The second dyke type also reflects distensional movement, but dyke formation was not provoked by growth of the mound. These dykes sharply crosscut the mound (Fig. 4 and 5b and e) and show a quite constant thickness. They also crosscut the erosional dykes described above. These dark red dykes represent multifilled fractures and contain conodonts of late Givetian (Villerambert) or both late Givetian and late Frasnian (Cyrnos) age, together with other bioclasts (e.g. bryozoans, brachiopods and corals). The same dark red dykes can therefore have opened several times, along the same distensional line of weakness affecting both the mound and the surrounding sedimentary pile. There are few mechanical causes that can explain such features. The relationship to earlier dykes, constant size, repetitive filling and

vertical nature of these dykes are herein related to repetitive mechanical shocks, provoking the tilting, fracturing and subsequent infill of the whole sedimentary package. The only possible origin for these phenomena is thought to be earthquake activity (Fig. 5d).

Seismo-tectonic activity appears to have been a recurring phenomenon in the whole area, at least from the Emsian to the late Devonian and particularly from the late Givetian to the late Frasnian. Renewed fracturing of the dark red dykes occurred during or after the late Frasnian: the Upper Frasnian conodont-bearing sedimentary filling of the Cyrnos quarry dyke is intersected by a new Mn-bearing phase of filling, also seen in similar dykes in the Villerambert and Rocamat quarries. In the Cyrnos quarry, Mn-enrichment also fills the stromatactid cavities, which were not completely closed at this time (Fig. 5e). Thus, homogeneous residual porosities of stromatactis buildups, as well as constant seismo-tectonic activity along the mound flanks allowed the concentration of ore-bearing dykes in close relationship to the mud-mounds. This fracturing allowed manganese enrichment of the dyke network (Fig.7) and of the stromatactid cavities, which were in contact with the opening dykes. A part of the manganese ore bodies in the southern Minervois are obviously related to this phase.

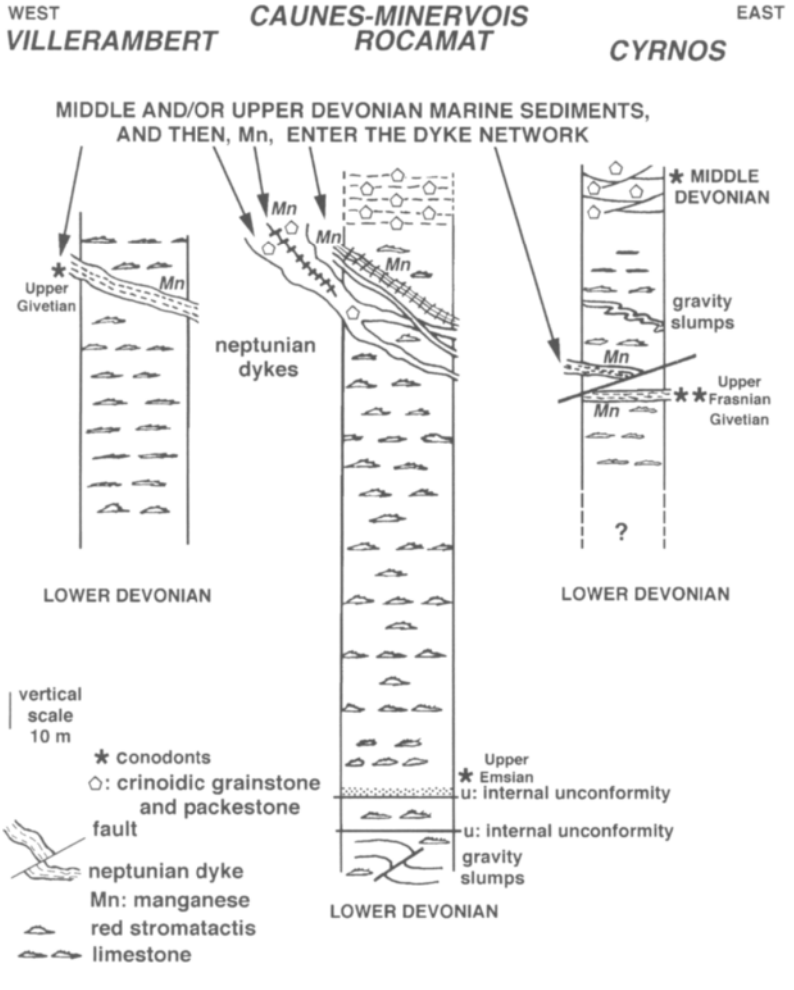

Figure 7. Schematic representation of the three mud-mounds studied in the Villerambert, Rocamat and Cyrnos quarries. Note that the mud-mounds have different thicknesses and that the Rocamat and Villerambert mounds show syndepositional and seismo-tectonic dykes, while the Cyrnos mounds only show the latter features.

THE EARLY CRETACEOUS IBERIAN-NORTH PYRENEAN MARGIN: SUB-PHOTIC TO PHOTIC MUD-MOUNDS

Extensional seafloor spreading from the late Jurassic to the late Cretaceous led to the progressive opening of the Bay of Biscay between the Iberian and southern European plates (Dewey et al., 1973; Choukroune, 1974; Souquet et al., 1980) and to the development of a series of complex sedimentary basins. During the Cretaceous, a marine north Pyrenean trough (Fig. 8) ran westwards to the Bay of Biscay (Curnelle et al., 1982). This trough was bounded to the north by the semi-passive Aquitaine margin and to the south by the active Iberian margin. Bourrouilh et al. (1995) presented an overview of the evolution of the North Pyrenean Basin and hydrocarbons of the area.

The general history of the Iberian margin and of the North Pyrenean basin is summarized in Fig. 9. Following the Variscan orogeny, post-orogenic clastics and then evaporites were deposited. Permian and late Triassic to early Jurassic extensional basins can be distinguished. In some areas, more than 500 m thick Permian and Lower Triassic red beds, as well as more than 1000 m thick Upper Triassic (Keuper) to lowermost Jurassic evaporites, accumulated. The evaporites produced structurally controlled synsedimentary diapirism in the Aquitaine and north Pyrenean basins. A shallow marine carbonate platform then developed across the whole area and

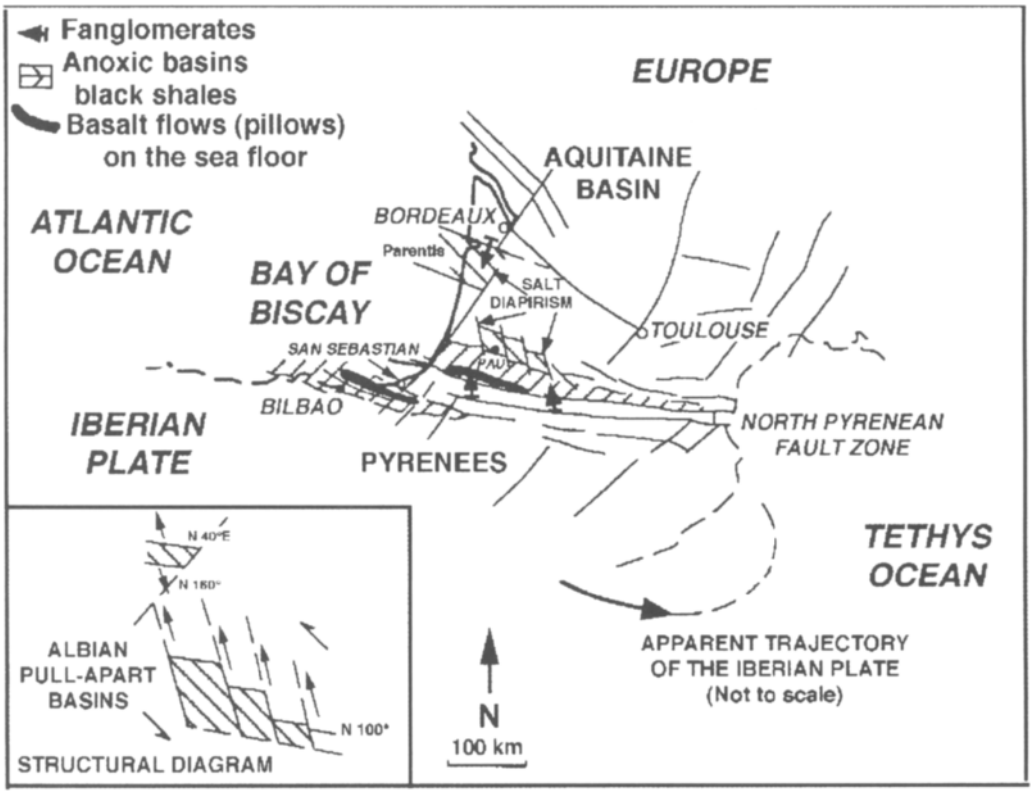

Figure 8. Origin and development of the Parentis and the north Pyrenean troughs: Aptian-Albian creation of anoxic pull-apart basins, filled by black shales and then subjected to floods of oceanic basalts. Initially, the trajectory of the Iberian plate (arrow down to the right) was free and reflected sea-floor spreading in the Bay of Biscay; the north Pyrenean trough margins were then purely extensional in character. This trajectory rapidly changed as northward movement of the African plate blocked free migration of the Iberian plate. Extensional divergence ceased and separation became controlled by transform motion (modified from Bourrouilh et al., 1995).

this persisted until the late Jurassic. This platform was diachronously emergent (late Jurassic to early Cretaceous) and was dissected during the progressive opening of the Bay of Biscay rift between Europe and Iberia (Fig. 8).

On the southern edge of this rift, the stratigraphic sequence (Fig. 9 and 10) shows a typical extensional and transgressive sequence: a late Jurassic to early Cretaceous disconformity is overlain first by continental sandstones (Grès de Lacq), then by lower Barremian lagoonal carbonates. From the Bay of Biscay, the sea invaded the area south of Pau during the Barremian and ammonitic black shales were deposited. Then an Aptian-Albian carbonate platform developed. Near the village of Arudy, south of the city of Pau, this platform was marked by the growth of late Aptian-Albian reefs and mud-mounds (Fig. 10). These buildups grew in a context of anoxic pull-apart basins. These pull-apart basins were progressively affected by basic volcanism with floods of basalts, indicating the eastward progression of seafloor spreading of the Bay of Biscay onto the European continent (Figs 8 and 10).

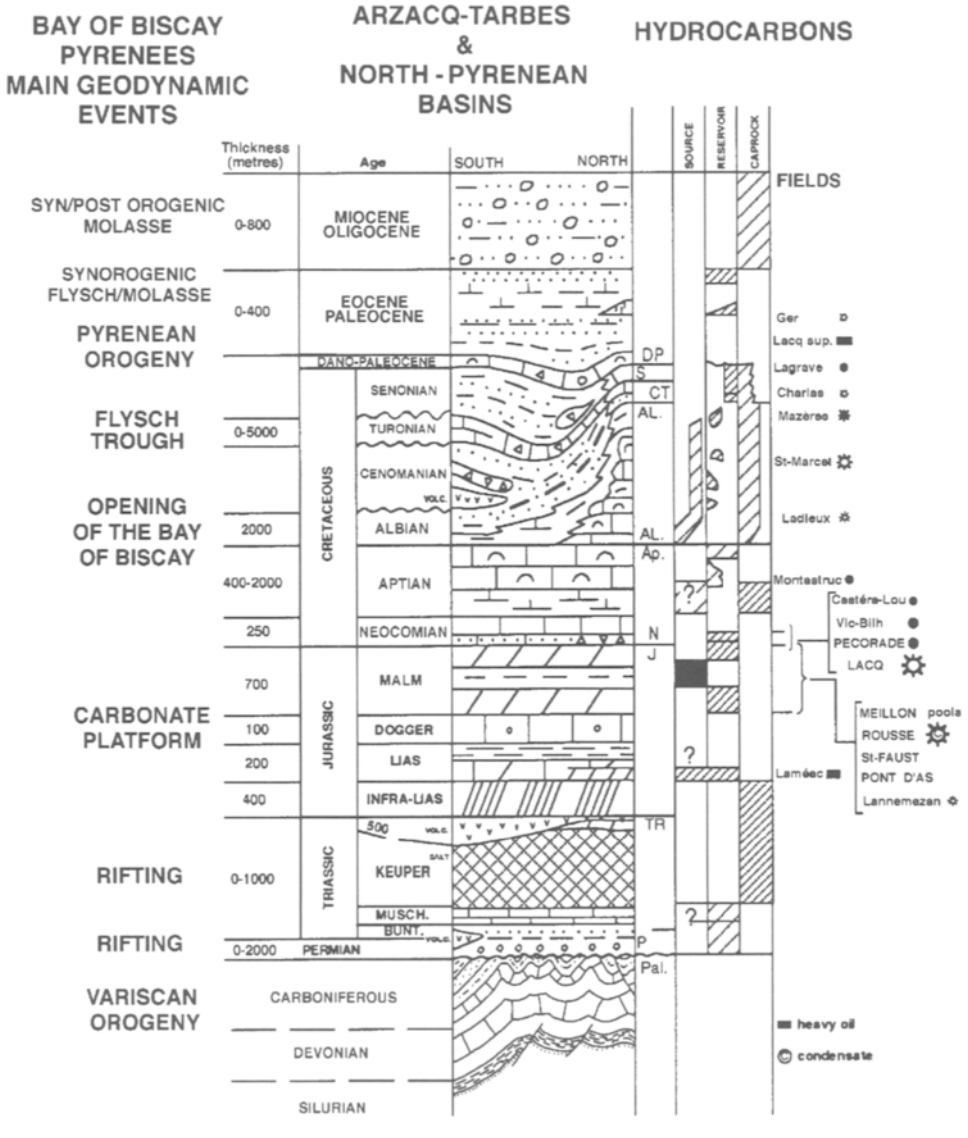

Figure 9. Geodynamic evolution of Bay of Biscay-Pyrenees and North Pyrenean basins (left), stratigraphical log (centre) and main features of hydrocarbon development in the Aquitaine-North Pyrenean basins (modified from Bourrouilh et al., 1995).

Immediately south of Arudy, several Aptian-Albian mud-mounds are worked for marbles. Geological studies (Bouroullec et al., 1979; N'Da Loukou, 1984; Van der Plaetzen, 1988), have discussed these structures' stratigraphy and micropaleontology. Digbehi (1987) was the first to present consistent sedimentological data on the area and to suggest that some of the reefs and mud-mounds were in fact large blocks that had slumped into the black shale basin. Lenoble and Canérot (1993) and Canérot (1996) studied the relationship of the buildups to sea level changes, but they did not consider that some of these buildups are not in their original position and have been gravitationally displaced from their primary depositional environment.

We will focus herein on the Bois du Bager mud-mound, situated 2 km southwest of Arudy. This mound consists of massive grey mudstones containing flat microsolenid corals. According to L. Beauvais (personal communication, 1995), microsolenids can develop in quite deep water and can tolerate a certain amount of turbidity. Those corals have umbrella-shaped morphologies, indicating a low energy environment; they grow in successive layers, producing the stratification of the upper part of the mound.

The base of the mound shows a locally deformed contact with the underlying black shales (Fig. 11). The lowermost part of the mound shows a slump breccia, with large elongated intraclasts, some of them with microsolenids, embedded in a black shale matrix. The mound also contains two beds of black shale, locally contorted and loaded. These shales can be interpreted either as reflecting the recurrence of mud sedimentation, or as shale intrusions into the mound

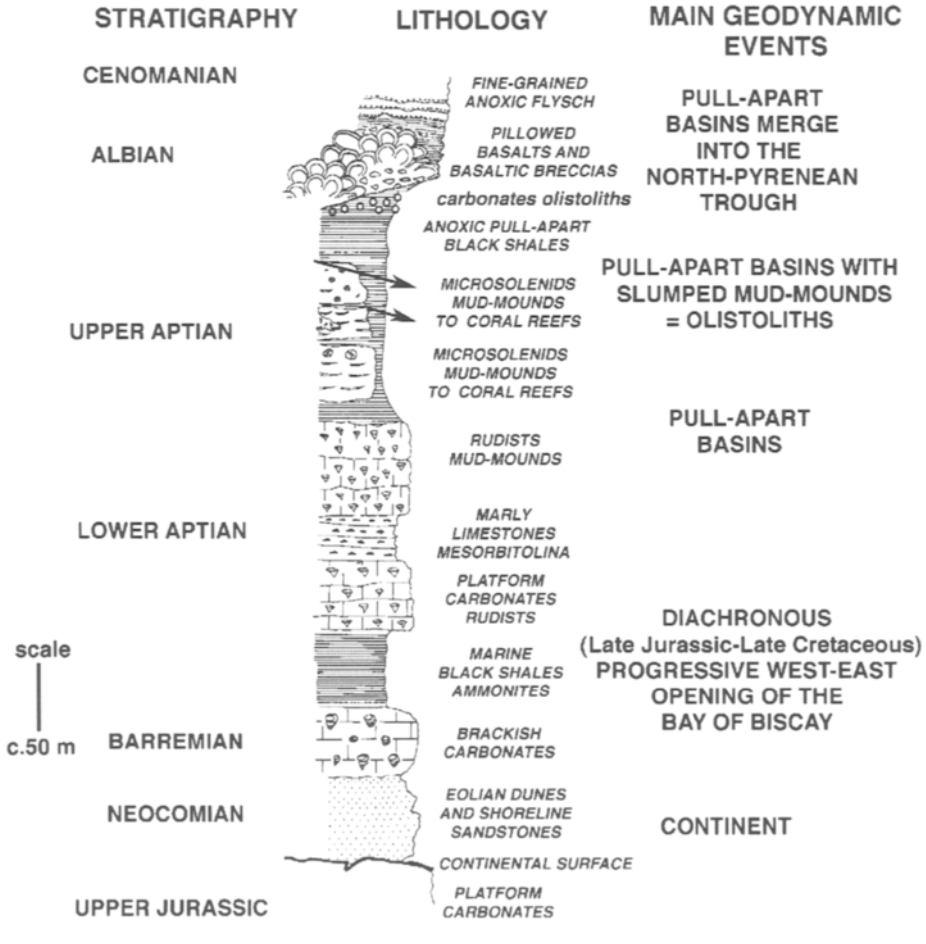

Figure 10. Stratigraphy (left), according to Van der Plaetzen (1988), N'da Loukou (1988), Digbehi (1987) and personal data; lithology (centre) and geodynamical evolution of the Arudy Basin.

which slid downslope with the mound itself. The orientations of the microsolenids show that these two black shales are obliquely oriented, and clearly indicate that the mud-mound has tilted over to an angle of at least 90° from its normal growth position, especially as the concave undersides of the umbrella-shaped microsolenids now face upwards.

The body of the mound consists of massive grey microsolenid mudstones but it also shows a large karstic erosional cavity that reflects emergence (Canérot, 1996 and present observations). The cave is filled with a karstic breccia, partly originating from the mound itself. This karstic collapse breccia appears on the two walls of the quarry, and it is particularly well developed on the wall trending N 10° E (Fig. 12). The breccia is largely impregnated by oil and is partly dolomitised.

A new geophysical tool, the electrostatic quadripole, has been used to determine the diagenesis of the mound and the quality of the marmorean limestone (Benderitter et al., 1997). A precise resistivity map of the diagenesis and fracturing was thereby obtained (Fig. 12), showing the mud-mound build-up, the karstic cave and its brecciated karstic infill. The side of the mound is karstified and the karstic cavities are filled with black shales (Figs 11, 2a and 2b). This area has a white to light grey colour and is largely dolomitised. Study of the dolomitisation shows that this reflects the contact of the mound with the phreatic lense (Bourrouilh-Le Jan, 1973; 1975) as a result of emergence.

A provisional scenario for mound development based on geometry, stratification, geopetal structures, karst, filling of the karst, diagenesis, oil migration and overall relationships of geometries is as follows (Fig. 11), with the developmental phases numbered as in that figure:

- The Bois du Bager mud-mound began to develop as soon as turbiditic black shale deposition input decreased significantly (microsolenids can tolerate a certain amount of turbidity). The

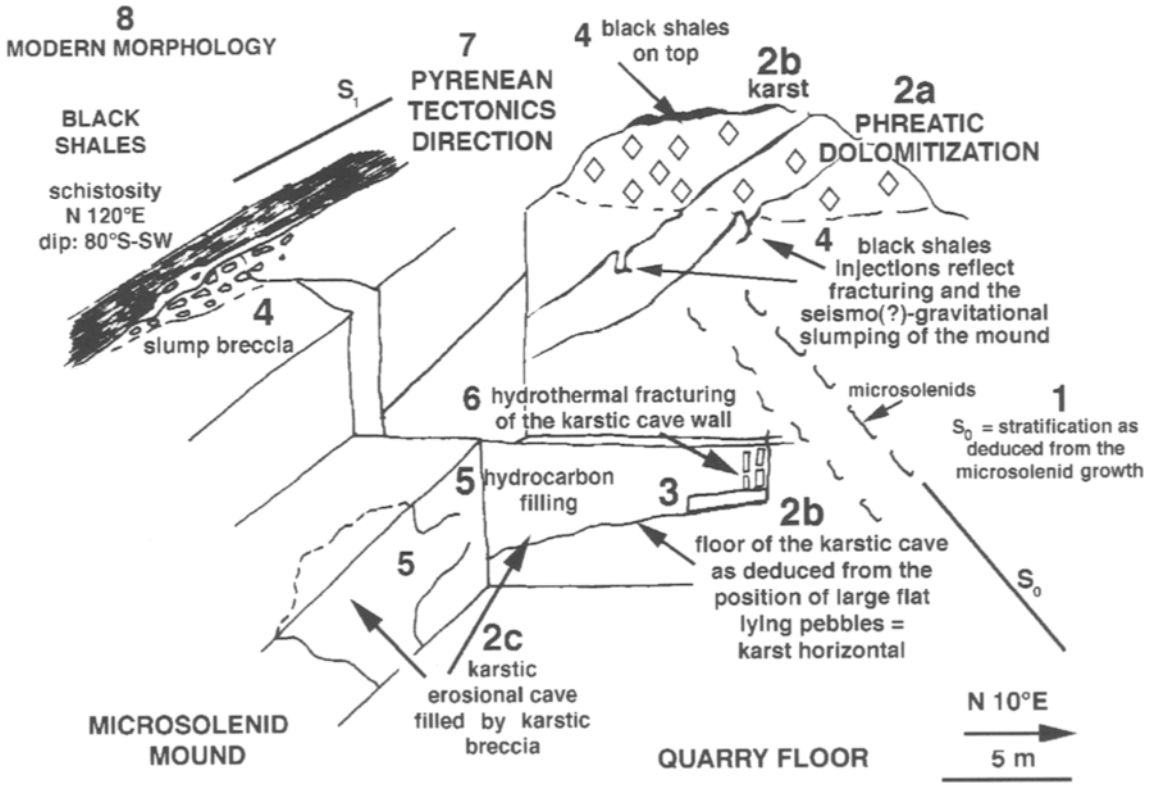

Figure 11. Sketch of the Bois du Bager quarry as visible in 1997, numbers refer to explanation in the text.

mound probably grew near to the aphotic-subphotic zone transition, but was certainly below storm wave base (no evidence of wave action). The original stratigraphy and position of the mound is shown by layers of microsolenids (S_o on Fig.11).

- Due both to growth and to the opening of the Arudy Basin, the mound slid and rotated 65° clockwise towards the NE (N 30° E). This rotation produced emergence of the SW flank of the mound and this emergence does not seem to be related to a sea-level fall, as proposed by Canérot (1996). Emergence was accompanied by aerial and karstic erosion of the mound. The flanks of the mound were eroded by surficial karstic cavities. Karstic erosion penetrated deep into the dead mound, resulting in the formation of a large karstic cavity, which was then filled by a breccia (Figs 11 and 12). A large part of the breccia is autochthonous, but blocks of overlying shallow water units, some as long as 2 metres, also fell down in the cavity (Figs 11 and 5f).
- These clasts are interpreted here as reworked parts of coarse graded supratidal to intertidal storm deposits (Fig. 11). The original deposits, from which they are derived, are not observed *in situ*, either laterally or directly overlying the mound, but the presence of such clasts among the karstic breccia show that supratidal to intertidal storm deposits must have been deposited near the emergent mound. These flatlying clasts indicate the horizontal plane during the karstification period (6 on Fig. 11), and their present angle is in agreement with the geometry of the karstification. We suggest that the storm deposits were eroded, fragmented and transported before falling down into the karstic cavity.

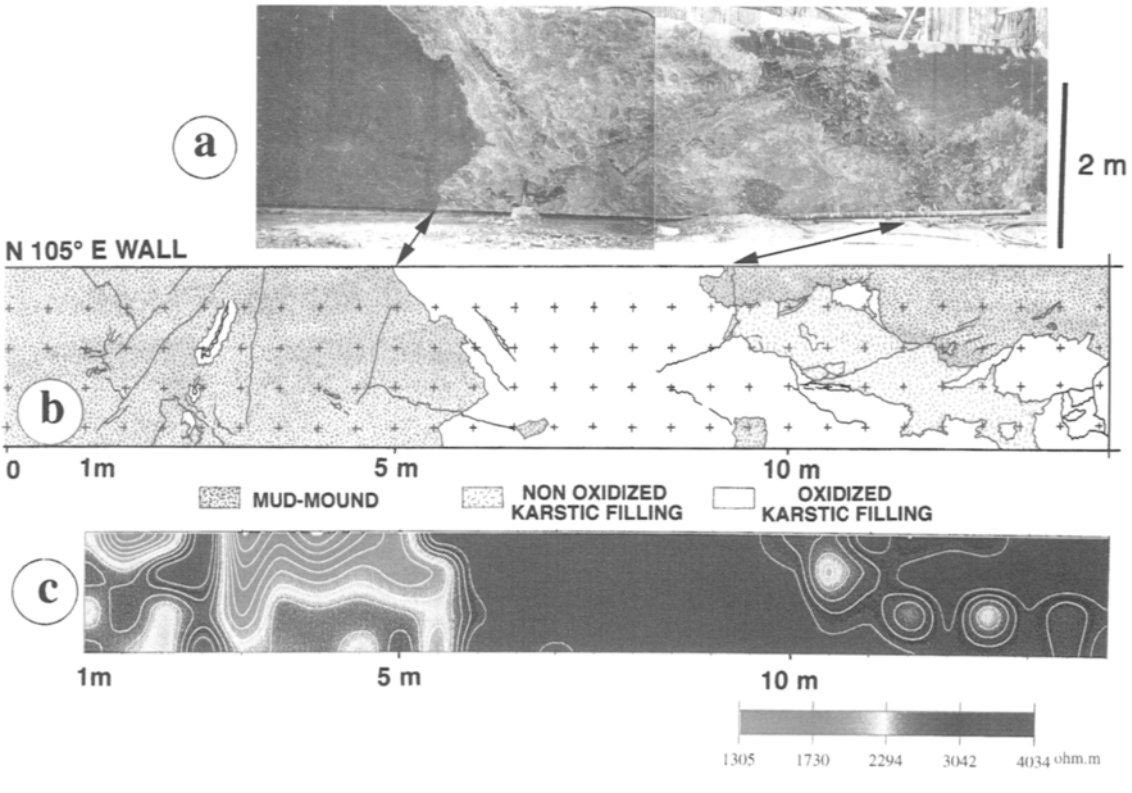

Figure 12. Geological and resistivity correlations for the N 105°E trending quarry wall of the Bois du Bager quarry, as visible in 1997. (a) Photograph of the quarry wall (hammer for scale). The fractured grey microsolenid mudstone (left and right) is eroded into (centre) by a large karstic cave. (b) Sketch and measured cartography of the same quarry wall. Crosses indicate the spaced network of resistivity measurements. (c) Resistivity map of the quarry wall (length in metres, as in map (b) above, Colour resistivity in Ωm). From Benderitter et al. (1997).

- Renewed tectonic activity led to an anticlockwise 125° rotation of the mound towards the SW (N 210° E). As a result, the mud-mound collapsed and slid down into the deep black shale basin, where it was buried, forming a large olistolith (the mound is covered by and embedded in the black shales: 4, Fig. 11). The slumping resulted in the formation of a slump breccia (on the base of the mound, 4, Fig. 11); the two intrusive black shale beds, parallel to the basal surface of the mound (4, Fig. 11) are interpreted as internal slump surfaces within the mound. These black shales are deformed and contorted.
- The dead mound was then buried in the black shales and later in the basin's evolution oil migrated into the karstic cave (5, Fig. 11).
- The thermal episode that matured the oil also seems have been responsible for exfoliation of the karstic cave wall above the reworked 'pebbles' (6, Fig. 11). Fragments of exfoliated cave wall are observed lying perpendicular to the basal clasts (Fig. 5f). White calcitic cements filling the pores between exfoliated wall fragments may also be of hydrothermal origin.
- The Pyrenean orogeny folded the whole area, producing N 120° E trending schistosity in the black shales and fracturing of the mound.

SUMMARY

Following the Caledonian orogeny, which produced an emergent continental area, the carbonate Devonian margin of the southern Montagne Noire began to develop with deposition of transgressive shallow water carbonates. As the extensional nature of the margin developed and subsidence occurred, progressively deeper water carbonate facies accumulated. Stromatactis mounds developed uppermost in the Emsian carbonate succession, when the sea was deep enough to allow the growth and development of a bryozoan-sponge community (Mont-Peyroux nappe, Puech de la Suque) and of a deeper community of sponges (Caunes-Minervois, Minervois nappe), as illustrated in Fig. 13.

The buildups began to grow when the subphotic to aphotic bryozoan and/or sponge community (Fig. 13) could develop sufficiently to trap significant amounts of mud, thus indicating subphotic conditions. In such conditions there were enough nutrients to maintain and

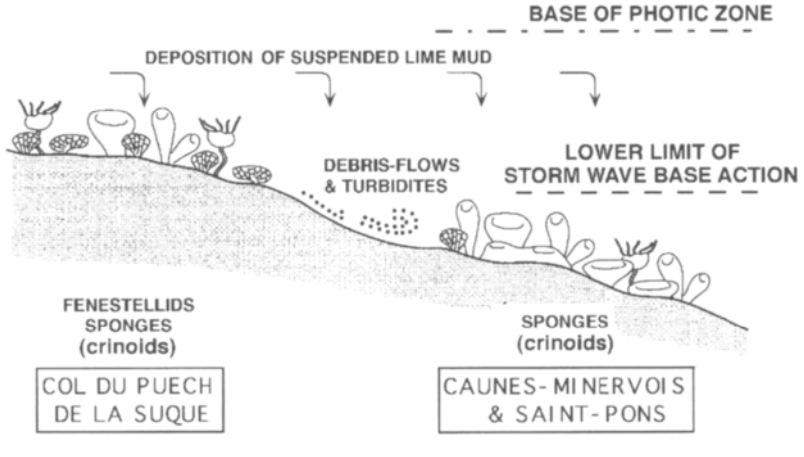

Figure 13. Model for depositional environments of Devonian deepwater stromatactis mounds of the Montagne Noire, developed below the photic zone at the lower limit of storm wave action. Stromatactis of the Mont Peyroux nappe (Col du Puech de la Suque, see Fig. 2) formed at a shallower depth than those of the Minervois nappe (Caunes-Minervois), as indicated by the biological communities (from Bourrouilh and Bourque, 1995).

sustain the whole community of bryozoans and sponges, but these were protected from photic predators. Mud-mound growth stopped when shallowing occurred and at such times shallower high-energy lithofacies such as crinoidal grainstones and packstones covered the mound.

From the beginning of the Emsian to the end of the Frasnian the Minervois Devonian succession is correlatable with the general eustatic sea-level curve suggested by Johnson et al. (1985). During the Emsian-Frasnian time interval, these workers suggested three marked sea-level falls: at the end Emsian (*serotinus* zone), in the middle Givetian (*varcus* zone), and at the Frasnian-Famennian boundary.

Ongoing seismo-tectonic activity periodically affected the margin and the mounds. This was responsible for the intermittent opening and filling of veins, crevices and dykes. Large amounts of Mn-rich fluids entered the open fracture systems during or after the late Frasnian, and Mn precipitation concentrated on open pores, both in swarms of fracture dykes, veins and faults but also in the stromatactid cavities of the mounds (Cyrnos quarry).

All these features make the bryozoan/sponge and sponge dominated mud-mounds good indicators of the ongoing subsidence and accommodation of the Devonian Minervois margin.

The Cretaceous Iberian-North Pyrenean margin is a typical rifted margin. The sedimentary succession deposited during the first phase of marine incursion is quite similar to the Lower Devonian succession of the Minervois nappe: following initial transgression, supratidal to intertidal carbonates were deposited, and with ongoing subsidence a subtidal carbonate platform with reefs and then mud-mounds developed. Because of oblique migration of the Iberian plate (see Bourrouilh et al., 1995), the purely extensional opening of the Bay of Biscay then ceased and was followed by transform-type divergence marked by the opening of pull-apart basins and the development of listric faults.

Reefs and mud-mounds situated on the edges of potential rollover blocks were subjected to various phases of tilting. The tilted mounds were first exposed to karstic erosion. With the continuation of transform tectonics, some mud-mounds continued to be affected by listric faults and finally slid into the anoxic basin. A high thermal gradient along the contact between the convergent Iberian and European plates resulted in early maturation of hydrocarbons from the black shales. Remnant porosity, fractures and karstic caves in the mud mounds were partly filled with hydrocarbons. The petroleum potential of Cretaceous black shales is well known in these areas (Tissot et al., 1980) and although the location and the oil filling of the Lower Cretaceous mud-mound of Arudy is exceptional, it allows us to understand the controls on mud-mound formation and the process by which oil can migrate from deep basinal black shales into mound reservoirs.

An attempt to summarize a model for mud-mounds as markers of basinal and marginal evolution is presented Fig. 14. Mud-mounds can develop anywhere in a sedimentary basin, from the supratidal zone, in shallow water in the photic zone, to deep water well below the photic zone. However, it seems that large and thick mud-mounds are typical of communities of organisms not in direct competition with true reefal communities i.e. they develop in the sub-photic and/or aphotic zone. Size, shape and morphology of mud-mounds vary. They can constitute single sedimentary bodies, isolated in finer sediments such as the Lower Cretaceous mounds of Arudy, or successive patches along a trending line as in the Minervois, or they may even form large and extensive tabular buildups (Massa, 1988). They can vary from a few metres to hundreds of metres in thickness, and from tens to hundreds of metres and sometimes kilometres in diameter. They can have a dome-shaped silhouette and/or a tabular shape. In the Minervois, most of the mud-mounds rapidly developed a tabular form. Shape seems to reflect the evolution of the margin, particularly whether or not that was stable, but also the nature and development of the mound-forming community.

Mud-mounds are not so strictly controlled by symbiosis, light conditions, salinity, temperature, terrigenous input and other linked limiting factors, and therefore have a larger

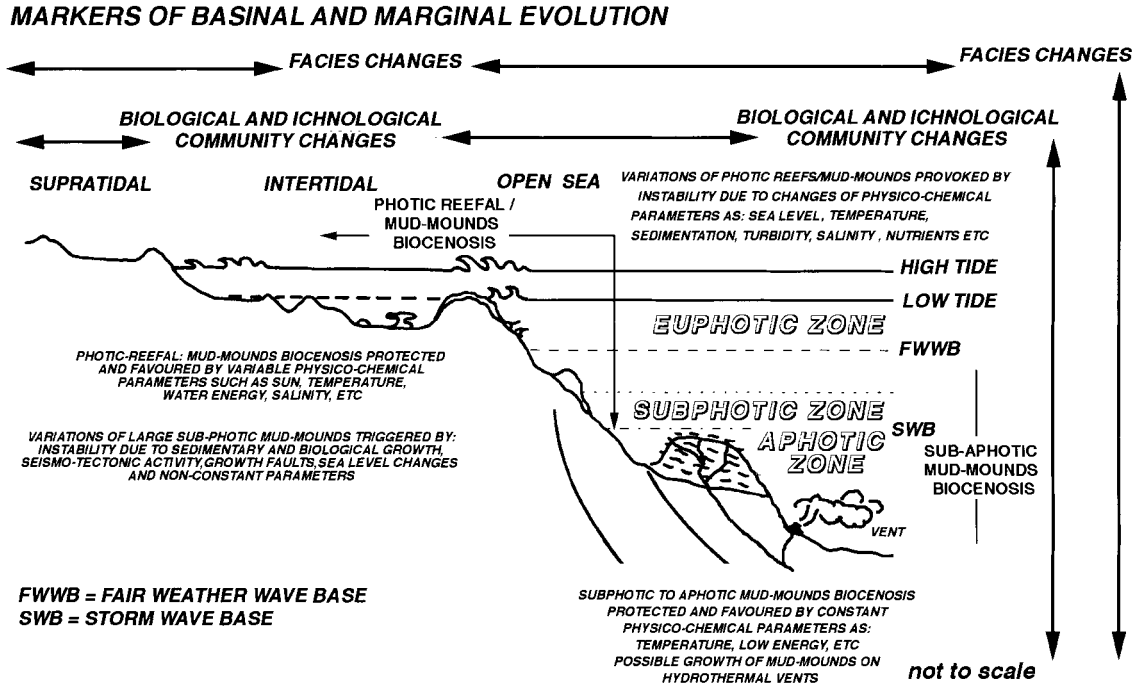

Figure 14. Model for reefs and mud-mounds as indicators of basinal and basin margin evolution. Reef, mud-mound, facies, biological and ichnological community changes will register and express variations in the main parameters controlling the evolution of a basin and/or a continental margin. See explanation in the text.

distribution and range than reefs. They are not restricted to carbonate environments but can appear in mixed siliciclastic/carbonate lithofacies. They can be also be constructed by a variety of organisms, from seagrass to bryozoans, annelids, corals, sponges and other organisms and particularly by microbial activity.

LIBYAN MUD-MOUNDS

Two main types of mounds have been described in Libya and these can be compared to the mounds described above or with younger examples.

Upper Ordovician Bryozoan Mounds, Ghadames Basin

Cratonic basins of Libya form part of the northern Gondwana margin and have been involved in Caledonian, Variscan and more recent tectonic events (Goudarzi, 1980). Most of the Palaeozoic succession of Libya comprises siliciclastic deposits. However, Massa (1988) described carbonate bioherms, constituting bryozoan mud-mounds, from the Upper Ordovician Djeffara Formation of Tripolitania, SW of Tripoli. Bergström and Massa (1991) identified early Ashgill conodonts in the mounds. Massa (1988) pointed out that these features have been identified in exploratory wells covering a very large area of more than 20,000 km^2. They seem to have developed on an East-West pre-Caledonian (i.e. Precambrian) positive trend, which may coincide with or parallel the later Mesozoic Nefusah Uplift. The carbonate succession containing the interbedded mounds extends over more than 300 km along this trend (Buttler and Massa, 1996). They preferentially grew bed by bed and formed tabular accumulations.

These bryozoan mud-mounds, 10 to 100 m thick, developed on the northern margin of the Ghadames Basin and their growth terminated diachronously as a result of the main Gondwanan glaciation to the south. The mounds mainly consist of wackestones with bryozoans and some biomicritic seams. Other fossils are trilobites, brachiopods, echinoderms, stromatoporoids, protospongia and ostracodes. Sparitic recrystallisation is common, often with intense dolomitisation (Bergström and Massa, 1995). Bryozoans, which are very fragile, show their outer walls preserved in fine detail and were apparently fossilized in life position. Buttler and Massa (1996) described the bryozoan fauna, which clearly inhabited a high-latitude Gondwana province. Thus, the late Ordovician bryozoan mounds of Libya developed north of the polar inland icecap, in a high latitude periglacial area and they are overlain by clastic deposits of the uppermost Mamuniyat Formation.

Recently, Hine et al. (1999) have described late Quaternary bryozoan buildups from the Australian Bight. These constitute mounds observed on seismic images in water depths of 200 to 350 m. They are oval- to ridge-shaped in plan view and have a depositional relief of up to 20 m. They range from isolated buildups in deeper water to mound complexes in shallower water. Cores through some of these buildups have revealed that they are primarily constructed by a diverse suite of bryozoans, mostly delicately branching, but also flat robustly branching, fenestrate and arborescent growth forms. These buildups are cool-water mounds, closely related to the occurrence of a glacial event 17 to 22 Ka ago when the warm interglacial Leeuwin Current stopped running off the southern Australian coast. Following this, glacial upwelling, reflecting the proximity of the Antarctic icecap, brought in large amounts of nutrients to the area, allowing the relatively rapid development of bryozoan dominated mud-mound communities.

By comparison with the south Australian continental margin, similar periglacial conditions can be proposed to explain the apparently anomalous occurrence of late Ordovician bryozoan carbonate buildups in the Ghadames Basin on the northern Gondwana margin, in a region of mainly clastic sedimentation.

If the location of the buildup community is strongly controlled by particular physiochemical conditions, such as for example fault-related upwelling or hydrothermal vents, a series of isolated conical mounds can develop, as in the Devonian 'kess-kess' of the Hamar Lakhdad Ridge, Anti-Atlas, Morocco (Mounji et al., 1998). According to Massa (1988), Bergström and Massa (1995) and Butler and Massa (1996), it seems that the bed-by-bed growth of the Ordovician bryozoan mounds of the Libyan Djeffara Formation was probably not constrained by such control and they therefore developed as large tabular structures.

Paleogene Mounds, Sirt Basin

The northern parts of Libya and especially the Sirt and Cyrenaica areas have been affected by the development of Tethys since the Jurassic (Wennekers et al., 1996). In the Sirt Basin, NW-SE trending faults of Cretaceous age created a series of rifted basins separated by horsts and structural ridges. Wennekers et al. (1996, p.33 and 34) noted "In the Sirt Basin, hydrocarbon production is from both upper (Thanetian) and lower (Danian) Paleocene carbonates and oil has been found in both structural and stratigraphic traps or a combination of both. The late Paleocene was a time of widespread reef growth in the basin and it is in such features that much oil is found. The Intisar and Nasser fields are the best examples of this. Carbonate banks and mounds are prevalent in the lower part of the sequence and are also notable hydrocarbon contributors. Examples of this type of accumulation are found in the Al Daffah and Al Bayda' fields."

Mud-mounds and reefs may show vertical succession: large mud-mounds preferentially develop deep in the basin but due to vertical growth or to a relative sea-level fall, the deepwater

mounds may therefore often be capped by shallower water facies and then by reefs. This is seen on the Minervois margin and also along the Lower Cretaceous Pyrenean margin. This has been particularly well documented by Bourque et al. (1995) for the Upper Viséan Waulsortian-type bioherms of the Béchar basin, Western Algeria. The Intisar A oil field (Perrodon, 1980) is located in a Paleocene-Eocene algal-foramineral build-up 5 km in diameter and up to 365 m thick. Most probably this represents a mound-reef association. Many carbonate anomalies observed in the Sirt Basin and Cyrenaica platform areas (Wennekers et al. 1996) should be explored systematically in terms of reefs and mud-mound buildups.

CONCLUSIONS

Because mud-mounds are sensitive to ecosystem changes, they will reflect sea-level changes, as well as subsidence and tectonic activity. They can be water, ore and/or hydrocarbon bearing and constitute interesting targets for exploration, while also providing a good tool for reconstructing the history of sedimentary basins and continental margins.

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Geological Exploration in Murzuq Basin
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CHAPTER 24

Late Ordovician glacially related depositional systems of the Gargaf Uplift (Libya) and comparisons with correlative deposits in the Taoudeni Basin (Mauritania)

C. BLANPIED,[1] M. DEYNOUX,[2] J.-F. GHIENNE[2] and J.-L. RUBINO[1]

ABSTRACT

The late Ordovician (Ashgill) glaciation was a widespread event with an ice cap covering a large part of Gondwana. This glaciation is now well documented from many places in the Sahara as well as around the Arabian craton. Previous studies have shown that the glaciation was complex, with depositional systems depending not only upon their location relative to the core of the inland ice but also on the amplitude of the ice retreat during the different phases.

In the Gargaf area of central Libya, the upper Ordovician succession comprises the Melaz Shuqran and Mamuniyat formations. Direct evidence of glacial processes is limited to glaciomarine microconglomeratic sandstone with possible dropstones in the Melaz Shuqran Formation. However, indirect evidence such as the complex nature of the Mamuniyat facies association – including high sediment discharge, internal unconformities and synsedimentary deformation – is also considered herein. It is suggested that the Melaz Shuqran and Mamuniyat formations were deposited in an overall glaciomarine and deltaic setting devoid of proximal glacial facies because they are either time equivalent with the development of the inland ice located further to the south, or correspond to reworked outwash facies deposited during the last phase of the waning ice sheet. The second hypothesis is favoured and the succession is subdivided into two coarsening upward sequences, representing the onset of the deglaciation and the balance between high sediment discharge, glacioisostatic rebound and glacioeustatic flooding. Thereafter the thin transgressive paralic sandstone which caps the Mamuniyat Formation and the overlying Silurian shales represent the restored normal subsidence and sedimentation of the platform.

In the Taoudéni Basin, the glacial drift corresponds to a megasequence which mainly reflects an overall deglaciation history. A basal polygenic unconformity of partly subglacial origin is overlain by aggrading glaciofluvial deposits, with glacial pavements reflecting minor glacial readvances. These outwash facies were flooded and covered by prograding glaciomarine and deltaic facies, with forced regressions in proximal areas subjected to postglacial rebound. The final ice retreat is marked by a transgressive

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ravinement surface and an unfossiliferous diachronous wave dominated transgressive wedge overlain by well-dated upper Ashgill to lower Silurian shales.

The facies associations and the sedimentary features observed in the Murzuq and the Taoudéni basins are very similar. Two depositional cycles are identified and interpreted as being the result of the latest phase of melting of the Ordovician ice-cap. In the future, the models developed in the Taoudéni Basin may therefore help better understanding of the time equivalent succession in the Gargaf area, and on a larger scale the entire late Ordovician development of the Murzuq Basin.

INTRODUCTION

World-wide observations concerning the northern Gondwana realm, including palaeontological data and recent isotopic studies (Marshall and Middleton, 1990; Brenchley et al., 1994; Paris et al., 1995; Underwood et al., 1997), support a short- lived glacial episode in the latest Ordovician lasting about a maximum of 1 million years, during the late Ashgill. Based on glaciogenic features such as striated pavements and glaciotectonic structures (Beuf et al., 1971; Deynoux, 1980; Vaslet, 1990; Ghienne, 1998), scientists generally agree that the core of the inland ice straddled present-day Central Africa and South America, which were then in the centre of the western Gondwana supercontinent and located at high southern latitudes (Torsvik et al., 1996). The maximum extent of the ice-front and the possible presence of localised ice-caps in the outer domains remain highly debatable topics (Fig. 1). In such frontier areas, the evidence for glaciogenic processes in outcrop relies on the occurrence of glaciomarine facies. The clastic-dominated sequences deposited in response to the melting of the ice-cap are characterised by

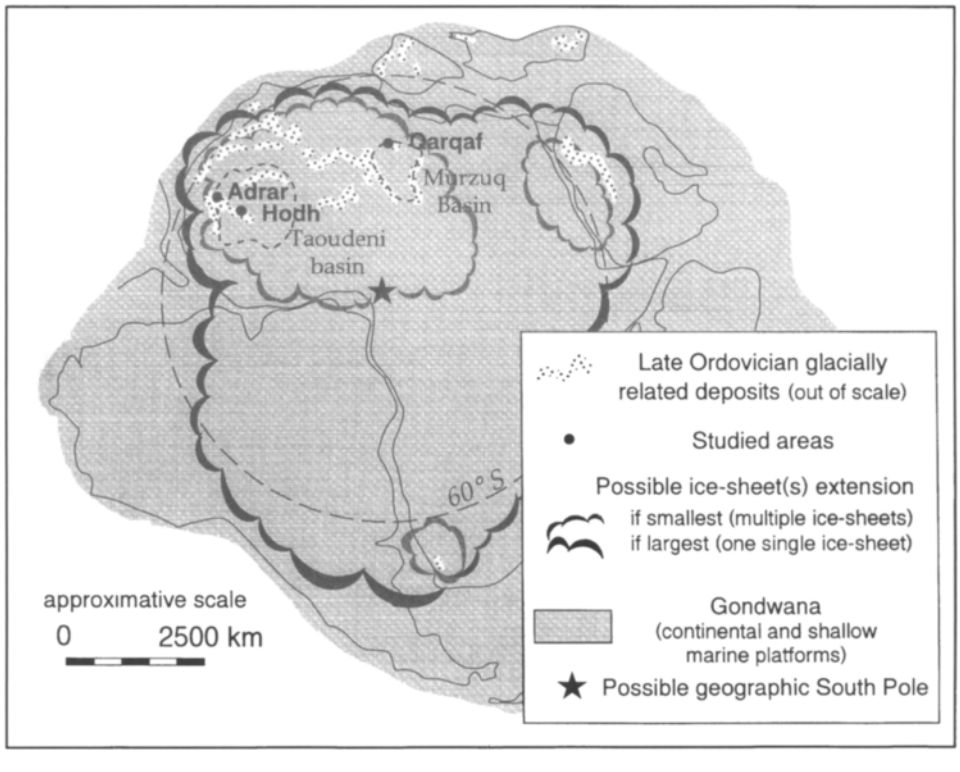

Figure 1. Location of the Late Ordovician ice sheet on the Gondwana Continent, and alternative hypotheses regarding its extent (after Ghienne, 1998).

facies associations classically related to a wide spectrum of environments, ranging from continental to fully marine settings. The precise dating of the overlying post-glacial deposits gives the only constraint which may indicate that the vertical succession, the lateral facies evolution, and the depositional processes observed in the underlying series may be the result of more or less distant glacial processes. The physical processes associated with the melting of the inland ice – such as isostatic rebound and eustatic sea level variations – have a number of complex effects on the depositional environment and on the transport of sediment towards the sea (Boulton, 1990). Although these processes have been modelled, and are more or less understood in the Quaternary, there is still a large degree of uncertainty regarding their effects (Scherneck et al., 1998; Klemann and Wolf, 1998), and this is particularly the case for the Ordovician glaciation.

During a general survey of the West African Taoudeni Basin between 1959 and 1962, petroleum geologists from the Société Africaine des Pétroles (S.A.P.) were the first to describe evidence of a late Ordovician glaciation in Mauritania (Michoud et al., 1963). A little later, Sougy and Lécorché (1963) in the Zemmour (south of the Tindouf Basin), and Debyser et al. (1965) in the Tassilis of the North Hoggar published similar observations. Subsequently late Ordovician glacial deposits have been reported in numerous publications, e.g. Dia et al. (1969), Deynoux et al. (1972), Trompette (1973), Deynoux (1980, 1985), Dia (1984) in Mauritania, Villeneuve (1984) in Guinea, Beuf et al. (1966, 1971), Rognon et al. (1968, 1972), Arbey (1968, 1971) in Algeria, Destombes (1968a, b), Destombes et al. (1985), Hamouni (1988), Ouanami (1998) in Morocco, Klitzsch (1981) and Massa (1988) in Libya, McClure (1978), Vaslet (1990), McGilliwray and Husseini (1992) in Arabia, Abed et al. (1993), Powell et al. (1994) in Jordan, Dean and Monod (1990) in Turkey, Robardet and Doré (1988), Storch (1990), Brenchley et al. (1991) in Europe. Present-day glacial depositional environments have been extensively studied and provide useful analogues sometimes applicable to ancient deposits (see reviews in Eyles, 1993; Hambrey, 1994). In recent years, a new approach involving thorough sedimentary facies analyses using sequence stratigraphical concepts, has shed light on the complex nature of deposition of the glacially-related succession in the Taoudeni Basin of Mauritania (Ghienne, 1998).

In this chapter, deposits related to the Late Ordovician glaciation which outcrop in the western Gargaf area of Libya are reviewed and compared with the time equivalent deposits of the Taoudeni Basin (Hodh and Adrar regions) in western Gondwana (Fig. 1). The interpretations given in this paper regarding the Gargaf area represent a preliminary geological assessment as part of an ongoing regional review in connection with petroleum exploration of the Murzuq Basin.

AGE LIMITS OF GLACIAL DRIFT IN NORTHERN GONDWANA

In Libya, as in many other northern Gondwanan cratonic basins, fossils are rare or absent, both in the glacially related deposits and in underlying formations. In addition, the rapid lateral facies changes and the fact that pre-glacial and/or glacial erosion has often cut deep into the underlying Lower Palaeozoic succession, render regional correlation uncertain and has resulted in a complex lithostratigraphic nomenclature with multiple and often synonomous formation names.

Ages of the Youngest Non-Glacial Ordovician Formations

Generally, in the inner parts of northern Gondwana, the dating of Lower Palaeozoic formations has proven difficult because of the lack of diagnostic fossils. This is the case in the Taoudeni,

Hoggar and Tibesti regions, while in Morocco outcrops contain a rich and diversified macrofauna permitting the establishment of a detailed stratigraphic framework within which the ages of the formations are well constrained (Destombes et al., 1985). In particular, based on the occurrence of brachiopods, Destombes (1968b) clearly dated the disconformity underlying the glacially related deposits in Algeria to the late Ashgill. In other regions various ichnofacies such as *Tigillites*, *Cruziana* and *Harlania* are the only reported signs of life in the pre-glacial deposits. Since these ichnofacies firstly indicate only an environment of deposition and secondly have not yet been extensively studied in these parts of Gondwana, they are still not considered as useful tools in assessing the ages of the formations (see also Seilacher, 2000). In the areas described in this paper, the precise dating of the pre-glacial units in outcrop remains a matter of uncertainty and awaits new techniques, particularly careful and intensive microfaunal sampling and possibly use of the more sophisticated methods such as chemostratigraphy or isotopic dating which have proved useful elsewhere (Glumac and Walker, 1998; Xiaofeng et al., 1998).

In recent years a few papers have demonstrated that thorough micropalaeontological studies of graptolites, acritarchs and chitinozoans in the subsurface may shed some light on the dating of the youngest pre-glacial strata, sometimes confirming previous interpretations. This is the case in Algeria where, in the 'Couloir–1' well of the Illizi Basin, and close to the Hoggar outcrops, Oulebsir (1992) demonstrated that chitinozoans date the youngest pre-glacial deposits to the *B. robusta* zone of Late Caradoc age. These deposits were then eroded by the glacial unconformity and in turn overlain by Upper Ashgill glacially-related microconglomeratic shale-dominated units. In the Libyan Ghadames Basin, subsurface data published by Massa (1988) indicate that conodonts in carbonate-rich strata herein regarded as part of the Djeffara Formation and characterised by thick bryozoan biostromes suggest an early Ashgill age. In places, this formation can be eroded by the glacial unconformity and then successively capped by reworked biostromal elements and by microconglomeratic shales. Therefore, in Libya as well as in Algeria, subsurface data at least as far north as the Gargaf Uplift indicate that the glaciation did not start before the end Caradoc, or perhaps not even before the mid Ashgill.

In the Taoudéni Basin, the ages of the pre-glacial formations are not constrained by any precise palaeontological data. The only fossils consist of *Lingula* found in *Skolithos*-bearing sandstone which can only be generally assigned to the Cambrian to Ordovician transition (Legrand, 1969).

Ages of the Oldest Post-Glacial Formations

In contrast to the pre-glacial Lower Palaeozoic formations, the post-glacial formations are well dated by graptolite, chitinozoan, and acritarch-rich shales throughout Gondwana. This is particularly the case in Mauritania where sedimentological and palaeontological data from the deep inner parts of the palaeocontinent permit constraint of the end of glaciation to the Late Ashgill (Deynoux, 1980; Willefert, 1988) and more precisely to the Upper Hirnantian *persculptus* zone (Ghienne, 1998; Underwood et al., 1998; Paris et al., 1998). In southern Libya, outcrops of the graptolite-rich Silurian Tanezzuft and Iyadhar formations contain a complete suite of graptolite zones in the southwestern Murzuq Basin (Massa and Jaeger, 1971), and indicate that glaciation was already terminated by the earliest Silurian. Subsurface data from the Ghadames Basin of Tunisia and northern Libya also support this interpretation (Massa, 1988).

To conclude, it is fair to say that the upper time limit of the glaciation is now well-constrained in Mauritania, while it is highly probable that use of similar techniques will permit equivalent results in Libya since all the required elements are present. In contrast, the timing of the onset of glaciation is still a matter of debate in both areas – largely due to the strong erosion that

commonly occurs underneath an ice cap. However because no other glacial event has been reported in the Ordovician, the Ashgill event remains the best candidate.

GEOLOGICAL SETTING OF THE GARGAF AREA

The Palaeozoic succession of Libya was described by Massa and Collomb (1960), and named after the outcrops located in the Gargaf Uplift area (Fig. 2, see also Bellini and Massa, 1980; Mamgain, 1980; and Massa, 1988, for comprehensive references). The succession is herein subdivided into pre, syn, and post-glacial formations.

Pre-Glacial Formations

The Lower Palaeozoic pre-glacial deposits are represented, in ascending order, by the Hasawnah, Ash Shabiyat and Hawaz formations. Except for some ichnofacies occurrences, these three formations are devoid of significant fossils.

The Hasawnah Formation constitutes the core of the Gargaf Uplift, with a thickness of more than 300 metres, and reaches 500 to 600 metres in the subsurface of the Ghadames Basin (Massa, 1988). It comprises fluvial cross-bedded, medium- to coarse-grained sandstone deposited by braided rivers and showing local tidal influence (Cepek, 1980; Pierobon, 1991). Its base post-dates the Panafrican tectonic phase since it overlies granites dated to 520–554 Ma (Jurak et al., 1978). This formation was assigned to the Cambrian by Massa (1988).

The overlying Ash Shabiyat Formation is less than 70 m thick. It comprises coarse-grained marine sandstone and it has been assigned to the Tremadoc mainly based on correlation with lateral equivalents in Tripolitania (Havlicek and Massa, 1973; Bellini and Massa, 1980; Massa, 1988).

The Hawaz Formation is about 100 m thick, and is composed of relatively fine-grained sandstone, locally heavily bioturbated (*Skolithos*). The depositional environments are highly differentiated and include wave-dominated shoreface to beach, tidal inlets and tidal bars (Blanpied and Rubino, 1997), without clear evidence of the fan deltas mentioned by Vos (1981). The Hawaz Formation is attributed to the Middle Ordovician (Llandeilo to Llanvirn) based on brachiopods of possible Caradoc age (Havlicek and Massa, 1973) in the overlying Melaz Shuqran Formation (see below).

Glacially-Related Formations

In the western parts of the Gargaf Uplift, the Melaz Shuqran and Mamuniyat formations show characteristic highly variable thickness developments. They unconformably overlie the older Palaeozoic formations, and have classically been regarded as constituting the glacially related formations. Their basal unconformity, related to the Late Ordovician glaciation, is a complex and often indeterminate surface. The sandy Mamuniyat Formation rests unconformably on the shale-dominated Melaz Shuqran Formation, but towards the east it progressively onlaps directly onto the Cambrian Hasawnah Formation.

The age of the Melaz Shuqran Formation is still uncertain. Originally dated on the basis of trilobites as probable Llandeilo-Llanvirn (Collomb, 1962), it was later attributed to the late Caradoc using brachiopods (Havlicek and Massa, 1973). On the other hand, in the northwesternmost part of Gargaf, Gundobin (1985) reported the presence of *Plectothyrella libyca* Havlicek and Massa, in the middle of the formation. According to H.S.Rozman (pers.

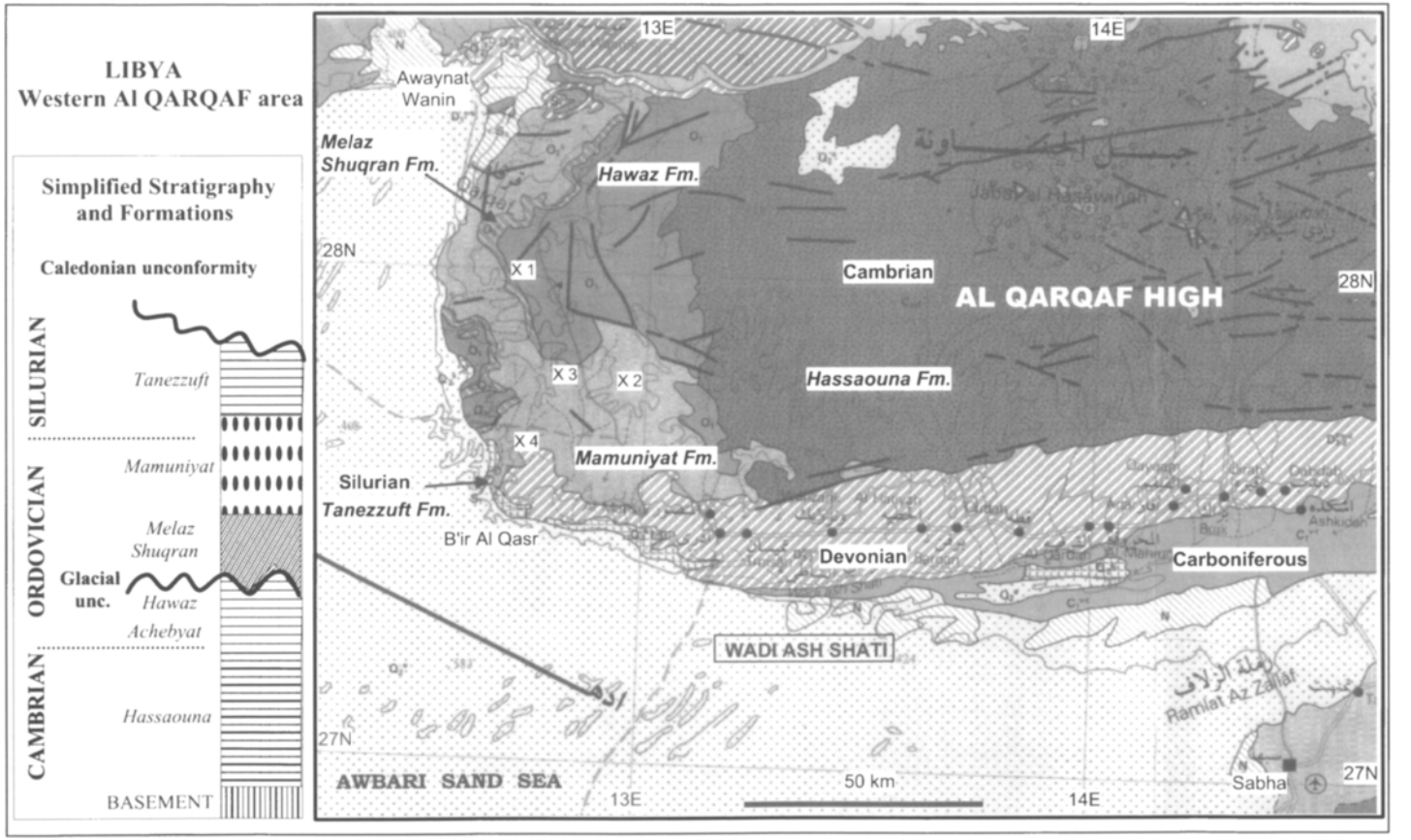

Figure 2. Location of Ordovician sections forming the basis of the composite lithocolumn of Fig. 3. Sketch map modified after I.R.C. Geological map of Libya 1: 500 000, 1985 Edition.

comm. in Gundobin, 1985), this taxon is typical of the Ashgill. In wells to the north of the Gargaf area, Belhaj (1996) reported late Ashgill chitinozoans within the Mamuniyat Formation. Additionally, wells in the Ghadames Basin contain chitinozoans (Jaglin, 1986; Massa, 1988) and conodonts (Bergström and Massa, 1991) of the same age in correlative deposits (Djeffara Formation).

As stated earlier, a number of recent publications demonstrate a very short lived glacial episode restricted to the Hirnantian, and subsurface data also tend to indicate that normal sedimentation occurred during Caradoc and even early Ashgill times in the Illizi (Oulebsir, 1992), and Ghadames basins (Massa, 1988). Therefore, in the Gargaf area, it is important to note this apparent age discrepancy based on the scattered macrofaunal finds. A well-documented microfaunal stratigraphy of the late Ordovician has now been established elsewhere. It is therefore highly probable that *in situ* sampling utilising light drilling equipment in the Gargaf area may permit recovery of non-weathered microfaunas enabling more precise determination of the ages of the Melaz Shuqran and Mamuniyat formations, thereby facilitating correlation with the Illizi and Ghadames subsurface data.

Post-Glacial Tanezzuft Formation

The Melaz Shuqran and Mamuniyat formations are unconformably overlain by the Lower Silurian Tanezzuft Formation. The graptolite-rich shales of this formation in the Gargaf area permit the oldest firm dating of the Lower Palaeozoic succession. They contain numerous graptolites characteristic of zones 18 to 20 (Lower to Middle Llandovery) in the B'ir Al Qasr locality to the southwest (Parizek et al., 1984) while graptolite from zones 20 to 21 (Middle Llandovery) are reported in the Awaynat Wanin area to the northwest (Gundobin, 1985). Therefore, the lowermost Silurian (Zones 16 to 17 – Lower Llandovery) is either missing, indicating a diachronous transgression, or more probably it corresponds to the uppermost Mamuniyat sandstone that is interpreted as possible undated basal Silurian transgressive sandstone in this westernmost Gargaf area. Although only two significant outcrops of Silurian shales have been mapped to date in the western Gargaf area, numerous but scattered hillocks show additional exposures of such shales below the Caledonian unconformity. Therefore, future detailed mapping of this formation together with extensive sampling may demonstrate that the onlapping shales contain the missing graptolite zones.

Thus, in this western Gargaf area, the glacially-related Mamuniyat and Melaz Shuqran formations are only firmly age-constrained by overlying shales of earliest mid to late early Llandovery age while the glacial and pre-glacial sequences are still poorly dated.

THE MELAZ SHUQRAN AND MAMUNIYAT FORMATIONS IN THE WESTERN GARGAF UPLIFT

In the investigated western part of the Gargaf Uplift, the Melaz Shuqran and Mamuniyat formations rest on the Hawaz Formation. The composite section depicted in Fig. 3 represents an attempt to reconstruct the vertical succession of the various units comprising the Mamuniyat and Melaz Shuqran formations – which are commonly juxtaposed rather than superimposed. This composite is based on a series of sections in the four main locations shown in Fig. 2, with additional observations along traverses selected on aerial photographs (Blanpied and Rubino, 1997; Deynoux, 1998). Hypotheses regarding the geometrical relationships are based on measured sections separated from each other by tens of kilometres and the regional thickness never reaches more than 150 m. Most of the contacts between these formations and the

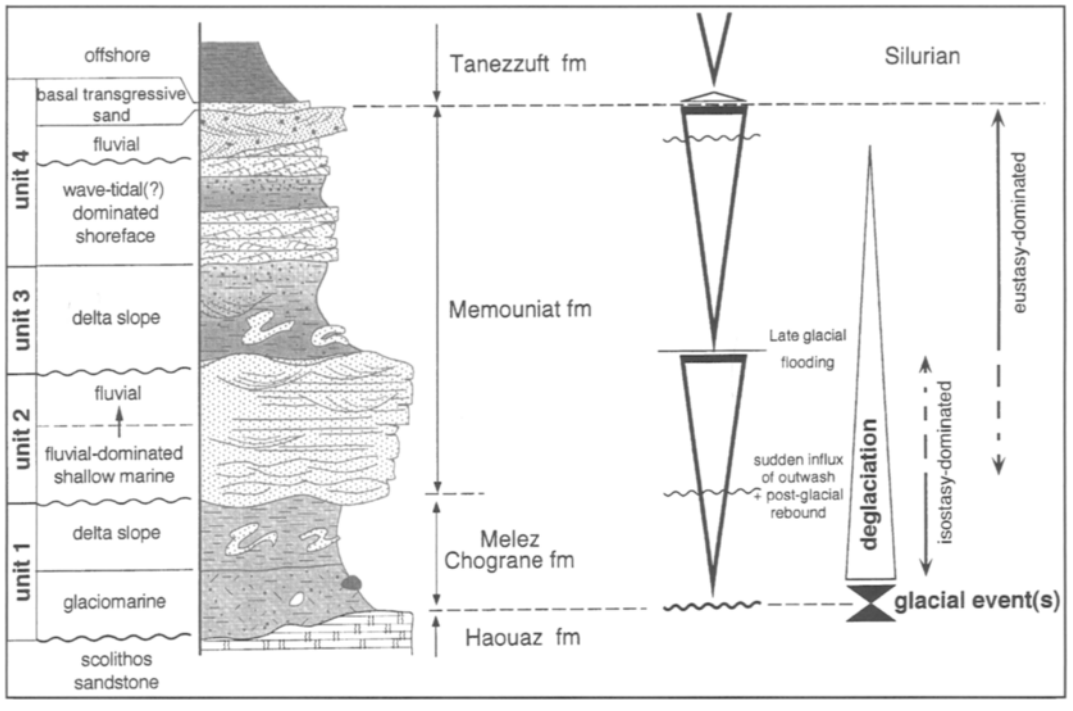

Figure 3. Composite section showing the possible relationships between the observed sequences and the Late Ordovician glacial event in the western Gargaf Uplift.

underlying and overlying series are often obscured by scree or by faulting. Accordingly, for the time being, both the proposed composite vertical succession and its maximum thickness remain speculative. Basically, the succession is interpreted as comprising two coarsening upward sequences deposited during the last retreat of the late Ordovician ice-sheet.

First Coarsening Upward Sequence

This sequence broadly comprises two units (Fig. 3). Unit 1 corresponds to the shale-dominated Melaz Shuqran Formation. Unit 2 consists of the sand-dominated basal part of the Mamuniyat Formation. Both are represented in these formations' type-sections (X1 and X2 respectively in Fig. 2).

The type locality of the Melaz Shuqran Formation, as cited in the Explanatory Booklet of the Idri Map Sheet (Parizek et al., 1984), forms a northward-trending 40 to 50 m thick argillaceous slope, capped by a 15 to 20 m thick sandstone cliff (Plate 1A). This constitutes the western flank of a large trough (Jabal ad Duwaysah) cut into the northwestward prograding Hawaz Formation. In this section, the top of the Hawaz Formation is not visible but the lower part of the Melaz Shuqran Formation appears to consist of mustard-green, microconglomeratic, argillaceous sandstone with scattered quartzitic pebbles 2 to 5 cm in size. This shows a sharp upper contact (Plate 1B) to poorly laminated grey silty shales to pure green claystones interbedded with thin, grey to reddish, micaceous siltstones to fine-grained sandstones (Plate 1C). Wave ripples are common features in the upper part of these storm-graded beds, which contain a key lumachelle horizon that has been identified at other places in the Gargaf area at approximately the same stratigraphic level. Slump structures appear immediately below the Mamuniyat sandstone, especially in a 2 m thick highly weathered greenish to whitish argillaceous horizon; this also shows fractures, sand balls and sand dykes injected from the overlying sandstone (Plate 1D) and rare square to angular translucent quartz pebbles up to several centimetres in size.

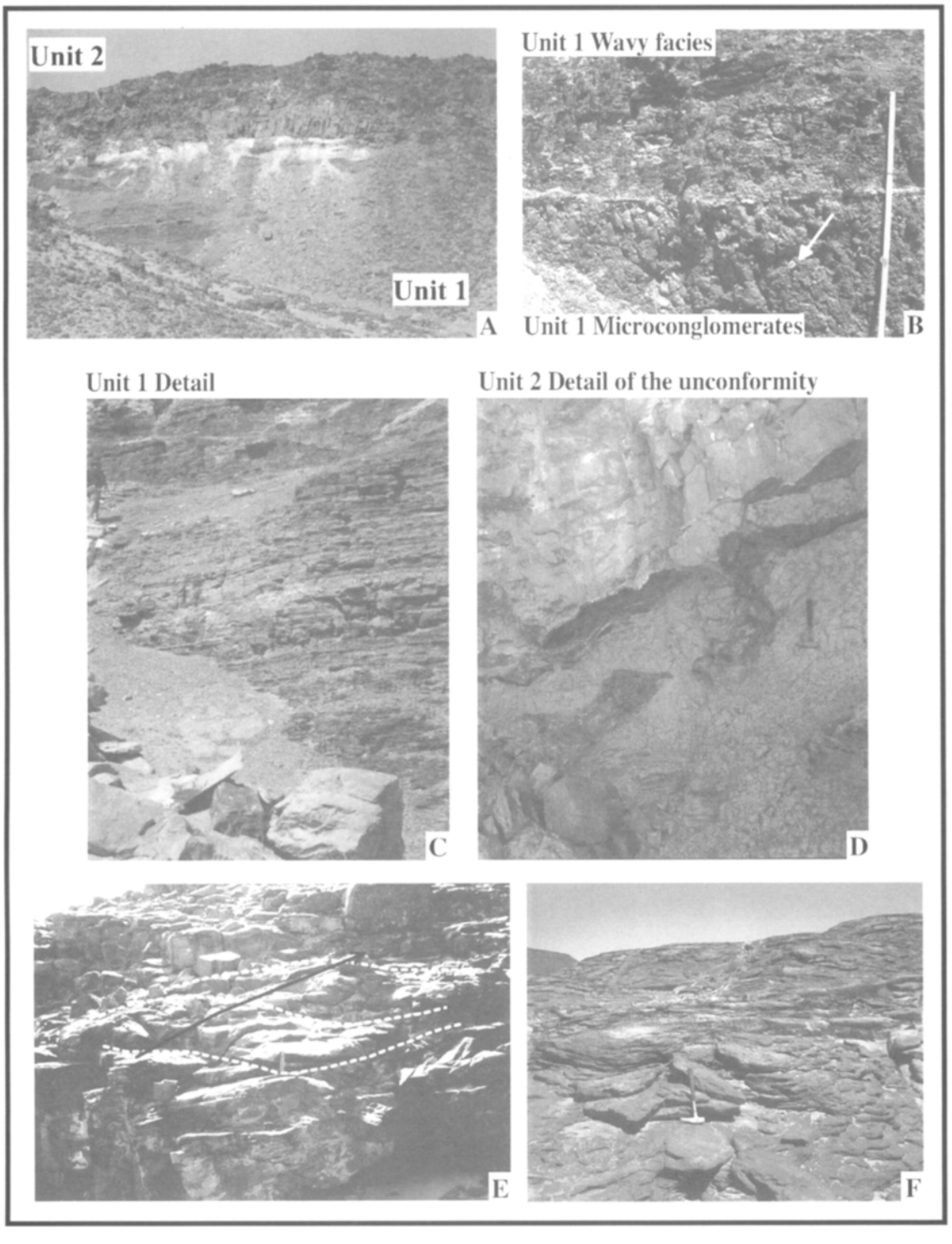

Plate 1. (*for description see end of chapter*)

The Mamuniyat Formation in this locality is only partially represented in the sandstone cliff. It starts with laterally discontinuous 1.5 to 2 m thick massive to locally cross-bedded fine-grained sandstone with an erosive channel-like base. This sandstone displays load structures, large-scale dewatering structures and dykes intruding down into the underlying silty shales. The rest of the cliff is made up of decimetre thick beds of medium-grained sandstone with rare intercalations of thinly laminated fine-grained sandstone. Climbing megaripples (Plate 1E), wave ripples and hummocky laminations are the main small-scale structures. On the overlying plateau, medium- to coarse-grained saccharoid sandstones form a 10 to 15 m high isolated hill. Sedimentary structures there consist of large-scale sets of trough cross-strata a few metres thick.

The overlying part of the composite section corresponds to the so-called 'Mamuniyat type-section' located 50 km southeast of the Melaz Shuqran type section (X2 in Fig. 2). This displays more than 100 m of coarse- to medium-grained sandstone interbedded with thinner and finer-grained horizons showing hummocky cross-stratification and wave ripples. Load and dish structures, sheet dewatering features, groove and prod marks and possible algal mats have been observed at various horizons. A particularly thick channelled unit (25 m thick) occurs in the middle part of this succession. This channel, which can be traced on the neighbouring hill, seems to be roughly N-S oriented and is probably more than 500 m wide.

The upper part of this first depositional sequence can be observed at the base of the so-called 'PhD section' located a few kilometres NNW of the Mamuniyat type section (X3 in Fig. 2). This displays a 25 m thick, coarse-grained sandy unit made up of stacked cosets of relatively flat festoons which become smaller upwards (Plate 1F). Two such units are superimposed, with the upper one possibly slightly eroding into, or shifted laterally relative to the lower one. These two units are interpreted as part of an overall prograding complex terminating the first sequence, the top of which was not observed in section X2, either because of lateral facies changes, the Caledonian unconformity, or Recent erosion.

The morphology of the upper bounding surface of the first coarsening upward sequence displays a peculiar mounded geometry (Plate 2A) that can be traced over an area of many square kilometres. The origin of this large-scale undulating surface is discussed below.

Second Coarsening Upward Sequence

Our interpreted second depositional sequence is based on the combination of two outcrops and additional observations between them. The first outcrop corresponds to section X3, and the second, where the junction between the Mamuniyat and the overlying Tanezzuft Formation may be observed, lies about 20 km WSW of this (X4 in Fig. 2). This second depositional sequence broadly comprises a thick lower shale-dominated unit (Unit 3) and an upper sand-dominated unit (Unit 4), all mapped as Mamuniyat Formation (Fig. 3).

A thin sandy level at the base of Unit 3 (Plate 2B), capping the underlying sandstone of Unit 2, is best developed in the palaeotopographic lows. It consists of a metre thick sandstone bed with wave ripples and parallel lamination, with a pitted and slightly ferruginous top surface. Where this unit is missing, Unit 3 directly onlaps the uppermost coarse-grained trough cross-bedded sandstone of the first sequence.

The bulk of Unit 3 is made up of 50 m thick, green to purple, micaceous thinly laminated siltstones and shales with thin intercalations of fine-grained sandstone showing wave and cogenetic ripples. Metre-sized slumped fine-grained sandstone blocks, contorted shale and siltstone packages and sandstone ball-and-pillows are very common features within this unit (Plate 2C).

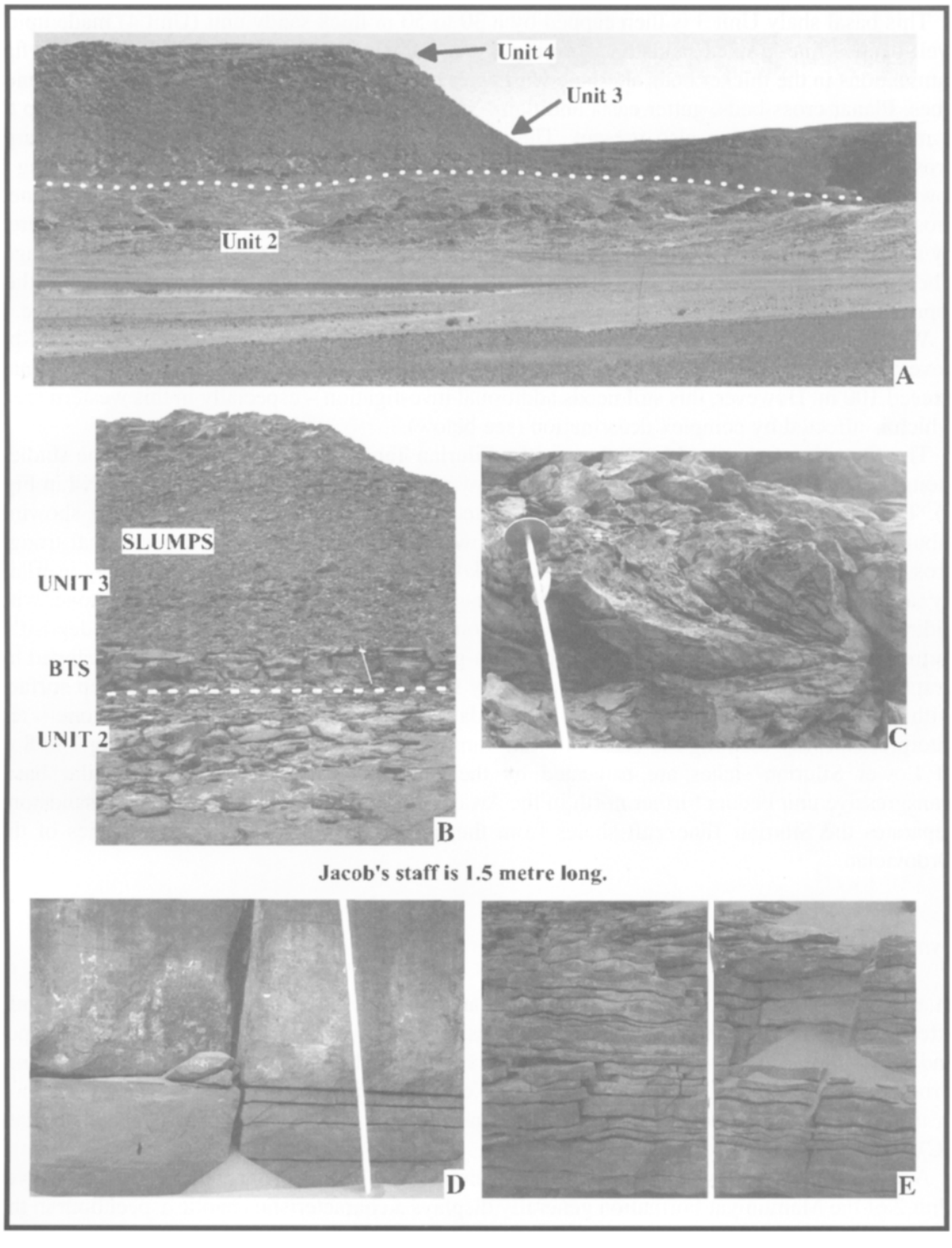
Unit 4
Unit 3
Unit 2
A
SLUMPS
UNIT 3
BTS
UNIT 2
B
C
Jacob's staff is 1.5 metre long.
D
E

Plate 2.

This basal shaly Unit 3 is then capped by a 30 to 50 m thick sandy unit (Unit 4) made up of well-bedded fine-grained sandstone forming a succession of tabular beds up to 80 cm thick; flat laminations in the thicker beds alternate with wave and current ripples in the intervening thinner ones. Planar cross-beds, gutter casts and flame structures are developed locally. Shallow (up to 1 m deep) channels are also present. The contact with the underlying silty shales is sharp, erosional and locally structurally discordant where this unit appears to have slumped along a low-angle fault plane. These tabular sandstones are capped by a few metres thick coarse-grained cross-stratified sandstone with a channel-like erosional base. The rest of the section is covered by scree with a few exposures of bioturbated fossiliferous dark sandstone beds of Devonian age. The origin of the upper coarse-grained sandstone therefore remains debatable – it could either represent a latest Ordovician fluvial succession, or a transgressive valley fill of Devonian age.

Westward from section X3, similar additional successions of tabular sandstone separated by covered finer-grained intervals are also exposed, and the maximum thickness of Unit 4 may exceed 100 m. However, this still needs additional investigation – especially in this western area, which is affected by complex deformation (see below).

The transition from the Mamuniyat to the Silurian Tanezzuft Formation can best be studied along a wadi and in a small hillock in the southwesternmost part of the Gargaf area (X4 in Fig. 2). The outcrops in the wadi display well-sorted fine to medium-grained sandstone showing tabular beds with planar lamination passing upward into wave ripples, and occasional trough cross-stratified beds (Plate 2D–E). In the hillock these tabular sandstones are erosively overlain by a few metres of medium to very coarse-grained trough cross-bedded sandstone with bidirectional paleocurrent patterns suggesting some tidal influence. This channel-like deposit is in turn overlain by a 10 to 50 cm thick medium-grained evenly laminated sandstone capped by graptolitic shales. This horizon shows a slightly ferruginous pitted and bioturbated top surface with vertical burrows. These two units – the tidal channel and the bioturbated sandstone – are interpreted as representing the basal Silurian transgressive system tract. The overlying 7 to 8 m of Lower Silurian shales are truncated by the Caledonian Unconformity. A similar basal transgressive unit occurs further north in the Awaynat Wanin area, where bioturbated sandstone separates the Silurian Tanezzuft shales from the underlying fluvial-dominated clastics of the Ordovician.

Synsedimentary Deformation

In this western Gargaf area, the Mamuniyat and Melaz Shuqran formations are commonly affected at various levels and in many localities by deformational structures of different types and magnitude (see also Glover et al., this volume). Metre to several metre large slump structures including sand balls and fractured or contorted siltstone-sandstone beds are common in the Melaz Shuqran Formation and in the shaly Unit 3 of the Mamuniyat Formation (Plate 2C).

Apart from the Mamuniyat type section, which shows a well-bedded succession, the lower Unit 2 of the Mamuniyat Formation generally displays a characteristic chaotic aspect both in the field and on aerial photographs. Large packages of sandstone beds, including several metre large slumps, are deformed and tilted in various directions. The deformation appears to affect specific portions of the unit, such as in the Wadi Dhub area where a kilometre-scale slump along a gently dipping décollement surface affects about 30 m of disturbed thickly bedded sandstone with highly variable grain-size, erosively overlain by apparently flat-lying well-organised planar sandstone beds (Plate 3A). Landslides along listric faults are locally evident in Unit 4 (Plate 3B), while deformation and tilting of sandy packages similar to that of Unit 2 also occur, but on a smaller scale.

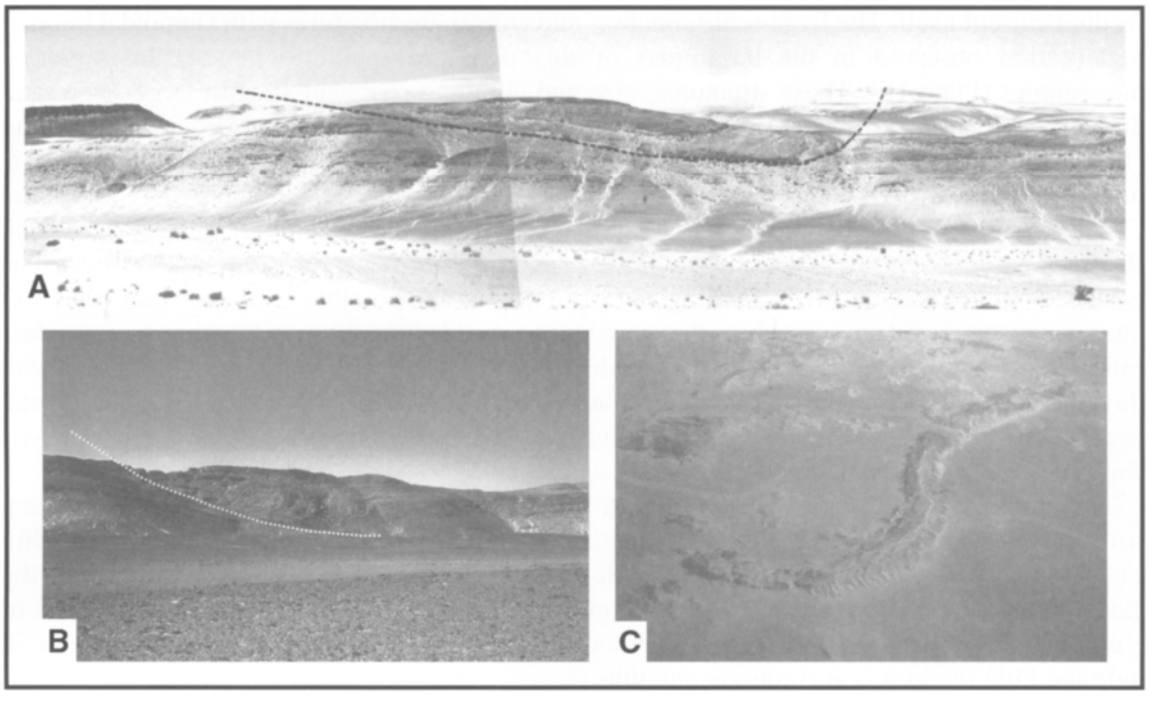

Plate 3.

INTERPRETATION OF THE MAMUNIYAT AND MELAZ SHUQRAN FORMATIONS IN THE WESTERN GARGAF UPLIFT

General Palaeoenvironments

The argillaceous and silty nature of the facies and the presence of wave-rippled siltstone to fine-grained sandstone intercalations as well as bioclastic storm beds suggest relatively distal shelf sedimentation above storm wave base for the Melaz Shuqran Formation (Unit 1). However, the mustard-green argillaceous microconglomeratic sandstone with small (dropped?) pebbles observed in the type section suggests some glaciomarine influence. Glacial features, such as large-scale dropstones or granitic boulders, striated rocks, and parallel striations mentioned by Parizek et al. (1984), have not been found in Gargaf. The sharp contact between the microconglomeratic sandstone and the overlying silty shales observed in the type section (Plate 1B), may reflect a drastic environmental change from glacial to interglacial distal shelf conditions as suggested by Boulton and Deynoux (1981: Fig. 7). In this model the massive argillaceous microconglomeratic sandstone represents glacially derived sediment deposited from suspension (clay matrix) or ice rafts (pebbles and sandy components). The absence of strong bottom currents and stable water stratification resulted in lack of lamination and anaerobic bottom conditions. With the onset of glacial retreat, oceanic circulation penetrated onto the hitherto glaciomarine shelf and deeper circulation developed, producing erosion, sorting and aerated bottom conditions which are reflected in the laminated silty shales, sandy wave and storm ripples and red-coloured laminae.

Unit 2 represents the basal part of the Mamuniyat Formation. The nature of the contact with the underlying shaly unit suggests a sudden and significant influx of sand into the basin. The sand balls penetrating into the underlying shales imply that the substrate was unlithified, probably still under water, and that the erosional effect was very limited and only caused by the

feeding current itself. The large-scale concave- and convex-up structures with sigmoidal internal organisation observed in the basal part of this unit correspond to large-scale migrating megaripples (Plate 1E). These structures' size and climbing character suggest large-scale sand discharge, probably of fluvial origin, entering a relatively deep-water body (associated wave and climbing ripples). A stream flood or sheet flood fluvially dominated paralic environment is proposed for the overlying tabular sandstone beds that form most of the Mamuniyat type section. The tabular bedded organisation with flat to wavy lamination, climbing megaripples, and shallow channels suggest the 'waning sediment laden stream flows' of Mutti et al. (1996). The presence of finer material with climbing and wave ripples and possible algal mats may represent intervening bays or lagoons, while the trough cross-bedded sandstones forming more or less extensive sand sheet bodies correspond to distributary channels. Finally, the unit ended with fluvial trough cross-bedded coarse-grained sandstone (Plate 1F), which marks the continental upper part of the first coarsening upward sequence. The entire unit can thus be interpreted as a slightly wave-reworked fluvial dominated system.

The laminated argillaceous siltstones with rippled sandy intercalations and abundant slump structures of Unit 3 are slightly coarser than those found in the Melaz Shuqran Formation (Unit 1), and were deposited in a similar setting. However this poorly exposed unit does not show the glacially derived mustard-green microconglomeratic facies or the bioclastic horizons typical of Unit 1. Unit 3 infills the pre-existing palaeotopography on top of Unit 2; its thickness (about 50 m in the PhD section) is accordingly variable.

Unit 4 is characterised by well-bedded fine-grained sandstone with abundant current or wave rippled interbeds and associated channelling. Even if the thick flat laminated beds (Plate 2D) are interpreted as streamflood rather than beach deposits, the entire unit is clearly wave-dominated. The fluvial input may have been diluted in shallow water lagoons or bays, and local rip channels seem to have incised the beach. A drastic change from shallow marine to continental environments is marked by the erosive channels of the few metre thick fluvial coarse-grained trough cross-bedded sandstones; these form the upper part of Unit 4 and represent the uppermost deposits in the second coarsening upward sequence.

As previously noted in the PhD section for Unit 2, a characteristic metre-thick basal transgressive sand with a bioturbated condensed top (hard ground) is present at the top of Unit 4, between the fluvial sandstone and the overlying shales of the Tanezzuft Formation. This level is interpreted as a basal transgressive sand in the sense of Abbott (1985), with the uppermost hard ground suggesting a major flooding surface.

It is interesting that the overlying graptolitic shales are present in many places not mentioned on the geological map. Aerial landscape panoramas suggest that they may onlap eastward onto the Mamuniyat sandstone. This suggests that the Silurian transgression of Gargaf was probably more extensive than suggested by previous work.

Glacially or Non-Glacially Controlled Sedimentation in Gargaf?

In the westernmost Gargaf area reviewed herein, direct evidence of glacial processes is limited to the existence of argillaceous microconglomeratic sandstone with possible dropstones in the Melaz Shuqran Formation. However, indirect evidence of glacial to periglacial processes includes the complex nature of the Melaz Shuqran and Mamuniyat facies associations, high sediment discharge, internal unconformities and synsedimentary deformational structures (large scale slumps). A characteristic sinuous sandstone (Plate 3C) is similar to features described in the Upper Ordovician glacial drift of Algeria (Beuf et al., 1971) and Mauritania (Deynoux, 1980; Ghienne, 1998; Ghienne and Deynoux, 1998) as 'cordons' (or ribbons). Variously interpreted as eskers, tunnel valleys, proglacial channels, or subaerial or subaquatic deltaic distributary

channels (see Ghienne, 1998 p. 271, for discussion), such structures are characteristic of the late Ordovician glacially related deposits. Based on its location within the fluvial dominated deposits of the Mamuniyat Formation, the Gargaf cordon is considered to be an anastomosed type of distributary channel in an overall deltaic environment.

The Melaz Shuqran and Mamuniyat formations appear to have been deposited in a deltaic setting devoid of typical glacial facies because they are either time equivalent with the development of inland ice located further to the south, or correspond to reworked outwash facies deposited during the last phase of the waning ice sheet. The first hypothesis assumes a subaerial fringe dominated by tills and braided stream systems where the sandstones are reworked between the ice front and an open marine setting. This interpretation implies that more proximal facies or more direct glacial evidence should be found to the south.

In the second hypothesis, which is favoured herein, the maximum advance of the glacier could have bypassed the Gargaf area. Regional data, mainly the occurrence of microconglomerates and dropstones interbedded with shales and sandy turbidites deposited in a glaciomarine setting in southern Tripolitanian exploration wells (lower Djeffara Formation; Massa, 1988), tends to support a glacial advance which extended to the north of the Gargaf area. This is also supported in the Ghadames Basin of southern Tunisia and northwestern Libya (Bonnefous, 1963) where the argillaceous Bir Tlacsin Formation includes microconglomerates which may correspond to distal diamictites deposited in an outer shelf setting not too far away from the ice front. This suggests that the maximum limit of the inland ice was probably significantly north of the Gargaf area. Large and deeply incised valleys or erosion surfaces known in the subsurface of the Murzuq, Illizi and Ghadames basins are too deep to result from fluvial incision. This is particularly the case for the base of the Melaz Shuqran Formation (Unit 1). Consequently, even if remnants of the maximum advance of the ice sheet have not been observed in the Gargaf area, the basal surface of unconformity is tentatively interpreted as a glacial erosional surface.

Internal unconformities noted within the glacial series have often been interpreted as evidence for supporting multiple phases of glaciation. This is the case in the Hoggar where Beuf et al. (1971) reported two to three possible glacial phases. Evidence of subglacial or ice contact environments is lacking in the Gargaf area, and internal unconformities within the Melaz Shuqran and Mamuniyat sequences can rather be explained by relative sea level changes and related erosion.

The surface separating Unit 1 from Unit 2 is characterised by a sharp and erosional contact separating a basal wave-dominated system from an overlying fluvial-dominated system. Such a contact could either be interpreted as the consequence of a significant (glacio-?) eustatic sea level fall, or, using the hypothesis of an overall glacial retreat, it could be linked to a sudden influx of detrital melt material combined with possible post-glacial rebound (Fig. 3). The second hypothesis is favoured. This is supported by the passage within Unit 1 from glaciomarine microconglomeratic argillaceous sandstones into wave dominated silty shales reflecting the withdrawal of glacial input from the shelf (see above). The increasing upward abundance of slump structures and the sharp and highly disturbed contact between units 1 and 2 suggest increasing instability as a result of high sediment discharge and glacioisostasic rebound. Instability persisted during the deposition of Unit 2 as suggested by the observed chaotic deformation structures.

The argillaceous siltstones which form the lower member (Unit 3) of the second coarsening up sequence form a transgressive development over the fluvial sandstones of the first sequence. They resemble those of the Melaz Shuqran Formation (Unit 1) but apparently (according to our limited observations) do not comprise glaciomarine microconglomeratic deposits. Slump structures are still present, but the siltstones pass upward into fine-grained shallow marine wave-dominated (Unit 4) rather than fluvial dominated (Unit 2) sandstones. This contact between siltstone and sandstone has been observed only in the Ph.D. section where it is sharp and angular

due to large-scale mass movements along listric fault planes. In landscape views of apparently undeformed areas the contact seems to be more gradual. These considerations suggest that the second sequence corresponds to a normal progradation following isostasic rebound (first sequence) and balancing the still active glacioeustatic rise.

According to the model proposed in Mauritania by Ghienne (1998), the fluvial deposits which top Unit 4 in section X4, and perhaps in the Ph.D. section X3, mark the end of the glacial period and the infill of the accommodation space which was created during the glacial period by glacioisostasy and glacial erosion. Thereafter, the transgressive Silurian shales represent restored normal subsidence and sedimentation on the platform.

COMPARISON WITH THE TAOUDENI BASIN

Ghienne (1998) has recently presented an extensive review of the Ordovician glaciation based on a detailed field study in the Taoudeni Basin in Mauritania (Adrar and Hodh areas, Fig. 1). The purpose of this work was to characterise the facies and sequential architecture of the glacially related deposits and to identify the precise roles of glacially driven eustatic and isostatic effects. Its major conclusions may be extended to the Libyan Melaz Shuqran and Mamuniyat succession.

In the Taoudeni Basin, the late Ordovician glacially controlled deposits occur in the Adrar and Hodh areas and are named the Njakane-Abteilli and Tichitt groups respectively (Fig. 4). These deposits unconformably overlie Cambrian to lower Ordovician formations made up of mainly continental to shallow marine sandstone (Trompette, 1973; Deynoux et al., 1985). The glacial sediments rest on a polygenic erosion surface, in part probably fluvially cut during preglacial time, in part subglacial in origin with local glacial pavements and glaciotectonic features. In an overall palaeogeographic scheme, the Hodh area appears more proximal with respect to the inferred south-central part of the inland ice (Deynoux, 1980). The glacial drift is generally composed of aggrading glaciofluvial deposits in an overall glacial retreat sequence, subsequently flooded and overlain by prograding deltaic to glaciomarine environments characterising the deglaciation which occurred in late Hirnantian time.

In both the Tichitt and Njakane-Abteilli groups, the upper Ordovician deposits can be subdivided into two members. The lower member, 0 to 100 m thick, is a complex suite of fluvial or glaciofluvial deposits. In the ice-distal Adrar area, multistorey fluvial deposits consist of fine to medium-grained, flat-bedded, sandstone deposited by sand-rich high-energy distributary channels which continuously infilled accommodation space. In the ice-proximal Hodh area, the lower member is made up of coarse-grained, trough cross-bedded sandstone forming braided channel systems; these include evidence of minor and local glacial readvances such as patches of diamictites and subglacial erosion surfaces with roches moutonnées (Deynoux, 1980). This aggrading lower member forms the lowstand and early transgressive system tracts of a retreating glaciofluvial complex.

The upper member (30 to 100 m thick) displays very different characteristics in the two studied areas. The major deglaciation phase resulted in subsequent flooding of the underlying glaciofluvial complex. In the basinward area (Adrar) it is covered by highstand prograding deltaic deposits made up of a broad coarsening-upward sequence including from base to top: prodeltaic argillaceous siltstones with graded beds and slump deposits, delta-slope muddy sandstone dominated by ripple-drift cross-stratification, delta-front fine to medium-grained sandstone, and finally sandy distributary channels. In the more ice-proximal Hodh area, glaciomarine deposition took place on a subglacial surface (Deynoux, 1985). This sequence was affected by forced regression (falling stage systems tract) related to postglacial isostatic rebound and it consists of striated dropstone-bearing (gravels to cobbles) microconglomeratic muddy

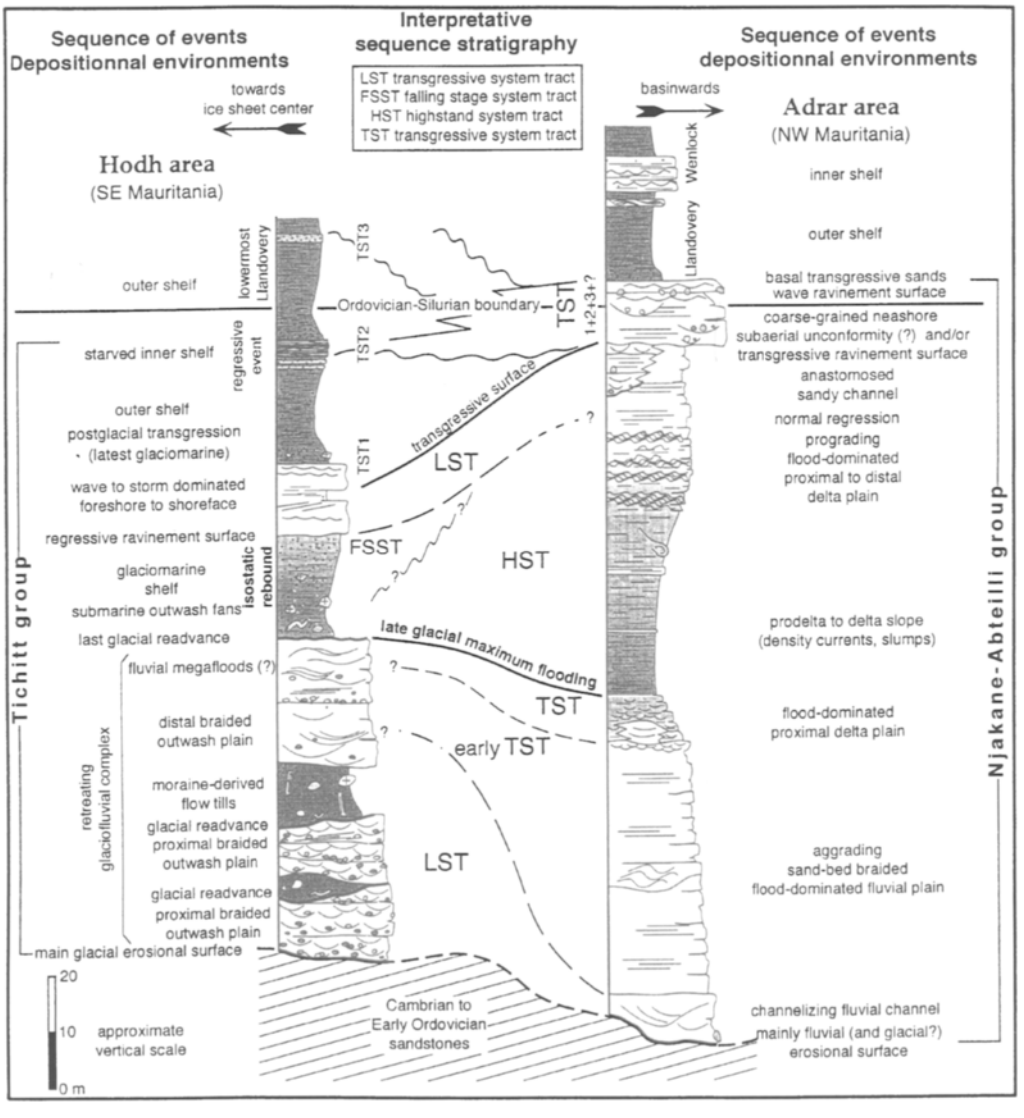

Figure 4. Synthetic sections, sedimentary facies and system tracts of upper Ordovician glacially related deposits in the Hodh and Adrar areas of Mauritania (Taoudeni Basin) (after Ghienne, 1998).

sandstone overlain by sharp-based sandstones of a storm-dominated shoreface. Highstand progradation in the Adrar was probably partly coeval with the forced regression in the Hodh.

The final ice retreat is marked by a transgressive ravinement surface and an unfossiliferous diachronous wave dominated transgressive wedge overlain by the latest Ordovician to Early Silurian graptolitic shales. In the Hodh, glaciomarine deposits are conformably topped by upper Ashgill-lowermost Silurian offshore graptolitic shales, showing the progressive disappearance of glacial input and the colonisation by planktonic marine fauna (Underwood et al., 1998; Paris et al., 1998). In the Adrar, deltaic deposits are capped by coastal coarse-grained sandstones, 10 to 20 m thick, overlain by the basal transgressive sands and shales of the early Silurian transgression.

In summary, the glacial drift in the Taoudeni Basin corresponds to a megasequence that mainly reflects an overall deglaciation history. An oversupply of sediment has continuously filled the accommodation space created by glacially controlled relative sea level changes (mainly late glacial glacioeustatic transgression balanced by isostatic rebound in proximal areas)

and partly by subglacial erosion. Conversely, the Silurian platform was starved, and sedimentation was mainly controlled by regional subsidence (Ghienne, 1998).

Comparison between the Taoudeni Basin and the Murzuq Basin shows that the proximal fluvioglacial deposits that form the lower part of the upper Ordovician succession in the Hodh (Fig. 4), are unrecognised in Libya. This could be explained by a basinward shifted location for the Gargaf Uplift resulting in an overflooded area contemporaneous with the onset of deglaciation. Consequently the Melaz Shuqran Formation (Unit 1) may record the early phase of the deglaciation history with its subaquatic, in part glaciomarine deposits. As discussed previously, this is partly supported by the suggestion that the ice cap extended further to the north. In such a peripheral location, an early isostatic rebound and abundant sedimentary supply resulted in the rapid passage from marine deposits into fluvial-dominated coastal deposits (Unit 2). These later deposits were then flooded during the platform-wide late glacial marine flooding phase corresponding to the generalised ice retreat over the whole cratonic domain. Unit 3 (which overlies a flooding surface) and Unit 4 should thus be coeval with the prograding deltaic complex identified in the Adrar area (Fig. 4). The absence in the Gargaf area of terminal glaciomarine sediments such as those found in the Hodh area, results from its ice-distal location. The shallow marine horizon, which locally forms a distinct level on top of Unit 4, is similar to the coarse-grained deposits capping the upper Ordovician succession in the Adrar area and is thought to represent a diachronous transgressive systems tract overlain by Silurian shales. These amalgamated transgressive deposits are apparently coeval with the eustatic cycles best developed in the Hodh area during the late Ashgill to early Silurian.

It should be borne in mind that the proposed correlation between the Melaz Shuqran and Mamuniyat formations and supposed coeval deposits in the Taoudeni Basin is based on an assumed late Ashgill age for all these deposits. This interpretation may also be supported by the sedimentary record in northern Mauritania, which is similar to the Libyan one, with glaciomarine deposits overlain by a prograding deltaic sequence and in turn capped by a transgressive sandy wedge below Silurian shales. This succession was described by Deynoux (1980) in the Zemmour area located in the more ice distal regions of Mauritania.

CONCLUSIONS

This preliminary comparison between the late Ordovician glacial succession outcropping in the Gargaf area of Libya and in the Taoudeni Basin of Mauritania shows a great number of similarities as regards both facies associations and sedimentary features. In both areas, two depositional cycles are identified and interpreted as being the result of the latest phase of melting of the Ordovician ice-cap. Local anomalies and lateral variations normally expected in this unusual type of environment may be explained by regional variation in tectonic activity and relative sea-level changes. Although at the moment varying amounts of work have been carried out and different sedimentological approaches utilised in the two areas, the models developed in the Taoudeni Basin (Deynoux, 1980; Ghienne, 1998) may help further interpretation of the Libyan succession.

A reappraisal of the Lower Palaeozoic section in the Gargaf region, particularly involving detailed mapping, is deemed compulsory to unveil the main questions raised during this preliminary assessment, such as the spatial correlation of units and the influence of deformational processes. If possible, integration of subsurface data and a biostratigraphic study based on microfossils and utilising light drilling apparatus should focus on the Melaz Shuqran Formation in order to confirm its age.

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PLATE CAPTIONS

PLATE 1

A. Silty shales of the Melaz Shuqran Formation (Unit 1) in its type section (X1 in Fig. 2). The shales are erosively overlain by a 15 m high cliff of sandstone corresponding to the base of Lower Mamuniyat Unit 2.

B. Massive glaciomarine microconglomeratic argillaceous sandstone, with characteristic – onion – weathering, sharply overlain by thinly laminated silty shales interbedded with wavy lenticular micaceous siltstones or fine-grained sandstones: Unit 1 of the Melaz Shuqran type section. Note the ice-dropped (?) clast 3 cm in size (arrow) in the microconglomeratic sandstone.

C. Wave dominated shaly to silty small scale parasequences within the upper part of Unit 1 in the Melaz Shuqran type section. People for scale.

D. Sand dyke intrusion from the Mamuniyat Sandstone (base of Unit 2) into the weathered silty shales of the Melaz Shuqran Formation (Unit 1 in the Melaz Shuqran type section).

E. Climbing megaripples in the lower part of the Mamuniyat Formation (Unit 2) in the Melaz Shuqran type section. Hammer for scale.

F. Stacked cosets of flat festoons in the coarse-grained sandstone of the upper part of Unit 2, Ph.D. section (X3 in Fig. 2).

PLATE 2

A. Ph.D. Type section (X3 in Fig. 2). At the base the fluvial sandstone of the upper part of Unit 2 is separated from the overlying silty shales of Unit 3 by an undulating surface. The lower part of the wave-dominated sandstone from the base of Unit 4 is visible on top of the hill.
B. Ph.D. section, near view showing the basal transgressive sandstone (BTS) between Unit 2 and the base of the slumped silty shales of Unit 3.
C. Slump structure with contorted sandstone on top of Unit 3 in the Ph.D. section.
D. Flat parallel laminated sandstone interpreted as a beach deposit in the upper part of Unit 4 in section X4.
E. Wave rippled shoreface sandstone in the upper part of Unit 4 in section X4.

PLATE 3

A. The north side of Wadi Dhub showing an internal unconformity (listric fault ?) in Unit 2 of the Mamuniyat Formation.
B. Synsedimentary deformation within Unit 4 of the Mamuniyat Formation. This channel-like structure is in fact limited by a low angle listric (?) fault.
C. Aerial view of a – cordon – structure in Unit 2 of the Mamuniyat Formation a few kilometres SE of section X2.

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Geological Exploration in Murzuq Basin
M.A. Sola and D. Worsley, editors.

CHAPTER 25

A bibliography of the geology of the Murzuq Basin

DAVID WORSLEY[1]

ABSTRACT

This listing presents a review of published and public domain literature on the geology of the Murzuq Basin. Despite our ever-expanding electronic world, many original sources of real data and information seem to be overlooked, resulting in much redundant activity – especially unfortunate in an extreme area that will always demand original thinking. Future work may benefit from established, although perhaps seemingly old-fashioned, observations and interpretations.

INTRODUCTION

From the pioneering exploration of Beyrich (1852) and Duveyrier (1864) to the papers presented in this volume, geoscientists have gradually begun to understand the development of this vast and demanding area in the central Sahara. Changing colonial regimes led to a series of papers by Italian and French authors in the first half of the 20th century. Subsequent national and international work has clearly shown the importance of the Murzuq Basin for a better understanding of the evolution of North Africa and the petroleum potential of this entire region. This multinational activity has resulted in a series of publications in different languages, usually with little cross-referencing and often resulting in duplication of effort and terminological confusion.

The bibliography of public domain literature presented below makes no claim to be complete, but it hopefully provides a compilation of literature on all aspects of the geology of this remote and still under-explored area. There are also many unpublished reports by individual companies and consultants – these are not included in this listing, but most are referred to in the reference lists of the individual papers in this volume and may be accessed in the NOC Library. This bibliography concentrates on the Murzuq Basin itself – readers interested in the geology of the adjacent Kufrah Basin are referred to the excellent review by Luning et al. in this volume.

The pioneering work carried out to date by geologists from many countries – not least including the geological mapping coordinated by the Industrial Research Centre – has established a solid framework for further studies of the Murzuq Basin – an important reference area for the Palaeozoic evolution of northern Gondwana.

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