Nuhu George Obaje

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Geology and Mineral Resources of Nigeria

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Geology and Mineral Resources of Nigeria

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Prof. Nuhu George Obaje
Nasarawa State University
Dept. Geology & Mining
Keffi
Nigeria
nobaje@yahoo.com

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Foreword

Books on Geology and Mineral Resources of Nigeria are very few and mostly not accessible in Libraries and Bookshops in Nigeria. This book by Professor Nuhu Obaje is therefore a welcome development and could not have come but at a better time with the renewed interest and activities in the Geology and Mineral Resources of Nigeria. The author has brought together several published and unpublished works into a comprehensive hand-out which I believe will be very useful to policy makers, the international community, investors, researchers and above all our students of geology in tertiary institutions in Nigeria and abroad. Additional insights were also provided with new geochemical data on the Muro Hills Iron Ore deposits as well as biostratigraphic and petroleum geochemical data on parts of Nigeria's sedimentary basins.

The figures are in plentiful abundance, in fact more abundant than the text pages, which makes the work look more like an album but this is good for our proper grasp of the subject matter under review.

The chapters are seemingly very disproportionate in size and content. Whereas very little has been presented on Cretaceous-Cenozoic magmatism and volcanism, the chapter on Mineral Resources looks like a book of its own. Furthermore, the in-depth discussion and data presented on the petroleum potentials of Nigeria's inland sedimentary basins makes the work look like the author is out again to convince us that oil can be found in Nigeria's other sedimentary basins outside the Niger Delta. Well, it is not surprising, knowing fully well that the author's geologic specializations are in sedimentology, petroleum geochemistry, biostratigraphy and other aspects of the Nigerian sedimentary terrain.

The petroleum sector has dominated the mineral resources of Nigeria and I find the presentations on the solid minerals very interesting, both in geologic occurrence and suggested policy modifications. Nobody would invest in the mining of the "solid minerals" unless the needed political environment is created.

I recommend this book as a must-be-in the libraries of all government policy makers, geologists in the academia and industry, national and international investors, and to all students of geology at the undergraduate and postgraduate levels.

Zaria, Nigeria Idris Isa Funtua

Preface

Since the book on the Geology of Nigeria by C.A. Kogbe, published by Elizabethan Publishing Company, appeared in 1976, no other attempt has been made to review, collate and publish the advances made in the geology of Nigeria in a comprehensive format. Yet over the years, many studies, evaluations and re-evaluations have been undertaken in many aspects of the geology of Nigeria. Kogbe's book on the Geology of Nigeria remained the only reference book in the aspect of understanding the regional geology of Nigeria.

Some aspects of the geology and stratigraphy of Nigerian sedimentary basins are available in Whiteman (1982) and Ofoegbu (1990). Nigeria is the 8th largest producer of crude oil, which is bowelled in her sedimentary basins. As at now, current production of all Nigeria's crude oil is derived from the Niger Delta basin. The geology of the Niger Delta has been the most studied because of the petroleum occurrence in the basin, yet several reports of potentials in the other onshore basins have been made. Some stratigraphic re-evaluations have also been undertaken in the study of these sedimentary basins. These re-evaluations are scattered in different published literatures, and were prior to this work not collated nor synthesized.

Abundant mineral deposits occur in all the components of Nigerian geology (Basement, Younger Granites, Sedimentary Basins) but the unavailability of a detailed geological textbook that can bring forward the advances made so far and the complexity of the Nigerian Mineral Act as well as the low technical capacity to properly assess the reserves, physico-chemical properties and industrial applications of these mineral resources have led to the inability to properly harness the mineral resources of Nigeria. The dominance of oil on the Nigerian economy has not helped matters. A proper knowledge of the geology and accurate inventory of the mineral resources of Nigeria and the dissemination and documentation of this information in the form of a book as has been attempted here are necessary to attract public and private sector investors to the minerals sector of the Nigerian economy which in turn should lead to the establishment of small and medium-scale enterprises. Such enterprises will resuscitate economic activities that will lead to economic growth, employment generation, poverty reduction and social transformations.

This work is generally a review and an assemblage of several separate works on different aspects related to the geology of Nigeria with some minor new data generated in the course of carrying out this project. It is therefore clear that most parts and indeed most of the chapters derive from previous works by other authors and in such cases, these have been clearly stated and the respective previous works and the authors duly acknowledged. It is important, however, to mention at this stage that the chapter on the Basement Complex benefited immensely from the work of Dada (2006) while the chapters on the Younger Granites and Cenozoic Volcanism were derived majorly from Bowden and Kinnaird (1984), Kinnaird (1985) and Wright (1985). Compilation on the Benue Trough came mainly from Obaje et al. (2004); the Chad and Dahomey Basins from Okosun (1995); the Sokoto Basin from Kogbe (1981b), the Bida Basin from Adeleye (1989) and Akande et al. (2005) and the Niger Delta from Stacher (1995). The works of Offodile (1981) and Woakes et al. (1987) contributed immensely to the discussion on the Mineral Resources of Nigeria.

It is not coincidental that most of the mines and minerals illustrated in figured photographs came from Nasarawa State. The reason can mainly be attributed in part to my academic location at the Nasarawa State University in Keffi over the past five years and the fact that Nasarawa State can be taken as a microcosms for the study of Nigerian geology. All the rock types that make up the components of Nigerian geology (Basement, Younger Granites and Sedimentary rocks) are all represented in Nasarawa State; so also are 80% of all the minerals that occur in the different geological environments in Nigeria.

His Excellency, the Executive Governor of Nasarawa State, Alhaji Aliyu Akwe Doma, *Garkuwan Doma*, is the Chief Executive of the State that is “Home of Solid Minerals”. He is also very enthusiastic about developing and harnessing the solid mineral resources of Nasarawa State to accelerate the economic development of the region. When we wrote our first monograph on the Geology and Mineral Resources of Nasarawa State, His Excellency called me personally to say he read every page of the book and gave us a pat on the back with lots of encouragements. Through that action of the Governor of Nasarawa State, I was encouraged to start this project and to expand the scope to cover the whole of Nigeria.

This work was funded by the *Alfried Krupp Wissenschaftskolleg Greifswald* (Germany) through a research-support-grant of the 2007/2008 fellows programme. I am therefore extremely grateful to the Board of Trustees, Executive Board, Advisory Board, and staff of the Alfried Krupp Wissenschaftskolleg. I want to particularly acknowledge and cherish the former and present Academic Directors, Professor Dr. Dr. h.c. Klaus Pinkau and Professor Dr. Bärbel Friedrich, respectively, as well as Mr. Joachim von der Wense (former Lord Mayor of the City of Greifswald and member of the Executive Board of the Institute), who helped me with immigration procedures at the Aliens and Residents Registration Office in Greifswald. I want to thank very gratefully Dr. Reinold Schmücker, the Administrative Director of the Institute, who received me very warmly to Greifswald and assisted with many day-to-day activities whenever I am in Greifswald. Mrs. Marianne von Weber, Mrs. Kathleen Carls, Mrs. Ulrike Borgwardt, Mrs Marlene Sülberg, Mr. Stefan Klatt, and Mr. Lars Rienow are also gratefully acknowledged for assisting in many technical and administrative aspects at the Krupp Kolleg. Finally, I thank all fellows of the 2007/2008 set at the Krupp Kolleg for companionship and stimulating discussions on our different working projects.

Professor Dr. Maria-Theresia Schafmeister was my academic host at the University of Greifswald. I thank her greatly along with Professor Dr. Martin Meschede, Professor Dr. Ingelore Hinz-Schallreuter and Professor Dr. Laurence Warr for directing my analytical work in the laboratories of the Geological Institute of the University of Greifswald.

The Management of Nasarawa State University is gratefully acknowledged for assisting in the field sample collections through supports to undergraduate field projects in the Department of Geology and Mining and a research grant in 2006. My colleagues in the Department of Geology and Mining particularly Messrs A. Moumouni, M. S. Chaanda, N. G. Goki, K. Nghargbu and I. Y. Tanko are duly acknowledged for the several contributions they brought into this work.

Finally, I thank my dear wife, Mrs. Aisha Mary Obaje, for her endurance, patience and love while I was working on this project both in Nigeria and in Greifswald.

Keffi, Nigeria Nuhu George Obaje

Contents

Part II Geology – Sedimentary Basins

Introduction

In 1914 the Protectorates of Southern and Northern Nigeria were amalgamated with the Colony (Lagos) by Lord Lugard to form what is now known as Nigeria. There are thirty six (36) federating states alongside the Federal Capital Territory (FCT) that make up the Federal Republic of Nigeria (Fig. 1). A total of 774 local government councils are recognized in the Constitution of the Federal Republic of Nigeria. Since 1991, the Nigeran capital has been the centrally-located city of Abuja; previously, the Nigerian government was headquartered in Lagos. Nigeria is famous for her huge population of about 140 million people – the largest national population on the African continent.

Geopolitically, Nigeria may be further subdivided into a North–South geopolitical dichotomy (Fig. 2) and further, for any political exigency, into North–West–East tripartite subdivisions (Fig. 3), which coincidentally accommodate the three major tribes (ethnic groups) in Nigeria. The *Hausas* constitute the major ethnic group in the North; the *Yorubas* in the West and the *Ibos* in the East. There are about 250 ethnic groups in total in Nigeria such that each of the regions with its major ethnic group carries a significant percentage of minority ethnic groups (Fig. 3). In fact, about 10 ethnic/ linguistic groups constitute more than 80% of the population: the other large groups are Tiv, Ibibio, Ijaw, Kanuri, Nupe, Gwari, Igala, Jukun, Idoma, Fulani, Itsekiri, Edo, Urhobo and Ijaw. The 1991 census indicates a population that is 51% male and 49% female. For further administrative reasons and for the purposes of further political exigencies, the country is grouped into six (6) geopolitical zones (Fig. 4). The official language in Nigeria is English. There are 3 main indigenous languages spoken by the 3 predominant ethnic groups. These are Yorubas in the West, Hausa-Fulani in the North and the Igbos in the East.

Petroleum accounts for about 90% of Nigeria's foreign exchange earnings and makes up about 70% of the nation's Gross Domestic Product (GDP). Presently, the entire production of petroleum in Nigeria is derived from the Niger Delta region. The South–South geopolitical zone along with Abia, Imo and Ondo States constitute the oil-producing states of Nigeria (Fig. 5). However, several geological studies have indicated that potentials to add to the nation's current reserves exist in sedimentary basins within several other states of Nigeria (Fig. 6).

Nigeria is situated in the West African sub-region (Fig. 7) and lies between longitudes 3° and 14°E and latitudes 4° and 14°N. It has a landmass of 923,768 sq. km.

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Fig. 1 Current federating states of Nigeria (36 in number as at 2008)

It is bordered to the north by the Republics of Niger and Chad and to the west by the Republic of Benin. It shares the eastern borders with the Republic of Cameroon right down to the shores of the Atlantic Ocean forming the southern limits of the Nigerian Territory. About 800 km of coastline confers on the country the potentials of a maritime power. Arable land is in abundance in Nigeria for agricultural, industrial and commercial activities.

Although Nigeria is wholly within the tropics, its climate varies from the tropical at the coast to sub-tropical further inland. There are two marked seasons: The rainy season lasting from April to October and the dry season from November to March. The maximum temperature in the coastal areas of the south can go up to 37°C while the absolute minimum temperature is 10°C. The climate is drier further north where extremes of temperature may range from 40° to 50°C.

The geology of Nigeria is made up of three major litho-petrological components, namely, the *Basement Complex*, *Younger Granites*, and *Sedimentary Basins* (Explanatory Note 1). The Basement Complex, which is Precambrian in age, is made up of the *Migmatite-Gneiss Complex*, the *Schist Belts* and the *Older Granites.* The Younger Granites comprise several Jurassic magmatic ring complexes centered around Jos and other parts of north-central Nigeria. They are structurally and petrologically distinct from the Older Granites. The Sedimentary Basins, containing

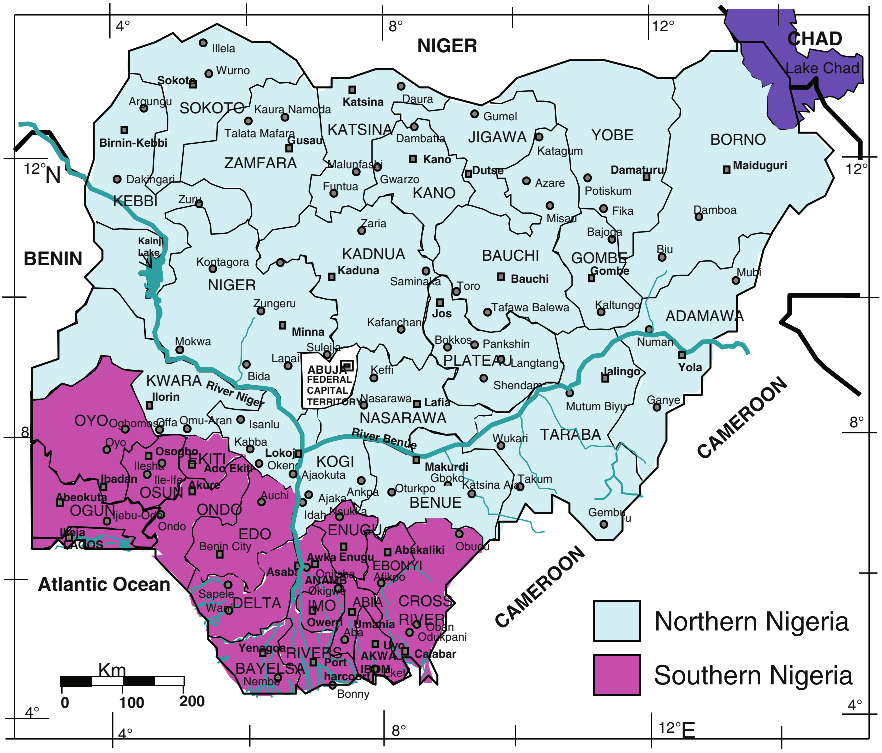

Fig. 2 Nigeria's geopolitical divide in a North - South dichotomy

sediment fill of Cretaceous to Tertiary ages, comprise the Niger Delta, the Anambra Basin, the Lower, Middle and Upper Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida-Nupe) Basin and the Dahomey Basin.

Abundant mineral deposits occur in all the components of Nigerian geology (Basement, Younger Granites, Sedimentary Basins). Solid mineral deposits of economic significance that include gold, iron ore, cassiterite, columbite, wolframite, pyrochlore, monazite, marble, coal, limestone, clays, barites, lead-zinc, etc, occur in the different geologic segments of Nigeria and indeed each of the 36 federating states and the Federal Capital Territory has a fair share of the solid mineral inventory of the nation. Oil and gas on the other hand occur prolificly in the Niger Delta Basin with oportunities to add to the national reserve asset existing in the other sedimentary basins, namely the Anambra Basin, the Benue Trough, the Chad Basin, the Sokoto Basin, the Bida Basin and the Dahomey Basin.

Despite such a huge mineral resources endowment, it is estimated that about 70% of the nation's population live below the poverty line, defined as living on less than one dollar per day. Abject poverty, violent clashes, kidnapping, extortion, etc, characterize the oil producing communities in the Niger Delta region. The existing socio-political bureaucratic arrangement gives the political elites, some cartel

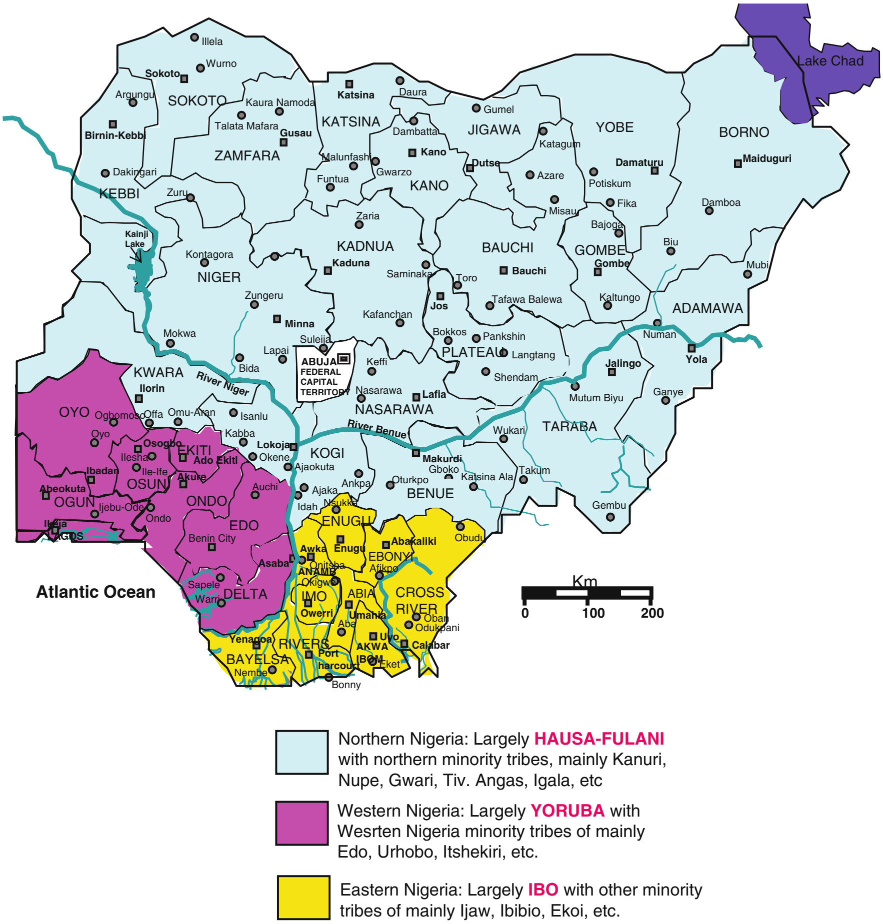

Fig. 3 Nigeria's geopolitical tripartite divide into North, East and West

managers and probably some terrorism sponsors, the access to manipulate the institutions arising as a result of endemic corruption, all of which aggregate to becloud the efficacy of government policies aimed at tackling the natural "resource curse".

The concept of the "resource curse," which emerged in the late 1980s alleged that natural resource abundance leads to a host of negative economic, political, and social outcomes. This theory, which directly opposed the prior conventional wisdom that natural resources were good for development, has now been adopted as the new orthodoxy and is espoused by such bodies as the World Bank and International Monetary Fund (IMF).

Comparative cross-country studies on economic performance have shown that an abundance of natural resources, particularly resources such as solid minerals and oil, can lead to undesirable economic consequences, such as slow or negative economic growth, inflation, low savings, high unemployment, export earnings

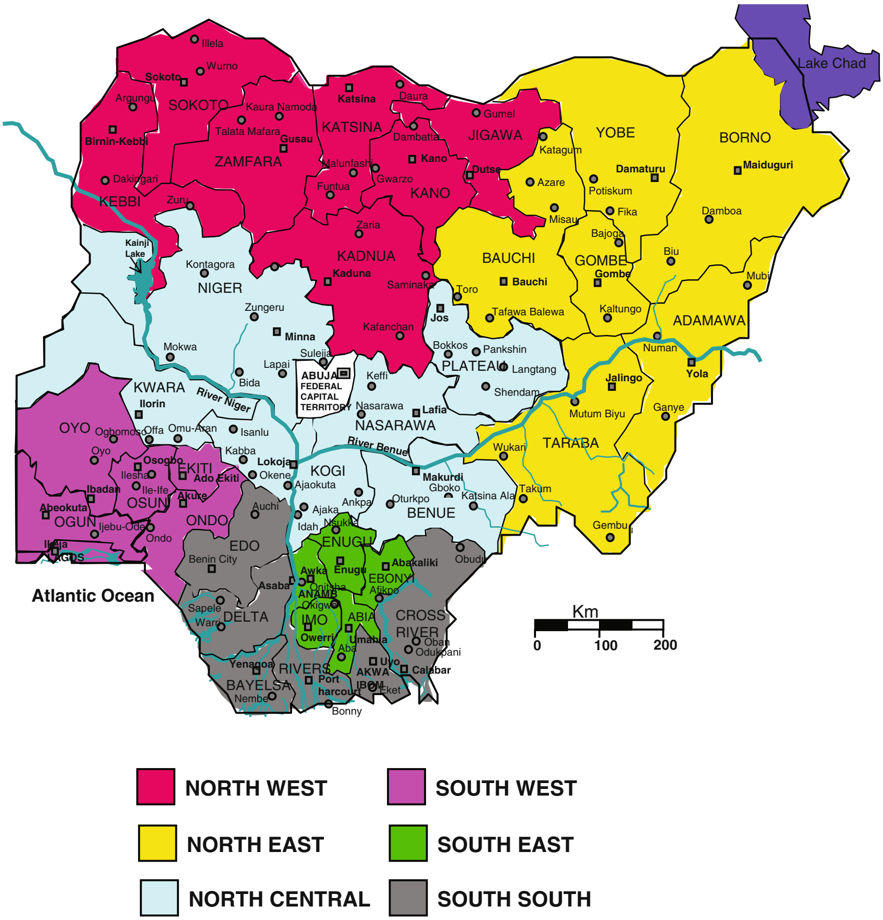

Fig. 4 The most commonly and currently used six geopolitical zones in Nigeria

instability, corruption, poverty, and low levels of human development. The concentration and "lootability" of resources can influence the type of war which takes place. The resource curse is also connected with political regime types, with many cross-country analyses showing that resource rich countries are less likely to be democratic, especially in the cases of oil and mineral wealth.

The literature on resource curse tends to be overly deterministic in attributing economic performance, civil wars, and political regime types to resource endowments alone. This ignores the substantial variation among resource rich countries and the factors which enable some resource abundant countries to overcome the resource curse. Some concrete suggestions in the literature include redistribution of resource wealth to citizens and privatization of natural resource sectors.

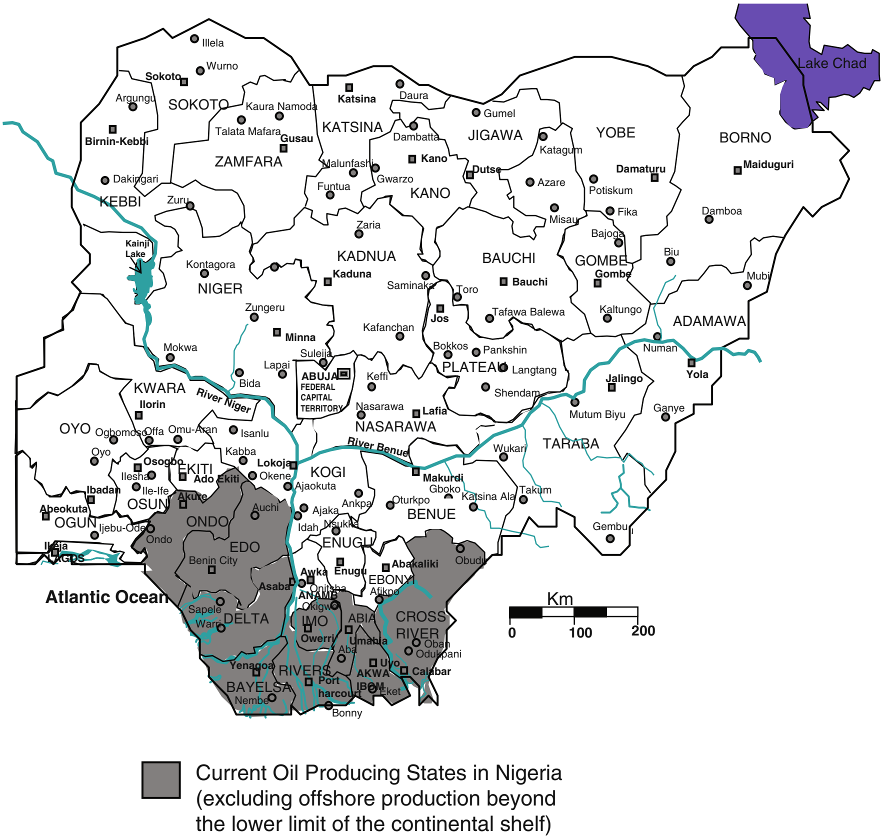

Fig. 5 States of Nigeria from which oil is currently being produced in commercial quantity: Sometime synonymous with the Niger Delta region

Nigeria will still need to adopt some policy modifications for the nation to derive maximum economic benefits from her mineral resources endowment (oil and solid minerals). It may have to allow some State and Local Governments to buy into her joint venture equities with the multinationals in the oil sector while adopting same model for the solid minerals sector.

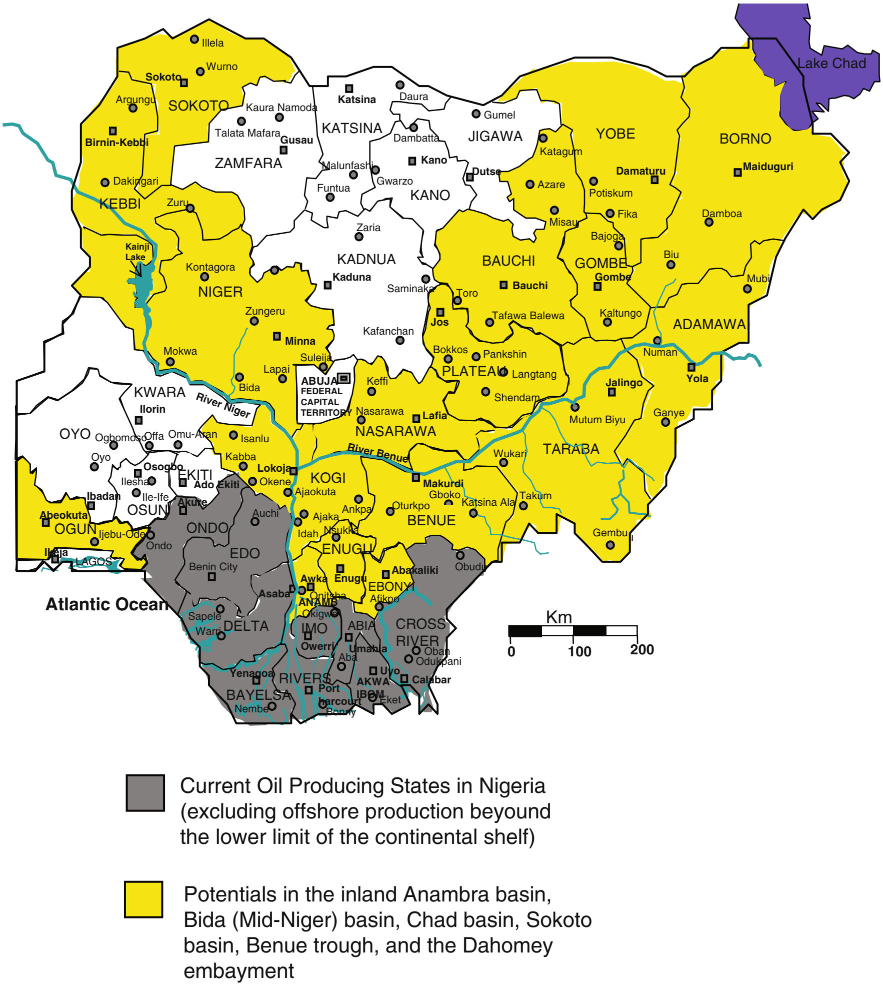

Fig. 6 States in Nigeria that have sedimentary basins with the potentials to add to current national reserve asset

Fig. 7 The location of Nigeria on the political map of Africa

Explanatory Note 1: The three major petro-lithostratigraphical components of the geology of˜Nigeria

GEOLOGY OF NIGERIA

The Geology of Nigeria is made up of three major geological components:

1. Basement Complex : Pan-African and older (Precambrian) $\geq \pm 600$ million years
2. Younger Granites : Jurassic 200 – 145 million years
3. Sedimentary Basins : Cretaceous to Recent $\leq$ 145 million years

Part I
Geology – Igneous and Metamorphic Rocks

Chapter 1
The Basement Complex

The basement complex is one of the three major litho-petrological components that make up the geology of Nigeria (Fig. 1.1). The Nigerian basement complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons (Fig. 1.2) and south of the Tuareg Shield (Black, 1980). It is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. The Nigerian basement (Fig.1.3) was affected by the 600 Ma Pan-African orogeny and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African craton and the active Pharusian continental margin (Burke and Dewey, 1972; Dada, 2006). The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma). The first three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further followed by extensive migmatization. The Pan-African deformation was accompanied by a regional metamorphism, migmatization and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Gandu et al., 1986; Olayinka, 1992)

Within the basement complex of Nigeria four major petro-lithological units (Fig.1.4; Explanatory Note 2) are distinguishable, namely:

1. The Migmatite – Gneiss Complex (MGC)
2. The Schist Belt (Metasedimentary and Metavolcanic rocks)
3. The Older Granites (Pan African granitoids)
4. Undeformed Acid and Basic Dykes

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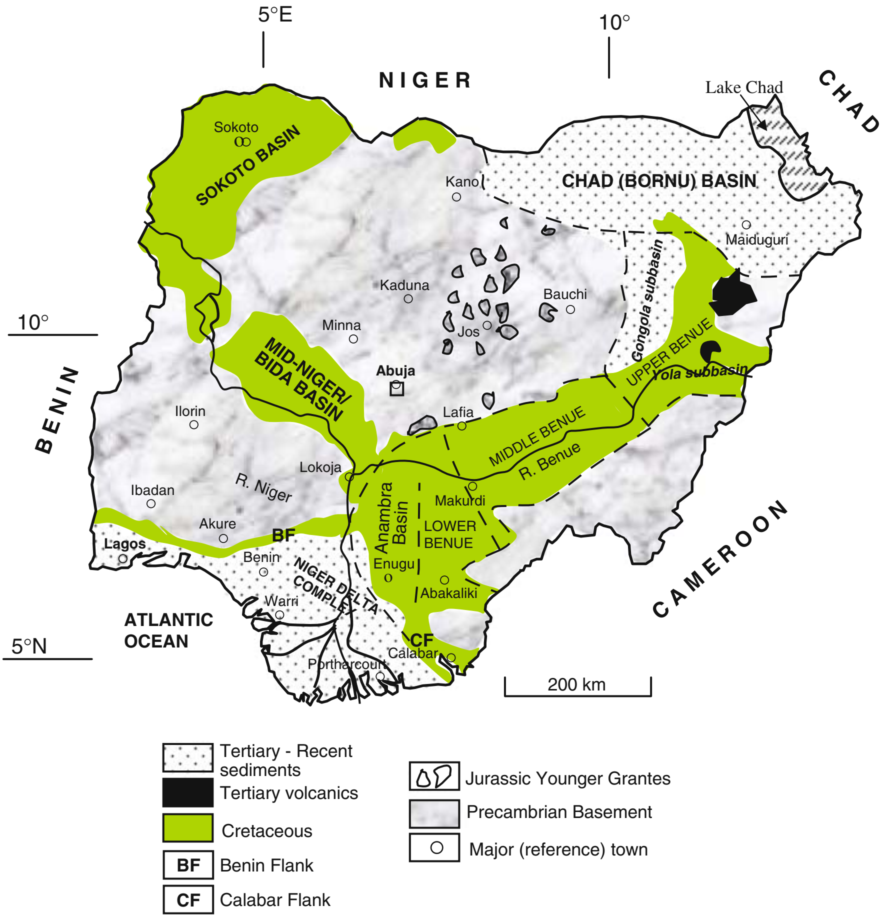

Fig. 1.1 Geological sketch map of Nigeria showing the major geological components; Basement, Younger Granites, and Sedimentary Basins

The Migmatite – Gneiss Complex (MGC)

The Migmatite – Gneiss Complex is generally considered as the basement complex *sensu stricto* (Rahaman, 1988; Dada, 2006) and it is the most widespread of the component units in the Nigerian basement. It has a heterogeneous assemblage comprising migmatites, orthogneises, paragneisses, and a series of basic and ultrabasic metamorphosed rocks. Petrographic evidence indicates that the Pan-African reworking led to recrystallization of many of the constituent minerals of the Migmatite – Gneiss Complex by partial melting with majority of the rock types displaying medium to upper amphibolite facies metamorphism. The Migmatite – Gneiss Complex has ages ranging from Pan-African to Eburnean.

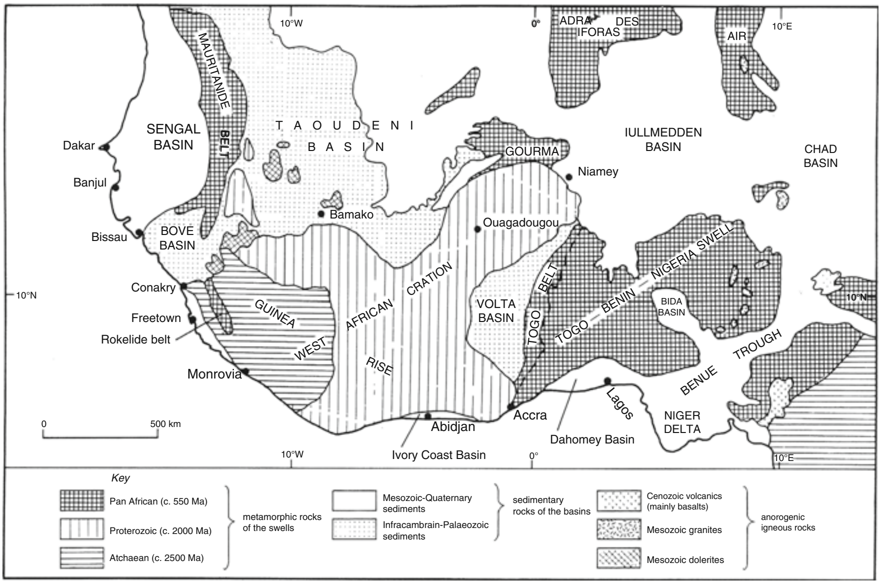

Fig. 1.2 Generalized geological map of Nigeria within the framework of the geology of West-Africa (Adapted from Wright, 1985)

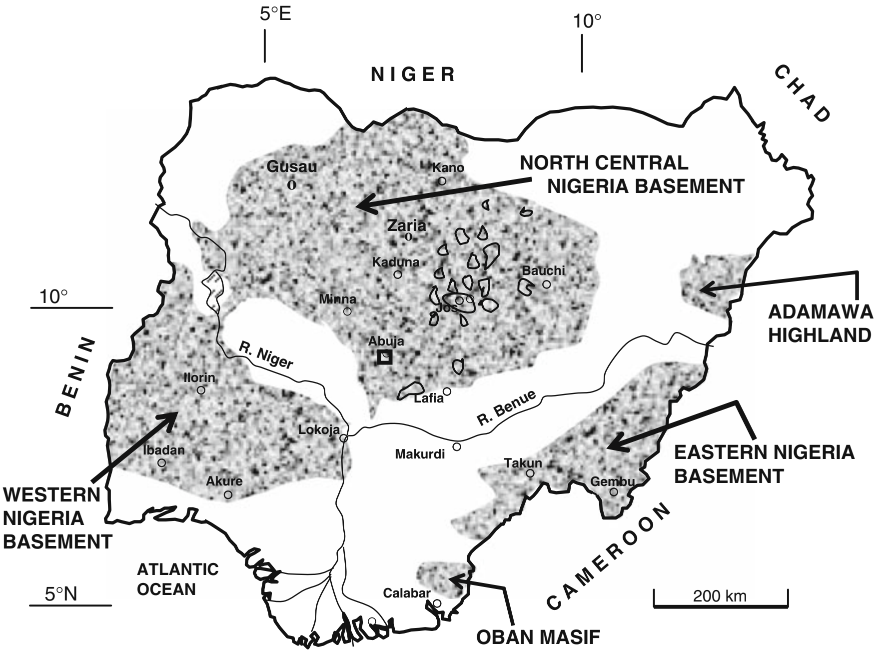

Fig. 1.3 Basement Geology of Nigeria

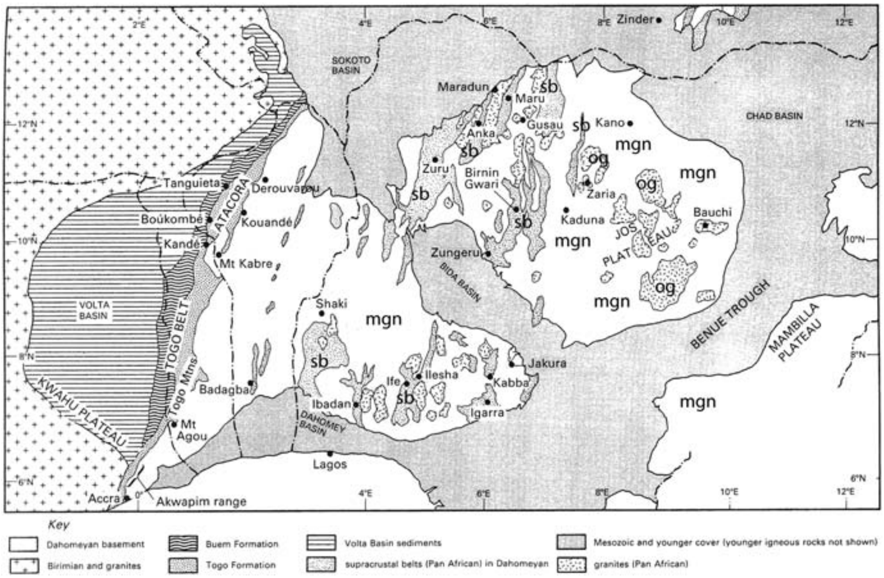

Fig. 1.4 Basement Geology of Nigeria: The Migmatite-Gneiss Complex (mgn), the Schist Belts (sb) and the Older Granites (og) (Modified from Wright, 1985)

The Migmatitie-Gneiss Complex also termed by some workers as the "migmatite-gneiss-quartzite complex" makes up about 60% of the surface area of the Nigerian basement (Rahaman and Ocan, 1978). These rocks record three major geological events (Rahaman and Lancelot, 1984); the earliest, at 2,500 Ma, involved initiation of crust forming proceses (e.g. the banded Ibadan grey gneiss of mantle origin) and of crustal growth by sedimentation and orogeny; next came the Eburnean, 2,000 ± 200 Ma, marked by the Ibadan type granite gneisses; this was followed by ages in the range from 900 to 450 Ma which represent the imprint

A. Migmatite-Gneiss Complex
(Migmatites, Gneisses, Granite -Gneisses)

B. Schist Belts (Metasedimentary and Metavolcanic rocks)
(Phylites, Schists, Pelites, Quartzites, Marbles, Amphibolites)

C. Older Granites (Pan African Granitoids)
(Granites, Granodiorites, Syenites, Monzonites, Gabbro, Charnockites)

D. Undeformed Acid and Basic Dykes
(Muscovite-, tourmaline- and beryl-bearing pegmatites, applites and syenite dykes; basaltic, doleritic and lampropyric dykes)

Explanatory Note 2:
Components of the Basement complex

of the Pan-African event which not only structurally overprinted and re-set many geochronological clocks in the older rocks, but also gave rise to granite gneisses, migmatites and other similar lithological units. The close analogy in time with the development of the Birrimian of the West African Craton is striking. However, although gold, manganese and iron mineral deposits are associated with Birrimian rocks, the same age rocks in Nigeria are very sparsely, if at all, mineralized. The extent of Eburnean and older rocks in Nigeria is not known. Definite geochemical evidence for the existence of these rocks exists for the area south of latitude 9°N (Rahaman and Lancelot, 1984). Lithologically similar rocks in other parts of Nigeria, especially in the northeast and southeast, have given only Pan-African ages (Tubosun, 1983).

Many areas in northern, western and eastern Nigeria are covered by rocks of the Migmatite – Gneiss Complex (Figs. 1.3, 1.5, 1.6, and 1.7). These areas include, but not limited to: Abuja, Keffi, Akwanga, Bauchi, Kaduna, Kano, Funtua, Okenne, Egbe, Ajaokuta (in northern Nigeria); Ibadan, Ile-Ife, Akure, Ikerre, (in western Nigeria) and Obudu and the Oban Massif areas in eastern Nigeria.

Fig. 1.5 Baement Complex outcrops: 30 km north of Bauchi on the Bauchi – kari road. Basement Complex rocks are generally low lying and concordant in contrast to the cross-cutting, discordant, and steeply occurring hilly outcrops in the form of ring dykes and cone sheets in the Younger Granites

Fig. 1.6 Abuja, the capital city of Nigeria built on Basement complex rocks: Northern view from the 6th floor of Nicon Luxury Hotel, Garki

Fig. 1.7 Keffic in Nasarawa State; an ancient town on the Basement complex (Road from NRDC to Emir's Palace). Inset: A migmatitic gneiss sample collected from Basement complex rocks in Keffi

The Schist Belt (Metasedimentary and Metavolcanic Rocks)

The Schist Belts comprise low grade, metasediment-dominated belts trending N–S which are best developed in the western half of Nigeria (Fig. 1.8). These belts are considered to be Upper Proterozoic supracrustal rocks which have been infolded into the migmatite-gneiss-quartzite complex. The lithological variations of the schist belts include coarse to fine grained clastics, pelitic schists, phyllites, banded iron formation, carbonate rocks (marbles / dolomitic marbles) and mafic metavolcanics (amphibolites). Some may include fragments of ocean floor material from small back-arc basins. Rahaman (1976) and Grant (1978) for example suggest that there were several basins of deposition whereas Oyawoye (1972) and McCurry (1976) consider the schists belts as relicts of a single supracrustal cover. Olade and Elueze (1979) consider the schist belts to be fault-controlled rift-like structures. Grant (1978), Holt (1982) and Turner (1983), based on structural and lithological associations, suggest that there are different ages of sediments. However, Ajibade et al. (1979) disagree with this conclusion and show that both series contained identical deformational histories. The structural relationships between the schist belts and the basement were considered by Truswell and Cope (1963) to be conformable metamorphic fronts and it was Ajibade et al. (1979) who first mapped a structural break.

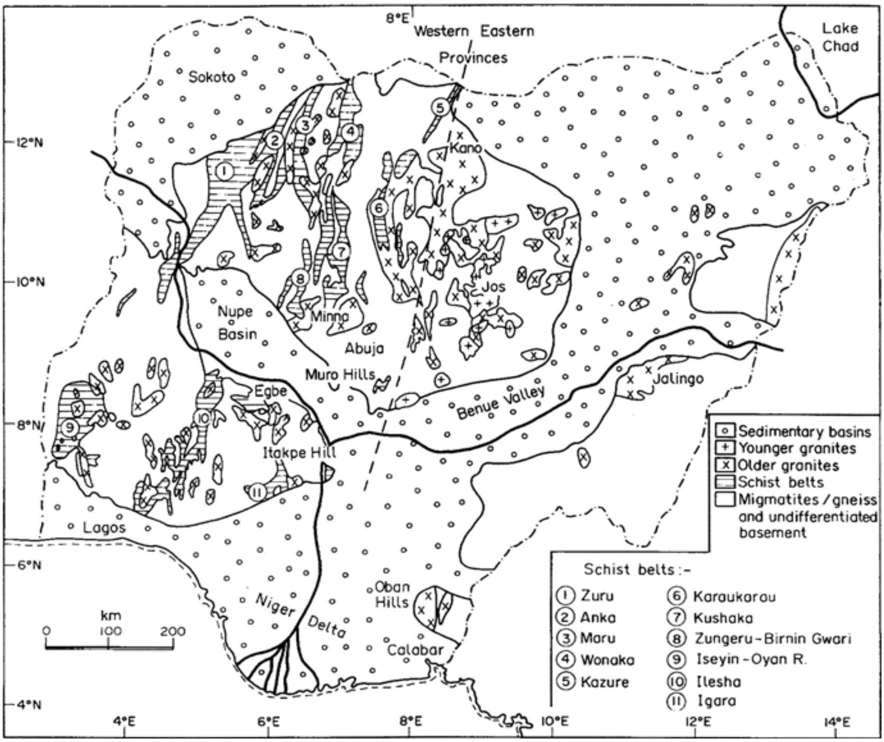

Fig. 1.8 Schist belt localities within the context of the Geology of Nigeria (After Woakes et al., 1987)

The geochronology of the schist belts remains problematical although the ages of the intrusive cross-cutting Older Granites provide a lower limit of *ca* 750 Ma. A Rb/Sr age of 1,040 $\pm$ 25 Ma for the Maru Belt phyllites has been accepted as a metamorphic age by Ogezi (1977).

The schist belt rocks are generally considered to be Upper Proterozoic. The geochemistry of the amphibolite complexes within the schist belts has also led to controversy. Klemm et al. (1984) have concluded that the Ilesha belt may be an Archaean greenstone belt. Olade and Elueze (1979), Ogezi (1977) and Ajibade (1980) have favoured dominantly ensialic processes in the evolution of the schist belts while Ajayi (1980), Rahaman (1981) and Egbuniwe (1982) have stressed that some include oceanic materials with tholeiitic affinities. Some metallogenetic features of the schist belts are relevant to these problems; the apparent absence of subduction related mineral deposits may be indicative of a limited role for the ensimatic processes; the distribution of primary gold occurrences in some belts but its marked absence in others may indicate that they do not represent a single supracrustal sequence. The schist belts are best developed in the western part of Nigeria, west of 8°E longitude, though smaller occurrences are found to the east but only sporadically. The belts are confined to a NNE-trending zone of about 300 km wide (Fig. 1.9). The area to the west of this zone is made up of gneisses and migmatites that constitute the Dahomeyan of Burke and Dewey (1972). Similarly to the east, no schist belts are known for a distance of 700 km until in Cameroun where a number of schist belts, considered to be Upper Proterozoic, occur in the Pan-African granite-migmatite terrain north of the Congo Craton.

The schist belts have been mapped and studied in detail in the following localities: Maru, Anka, Zuru, Kazaure, Kusheriki, Zungeru, Kushaka, Isheyin Oyan, Iwo, and Ilesha where they are known to be generally associated with gold mineralization.

Case Studies on Schist Belts (Derived Mainly from Turner, 1983)

The Kusheriki Schist Group

A key for the interpretation of the Nigerian schist belts is the district around Kusheriki in northern Nigeria. Detailed mapping was carried out by Truswell and Cope (1963) and extended southwards to the Zungeru area by Ajibade (1980). Four formations were recognized for the Kusheriki Schist Group, namely:

1. The Kusheriki Psammite Formation at the base of the succession,
2. The Kushaka Schist Formation,
3. The Zungeru Granulite Formation and
4. The Birnin Gwari Schist Formation at the top.

The Birnin Gwari Schist Formation and the underlying quartzo-feldspathic rocks of the Zungeru Granulite Formation together form a single structural unit, termed the

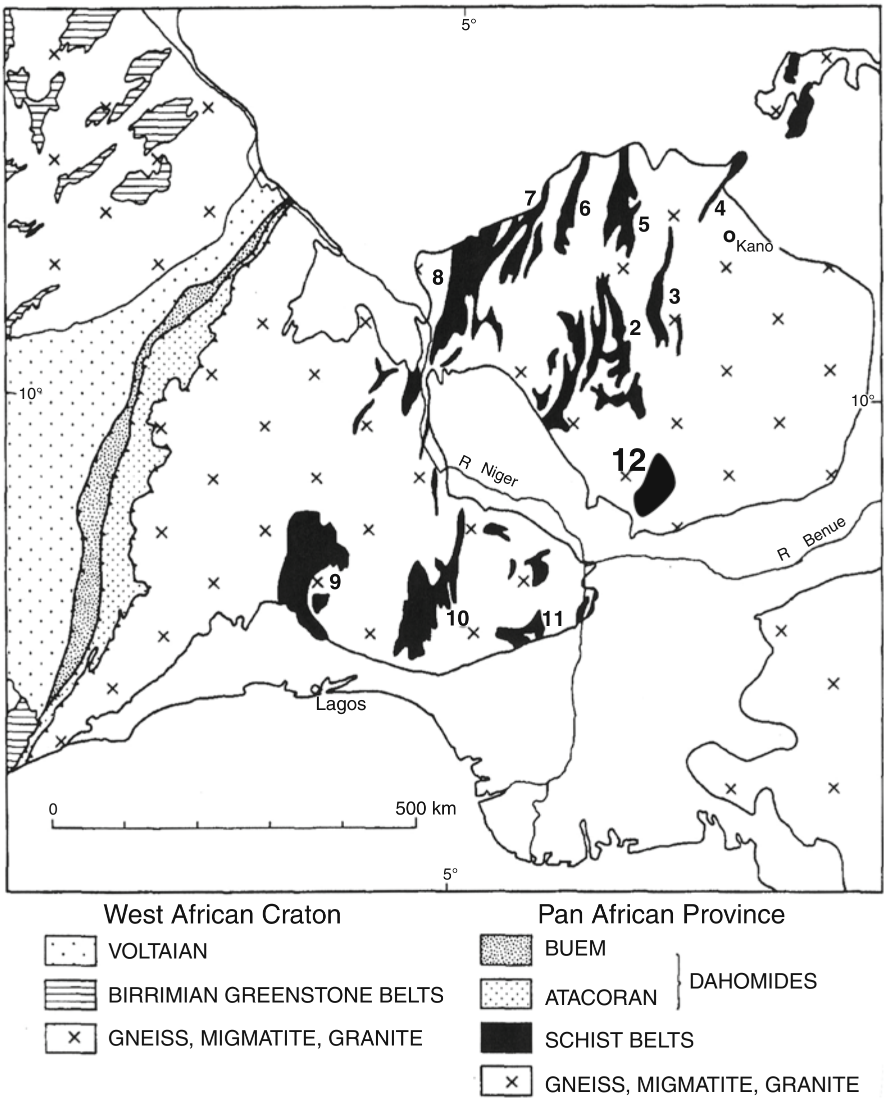

Fig. 1.9 Schist Belt localities in Nigeria within the context of the regional geology of parts of West Africa (After Wright, 1985). 1. Zungeru-Birnin Gwari, 2. Kusheriki-Kushaka, 3. Karaukarau, 4. Kazaure, 5. Wonaka, 6. Maru, 7. Anka, 8. Zuru, 9. Iseyin-Oyan River, 10. Ilesha, 11. Igara, and 12. Muro Hills

Zungeru-Birnin Gwari Schist Belt. This is a simple N–S syncline, 150 km long, with the northern part displaced dextrally by a NE–SW transcurrent fault. The Zungeru Granulite Formation outcrops on both flanks of the schist belt. It is largely made up of fine-medium grained quartzo-feldspathic rocks which are interbedded with amphibolites and some quartzites.

The Birnin Gwari Schist Formation occupies the synclinal axis of the schist belt. The lower part consists of finely banded phyllites in the west and higher grade biotite-muscovite schists in the east. They are overlain by the Durimi pebbly schist, a metamorphosed mudstone conglomerate containing some beds of impure quartzite or metagreywacke.

The Kushaka Schist Formation forms a number of curving schist belts, separated by domes and anticlines of gneiss. They contrast with the Zungeru-Birnin Gwari belt in lithology, structure and igneous associations. The main rock type is semi-pelitic biotite-muscovite schist, in places containing garnet and staurolite. Other rocks are phyllites, metasiltstones and graphitic schists. Several thick units of banded garnet-grunerite iron formation are interbedded with the schists. A variety of amphibolites and amphibole, epidote, chlorite and talc-bearing schists correspond at least partly to tholeiitic basalt (Elueze, 1981). Amphibolites are locally very thick, suggesting large volcanic accumulations. The curving Kushaka Schist Belt contrasts with the straight Zungeru-Birnin Gwari Belt. Grant (1978) described smaller scale structures in the Kushaka Schist Formation which demonstrate its longer and more complex history. Another important difference between the Zungeru-Birnin Gwari and Kushaka Schist Formations is in their relationship with Pan-African granite plutons. Although granites intrude both the Zungeru and Birnin Gwari Formations, they penetrate into the marginal part of the Birnin Gwari schist belt only; the centre is free from granite intrusions. In contrast the Kushaka schist belts are invaded extensively by plutons of granite, granodiorite and syenite, which often penetrate the axial zone of the belts. Ages in the Kusheriki Schist Group have been estimated to be in the Kibaran (1,159 $\pm$ 70 Ma)

The Karaukarau Schist Belt

East of the Kushaka schist belts, migmatites and gneisses form a zone nearly 50 km wide, bounded in the east by the Karaukarau Schist Belt. This consists mainly of muscovite and muscovite-biotite schists and phyllites interbedded with thin quartzites (McCurry, 1976). The politic rocks include minor graphitic and feldspathic schists, and contain frequent quartz and quartz-tourmaline veins. Interbedded quartzites are generally thin, but may be grouped to give sections which are dominantly quartzite, and units of well-bedded quartzite, several tens of metres thick, also occur. Minor rocks are spessartite quartzite, calc-silicate rocks and anthophyllite cordierite schist. Amphibolites form occasional discontinuous bands, but the largest occurrence is only approx. 12 m thick. The Karaukarau belt has been compared lithologically with the Kushaka schist belts (Grant, 1978), but there are important differences: the quartzites are detrital and not chemically precipitated iron-silica formations; and rocks of basic igneous composition are much less important. The rocks represent a fairly well differentiated sequence of muds and fine-grained sands. Structurally, the Karaukarau belt appears similar to the Zungeru-Birnin Gwari Schist Belt, matching it closely in size and form. Ages in the Karaukarau schists have been estimated to be Pan-African.

The Kazaure Schist Belt

The Kazaure Schist Belt is situated northeast of the Karaukarau belt. It is dominated by massive quartzites which can be traced for 90 km south from the Niger border. Associated rocks, exposed in the north, are schists and metaconglomerates, the latter containing rounded deformed pebbles and cobbles of quartzite and schist in a matrix of ferruginous schist. A possible extension to the Kazaure Schist Belt is seen about 100 km to the northeast in the Damagaram area of southern Niger Republic. Here, thick quartzites with associated schists occur as long curving ridges, showing a more open style of folding than the quartzites of the Kazaure belt which have linear outcrops with some moderately tight fold closures. Correlation with the Kazaure belt is uncertain. The presence of conglomerates and thick quartzites suggests a continental or littoral environment, which is consistent with its position at the eastern margin of the region containing Upper Proterozoic metasediments. It seems structurally simple, free from central granite intrusions and from mafic igneous rocks. Therefore, it is provisionally correlated with the Birnin Gwari Schist Formation and the Karaukarau belt rather than the Kushaka belt. Pan African ages have been estimated for the Kazaure schists by Turner (1983).

The Maru Schist Belt

The Maru Schist Belt lies 200 km NE of the Kushaka schists, with which it corresponds quite closely in lithological assemblages. In the Maru belt, pelitic rocks are dominant, mainly as phyllites and slates interlaminated with siltstones. Banded iron formation, containing magnetite, hematite and garnet is also present. Impure micaceous quartzites occur near the eastern margin of the belt. Mafic volcanic rocks are represented by the amphibolites at several localities. The fine-grained laminated sediments, both pelites and iron formation, indicate quiet water conditions; the predominance of iron oxides suggests oxygenated waters, although sometimes pyrite occurs, indicating anoxic conditions. Metasandstones were deposited in a higher energy environment, reflecting shallowing water or increased sediment supply. The lithological similarities between the Maru and Kushaka schists suggest that the two could be correlated. Like the Kushaka belts, the Maru Schist Belt also contains internal plutons of granite, granodiorite and syenite. There is, however, an important difference in structure: the Maru belt shows little of the complexicity and variable fold trends shown by the Kushaka belt. It is a straight NNE-trending belt with a steeply dipping foliation which is axial planar to tight folds and deformed by later crenulation cleavages. Kibaran ages have been estimated for the Maru Schist Belt.

The Anka Schist Belt

This belt lies west of the Maru belt, the two being separated by the Pan-African Mai-inchi granodiorite and by a probably older gabbro-granite-pegmatite complex. The rocks contrast with those of the Maru belt and include metaconglomerates, sandstones, slates, phyllites and acid volcanic rocks (Holt, 1982). Metaconglomerates form several units with thicknesses reaching 150–250 m, but which die out laterally and are interbedded with feldspathic metasandstones. They contain rounded to angular boulders and pebbles composed of granite, quartzite, quartz, phyllite and volcanic rocks. In a partly faulted outlier near Sado, east of the main belt, green and purple grits are interbedded with shales and siltstones which show fine cross bedding and ripple marks (Turner, 1983). In the western part of the belt, phyllites are dominant with some metasiltstones and metasandstones, and rhyolitic to dacitic volcanic rocks. The coarse clastic sediments were deposited in a much higher energy environment than the pelites and iron formation of the Maru belt and belong to a more active tectonic setting. The laminated and ripple-marked sediments in the east are shallow-water deposits; purple colouring suggests drying and oxidation. A possible environment is an intermontane or rifted basin. The Anka belt includes both Kibaran and Pan-African elements. A possible Kibaran igneous feature is the metamorphosed complex of mafic and ultramafic rocks and very extensive epidotised granite and pegrnatite which extends for 100 km along the east side of the Anka belt. Ogezi (1977) discussed the possibility that an ophiolite relic may be represented in the ultramafic rocks, which form a very minor outcrop near Sado, together with the amphibolites which have a tholeiitic composition. The Anka belt also includes a post-orogenic element of Pan-African age; the unmetamorphosed volcanic and sedimentary rocks of the Maradun and Kiserni areas which rest unconformably on the schists and granites and are dated provisionally at 516 ± 20 Ma (McCurry, 1976).

The Zuru Schist Belt

This is the largest of the northern schist belts with a length of 280 km and a maximum width of 40 km. Its geology is little known, except for work in the NE sector (McCurry, 1976). The main rock type is quartzite, locally feldspathic, interbedded with quartz – muscovite schists. Structures are complex, varying widely in dip and strike. Low angle dips of bedding relative to open E–W folds, upon which steep N–S structures have been superimposed. There is a marked discontinuity across the boundary with the Anka belt with its straight steep structures, although at the boundary the two belts show parallel trends and the relations between the Zuru quartzitas and the Anka pelites are not known. There is little evidence on the age of the Zuru schist belt although the complex structures suggest correlation with the Kushaka schist belts and therefore possibly of a Kibaran age.

The Iseyin-Oyan River Schist Belt

This large arcuate schist belt is wrapped around the nucleus of Archaean and Lower Proterozoic rocks centred on Ibadan. It is composed mainly of mica schists. Quartzites occur near the margins of the belt in the Iseyin district. Banded amphibole schists are widespread, mainly as thin discontinuous sheets, and have been interpreted as metamorphosed calcareous sediments; more massive amphibolites may represent mafic igneous rocks (Jones and Hockey, 1964). Metamorphism is higher in grade than in most northern schist belts, with pelitic rocks containing biotite, garnet, staurolite and locally sillimanite (Rahaman, 1976). The outstanding feature of the Iseyin-Oyan River Schist Belt is the remarkable crowding of granite plutons within the schist belt and at its margins, in contrast to their virtual absence from the surrounding migmatite-gneiss terrain. The most abundant granite type, occurring as well defined intrusions, is the porphyritic potassic granite which is the major variety of Pan-African granite throughout Nigeria. Associated with these are two large plutons of mafic potassic syenite (Oyawoye, 1972; Rahaman, 1976). The Iseyin-Oyan River belt is generally poorly exposed, and structural data are sparse. Kibaran ages have been obtained in rocks of the Isheyin-Oyan River Schist Belt.

The llesha Schist Belt

The Ilesha Schist Belt lies east of the Ibadan Archaean to Lower Proterozoic massif. It has a N–S length of over 200 km and reaches its maximum width of 60 km in the south. Here it consists of two structural units with contrasting lithology, separated by the NNE-trending Ife fault zone (Hubbard, 1975). The western unit consists of amphibolite, amphibole schists and pelitic schists with much intimately associated trondhjemitic granite, gneiss and pegmatite. It shows a moderately open style of folding with N–S axes. Metamorphism is mainly in the amphibolite facies, but locally in the greenschist facies. East of the fault, quartzite is dominant, occurring together with quartz schist, quartzo-feldspathic gneiss and minor iron-rich schists and quartzites. This assemblage, named the Effon Psammite Forrnation, shows amphibolite facies metamorphism and tight isoclinal folds. About 30 km NE of Ilesha it apparently overlies amphibole schists of western type, although it is not known whether this is a stratigraphic superposition or an overthrust relationship. Geochemically, the western amphibolites resemble low potassium tholeiites although some show evidence of minor crustal contamination or metasomatic alteration (Olade and Elueze, 1979). Associated talc-tremolite rocks represent metamorphosed ultramafic minor intrusions or lavas. A deformed and altered mafic to ultramafic complex adjacent to the fault zone may be an ophiolite fragment. This association of mafic and ultramafic rocks with metamorphosed granitic rocks and extensive pegmatites is similar to that found in the Anka meta-igneous complex in north-western Nigeria. Granite-gneiss at Ife, west of the fault zone, gave a Rb/Sr isochron age of 1,190±140 Ma (Grant et al., 1972).being therefore Kibaran, correlating with the Kushaka and Maru belts in the north.

Igarra Schist Belt

The most easterly schist belts in south-western Nigeria are distributed around the Okene migmatitic nucleus. It trends NNW with a length of only 50 km and in the west is joined to the NW-trending Owo belt and to the Itobe belt in the east which may have extended into the Muro Hills in the north. The presence of both calcareous rocks and conglomerates sets it apart from the other schist belts described. These rock types, together with quartzites, occur as bands in the dominant biotite schists. Gneisses at the margins of the belt may be a highly metamorphosed basal part of the sequence; they are equivalent to the non-migmatitic gneisses described by Furon (1960) from the margins of other schist belts in this eastern region. The main structure is an open synform, but this re-folds earlier E–W folds. Porphyritic granites intrude the centre and margins of the belt. Similar lithologies occur in schist belts in the Kabba, Jakura and Lokoja areas which also have associated granite plutons. They represent well-sorted shelf and littoral deposits. Their diverse structural trends and association with Pan African granites had indicated a Kibaran age.

Comments on the Kibaran and Pan African Orogenies

The Kibaran Orogeny

The Kibaran Orogeny is recognised in several regions of Africa. It is named from the Kibara Mountains of eastern Zaire (now Democratic Reublic of Congo), and the age of the orogeny ranges from 1,300 Ma for the main tectonic phase to 900 Ma for the emplacement of late granites and pegmatites. Together with the parallel and probably contemporaneous Irumide belt of Zambia, the Kibarides have been interpreted as ensialic, floored by and terminated within an older continental basement. Also of Kibaran age is the Namaqua-Natal belt of southern Africa; although this shows evidence for ocean floor obduction and continental convergence (Turner, 1983). In contrast to these well-defined orogenic belts, Kibaran relics in West Africa are scattered, discontinuous and generally overprinted by Pan-African structures and magmatism. Dated and inferred Kibaran rocks occur in widely separated areas of the Pan-African Province; in the Hoggar, in NW and SW Nigeria, and north of the Congo Craton in Cameroun. There is thus, in part, a coincidence between the Kibaran and Pan-African orogenic belts in West Africa. At Ibadan, 60 km to the southwest schist belts, Archaean and Lower Paleozoic rocks contain no isotopic record of a Kibaran event; this area, therefore, remained as a stable craton. West of the stable Ibadan block is the Kibaran sequence of mainly clastic sediments and minor mafic volcanics in the large Iseyin-Oyan River Schist Belt. Thus, the Kibaran Orogeny in NW Nigeria was a significant thermal and tectonic event, apparently of ensialic type. The Kibaran schist belts of Cameroun and the Hoggar show similarities with the Nigerian belts which indicate an essential unity to Kibaran events in this large region. The Poli Schist Belt in Cameroun resembles the Nigerian belts in its volcanic to clastic assemblage, and its association with Pan African granites. Hubbard (1975) has suggested that the NNE-trending zone of Kibaran schist belts in Nigeria developed as an extensional feature parallel to the Pan-African geosyncline to the west. The Kibaran schist belt zones of Nigeria and Cameroun give a bilateral symmetry to the Pan-African Province between the West African and Congo Cratons, the central zone between them being dominated by voluminous Pan-African granites and migmatites.

The Pan-African Orogeny

Deposits of Pan-African age are probably represented in the Northern Nigerian schist belts only. They consist almost entirely of clastic sediments; Pan African volcanics are absent or of very minor importance, and so are the iron formations found in the Kibaran belts. An aspect of the Nigerian schist belts deserves a further comment, being the coincidence of schist belts of Kibaran and Pan African ages in the same zone and their absence in areas to the east and west. In the Hoggar region to the north, great mylonite zones divide the crust into compartments with contrasting geology. No such mylonites are known in Nigeria, but the well-defined schist belt zone does appear to be a region with a different crustal structure, composition and history from the areas on its flanks. Also is the tendency for the Pan-African granites to be concentrated in the Kibaran schist belts and not in the Pan-African belts. Part of the explanation for this may lie in the relative ease with which granite magma was able to rise into the already metamorphosed Kibaran schist belts compared with the cooler water-bearing sediments of the Pan-African belts.

The Older Granites (Pan African Granitoids)

The term "Older Granite" was introduced by Falconer (1911) to distinguish the deep-seated, often concordant or semi-concordant granites of the Basement Complex from the high-level, highly discordant tin-bearing granites of Northern Nigeria. The Older Granites are believed to be pre-, syn- and post-tectonic rocks which cut both the migmatite-gneiss-quartzite complex and the schist belts. They range widely in age (750–450 Ma) and composition. They represent a varied and long lasting (750–450 Ma) magmatic cycle associated with the Pan-African orogeny. The rocks of this suite range in composition from tonalites and diorites through granodiorites to true granites and syenites. Charnockites form an important rock group emplaced during this period. They are generally high level intrusions and anataxis has played an important role (Rahaman, 1981). The Older Granites suite is notable for its general lack of associated mineralization although the thermal effects may play a role in the remobilization of mineralizing fluids.

The Older Granites are the most obvious manifestation of the Pan-African orogeny and represent significan additions of materials (up to 70% in some places) to the crust (Rahaman, 1988). Attempt to classify the Older Granites with respect to timing during an orogenic event are valid over only short distances. Contact features between members of the Older Granites suite suggest the coexistence of several magmas. Compositionally, the granites plot in the field of calc-alkaline rocks on the AFM diagram and although they contain significant amount of alkalis, are also often slightly corundum normative. Dada (2006) was of the opinion that the term "Pan African Granitoids" be used for the Older Granites not only on the merit of age which was not available at the time they were named Older Granites, but because it covers several important petrologic groups formed at the same time.

The granitoids which outcrop with the schist belts in northwestern and southwestern Nigeria include biotite granites, biotite muscovite granites, syenites, chanockites, serpentinites and anorthosites.

Rahaman (1988) discarded the earlier classification of members of the Older Granites suite on the basis of their texture, mineraological composition and the relative timing of their emplacement. In its place, members of the Older Granite suite were classified as follows, based mainly on the textural characteristics:

1. Migmatitic granite;
2. Granite gneiss;
3. Early pegmatites and fine-grained granite;
4. Homogeneous to coarse porphyritic granite;
5. Slightly deformed pegmatite aplites and vein quarz; and
6. Undeformed pegmatites, two-mica granites and vein quartz.

In northern Nigeria, the abundance of Pan-African granites appears to increase eastward. In the area west of Zaria these occur as isolated intrusions (McCurry, 1973), whereas in the region between Rahama and the Mesozoic-Cenozoic cover the intrusive granites and related rocks envelope remnants of Migmatites. McCurry (1973) working mainly west of Zaria divided the granites into two main groups according to their field relationships. The first "syntectonic" group comprised elongate batholithic sheets that are partly concordant, and foliated. The second group "late tectonic" are made up of poorly foliated discordant bodies, rich in mafic xenoliths and having a lower proportion of potash feldspar. The late granites are considered to be the products of widespread mobilisation and reactivation of older basement rocks during the Pan-African orogeny. The Older Granites occur intricately associated with the Migmatite-Gneiss Complex and the Schist Belts into which they generally intruded. Older Granite rocks therefore occur in most places where rocks of the Migmatite-Gneiss Complex or of the Schist Belt occur. However, Older Granites are particularly noteworthy in and around Wusasa (Zaria), Abuja, Bauchi, Akwanga, Ado-Ekiti and Obudu areas. In Bauchi area and some parts of southwestern Nigeria, most of the Older Granite rocks occur as dark, greenish-grey granites with significant quantities of olivine (fayalite) and pyroxene occurring with quartz, feldspars and micas. For this unusual composition, the Older Granites in these areas are termed *Bauchite* (in Bauchi area) and *Oyawoyite* (After Professor Oyawoye who first mapped them) in southwestern Nigeria. For uniformity of terminology, both the Bauchites and Oyawoyites constitute the charnockitic rocks (*Charnockites*) of the Basement Complex.

Charnockites

According to Dada (1989), it was at Toro that charnockite was first described within the Nigerian basement by Falconer (1911) where it was then referred to as a "quartz diorite porphyrite". It was assumed to present a certain affinity with the basic members of the charnockitic series of the Ivory Coast. Wright (1970) described it as an annular complex of *hypersthene diorite* at the centre of three circular, concentric granites. He considered the hypersthene diorite as older than the granites from contact relations. Cooray (1975) in his review of charnockitic rocks of Nigeria came to the same conclusion, using for argument the presence of granitic veins In the diorite, of dioritic xenoliths in granites and microcline porphyroblasts in the diorite. A field study of the same hybrid rocks led Rahaman (1981) to consider both the granites and the charnockites as either contemporaneous or the latter emplaced shortly after the former. The basement in Toro area consists of gneisses and migmatites into which the Toro Charnockitic Complex intruded (Dada et al., 1989); Older Granites and charnockites which constitute the complex proper; and undeformed basic (doleritic) dykes considered to be later than the Pan-African Granites.

The Toro charnockite was described by Dada (1989) to be typically greenish black, fine to medium-grained, equigranular and massive, sometimes porphyritic. The granites consist from the periphery of the complex (in contact with the migmatitic gneiss) towards the centre (in contact with the hypersthene diorite) of: a fine to medium grained biotite-muscovite granite, an equigranular biotite-hornblende granite and a porphyritic biotite-hornblende granite. In general, these granites as well as the diorites are not affected by a penetrative deformation, but undulatory extinction of the quartz and fractures in feldspar crystals indicate local brittle deformation.

The Older Granites are recognized as of Pan-African age. Despite the close association and field relations with the Older Granites, older ages have been suggested for the charnockites. These ages are in contradiction to the evidence of mix reactions at the contact between the charnockites and the Older Granites advanced by Rahaman (1981). Van Breemen et al. (1977) obtained the imprecise ages of 663 ± 164 Ma and 668 ± 128 Ma. on the bauchites in the areas around Bauchi. Tubosun et al. (1984) using U-Pb method on zircons attributed precise Pan-African ages of 620 ± 20 Ma and 634 ± 21 Ma to the charnockites of Ikerre and Akure respectively. For the Idanre Complex they obtained late Pan-African ages of 580 ± 10 Ma and 593 ± 11 Ma thereby confirming definite Pan-African ages for the charnockitic complexes of SW Nigeria.

Charnockitic rocks constitute one of the important petrological units within the Precambrian Basement Complex of Nigeria. They are generally characterized by their dark greenish to greenish grey appearance which makes them easily recognisable in hand specimen. They usally contain quartz + plagioclase + alkali feldspar + orthopyroxene + clinopyroxene + hornblende ± biotite ± fayalite. Accessory minerals are usally zircon, apatite, and iron ores (Olarewaju, 2006). Apart from Toro, other localities of charnockite occurrence include Bauchi, Ado-Ekiti, Ikere (Ekiti), Akure, Idanre, and in the Obudu Plateau.

Undeformed Acid and Basic Dykes

The undeformed acid and basic dykes are late to post-tectonic Pan African. They cross-cut the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites. The undeformed acid and basic dykes incude:

a. Felsic dykes that are associated with Pan African granitoids on the terrain such as the muscovite, tourmaline and beryl bearing pegmatites, microgranites, aplites and syenite dykes (Dada, 2006)
b. Basic dykes that are generally regarded as the youngest units in the Nigerian basement such as dolerite and the less common basaltic, felsite and lamprophyric dykes.

The age of the felsite dykes has been put at between 580 and 535 Ma from Rb-Sr studies on whole rocks (Matheis and Caen-Vachette, 1983; Dada, 2006), while the basic dykes have a much lower suggested age of ca. 500 Ma (Grant, 1970). The structural and geochronological importances of this suite of rocks, which have been put to immense chronological use elsewhere (Dada, 2006) are often overlooked in Nigeria. When they cross-cut basement, they could be used to infer relative age of metamorphic structures and rock suites and could also suggest the existence of older basement windows in the Nigerian schist belts, apart from the immense guide they provide in sampling for isotope geochemistry, analysis and interpretation (Dada, 2006).

Chapter 2
The Younger Granites

General Description

The Mesozoic Younger Granite ring complexes of Nigeria (Fig. 2.1) form part of a wider province of alkaline anorogenic magmatism. They occur in a zone 200 km wide and 1,600 km long extending from northern Niger to south central Nigeria. Rb/Sr whole rock dating indicates that the oldest complex of Adrar Bous in the north of Niger is Ordovician in age, with progressively younger ages southwards. The most southerly ring complex of Afu is Late Jurassic in age (Bowden et al., 1976). Aeromagnetic anomalies suggest that a series of buried NE–SW lineaments of incipient rifts controlled the disposition of the individual complexes (Ajakaiye, 1983).

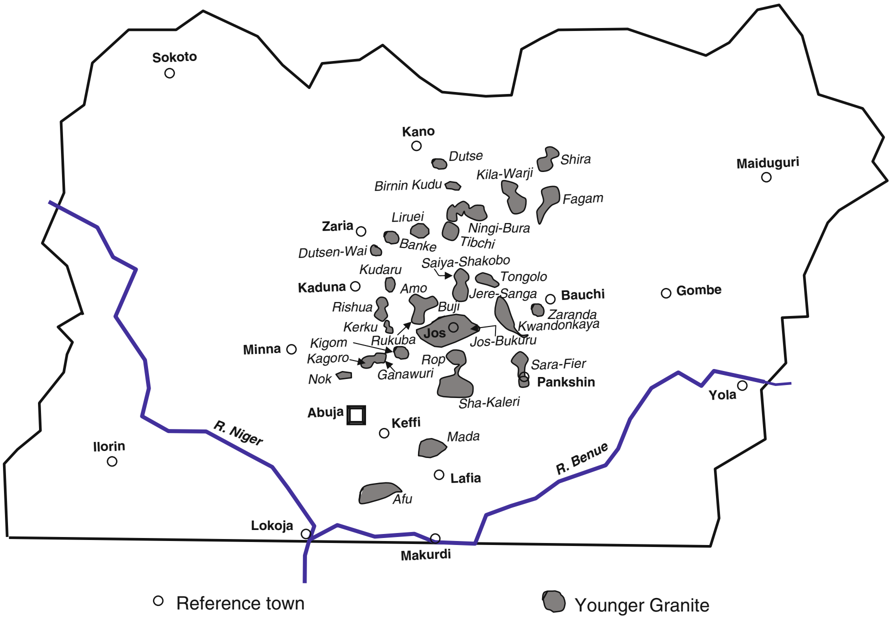

Fig. 2.1 Major Founger Granites localities in Nigeria

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The Younger Granites have been studied in most detail in Nigeria, partly for their intrinsic interest, providing comparative data for study of similar formations elsewhere in the world, but mainly because in the early 1900s they were recognized as the source of rich alluvial cassiterite deposits that had long been known to exist on and around the Jos Plateau Detailed filed mapping of the ring complexes has demonstrated a consistent succession of magmatic activity from volcanism to plutonism associated with the emplacement of mainly granite melts at high levels in the crust. The most striking petrographic feature of the whole province is the overwhelmingly acid nature of the rocks and the similarity of the rock types found in all areas. Over 95% of the rocks can be classified as rhyolites, quartz-syenites or granites, with basic rocks forming the remaining 5%. Many of the rocks have strongly *alkaline* to *peralkaline* compositions, other are *aluminous* to *peraluminous*.

More than 50 complexes occur in Nigeria varying from <2 to >25 km in diameter (Kinnaird, 1981). The ring complexes cover a total area of about 7,500 km^2 with individual massifs varying from 1,000 km^2 to <1 km^2. The majority are between 100 and 250 km^2 with circular or elliptical outlines (Figs. 2.2, 2.3, 2.4, 2.5, and 2.6). Each of the ring complexes, whether they consist of overlapping centres, as at Ningi-Burra, or individual centres, such as Ririwai, began as chains of volcanoes (Bowden and Kinnaird, 1984). Early ash-fall tufts and agglomerates were deposited

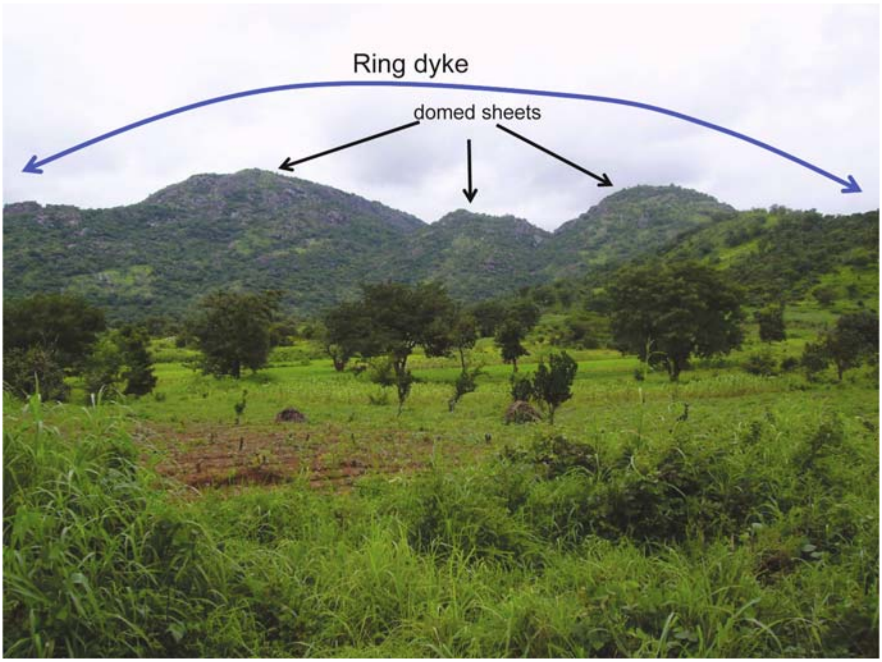

Fig. 2.2 A portion of the Mada Younger Granite complex near Akwanga in Nasarawa State. Note the migrating domed sheets and the circular nature of the complex

Fig. 2.3 Different views of a portion of the Kagoro Younger Granites visible on the Forest – Jos road. Domed sheets are less developed, but the dyke is extensive

from eruptions of explosive activity (Fig. 2.7). Abundant ignimbrites deposited from ash flows dominate the volcanics with only minor rhyolitic and thin basic flows. Volcanic feeder intrusions are a minor but important link during the caldera-forming stage, between the subvolcanic roots and the overlying volcanic pile. Fayalite hedenbergite quartz porphyry often has ignimbritic textures.

The Younger Granites are discordant high level intrusions (Figs. 2.2, 2.3, 2.4, 2.5, and 2.6) emplaced by means of piecemeal stoping through the collapsed central block. Initial stages in development of the complexes involved intrusion of vast amounts of acid lavas, tuffs and ignimbrites, now only partly preserved as a result of subsidence along ring faults. Almost everywhere these rhyolitic rocks directly overlie the metamorphic basement, which means that the younger granites were emplaced in uplifted areas that were undergoing erosion. Granitic *ring dykes* are the major component of most complexes, ranging from 5 km or less to over 30 km in diameter, and varying in plan from the polygonal to circular or crescent, and through

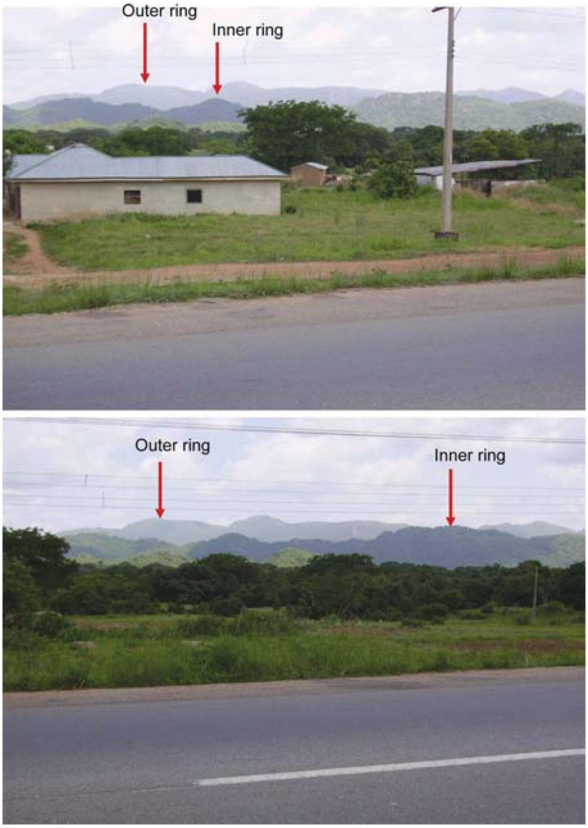

Fig. 2.4 Different views of the Jos-Bukurn Younger Granties complex. (Viewed approaching Jos from Tilde Fulani). Note outer ring and inner ring

more irregular shapes to simple stocks and bosses. Some complexes have a broadly concentric pattern, indicating that the activity was confined to one area, but others have overlapping rings, because the centre of activity migrated with time. Erosion of the volcanics in the more southerly complexes has revealed good exposures of granite. Even where ring complexes have no associated volcanic at all, this is probably because they have been removed by erosion rather than because they were never erupted. The ring dykes were probably emplaced by mechanisms involving underground *cauldron subsidence* (Fig. 2.7). The granitoid suite is more than 95% granite. Intermediate and basic rocks constitute less than 5% of the area. There are several distinctive granite types:

(i) Peralkaline granites and related syenites (with alkali or calcic amphibole in the compositional range ferrorichterite to arfvedsonite in the granites and ferrodenite to ferroactinolite in the syenites) plot close to Q-A join in the Streckeisen Q-A-P plot;
(ii) Peraluminous biotite alkali feldspar granites and biotite syenogranites plot close to the boundary between the two fields on the Streckeisen diagram;

Fig. 2.5 Different views of the southern end of the outer ring of the Jos-Bukurn Younger Granites complex (**a**) viewed from the Police Staff College Jos on the approach to the Pankshin Junction roundabout (**b**) on the approach to the Police Staff College Jos from the Pankshin junction roundabout

(iii) Metaluminous fayalite and hornblende-bearing granites and porphyries with amphiboles or biotite plot in the granite field.

The granites of the Younger Granites series are mainly in the form of ring complexes, of soda pyroxenes and amphiboles, biotite, and fayalite granites, syenites and trachytes with minor gabbros and dolerites. Rhyolites, tufts and ignimbrites are rarely preserved. The centres normally overlap one another, and there is a general tendency for a southern shift in intrusion. However, NE trending alignments of complexes are noticeable, perhaps reflecting deep seated zones of weakness in the basement, but there are no obvious surface relationships between location and regional tectonic features (Black and Girod, 1970). The complexes have been well studied, partly because of their classical structures, petrographic type, and mid-plate anorogenic character, but not least for their economic interest since they are associated with considerable cassiterite, wolframite, scheelite and zinc mineralization, and have sustained an important alluvial tin mining industry. Fifteen of the complexes

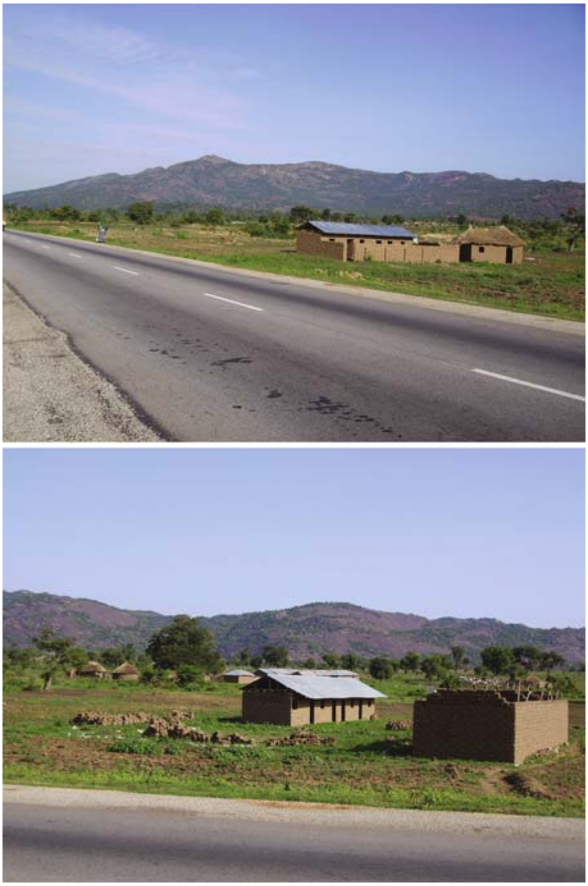

Fig. 2.6 Different views of the Kwandonkaya Younger Granite complex on the Jos – Bauchi road

have been isotopically dated and a perceptable trend in the north from 213 ± 7 Ma (Dutse), 186 ± 15 Ma (Zaranda) and 183 ± 7 Ma (Ningi-Burra) to those in the south at 151 ± 4 Ma (Pankshin), 145 ± 4 Ma (Mada), and 141 ± 2 Ma (Afu) is discernable. This progressive change in age, and the fact that similar alkali granite ring complexes in southern Niger and further north in Air are Carboniferous, Devonian and Ordovician in age has prompted authors (e.g. Bowden et al., 1976) to advocate a sequential age trend covering some 500 Ma over a distance of more than 2,000 km. More recently Rahaman et al. (1984) and Bowden and Kinnaird (1984) have provided further isotopic evidence of this age progression. Of all the African ring complex provinces the Younger Granites of Nigeria have been most studied, and although providing fine examples of ring structures and petrogenetic evolution, these features can be as well seen in other provinces. They are however, economically more significant (Kinnaird, 1984) than any of the other groups, excluding the carbonatite complex of Palabora (Bowden and Kinnaird, 1984). Major characteristics of the Nigerian Younger Granite rocks in comparism to the Older Granite suites are given in Explanatory Note 3.

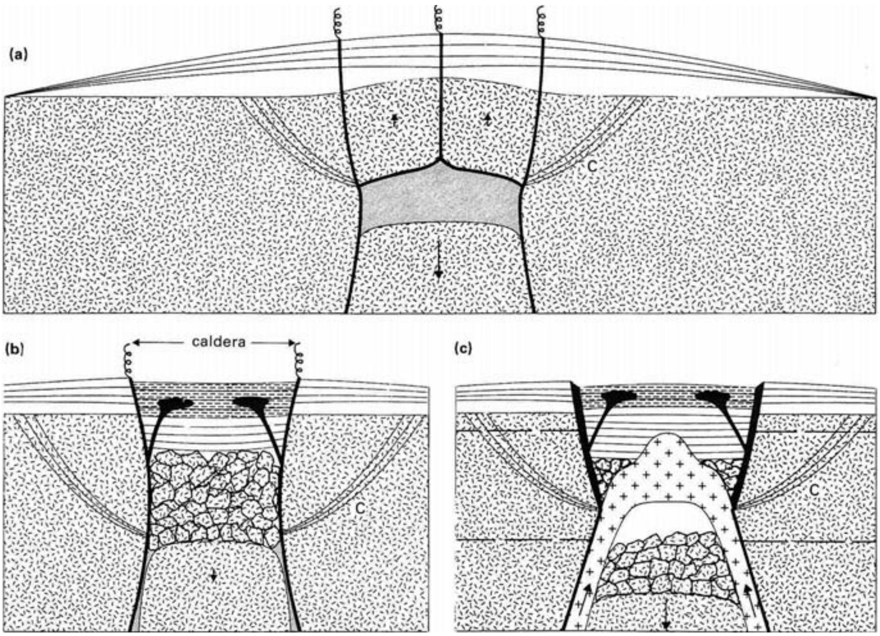

Fig. 2.7 Schematic cross section to show stages in the development of Younger Granite complexes (After Wright, 1985) **a**) A mass of granite (shaded) rises high into the crust (basement gneisses, migmatites and granites), supplied along ring fractures from below. Emplacement is accompanied by doming or swelling of the overlying crust and by initial subsidence of the underlying crustal block. Cone sheets (C) may be emplaced. Predominantly rhyolitic magmas are erupted, mainly as ignimbrites, from acuate vents along the ring fracture and also from central vents. **b**) Rapid eruption of ignimbrites empties the magma chamber so that the overlying crustal cylinder breaks up and collapses into the resulting void, and there may also be further subsidence of the crustal block beneath. Early volcanics are downfaulted into the surface calders, which is filled by eruptions of later rhyolites in the form of both ignimbrites (dashes) and viscous lava masses (black). These are minly supplied by magma rising along the ring fractures. Caldera subsidence continues during eruption of the rhyolites. **c**) Eruptions cease and the ring fractures are filled with grantie porphyries to form marginal ring dykes (black). Emplacement of granites (crosses) occurs by subterranean cauldron subsidence: intermittent large-scale sinking of the roughly cylindrical crustal block beneath. The granites are emplaced into the upper crust, intruding and sometimes doming the earlier doming the earlier volcanics. The heavy briken lines indicate approximate upper and lower limits of presentday levels seen in complexes in different places

Hydrothermal Alteration

In the anorogenic ring complexes, a series of hydrothermal alteration processes with related mineralization was recognized by Kinnaird (1979). Early sodic metasomatism may affect both peralkaline and peraluminous granites whilst later processes, beginning with potash metasomatism, affect only the biotite granites. Subsequent acid metasomatism results in processes of greisenization and silicification – each with a clearly defined sequence of ore deposition. Chloritization and argillization

1. Anorogenic; the Older Granites are orogenic
2. Intrude the basement discordantly to form highly steeped hills; basement complex rocks are generally flat/low lying and lowly steeped
3. Occur generally as ring dykes and cone sheets, sometimes with outer and inner rings; Older Granites occur as massive batholiths
4. The Younger Granites are of Jurassic age; the Older Granites are Precambrian (Pan African)
5. The Younger Granites are generally peralkaline (high amounts of Na and K: feldspars are albitic, pertitic, K-feldspars; sodic amphiboles like arfvedsonites and riebeckites, alkaline pyroxenes like aegerines are very common); Older Granites are generally calk-alkaline and peraluminous.

Explanatory Note 3: Perculiarities of the Younger Granites

are important but more restricted processes. These processes have been discussed in detail in Bowden and Kinnaird (1984), Kinnaird (1985) and Kinnaird et al. (1985) and are briefly summarized below.

Sodic Metasomatism

The mineral assemblages generated during sodic metasomatism depend on the intensity of rock-fluid interaction, the strongly peralkaline granites showing the greatest effect (Bowden and Kinnaird, 1984). The process is responsible for the pervasive alteration of potash feldspar to albite, desilication when the process becomes intense, and enrichment in trace and rare elements. In the Nigerian province it is the albitized granites that have the highest uranium enrichment (Bowden et al., 1981). If the sodic metasomatic process is continued to lower temperatures then mineral assemblages characteristic of propylitic alteration may be generated. Such assemblages include albite, epidote and chlorite. Sodic metasomatism is economically important for the introduction of Nb-bearing ore minerals occurring as columbite in peraluminous biotite granites and as pyrochlore in the peralkaline granites and, of less importance, as fergusonite in metaluminous hornblende biotite granites.

Peralkaline granites: In the peralkaline granites, the process of sodic metasomatism is characterized by the development of albite, aegirine and alkali amphiboles in the compositional range riebeckite to lithian arfvedsonite accompanied by pyrochlore, Th-rich monazite, cryolite, astrophyllite and sometimes by narsarsukite and chevkinite (Bennett, 1981).

Peraluminous Biotite granites: In the apical region of a biotite granite cupola, the original perthitic feldspar is albitized and there is a development of new mica. The albitization process is characterized by a textural change from medium or fine grained equigranular or porphyritic perthitic granite to a sacchroidal fine grained albite protolithionite granite or, more rarely, to albite zinnwaldite or lepidolite granite (Bowden and Kinnaird, 1978). There is a destruction of original Ti-Fe oxides, enrichment in uranium, and the introduction of columbite with minor cassiterite, thorite, xenotime, Th-rich monazite and Hf-rich zircon. Surface samples of the Ririwai complex, compared with drill-core samples, show that there is a diminishing proportion of albite within replacement perthite as depth increases (Kinnaird et al*.*, 1985). At a depth of 295 m the biotite granite consists of quartz, microcline perthite – showing little or no evidence of albitization and annitic mica. In contrast, at 400 m, in the roof zone of another biotite granite, an albite-rich, almost monomineralic rock is encountered (Kinnaird, 1984).

This evidence therefore suggested that sodic metasomatism was concentrated in the apical region of a granite cupola although in many of the complexes the petrological evidence was not well preserved. Such lack of evidence was probably due either to erosion below the apical zone or to continued fluid reactions which had masked the earlier sodic metasomatism.

Metaluminous (hornblende-biotite) granites: Sodic metasomatism may also affect the metaluminous granites to a limited extent. In the hornblende-biotite alkali feldspar granites the perthite feldspar domains have dentate margins with small intergranular grains of ordered albite (Bowden, 1982) Fergusonite, a rare-earth niobate, is common in placer deposits derived from these rocks. The best known localities are in the Sara Fier and Jarawa complexes.

Potassic Metasomatism

Potassic metasomatism is characterized by the development of intermediate to ordered microcline with mica in the compositional range from annite to siderophyllite and chloritization of original mica (Bowden and Kinnaird, 1984). Accessory monazite, zircon, cassiterite, TiO_2 minerals, molybdenite and occasionally wolframite are associated with phyllosilicate minerals. At the same time as K for Na exchange, iron is released from the feldspar lattice and forms minute haematite rods which give a distinctive red colouration to the microcline. As with sodic metasomatism there is desilication when the potassic process becomes intense. When the potassic process is extreme the desilication produces a honeycomb textured microclinite. Where the process of potassic metasomatism is less intense a monomineralic rock is not produced; the original perthitic feldspar is altered to reddened microcline, the quartz remains and the original biotite of the granite is modified. This modification may take the form of chloritization, or pale coloured overgrowths of new Li-Al-rich mica rim the original Fe-Ti-rich dark green/brown biotite. The process of microclinization occurs in two different geological environments within a granite pluton: (1) as the dominant wallrock alteration process along major fractures in the Ririwai and Tibchi complexes; (2) in greisen bordered pockets at biotite granite margins. The pockets are clearly related to an early stage of vapour separation. They are lined by small pink microcline crystals which may be accompanied by euhedral cassiterite up to 2 mm diameter and tiny transparent spheres of fluorite

Acid (Hydrogen Ion) Metasomatism and Hydration

There may be a gradual change in the mineral assemblage generated during lower temperature metasomatism in response to the changing K^+/H^+ ratio in the fluid. Such acid metasomatism is characterized by the breakdown of granitic minerals to produce a new mineral assemblage. However, since acid metasomatism can be superimposed on various earlier mineral assemblages the petrological characteristics depend on the intensity of earlier sodic or potassic metasomatism. Acid metasomatism of an unaltered perthitic alkali feldspar granite results in the formation of a sericite-topaz-quartz assemblage conforming to a classic greisen. In contrast, in granites affected by sodic metasomatism, albite destabilizes to form fluorite, cryolite and topaz with some montomorillonite. In granites affected by potash metasomatism, microcline is transformed into micaceous aggregates, chlorite or, more rarely, kaolinite where the cation/H^+ ion ratio was low enough to enter the kaolinite field. Thus the effect of the acid metasomatism and the resulting mineral assemblage depends on the initial mineral assemblage.

The acid metasomatism may be a disseminated process or form pervasive pockets associated with microclinite; it may diffuse along zones or may occur in fissure-filling veins. The accessory minerals associated with acid metasomatism are commonly concentrated in the mica clusters. The assemblage of ore minerals is mainly of oxides, but in the later stages of deposition, sulphide minerals also occur.

Chloritic (Propylitic) Alteration and Fluorization

Chloritic alteration is characterized by the chloritization of annitic mica, alteration of perthitic feldspar to pale coloured micaceous aggregates, lack of leaching of alkalis, introduction of appreciable iron, reduction in silica and the transformation of biotite and/or feldspar to chlorite. This process of alteration has been described as propylitic alteration. Chlorite alteration tends to be strongest in granite basement rocks adjacent to younger biotite granite contacts. The intensity of alteration is greatest at the contact, grading outwards to merge with normal deuteric or metamorphic alteration phenomena. Abundant sulphide deposition appears to be related to a strong fluorization that often accompanies the chloritic alteration. This is dominated by sphalerite and chalcopyrite. The abundance of fluorite and the low percentage of quartz associated with some chlorite alteration suggest SiO_2 removal in HF-rich fluids.

Silica Metasomatism

Silica metasomatism is characterized by an increase in the modal proportion of quartz relative to all the other minerals in the altered rock. Like potash and hydrogen ion metasomatism, the process may be pervasive or vein-controlled. Quartz may be pervasively deposited into vugs in a cupola created by the earlier potash or hydrogen ion metasomatism, or it may replace all earlier formed minerals. Even more common, are the quartz fissure-filling veins which are found in virtually all biotite granite masses. There is a major sulphide deposition of ores dominated by sphalerite associated with quartz vein development, particularly in lodes at Ririwai and Tibchi. Early cassiterite is followed by abundant dark brown sphalerite, chalcopyrite galena and sometimes arsenopyrite or pyrite.

Argillic Alteration

Argillic alteration is a late stage process, characterized by the formation of clays in the kaolinite and montmorillonite groups at the expense of the feldspars. Argillic alteration is very limited. It is only an important process in three areas and in each of these there has been an earlier extensive albitization of the feldspars during sodic metasomatism. In these areas, the granite has been pervasively reduced to the consistency of clay. Elsewhere the formation of clays is very patchy. Clay minerals may infill vugs in major veins, or coat crystals and fill intracrystal voids in smaller veins. An argillic alteration halo or zone which is commonly associated with porphyry copper deposits does not surround similar mineralized veins in Nigeria.

Geochemistry of the Alteration Processes

Geochemical data have indicated that each of the alteration processes is characterized by a change in alkali element ratios accompanied by an enrichment in specific trace elements (Kinnaird, 1984). Each process can also be distinguished by normative variations in Q-Or and Ab. The early fluids responsible for soda metasomatism, in addition to concentrations of Na, contained Fe combined with Nb, Y, U, Th, Zr, and HREE relative to unaltered granite. Potash metasomatism is characterized by an increase in K_20, Rb, Li and Zn, a loss of Na_2O and trace element depletion. Chemically, H^+ ion metasomatism and greisen development is characterized by a marked decrease in K and AI due to feldspar breakdown with a complementary increase in Si. The chondrite-normalized rare-earth spectrum shows an enrichment in light rare-earth elements, a slight enrichment in Eu, coupled with increasing Yb and Lu (Kinnaird et al., 1985; Bowden, 1985). The silicification process shows the obvious increase in Si balanced by a decrease in all the other major elements except Fe in some cases. There is an increase in Sn, Zn, W, Bi, Cu and Pb. Norm calculations by Kinnard et al. (1985) show that soda metasomatism is characterized by increasing Ab. As potash metasomatism progresses this normative Ab is dramatically reduced and balanced by an increase in normative Or so that the compositions plot away from the central biotite granite field towards the Q-Or join. During H^+ ion metasomatism there is a reduction in both Ab and Or components. The plotting position on the Q-Ab-Or diagram depends on the intensity of earlier processes, thus samples which have been albitized and subsequently greisenized will plot towards the Q pole on the Ab-Q side of the diagram. In contrast, samples which have been microclinized and then greisenized will plot towards the Q pole but on the Or-Q side of the diagram. Those samples which have been subjected to all three processes will plot close to the vertical Q + (Or = Ab).

Structural Setting and Styles of Mineralization

The hydrothermal processes mainly affect biotite granites. Where these processes have been extensive, disseminated and vein deposits of Sn, Zn, W and Nb with Cu, Fe, Bi, U and REE are developed in and around the roof and marginal zones of medium or fine grained granite cupolas, with veins extending up to 2 km out into the country rock. Different styles of mineralization can be recognized:

(i) pegmatite pods with quartz, topaz, beryl and feldspar;
(ii) pervasive metasomatic disseminated mineralization with columbite or pyrochlore ± cassiterite;
(iii) prejoint and postjoint pegmatitic pods and lenses with albite or microcline, genthelvite, uraninite, columbite and thorite;
(iv) quartz rafts, stockworks, sheeted veins and altered wall rock with cassiterite, wolframite and sulphidcs;
(v) fissure-filling veins or lodes with cassiterite, wolframite and sulphides;
(vi) irregularly shaped replacement bodies with cassiterite and sulphides;
(vii) quartz veins with wolframite or scheelite, bismuth minerals, sometimes abundant cassiterite and/or sulphides;
(viii) mineralized ring-dyke with cassiterite and sulphides;
(ix) alluvial and eluvial deposits of columbite, cassiterite, zircon, etc.

The different processes of alteration and associated mineralization are characteristic of different parts of a granite pluton. These different structural environments of deposition can be regarded as five separate zones.

Environmental Zones of Deposition

The roof zone: The roof zone of an intrusion is characterized by disseminated mineralization related to sodic or potassic metasomatism, quartz rafts (sheeted vein systems), pegmatite pods and veinlets, irregularly shaped replacement bodies and fissure-filling veins in the apical region, e.g. at Ririwai-Ginshi Hill adit area and at Banke-Baban Damu.

The marginal zone: The marginal zone: of the intrusion may extend over a horizontal distance of 200–500 m inside the granite contact. It is characterized by stockworks, sheeted veins, associated wall rock alteration and pegmatitic pods, containing a complex paragenesis of oxide and sulphides associated with greisenization and silicification, e.g. at Rishi, in the Saiya Shokobo complex.

The contact area: The contact area occupies a zone of ca 200 in on either side of the granite contact. The zone is characterized by stockworks, fissure-filling veins and intense alteration. If the country rock is basement, chloritic alteration is often very intense and massive sulphide deposits may be deposited. Beneath a volcanic cover, pegmatitic quartz, feldspar and genthelvite may occur.

The country rock: Where the country rock is basement, mineralization occurs in quartz veins and stringers, or sometimes in marginal greisens. The quartz veins are wolframite- or scheelite-bearing with occasional bismuth minerals and sometimes abundant cassiterite or sulphides. Tile country rock may consist of an ignimbritic pile which is poorly jointed. Mineralization is restricted to thin stringers with cassiterite and sulphides. If the country rock consists of intrusions of earlier granites, thinsheeted vein systems may occur where individual veins are of the order of 2 mm–1 cm wide. Often these veins are unmineralized, greisenized granite, although occasionally they contain cassiterite and sulphides.

Ring-dykes: Circular, elliptical or polygonal porphyritic ring-dykes characterize many of the ring complexes. Mineralization may occur as disseminations within the porphyry ground mass or along joint planes. The mineralization, which is always sporadic and economically insignificant, is characterized by a sulphide assemblage of ores dominated by sphalerite, chalcopyrite and galena.

Styles of Mineralization

Pegmatitic pods with quartz ± beryl + feldspar. Generally the margins of the granites are not characterized by pegmatitic development. Where this does occur the resultant pods are sporadic and usually only of the order of a few centimetres or less. The pegmatite pods may be composed of clear or smoky quartz with long prism faces, alkali feldspar sometimes twinned, blue-green beryl, often of gem quality, aquamarine and colourless to pale blue topaz, also often gem quality. Crystals rarely exceed 8 cm in size but crystals of topaz and beryl are commonly 5 cm.

Pervasive metasomatic disseminated mineralization: The most important phase of disseminated mineralization is related to sodic metasomatism since disseminated potash metasomatism is not a widespread process and fracturing and fissuring of granites during late stage cooling usually channels late stage fluids into distinct tabular zones. During sodic metasomatism of the peralkaline albite arfvedsonite granites, the dispersed mineralization is dominated by pyrochlore which forms distinct irregularly- distributed, honey-coloured octahedra in six localities. At each of these, the albitized peralkaline facies covers only a small area. The pyrochlore may contain up to 5% Uranium, but despite localized high concentrations, the heterogeneous dispersed nature of mineralization over such small areas have proved to be too difficult and expensive to attract mining interest so far. During sodic metasomatism of biotite granites a series of oxide ores, principally columbite and cassiterite, is disseminated throughout the apical zone. Subsequent unroofing by erosion of these ore-rich apical zones has resulted in the formation of economically important alluvial and eluvial ore deposits. Many of the alkali biotite granites in Nigeria show slight sodic metasomatism. However, the most intense albitization and highest primary enrichment occurs in localized parts of the Jos- Bukuru complex and Udegi area of the Afu complex. In these areas the granite has been decomposed to the consistency of clay by late stage argillic alteration. This allows the extraction of the ore minerals by the use of monitor and gravel pumps. At Jantar, 12 km south of Bukuru, the white granite forms sills and irregularly branching dykes feathering out upwards into small white veinlets cutting the dark coloured schistose basement. There is a very large variation in columbite content from <30 to >2,200 ppm Nb_20_5. At Harwell, 5 km NE of Bukuru, the columbite-rich facies also contains abundant thorite, xenotime and monazite with traces of ilmenite, magnetite and zircon. The zircon which forms brown, almost opaque crystals contains up to 5% Hf. There is a substantial enrichment in heavy rare-earth elements and also uranium in the ores, particularly in the thorite, xenotime, monazite and zircon. In the Udegi area, the fine grained, columbite-rich albite zinnwaldite granite forms an elliptical plug into the surrounding pink perthite granite. It is approximately 3,000 m long and 1,400 m wide trending NE-SW with the greatest decomposition and columbite enrichment along the northern and southern margins. The average grade described by Jones (1953) is equivalent to 1,200 ppm, with an average Nb_20_5 : Ta_2O_5 ratio of 13: 1. This grade has decreased with depth of working.

Pegmatite pods and lenses with albite or microcline: The pegmatites are sporadically distributed and unimportant in economic terms. They are <1.5 m in width and traceable as lenses over 100 m. They are characterized by abundant feldspar with two types depending on the dominant feldspar. At Harwell, both types of pegmatites are found cutting the decomposed columbite-bearing albite zinnwaldite granite in a disused mining paddock. The earlier of the two types, the albite pegmatite, is commonly sinuous in form and < 1.5 m in width. It contains occasional patches of genthelvite, associated protolithionite and accessory thorite and columbite. The later pegmatites are strongly tabular in form, commonly only a few centimetres wide and are characterized by green amazonite as a major constituent with some quartz, protolithionite, genthelvite and microlite. A uraninite-bearing albite pegmatite with quartz and genthelvite occurs in the Saiya Shokobo complex. Uraninite forms as small black crystals approximately 1 mm in size, clustered on the feldspar crystals. The pegmatite is associated with greisens that have developed along both horizontal and vertical joints. A similar relationship between pegmatite and greisen occurs in the Baban Damu area of the Banke complex, 5 km WNW of Banke School. Here, sinuous quartz, albite, green-mica pegmatites, containing knots of blue-green aquamarine, lie approximately parallel to horizontal greisens which are interlinked by vertical greisens.

Quartz rafts, sheeted veins attd stockworks. Quartz rafts characterize the roof zone of a biotite granite cupola. They occur at the contact zone between the granite and the overlying volcanic pile where the volcanics have not fractured to allow fluid escape. They are not common throughout the province possibly because the right erosional level is exposed in so few complexes. Nor are they richly mineralized, although there does seem to be an enrichment in ore minerals beneath the rafts. The best developed is at Uwar Gida near Ginshi Hill, Ririwai. Here the pink medium grained biotite perthite granite becomes a quartz feldspar porphyry and then immediately beneath the volcanics becomes a genthelvite-rich microgranite. Between this and the banded volcanics lies a zone of pure massive, milky quartz up to 2 m thick. Although the quartz is only slightly mineralized, the underlying stockwork within the top 30 m of the granite roof is richly mineralized and has been worked by trenching and adits, mainly for cassiterite. The sulphides, which have not been worked, appear to be disseminated below the main cassiterite horizon. Sheeted veins and stockworks characterize the marginal and contact zone of a biotite granite. Sheeted veins consist of a series of thin, subparallel veins. They are found in many complexes but are particularly well-developed in the Ladini area of the Saiya Shokobo complex and in the Banke complex. The sheeted veins may be subhorizontal as at Banke, or steeply dipping as at Saiya Shokobo. Individual veins may vary from 1 mm to 0.5 m and usually consist of a greisen assemblage of quartz-siderophyllite, occasionally with a thin central stringer of quartz. The stockworks are similar to the sheeted veins except that they do not occur as parallel veins but as a series of anastomosing ramifications within the marginal or contact zone of a granite intrusion. Mineralogically the veins systems are characterized by quartz, pale or green coloured Li-AI or Li-Fe mica usually with abundant topaz and some fluorite, cassiterite or, more rarely, traces of sulphides. Both stockworks and sheeted vein systems differ from fissure-filling lode systems in terms of size and complexity, they are much smaller and have a much simpler paragenesis.

Fissure filling lodes: Only two major lodes have been noted in Nigeria and occur in the adjacent complexes of Tibchi and Ririwai: In both these complexes it appears that the earliest igneous activity was violent and eruptive culminating in the formation of a central shield volcano built on an updomed terrain (Ike, 1983; Kinnaird et al., 1985). The lodes are aligned along fractures formed during the updoming of the underlying central biotite granite. In the Tibchi complex the elliptical intrusion has a long axis orientated north-west–south-east whereas in Ririwai the axis of the ellipsoid intrusion lies east-west with an east-west orientation to the lode. In both complexes the lodes are the product of several alteration processes with fluids channelled in enlarged steeply dipping tectonic master joints. In the Tibchi complex the mineralized veins extend out into the basement which overlies the biotite granite, but in both complexes the lode system is confined within the outer ring-dyke. The lodes are rich in cassiterite and wolframite and have been surface mined on a small scale for many years. About 50 tonnes of wolframite were extracted from the Ririwai lode during Second World War (Jones, 1953). In both complexes sphalerite is the major ore mineral. In Ririwai this is about 1.5%, followed by cassiterite with 0.5%. It is estimated as at 1986 that when in production the mine wouldl produce 1,600 tonnes of tin metal a year and 6,000 tonnes of zinc metal. The Ririwai lode was opened up as an underground mine and was undergoing assessessment at the time for future production of primary cassiterite as alluvial ores were being depleted.

The Ririwai lode has been described in detail by Kinnaird et al. (1985*).* It extends for a distance of 5 km in an east-west direction and to over 400 m depth and dips to the south at 85°. The maximum surface width of the lode system is 8 m. The lode, which is extensively mineralized, consists of a series of parallel to subparallel or braided quartz veins enclosed by zones of grey greisen grading outwards into reddened wall rock and occasionally through a narrow buff-coloured zone out into the pale pink equigranular biotite perthite granite. Hydrothermal alteration began with potash metasomatism and perthitic feldspar adjacent to the fissure was microclinized. Early monazite, zircon and ilmenite deposition was followed by the formation of cassiterite, wolframite and rutile and finally by the introduction of molybdenite (Kinnaird et al., 1985). During subsequent hydrogen ion metasomatism the microcline was altered. Greisen was formed, consisting of green coloured lithium siderophyllite or grey zinnwaldite and quartz. Localized concentrations of ore are associated with clusters of mica. The sequence of oxide ore deposition, beginning with early monazite, is similar to that associated with potash metasomatism. However, sphalerite with stannite, pyrite and marcasite and finally chalcopyrite follows molybdenite. During silica metasomatism, in addition to the deposition of quartz into vugs created by earlier processes major fissure-filling quartz veins up to 75 cm are formed. Cassiterite is the first ore to be deposited at this stage followed by a major deposition of sphalerite, traces of stannite, pyrite and marcasite, abundant chalcopyrite, and other minor copper and bismuth ores as exsolution blebs in the main sulphides. Abundant galena is the last major ore. Large cavities (30–100 cm in size) occur within the quartz veins and are infilled with kaolinite. Supergene alteration of the ore minerals is limited.

The Tibchi biotite granite has long been recognized as one of the most intensely mineralized in the province (Falconer and Raeburn, 1923). Within the granite, there are two lode systems forming a letter Y. One orientated N–S, between 3 and 15 m wide and strike length of at least 1 km, the other is orientated NW–SE, with similar dimensions and a strike length of over 2 km. This is believed to be the earlier of the two systems since it does not cross the N–S lode (Bowden, 1982). The north–south lode consists in the south of reddened quartz veins rich in cassiterite and wolframite with an almost complete absence of sulphides. In the north it is poorly mineralized and is often characterized by the development of mica-rich pods. The NW–SE lode follows the main axis of the elliptical biotite perthite granite. It is similar to Ririwai with a reddened microcline-rich outer facies grading through a greenish grey greisen to fissure-filling quartz, which is sometimes massive and milky, sometimes well crystallized (Ike, 1979). Early albitization of the biotite granite preceded a weak vein-controlled microclinization which was followed by greisenization and silicification. Oxides dominated by cassiterite are disseminated through the greisen and red quartz-microcline wall rock. Sphalerite and chalcopyrite accompanied by pyrite, molybdenite, arsenopyrite and galena with traces of stannite and other minor sulphides were thought to be probably related to silicification (Bowden, 1985). The lode is well exposed on Kogo Hill which rises 100 m above the surrounding biotite granite.

In both the Tibchi and Ririwai complexes therefore, it is apparent that there are several phases of deposition of the major ore minerals and that mineralization was repeatedly emplaced in the same lode system. Wall rock alteration may occur marginal to the quartz veins or the veins may infill fissures in a lode system with mineralized greisen, as at Tibchi and Ririwai. Also the quartz veins may cut the granite or country rock without any marginal alteration. The quartz veins that occur in the basement are generally characterized by wolframite of ferberite composition. The wolframite occurs sporadically as bladed crystals, at the margin or vein centre, orientated parallel or perpendicular to the strike of the vein. The wolframite is accompanied by some cassiterite and minor sulphides and often by bismuth minerals. The wolframite-rich quartz veins of the Dagga Allah area occur at a greater distance from the Younger Granites than is usual. It seems likely that they are related to Younger Granites which may exist at shallow depth within the Dagga Allah ring-dykes. Geophysical prospecting supports this possibility (Ajakaiye, 1983). The quartz veins within the Younger Granites, such as in the Ririwai lode, may contain a wider spectrum of ore minerals than those of the basement.

Irregularly shaped replacement bodies: Irregularly shaped replacement zones containing massive or disseminated ore may occur in the roof and contact zones of biotite granite bodies. Generally they are composed of mica-rich greisens formed by hydrogen ion metasomatism of granite already altered by potash metasomatism. The best examples occur in the Rishi biotite granite and at Rafin Gabas in the Afu complex. At Rafin Gabas the host granite is coarse grained biotite perthite granite. In the mineralized zone, deposition of cassiterite and wolframite, accompanied by siderite, was followed by massive sphalerite and chalcopyrite, then pyrite and green fluorite formation. The dark iron sphalerite, with up to 17% Fe forms massive well twinned crystals <25 cm in size which are brecciated and recemented by late stage wolframite-bearing quartz veins. Brecciation probably took place during sphalerite formation as the chalcopyrite exsolution blebs within the sphalerite are elongated into rods. The sphalerite clasts often have a thin crust of quartz crystals. The ore bodies were first worked by opencast techniques and a block of cassiterite weighing 9 tonnes came from here. The area was also a major source of wolframite during the Second World War.

Quartz veins: The quartz veins are generally vertical and vary from massive milky veins 30 m wide to clear comb-textured veins 1 cm wide. Virtually all the granites of the province show late stage quartz-veining but only those granites which have disseminated mineralization have ores within the quartz veins.

Mineralized ring dykes. Ring-dykes of granite porphyry characterize many of the complexes. Fluids escaping along these steeply dipping fractures locally react with, and mineralize the porphyry. Where fluid interaction has occurred, the fine grained matrix has been largely altered to a greisen assemblage leaving the K-feldspar phenocrysts unaltered or partially transformed to microcline. Often these petrological changes are limited to narrow zones although the degree of reaction may be locally intense. The mineralization is characterized by a sulphide assemblage of ores dominated by sphalerite, chalcopyrite and galena, with pyrite, pyrrhotite, stannite, arsenopyrite and molybdenite. At Zarara quarry in the ring-dyke of the Banke complex Bowden (1982) noted that the porphyry has been brecciated and cemented by mineralizing fluids and late stage vein quartz. At Gindi Akwati in the Rop complex, the ring-dyke has brecciated, metamorphosed and permeated an earlier basic-dyke. The breccia has been cemented by pale coloured mineralized veins in which quartz or fluorite may be the main gangue.

Alluvial and eluvial mineralization: Uplift of the central part of Nigeria which began in Neogene (Kogbe, 1981b) led to the formation of an upstanding area known as the Jos Plateau, in the Jos-Bukuru area. The plateau, which rises >400 m above the surrounding basement plain, has an above average rainfall for this part of Nigeria, resulting in more rapid denudation of the granite cupolas. The plateau region forms a major watershed so the ore minerals eroded from the granites are widely distributed in the modern river systems and are readily worked due to the almost perpetual availability of water. During the Pleistocene, thick deposits of cassiterite-bearing alluvium were laid down in the broad shallow valleys of the central plateau. These deposits are the targets for the extensive mining activity on the Jos Plateau, especially in the Ngell River area, west of Sabon Gida. Large reserves of high grade placer deposits are still preserved beneath basalt where Quaternary to Recent basalt lava flows have filled the broad Pleistocene valleys. The concentration of mining in the Jos-Bukuru and Rop areas reflects the widespread secondary distribution of ore minerals and does not necessarily reflect the abundance of the primary source. More than 95% of Nigeria's tin export is produced from alluvial deposits. Between 1905 and 1971 about 630,000 tonnes of cassiterite was exported with maximum production in 1946 when 14,255 tonnes of concentrate containing between 72% and 74% tin was produced. In 1981 cassiterite production was 3,750 tonnes and has since fallen below 2,500 tonnes per year. Prior to 1965, 95% of the world's columbite consumption was supplied by Nigeria and peak production was in 1963 when 3,334 tonnes were exported (Kogbe and Obialo, 1976). Alluvial monazite, thorite, zircon, pyrochlore and xenotime have all been sold sporadically with annual combined export from zero to 1,000 tonnes.

Chapter 3
Cretaceous – Cenozoic Magmatism and Volcanism

Basaltic lava plateaus, trachyte plugs and domes, large central volcanoes and small basalt cinder cones with thin flows are all found among the more southerly manifestations of Cenozoic volcanism in West Africa (Wright, 1985). This province also includes the remarkable offshore continuation of the Cameroon volcanic line, the four islands situated in the Gulf of Guinea itself. Areas of basement doming include the Jos Plateau, southeast of the Benue Trough, with probably still greater uplifts; and the Adamawa Highlands further east, where lavas of the Ngaoundere Plateau overlie the Ngaoundere fault zone, which was reactivated in the Cretaceous. The flood basalts of the Biu Plateau are situated on the Zambuk Ridge of the Upper Benue Trough, and the smaller Longuda Plateau lies near the bifurcation of the Upper Benue Trough, which has been identified as a possible secondary triple junction (Fig. 3.1).

On the Jos Plateau, the earliest eruptions were basaltic lavas of the somewhat enigmatic *Fluvio-Volcanic Series*. These deposits form laterite-capped sheet and residual flat-topped hills at elevations varying from about 1,100 to 1,400 m, and consist of fluvio-lacustrine gravels, sands and clays, interbedded with or overlain by yellow and purple clays representing kaolinised and bauxitised basalt lavas. The laterite capping to these beds has been correlated with the laterite developed on the Paleocene Kerri–Kerri Formation of the Upper Benue Trough, such that the *Fluvio-Volcanic Series* may also be of Lower Tertiary age. The sediments and volcanics reach a maximum thickness of 300 m and were deposited in depressions on an ancient landscape of moderate relief, burying all but the highest hills.

Basalts post-dating the fluvio-volcanics on the Jos Plateatu have been divided into Older and Newer Basalts on the somewhat subjective criteria of relative degrees of weathering and lateritization. Radiometric dating suggests that they are not older than 3 Ma and there was probably more or less continuous activity from late Pliocene to very recent time. Some of the cinder cones and their thin valley-filling flows look very young and there are all gradations to heavily eroded cones and to lava sheets and remnants without a discernible source. Several cones are aligned along presumed basement fracture trends. The youngest cones contain abundant ultramafic nodules and megacryst phase of upper mantle origin. Rounded fist-sized fragments of diopsidic pyroxene and magnesium (pyropic) garnet are especially striking. Other minerals include magnesium ilmenite, alkali amphibole and sodic

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Fig. 3.1 Cretaceous-Tertiary igneous activities generally located within the Benue Trough in Nigeria (Captured from Wright, 1985)

plagioclase. The most unusual megacryst phases occur in extensive basalt flows immediately south of the Jos Plateau, which contain large number of zircon and corundum crystals, many of gem quality (Wright, 1985).

A single plug of trachytic phonolite on the Jos Plateau probably pre-dates the basalts. It is of particular interest for its rich content of upper mantle and crustal inclusions (peridotite, gabbro, anorthosite, syenite, granite) and large megacrysts of anorthoclase feldspar. In the Middle and Upper Benue Trough and in the Yola arm, plugs and domes (tholoids of trachyte and phonolite) form characteristically steep–sided hills. Samples of these rocks have given ages of between 12 and 22 Ma, placing them in the Miocene. In the Benue Trough, basaltic volcanism probably did not begin until the end of the Miocene, when the Biu and Longuda Plateaus were built. The bulk of the Biu Plateau consists of Pliocene basalts, erupted from small vent or fissures and spreading thinly over wide areas. There are numerous small pyroclastic cones within the sequence, interpreted as the result of explosive eruption, caused by ground water percolating into lava pile and coming in contact with fresh lava (Wright, 1985). There was a break in activity at the end of the Pliocene, with weathering, erosion and laterite formation. According to Wright (1985) activities resumed in the Quaternary, in the form of thin valley-filling basalt flows from small cinder cones, some of which have very youthful aspects. These cones are also notable for their abundant inclusions of upper mantle peridotite and plentiful megacrysts of minerals similar to those found in Quaternary basalts on the Jos Plateau.

The chronology of the Biu Plateau is well controlled by radiometric dating with sample of the plateau basalts falling in the 7–2 Ma range, the Quaternary basalts giving 1 Ma or less. The smaller Longuda Plateau to the southwest has not been dated, but its geomorphology suggests that it is also built of Pliocene basalts, though there are no later Quaternary cones there. In contrast, the area to the southeast of the Biu Plateau consists entirely of Quaternary flows and cones aligned WNW – ESE, parallel to the boundary between basement and Yola arm of the Benue Trough. There are great numbers of basaltic necks and plugs and flow remnants among the Cretaceous sediments in the Middle and Upper Benue Trough, extending in to the Yola arm (Fig. 3.1). Although their physiographic aspect might suggest that they are similar in age to the phonolite and trachyte bodies, radiometric dating of some of them has given Pliocene ages, such that they are contemporaneous with the growth of the Biu and Longuda Plateaus. The Cenozoic volcanics of the Benue Trough can almost invariably be distinguished from the Cretaceous igneous rocks by their fresh and unaltered aspect, both in outcrop and in thin section.

The Cameroon Line

The main Cameroon Line extends from the islands in the Gulf of Guinea through Mount Cameroon and the Bamenda Highlands, and across the Yola arm of the Benue Trough towards Lake Chad. It is defined both by Lower Tertiary Younger Granite complexes and by the Cenozoic volcanics. An eastern branch diverges north of the Bamenda Highlands and extends to the Ngaoundere Plateau of the Adamawa Highlands, which lies on the Ngaoundere fault zone. Volcanism was spare along the northern third of the line, where domes, plugs and necks of phonolite, trachyte and basalt may belong to the Miocene and Pliocene episodes of the Benue Trough.

The oldest lavas on the Bamenda Highlands are basalts that have been altered to multi-coloured clays resembling those of the *Fluvio-Volcanic Series.* Most of the volcanic activities in Cameroon was probably Pliocene, producing mainly basalts, but also flows and plugs of trachyte, rhyolite and subordinate phonolite in the Bamenda Highlands and the Ngaoundere Plateau. There are large basaltic and trachyte – rhyolite shield volcanoes with summit calderas in the Bamenda Highlands and basalt trachyte volcanism characterizes the Manenguba Mountains to the south (Wright, 1985).

Signs of recent basaltic activity in several places show that volcanism persisted through the Quaternary, and Mount Cameroun is still active. It is the largest mountain in West Africa, rising some 4,000 m above sea level, built mainly of basaltic lavas and ashes, with cinder cones scattered about its flanks. The last significant eruption was in 1922, when lavas emanated from small cones on the upper slopes and reached the sea on the west side of the mountain. The most recent eruptions were in 1954, 1959 and 1982.

The adjacent offshore island of Bioko (formerly Fernando Po) is also built mainly of basalts, probably mostly of Pliocene age. The more distant offshore islands are also formed mainly of basalt flows, overlain and intruded by phonolites and trachytes, sometimes followed by more basalts. Radiometric dates and field relationships suggest that volcanism commenced as long ago as the late Oligocene (c. 30 Ma), but at least some of the phonolites and trachytes are Pliocene (3–3 Ma). There is a striking resemblance between the distribution of the main

Pliocene-Quaternary volcanics in the Gulf of Guinea province and Y-shape of the Benue Trough, and the two patterns can be superimposed. When the South Atlantic opened around 100 Ma ago, the Benue Trough originated as the failed arm of the Gulf of Guinea triple junction. A zone of crustal attenuation and elevated heat flow asthenosphere, bifurcating in the northeast to form the Yola branch of the trough. Over this zone, the sedimentary basin developed, accompanied by some igneous activity.

Analysis of magnetic anomaly patterns, transform faults and bathymetry in the south Atlantic has been used to suggest that, about 80 Ma ago, the African plate was rotated clockwise slightly. It is proposed that as a result the linear plume in the asthenosphere came to lie southeast of the Benue Trough and from its new position it subsequently generated the Cenozioc volcanism of the Cameroon Line.

Controls of Cenozoic Magmatism

The difficulties of relating magmatic activity of continental regions to the influence of long-lived stationary mantle plumes or hot spots were reviewed by Wright (1985). The basin and swell structure of the African continent began to take shape soon after the end of the Pan African event, as the continental crust and lithosphere adjusted to lateral inhomogeneities of structure and composition. Some parts became warmer and thicker and more buoyant than others, possibly in part because of regional variations in the concentration of radioactive heat-producing elements. The swells have been the site of uplift and potential or actual igneous activities at intervals throughout the succeeding several hundred million years. Their positions are fixed with respect to the lithospheric plate itself and must move with it over the underlying mantle.

Economic Potential of Cenozoic Volcanics

Although it is not intended that the economic potentials of the different components of Nigerian geology be discussed separately outside the chapter on Mineral Resources, a brief discussion on that of the Cenozoic volcanism is presented at this stage since most its mineral potentials are no more significant to be presented for discussion again in Chap. 10. Apart from their uses as crushed rock for aggregates and road building, basaltic and related volcanic rocks are generally of little economic value in Nigeria. Extensive lava plateaus may have pyroclastic layers and well jointed flows that will provide small but useful water-bearing layers. Under the right conditions, basaltic rocks weather to kaolinite-rich clays. For example, among the Fluvio-Volcanics of the Jos Plateau there are clays that have some potential for ceramics and brick manufacture. Deep weathering of basaltic volcanics in the Adamawa region of Cameroon has produced a bauxite deposit estimated to contain over a billion tones of ore (Woakes et al., 1987)

Basal gravel and sand layers of the Fluvio-Volcanics are also repositories of alluvial cassiterite derived from early unroofing of the Younger Granites, and some of these deposits are among the richest to be worked. Elsewhere on the Jos Plateau, the thin basalt flows of the youngest volcanoes are a hindrance to tin mining, for they occupy old river valleys and thus cover the alluvium with a hard resistant capping. This interferes with geophysical prospecting for concentrations of cassiterite and columbite in the underlying alluvium, and it makes exploratory drilling very expensive.

River gravels south of the Jos Plateau contain alluvial concentrations of megacryst corundum and zircon, weathered out of basaltic lava flows. Some of the corundum crystals are gem quality sapphires, and the larger zircon crystals could have some potential as semi-precious stones. Indeed, the alluvia; deposits of the Jos Plateau region are not known to contain gem quality crystals derived from basement pegmatites.

Part II
Geology – Sedimentary Basins

Chapter 4
The Benue Trough

The Benue Trough of Nigeria is a rift basin in central West Africa that extends NNE–SSW for about 800 km in length and 150 km in width. The southern limit is the northern boundary of the Niger Delta, while the northern limit is the southern boundary of the Chad Basin (Fig. 4.1). The trough contains up to 6,000 m of Cretaceous – Tertiary sediments of which those predating the mid-Santonian have been compressionally folded, faulted, and uplifted in several places. Compressional folding during the mid-Santonian tectonic episode affected the whole of the Benue Trough and was quite intense, producing over 100 anticlines and synclines (Benkhelil, 1989). Major such deformational structures include the Abakaliki anticlinorium and the Afikpo syncline in the Lower Benue, the Giza anticline and the Obi syncline in the Middle Benue, and the Lamurde anticline and the Dadiya syncline in the Upper Benue Trough.

Following mid-Santonian tectonism and magmatism, depositional axis in the Benue Trough was displaced westward resulting in subsidence of the Anambra Basin. The Anambra Basin, therefore, is a part of the Lower Benue Trough containing post-deformational sediments of Campanian-Maastrichtian to Eocene ages. It is logical to include the Anambra Basin in the Benue Trough, being a related structure that developed after the compressional stage (Akande and Erdtmann, 1998).

The Benue Trough is arbitrarily subdivided into a lower, middle and upper portion (Figs. 4.1, 4.2, 4.3, and 4.4). No concrete line of subdivision can be drawn to demarcate the individual portions, but major localities (towns/settlements) that constitute the depocentres of the different portions have been well documented (Petters, 1982; Nwajide, 1990; Idowu and Ekweozor, 1993; Obaje et al., 1999). The depocentres of the Lower Benue Trough comprise mainly the areas around Nkalagu and Abakaliki, while those of the Anambra Basin centre around Enugu, Awka and Okigwe. The Middle Benue Trough comprises the areas from Makurdi through Yandev, Lafia, Obi, Jangwa to Wukari. In the Upper Benue Trough, the depocenters comprise Pindiga, Gombe, Nafada, Ashaka (in the Gongola Arm) and Bambam, Tula, Jessu, Lakun, and Numan in the Yola Arm.

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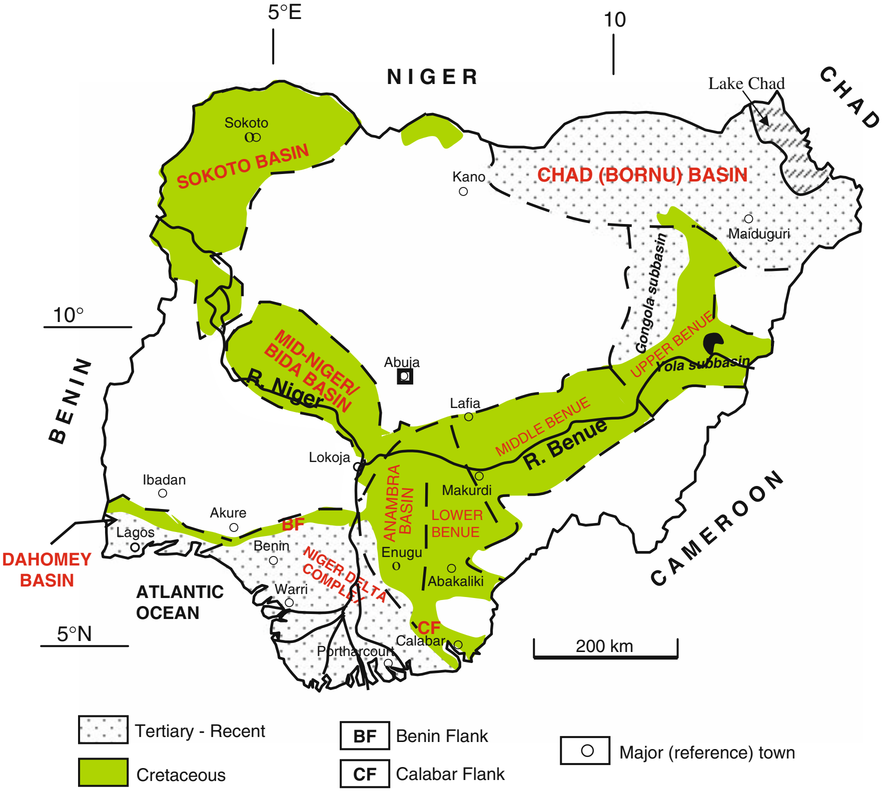

Fig. 4.1 Sedimentary Basins of Nigeria

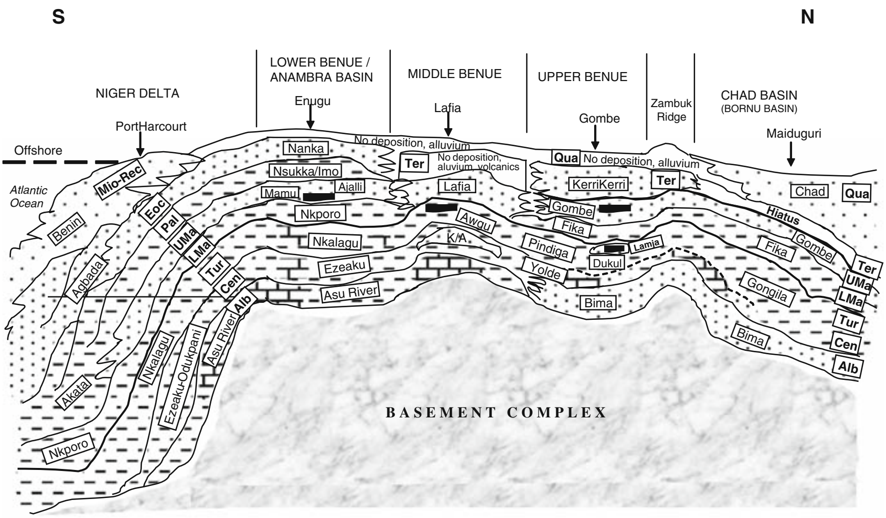

Fig. 4.2 Idealized N–S stratigraphic cross-section across the Benue Trough and the relationship to the Niger Delta and the Chad Basin (vertical scale exaggerated; erosion and uplift not considered)

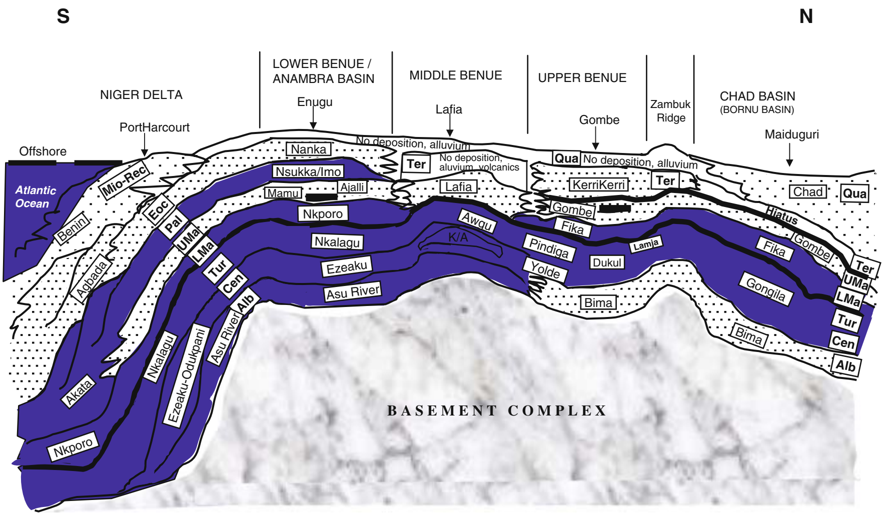

Fig. 4.3 Idealized N–S stratigraphic cross-section across the Chad Basin–Benue Trough – Niger Delta depicting a connected Trans-Atlantic seaway between the South Atlantic and the Tethys Sea during the Coniacian – Turonian

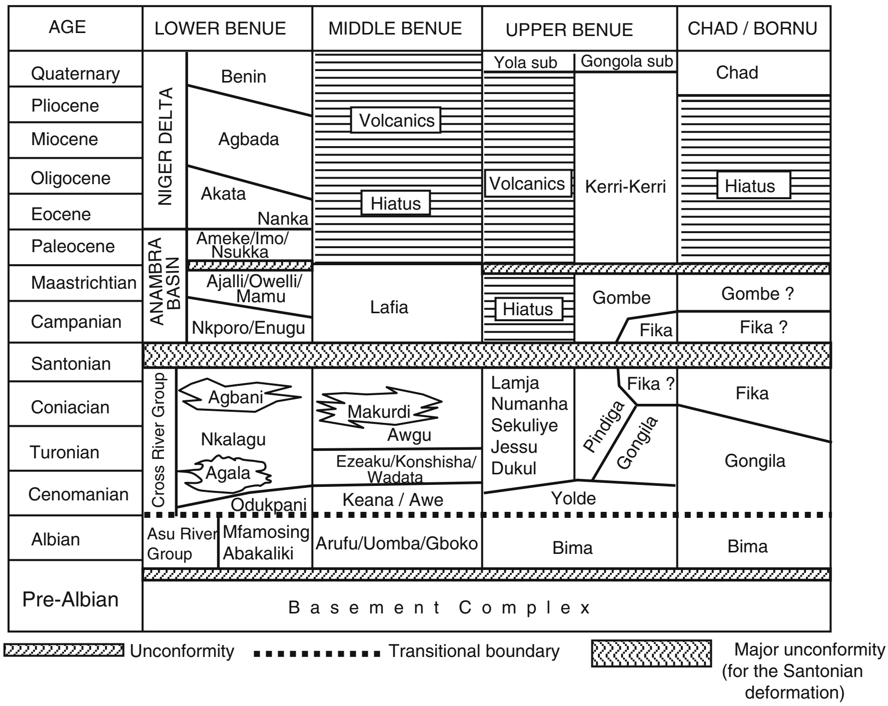

Fig. 4.4 Stratigraphic successions in the Benue Trough and the Nigerian sector of the Chad Basin

The Lower Benue Trough and the Anambra Basin

Sedimentation in the Lower Benue Trough commenced with the marine Albian *Asu River Group*, although some pyroclastics of Aptian – Early Albian ages have been sparingly reported (Ojoh, 1992). The Asu River Group in the Lower Benue Trough comprises the shales, limestones and sandstone lenses of the *Abakaliki Formation* in the Abakaliki area and the *Mfamosing Limestone* in the Calabar Flank (Petters, 1982). The marine Cenomanian – Turonian *Nkalagu Formation* (black shales, limestones and siltsones) and the interfingering regressive sandstones of the *Agala* and *Agbani Formations* rest on the Asu River Group. Mid-Santonian deformation in the Benue Trough displaced the major depositional axis westward which led to the formation of the *Anambra Basin*. Post-deformational sedimentation in the Lower Benue Trough, therefore, constitutes the Anambra Basin. Sedimentation in the Anambra Basin thus commenced with the Campanian-Maastrichtian marine and paralic shales of the *Enugu* and *Nkporo Formations*, overlain by the coal measures of the *Mamu Formation*. The fluviodeltaic sandstones of the *Ajali* and *Owelli Formations* lie on the Mamu Formation and constitute its lateral equivalents in most places. In the Paleocene, the marine shales of the *Imo* and *Nsukka Formations* were deposited, overlain by the tidal *Nanka Sandstone* of Eocene age. Downdip, towards the Niger Delta, the *Akata Shale* and the *Agbada Formation* constitute the Paleogene equivalents of the Anambra Basin (Figs. 4.2, 4.4, 4.5, and 4.6; Explanatory Note 4).

The Enugu and the Nkporo Shales represent the brackish marsh and fossiliferous pro-delta facies of the Late Campanian-Early Maastrichtian depositional cycle (Reijers and Nwajide, 1998). Deposition of the sediments of the Nkporo/Enugu Formations reflects a funnel-shaped shallow marine setting that graded into channeled low-energy marshes. The coal-bearing Mamu Formation and the Ajali Sandstone accumulated during this epoch of overall regression of the Nkporo cycle. The Mamu Formation occurs as a narrow strip trending north–south from the Calabar Flank, swinging west around the Ankpa plateau and terminating at Idah near the River Niger (Fig. 4.5). The Ajali Sandstone marks the height of the regression at a time when the coastline was still concave. The converging littoral drift cells governed the sedimentation and are reflected in the tidal sand waves which are characteristic for the Ajali Sandstone. The best exposure of the Nkporo Shale is at the village of Leru (Lopauku), 72 km south of Enugu on the Enugu – Portharcourt express road, while that of Enugu Shale is at Enugu, near the Onitsha-Road Flyover. The Mamu Formation is best exposed at the Miliken Hills in Enugu, with well-preserved secions along the road cuts from the King Petrol Station up the Miliken Hills and at the left bank of River Ekulu near the bridge to Onyeama mine.

The Nsukka Formation and the Imo Shale mark the onset of another transgression in the Anambra Basin during the Paleocene. The shales contain significant amount of organic matter and may be a potential source for the hydrocarbons in the northern part of the Niger Delta (Reijers and Nwajide, 1998). In the Anambra Basin, they are only locally expected to reach maturity levels for hydrocarbon expulsion. The

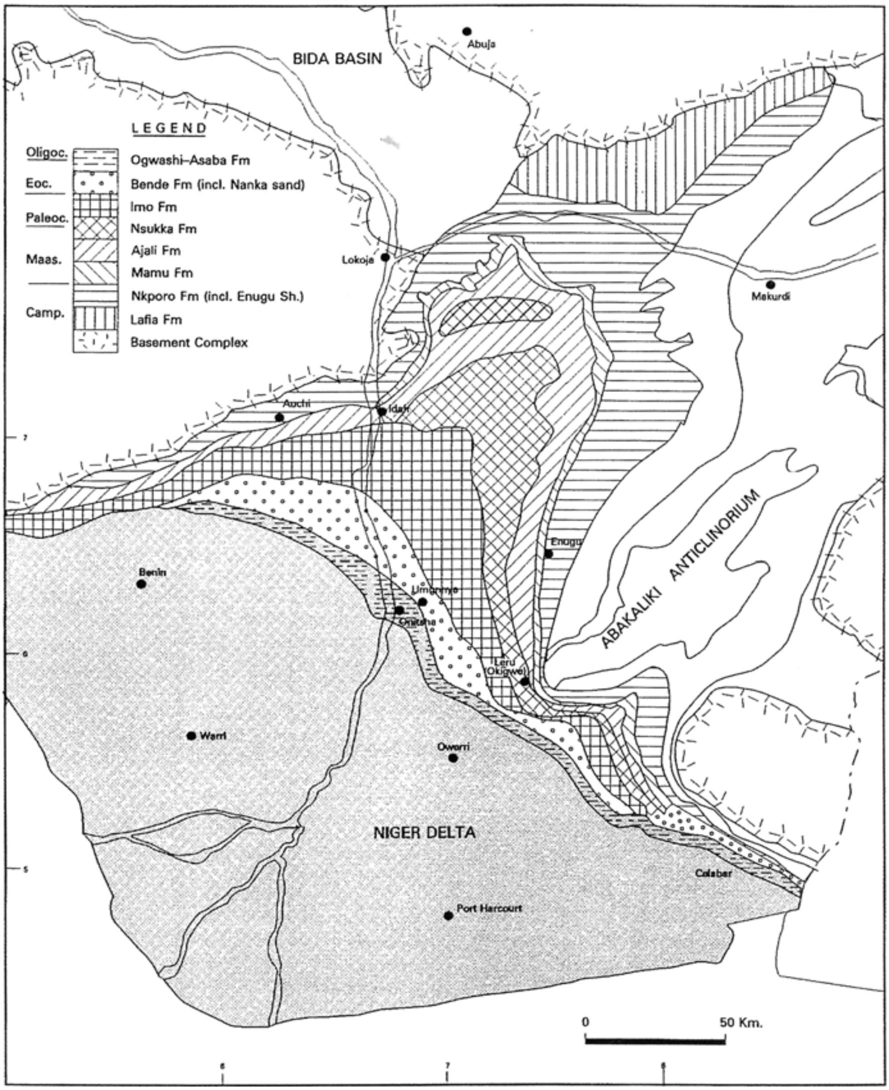

Fig. 4.5 Geological sketch map of the Anambra Basin

Eocene Nanka Sands mark the return to regressive conditions. The Nanka Formation offers an excellent opportunity to study tidal deposits. Well-exposed, strongly assymetrical sandwaves suggest the predominance of flood-tidal currents over weak ebb-reverse currents. The presence of the latter are only suggested by the bundling of lamine separated from each other by mud drapes reflecting neap tides. A good outcrop of the Nanka Formation is the Umunya section, 18 km from the Niger Bridge at Onitsha on the Enugu – Onitsha Expressway.

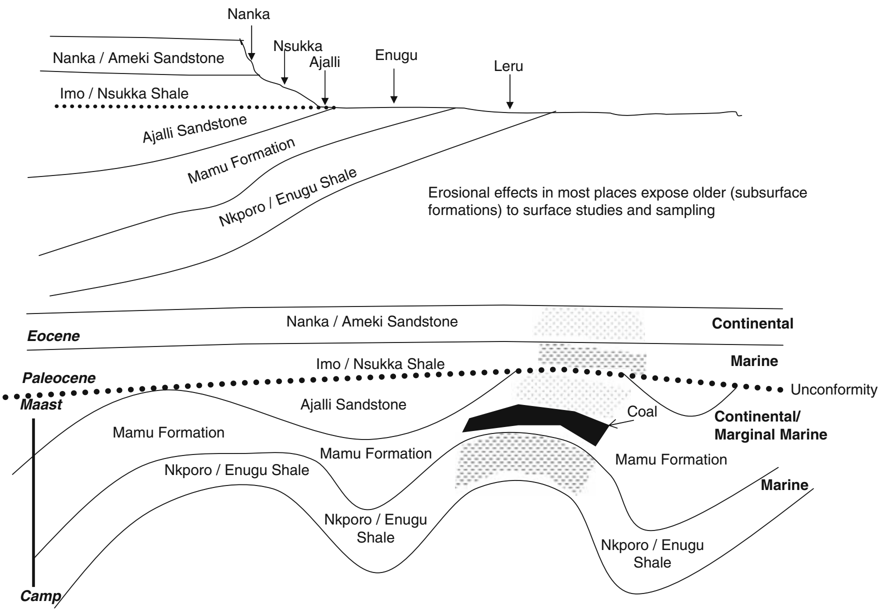

Fig. 4.6 Stratigraphic successions in the Anambra Basin

Explanatory Note 4:
Sedimentary Basins of Nigeria

1. The Benue Trough
   - The Lower Benue Trough
     - The Anambra Basin
   - The Middle Benue Trough
   - The Upper Benue Trough
     - The Gongola Basin
     - The Yola Basin
2. The Chad Basin
3. The Mid-Niger / BidaBasin
4. The Sokoto Basin
5. The Dahomey Basin
6. The Niger Delta Basin

The Middle Benue Trough

In the Middle Benue Trough, around the Obi/Lafia area, six Upper Cretaceous lithogenic formations comprise the stratigraphic succession (Fig. 4.7). This succession is made up of Albian *Arufu*, *Uomba* and *Gboko Formations*, generally

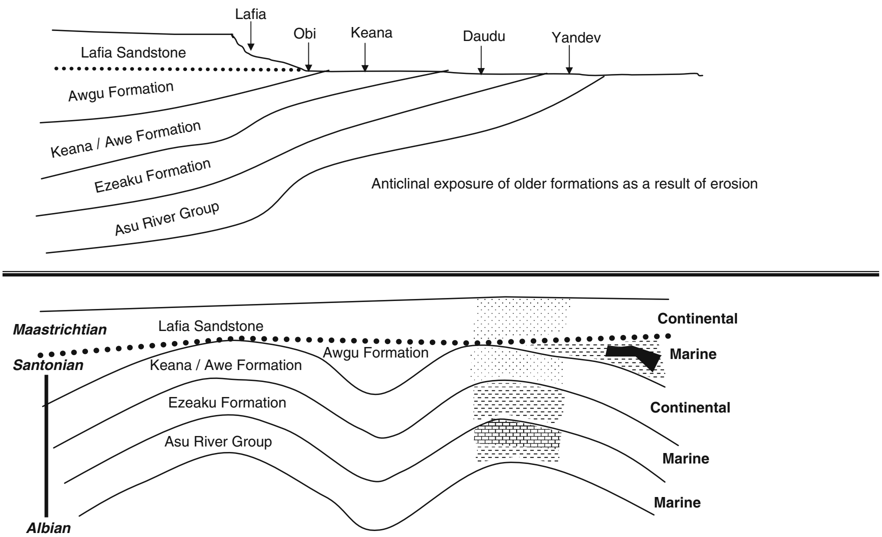

Fig. 4.7 Stratigraphic successions in the Middle Benue Trough

referred to as the *Asu River Group* (Offodile, 1976; Nwajide, 1990). These are overlain by the Cenomanian – Turonian *Keana* and *Awe Formations* and the Cenomanian – Turonian *Ezeaku Formation*. The Ezeaku Formation is coterminous with the *Konshisha River Group* and the *Wadata Limestone* in the Makurdi area. The Late Turonian – Early Santonian coal-bearing *Awgu Formation* lies conformably on the Ezeaku Formation. In the Makurdi area, the Makurdi Sandstone interfingers with the Awgu Formation. The mid-Santonian was a period of folding throughout the Benue Trough. The post-folding Campano-Maastrichtian *Lafia Formation* ended the sedimentation in the Middle Benue Trough, after which widespread volcanic activities took over in the Tertiary.

The Asu River Group outcrops mainly in the Keana anticline east of Keana town and south of Azara; and in the area around Gboko with a typical section in the Quarry of the Benue Cement Company near Yandev. The lithologic composition of the Asu River Group comprises limestones, shales, micacous siltstones, mudstones and clays (Offodile, 1976; Obaje, 1994). The average thickness is estimated to be about 1,800 m.

The Awe Formation was deposited as passage (transitional) beds during the Late Albian Early Cenomanism regression. Its typical sections occur around the town of Awe, where Offodile (1976) estimated the thickness to be about 100 m. The formation consists of flagy, whitish, medium to coarse grained calcareous sandstones, carbonaceous shales and clays. The Keana Formation resulted from the Cenomanian regression which deposited fluviodeltaic sediments. The formation consists of cross-bedded, coarse grained feldsparthic sandstones, occasional conglomerates, and bands of shales and limestones towards the top. Massive outcrops occur at Keana, Noku, Chikinye, Jangerigeri, Azara, and Daudo.

The deposition of the Ezeaku Formation is attributed to the beginning of marine transgression in the Late Cenomanian. The sediments are made up mainly of calcareous shales, micaceous fine to medium friable sandstones and beds of limestones which are in places shelly. The deposition took place in a presumably shallow marine coastal environment. Outcrops of the Ezeaku Formation include those at Ortesh, about 4 km east of the village of Jangerigeri, where the sediments are composed mainly of shelly limestones (almost entirely of oystr shell). In the bank of River Tokura, about 20 km east of Keana town, on the Chikinye – Awe road, a typical section of the Ezeaku Formation occurs, consisting mainly of intercalations of shelly limestones and black shales, with brownish fine to coarse grained feldspartic sandstones at the top.

The deposition of the Awgu Formation marks the end of marine sedimentation in this part of the Benue Trough. The formation is made up of bluish-grey to dark-black carbonaceous shales, calcareous shales, shaley limestones, limestones, sandstones, siltones, and coal seams. The major outcrop of the coal-bearing Awgu Formation is at the bank of River Dep in Shankodi, 7 km to the west of the village of Jangwa. Along the bank of this river, the coal seams can be traced laterally for about 500 m. The borehole cores of the Steel Raw Materials Exploration Agency (formerly National Steel Council) stock-piled at the Obi camp contain coal seams and coal bands at various depths within the Awgu Formation. The occurrence of low diversity arenaceous foraminifera in the Awgu Formation (Fig. 4.8) indicate deposition in marshy, deltaic and shallow marine conditions (Obaje, 1994).

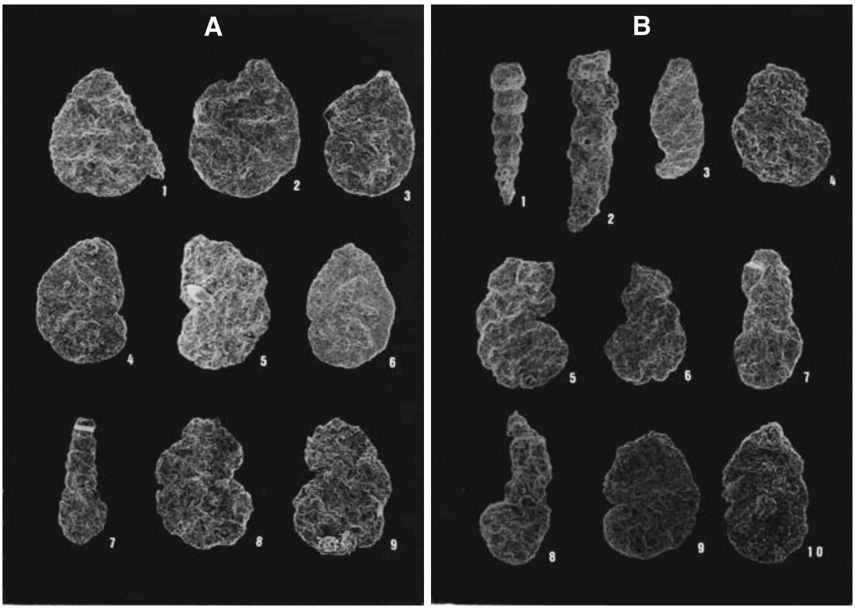

Fig. 4.8 Arenaceous benthic foraminifera from the Turonia – Coniacian Awgu formation in the Middle Benue Trough, indicating marshy – shallow water – deltaic conditions (captured from Obaje, 1994)

The Lafia Formation is the youngest formation in this area. The formation was deposited under continental condition (fluviatile) in the Maastrichtian and lies unconformably on the Awgu Formation. It is lithologically characterized by ferruginized sandstones, red, loose sands, flaggy mudstones, clays and claystones. Outcrops and sections of the Lafia Formation occur in and around the town of Lafia, and along the bank of River Amba on the Lafia – Doma road.

The Upper Benue Trough

The Upper Benue Trough is made up of two arms, the Gongola Arm and the Yola Arm (although some authors have sub-divided the Upper Benue Trough to include a third central Lau-Gombe sub-baisn, eg. Akande et al., 1998), and the stratigraphic succession is as shown on Figs. 4.4, 4.9 and 4.10. In both arms of the basin, the Albian *Bima Sandstone* lies unconformably on the Precambian Basement. This formation was deposited under continental conditions (fluvial, deltaic, lacustrine) and is made up of coarse to medium grained sandstones, intercalated with carbonaceous clays, shales, and mudstones. The Bima Sandstone was subdivided by Carter et al. (1963) into a Lower, Middle and Upper Bima. The Middle Bima is reported to be shaley in most parts with some limestone intercalations and was assumed to be deposited under a more aqueous anoxic condition (lacustrine, brief marine). An

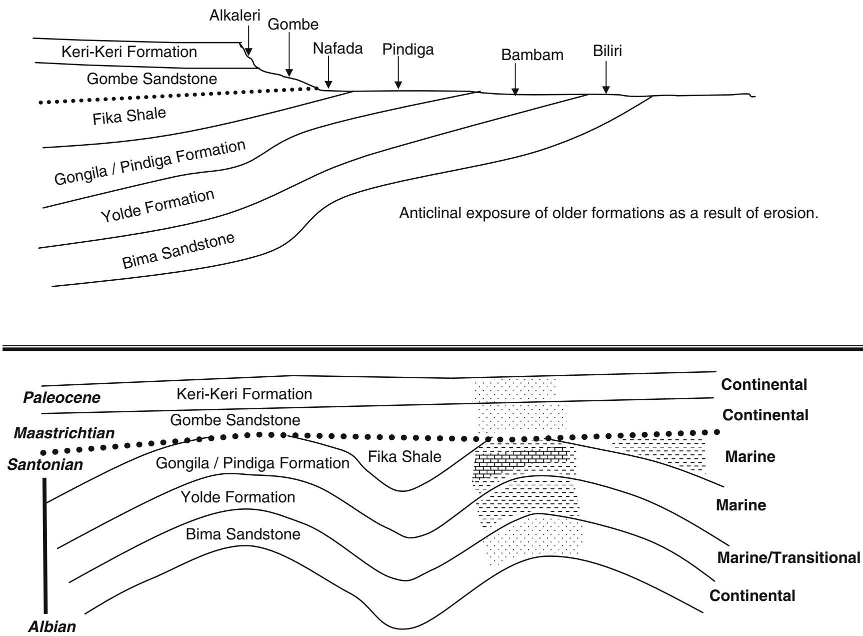

Fig. 4.9 Stratigraphic successions in the Upper Benue Trough (Gongola Arm)

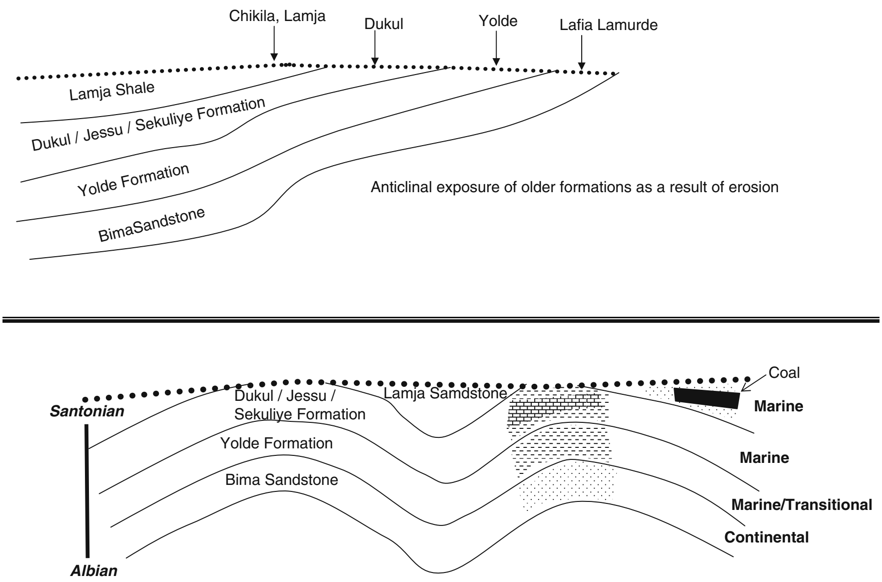

Fig. 4.10 Stratigraphic successions in the Upper Benue Trough (Yola Arm)

approximation to this description are the dark, carbonaceous shales within the Bima Sandstone in the section along the river channel to the south of the bridge, 200 mm (just) before the village of Bambam. Similar shales also occur within units of the Bima Sandstone that outcrop extensively on the Lamurde anticline (2 km to the town of Lafiya, on the Gombe – Numan road). Good exposures of the Bima Sandstone (however, without the so-called Middle Bima can be studied at Biliri, Filiya and Shani.

The *Yolde Formation* lies conformably on the Bima Sandstone. This formation of Cenomanian age represents the beginning of marine incursion into this part of the Benue Trough. The Yolde Formation was deposited under a transitional/coastal marine environment and is made up of sandstones, limestones, shales, clays and claystones. Typical localities of the Yolde Formation are along the valley of Pantami River in Gombe town and in the village of Yolde, 50 km to Numan town.

In the Gongola Arm, the laterally equivalents *Gongila* and *Pindiga* Formations and the possibly younger *Fika Shale* lie conformably on the Yolde Formation. These formations represent full marine incursion into the Upper Benue during the Turonian – Santonian times. Lithologically, these formations are characterized by the dark/black carbonaceous shales and limestones, intercalating with pale colored limestones, shales and minor sandstones. The type locality of the Gongila Formation is at the Quarry of the Ashaka Cement Company at Ashaka, while that of Pindiga Formation is at Pindiga village. The Fika Shale is lithologically made up of bluish-greenish carbonaceous, sometime pale gypsiferous, highly fissile shales

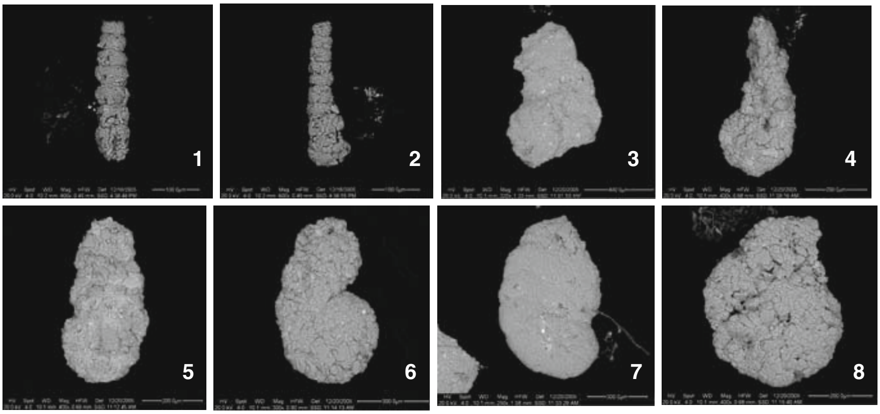

Fig. 4.11 Arenaceous foraminifera from the Sekuliye Formation in the Yola Arm of the Upper Benue Trough, indicating shallow marine environment when interpreted alongside the planktonic assemblage. *1. Ammobaculites plummerae*, *2. Ammobaculites sp.*, *3. Ammobaculites bauchensis*, *4. Ammobaculites gombensis*, *5. Ammobaculites coprolithiformis*, *6. Ammobaculites benuensis*, *7. and 8. Haplophragmoides bauchensis*

and occasional limestones in places. The formation is entirely marine and has its type locality at Nafada village on the Gombe – Ashaka road.

In the Yola Arm, the *Dukul, Jessu* and *Sekuliye Formations*, the *Numanha Shale*, and the *Lamja Sandstone* are the Turonian – Santonian equivalents of the Gongila and Pindiga Formations. The Turonian – Santonian deposits in the Yola Arm are lithologically and palaeoenvironmentally similar to those in the Gongola Arm, except the Lamja Sandstone which has a dominating marine sandstone

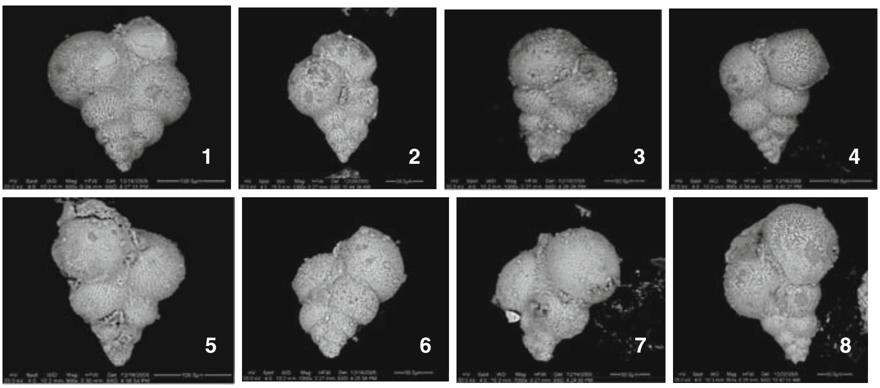

Fig. 4.12 Planktonic foraminifera from the Sekuliye formation in the Yola Arm of the Upper Benue Trough, indicating deep to shallow marine environment when interpreted alongside the arenaceous assemblage. *1.*, *2. Heterohelix globulosa*, *3.*, *4.*, *5.*, *6. Heterohelix reussi*, *7. and 8. Pseudotextularia elegans*

lithology. The recovery of diversed assemblages of arenaceous alongside planktonic foraminifera from samples obtained from the Dukul, Jessu and Sekuliye formations (Figs. 4.11, 4.12) indicate deposition in shallow marine – neritic – shelfal environments. The type locality of the Dukul Formation is in the village of Dukul with good exposures also at Bambam and Lakun on the Gombe – Yola road. All the other formations have their type localities in the villages named after them.

The Santonian was a period of folding and deformation in the whole of the Benue Trough. Post-folding sediments are represented by the continental *Gombe Sandstone* of Maastrichtian age and the *Keri–Keri Formation* of Tertiary age. The Gombe Sandstone is lithologically similar to the Bima Sandstone, attesting to the re-establishment of the Albian palaeoenvironmental condition. The Gombe Sandstone Formation, however, contains coal, lignite, and coally shale intercalations which in places are very thick. The type locality of the Gombe Sandstone is along the bank of Pantami River in town. Good exposures are also encountered in many parts of Gombe town and Birin Fulani village.

The Keri–Keri Formation is made up of whitish grey sandstones, siltstones, and claystones with the claystones dominating the lithology in most places, Typical sections are exposed in Gombe Aba, Duku (not Dukul) and Alkaleri.

Chapter 5
The Bornu Basin (Nigerian Sector of the Chad Basin)

The Nigerian sector of the Chad Basin, known locally as the Bornu Basin, is one of Nigeria's inland basins occupying the northeastern part of the country. It represents about one-tenth of the total area extent of the Chad Basin, which is a regional large structural depression common to five countries, namely, Cameroon, Central African Republic, Niger, Chad, and Nigeria. The Bornu Basin falls between latitudes 11°N and 14°N and longitudes 9°E and 14°E, covering Borno State and parts of Yobe and Jigawa States of Nigeria.

The Chad Basin belongs to the African Phanerozoic sedimentary basins whose origin is related to the dynamic process of plate divergence. Notable exceptions, however, are the deformed basinal sequences of the Paleozoic fold belts of Moroco and Mauritania which resulted from the Hercynian convergent motion and collision of Africa and North America, and the Tindouf and Ougarta basins which are Paleozoic successor basins (Burke, 1976; Petters, 1982). It is an intracratonic inland basin covering a total area of about 2,335,000 km^2 with Niger and Chad Republics sharing more than half of the basin. The basin belongs to a series of Cretaceous and later rift basins in Central and West Africa whose origin is related to the opening of the South Atlantic (Obaje et al., 2004). In Nigeria, other inland basins of the same series include the Anambra Basin, the Benue Trough, the Mid-Niger (or Bida) Basin and the Sokoto Basin. The Nigerian sector of the Chad Basin, known locally as the Bornu Basin represents about one-tenth of the whole basin. It constitutes the southeastern sector of the Chad Basin.

Geological and Hydrogeological Setting

Maduabuchi et al. (2006) undertook some groundwater investigations in the Nigerian sector of the Chad Basin and in the process gave some brief descriptions of the geologic and hydrogeologic settings of the Chad Basin. The Precambrian Basement Complex constitutes the bedrock on which sediments ranging in age from Palaeozoic to the Quaternary have been deposited. Furon (1960) suggested that the Chad Basin was a tectonic crosspoint between a NE–SW trending "Tibesti-Cameroon Trough" and a NW–SE trending "Aïr-Chad Trough" in which over 3,600 m of sediments have been deposited. The crystalline basement outcrops in the eastern,

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southeastern, southwestern and northern rims of the basin; its configuration beneath the sediments around the lake has the semblance of horst and graben zone (Oteze and Foyose, 1988). The stratigraphy consists of sediments accumulations dated from Paleozoic (dominantly arenaceous), Lower Cretaceous (Continental Intercalaire arenaceous), Middle Cretaceous (marine limestones), Continental Hamadien (equivalent of the Continental Intercalaire), Upper Cretaceous (continental sandstones), Continental Terminal (lacustrine and deltaic types of sediments dated Mio-Pliocene) lying unconformably on the Upper Cretaceous and the basement complex.

The Continental Terminal Formations are represented by the "Kerri–Kerri" Formations dated Palaeocene age in Nigeria, elsewhere it is dated Eocene–Miocene. Recently drilled boreholes in parts of Cameroon, Chad and Nigeria have encountered the Continental Terminal sediments similar in every respect to the extensive outcrops in southern Chad, Cameroon and north-central Chad (Oteze and Foyose, 1988). The Chad Basin in the Nigerian sector shows a depositional sequence from top to bottom: Quaternary, Early Pliocene, Continental Terminal, Gombe Sandstone, Fika Shale, and Gongila, Yolde and Bima Sandstones Formations (Maduabuchi et al., 2006).

The Bima Sandstone is the lateral equivalent of the regional Nubian Sandstone which is the target aquifer unit in Niger, Chad, Sudan, Libya and Algeria. It is the deeper part of the aquifer series in the Nigerian sector of the basin and rests unconformably on the basement. The thickness ranges from 300 to 2,000 m and the depth between 2,700 and 4,600 m. The Plio-Pleistocene Chad Formation and the younger overlying Quaternary sediments are the main source of groundwater in the in the Nigerian sector of the Chad Basin. The Chad Formation is essentially an argillaceous sequence in which minor arenaceous horizons occur. Barber and Jones (1965) named three clearly defined arenaceous horizons in the NE Nigeria of Chad Basin consisting of the upper aquifer and two confined middle and lower aquifers. The upper aquifer consists of Quaternary (lower Pleistocene) alluvial deposits of lake margin origin, alluvial fans or deltaic sediments related to sedimentation around Lake Chad covered in many locations by recent sand dunes. The thickness increases considerably from 15 to 100 m north of the lake. The reservoir is composed of interbedded sands, clays, silts and discontinuous sandy clay lenses which give aquifer characteristic ranging from unconfined, semi-confined to confined type. The transmissivity ranges from 0.6 to 8.3 m2/day and the aquifer which recharges from rainfall and run-off is mainly used for domestic water supply (hand dug wells and shallow boreholes), vegetable growing and livestock watering (Maduabuchi et al., 2006). The lower Pliocene sequence composed of grey to bluish grey clays varying in thickness from few tens of meters to over 350 m at the edge of the lake separates the middle aquifer from the upper aquifer. The middle aquifer is the most extensively encountered aquifer in the Nigerian sector of the Chad Basin. It lies at a depth between 240 and 380 m and consists of 10–40 m thick sand beds with interbedded clays and diatomites of Early Pliocene age. The sand fraction consists of moderately coarse to coarser grains of quartz, feldspar, mica and Fe-oxides. The aquifer geometry has a gentle northeast dip and does not outcrop in the Nigeria sector of the Chad Basin. The average transmissivity is 360 m2/day and the hydraulic gradient is 0.015% in the NE direction (Maduabuchi et al., 2006). The aquifer bears mineralized water comparing to the upper unit and 70% of the pumping wells are artesian (head pressure up to 21 m above ground surface) or the water table rises up to shallow depth due to pressure release. Heavy pumping, to meet water demand, has lowered the water table of the shallow and deep artesian aquifers since the beginning of the 1980s (between 1.1 and 3 m/year) (Oteze and Foyose, 1988; Ndubisi, 1990; Goni et al., 2000) and has provoked lose of artesian conditions in some wells.

Tectonic Setting

A model of the tectonic setting of the Chad Basin in general was presented by Genik (1992). Four stages characterized the tectonic framework and evolution of the Bornu Basin:

Pan African Crustal Consolidation Stage (750–550 Ma)

Major basement lineaments and faults were produced within the basin during the Pan African crustal consolidation. The structures formed precursor directions or the "essential structure" for the future rift basins. The dominant NE–SW trending fault system (Avbovbo et al., 1986; Benkhelil, 1989) of the Bornu Basin belongs to this phase.

Early Rift Stage (130–98 Ma)

This was the period of the rift basin formation. The Benue Trough and Bornu Basin represent the third and failed arm of the triple junction rift system which was formed during the break – up of the Gondwanaland and the start of the separation of the African and South American continents in the early Cretaceous at about 130 Ma (Benkhelil, 1989; Fairhead and Blinks, 1991; Genik, 1992). This separation gave birth to the South Atlantic Ocean. According to these authors, the strike – slip movements of wrench faults which originated from South America to Nigeria in response to the separation of the two continents played a major role in the development of the Bornu Basin. The lateral movements of a block relative to the other crustal blocks at this time resulted in the transtensional opening of the Benue Trough and the Bornu Basin.

Late Rift Stage (98–75 Ma)

Rift formation slowed down and a tectono–custic rise in sea level led to epicontinental transgressions which came from the Tethys and the South Atlantic via Algeria, Nigeria and the Benue Trough respectively to the basin. This has been proved from macro- and micro-fauna (Reyment, 1980; Allix et al., 1981; Benkhelil and Robineau, 1983; Okosun, 1992). According to Genik (1992), the slow down in the rift development due to changes in the stress regime caused by variations in the spreading rate and direction between the Equatorial and Southern Atlantic plates culminated in a marked tectonic pulse at about 85 Ma. This tectonic pulse was a basin – modifying event, which caused folding and basin inversion in the Benue, Yola and Bornu basins (Avbovbo et al., 1986; Genik, 1992; Guiraud, 1993). The subordinate NW–SE trending fault system which have a restricted occurrence in the sediments and was developed as relief faults in response to changes in the stress regime after the Santonian deformation belong to this phase. Majority of the faults in the basin are basement-involved faults; movements along these faults led to high angled faults in the overlying strata. According to Avbovbo et al. (1986), the basement-involved faults resulted in the genesis of horst, grabens and similar structures. Many of the faults within the basin terminate below the Cretaceous – Tertiary boundary unconformity. The tectonic regime during this phase was probably dominated by tensional movement as indicated by the preponderance of high – angled normal faults and the scarcity of reverse faults. Folds within the basin are simple and symmetrical with low fold frequencies and amplitudes which increase towards the centre of the basin. They have a spatially restricted occurrence to the southeastern part of the basin (Avbovbo et al., 1986). According to these authors, numerous faults from the two fault systems transgress the folds. The fold axes extend over long distances and in most cases without effective strike closures. The chief fold axes strike NW–SW. The folds probably are flexural folds which developed from the graben subsidence in the basement. An anticline and syncline at Dumbluwa and Mutwe both which trend NW–SE constitute the dominant folds within the basin.

Post Rift Stage (66–0 Ma)

There was no significant tectonic activity during this phase. Earth movements ceased within the basin before 66 Ma which represents the Paleocene, hence no faulting and significant folding has been observed in the Tertiary and younger strata. These units have gentle dips to the north and northeast towards the centre of the Chad Basin, which is in conformity with the general slope direction of the basin.

Lithostratigraphy

Geologic outcrops in the Chad Basin are scarce, being blanketed by Quaternary sediments. The rare exposures of the older series of Early Cretaceous are mostly found in the Niger Republic part of the basin. The sedimentary fill in most parts of the basin is made of Late Cenozoic – middle Eocene continental sediments and

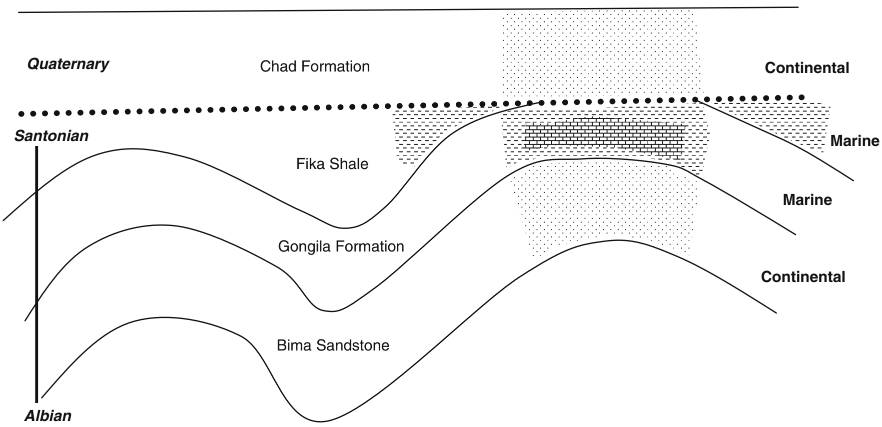

Fig. 5.1 Stratigraphic successions in the Nigerian sector of the Chad Basin

Cretaceous and Tertiary series accumulating preferentially in tectonic rifts. Data gathered from the adjacent basins and boreholes indicate that the Bornu Basin is made up of five stratigraphic units that include the Bima Sandstone at the bottom, the Gongila Formation, the Fika Shale, the Keri–Keri and Chad Formations. In most cases the Chad Formation lies directly unconformably on the Fika Shale (Fig. 5.1).

The Bima Sandstone

The stratigraphic succession in the Bornu Basin commenced in the Albian–Turonian time with deposition of the Bima Sandstone resting unconformably on the Precambrian basement. This formation is diachronous and probably of Albian–Turonian age. It is a poorly sorted, medium to coarse-grained, thick to massive – bedded, and cross – stratified feldspathic sandstone with variable colors; from brown, reddish brown, grey to white. The Bima Sandstone evolved from the weathering of the basement rocks. It constitutes the upper part of the regionally known Continental Intercalaire. This comprises all sediments derived from the Basement Complex between the Permian and Albian times in response to uplift and weathering.

The Gongila Formation

The Bima Sandstone is overlain by the Gongila Formation This is composed of thin to moderately thick interbeds of calcareous gray to dark shales and silty sandstones deposited in a shallow-marine environment. The deposition of this formation is taken to mark the onset of marine incursion into the Chad Basin in the Turonian (Olugbemiro et al., 1997; Obaje et al., 2004). Carter et al. (1963) recorded an average thickness of 420 m and the occurrence of numerous Cenomanian – lower Turonian ammonites from the basal limestone facies in outcrop of the formation in adjacent basin. Avbovbo et al. (1986) reported a thickness of 0–800 m from seismic data while Okosun (1995) and Olugbemiro et al. (1997) recorded a thickness of 1,410 m from Kinasar-1 well and between 162–420 m from Kanadi and Albarka wells respectively.

The Fika Shale

The Fika (Shale) Formation overlies the Gongila Formation and was deposited during the continued marine transgression in the Turonian–Coniacian. Carter et al. (1963) dated this formation as Turonian–Maastrichtian in age. It is a fully marine blue–black shale locally gypsiferous with intercalation of limestones. The recovery of diversed assemblages of arenaceous alongside planktonic foraminifera (Figs. 5.2, 5.3) in samples obtained from the Fika Shale indicates deposition in shallow to deep marine environments. Thicknesses of 430 m, 0–900 m, 890 m and 840–1,453 m were recorded from exploratory wells by Carter et al. (1963), Avbovbo et al. (1986), Okosun (1995) and Olugbemiro et al. (1997), respectively. The Fika Shale and the underlying Gongila Formation are said to constitute the potential petroleum source rocks in the Bornu Basin (Moumouni, 2008).

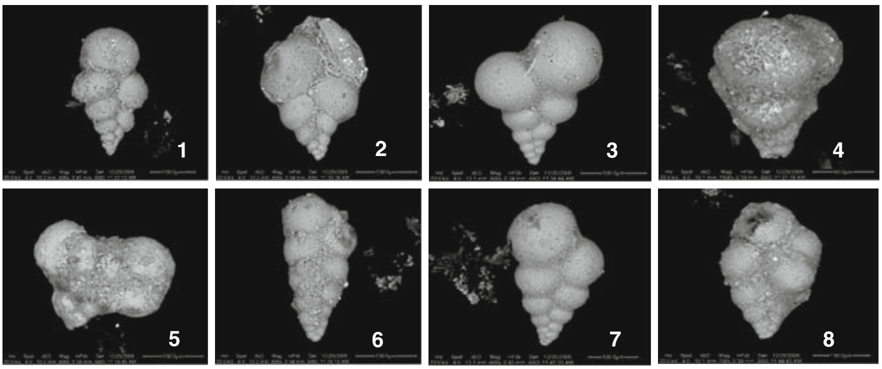

Fig. 5.2 Planktonic foraminifera from the Fika Shale in the Nigerian sector of the Chad Basin, indicating deep to shallow marine environment when interpreted alongside the arenaceous assemblage. 1. *Heterohelix reymenti*, 2. *Heterohelix pulchra*, 3. *Pseudotextularia elegans*, 4. *Guembelitra sp.*, 5. *Pseudoplanoglobulina austinana*, 6. *Heterohelix moremani*, 7. *Heterohelix globulosa, and* 8. *Pseudoplanoglobulina sp.*

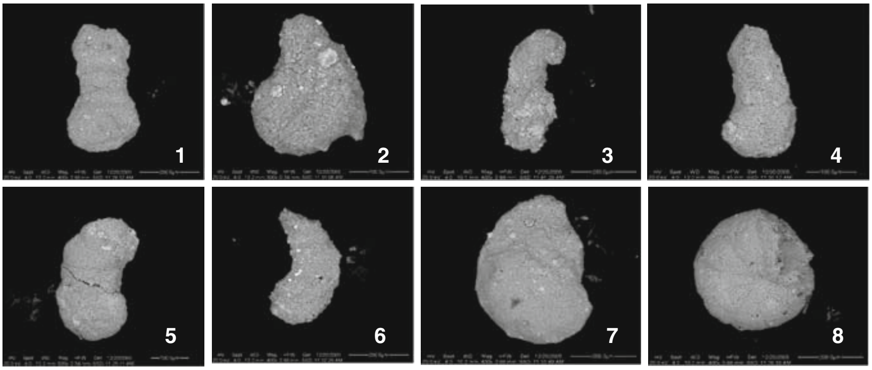

Fig. 5.3 Arenaceous foraminifera from the Fika Shale in the Nigerian sector of the Chad Basin, indicating shallow marine environment when interpreted alongside the planktonic assemblage. 1. *Ammobaculites coprolithiformis*, 2. *Ammobaculities benuensis*, 3. *Ammobaculites sp.*, 4. *Ammobaculites gombensis*, 5., 6. *Ammobaculites benuensis*, 7. *and* 8. *Haplophragmoides bauchensis*

The Gombe Sandstone

This formation has not been penetrated by wells used variously in the past for the study of the Chad Basin and its occurrence in any significant proportion in the basin is doubtful. Generally, it is made of intercalations of siltstones, shales and ironstones but without coal seam interactions as in the Upper Benue Trough (Obaje et al., 1999). The Gombe Sandstone was deposited during the Maastrichtian in an estuarine/deltaic environment.

The Kerri–Kerri Formation

This formation was not encountered in any of the exploratory oil wells drilled by the Nigerian National Petroleum Cooperation (NNPC) since drilling was concentrated north of Maiduguri around Lake Chad. It occurs in the south of the basin along the boundary with the Benue Trough. The formation consists of cross-bedded ferruginized sandstone and massive gritty clay with colors varying from reddish brown, pink, yellow, purple to grey. Carter et al. (1963) measured a thickness of 130 m in the adjoining Upper Benue Trough.

The Chad Formation

This is the uppermost Pliocene–Pleistocene formation consisting of fluviatile and lacustrine thick bodies of clay, separating three major sand bodies, with lenses of diatomite up to a few meters thick (Wright, 1985). The sand is uncemented with angular and subangular quartz grains. The clay is massive and locally gritty in texture. Both the sand and the clay are of variable colors ranging from brown, yellow, and white to grey. The three sand bodies correspond to the upper, middle and lower aquifers defined by Barber and Jones (1965). The lower member is made of sands and sandy clays while the middle and the upper consist of sandy clays with diatomite and clays and sands, respectively. Based on exploratory wells studied by Moumouni et al. (2007), the Fika / Chad Formations boundary is fixed at about 1,500 m depth except in Kasade – 1 where it is estimated to be at about 700 m.

Chapter 6
The Sokoto Basin (Nigerian Sector of the Iullemmeden Basin)

The Iullemmeden Basin in north-western Nigeria is known locally as the "Sokoto Basin". It consists predominantly of a gently undulating plain with an average elevation varying from 250 to 400 m above sea-level. This plain is occasionally interrupted by low mesas. A low escarpment, known as the "Dange Scarp" is the most prominent feature in the basin and it is closely related to the geology.

The sediments of the Iullemmeden Basin were accumulated during four main phases of deposition. Overlying the Pre-Cambrian Basement unconformably, the Illo and Gundumi Formations, made up of grits and clays, constitute the *Pre-Maastrichtian* "Continental Intercalaire" of West Africa. They are overlain unconformably by the *Maastrichtian Rima Group*, consisting of mudstones and friable sandstones (Taloka and Wurno Formations), separated by the fossiliferous, shelly Dukamaje Formation. The Dange and Gamba Formations (mainly shales) separated by the calcareous Kalambaina Formation constitute the *Paleocene Sokoto Group*. The overlying continental Gwandu Formation forms the *Post-Paleocene Continental Terminal*. These sediments dip gently and thicken gradually towards the northwest, with a maximum thickness of over 1,200 m near the frontier with Niger Republic. The geological map of the Sokoto Basin of northwestern Nigeria is shown on Fig. 6.1 while Fig. 6.2 summarizes the geological sequence in the basin.

Pre-Maastrichtian Deposits (The Continental Intercalaire)

In the Sokoto Basin, the pre-Maastrichtian sediments are of fluviatile and lacustrine origin. They belong to the *Illo* and *Gundumi* Formations which extend northwards into Niger Republic. These deposits belong to the upper part of the "Continental Intercalaire" which comprises a group of poorly fossiliferous sediments covering a very extensive area, bounded on the west by the crystalline basement rocks of Niger Republic, and on the east by the Quaternary sands of the Chad Basin. The Gundumi Formation lies unconformably on the basement and consists of basal conglomerates, and gravels with sand and variegated clays increasing upwards; the maximum thickness is about 350 m. The Illo Formation includes interbedded clays and grits, with an intermediate pisolitic and nodular clay member, and attains over 240 m

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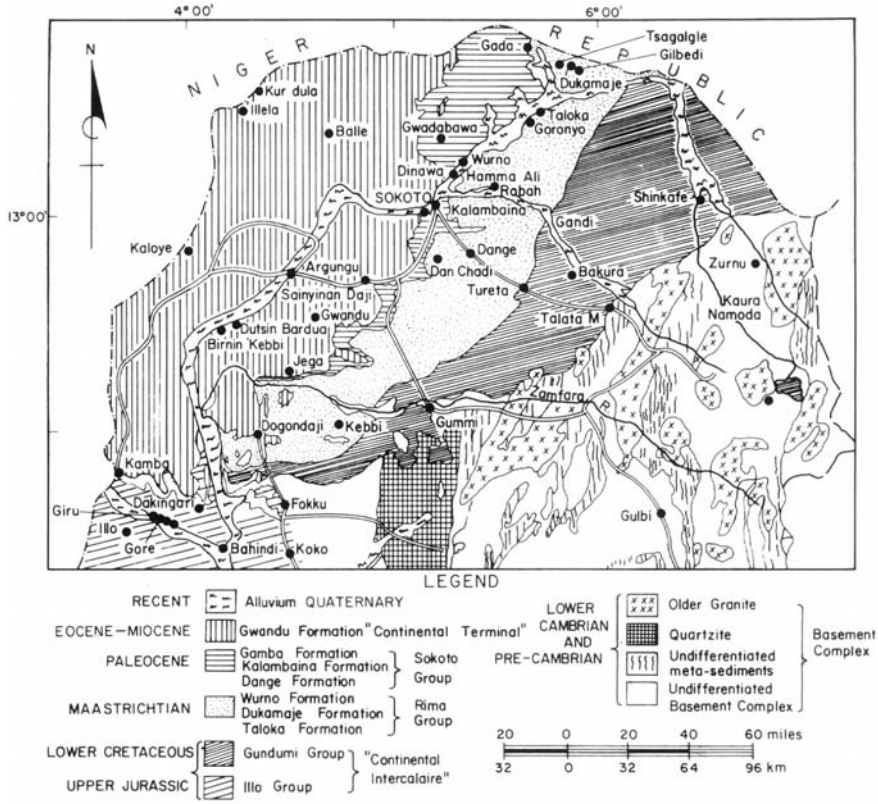

Fig. 6.1 Geological sketch map of the southeastern sector of the Iullemmeden Basin (Sokoto Basin) (After Kogbe, 1981b)

in thickness. The continental period represented by the Gundumi and Illo Formations was terminated by a Maastrichtian marine transgression. The sea penetrated the interior of the continent both from the north (the Tethys), and from the south (Gulf of Guinea), through the mid-Niger Basin. The type section and type locality of the Gundumi Formation are at Dutsin Dambo.

The contact of the Gundumi Formation with the basement is conglomeratic. At Kona Rolga, on the Sokoto-Gusau road, a good exposure of the basal conglomerates occurs at about 11 km north of Talata Mafara where the basement outcrops. These conglomerates outcrop for hundreds of square kilometres, with large, well-rounded pebbles in a massive clayey feldspathic and ferruginous matrix. The pebble conglomerates occur also abundantly around Tureta.

The Illo Formation is a lateral equivalent of the Gundumi Formation. Like the Gundumi sediments, the Illo Formation overlies the basement unconformably. The deposits are continental, fluviatile to fluvio-lacustrine in origin. They dip gently north-westwards with a NE–SW direction of strike. The Illo Formation consists

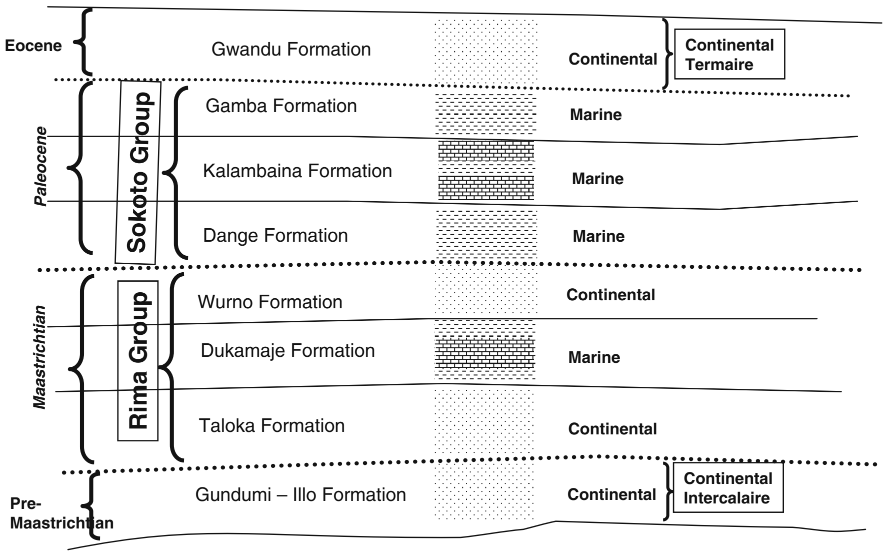

Fig. 6.2 Stratigraphic successions in the Nigerian sector of the lullummeden Basin (Sokoto Basin)

predominantly of cross-bedded grits with a major intercalation of pisolitic and nodular clay. Laterites and lateritic ironstones form a resistant capping on top of the grits and thin layers of multicoloured ferruginous deposits occur randomly within the grits. The type section of the Illo Formation is on the hill east of Gore village about 3.5 km north of Giro.

Correlation has been made with the Bima Sandstone of north-eastern Nigeria, based on structures and contacts with the basement. An outstanding characteristic in the Bima Sandstone is current bedding, which is also a widespread feature in the Illo and Gundumi Formations. In addition, wherever their lower contact could be observed, the Bima Sandstone rests directly on the basement (Murat, 1972). The same observation is true for the Gundumi and Illo Formations which are underlain by basal conglomerates that become hardened towards the contact with the basement. It has also been suggested that the Bima Sandstone was deposited by fluviatile currents flowing from the north-west, repeatedly interrupted by minor disturbances, a fact confirmed by the direction of cross-beds in the area.

The "Continental Intercalaire" is important in Africa. It is remarkable for the unity of facies, flora and fauna, implying that there was a uniform climate over large parts of the continent, and a continuous transition from the Jurassic to Cretaceous. The Karoo Series of South Africa can be correlated with the upper beds of the lower portion of the "Continental Intercalaire" (Furon, 1960). The "Continental Intercalaire" corresponds to the upper part of the Nubian Sandstone, which, in the Arabo-Nubian shield, begins at the base of the Palaeozoic. The Iullemmeden Basin, as well as many other parts of North and South Africa, experienced extensive periods of continental sedimentation with the accumulation of fluvio-lacustrine nature in pre-Cenomanian times. The northern limits of the continental deposition coincides with the Algeria- Moroccan Sahara and extends eastward into Egypt and the Sudan. The southern limits extend as far as South Africa.

Maastrichtian Deposits (The Rima Group)

The second phase in the depositional history of the sediments of the Sokoto Basin began during the Maastrichtian, when the Rima Group was deposited unconformably on pre-Maastrichtian continental beds. The type sections of the three Maastrichtian formations are at Taloka, Dukamaje and Wurno. The unconformity is well exposed at Wurno. The lower sandstones and mudstones of the Rima Group belong to the Taloka Formation; with a maximum thickness of about 100 m. Excellent exposures of the upper portion of the formation can be observed at Goronyo, Taloka and Shinaka. The basal beds are exposed further to the east near Takarau and Gidan Mata. The formation consists essentially of white, fine-grained, friable sandstones and siltstones, with thin intercalated mudstones and carbonaceous mudstones or shales. In the Gilbedi district, on the northern side of the Rima valley, the Taloka Formation occupies the base of a high scarp feature which is the northern terminal of the "Dange Scarp", a prominent topographic feature which runs southwards towards Dange. The upper levels of the escarpment are occupied by younger formations. The hills near Goronyo on the southern side of the Rima valley are lower. The greater part of the hill is made up of sediments of the Taloka Formation, with the overlying Dukamaje Formation poorly developed. The Wurno Formation is only represented at the summit where it is preserved by laterite.

The Taloka Formation

The type locality of the Taloka Formation is at Taloka village, about 2 km east of Goronyo. The type section is on a hill that forms part of a continuous exposed ridge between Shinaka, through Taloka to Goronyo. These beds disintegrate rapidly on exposure, and the base of the ridge is covered by a layer of overburden. Four major lithofacies can be recognized.

(i) The lowest siltstone layer is reddish-purple to brown in colour. The siltstone is clayey and poorly consolidated. The total thickness is about 6 m.
(ii) Whitish-grey, light-brown siltstone with thin beds of carbonaceous shale; semi-consolidated with intercalations of grey siltstone with black lignitic siltstone. The total thickness is about 5 m.
(iii) Well-bedded light b rown, friable siltstone with alternate bands of yellowish brown clay-stone and carbonaceous shale with a total thickness of about 18 m.
(iv) White poorly-consolidated siltstone, alternating with brown layers attaining a maximum thickness of 13 m. The topmost beds are in contact with the

"*Callianassa*-burrowed" horizon of the overlying Dukamaje Formation. The siltstones are generally finely bedded often varicoloured as a result of chemical alteration. The thin-beds or "laminae" are typical of tidal flat environments and each lamina represents an individual tidal cycle. Small load casts and bioturbation structures are abundant. These are indicative of low energy marine environments (e.g. bays), lenticular bedding ("Flaser bedding") and wavy bedding are also common. These point to a tidal-flat environment.

The Dukamaje Formation

The Dukamaje Formation consists predominantly of shales with some limestones and mudstones. The type section of the formation is exposed on the hill south-west of the village of Dukamaje. The base of the section is well exposed and the sharp contact with the underlying Taloka Formation can be observed in several sections on the foot of the hill south-west of the village The formation varies from about 12 m at the type area to less than 0.5 m, 50 km further south. The fauna includes the upper Maastrichtian ammonite, *Libycoceras* sp., found at Dukamaje and Gilbedi. Excellent exposures of the formation can also be observed at the village of Dogondaji about 3 km south of Dukamaje and at the Wurno Hills where the base of the formation does not outcrop. The thickness of the Dukamaje Formation at Taloka is about 6 m. It thins out rapidly westwards towards Goronyo and disappears about 1 km from Taloka. At Gilbedi, on the hills south of the village, excellent sections of the Dukamaje Formation can be observed. Details of the base of the formation are best studied in Gilbedi where the outcrops are well preserved. Detailed lithologic description of the Dukamaje Formation exposed at Gilbedi shows that the formation is made up of about 0.15 m ferruginized concretionary bed and ironstone with abundant burrows of *"Callianassa"* at the base, 0.3 m light grey shale with gypsum, 0.5 m of silty shale, 0.1 m of second bone-bed, 0.5 m of siltstone and 0.1 m of second ferruginized concretionary horizon, 3.0 m of greyish gypsiferous shale with some greyish black horizons. The shales are very rich in reptilian bones, 0.5 m of massive gypsiferous and ferruginous altered cocnretionary limestone, 2.0 m of grey laminated shale, gypsiferous, with abundant reptilian bones, 0.8 m of lateritic capping. The presence of two horizons of bone beds at the base of the Dukamaje Formation in Gilbedi is significant and supports the view that the bone bed is due to the action of winnowing forces along the strand-line of a transgressive sea during the Maastrichtian (Kogbe, 1981b).

The Wurno Formation

The Wurno Formation is very similar to the Taloka Formation. The sediments consist of pale friable, fine-grained sandstones, siltstones and intercalated mudstones. In boreholes, the sediments of the Wurno Formation are dark-coloured, which is due to the presence of carbonaceous material and finely disseminated iron sulphides. Good outcrops of this formation can be observed at Gada near the frontier with Niger Republic. The loosely-consolidated nature of the sediments makes them susceptible to weathering. Small-scale load-cast, bioturbation structures and flaser bedding noted in the Taloka Formation are also abundant in the Wurno Formation, which is evidence of identical origin of both formations.

At Wurno, about 20 m of siltstones outcrop behind the village. The type section of the formation was described in Kogbe (1972). Behind the village of Wurno, over 50 m of Maastrichtian and Lower Tertiary deposits outcrop. The section begins with the Taloka Formation, the Dukamaje Formation, the Wurno Formation and upper half of the section is made up of Paleocene Dange shales and limestone. Another good exposure of the Wurno Formation can be observed at Gada where the erosional contact with the Dange Formation can also be seen. At Gada, the Wurno Formation is massive at the base of the section but well bedded towards the contact with the Dange Formation.

The sedimentary structures exhibited by the Taloka and Wurno Formations tend to confirm a tidal flat depositional environment. The most convincing evidence for the tidal-flat environment is the presence of abundant bioturbation structures, the flaser bedding and the wavy bedding. Tidal flats develop along gently dipping coasts with marked tidal rhythms from high-water level to low-water level (Reineck and Singh, 1973). Since a tidal flat sediment-body is usually elongated parallel to the shore-line, it is possible to reconstruct the ancient shore-line in the Iullemmeden Basin from the strike of the outcropping beds at Wurno, Taloka, Dukamaje, Gilbedi, etc.

Paleocene Deposits (The Sokoto Group)

The third phase in the depositional history of the sediments of the Sokoto Basin took place during the Paleocene when the Sokoto Group, comprising the Dange, Kalambaina and Gamba Formations, was deposited unconformably on the Rima Group.

The Dange Formation

The Dange Formation forms the base of the Sokoto Group of sediments of Late Paleocene age. The Dange Formation consists of slightly indurated bluish-grey shale, interbedded with thin layers of yellowish-brown limestone. In surface outcrops, the maximum thickness of the formation is about 22 m near Sokoto, but in subsurface wells, it attains a thickness of over 45 m. Generally, outcrops of the formation are restricted to the slopes of the “Dange Scarp”. The shales include bands of fibrous gypsum with numerous irregular phosphatic nodules. The nodules are characteristically marked with irregular striations, and have an off-white external colour, but are bluish-grey internally. Specimens analysed by Jones (1948), were found to consist largely of calcium phosphate, which is most probably derived from the abundant fossil vertebrate remains present in the formation. Numerous vertebrate fossils, including osteoliths have been described by Kogbe (1976). The most prolific sites for Paleocene fossil vertebrates are Sokoto, Wurno and Gada and on the slopes of the hills between Gada and Tsagagale (Kogbe, 1981b). At the base of the Dange Formation there is an erosional plain represented by a thin bed of conglomerate. The presence of coproliths, gypsum, as well as the remains of molluscs (lamellibranchs) in the conglomeratic bed, suggests that the base of the Dange Formation must have been affected by erosion. The siliceous and arenaceous underlying Wurno Formation also suffered considerable erosion and hence the top of the formation is absent. This erosional horizon now constitutes the Cretaceous-Tertiary boundary in this part of the Iullemmeden Basin. The intensiveness of the erosion is indicated by the absence of lower Paleocene beds in the basin (Kogbe, 1981b).

The type section of the Dange Formation is at Dange village about 28 km south of Sokoto, along a road-cut on the Sokoto- Gusau road. The section described by Kogbe (1976) has suffered considerable erosion but still portrays the essential features of the formation. The base of the formation does not outcrop at Dange but at Wurno and at Gada, limestone beds about 0.5–1.0 m in thickness overlie the erosional horizon on top of the Wurno Formation. These basal limestone bands are usually unfossiliferous. They are overlain by grey gypsiferous shales rich in macrofossils and fossil vertebrates. There is a conformable contact with the overlying Kalambaina Formation. Geological Survey borehole No. 3512, drilled at Dange village, reveals the thickness of the formation to be over 23 m. South of Birnin Kebbi, the Dange Formation is about 15 m thick in Geological Survey borehole No. 2483. “l”hc upper shales of the formation include bands of fibrous gypsum plus a large number of irregularly shaped phosphatic nodules. At the quarry site of the cement factory near Sokoto, fresh samples of this shale could be observed below the limestone. The Dange Formation attains a thickness of 9 m at Kaloye, 50 m at Balle, 4 m at Argungu, and 21 m at Sokoto. Kogbe (1989) identified abundant and rich assemblages of calcareous benthic and agglutinated foraminifera in the Dange Shale.

The Kalambaina Formation

The Kalambaina Formation consists of marine white, clayey limestones and shales. The type section of the formation is at the quarry of the cement factory, near the village of Kalambaina, located about 6 km to the south-west of Sokoto township. The thickness of the formation is quite variable, because of the subsurface dissolution of the limestone. The maximum thickness in the boreholes is over 20 m, but usually only about 12 m of section is exposed in the quarry. Near the village of Dange, the Kalambaina Formation is reduced to about 5 m, but at Birnin Kebbi, further south, the formation is approximately 18 m thick. The formation is rich in invertebrate fossils, mainly echinoids, corals, nautiloids, lamellibranchs and gastropods. Foraminifera and ostracods have also been described from the formation by Reyment (1965), Kogbe (1976) and Petters (1978).

At the type locality, the type sections of the Kalambaina and Gamba Formations are well exposed. The profile consists of the Kalambaina Formation at the base, overlain conformably by the Gamba Formation, which in turn is succeeded by an oolitic ironstone unit. The KaIambaina Formation is generally marly with increasing caly content upwards. The formation is richly fossiliferous. Megafossils include the shallow-water pelecypod *Lucina pharaonis, Panopea sahariensis, Ostrea lamellaris,, Ostrea multicostata,* the gastropod *Volutilithes muricina,* and some nautiloids, *Deltoidonautilus molli* and *Cimomia sudanensis.* Echinoids are particularly abundant, especially *Linthia sudanensis, Gisortia brevis,* and *Rhabdocidaris cottreaui* have also been reported The rich microfaunal assembalege is similar to those described in the Dange Formation.

At Malbaza, in Niger Republic, the limestone is generally purer with a variable thickness of between 6 and 18 m (Kogbe, 1981b). About 16 km south of Sokoto, on the Sokoto-Gusau road, approximately 4 m of section is exposed in a road cutting; it consists mainly of weathered Kalambaina limestone capped by a thin layer of laterite. Here, the Gamba Formation has been stripped off so that laterite has formed directly on the limestone.

The Gamba Formation

The Gamba Formation consists of grey laminated shale overlying the calcareous Kalambaina Formation. The shales appear to be "folded" due to the removal by solution of the underlying limestone and the slumping of the overlying beds. Except when overlain by the Gwandu Formation, the formation is covered by a mantle of loose sand and laterite. The laterite, usually 1.5–3 m thick, often passes down into oolitic ironstone 3–5 m thick.

The type locality of the Gamba Formation is at Gamba village near Sokoto. The type section is in the quarry of the Cement Company of Northern Nigeria. The thickness of the shale ranges from 4 m in outcrops at the quarry, to 10 m in boreholes (GSN 2458). Within the shale, there is a distinct horizon characterized by the presence of abundant phosphatic pellets and small coproliths from 0.1 to 1.0 cm in size. These are interpreted as being the faeces and other remains of free swimming organisms. This horizon probably persists over a wide area and therefore makes a good potential marker bed. Phosphatic pellets were not recorded in many of the Geological Survey borehole samples, which could be due to poor core recovery in the uppermost part of the shales. The existence of this marker-bed of phosphatic pellets just below the base of the ironstone, even in areas where the limestone is greatly reduced in thickness, or entirelv absent, proves that the reduction in thickness of the limestone cannot be ascribed to erosion and downsward laterization from the surface, for such a process could not have taken place without the removal of the phosphatic marker-bed. The Gamba Formation, which is very richly fossiliferous, is of Late Paleocene age. The Gamba Formation is also very rich in foraminiferal microfauna as in the Dange and Kalambaina Formations.

Palaeobiogeographical Deductions and the Transaharan Seaway

Outcrops of the Maastrichtian-Paleocene marine sediments in the Nigerian sector of the Iullemmeden Basin form an arcuate belt that trends in a north-southwest direction. Regionally, the outcrop belt narrows south-westwards where there is pronounced thinning and wedging-out of marine units. They represent the proximal portion of the sedimentary sequence that thickens towards the north-west and attains its maximum development in Niger. Marginal marine conditions prevailed on the Nigerian side during Maastrichtian times, when the Tethys sea extended to the south-east of the interior of western Africa. This resulted in the deposition of evaporite-bearing shales, the Dukamaje Formation, well known for its reptilian and fish remains. The localities described by Kogbe (1989) contain abundant arenaceous foraminifera but an extremely limited calcareous microfauna. Pelagic foraminifers are absent in these sediments; attesting to the shallow and marginal conditions under which sedimentation took place.

Following a mild regression of Danian-Montain age, a transgressional maximum occurred in the late Paleocene (Thanetian), which resulted in a marly, limestone lithofacies, the Kalambaina Formation. This formation is underlain and overlain by gypsiferous grey shale. The bottom shale, the Dange Formation, contains vertebrate remains, and the foraminiferal assemblage is entirely arenaceous and rather impoverished. The ostracod fauna, reported by Kogbe (1972) from the subsurface, supports a late Paleocene age for the Dange Formation and further indicates that there is no real age difference between the Dange, Kalambaina and Gamba Formations. The arenaceous microfauna would support a lithofacies interpretation that the Dange Formation is the transitional facies equivalent of the open marine calcareous Kalambaina Formation. The contact between the Dange and Kalambaina Formations is gradational and well-exposed on the slopes of the ridge at the northern extremity of Sokoto Basin. The lithologic change is marked by a gradual increase in the lime content. These lower marls contain the richest microfauna of the Kalambaina Formation. This is a shallow-water benthic foraminiferal assemblage dominated by larger rotaliids, nonionids and cibicidids. In addition, the overlying marls contain larger foraminifers that permit precise age assignment. Planktic foraminifers are absent. The thinly laminated grey shales of the formation bear a striking similarity to the Dange shales and overlie the Kalambaina marly limestones conformably. The best exposure of this formation is at its type locality in the Kalambaina quarry. It represents the return to marginal marine conditions and the final withdrawal of the sea from the region.

The similarity of the ostracod assemblages between North Africa (Libya), the Sudan district (Mali, etc.), the Iullemmeden Basin and southern Nigeria (Reyment,

1965) confirms the existence of epicontinental seas during the Paleocene. The results of the study by Kogbe (1989) support the view that the southern Nigerian coastal basin was connected with the northern sea during the Paleocene through the Mid-Niger Basin and not via the Benue Trough as suggested some workers.

Most workers on Saharan and sub-Saharan geology tend to agree on the existence of several transgressive periods during the Cretaceous when marine waters from the Tethys sea moved southwards into the African continent through the Sahara. Simultaneously, Atlantic waters from the Gulf of Guinea moved northwards through the Benue Trough in the Turonian, and most probably through the mid- Niger Basin in the Maastrichtian, to link up with the Tethys transgression somewhere in the Niger Republic (Furon, 1960; Reyment, 1966; Adegoke, 1969; Adegoke, 1972; Adeleye, 1975; Kogbe 1976; Offodile, 1976). According to Kogbe (1989), the Turonian seaway passed through the east of the Hoggar but field evidence seems to suggest that the seaway was gradually displaced westwards during the Senonian (Reyment, 1966). By the end of the Maastrichtian, it was restricted to the western fringes of the Hoggar as evidenced by the absence of marine deposits of Maastrichtian age east of the Hoggar and none as well in the Upper and Middle Benue where the continental Gombe and Lafia Formations were deposited, respectively. The absence of fossiliferous limestones with the diagnostic Cenomanian ammonite genus *Neolobites* in the Goa Trench and the abundance of representatives of this genus in well documented beds in the Tenere, Damergou and Adar Doutchi, all east of the Hoggar, constitutes excellent evidence in favour of an eastern passage for the Turonian transaharan seaway. It is still difficult to establish whether the Turonian sediments of the Damergou and Bilma were deposited in a sea extending from north Africa, or whether they derived from an extension of the sea stretching inland from the Gulf of Guinea. This difficulty does not however, eliminate the strong probability of a linkage of both waters during the Turonian (Kogbe, 1989). The Turonian transgression must have passed through the Benue Trough, as there is no record of any marine Lower Cretaceous sediments in the Mid-Niger and Sokoto Basins. In these basins continental deposition prevailed at this time with the deposition of the Illo and Gundumi Formations (Continental Intercalaire) in the Iullemmeden Basin.

During the Maastrichtian, the connection was definitely through the Mid-Niger basin where the marine Patti Formation alongside the Nkporo Shale of the Lower Benue (Anambra Basin) and the Dukamaje Formation in the Sokoto Basin were deposited.

Post-Paleocene Deposits (The Continental Terminal)

The fourth phase in the depositional history of the sediments of the Sokoto Basin took place during the Eocene when the Gwandu Formation of the Continental Termial was deposited.

The term "Continental Terminal" was first proposed by Kilian (1931) for Saharan continental sediments of Miocene-Pliocene age. The terminology is now widely used in West and Central Africa as a stratigraphic unit covering sediments which are both continental and marine in origin. As a result of this imprecise utilization of the term, it has become a most inappropriate designation in West African stratigraphy. Project 127 of the International Geological Correlation Programme tried to review the concept of the "Continental Terminal". One of the important decisions of the working group on Project 127 was to restrict the usage of the term "Continental Terminal" to sediments of continental origin of Post-Paleocene and Pre-Quaternary age" (Kogbe, 1979). According to the new definition of the Continental Terminal, the upper and lower boundaries are determined by geodynamic events. AIthough these tectonic events are not strictly synchronous over the whole of north and West Africa, they are considered to have been caused by related stress patterns of supra-regional validity.

The Gwandu Formation

Throughout the sedimentary basin of north-western Nigeria, the Tertiary marine sediments of the Sokoto Group are overlain disconformably by a thick series of deposits consisting predominantly of red and mottled massive clays, with sandstone intercalations. These sediments belong to the Gwandu Formation, with the type section and the type area in the Gwandu Emirate of northern Nigeria (Kogbe, 1972). Outcrops of the formation cover almost 22,000 km^2 in north-western Nigeria. It contains a number of prominent ridges and groups of flat-topped, steep-sided hills capped by ironstone. Other hills covered with ironstone debris occur in all stages of disintegration, rising out of the sandy plain over which the products of erosion have been distributed. Rock exposures are rare on the plain, but numerous on the hillsides where, however, they are usually small and obscured by rain-wash and ironstone scree. These sediments also outcrop extensively in Niger Republic, and northern Benin, where they were referred to by Hubert (1908) as the "Gres du Niger" and by Urvoy (1936) as "Gres du Moyen Niger". They have been correlated with deposits of Miocene-Pliocene age in the Central African Republic and in Mauritania, where they are known as the "Continental Terminal" (Kilian, 1931). The non-marine origin of the Gwandu Formation is certain, and the sediments can be correctly attributed to a continental environment, or more precisely, to a lacustrine environment (Kogbe, 1976). The best outcrops of the Gwandu Formation occur around Birnin-Kebbi and Argungu. The sediments consist of massive white clays interbedded with coarse and medium-grained red sandstones and mudstones with occasional peat bands. The type section proposed for the formation by Kogbe (1976) shows the typical lithologic characteristic of the formation. Beneath the lateritic capping is a hard ferruginous sandstone layer which is easily eroded into a network of gullies. These are underlain by red sandy clays and white massive mudstones, which are invariably stained pale brown or pink. The mudstone with sandstone intercalations extends monotonously throughout the sections. Similar sections of the Gwandu Formation occur on the slopes of the Gwandu outliers within the Kalambaina Formation on the outskirts of Sokoto township near the cement factory. The sands at the surface are quite red in colour, often showing colour banding and poor stratification. The mudstones often show a nodular structure with nodules suggestive of local turbulence in the depositional environment. By correlation with palynomorphs from tropical Tertiary deposits earlier mentioned, the age of the Gwandu Formation was tentatively put as Eocene- Miocene (Kogbe, 1976).

Lateritic and Ferruginous Cappings

The ferruginous deposits of Sokoto Basin occur extensively, capping sediments which outcrop over thousands of square kilometres. These deposits can be subdivided into three major groups:

1. Ferruginous oolites – (Primary deposits of Paleocene age).
2. Crusty-concretionary laterites – (Post Gwandu Formation)-secondary deposits.
3. Ferruginous sandstones – Mostly primary deposits capping continental deposits.

The iron-rich oolites are primary deposits and the deposition of ferruginous materials occurred during the late Paleocene. All gradations can be traced between a pure oolitic ironstone and concretionary laterite, with scattered oolitic grains of limonite. The primary nature of these deposits is evident from the primary bedding concordant with those of the underlying Gamba shales. The crusty laterites and ferruginous sandstone were formed during the late Tertiary or early Quaternary. They are definitely post-Miocene in age, and consist of abundant angular quartz grains embedded in a matrix of goethite, haematite, limonite and clay. The laterites and oolites possess different element concentrations which indicate formation under different environmental conditions ranging from deep marine through shallow near shore, marine, to continental (fluviatile and lacustrine). The crusty laterites and ferruginous sandstones in the Sokoto Basin attain a thickness of approximately 4 m or more, forming the crust of flat-topped hills or mesas. They are almost certainly equivalent to the laterites covering much of the northern plains and the fluvio-volcanic series of the Jos Plateau. In north-western Nigeria the laterites are restricted to outcrops of sediments of favourable composition and drainage properties (e.g. sandstones). These ferruginous sandstone deposits are usually massive and stratified with almost horizontal bedding planes, marked by abrupt or gradual changes in morphology and lithology. Cross-bedding and ripple-marks were observed by Kogbe (1989) at Gundumi, Imasa and Birnin Kebbi as well as on the Gwandu outliers on the outskirts of Sokoto. Laminations are generally localized. The abundance of ferruginous oolites, laterites and ferruginized sandstones in the Iullemmeden Basin has been known for a long time (Falconer, 1911; Kogbe, 1976). These beds form a capping of considerable thickness. There is usually a band of pale, clayey material between the ironstones and the unaltered rock, and at many localities there are several levels of these ironstone deposits, indicating several periods of laterization. Three major morphologic types are distinguishable, varying with the lithologic nature of the underlying deposits as well as the environment of deposition. Several hypotheses have been put forward to explain the mode of formation, or origin, of these ferruginous oolites and laterites. According to Falconer (1911) the oolites and laterites are of primary origin, and the deposition of ferruginous material took place during the latest stage in the history of Eocene sedimentation. Reformatsky (1935) studied the ironstones in the west of the Niger Kepublic which cap the "Gres du Niger" corresponding to the Gwandu Formation of northwestern Nigeria. He stated that they were formed during the decomposition of the rocks and could be regarded as true laterites. Lambert (1938) mentioned the "lateritic crust" on the Gwandu and Sokoto Groups, but did not describe their mode of formation.

Kogbe (1989) proposed a subdivision of the Sokoto Basin ferruginous deposits into two groups:

(1) The ferruginous oolites overlying the Paleocene sediments and
(2) The crusty laterites and ferruginized sandstones overlying the Gwandu and all other formations.

According to him, the former are autochthonous in origin and must have been formed by precipitation of the iron brought by incoming streams into the open Paleocene sea. The latter is obviously a superficial deposit of autochthonous and allochthonous origin. The crusty laterites are most probably allochthonous and the ferruginous sandstones are most probably autochthonous. These are both of continental origin.

Economic mineral deposits in the Sokoto Basin include Clays, Limestone, Gypsum, and Phosphate.

Chapter 7
The Mid-Niger (Bida) Basin

The Mid-Niger Basin otherwise known as the Bida Basin or the Nupe Basin is a NW–SE trending intracratonic sedimentary basin extending from Kontagora in Niger State of Nigeria to areas slightly beyond Lokoja in the south. It is delimited in the northeast and southwest by the basement complex while it merges with Anambra and Sokoto basins in sedimentary fill comprising post orogenic molasse facies and a few thin unfolded marine sediments (Adeleye, 1974). The basin is a gently downwarped trough whose genesis may be closely connected with the Santonian orogenic movements of southeastern Nigeria and the Benue valley, nearby. The basin is a NW–SE trending embayment, perpendicular to the main axis of the Benue Trough and the Niger Delta Basin (Fig. 4.1). It is frequently regarded as the northwestern extension of the Anambra Basin, both of which were major depocentres during the third major transgressive cycle of southern Nigeria in Late Cretaceous times. Interpretations of Landsat images, borehole logs, as well as geophysical data across the entire Mid-Niger Basin suggest that the basin is bounded by a system of linear faults trending NW–SE (Kogbe et al., 1983). Gravity studies also confirm central positive anomalies flanked by negative anomalies as shown for the adjacent Benue Trough and typical of rift structures (Ojo, 1984; Ojo and Ajakaiye, 1989).

The Benue Trough is a failed arm of a triple junction (aulacogen) that existed beneath the present position of the Niger Delta during the Cretaceous times. The trough is filled with over 5,000 m of predominantly Aptian to Maastrichtian sediments in the lower, middle and upper Benue geographical regions. The Lower Benue Trough which includes the Anambra Basin is considered as the southern extension of the Bida Basin. Initial gravity studies in the Bida Basin put the maximum thickness of the sedimentary successions at about 3.5 km (Ojo, 1984) in the central axis. Although the hydrocarbon potential of the basin has not been fully tested with seismics and the basin remains undrilled, both ground and aeromagnetic studies by several workers have outlined the basin configuration (Adeniyi, 1985; Udensi and Osazuwa, 2004). A recent spectral analysis of the residual total magnetic field values over several sections of the basin reveals an average depth to the basement rocks to be ca. 3.4 km with sedimentary thickness of up to 4.7 km in the central and southern parts of the basin (Udensi and Osazuwa, 2004). In general, sediment thickness decreases smoothly from the central portion to the flanks of the basin.

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Previous studies on the geology of the Bida Basin were reported in Adeleye (1973) and the micropaleontological studies of Jan du Chene et al. (1979) which documented the palynomorph-foraminiferal associations including the interpretation of the paleoenvironments of the Lokoja and Patti Formations. Akande et al. (2005) interpreted the paleoenvironments of the sedimentary successions in the southern Bida Basin as ranging from continental to marginal marine and marsh environments for the Cretaceous lithofacies. Whereas the origin of the oolitic ironstones in the Bida Basin has been a principal subject of several workers (e.g. Adeleye,1973; Ladipo et al., 1994; Abimbola, 1997), only few investigations have been made on the hydrocarbon prospectivity of the basin.

Stratigraphic Setting and Paleogeography

The stratigraphic succession of the Mid-Niger Basin, collectively referred to as the Nupe Group (Adeleye, 1973) comprises a two fold Northern Bida Basin (Sub-Basin) and Southern Bida Sub-Basin or Lokoja Sub-Basin. The Bida Basin is assumed to be a northwesterly extension of the Anambra Basin (Akande et al., 2005). The basin fill comprises a north west trending belt of Upper Cretaceous sedimentary rocks that were deposited as a result of block faulting, basement fragmentation, subsidence, rifting and drifting consequent to the Cretaceous opening of the South Atlantic Ocean. Major horizontal (sinistral) movements along the northeast–southwest axis of the adjacent Benue Trough appear to have been translated to the norths-south and northwesterly trending shear zones to form the Mid-Niger Basin perpendicular to the Benue Trough (Benkhelil, 1989). Although the sedimentary fill of the Benue Trough consists of three unconformity-bounded depositional successions (Petters, 1978), the Bida and Anambra geographical regions were platforms until the Santonian. Pre-Santonian sediments are recorded principally in the older Benue Trough and parts of the southern Anambra Basin. The collapse of the Mid-Niger and Anambra platforms led to the sedimentation of the Upper Cretaceous depositional cycle commencing with the fully marine shales of the Campanian Nkporo and Enugu Formations which may have some lateral equivalents in the Lokoja Formation of the Bida Basin. Overlying the Nkporo Formation is the sedimentary units of the Mamu Formation. These consist of shales, siltstones, sandstones and coals of fluvio-deltaic to fluvio-estuarine environments whose lateral equivalents are the conglomerates, cross-bedded and poorly sorted sandstones and claystones of the Lokoja and Bida Formations in the Bida Basin.

The Mamu Formation is succeeded by sandstones of the Lower Maastrichtian Ajali Formation laterally equivalent to the Patti, Sakpe and Enagi Formations of the Bida Basin. These sandstones are well sorted, quartz arenite that are commonly interbedded with siltstones and claystones and similar in part to the lithologies of the Patti and Enagi Formations. The Patti and Enagi Formations are overlain by

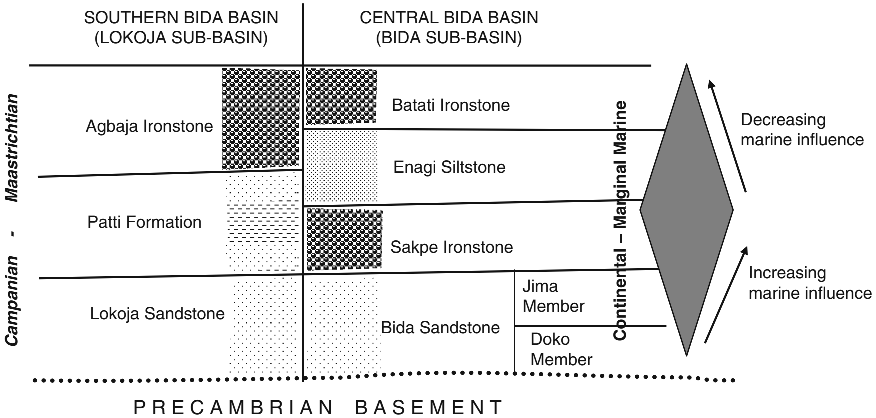

Fig. 7.1 Stratigraphic successions in the Mid-Niger Basin (also known as Bida or Nupe Basin)

the Agbaja and Batati Formations (lateral equivalents) of Upper Maastrichtian age (Fig. 7.1). These consist of oolitic, pisolitic and concretionary ironstones deposited within a continental to shallow marine setting. The Upper Cretaceous sedimentary sequences in the Bida Basin suggest that fully marine conditions was not established compared with the initial marine sedimentation established for the Campanian Nkporo Formation in the adjacent Anambra Basin during that transgressive cycle. A comparison of the sediment thicknesses in the two basins indicate that the successions of the Anambra Basin reached up to 8 km thickness compared with an average of 3.4 km sediment thickness in the Bida Basin (Akande and Erdtmann, 1998).

Lithostratigraphy and Depositional Environments

The stratigraphy and sedimentation of Upper Cretaceous succession of the Bida Basin have been documented by Adeleye and Dessauvagie (1972) in the central parts of the basin around Bida. Four mappable stratigraphic unites are recognized in this area, namely, the *Bida Sandstone* (divided into the *Doko Member* and the *Jika Member*), the *Sakpe Ironstone*, the *Enagi Siltstone*, and the *Batati Formation*. These are correlatable with the stratigraphic units in the Southern Bida Basin (Fig. 7.1).

In the southern Bida Basin (which has been best studied), exposures of sandstones and conglomerates of the *Lokoja Formation* (ca. 300 m thick) directly overly the Pre-Cambrian to Lower Paleozoic basement gneisses and schists. This is overlain by the alternating shales, siltstones, claystones and sandstones of the *Patti Formation* (ca. 70–100 m) thick in the Koton-Karfi and Abaji axis (Fig. 7.2) and succeeded by the claystones, concretionary siltstones and ironstones of the *Agbaja Formation*.

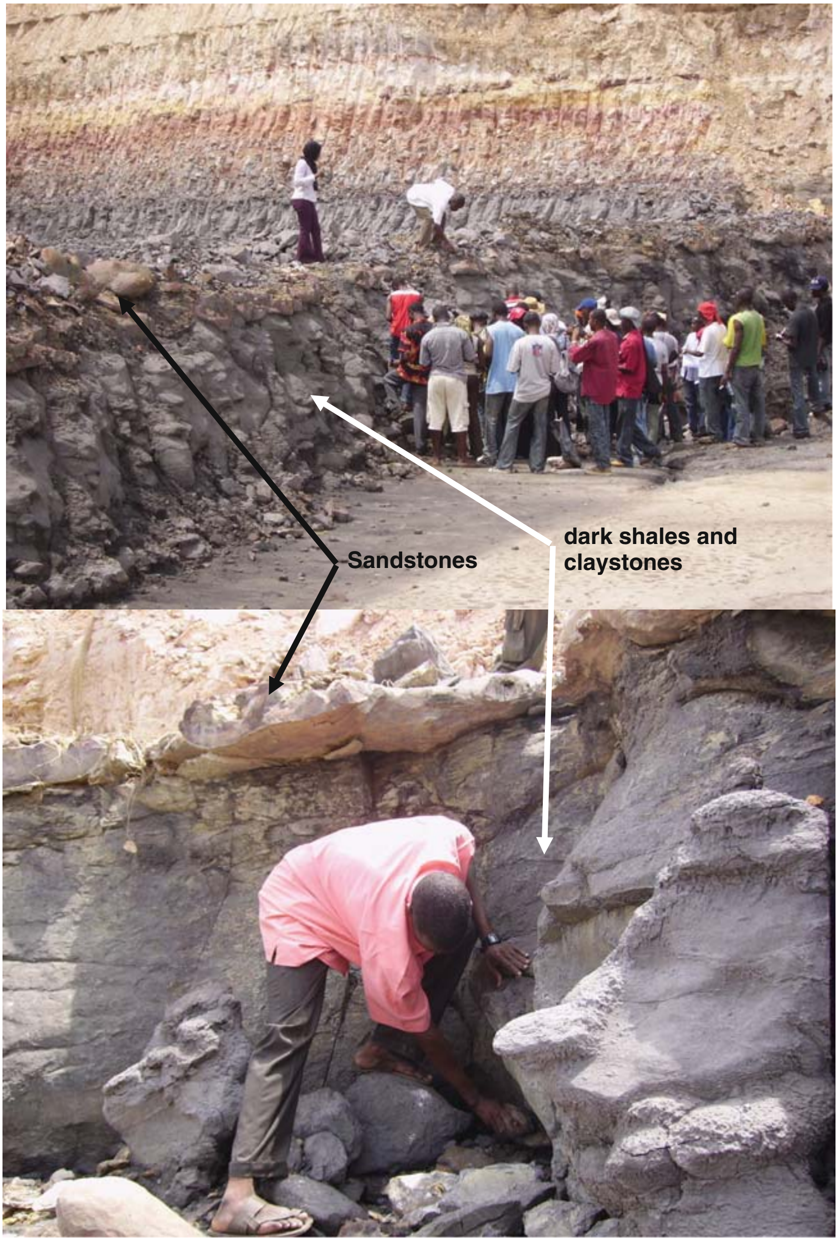

Fig. 7.2 Sections of the Patti formation at Ahoko showing dark-grey-black carbonaceous shales and claystones interbedded with sandstones and siltstones

Central/Northern Bida Basin

The Bida Sandstone

The Bida Sandstone is divisible into two members, namely the Doko Member and the Jika Member. The Doko Member is the basal unit and consists mainly of very poorly sorted pebbly arkoses, sub-arkoses and quartzose sandstones. These are thought to have been depositied in a braided alluvial fan setting. The Jima Member is dominated by cross-stratified quartzose sandstones, siltstones and claystones. Trace fossils comprising mainly *Ophiomorpha* burrows have been observed. These were also observed n the overlying Sakpe Ironstone, suggesting a possible shallow marine subtidal to intertidal influence during sedimentation. The Jima Sandstone Member is thus considered as the more distal equivalent of the upper part of the Lokoja Sandstone, where similar features also occur.

The Sakpe Ironstone

The Sakpe Ironstone comprises mainly oolitic and pisolitic ironstones with sandy claystones locally, at the base, followed by dominantly oolitic ironstone which exhibits rapid facies changes across the basin, at the top.

The Enagi Siltstone

The Enagi Siltstone consists mainly of siltstones and correlates with the Patti Formation in the Lokoja sub-Basin. Other subsidiary lithologies include sandstone-siltstone admixture with some claystones. Fossil leaf impressions and rootlets have been found within the formation. The formation ranges in thickness of between 30 and 60 m. Mineral assemblage consists mainly of quartz, feldspars and clay minerals.

The Batati Formation

This formation constitutes the uppermost units in the sedimentary sequence of the Bida Basin. The Batati Formation consists of argillaceous, oolitic and goethitic ironstones with ferruginous claystone and siltstone intercalations and shaly beds occurring in minor proportions, some of which have yielded nearshore shallow marine to fresh water fauna (Adeleye, 1973).

Southern Bida Basin

The Lokoja Formation

Lithologic units in this formation range from conglomerates, coarse to fine grained sandstones, siltstones and claystones in the Lokoja area. Subangular to subrounded cobbles, pebbles and granule sized quartz grains in the units are frequently distributed in a clay matrix. Both grain supported and matrix supported conglomerates form recognizable beds at the base of distinct cycles at outcrop. The sandstone units are frequently cross-stratified, generally poorly sorted and composed mainly of quartz plus feldspar and are thus texturally and mineralogically immature. The general characteristics of this sequence especially the fining upward character, compositional and textural immaturity and unidirectional paleocurrent trends, suggest a fluvial depositional environment dominated by braided streams with sands deposited as channel bars consequent to fluctuating flow velocity. The fine grained sandstones, siltstones and clays represent flood plain overbank deposits. However, Petters (1986) reported on the occurrence of some diversiy arenaceous foraminifera (Fig. 7.3) from clayey interval of the Lokoja Formation indicating some shallow marine influence. These foraminiferal microfossils identified by Petters (1986) are however more common in the overlying Patti Formation where shallow marine depositional conditions are known to have prevailed more.

The Patti Formation

Outcrops of the Patti Formation occur between Koton-Karfi and Abaji (Fig. 7.2). This formation consists of sandstones, siltstones, claystones and shales interbedded with bioturbated ironstones. Argillaceous units predominate in the central parts of the basin. The siltstones of the Patti Formation are commonly parallel stratified with occasional soft sedimentary structures (e.g. slumps), and other structures such as wave ripples, convolute laminations, load structures. Trace fossils (especially *Thallasanoides*) are frequently preserved. Interbedded claystones are generally massive and kaolinitic, whereas the interbedded grey shales are frequently carbonaceous. The subsidiary sandstone units of the Patti Formation are more texturally and mineralogically mature compared with the Lokoja sandstones. The predominance of argillaceous rocks, especially siltstones, shales and claystones in the Patti Formation requires suspension and settling of finer sediments in a quiet low energy environment probably in a restricted body of water (Braide, 1992b). The abundance of woody and plant materials comprising mostly land-derived organic matter, suggests prevailing fresh water conditions. However, biostratigraphic and paleoecologic studies by Petters (1986) have revealed the occurrence of arenaceous foraminifera in the shales of the Patti Formation with an assemblage of *Ammobaculites*, *Milliamina*, *Trochamina* and *Textularia* (Fig. 7.3) which are essentially cosmopolitan marsh species similar to those reported in the Lower Maastrichtian marginal marine

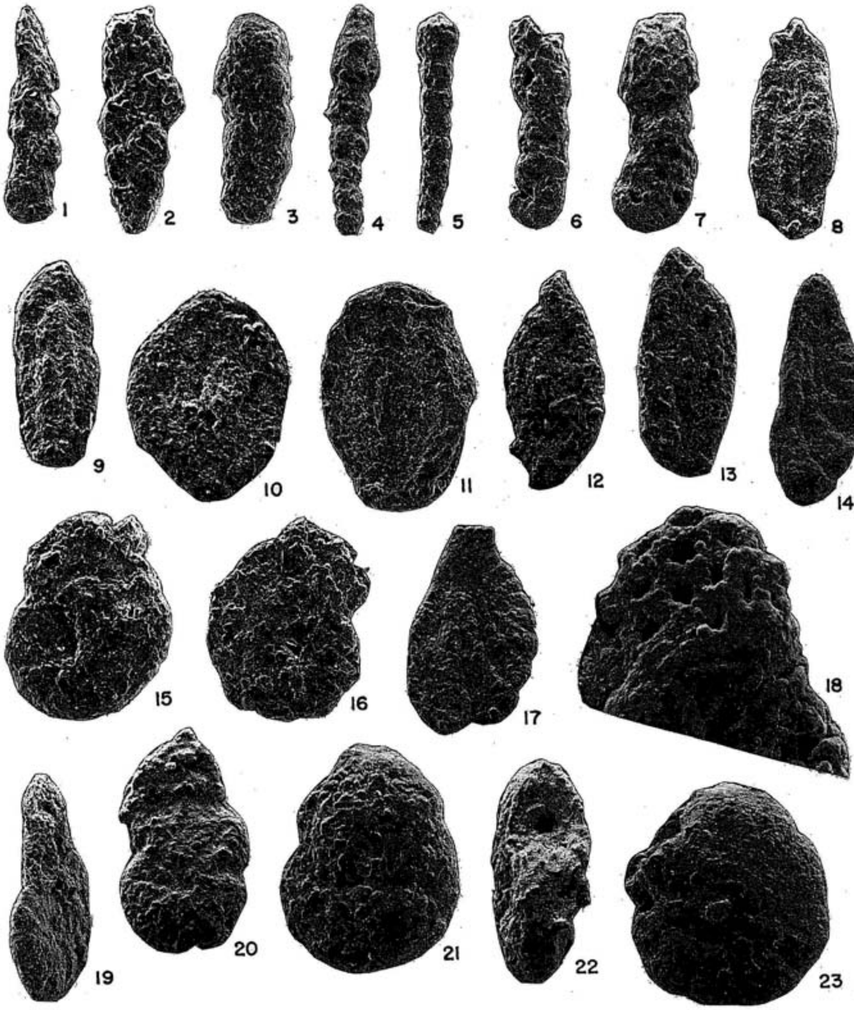

Fig. 7.3 Cretaceous arenaceous foraminifera from the Southern Bida Basin and Upper Benue Trough (captured from Petters, 1995) indicating deltaic to shallow marine conditions in the Lokoja Sandstone and the Pindiga formation

Southern Bida Basin (basal mudstone of the Lokoja Formation)

1. Ammobaculites plummerae, *2. Pseudobolivina varianta*, *3. Spiroplectammina hausorum*, *4. Reophax guineana*, *5. Reophax minuta*, *6. Ammomargilina emir*, *7. Ammobaculities coprolithiformis*, *8.*, *9. Miliammina petila*, *10.*, *11. Miliammina telemaquensis*

Upper Benue Trough (Pindiga Formation)

12., *13. Miliammina pindigensis*, *14.*, *17.*, *18. Ammoastuta nigeriana*, *15.*, *16. Ammobaculites bauchensis*, *19.*, *20. Ammobaculites benuensis*, *21.*, *22.*, *23. Haplophragmoides bauchensis*

Mamu Formation (the lateral equivalent) in the adjacent Anambra Basin (Gebhardt, 1998). Shales of the Mamu Formation on the south side of the Anambra Basin are commonly interbedded with chamositic carbonates and overlain by bioturbated siltstones, sandstones and coal units in coarsening upward cycles towards the north side of the basin (Akande et al., 1992). This sequence is overlain by herringbone crossbedded mature sandstones of the Ajali Formation (Middle Maastrichtian) in the northern fringes of the basin hence providing strong evidence for shallow marine, deltaic to intertidal depositional environments for the Maastrichtian sediments of the Anambra Basin. The Patti Formation therefore appears to have been deposited in marginal shallow marine to brackish water condition identical to the depositional environments of similar lithologic units of the Mamu and Ajali Formations in the Anambra Basin (Ladipo, 1988; Adeniran, 1991; Nwajide and Reijers, 1996). The more marine influences in the adjacent Anambra Basin is probably related to the nearness of that basin to the Cretaceous Atlantic Ocean prior to the growth of the Niger Delta.

The Agbaja Formation

This formation forms a persistent cap for the Campanian – Maastrichtian sediments in the Southern Bida Basin as a lateral equivalent of the Batati Formation on the northern side of the basin. It consists of sandstones and claystones interbedded with oolitic, concretionary and massive ironstone beds in this region. The sandstones and claystones are interpreted as abandoned channel sands and overbank deposits influenced by marine reworking to form the massive concretionary and oolitic ironstones observed (Ladipo et al., 1994). Minor marine influences were also reported to have inundated the initial continental environment of the upper parts of the Lokoja Sandstone and the Patti Formation (Braide, 1992; Olaniyan and Olobaniyi, 1996). The marine inundations appear to have continued throughout the period of deposition of the Agbaja ironstones in the southern Bida Basin (Ladipo et al., 1994).

A Case Study on the Doko and Jima Members of the Bida Sandstone

Adeleye (1974) made a detailed sedimentological study of the Doko and Jima Members of the Bida Sandstone and reported that the Doko Member is about 183 m thick and shows localized development of cross-stratification; the Jima Member about 90 m in thickness is predominantly sandy with widespread cross-stratification.

The Doko Member

The Doko underlies the Jima, and the two rock units show gradational relationships. They both contain sandstones, breccias and argillaceous rocks in varying proportions. The sandstones of the Doko Member (Doko Sandstone subfacies) are arkosic to quartzose, generally poorly sorted, with angular to sub-angular grains. Massive appearance is common. Thick to very thick flat-bedding and localised cross-stratification are also present. Many of the coarser quartz grains commonly show smooth, flat surfaces giving the impression of vein quartz. Milky white and colourless quartz grains are most common, with subsidiary pink, smoky and light chocolate-coloured grains. Feldspar grains are pink to beige and sometimes partly altered. The quartz and feldspar grains are irregular, rod-like or roughly tabular. The arkosic sandstones are the basal units exposed. They are commonly medium to very coarse and pebbly. The sorting is fair to poor. The arkoses are often mottled: brown, yellow, grey and pink. They are interbedded with finer-grained lithic feldspathic and feldspathic sandstones. Very poorly sorted, very coarse to fine argillaceous and pebbly quartzose sandstones and subsidiary subgreywacke, however, dominate the subfacies. They succeed and grade into the basal arkoses. Some are friable, medium to very coarse and pebbly, whereas others are hard, medium to very fine, argillaceous and poorly sorted. Several palaeo-channels were observed in the Doko Sandstone subfacies. The channel axis trends 310°, but the base is unexposed. The channel-filling contrasts with the underlying beds. Some spherical to sub-spherical masses of coarse argillaceous sandstones with occasional quartz pebbles in the outer areas occur locally. Discontinuous shells of finely sandy, black claystones are present in these masses (6–10 cm size). Siltstone and mudstone pebbles, and some thin, indurated, ferruginized, dark-brown sandstone bands are present in several localities.

The Jima Member

The sandstones of the Jima Member (Jima Sandstone subfacies) are dominantly quartzose, non-arkosic and brownish. Thin intercalations of poorly sorted, hard; whitish, argillaceous sandstones similar to a lithology in the Doko subfacies, are locally present in the lower parts of the Jima subfacies. The colours of the quartz grains are also similar to those of the underlying subfacies. Three principal lithologies are identifiable in the Jima subfacies:

(1) Very fine to medium, silty, well-sorted, friable, laminated sandstones which locally develop small-scale cross-stratification. They are rarely coarse, poorly-sorted, and show alternating laminations of claystone fragments and quartz grains. Laminae rich in black, heavy minerals and micaceous minerals are common.
(2) Beds showing large-scale cross-stratification. These are commonly fine to coarse grained, friable, locally pebbly and granular. The sets vary from 30 cm to over 1 m thickness. Often, the azimuths of the sets, in the coset, are very variable. Cases of consistent azimuths are also known. A preferred northerly azimuth is indicated over the entire Bida area. Planar cross-stratification is dominant. Deformational structures include localised steep dips and hooked sandstone bodies, contorted bedding of short lateral extents, folded sandstone

blocks and partially deformed cross-stratification. Thin ferruginized beds, mud clasts, and leaf impressions occur locally.

(3) Thinly to thickly flat-bedded, massive or graded, coarse to very coarse, granular and pebbly, poorly sorted sandstones and mud clasts are locally abundant. Various types of concretions occur in the sandstone facies that is spherical to sub-spherical, sausage-shaped as well as in irregular and compound shapes. Their contacts are gradational into the adjacent sandstones. Lustrous, blackish ferruginous mineral {possibly goethite/haematite} form the cement. Some weak to strong concentric growth shells are displayed.

Depositional Environments

The Doko Member

The cyclothems of the formation are generally similar to the fluviatile cyclothems of Allen (1965) and Pettijohn et al. (1965). Aeolian, estuarine, beach and neritic environments of deposition are excluded by the texture and apparent lack of invertebrate fossils in the formation. The occurrence of a palaeochannel is consistent with this deduction. The fining upwards of the entire formation is a reflection of the decrease of stream power, with time, during deposition. Such a decrease in power may be related to decrease in slope associated with aggradation and geomorphic maturity of the basin. The predominance of massive beds and flat-bedding in the Doko Member suggests the importance of deposition in the upper flow regime. The Doko strata were probably deposited by high-power, high-gradient, braided streams. The locally occurring cross-stratified sandstones could be interpreted as bar deposits (Douglas, 1962). The evidence of mud clasts suggests the presence of some low-energy environments in which suspended fines were originally deposited. The occurrence of flood plains flanking the braided streams seems to fit the observation (Allen, 1970). The redistribution of the flood-plain deposits probably resulted from bank erosion and stream-shifts, during floods (Allen, 1970). The breccia of the Doko Member seems to represent channel lag deposits. The presence of feldspar-rich detritus in the basal parts of the sections, suggests rapid rates of erosion in the source area, accompanied by rapid rates of sedimentation. Other agents for the preservation of feldspars (arid or cold conditions) as demonstrated by Pettijohn (1957) were not used by Adeleye (1974). The later disappearance of feldspars, up the vertical profiles, may be evident of peneplanation of the source areas.

The Jima Member

The widespread occurrence of cross-stratification in the Jima Member suggests less turbulent conditions of flow than in the preceeding unit (Allen, 1970). The currents seem to have been mainly in the lower flow regime of Allen (1967). The very variable azimuths in the cosets are indicative of changing directions of flow in space and time; since the cross-stratum normally dips downcurrent. Estuarine bimodal cross-stratification is absent. A considerable part of the Jima Member, therefore, seems to suggest deposition by meandering rivers. Some recent meandering stream deposits similar to the cyclothems of the Member have been described (Ladipo, 1988). The thin to thickly flat-bedded sandstones together with the breccias probably document channel-base deposition under relatively high current power. The cross-stratified sandstones may document deposition mainly in the point-bar and meander-bar sub-environments. The laminated sandstones together with their small-scale cross-stratification seem to suggest deposition mainly on channel beaches (heavy-mineral laminations) and under slackened flow conditions in the upper parts of the meander and point bars. The heavy-mineral laminations, though on a much smaller scale, are somewhat similar to those described along the Carolina coastline (McKelvey and Balsley, 1948). The argillaceous facies probably documents flood plain or overbank sedimentation. The flora is consistent with this interpretation. The brown laminations of the facies possibly document partial ferruginization of the tops of the fresh deposits, during drier seasons (Allen, 1970). The origin of the deformational structures is not well understood. They may have originated, in part, from the undercutting and slumping of fairly cohesive bar sands, during floods. The common occurrence of claystone fragments in the Jima Member is evidence of the operation of processes of active penecontemporaneous erosion, during deposition.

Chapter 8
The Dahomey Basin

The Dahomey Basin is a combination of inland/coastal/offshore basin that stretches from southeastern Ghana through Togo and the Republic of Benin to southwestern Nigeria. It is separated from the Niger Delta by a subsurface basement high referred to as the Okitipupa Ridge. Its offshore extent is poorly defined. Sediment deposition follows an east-west trend. In the Republic of Benin, the geology is fairly well known (Billman, 1976; De Klasz, 1977). In the onshore, Cretaceous strata are about 200 m thick (Okosun, 1990). A non-fossiliferous basal sequence rests on the Precambrian basement. This is succeeded by coal cycles, clays and marls which contain fossiliferous horizons. Offshore, a 1,000 m thick sequence consisting of sandstones followed by black fossiliferous shales towards the top has been reported. This was dated by Billman (1976) as being pre-Albian to Maastrichtian. The Cretaceous is divisible into two geographic zones, north and south. The sequence in the northern zone consists of a basal sand that progressively grades into clay beds with intercalations of lignite and shales. The uppermost beds of the Maastrichtian are almost entirely argillaceous. The southern zone has a more complicated stratigraphy with limestone and marl beds constituting the major facies.

Sedimentation in the northern zone which is located inland and close to the basin periphery, began during the Maastrichtian when a thin sequence (<200 m) of unconsolidated sands, grits, silts, clays and shales, was deposited. This sequence rests on the basement; the transitional facies is marked by a basal conglomerate or white to grey sandy and kaolinitic clays derived as degradation products from the surrounding Precambrian rocks.

In the southern zone, which is coastal and offshore, the oldest sediments consist mainly of loose sand, grits, sandstones and clay with shale interbeds which progressively grade into shale. They are late Albian and possibly Neocomian in age (Omatsola and Adegoke, 1981). The basal conglomerates have been reported from outcrops and boreholes (Jones and Hockey, 1964; Omatsola and Adegoke, 1981). The onshore sequence towards the basin periphery in Nigeria correlates well with the Maastrichtian onshore in the Republics of Benin and Togo. The geology of the Togo sector is very similar to that of Nigerian and Benin sectors. The Cretaceous succession shows marked lithological changes which have been expressed in terms of formal and informal lithostratigraphic nomenclature by previous workers (Fig. 8.1). This can lead to dual or multiple nomenclature and thus confusion.

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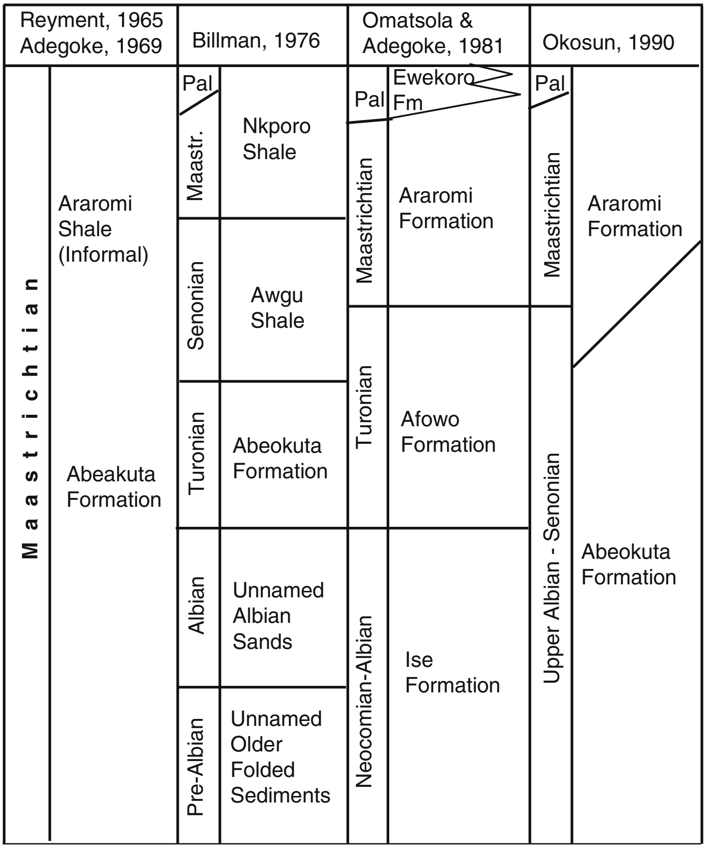

Fig. 8.1 Stratigraphic successions in the Dahomey Basin as variously erected by previous workers. The succession by Okosun (1990) is adopted in this work

Okosun (1990) carefully reviewed the stratigraphy of the Dahomey Basin. Little work has been published on the Cretaceous stratigraphy of the Dahomey Embayment. This is due in part to the confidentiality of oil company reports and the absence of readily available deep borehole cores. Jones and Hockey (1964) established the Abeokuta Formation for the Cretaceous sands, grits, clays and shale in the Nigerian sector. Reyment (1965) reported the occurrence of the Ajali Sandstone and the Nsukka Formation close to the basin margin around Ijebu-Ode and Okitipupa. He also reported the occurrence of Nkporo Shale in the subsurface of the basin. Billman (1976), from a study of some offshore sequences in the Republic of Benin, proposed two informal lithostratigraphic units: unnamed Older Folded Sediments and unnamed Albian Sands. The remaining portion of the Cretaceous sequence was referred to as the Abeokuta Formation, and the Awgu and Nkporo Shales. Jan du Chene et al. (1979), from a study of a coastal borehole (Ojo-1), reported the occurrence of strata of Albian to Maastrichtian age. Omatsola and Adegoke (1981) established three new, formal lithostratigraphic units, the Ise, Afowo and Araromi Formations, the first two of which correspond to the unnamed Older Folded Sediments and unnamed Albian Sands, respectively, while the Araromi Formation was considered equivalent to the Nkporo Shale of Billman *(op. cit.).* The Ise and Afowo Formations were dated as Neocomian (Valanginian) and Albian-Turonian respectively by these workers.

Stratigraphic Nomenclature

There has been a nomenclature problem in the stratigraphy of the Dahomey Basin, as can be seen in Fig. 8.1. Jones and Hockey (1964) established the name Abeokuta Formation for the mainly arenaceous strata with mudstone, silt, clay and shale interbeds that crop out onshore. Billman (1976) subdivided the Abeokuta Formation into three lithostratigraphic units: the "Unnamed Older Folded Sediments", "Unnamed Albian Sands" and Abeokuta Formation. On the basis of age equivalence he referred the remaining Cretaceous strata to the Awgu and Nkporo Shales. Omatsola and Adegoke (1981) disagreed with this nomenclature on two main grounds. The first of these is that a rule of accepted stratigraphic practice is contravened because when the Abeokuta Formation was subdivided the same name was used for only one part of the succession. The second is that the application of the well-established Anambra Basin names: Nkporo and Awgu Shales to the Dahomey Basin solely on the basis of age is invalid. As a result, they proposed three new lithostratigraphic units, the Ise, Afowo and Araromi Formations, and referred these to the Abeokuta Group. In their classification, the Ise Formation is equivalent to the Unnamed Older Folded Sediments and the Unnamed Albian Sands, the Afowo Formation to the outcropping Abeokuta Formation, and the Araromi Formation to the Awgu and Nkporo Shales.

The view that Anambra Basin lithostratigraphic names should not be used in the Dahomey Basin solely on the basis of age was supported by Okosun (1990). Furthermore, it is inappropriate to use the same names for lithostratigraphic units situated in different basins which are both widely separated from each other and have had different geologic history. This is also true if material for comparison of complex lithologic sequences is only present in deep well cores that are not readily available for study. Thus the strata previously referred to as the Nkporo Shale were renamed Araromi Formation by Okosun (1990). The lithology of Ise and Afowo formations as defined by Omatsola and Adegoke (1981) show a high degree of similarity. Both are essentially sands and sandstones, but the latter contains thick interbeds of shale. This difference is not suficient to warrant the establishment of separate lithostratigraphic units. The two formations were considered synonymous by Okosun (1990). In that study, it was observed that the Ise, Afowo and Abeokuta formations have similar lithologic and electric log characters. The uppermost beds of Abeokuta Formation which crop out in the Ijebu-Ode area and in the shallow boreholes, at Itori, Wasimi and Ishaga onshore, consist mainly of fine- to coarse-grained sand and interbeds of shale, mudstone, limestone and silt. These lithofacies correlate well with the upper portion of the neostratotype in the Ojo-1 Borehole. studied by Okosun (1990). Although the Afowo Formation contains shale interbeds, Okosun (1990) emphasized that its essentially sandy character qualifies it along with the arenaceous Ise Formation, for inclusion in the Abeokuta Formation which also contains shale interbeds as demonstrated in the neostratotype described by him and as seen also in many surface outcrops. The use of the names Ise and Afowo.

Formations was therefore discontinued and replaced by the Abeokuta Formation which has priority of publication and a wider accepted usage. The Abeokuta Formation was defined by Jones and Hockey (1964) to consist of grits, loose sand, sandstone, kaolinitic clay and shale. It was further characterized as usually having a basal conglomerate or a basal ferruginised sandstone.

Litho-Biostratigraphy

Two lithostratigraphic units, the Abeokuta and Araromi Formations, have been recognized in the Cretaceous of the eastern Dahomey Embayment. Further surface and subsurface data are necessary to confirm the occurrence of strata with lithologic similarity to Ajali Sandstone and Nsukka Formation which were reported to occur in the embayment by Reyment (1965). An account of the stratigraphic units as described by Okosun (1990) is given below.

The Abeokuta Formation

The Abeokuta Formation in surface outcrops comprises mainly sand with sandstone, siltstone, silt, clay, mudstone and shale interbeds. It usually has a basal conglomerate which may measure about 1 m in thickness and generally consists of poorly rounded quartz pebbles with a silicified and ferruginous sandstone matrix or a soft gritty white clay matrix. In outcrops where there is no conglomerate, a coarse, poorly sorted pebbly sandstone with abundant white clay constitutes the basal bed. The overlying sands are coarse grained, clayey, micaceous and poorly sorted, and indicative of short distances of transportation or short duration of weathering and possible derivation from the granitic rocks located to the north. Higher up stratigraphically at outcrop the shale content of the formation progressively increases. At some levels, particularly around Ijebu-Ode close to the eastern margin of the embayment, thin beds of lignite are present together with a high impregnation of bitumen in the sands and clays (Okosun, 1990). These occurrences are very strongly manifested in most of the eastern part of the basin where they are locally referred to as tar sands. The upper horizons of the basal beds were found in some outcrops to contain thin beds of oolitic ironstone.

Subsurface data on the Abeokuta Formation was obtained from Ise-2, Afowo-1, Orimedu-1, Bodashe-l, Ileppaw, Ojo-1 and Itori Boreholes by Okosun (1990).

The formation has a thickness of 849, 898, 624, 54.4 and 888 m in Ise-2, Afowo-1, Ileppaw, Itori and Ojo-1 Boreholes respectively. In the Ise-2 Borehole, the essentially arenaceous sequence between 1261.5 and 2142.1 m, which consists of sand, grits, sandstone, siltstone, clay and shale, constitutes the formation. The interval 1,076–1,907 m, which is made up of very coarse loose sand with sporadic thin intercalations of multicoloured shale and limestone, represents the formation in Ojo-1 Borehole. The strata from 44 to 98.4 m in the Itori Borehole, which consists of coarse-, fine- and medium-grained sand, silt and sandy clay horizons, constitutes the upper portion of the formation. The Ise-2 Borehole also penetrated a basal conglomerate. The ages of the lower and upper limits of the formation in the neostratotype described by Okosun (1990) are late Albian and late Senonian. This stratigraphic dating was obtained from the results of palynological studies by Jan du Chene et al. (1978) who recorded the pollen and spores *Reticulatasporites jardinus*, *Cicatricosisporites potomacensis*, *Reticulatasporites* sp., *Cingulatisporites* sp., *Lycopodium* sp., *Corrugatisporites ivoirensis*, *Pelleteria minutaestriata*, *Classopollis* sp., *Araucariacites* sp., *Trifossapollenites* group and *Deltoidospora* sp from 1,984 to 1,900 m in the basal sequence, which was taken to indicate a late Albian-early Cenomanian age. Close to the top of the formation, at 1,154 m, *Foveotricolpites giganteus* was recorded. This is a characteristic species for the late Turonian-early Senonian of the Ivory Coast and was reported from the Coniacian-Campanian of Gabon by Boltenhagen (in Archibong, 1978). The occurrence of this pollen therefore suggests a late Senonian age for the upper strata of the Abeokuta Formation. Between the lowest and highest levels of the neostratotype *Droseridites senonicus, Triorites* sp. and *Classopollis* were recorded from 1,647 m to 1,834–1,988 m respectively. These palynomorphs indicate an early Senonian age. According to Okosun (1990), the Neocomian (Valanginian) age proposed for the lower sediments referable to the Abeokuta Formation in Ise-2 Borehole by Omatsola and Adegoke (1981) required further studies and clarification.

The Araromi Formation

This formation was defined by Omatsola and Adegoke (1981) as comprising a fine to medium-grained basal sand overlain by shale and siltstones with thin intercalations of marl and limestone. The shale is grey to black and has a high organic content; thin beds of lignite are frequent. The formation is very similar in composition to the Nkporo Shale, but as mentioned earlier, their occurrence in separate basins with different geologic histories and the lack of adequate outcrop sections necessitate a separate nomenclature. The formation according to Okosun (1990) is equivalent to the "Araromi Shale" of Reyment (1965), and the Awgu Formation and Nkporo Shale of Billman (1976). Observations made by Okosun (1990) support the inclusion of thin interbeds of sandstone, shelly limestone and shale in the definition of the formation. The lithostratigraphic unit does not occur in outcrops. It was encountered in drillholes at Araromi, the type locality, at 446–583 m, and also in Ojo-1, Gbekebo-1, Ise-2 and Afowo-1 at depths 756–1,075, 880–1,039, 1,834–2,000 and 969–1,230 m respectively. The ages of the lower and upper limits are Campanian and late Paleocene. In the Araromi Borehole the formation is present between 446 and 583 m.

The foraminifera *Rugoglobigerina rugosa* (Plummer), *Hedbergella monmouthensis* (Olsson), *Bolivina afra* (Reyment) and *Heterohelix* sp. were recovered from the interval 510–582 m. These indicate a Campanian-Maastrichtian age. The occurrence of *Globorotalia pseudobulloides* (Plummer), *Globorotalia compressa* (Plummer) and *Globorotalia deubjergensis* Bronnimann in the interval 446–510 m supports an early Paleocene age for the upper beds. Thus in the holostratotype (Okosun, 1990), the age of the formation is Campanian-early Paleocene. In the Ojo-1 Borehole, the interval 756–1,075 m which represents the Araromi Formation is Maastrichtian-late Paleocene. The occurrence of the foraminifera *Bolivina afra*, *Buliminella quadrilobata, Gabonita spinosa*, *Rugoglobigerina* sp., and *Heterohelix* sp. in the basal sequence of 771–1,075 m indicates a range from the Senonian to early Maastrichtian, as in Gabon. The regular occurrence of *Foveotriletes margaritae* pollen and the dinoflagellate *Svalbardella* sp. together with these foraminifera provided sufficient evidence from which to infer a Maastrichtian age (Okosun, 1990). The reported occurrence of the foraminifera *Eponides pseudoelevatus* Graham et al., *Globorotalia velascoensis* Cushman and *Globigerina triloculinoides* Plummer in the upper part of the formation from 753 to 771 m indicates a late Paleocene age. Thus the data available from both the Ojo-1 and Araromi-1 Boreholes indicate that the age of the formation is Campanian to late Paleocene.

In summary therefore the stratigraphic nomenclature of Cretaceous sediments in eastern Dahomey Basin has been revised and two lithostratigraphic units, the Abeokuta and Araromi Formations are recognized. The former comprises predominantly unconsolidated sands with intercalations of grey shale, mudstone, silt and clay while the latter consists of dark grey and black shales with interbeds of sandstone, limestone, marl, and silty and glauconitic shale. The detailed description of the holostratotype and the establishment of a hypostratotype for the Araromi Formation (Okosun, 1990) became necessary for the proper definition and recognition of the formation. The neostratotype proposed for the Abeokuta Formation replaced the holostratotype which has been invalidated. The age of Araromi Formation is based on microfossils from the holo- and hypostratotype sections described by Okosun (1990) which indicate Campanian-late Paleocene while those in the Abeokuta Formation gave ages of late Albian-late Senonian.

Chapter 9
The Niger Delta Basin

The Cenozoic Niger Delta is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of the continents of South America and Africa in the late Jurassic (Whiteman, 1982). Subsidence of the African continental margin and cooling of the newly created oceanic lithosphere followed this separation in early Cretaceous times. Marine sedimentation took place in the Benue Trough and the Anambra Basin from mid-Cretaceous onwards. The Niger Delta started to evolve in early Tertiary times when clastic river input increased (Doust and Omatsola, 1989). Generally the delta prograded over the subsidizing continental-oceanic lithospheric transition zone, and during the Oligocene spread onto oceanic crust of the Gulf of Guinea (Adesida et al., 1997). The weathering flanks of out-cropping continental basement sourced the sediments through the Benue-Niger drainage basin. The delta has since Paleocene times prograded a distance of more than 250 km from the Benin and Calabar flanks to the present delta front (Evamy et al., 1978). Thickness of sediments in the Niger Delta averages 12 km covering a total area of about 140,000 km^2.

Whilst the early Niger Delat is interpreted as being a river-dominated delta, the post-Oligocene delta is a typical wave-dominated delta with well-developed shoreface sands, beach ridges, tidal channels, mangrove and freshwater swamps. It is one of the world's largest deltas and shows an overall upward transition from marine shales (Akata Formation) through a sand-shale paralic interval (Agbada Formation) to continental sands of the Benin Formation. Depending on sea level changes, local subsidence and sediment supply, the delta experienced phases of regressions and trangressions. The stratigraphic framework and the detailed Tertiary stratigraphy of the Niger Delta are based on correlation of palynomorphs and foraminifera zones.

Stratigraphic Framework

The stratigraphic sequence of the Niger Delta comprises three broad lithostratigraphic units namely, (1) a continental shallow massive sand sequence – the *Benin Formation*, (2) a coastal marine sequence of alternating sands and shales – the

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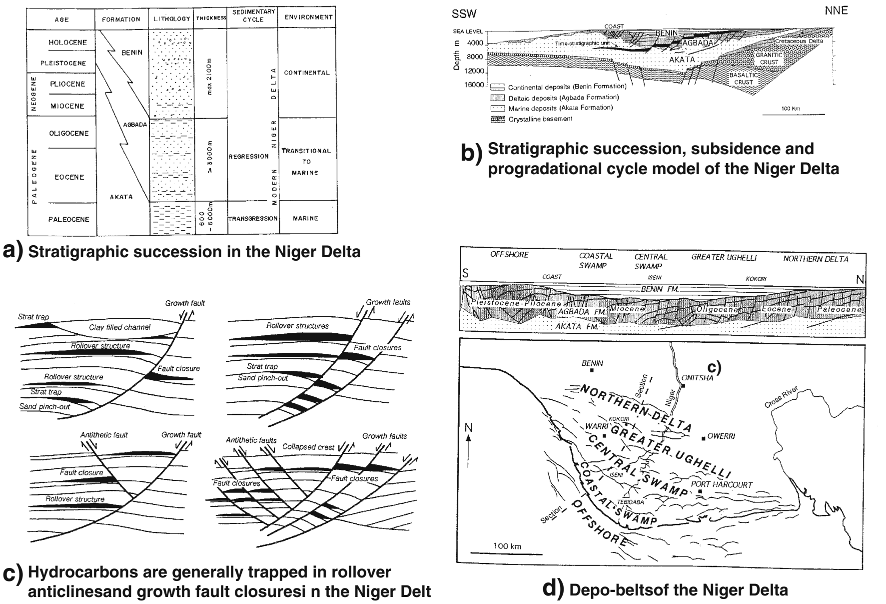

Fig. 9.1 Stratigraphy, structural elements and modes of hydrocarbon occurrence in the Tertiary Niger Delta

Agbada Formation and (3) a basal marine shale unit- the *Akata Formation* (Fig. 9.1). The Akata Formation consists of clays and shales with minor sand intercalations. The sediments were deposited in prodelta environments. The sand percentage here is generally less than 30%.

The Agbada Formation consists of alternating sand and shales representing sediments of the transitional environment comprising the lower delta plain (mangrove swamps, floodplain, marsh) and the coastal barrier and fluviomarine realms. The sand percentage within the Agbada Formation varies from 30 to 70%, which results from the large number of depositional off lap cycles. A complete cycle generally consists of thin fossilferous transgressive marine sand, followed by an offlap sequence which commences with marine shale and continues with laminated fluviomarine sediments followed by barriers and/or fluviatile sediments terminated by another transgression (Weber, 1972; Ejedawe, 1989).

The Benin Formation is characterized by high sand percentage (70–100%) and forms the top layer of the Niger Delta depositional sequence. The massive sands were deposited in continental environment comprising the fluvial realms (braided and meandering systems) of the upper delta plain.

The Niger Delta time-stratigraphy is based on biochronological interpretations of fossil spores, foraminifera and calcareous nonnoplaknton. The current delta-wide stratigraphic framework is largely based on palynological zonations labeled with Shell's alphanumeric codes (e.g. P630, P780, P860). This allows correlation across all facies types from continental (Benin) to open marine (Akata). There have been concerted efforts, within the work scope of the stratigraphic committee of the Niger Delta (STRATCOM), to produce a generally acceptable delta-wide biostratigraphic framework (Reijers et al., 1997) but not much again has been accomplished after several data gathering exercise by the committee.

The sediments of the Niger Delta span a period of 54.6 million years during which, worldwide, some thirty-nine-eustatic sea level rises have been recognized (Adesida et al., 1997). Correlation with the chart of Galloway (1989) confirms the presence of nineteen of such named marine flooding surfaces in the Niger Delta. Eight of these are locally developed. Adesida et al. (1997) defined eleven lithological mega sequences marked at the base by regional mappable transgressive shales (shale markers) that are traceable across depobelt boundary faults and proposed these as the genetic sequences that can be used as the basis for lithostratigraphy of the Niger Delta.

Structural Geology

The escalator regression model of Knox and Omatsola (1989) describes the one-way step-wise outbuilding of the Niger Delta through geologic time. The units of these steps are the depobelts. Depobelts, as defined therein, represent successive phase of delta growth. They are composed of bands of sediments about 30–60 km wide with lengths of up to 300 km. They contain major fault–bounded sequences which contain a shoreface alternating sand/shale sequence limited at the proximal end by a major boundary growth fault and at the distal end by a lithofacies change, a counter-regional growth fault, a major boundary fault of a succeeding depobelt, or any combination of these. Seawards, successive depobelts contain sedimentary fills markedly younger than the adjacent ones in a landward direction.

On a delta dip section, a relationship is apparent between successive depobelts. The base alluvial sand facies of an updip (older) depobelt is approximately time equivalent to the initiation of the base sand/shale sequence in the down-dip depobelt. The deposition of parallic sequences within any depobelt is terminated by a rapid advance of an alluvial sand facies over the proximal and central areas of the belt. This advance initiates deposition of the parallic sand/shales sequences in the succeeding depobelt. A parallic sequence develops in this new depobelt, and in the exterior part of the older depobelt, while the continental sands/gravels advance dischronously. This sequence of events repeated itself five to six times over the last 38 million years to define a series of depobelts in the Niger Delta. Five major depobelts are generally recognized namely, *Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and Offshore* (Fig. 9.1). The most striking structural features of the Niger Delta are the large syn-sedimenatry growth faults, rollover anticlines and shale diapirs which deformed the delta complex (Evamy et al., 1978). The greater percentage of the on fields in the Niger Delta is associated with rollover anticlines.

Sand Fairways and Sequence Stratigraphy

Applying sequence stratigraphic concepts in the Niger Delta, a shelf-break/slope model with well developed lowstand, transgressive and high stand systems tracts can be applied in various parts of the northern and coastal delta where bathyal paleo-water-depths were interpreted (Weber, 1986), whilst a shallow ramp model with mainly transgressive and highstand systems tracts is applicable in major parts of the central delta where paleo-water-depths did not exceed 150–200 m (outer neritic).

Sand percentages versus depths for selected wells were studied by Obaje (2005) as a basis for understanding the sand/shale ratios as well as the stacking patterns of sedimentary sequences in the Niger Delta. This was also with the aim to enhance a clearer understanding of the sequence stratigraphic framework of the Niger Delta based on the vertical sand-stacking pattern.

In the Niger Delta, the Galloway's (1989) genetic sequence concept is followed as a basis for lithostratigraphy. The *mfs*'s within the marker shales are the boundaries of the sequences. They can be traced from seismic (Vail, 1987) and/or derived from wireline logs (Durand, 1995) and confirmed biostratigraphically. Sand percentages are derived form wireline logs including Gamma Ray log of which the vertical sand stacking pattern is an inversion (mirror image). Thick shale units separate reservoir sands and are candidates for the *mfs*; the thin ones are usually interbedded in shoreface deposits and contain lower-order flooding surfaces (Reijers et al., 1997). Stacking pattern between *mfs* allow recognition of sequence boundaries. Progradation is reflected by upward-increasing sandiness and retrodegration by an upward-decreasing sandiness or upward-increasing shalyness. Two such patterns are separated by a surface, which reflects the time of maximum basinwards shift of the shoreline (sequence boundary: *SB*). The *mfs* must be checked against the maximum depth reflected in the biofacies, and should coincide with the level showing the highest foraminiferal and planktonic abundance and diversity.

The Niger Delta "channels" are relics of incised valleys (Reijers et al., 1997) and they are seismically detectable sequence boundaries of large magnitude. The position of the *SB* may also be marked by condensed sequences, by sharp bases of thick sand units, by the inflection point between coarsening sequences, and fining-up abound by faunal evidence of shallow environments. The interval between an *SB* (below) and *mfs* (above) is a transgressive systems tract (*TST*). In the Niger Delta it usually is a thin unit (Reijers et al., 1997). A sequence boundary may also be overlain by a low stand systems tract (*LST*) which should be checked against the bathymetry indications of the fauna, the log response of possible basin floor fans (sharp-based, blocky massive sands); slope fans (sand–poor facies with rounded shapes of spiky sand packages) or lowstand prograding complexes (thick intervals with increasing upward-sandiness). The interval between *mfs* (below) and a *SB* (above) is a highstand systems tract (*HST*) in which a variety of depositional systems may occur.

The trends derived from the sand percentage maps of Obaje (2005) revealed better the delta morphology with time and also emphasized the depositional control on lithofacies distribution. The maps constructed indicate regional trends in the depositional pattern of the delta for the given pollen subzone and mfs interval. The points of major sand inputs (channels, mouth bars) from the onshore into the shallow, deep and ultra-deep offshore are reflected by lobes protruding in a seaward direction. These lobes (sand fairways) are expected to constitute pathfinders to deep-water reservoir prospects. Intervals with average high sand percentage with paleobathymetry interpreted from fauna that indicate middle-outer neritic paleowater depth and other slope environments are expected to be possible turbidite targets (Mitchum et al., 1994).

Part III
Mineral Resources

Chapter 10
Solid Mineral Resources

Introduction

Nigeria as a nation is blessed with abundant solid mineral resources distributed fairly in all the states of the federation (Fig. 10.1; Table 10.1). According to reports by the Geological Survey of Nigeria Agency, Nigeria has some 34 known major mineral deposits distributed in locations across the country and offers considerable attraction for investors. Exploration in Nigeria for several solid minerals, e.g. tin, niobium, lead, zinc and gold, goes back for more than 90 years but only tin and niobium production have ranked on a world-wide scale. While the major international exploration groups have seldom paid more than a passing interest, there has been general exploration carried out by the tin mining groups and since the mid 1970s by several parastatal organizations and in particular the Nigerian Mining Corporation. Throughout its long history the Geological Survey of Nigeria Agency has played an active role in the exploration for mineral deposits many of which have been first reported by its officers. The Geological Survey of Nigeria Agency has also been responsible for the regional mapping, airborne magnetic and radiometric surveys which provide an invaluable base for more detailed exploration. There is at present an upsurge of interest in the development of solid mineral resources whose production in the last 30 years has been declining in every case. The privatization, commercialization and general reform exercises currently being undertaken by the government of Nigeria are expected to lead to an upsurge in the exploration and development of Nigeria's solid mineral resources.

Solid Minerals in the Basement Complex Including the Younger Granites

Iron Deposits

Three types of metamorphosed iron oxide rich layered metasediments are found in the NW and central parts of the Nigerian basement. The most important

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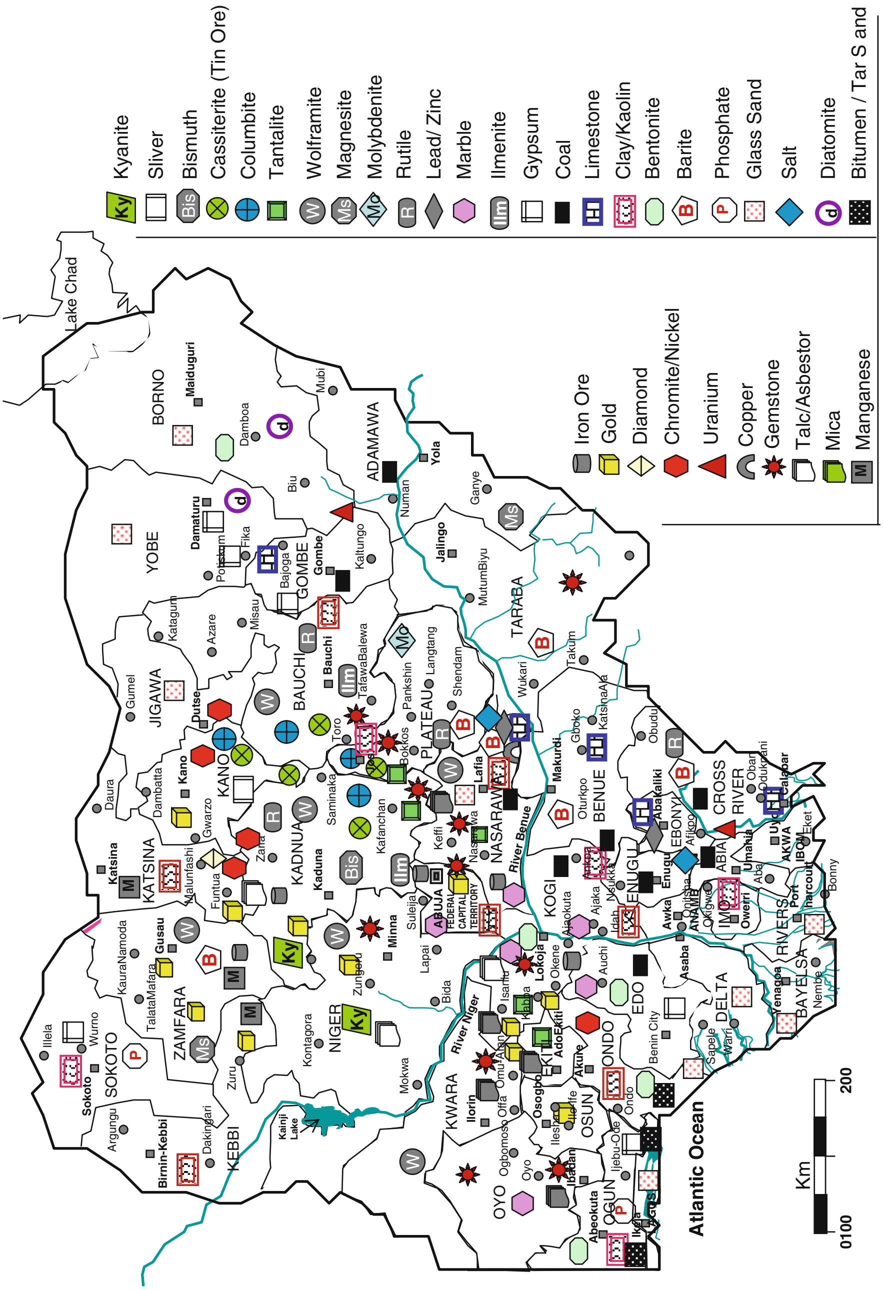

Fig. 10.1 An overview of the solid mineral resources distribution map of Nigeria (unlike petroleum, every state in the federation has a fair representation of solid mineral deposits)

Table 10.1 Solid mineral occurrences in the federating states of Nigeria

SN	Mineral	Occurrences (In states of Nigeria)
1	**Tantalite**	Cross River, Ekiti, Kogi, Kwara, Nasarawa
2	**Kaolin**	Akwa Ibom, Anambra, Bauchi, Bayelsa, Ekiti, Imo, Katsina, Kebbi, Kogi, Ogun, Ondo, Plateau, Rivers
3	**Mica**	Ekiti, Kogi, Kwara, Nasarawa, Oyo
4	**Baryte**	Benue, Cross River, Nasarawa, Plateau, Taraba, Zamfara
5	**Coal**	Abia, Adamawa, Anambra, Bauchi, Benue, Cross River, Delta, Ebonyi, Edo, Enugu, Gombe, Imo, Kogi, Nasarawa, Plateau
6	**Rutile**	Bauchi, Cross River, Kaduna, Plateau
7	**Talc**	Ekiti, Kaduna, Kogi, Niger
8	**Bismuth**	Kaduna
9	**Gypsum**	Adamawa, Edo, Gombe, Ogun, Sokoto, Yobe
10	**Feldspar**	Bauchi, Borno, FCT, Kaduna, Kogi,
11	**Gold**	FCT, Kaduna, Kano, Katsina, Kebbi, Kogi, Kwara, Niger, Osun, Zamfara
12	**Clay**	In all the states of the federation
13	**Silver**	Ebonyi, Kano
14	**Ilmenite**	Bauchi, Cross River, Kaduna, Plateau
15	**Limestone**	Benue, Cross River, Ebonyi, Edo, Gombe, Kogi, Ogun, Sokoto
16	**Columbite**	Bauchi, Cross River Kaduna, Kano, Kwara, Nasarawa, Plateau
17	**Cassiterite**	Bauchi, Cross River, Kaduna, Kano, Kwara, Nasarawa, Plateau
18	**Diatomite**	Borno, Yobe
19	**Silica sand**	Delta, Jigawa, Kano, Lagos, Ondo, Rivers
20	**Fluorite**	Bauchi, Ebonyi, Plateau, Taraba
21	**Bitumen**	Edo, Lagos, Ondo, Ogun
22	**Lead**	Cross River, Ebonyi, FCT, Plateau, zamfara
23	**Zinc**	Cross River, Ebonyi, FCT, Plateau, Zamfara
24	**Benonite**	Borno, Edo, Kogi, Ogun, Ondo
25	**Kyanite**	Kaduna, Niger
26	**Iron ore**	Enugu, FCT, Kaduna, Kogi, Nasarawa, Zamfara
27	**Lithium**	Kaduna, Nasarawa, Niger, Zamfara
28	**Magnesite**	Adamawa, Zamfara
29	**Wolframite**	Bauchi, Kaduna, Kano, Kwara, Nasarawa, Niger, Zamfara
30	**Phosphate**	Ogun, Sokoto
31	**Marble**	Edo, FCT, Kogi, Kwara, Nasarawa, Oyo
32	**Molybdenite**	Plateau
33	**Manganese**	Katsina, Kebbi, Zamfara
34	**Gemstones**	Bauchi, Kaduna, Kogi, Kwara, Nasarawa, Niger, Ogun, Oyo, Plateau, Taraba

economically are those occurring within the Okene migmatite complex in south-central Nigeria. Olade (1978) described the Itakpe Hill deposit, the largest of several similar deposits in the district, as a hematite-magnetite quartz body, and termed it as a ferruginous quartzite of the *Itabirite* type. Thereafter, Muecke and Neumann (1985) concluded on mineralogical grounds that the deposit represents a replacement of basement gneisses and amphibolites by iron rich solutions emanating from nearby granitic bodies of the Pan-African Older Granite suite. Mineable reserves

Fig. 10.2 The Ajaokuta Iron and Steel Complex in Kogi State: Designed to use Nigeria's Iron ore deposits as raw material for Iron and Steel production; a conception still very far from realization

of about 111,400,000 tonnes grading about 35% Fe was repoted by Umunnakwe (1985) which could easily be upgraded and was subsequently partly developed for open pit mining to provide feed for the Ajaokuta steel complex close by (Fig. 10.2).

The most extensive occurrence of iron is in the form of Banded Iron Formation (BIF) in the Maru and Kushaka schist belts. The BIF occurs with fine grained pelitic sediments as thinly layered sedimentary rocks of probable chemogenic origin, often spatially associated with amphibolitic units. Structurally these units occur as linear ridges aligned N–S but internally relicts of complex fold patterns are found reflecting several phases of deformation. These deposits were investigated by the Geological Survey of Nigeria and National Steel Council in the 1960s and 1970s as potential iron ore sources but they were found to be low-grade (<30% Fe) and work was stopped. More recently a new discovery has been reported at the Muro Hills (Toto LGA, Nasarawa State) (Figs. 10.3, 10.4), where within a hitherto unreported

Fig. 10.3 (**a**) Sample of Iron ore deposit obtained from the Muro Hills near Gadabuke in Nasarawa State. A more economical Iron ore deposit occurs within Precambrian basement rocks in the Itakpe-Ajaokuta area. (**b**) A distant view of the metasedimentary banded iron formation of the Muro Hills near Gadabuke in Nasarawa state

schist belt, a banded iron oxide quartz rock is associated with marble and dolomitic rocks (Obaje et al., 2006). Geochemical assessment of two representative BIF samples from the Muro Hills undertaken by the author at the Geological Laboratory of the University of Greifswald, Germany in 2008 gave iron content values of 43% (Table 10.2). The iron ore is interbanded with quartzites and is paragenetic with such Precambrian rocks as dolomitic marble, pure marble, phyllite, calc-gneiss, schist and minor intrusives, all of which have been subjected to at least two periods of folding as well as multiple fracturing and sharing. The iron ore occurs in association with a large deposit of marble which in places is almost pure dolomite. The presence of this marble is expected to enhance the prospects of mining the iron ore, which is also favourably disposed for open cast mining. Iron ore is one of the important minerals used in industry. Where Iron and Steel manufacture is undertaken, many secondary industries normally follow.

(a)
(b)

Fig. 10.4 (**a**) Another view of the Iron ore-rich Muro Hill. (**b**) As is usually the case with accessibilty to most mineral deposit localities in Nigeria, this road is very rugged but it leads to the Iron ore deposits at the Muro Hills

Gold and the Other Precious Metals

Though the precious metals are not essential for industrialization, they are a valuable source of foreign exchange and their exploitation to a large scale promotes the establishment of ancillary industries. In Nigeria traces of gold have been found in

Table 10.2 XRF geochemical data on two representative samples from the Muro Hills banded iron deposit (BIF = Banded Iron Formation). Note content of Fe_2O_3 in both samples = 43.3% (Courtesy: Geological Laboratory, University of Greifswald, Germany, 2008)

	SiO_2 (%)	TiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MnO (%)	MgO (%)	CaO (%)	Na_2O (%)	K_2O (%)	P_2O_5 (%)	GV1000°C (%)	H_2O- (%)	**Sum** (%)
BIF-2-Muro	56,65	0,014	0,26	**43,3**	0,062	0,45	0,05	0,02	0,01	0,020	–0,04	0,10	100,9
BIF-7-Muro	56,46	0,022	0,59	**43,3**	0,064	0,50	0,10	0,11	0,08	0,024	–0,01	0,10	101,3
	Ba (mg/kg)	Ce (mg/kg)	Co (mg/kg)	Cr (mg/kg)	Cu (mg/kg)	Ga (mg/kg)	Hf (mg/kg)	La (mg/kg)	Mo (mg/kg)	Nb (mg/kg)	Nd (mg/kg)	Ni (mg/kg)	Pb (mg/kg)
BIF-2-Muro	94	< 24	26	10	< 50	< 3	< 5	< 20	8	< 3	21	< 5	< 5
BIF-7-Muro	124	< 24	23	8	< 50	< 3	< 5	< 20	10	< 3	24	< 5	< 5
	Rb (mg/kg)	Sc (mg/kg)	Sr (mg/kg)	Ta (mg/kg)	Th (mg/kg)	U (mg/kg)	V (mg/kg)	W (mg/kg)	Y (mg/kg)	Zn (mg/kg)	Zr (mg/kg)		
BIF-2-Muro	9	< 5	< 3	< 5	7	< 4	< 12	< 5	< 3	11	< 5		
BIF-7-Muro	10	< 5	< 3	7	7	< 4	< 12	< 5	< 3	13	5		

every area underlain by the Basement Complex and mining on a small scale has taken place in many areas. The Nigerian gold contains varying amounts of silver. Small amounts of silver are also present in the lead-zinc ores and this could probably be recovered as a by-product if the ore is mined on a sufficiently large scale.

Probably 90% of Nigeria's total gold production has been from alluvial deposits derived from primary gold mineralization in the basement rocks. All the producing areas have been in the western part of the basement where the schist belts are best developed and there is a spatial relationship with some schist belts although gold-quartz veins also occur in gneisses (e.g. Malele, Diko and Iperindo). Four gold fields can be outlined, Ilesha-Egbe, Minna-Birnin Gwari, Sokoto and Yelwa (Woakes and Bafor, 1983), and each covers several thousand square kilometers.

Gold mining reached its peak in the period 1935–1941 but since 1950 has been generally limited to very small scale alluvial workings. In recent years the defunt Nigerian Mining Corporation did some extensive exploration work and planned a production from alluvials in the Ilesha area. Typically, gold bearing quartz veins carry some sulphides, galena and pyrite being the most common. The veins are very often conformable with the general N–S to NNE–SSW structural grain of the basement and occur in a variety of geologic settings which suggests that there was more than one period of mineralization. Regionally it was observed by Woakes and Bafor (1983) that primary gold deposits are associated with some schist belts (e.g. Ilesha, Maru, Anka, Kushaka) but not with others (e.g. Wonaka, Karaukarau, Iseyin-Ogun River), and that they are often spatially related to amphibolites and regional NE–SW to N–S fault or shear zones, with no specific relationship to the Older Granites or BIF. In the Ilesha (Elueze, 1981) and Egbe (Garba, 1985) areas, gold occurs in the amphibolites in amounts above the average primary gold content for similar rocks and is sufficient to provide the source of some of the alluvial deposits. The alluvial deposits throughout the goldfields are found not only in the present river channel deposits but also in older buried placers which in places have been eroded by the modern drainage system and are the source of modern placers. Russ (1957) also reported small quantities of gold in the basal conglomerates of the Cretaceous Nupe Sandstone in several localities fringing the Mid-Niger Basin. No similar deposits have been reported from the Benue Trough where the Cretaceous and later sediments are derived from basement areas with only very minor schist occurrences.

Tin-Tantalum-Niobium Pegmatites

In terms of money values, the production of tin far exceeds that of any other solid mineral in Nigeria. Tantalum, niobium and other metals occur with the tin and have been produced as by-products. It is estimated that more than 95% of the over 650,000 tonnes of cassiterite (tin) produced has been from alluvial deposits derived from the Mesozoic Younger Granites. The remaining 5% of the tin has been derived from pegmatites which form a well defined ENE–WSW trending zone from the central Jos Plateau to the Ife-Ilesha area (Fig. 10.5). Some pegmatites also contain gem quality corundum and are being mined on the Jos Plateau. This pegmatite zone was

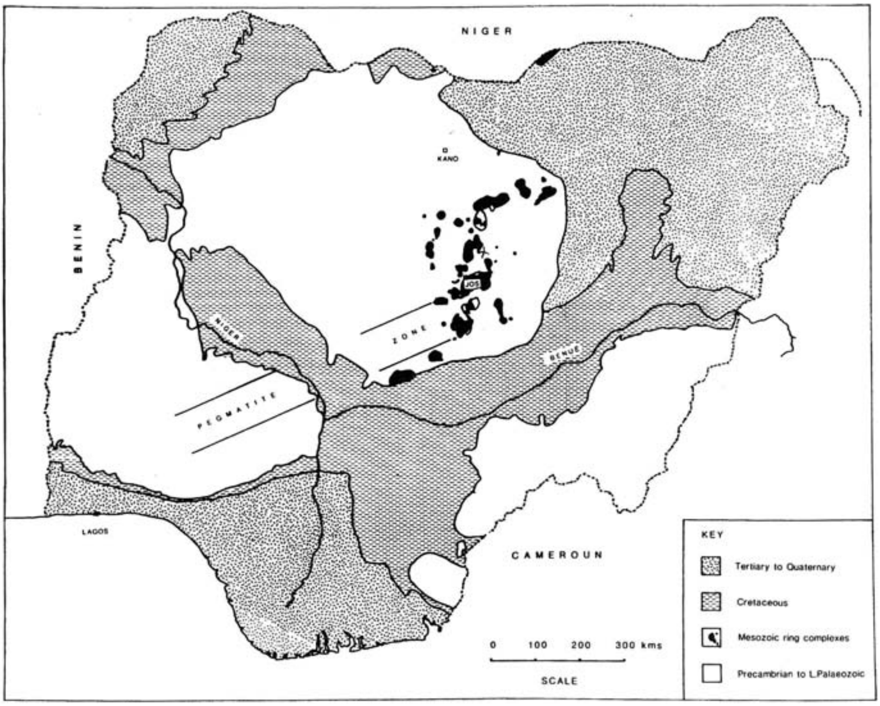

Fig. 10.5 The ENE-WSW trending *Pegmatite Zone* in Nigeria and its structural relationship to mineralization in the Younger Granites

noted by Jacobson and Webb (1946) and later elaborated by Wright (1970). Both recognized that the pegmatites are older than the Mesozoic Younger Granites and linked them with the Pan-African Older Granite suite which often occurs in close proximity. However, Matheis and Vachette (1983) have distinguished barren and tin-bearing pegmatites where the latter are 100 Ma younger than the granites and barren pegmatites. They also point to the close association in Ilesha and Egbe area of tin-bearing pegmatites with schist belts and suggest metamorphic processes as important although Kinnaird (1984) relates them to late or post-Pan-African orogenic granites. It is pertinent to note that the zone of mineralized pegmatites is the only basement metallogenetic feature that cross-cuts the schist belt structures although most pegmatites are oriented N–S. The pegmatite zone is parallel to the ENE–WSW linear pattern of Younger Granite intrusions and the Cretaceous Benue Trough. Mineralized pegmatites consist of quartz, potash feldspar, albite, muscovite and less commonly, biotite and a range of accessory minerals including tourmaline and economically important cassiterite and columbo-tantalite (Fig. 10.6a). Individual bodies occur as dykes and flat-lying sheets up to 2 km along strike. The primary mineralization has been mined when deeply weathered and significant amounts in alluvials derived from pegmatites have also been exploited.

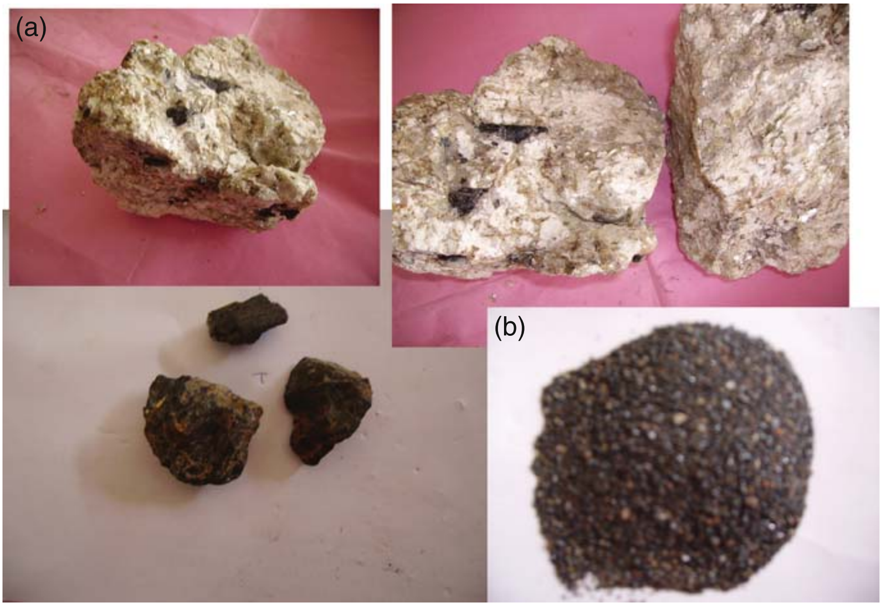

Fig. 10.6 (**a**) Samples of Tantalite deposite obtained from Andaha in Nasarawa state (**b**) Processed Columbite obtained from the Afu Younger Granite complex around Udege Beki in Nasarawa state

Tin is believed to be one of the first metals used by man. In antiquity it was principally employed in making bronze and pewter, and later in lining cooking utensils. For many centuries it was one of the most important metals produced by man. Of its newer uses, the principal one is the manufacture of tin-plated steel (tin plate), which finds universal employment in food-canning, the making of solder, type metal and collapsible tubes employs large quantities of tin, and it is also used in bearing metals. Its compounds are used in dyeing and fire-proofing.

Niobium (or columbium, as it is commonly termed in America) is a rare element with a high resistance to corrosion. It is almost always accompanied in its ores by varying amounts of the related elements tantalum. Its main use is in making certain heat- and corrosion-resisting steels that are at present principally used in gas-turbine engines. Because of its use in gas-turbine engines, niobium has become a metal of vital strategic and industrial importance.

Columbite, the ore of niobium, is a black mineral which is found in Nigeria with tinstone in alluvial deposits associated with the Younger Granites and Older Granites of the Plateau Tinfield (Fig. 10.6b). The columbite derived from the Older Granite pegmatites commonly occurs as massive dull, iron-black lumps and crystals, containing varying amounts of tantalum. The most important pegmatite deposits are found in the Wamba-Jema'a region of Nasarawa and Kaduna States (Fig. 10.7). The high-grade columbite from the Younger Granites occurs in the form of small, black, platy crystals, averaging less than 0.03 cm in length.

Fig. 10.7 Abandoned Tantalite mines in Andaha. Large Tantalite deposits stil occur in this area. Depending on the trend of the vein, the mine may be circular (**a**) or elongated (**b**)

Chromite, Nickel, Talc and Asbestos

To date the only known occurrences of chromite and asbestos that are of interest are within the northwestern schist belts of Sokoto State where a well defined alignment of serpentinite bodies can be traced for 150 km from Ribah, through Tungan Kudaku and Maikwonaga to Sado. The Tungan Kudaku serpentinite is itself cut by a diorite which is unaltered and only affected by movements at its margins, suggesting a late Pan-African age. Another serpentinite body at Mallam Tanko lies 100 km east of the Sokoto linear and is an 8 km string of small bodies aligned N–S in gneisses but forming a southern projection of part of the Wonaka schist belt. There are reported cases of serpentinite occurrence in the Federal Capital Territory but yet to be properly mapped.

The Sokoto and Mallam Tanko serpentinites are typically intrusive bodies up to 15 km in length and 1 km in width. Small pods, up to 0.5 m, of massive chromite have been found and the chromite also occurs in layers, in spotted texture form and as fine disseminations. The few available analyses indicate Cr_20_3 contents from 40 to 60% (Shibayan, 1985). Anthophyllite asbestos occurs commonly on the microscopic scale but larger veins are also found. Some derived soils of limited extent are enriched in nickel (Ogezi, 1977). A number of talc (with or without magnesite) bodies have been reported (Elueze 1982) occuring in close relationship to the serpentinite.

Ni-Sulphide and Base-Metal Deposits

Several authors (e.g. Bafor, 1981; Elueze, 1981) have reported a variety of sulphide minerals including pyrite, pyrrhotite, pentlandite, bornite and chalcocite occurring in small amounts in gabbro intrusives and the metavolcanics of the schist belts. The Nigerian basement offers the possibilities of Ni-Cu-sulphide minerals in magmatic synvolcanic bodies especially komatiites but also tholeiites. Klemm et al. (1984) described the Ilesha schist belt as having field and geochemical characteristics "typical for Archaean granite greenstone terrains" contrary to the views of other workers that it represents an Upper Proterozoic sequence (Rahaman and Lancelot 1984). Klemm et al. (1984) went even further to identify komatiites (also known as metapyroxenites), within the amphibolite complex. Important Ni-sulphide ore deposits in the Archaean terrains of Australia, Canada and Zimbabwe are associated with the base of komatiite flows. Elsewhere in the schist belts the tholeiitic volcanics of the Maru, Kushaka and other schist belts might be comparable to the Pechanga (USSR), Lynn Lake (Canada) and other deposits world-wide where some minor amounts of sulphides have been reported.

Within the Nigerian schist belts of the northwest, the dominance of clastic sediments over tholeiitic volcanics combined with the possible rift subsidence setting of the schist belts (Olade and Elueze, 1979) is indicative of a favourable environment for either the Besshi-Kieslager Cu-Zn type or for the exhalative Pb-Zn sedimentary type. The Nigerian schist belts may be compared to the Pan-African Damara Belt of Namibia (Martin, 1978) within which the Matchless Amphibolite Belt contains several Besshi-Kieslager type copper deposits such as the Otjihase (Goldberg, 1976). These deposits occur close to large volcanic masses within a thick sequence of clastic sediments and are associated with small bodies of exhalative iron formation and zones of strong chloritic alteration. The Nigerian schist belts contain such features and a more detailed search for Cu/Zn deposits guided by these criteria seems justified.

Manganese

Manganese deposits occur at Tudun Kudu within the Karaukarau schist belt west of Zaria in northwestern Nigeria. Muecke and Okujeni (1984) published detailed mineralogical studies in support of an epigenetic origin. The maganese occurrences of northwestern Nigeria have been variously described as "conformable beds of quartzite" (Wright and McCurry, 1970), "interbedded manganiferous quartzites within the phyllite" (Moneme et al., 1982) and as "veins parallel to the foliation of the phyllites with sharp contacts" (Muecke and Okujeni, 1984). They are known to occur in only two of the schist belts, Maru (which also contains BIF, gold and amphibolites) and Karaukarau (which contains detrital quartzites but no iron-rich chemogenic quartzite, no gold and very minor amphibolites). Manganese is an essential substance in refining of steel. It acts principally by removing oxygen and sulphur from the molten metal.

Uranium

The possibility of finding uranium in Nigeria started to get more attention with the discovery of the mineral in bordering Niger Republic as well as the discovery of secondary uranium minerals in Cameroun. Recent studies have given stronger indications of the occurrence of uranium ore in some parts of the country. The first indications were registered in the results of the airborne radiometric surveys carried out by the International Resources Inc. USA, in parts of the country. The radioactive anomalies refer mostly to the continental – paralic Cenomanian-Turonian deposits of the Bima, Keana, Makurdi and Ezeaku Formations and the adjoining Basement and Younger Granite rocks. Uranium deposits in Nigeria could be peneconcordant or discordant. This implies that Nigeria's uranium ore could have been eroded from nearby source rocks, transported and concentrated in old river channels, fractures and other voids within the typically, fluviatile arkosic sandstones, or the basal micaceous sandstones of the host formations. Fossil organic matter (plant debris), which are potential precipitating agents, abound in these rocks. Alternatively, it could also be deposited by the secondary enrichment from the underlying igneous and Basement rocks along the fracture zones in the arenaceous formations. Uranium, with niobium and thorium, occurs with pyrochlore in the Nigerian Younger Granite rocks. Pyrochlore is a constant accessory in the albite-riebeckite granite of the Younger Granite complex, which has a background of 10–12 ppm Uranium (Bowden, 1982). The relationship between the Younger Granite rocks and the indicated uranium occurrences in the Cretaceous of the Benue Trough is not very clear. However, it has been shown, from current bedding analysis and other palaeogeographic studies that the detrital materials of the Cretaceous sediments originated from the surrounding Basement and Younger Granite rocks.

Uranium Mineralization in Migmatite-Gneiss Complex

Limited geochemical studies on the basement rocks of southwestern Nigeria indicate that the schists and quartzites have low uranium contents (average of 0.3 and 1.1 ppm U, respectively). The average uranium concentrations observed in the migmatites and gneisses is 4 ppm U. Similar levels of uranium concentration (average 3.4 ppm U) are also observed in some metasediments and gneisses in the northeastern part of the country. However, airborne radiometric survey has indicated a belt of uranium anomalies in the migmatite-gneiss complex, stretching from Katsina-Ala to Donga in present day Benue and Taraba States, respectively.

Uranium Mineralization in the Older Granites

Whole rock strontium isotopic isochron studies on the Older Granites from central and northeastern Nigeria (Matheis and Caen-Vachette, 1981) and southwestern Nigeria (Rahaman et al., 1983) show that these rocks are characterized by high initial 87Sr/86Sr ratios. The results indicated a significant crustal component in the magmas that crystallized the Older Granites. The significance of derivation of the Older Granites by crustal remobilization is that the melts from which the Older Granites were derived could be enriched in uranium by anatexis of crustal rocks of moderate to high uranium contents. Uranium may be further concentrated in the granites by magmatic differentiation. It is worthy to note that most granitic rocks of similar Older Granite (Pan-African) age elsewhere in the mobile belt of Africa, such as the Damara-Katanga belt in Zaire and Namibia (Dahlkamp, 1980), are known to host uranium deposits. Some pegmatites around Adada, northeast of Yola, contain as much as 72 ppm U. This value is about 18 times as much as the average concentration of uranium in normal granitic rocks and suggests a possible low grade uranium mineralization. Although the mode of uranium concentration in these rocks is not known it is probably due to late magmatic differentiation, similar to that observed in the pegmatites of Rossing, Namibia or Bancroft in Canada. Other pegmatitic rocks which may be expected to be similar in uranium contents to the Adada rocks include the muscovite bearing pegmatites which cross cut the migmatites around Kano and Zaria, Guibi near Bauchi and Egbe.

In addition to the possibility of low grade uranium mineralization in pegmatitic granites, high grade uranium mineralization has been observed around Manza and Monkin near Mayo Belwa in NE Nigeria. Mineralization occurs along what appear to be silicified fault zones. The principal ore is pitchblende in form of disseminations and veinlets. Torbenite and autunite were also observed. Gangue is mostly in form of silica and haematite. Preliminary chemical analysis of the ore gave average contents of 0.12–4.12% U_3O_5. There are other several uranium occurrences but of low-grade in N. E. Nigeria. Kanawa and Mika mineralizations are among the most prominent (Funtua et al., 1996). An interesting observation in the Basement Complex of Nigeria is the occurrence of uranium anomalies at the boundary between the Precambrian Basement Complex and the overlying Cretaceous sediments in places such as Kontagora, Wawa and Nasarawa. These areas of uranium anomaly may be further investigated for the unconformity vein-type uranium mineralization which is sometimes found at unconformities between basement rocks and overlying younger sediments.

Uranium Mineralization in the Younger Granites

The Younger Granites in Nigeria may be compositionally classified into two end members: peralkaline and non-peralkaline. The peralkaline granites are mostly riebeckite-arfvedsonite bearing while the non-peralkaline ones are mostly biotite bearing. Only the peralkaline granites seem to be significant in the Younger Granite Series with respect to uranium mineralization. Uraniferous pyrochlore has been reported in some peralkaline albite riebeckite granites of the Lirueri Complex at Kaffo (Jacobson and Macleod, 1977) and in the Rop Complex at Durowa (Buchaman et al., 1971). Radiometric anomalies are also located around Nasarawa in the Afu Complex Other albite-riebeckite granites such as those in Dustein Wai, Buji, Amo and Shere Complexes may also be mineralized with uranium. The close association of uranium mineralization and the peralkaline granites may be explained in terms of the genesis of the rocks. According to Jacobson and Macleod (1977) some of the peralkaline rocks, particularly the albite-riebeckite granites are formed by albitization of pre-existing riebeckite granite by deuteric solutions rich in fluorine and believed to have been derived from volatile rich magma residue (autometasomatism). It may be expected that such volatile rich magma residues in addition to their high concentration of fluorine and rare metals (Sn, Nb, Ta, etc.) also contain significant amounts of uranium and thorium which also tend to accumulate in residual magmas.

Industrial Mineral Deposits

A variety of industrial mineral occurrences are found in the metamorphic terrain of the basement complex including marbles, talc, sillimanite, graphite and feldspar. Many of the Older Granites and other crystalline rocks are extensively quarried (Fig. 10.8) for road construction and building materials.

Fig. 10.8 Granites for construction purposes are amongst the most exploited mineral deposits in several places in Nigeria

Fig. 10.9 A Marble mine at Ugya in Toto local government area of Nasarawa state

(i) *Marble* occurs within the migmatite-gneiss-schist-quartzite complex as relicts of sedimentary carbonate rocks (Fig. 10.9). These are Upper Proterozoic schist belt metasediments which are normally marked by a general absence of carbonates. Several of these marble deposits are currently being exploited for cement (Ukpilla, Obajana) and decorative stone (Jakura, Kwakuti and Igbetti) with some production of ground rock for industrial use. Such marble deposits appear to be limited to the western portions of the south and central parts of the country. Large marble deposits occur in the Muro Hills and at Ugya in Toto Local Government Area of Nasarawa State. The deposits in these areas (Muro Hills and Ugya) are being mined sparingly and locally. The deposits are large enough to attract the attention of investment in cement manufacturing (Figs. 10.9, 10.10, and 10.11).

(ii) *Talc* is not yet exploited though there are many occurrences some of which are high grade though coloured. These deposits are associated with the

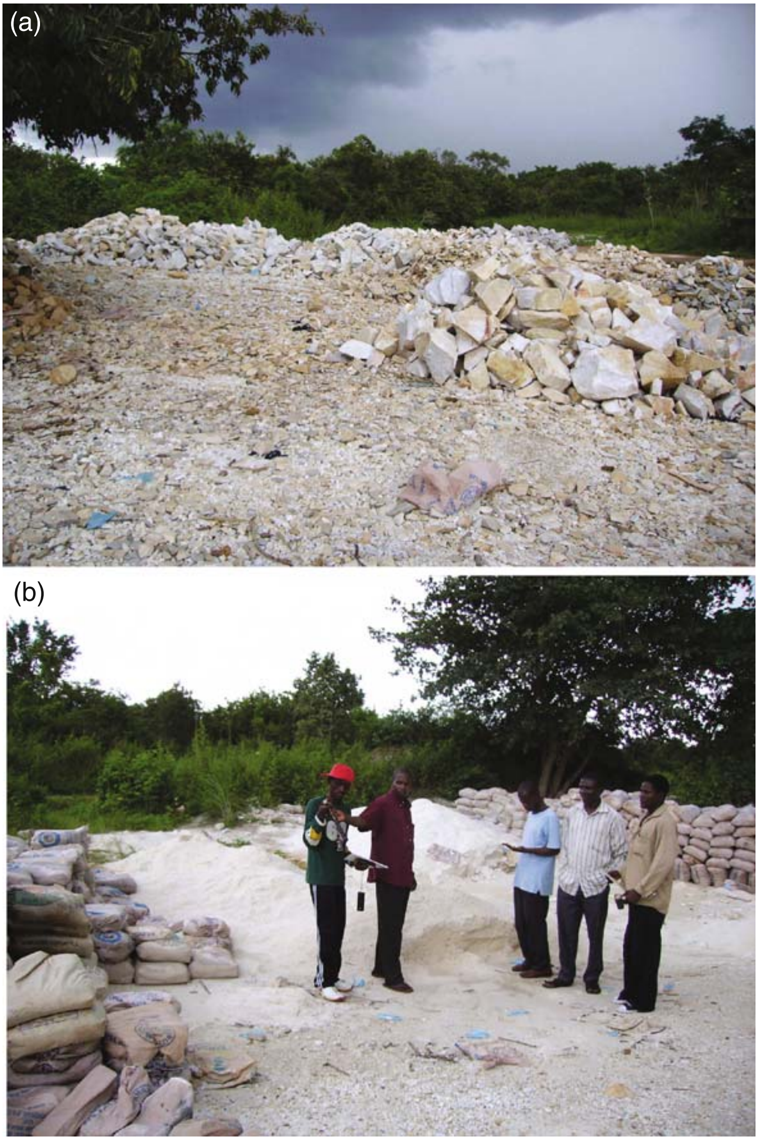

Fig. 10.10 (**a**) Dugged out Marbles from the Ugya mine; (**b**) Mined and processed Marble at the Ugya mining site

amphibolites of the schist belts (Elueze, 1982) and further exploration may be expected to lead to commercial development.

(iii) *Sillimanite* occurrences in several schists (McCurry, 1976; Rahaman, 1976) have been reported. These occur as isolated higher grade metamorphic "islands" within the generally low-grade facies schist belts of western Nigeria.

Fig. 10.11 (**a**) Marble everywhere at Ugya; (**b**) Road to the Marble mining sites at Ugya

(iv) *Graphite* occurs south of Jalingo in Taraba State, Northeastern Nigeria, where several extensive but low grade deposits have been reported in the basement rocks. In the Kushaka (Ajibade, 1980) and Maru (Egbuniwe, 1982) schist belts, graphitic slates and graphitic phyllites occur.

(v) *Feldspars*, both potash and soda varieties are exploited on a small scale for glazed ceramics in Suleija from pegmatites of the Older Granite suite. Further development of these and other deposits is possible.

(vi) *Mica*: The mineral mica is quite common in the pegmatites of central Nigeria, but to be of value it has to be found in unbroken sheets several centimeters across, and must be free from inclusions. Some workable quantities of micas occur in Lokoja (Kogi State), Wamba, Gidan Kwano and Toto areas of Nasarawa State. White mica, or muscovite, is essential in the manufacture of many kinds of electrical equipment.

Gemstones

Most of the gemstones occur in pegmatites and quartz veins in rocks of the Basement Complex and Younger Granites. Like the precious metals, gemstones can be an important source of income for a developing country like Nigeria. There are many varieties of gemstones, too numerous to list here (Figs. 10.12, 10.13, 10.14, 10.15, 10.16, and 10.17). Important ones in terms of quantity are aquamarine, emeralds, sapphire, ruby, topaz, tourmaline, zircon and almandine.

Solid Minerals in the Sedimentary Basins

Barytes

The zone of mineralization resulting from the tectonic activities in the Benue Valley appears to run in the narrow tract extending from the southeast in the Abakaliki

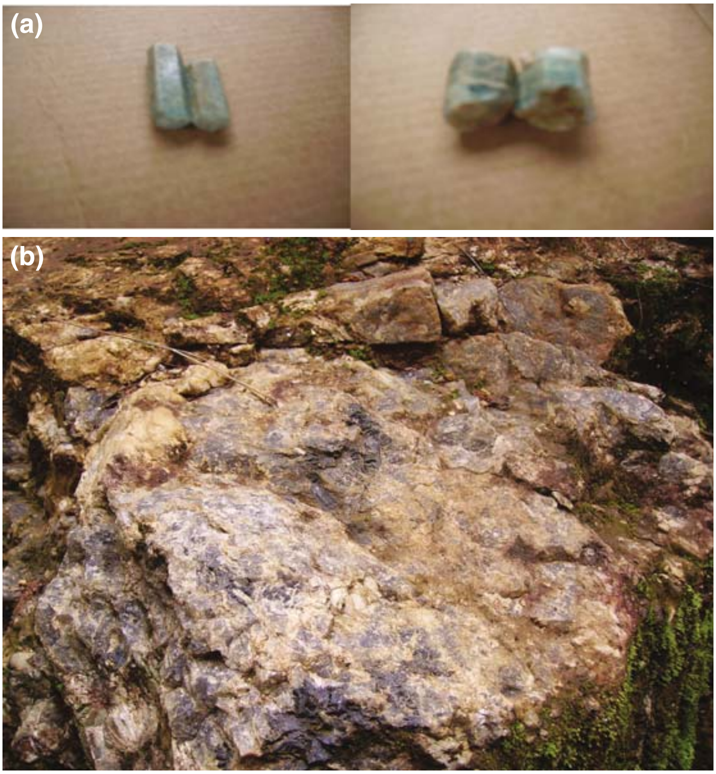

Fig. 10.12 Beryl (Gemstones) from Andaha in Akwanga local government area of Nasarawa state (**b**) Beryl-bearing pegmatite rocks at Andaha near Akwanga

Fig. 10.13 (**a**) Loto Mine for Beryl in Andaha, near Akwanga and (**b**) Advanced view of the Loto Mine

trough axis to the northeast. The associated intrusives are distributed from Ishiagu in the southeast to as far north as Dadiya, in the northeast, a distance of about 500 km. These two minerals, barytes and lead-zinc, are associated with the brine-springs. There are differing views on their relationships. But there is the possibility of chemical interaction between the rising metal bearing hydrothermal fluid with the surrounding country rock in the saliferous or evaporitic zones, resulting in the deposition of barytes (Fig. 10.18) and lead-zinc (galena, sphalerite).

A study of the best known deposit of barytes at Azara in the Middle Benue Trough (Figs. 10.18b, 10.19, and 10.20) shows that the mineral, like the lead-zinc, infills fracture systems, but in generally arenaceous deposits. The fractures occur as single linear structures or as a series of irregular fractures interconnected and spaced over a considerable width and distance. The single linear veins, in most occurrences, show a low profile, with thicknesses of generally.not more than 0.5 m while in contrast, the gash or composite veins are invariably marked by a high ridge,

Fig. 10.14 (**a**) Advancing to locate Aquamarine deposits and mine sites in the hill top behind Nasarawa Eggon. Thick vegetations and bushes must be overcome to get to most sites of mineral deposits. Inset: Aquamarine gemstones; (**b**) Crossing of rivers and streams must also be reckoned with. A tortuous advance to locate Aquamarine deposits and mine sites in the hill top behind Nasarawa Eggon

often towering well above the general landscape. The veins often end abruptly along their strikes. They are found to concentrate around the end of the Keana anticline on the major fold axis, which appears to plunge gently to the east. In the Azara barytes fields, the dips are generally low with a range, $5''$ to $20''$.

Barytes mineralization is associated with quartz, galena, sphalerite and iron minerals, as gangue. In all, about 20 veins have been mapped in Azara, most of them represented by narrow, winding structures. Conservative estimates carried out in three rich veins, out of the 20 occurrences in this locality, indicated a reserve of up to 130,000 tonnes of contained $BaSO_4$, and for only 10 m depth. This reserve, excludes the biggest deposit, which for some unforeseen problems, were not incuded in the study by Offidile (1980). The indication is that the reserves could more than double this figure, as investigation continues. There are also other known occurrences in Keana, Gbande, and Abakaliki. Around Azara, other principal known occurrences are at Aloshi, Akiri, Wuse and Keana.

Fig. 10.15 (**a**) Aquamarine mines on the hill top behind the town of Nasarawa Eggon (**b**) Active and abandoned Aquamarine mines on the hill top behind the town of Nasarawa Eggon

The importance of barytes in the oil, paint and paper industries is well known. At the present time, Nigeria imports a considerable quantity of this mineral for use in its oil-operations. Baryte is the chief constituent of lithopone paint and it is also extensively used as an inert volume and weight filler in drilling mud, rubber, glass, paper, etc. and in the chemical industry.

Lead-Zinc

Lead-zinc (galena, sphalerite), often associated with barites mineralization, is thought to be hydrothermal in origin. Fracturing and jointing are intense in the areas of mineralization. In places the structures are locally contorted, obscuring the regional geology. The main sets of fractures run generally in the directions of 45″ to 80″ to each other and, invariably almost at right-angles, transverse to the fold axis.

Fig. 10.16 Winning of Aquamarine gemostones from mine debris at the mine sites behind the town of Nasarawa Eggon

The mineralization consists essentially of siderite, sphalerite, galena and barytes assemblages with a minor amount of gold and silver. It is typical of the fracture-filling types. It has been observed that the lead-zinc mineralization is dominant, with only accessory barytes, in the more argillaceous sediments viz: the Albian Asu River Formation of the Abakaliki and Zurak provinces. Over 30 lodes of lead-zinc with an aggregate length of about 7,000 m have been reported in the Nigerian lead-zinc field. The mineralization was shown by drilling to be up to 100 m deep. In the Abakaliki area, in particular, lead-zinc mineralization was found associated with calcareous shales and shaly limestones. In the two occurrences at Ameri and Nyeba, the Nigerian Lead-Zinc Mining Company (1956) gave a conservative indicated ore reserve of 693,000 tonnes with 9.0% lead and 7.0% zinc. In the lead-zinc fields, two types of rocks are indentifiable, the galena and sphalerite rich rocks. The Abakaliki field is still Nigeria’s most important lead-zinc deposit.

Fig. 10.17 Gemstones (Topaz, Aquamarine and Tourmaline) won from different localities in Nasarawa State. Gemstones are very common in many of the pegmatite veins is Nigerian basement complex rocks

Lead is used in the manufacture of cable coverings, pigments, storage batteries, solder, sheet lead and pipes, shot, and bearing metals. Other uses of zinc include galvanizing steel plate, the manufacture of brass and other alloys, rubber vulcanizing, and the production of pigments and certain medicines and chemicals.

Coal

Apart from spasely reported occurrences of lignites and minor sub-bituminous coals in the Sokoto Basin (Kogbe, 1976) and in the Mid-Niger Basin (Adeleye, 1989), all the coal deposits of Nigeria occur in the Benue Trough. Mineable coal deposits in Nigeria occur at Enugu, Okaba, Ogboyaga, Orukpa, Lafia-Obi, Gombe and Chikila. These coalfields fall into two main groups: the Turonian-Coniacian and the Campano-Maastrichtian coals.

The Coniacian Coals

The Lafia-Obi coal deposit is geologically, the oldest coal deposit in Nigeria so far discovered. This deposit is believed to be Turonian-Coniacian in age (Offodile, 1976, 1980; Obaje and Hamza, 2000). During the Turonian-Coniacian transgression, swampy environments appear to have developed near the edge of the trough in

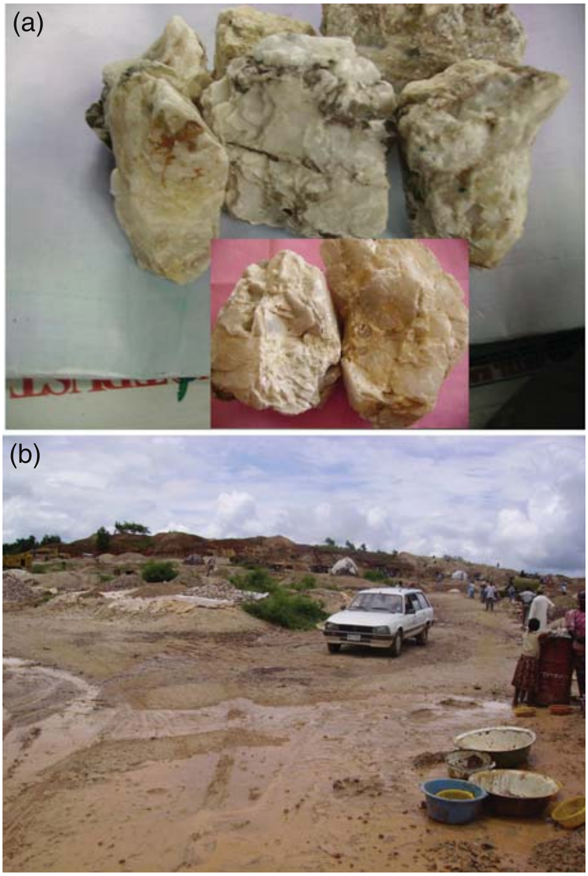

Fig. 10.18 (**a**) Samples of Baryte deposits obtained from Azara in Nasarawa State; (**b**) One of the active Baryte mine sites at Azara

which coals were formed. The Lafia-Obi coal seams are, unfortunately rather thin in outcrop (Fig. 10.21), with the thickest seam only about 0.6 m. However, Obaje (1994) reported that coal seams of up to 5m were encountered in the boreholes drilled by the National Steel Raw Materials Exploration Agency. These coals are of high-medium volatile bituminous rank with vitrinite reflectivity in the range of 0.70–1.20%. The coals occur within the Awgu Formation and are widely exposed in outcrops along the bank of River Dep at Shankodi near Jangwa and in many boreholes drilled by the Steel Raw Materials Exploration Agency in the Obi-Agwantashi-Jangerigeri areas. These coal deposits have the highest rank among all Nigerian coal deposits and have been assessed to be suitable for coke making in steel manufacture, when slightly blended (Obaje, 1994, 1997). The Lafia-Obi deposit has estimated reserve of 22.4 million tonnes and the greater part of the deposit is yet to be fully explored. The vitrinite reflectance values of the coals (0.70–1.20%) also fall within the "oil generation window". However, vitrinites predominate in the maceral compositon.This couple with the fact that most of the vitrinite reflectance values

Fig. 10.19 Baryte mines showing different vein orientations at the Wuse mine site near Azara

Fig. 10.20 Large deposits of Barytes won from the Azara mines prepared for sale to receivers

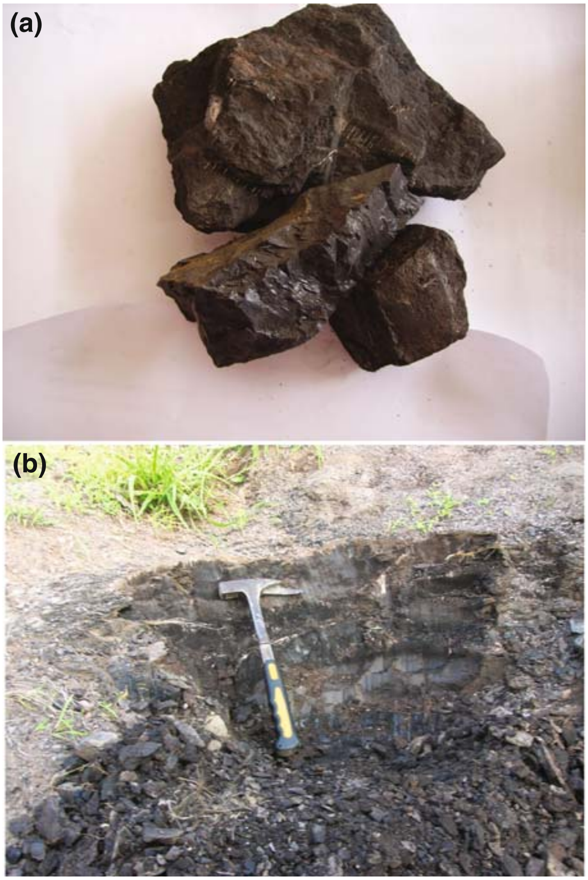

Fig. 10.21 (**a**) Samples of Coal deposit obtained from Shankodi near Jangwa in Nasarawa state; (**b**) A portion of surface exposure of the Shankodi Coal deposit. This coal has the highest rank (high-medium volatile bituminous rank) amongst the Coal deposits of Nigeria

are closer to the end line of oil generation (1.20%), it is expected that more gas rather than oil would be generated. Coal beds are now widely known to be a major source of oil and gas and are becoming increasingly exploration targets for hydrocarbon accumulations in many parts of the world. Jauro et al. (2007) also reported the occurrence of coals of high to medium volatile rank within the Lamja Formation in the Upper Benue Trough attributed to Turonian-Coniacian age.

The Campano-Maastrichtian Coals

The Nkporo Formation (Campano- Maastrichtian), with its shales and poorly developed coals at the top, is transgressive and marine in origin but passes upwards, without any apparent break, into the typically paralic Mamu Formation (Maastrichtian). The Mamu Formation consists essentially of fine-grained sandstone, shale, mudstones and sandy shales with some coal-seams. Seam No. 3 (about 2 m) is worked by the Nigerian Coal Corporation in the Enugu and Orukpa areas of the Enugu and Benue States respectively. The Mamu Formation marks the regressive phase of the Upper Campano- Maastrichtian transgressive cycle and is completely non marine, unlike the Lafia-Obi coals which were interrupted by marine oscillatory incursions. In the Gombe area of the Upper Benue Trough the poorly developed coalfields occur within the Gombe Sandstone, also of Maastrichtian age. The coals probably occur towards the top of the Maastrichtian and are thought to be younger than the Enugu-Orukpa fields. The coals in Gombe area were intercepted at shallow depths of about 15–35 m. The seams are generally thin, though one seam was reported to be up to 2 m thick. The rank is more or less lignitic and with a somewhat high ash content.

Much of Nigerian coals are consumed locally. Only about 110,000 tonnes per year are exported, mainly to Ghana. The Lafia-Obi coal was expected to produce for the Ajaokuta steel complex at the rate of 50,000 tonnes per annum. Work on the project reached an advanced stage and beagn to slow down since the early 1990s. The Enugu mines produced about 240,000 to 360,000 tonnes per annum as at 1980, and with the completion of the first phase of the mechanization programme of the Nigeria Coal Corporation, coal production rose to 1.6 million tonnes a year. The coal deposits are expected to provide the much needed energy for a number of cement factories and power stations planned in these areas. Coal production has been on the increase since 1970, despite the effects of the civil war and the dieselization of the Nigerian Railway Corporation. Moreover, the critical energy situation in the world, particularly in Nigeria, will make these relatively poor quality coals even more important in the economic development of the country.

Clays

Deposits of clays in mineable quantities occur in almost all the States of the Federation. Major deposits occur in Kankara in Katsina State, Naraguta (Jos) in Plateau State, Alkaleri in Bauchi State, Shabu (Fig. 10.22) and Lafia areas of Nasarawa State and at Ahoko near Lokoja in Kogi State (Figs. 10.23, 10.24). Clay is one of the earliest mineral substances utilized by man. It played an extremely important part in ancient civilizations, records of which were preserved in brick buildings, in monuments and in pottery, and as inscriptions upon claytablets. Clay is still an indispensable raw material today. The present uses of clay and clay products are too numerous to list completely. In domestic life, clay is used extensively in pottery, earthenware, china, cooking ware, vases, plumbing fixtures, tiles, porcelain wares and ornaments. In building, it is used for building bricks, vitrified and enameled bricks, tiles for floors, roofs, walls and drains, sewer pipes and as an ingredient of cement. In the electrical industry, it is used for conduits, sockets, insulators and switches. It is used on a large scale in making refractory ware, such as fire bricks, furnace linings, chemical stone ware, crucibles, retorts and saggars. From the practical point of view, the most important physical properties of clay are plasticity, shrinkage, fusibility and colour.

Fig. 10.22 High quality Clay deposits occur in Shabu near Lafia, Nasarawa state

Limestone, Phosphates and Gypsum

The minerals, limestone, phosphate and gypsum are closely associated in the sedimentary basins of Nigeria. Limestone-forming environments (shallow coastal marine conditions), appear to have occurred several times in the geological history of the basins. In all occurrences the deposition of this mineral is related to the transgressive and regressive cycles in the basins. The first Middle Albian transgression ended about the Cenomanian, marking its shorelines with the deposition of the limestones of the Odukpani Formation, at the Calabar flank, in the southeast. The Odukpani limestones are substantial in quantity and provide the raw material for the Calabar Cement Factory. At the Odukpani type section, two limestone beds, with thicknesses of about 25 m and 65 in, are exposed. The Late Cenomanian-Turonian transgression caused the deposition of the extensive limestone deposits, stretching from the southeast to the northeast. A number of limestone beds occur in the Ezeaku Formation of the Lower and Middle Benue, the Pindiga, Jessu and Dukul Formations of the Zambuk and Upper Benue areas of the northeast. The limestones of the Ezeaku Formation include the Nkalagu, Igumale, Makurdi, Gboko (Yandev)? and the Akahana- Jangerigeri deposits, while those of the Pindiga/Jessu/Dukul Formations occur in Kanawa, Deba Habe, Jalingo and Ashaka. The Gboko limestone can be correlated to the Jangerigeri limestone in terms of age and environment of deposition. Recently large discoveries of limestone deposits were made near Awe

Fig. 10.23 Clay deposits in different colours and varieties at Ahoko near Lokoja in Kogi State

in Nasarawa State and proposals for investment in cement production using these limestone deposits have been solicited from both the federal and the Nasarawa State governments. Most of the limestone deposits are high in quality, generally containing over 80% $CaCO_3$. At Yandev, the main limestone bed is up to 35 m thick, and an indicated reserve of 68 million tonnes was estimated. Nearly all the limestone deposits in the country are used for the manufacture of cement.

Phosphate occurs in economic quantities within the Dukamaje Formation in the Sokoto Basin at Wurno and within the Kalambaina Formation at Dange and Shuni in the same basin. Occurrences in economic quantities have also been reported from the Dahomey Basin within the Ewekoro Formation in Southestern Nigeria. Not much is known about the phosphatic beds associated with the top parts of the Pindiga Formation at Pindiga near Gombe. Carter et al. (1963) first reported the existence of this rock associated with the top part of the formation. Offodile (1976) has reported the occurrence of about 34 m of phosphatic clays and limestones with

Fig. 10 24 (**a**) Externally feruginized kaolinitic claystone outcrop at Aseni in the Mid-Niger Basin, near Lokoja; (**b**) Clay deposits mined and stock-piled at Ahoko for collection by the lease holder and other receivers

intercalations of gypsum at type locality of the Pindiga Formation in Pindiga. These beds were found to be directly overlain by the continental Gombe sandstones. The quality and lateral extent of the deposit is a subject for further investigation. Gypsum occurs in close association with the phosphates in the Dukamaje Formation at

Wurno and in the Dange Formation at Dange. Occurrences of gypsum have also been reported from Nafada and Potiskum in the Upper Benue Trough as well as from around Gboko in the Middle Benue Trough. The amount of gypsum normally collected, though not enough for export, are just enough to meet the demands of the local cement factories located in these localities.

Brine-Fields / Salt Deposits

The occurrence of brine-springs in the Benue Valley has attracted considerable attention. The most important seepages are found in the Abakaliki, Keana and Mutum Daya areas of the Lower, Middle and Upper Benue Trough respectively. Towns and villages around these localities have maintained a locally viable age-old trade, based on salt produced from the native salt refineries (Fig. 10.25). The economic importance of the mineral in a country that imports more than 90% of its common salt and allied chemicals cannot be over-emphasized. This situation has led to the intensification of the search for rock salt. The origin of the brines is thought to relate to evaporites, possibly occurring in the continental, pre-marine Albian rocks or in the transitional beds of the Upper Albian-Lower Cenomanian Awe Formation (Offodile, 1976). Some interesting field evidence points to the probability of the occurrence of dome structures in the brine bearing sediments.

Most of the Benue brine-fields are underlain by formations of Cretaceous age. The tectonic set up in the three main fields (Abakaliki, Keana-Awe and Mutum Daya) is also similar. The Abakaliki, Keana-Awe and the Mutum Daya brine-fields are dominated by the Abakaliki, Keana and Lamurde anticlinoria. In each locality, brine-springs, are closely associated with these structures and are seen to issue from the flanks of the anticlinoria. The environments of deposition of the saline sediments of the Benue Trough are different from those of the South Atlantic basins. In the Gabon and Congo basins there is evidence of restricted access to the sea which allowed only an intermittent, but regular, supply of marine water into the basin, mainly in the Aptian to Albian, a condition favourable for the accumulation of evaporites. On the other hand, there is evidence of the existence of a positive basement barrier beneath the mouth of the present Niger Delta. It is not clear whether this feature could have restricted the movement of the sea both in and out of the valley, as in the South-West African basins. The indication is that the Benue sea-way maintained an open communication with the Atlantic throughout the Cretaceous. The parallel to subparallel folds are almost at right angles to the coast and these could not also have impeded the inflow of sea water during this time. However, the marine transgressive and regressive episodes were controlled, essentially, by tectonic and/or eustatic factors and evaporitic conditions appear to have developed, during the regressive phases when parts of the sea were cut off, with shoals and lakes forming in isolated areas under dry continental conditions (Offodile, 1976).

The occurrences of the brines are in form of springs, dug-holes and salt ponds (Figs. 10.26, 10.27), which had been used for ages as the main raw material for local salt production within the associated communities. However, most of the associated

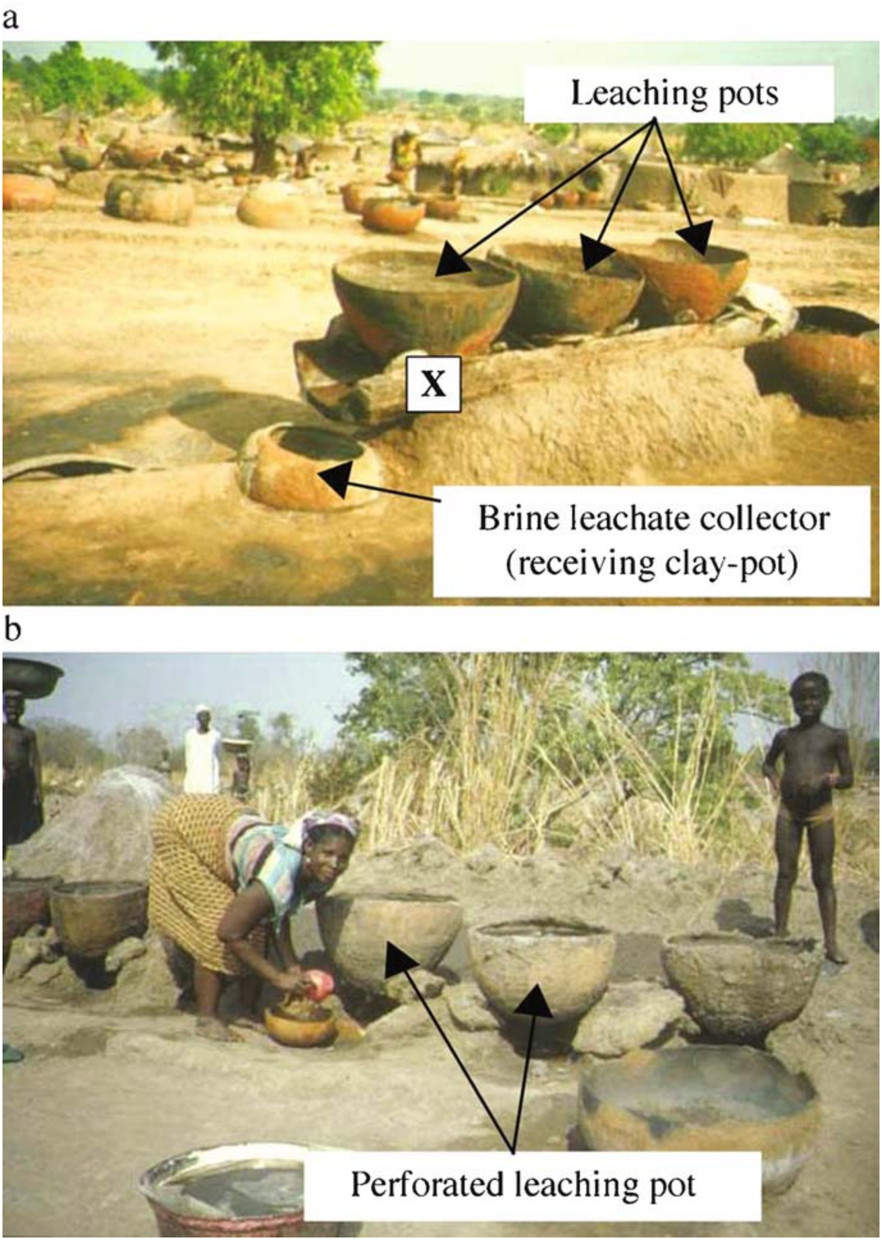

Fig. 10.25 Salt processing center at Ribi in Nasarawa state, showing boiling to dryness and crystallization of salts from the brine leachate. (Captured from Tijani and Loehnert, 2004)

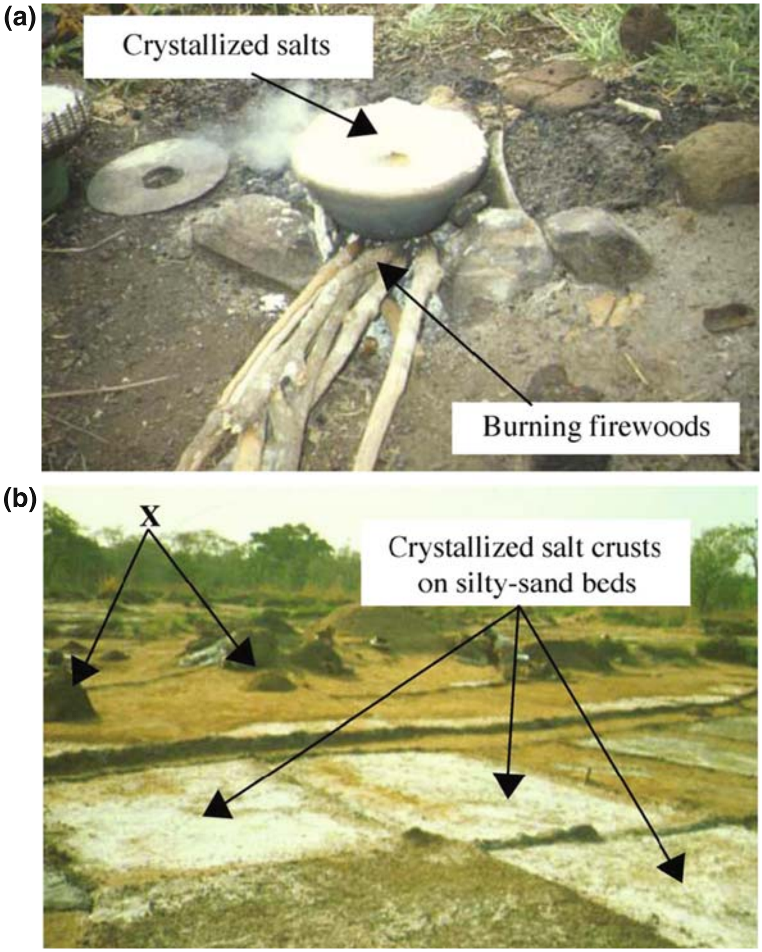

Fig. 10.26 (**a**) Salt processing center in Ribi, showing boiling to dryness and crystallization of salts from the brine leachate. (Note the burning fire woods which is to ensure boiling to dryness and crystallization). (**b**) Solar evaporative crystallization (Note the heaps of already scraped salt-impregnated soil materials, to be used in the leaching process, marked "X" at the background). (Captured from Tijani and Loehnert, 2004)

communities had mystified the occurrence of these brines (saline groundwaters) with some traditional restrictions and rituals in most cases. In most of the communities, it is only women-folk that have access to the saline waters while non-indigenes or men are either totally not allowed or allowed only after an initial traditional ritual. By and large, the salt-making venture is generally a women-folk affair and had been, over the years, a source of income for greater proportion of these rural women, though at a subsistence level. In terms of the occurrence, the brines in the Benue Trough are primarily confined to the predominantly shaly marine and parallic

Fig. 10.27 (**a**) A saline/salt spring source in the Keana-Awe area of Nasarawa State. (Note the sets of leaching clay pots, marked "X" at the background). (**b**) A salt lake/pond in the Keana – Awe area (Note the typical scene during a specified collection schedule is aimed at giving equal access to all the women-folk and allow for recharge) (Captured from Tijani and Loehnert, 2004)

sequences of the Asu-River Group (Albian–Cenomanian) and the Eze-Aku as well as the Awgu Formation (Turonian–Coniacian). However, the variation in the local lithology at the outcrop sites from predominantly shales in lower region to sandstones and intercalation of shale/limestone units in the middle region suggests that the brines are not lithologic controlled. Furthermore, the occurrences in form of springs, ponds and dug-holes are rather closely associated with the fracture systems within the trough. Hence, irrespective of the mode of occurrence, it is quite clear that the seepage movements or inflows of the brines are mostly controlled by the fracture systems within the trough. Hydrochemical evaluation as presented in Tijani et al. (1997) pointed out that the evolution of the brine in the Benue Trough through the processes of evaporite formation and/or dissolution are less favored, while the source of the primary solution was said to be strongly linked to modified marine fossil seawater or formation water. However, the interplay of water–rock interactions (e.g. dolomitization and ion exchange processes), dilution/mixing process as well as leaching/dissolution of possible disseminated intergranular marine salts or pore fluids are regarded as controlling processes for the observed differences in chemical characters compared to that of seawater.

Uranium in the Sedimentary Basins

About 85% of the world's production of uranium comes from deposits associated with sedimentary and supergene processes. Such deposits include those occurring in (1) quartz-pebble conglomerates, (2) sandstones, (3) caicrete and (4) shales, phosphates and other related sediments. The sandstone-type deposit is the richest and best exploited in Nigeria. Most of the known major occurrences of sandstone type uranium deposits in the world are of Carbonaceous or younger age, although some few deposits of the tectolithologic type, such as the Athabasca deposits (Canada), also occur in the Proterozoic. The best known examples of the sandstone type deposits include those hosted by Triassic and younger sediments in the Colorado/Wyoming Province of the USA, the Carbonaceous and younger sediments on the western margin of the Air Massiff in Niger Republic and in the sediments of the Franceville Basin of Gabon.

In Nigeria continental sandstones of equivalent age and/or sedimentary environments to those of Colorado and Niger occur in Sokoto, Chad, Benue and the Middle Niger Basins. These sediments have been formed in basins surrounded by older crystalline and volcanic rocks of the Basement Complex which may act as sources of uranium mineralization in these sediments. The Sokoto Basin in the northwestern corner of the country is filled with continental sediments namely, the Gundumi, Illo and Gwandu Formations and brackish to marine sediments – the Rima and Sokoto Groups. It is noteworthy that the Sokoto Basin is the southern extension of the Iullemmeden Basin, a sedimentary basin which also contains the uranium producing Agades sandstones of the Niger Republic. Based on the occurrence of uranium deposits in Niger Republic, any uranium mineralization in the Gundumi and Illo Formations should be concentrated within the basal conglomerates and arkoses which are closely associated with unconformities. The loose cementation of the sediments in the Wurno Formation makes them permeable to any uranium rich groundwater. The formation is also characterized by abundant plant and animal remains and also pyrite which may serve as reductants for uranium fixation. The interbanding of permeable sandstone and mudstone with impervious clays in the Gwandu Formation is particularly favourable for the roll type uranium mineralization (Dahlkamp, 1978) with the peat bands providing the necessary uranium reductant. Airborne radiometric surveys carried out by the Geological Survey of Nigeria in the Sokoto Basin indicate some uranium anomalies in the area.

The northeastern part of Nigeria is occupied by part of the Chad and Upper Benue Basins. The two depositional basins are separated by the Zambuk Ridge. The geological setting of both the Bima and Kerri-Kerri Formations suggests that they are potential hosts of uranium mineralization. For example, the Bima Sandstone has the following features which are similar to those found in hosts of uranium deposits in Colorado, Wyoming and elsewhere (see Grutt, 1971): (1) derived from provenance of granitic and metamorphic rocks; (2) lies on an unconformity; (3) sediments are mostly fluviatile and (4) the sandstones are greenish to greyish, feldspathic and arkosic with interbanding of shales and mudstones. The last feature is indicative of deposition of the sandstone in a reducing environment necessary for uranium deposition and preservation. The thickness of the sediments varies from 100 to 300 m. The Kerri-Kerri Formation is characterized by many of the features of peneconcordant sandstone deposits. The cross-bedded and gently dipping formation rests unconformably on folded older rocks. It is bounded in many places by granitic and metamorphic rocks of the Basement Complex and members of the Younger Granite suits. These uraniferous rocks are possible sources from which uranium might be leached into the permeable Kerri-Kerri Formation. Plant remains in the formation serve as potential reductants for the transported uranium.

The southern part of the Benue Trough which occupies most of the eastern part of the country is filled with Cretaceous to Quaternary sediments. Most of these sediments are marine and consequently of no potential for uranium mineralization. However, uranium anomalies which may be indicative of uranium mineralization have been located by airborne spectrometric survey in some of the continental sediments, notably in the Ajali Sandstone. The anomalies in the formation occur along a belt stretching from Okigwe in the south to Angba about 150 km away in the north.

The Mid-Niger Basin is a shallow trough filled with Cretaceous marine to continental sediments. The continental sediments (Nupe Group) are probably post-orogenic molasse facies and are predominantly sandstone with subsidiary claystones, fine conglomerates and siltstones. The arkosic and feldspathic sandstone common at the base of the sequence may be expected to host uranium mineralization. This is supported by the occurrence of many uranium anomalies in the basin although it is not certain if these uranium anomalies are due to significant uranium mineralization.

Tar Sands / Bitumen

Extensive geological and geophysical studies (Ogunsola and Williams, 1988) have shown the existence of huge deposits of tar-sands in Nigeria from which more than 31 billion barrels of heavy oil can be produced (Ogunsola and Williams, 1988). Heavy oils extracted from the Nigerian tar-sands are comparable in properties with those that were imported earlier. The tar-sand is composed of sand, heavy oil (bitumen), mineral-rich clay and water in varying proportions. These proportions were found to be 84, 12, 2 and 4% respectively (Fasasi et al., 2003). This heavy oil in tar-sand is commonly referred to as bitumen. It is a viscous and complex mixture of hydrocarbons and other heterocyclic substances. Its formation could be due to thermal alteration, microbial degradation, water-washing or gas deasphalting. It may also be formed from radioactive bombardment (Fasasi et al., 2003). Extensive seepages of bituminous sand are known to occur along an East-West belt stretching over an area of about 120 km $\times$ 6 km across Lagos, Ogun, Ondo and Edo States in southwestern Nigeria (Ogunsola and Williams, 1988). The Nigerian tar sands constitute important raw materials, like those that are needed by the Kaduna Refinery for the production of some non – conventional petroleum products such as lubricating greases, lubricating oil, waxes, bitumen and asphalt.

Chapter 11
Petroleum Resources

Introduction

The attached explanatory notes show that Nigeria is the world's 8th largest producer and 6th largest exporter of petroleum. It is the largest producer and exporter on the African continent and is currently closely followed in production level by Angola, Libya and Gabon. Current reserves (as at 2008) are put at 35 billion barrels for oil and 180 trillion standard cubit feet for gas. At the moment production is entirely from fields in the Niger Delta region while exploration campaigns have been carried and/or ongoing in different segments of Nigeria's sedimentary basins.

The Niger Delta, offshore Dahomey Basin and some parts of the Anambra Basin constitute currently the oil province of Nigeria. The Niger Delta oil province is rated to be about the 12th largest in the world. Up to date a total of about 1,182 exploration wells have been drilled with 1,182 of them being on the delta. About 400 oil and gas fields of varying sizes have been documented. For the entire period of oil exploration and production in Nigeria, 49% of the exploration wells can be termed successful (575 discoveries for 1,182 exploration wells). In the early years 52% of the exploration wells were successful and in the latter years the success rate increased to 68%. However, during a period of 1966–1976 only 40% of the wells were considered successful. The increased success during the later years is attributed to improved seismic technology. The sizes of the fields have decreased over the period. Analysis of the discoveries shows that 3% of the discoveries are giants and represent 32% of the total reserves found. In retrospect, 40% of the discoveries represent smaller fields with only 3% of the total reserves found to date. Collectively, the giant fields produce in excess of 1 million barrels a day out of the nation's total production of about 2.1 million barrels per day. A giant oil field is classified as a field with an estimated ultimate recoverable oil of more than 500 million barrels. The giant fileds in Nigeria include Oso, Ubit, Assan, Meren, Abo, Bonga, Agbami, etc. The Bonga is located 120 kilometres (75 miles) offshore and has a daily production capacity of 200,000 barrels of oil and 150 million standard cubic feet of gas. Most Nigerian oilfields produce 20,000–40,000 barrels per day. Nigeria's average well produces 1,000 barrels a day. Those fields with estimated recoverable oil in place

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of 30 million barrels and less are termed "marginal fields" and are hardly further developed by the major operating companies.

Within the inland basins of Nigeria, the Nigerian National Petroleum Corporation (NNPC) through its frontier exploration services arm (NAPIMS) drilled about 23 wells in the Nigerian sector of the Chad Basin and only gas shows were encountered. The first well in the Benue Trough region, *Kolmani-River-1*, drilled by Shell Nigeria Exploration and Production Company (SNEPCO) to a depth of about 3,000 m in 1999 encountered some 33 billion standard cubic feet of gas and little oil (that has been the only well drilled by that company in that area to date). Two other wells, *Kuzari-1* and *Nasara-1*, drilled by Elf Petroleum Nigeria Limited (TotalFinaElf) in 1999 to a depth of 1,666 m and Chevron Nigeria Limited (ChevronTexaco) in 2000 to a depth of about 1,500 m, respectively, were reported dry.

Hydrocarbon Habitat of the Niger Delta

Geochemical analyses of Niger Delta oils generally indicate land plant material and structurelss organic matter (SOM) as the major source of the hydrocarbons (Stacher, 1995). Source rock anaylses have shown that clays from (1) the lower coastal plain, (2) the marine-deltaic depositional areas (prodelta) and (3) the fully marine areas can be enriched in both land plant material and structureless organic matter. Lower coastal plain deposits (1), such as swamp clays and coals, are rarely preserved in-situ in large volumes in the Niger Delta. These sediments are usually reworked and re-deposited as marine-deltaic clays (2) and full marine clays (3).

Marine-deltaic clays form part of deeper, prospective Niger Delta well sections characterized by shales with sand interbeds. Source rock analyses show peaks of organic material with individual parasequences. However, significant source rock thicknesses are rarely encountered.

Marine clays (3), which are interpreted to be present in large volumes at greater depths are refered to in the literature as Akata Shale (Stacher, 1995). A number of authors have concluded that source rocks of economic significance are to be found in the Akata Shales (Weber and Daukoru, 1975; Evamy et al., 1978; Ekweozor and Daukoru, 1984; Weber, 1986). Because of the over-pressure encountered in deep exploration wells major sequences of Akata Shales have rarely been penetrated. Temperatures and maturity profiles set the hydrocarbon kitchen at variable depths below the penetrated hydrocarbon accummulations where mainly Akata Shales are usually predicted.

Biostratigraphic analyses and mapping of paleo-water-depths show distinguished areas of mainly shallow water depths and the position of slopes and deeper water areas. Third order lowstand systems tracts were not formed in the area of the central delta where a shallow ramp model with formation of mainly highstand and transgressive systems is applicable. Clays deposited in this setting have not yielded significant source potential. Samples from wells with deeper continuous shales, identified as Akata Shales, have been interpreted as deposits from deeper water areas. Detailed analyses have shown that these shales can contain intervals with high amounts of land-derived organic matter qualifying them as source rocks.

Deposition of land-derived fine organic matter in deeper waters of the distal delta may be explained by sequence stratigraphy. During sea-level lowstands, major erosion took place in exposed areas, forming incised valleys by river rejuvenation. Eroded sands, silts, clays and fine organic matter from lower coastal plains were transported down into the basin through newly cut channels. Organic material and clays in water suspension were transported further offshore and sedimented in deeper water, low energy areas. A favourable balance of terrestrial organic input, low energy conditions and oxygen deficiency was required for maximum accumulation and preservation of organic matter.

Almost all the commercial accumulations of oil and gas are found in deltaic sandstones of the Agbada Formation. Hydrocarbon accumulations are mainly related to growth fault structures where traps occur in dip-closed crestal areas or against one or more faults especially in their upthrown side (Fig. 9.1). Growth faulting is induced by load, compaction and differential subsidence resulting from rapid sedimentation. In addition to conventional growth-fault related traps, there are other non-conventional stratigraphic traps related to channel fills, regional sand pinch-outs and truncation. Sand/shale ratios determine gross reservoir properties and sealing potential of faults.Transgressive marine shales form important regional top seals, whilst faults fequently form lateral seals. The sealing capacity of a fault is a function of the thickness and quality of shales that are juxtaposed across faults and the degree of smearing along the fault planes.

As a consequence of sand/shale alternations and the trapping mechanism, most fields are of a multiple reservoir type with stacked columns. Most of the reservoirs have column heights of up to 15 m and in some cases column heights may be up to 50 m (Stacher, 1995). The majority of reservoirs do no appear to be filled up to split point. Gas-condensate-oil ratios are highly variable through the delta. High gas to oil ratios are found in the south central, eastern and northern part of the delta (Stacher, 1995). Gas chromatograms of whole crude and saturated compounds show variable oil compositions which indicate the differences in the environment of deposition of the related source rocks. Variations in pristane/phytane ratios are related to source rock environments changing from acid back-swamps with hardly any bacterial reworking to more aquatic, less acidic environments where bacteria rework algal and plant material to SOM (structureless organic matter). Wax content and pour points of non-biodegraded oils (API $> 25^{\circ}$) are variable and depend on the quality of plant wax in the original source rocks. Variations in the composition of Niger Delta oils at low carbon numbers are as a result of biodegradation and gas/water flushing. Medium to heavy crudes (API $< 25^{\circ}$) are usually biodegraded. Stacher (1995) observed that the vertical distribution of heavy degraded crudes directly relates to the thickness and depth of the freshwater continental sands of the Benin Formation. Contents of sulphur, nickel and vanadium of Nigerian crude oils are generally very low. Maturity indications for oil expulsion vary according to depobelt. This is in line with observations of the hydrocarbon distribution over the delta and suggests that individual macro-structures and depocentres form independent hydrocarbon provinces with their own burial, maturation, migration and trapping history.

Potentials in the Inland Basins

Some exploration campaigns have been undertaken in the inland basins of Nigeria with the aim to expanding the national exploration and production base and to thereby add to the proven reserves asset. The inland basins of Nigeria comprise the Anambra Basin, the Lower, Middle and Upper Benue Trough, the southeastern sector of the Chad Basin (locally known as the Bornu Basin), the Mid-Niger (Bida) Basin and the SE Iullemeden Basin otherwise known as the Sokoto Basin. However, these inland basins have continued to frustrate the efforts of many explorers, principally because of the poor knowledge of their geology and the far distance from existing infrastructure (discovery must be large enough to warrant production investments), and for these reasons, many international companies have turned their focus away from frontier onshore to frontier deep-water and ultra deep-water offshore of the Niger Delta area.

The inland basins of Nigeria constitute one set of a series of Cretaceous and later rift basins in Central and West Africa whose origin is related to the opening of the South Atlantic (Fig. 11.1). Commercial hydrocarbon accumulations were sometime ago discovered in Chad and Sudan within this rift trend. In SW Chad, exploitation of the *Doba* discovery (with estimated reserves of about 1 billion barrels

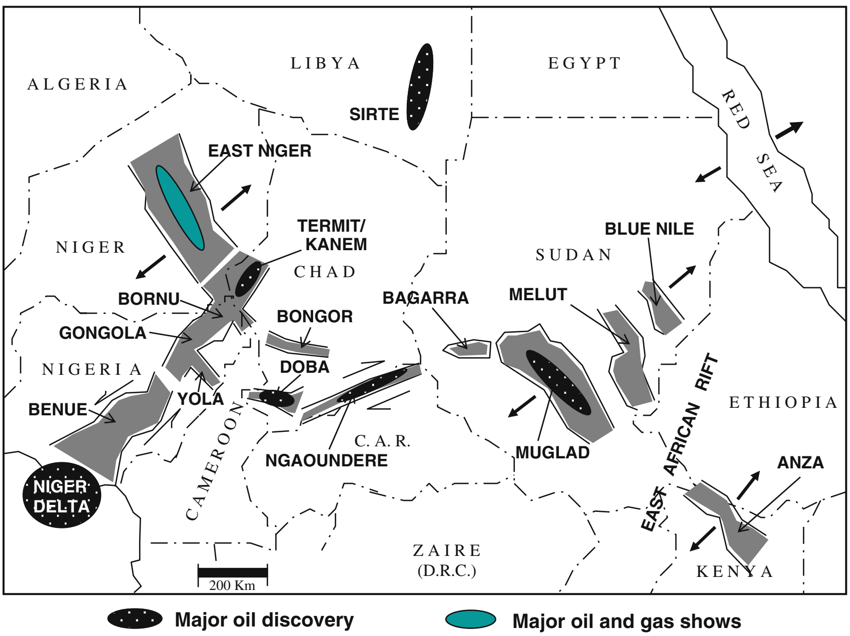


Fig. 11.1 Regional tectonic map of western and central African rifted basins showing the relationship of the Muglad, Doba and East Niger Basins to the Benue Trough/Gongola Basin. Locations of regional shear zones (marked with *half-arrow*) and major zones extension (*complete arrow*) are shown. (Adapted from schull, 1988)

of oil) has caused the construction of a 1,070 km-long pipeline through Cameroon to the Atlantic coast. In the Sudan, some "giant fields" (*Unity 1 and 2, Kaikang, Heglig,* etc) have been discovered in the Muglad Basin (Mohamed et al., 1999). The major source rocks and reservoirs are in the Aptian-Albian-Cenomanian continental deposits of the Abu Gabra and Bentiu formations, respectively, which are similar and correlatable to the well-developed Bima Sandstone in the Nigerian Upper Benue Trough. In Niger Republic, oil and gas shows have also been encountered in Mesozoic – Cenozoic sequences in the East Niger Graben, which is structurally related to the Benue-Chad-Sudan-Libyan rift complexes (Zanguina et al., 1998). With relentless and re-invigorated geological and geophysical studies, particularly with respect to the evaluation of potential petroleum systems, commercial success can also be achieved in the Nigerian sector of Africa's inland basins, even if it may take some time to put all the elements together.

At the core of any petroleum system is a good quality source rock (TOC $> 0.5\%$, HI > 150 mgHC/gTOC, liptinite content $> 15\%$, Tmax $\geq 430°$C, Ro 0.5–1.2%, biomarker validation). However, other petroleum system elements must include, apart from established source rocks, also reservoir and seal lithologies, establishable trapping mechanisms and favorable regional migration pathways. Succintly discussed below are extracts of the results of the work of Obaje et al. (2004) on the hydrocarbon propospectivity of Nigeria's inland basins from the view point of organic geochemistry and organic petrology.

Lower Benue Trough / Anambra Basin

Table 11.1 shows the Rock Eval pyrolysis results of some samples from the Anambra Basin. High TOC contents (up to 60.8 wt%) and hydrogen indices (HI) between 266 and 327 mgHC/gTOC characterize the coal beds of the Mamu Formation. The underlying Nkporo and Enugu shales have TOC contents of 1.35 to 3.51 wt% and HI values between 22 and 65 mgHC/gTOC. The regression equation based on the S_2 vs. TOC diagrams gave an average HI value of 364 mgHC/gTOC for the Mamu coals and 84 mgHC/gTOC for the Nkporo and Enugu shales (Fig. 11.2) (Obaje et al., 2004). A plot of S_2 versus TOC and determining the regression equation was used by Langford and Blanc-Valleron (1990) as the best method for determining the true average hydrogen index (Av. HI) and measuring the adsorption of hydrocarbons by the rock matrix. The Tmax and vitrinite reflectance values obtained on the coals indicate immature to early mature stages (early oil window) for the successions in the Anambra Basin. Peters (1986) stated that at a thermal maturity equivalent to vitrinite reflectance of 0.6% (Tmax 435°C), rocks with HI above 300 mgHC/gTOC will produce oil; those with HI between 300 and 150 will produce oil and gas; those with HI between 150 and 50 will produce gas; and those with HI less than 50 are inert. However, Sykes and Snowdon (2002) are of the opinion that coaly source rocks are sufficiently different from marine and lacustrine source rocks in their organic matter characteristics to warrant separate guidelines for their assessment based on Rock-Eval pyrolysis. Based on a study of some New Zealand coals, they

Table 11.1. Rock Eval pyrolsis data of samples from the Anambra and the Mid-Nigar (Bida) Basins (Courtest: Bundesanstalt for Geowissenschaften und Rohstoffe, Hanover, Germany)

Sample ID	Localicty	Formation	TOC (wt%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI*	OI**
ANAMBRA BASIN									
MAMU 25	Enugu	Mamu	30.80	0.95	81.81	5.54	430	266	18
MAMU 22	Enugu	Mamu	32.50	1.61	92.36	4.84	431	284	15
MAMU 19	Enugu	Mamu	60.80	4.53	188.57	9.00	431	310	15
MAMU 16	Enugu	Mamu	52.00	1.45	170.16	5.93	433	327	11
ENUG 13	Enugu	Enugu	3.51	0.07	1.81	1.03	426	52	29
NKPO 8	Leru	Nkporo	1.35	0.02	0.30	0.27	427	22	20
NKPO 7	Leru	Nkporo	1.57	0.02	0.35	0.28	431	22	18
NKPO 5	Leru	Nkporo	3.03	0.06	1.97	1.28	432	65	42
NKPO 4	Leru	Nkporp	2.03	0.05	0.64	0.30	423	32	15
MID-NIGER/BIDA BASIN									
AHOK 5	Ahoko/Lokoja	Patti	2.74	0.07	2.98	2.30	429	109	84
AHOK 3	Ahoko/Lokoja	Patti	2.79	0.06	2.39	2.30	425	86	82
AHOK 2	Ahoko/Lokoja	Lokoja	2.39	0.06	1.78	1.92	423	74	80
AHOK 1	Ahoko/Lokoja	Lokoja	2.73	0.05	1.71	2.08	421	63	76

* mgHC/gTOC; ** mgCO_2/gTOC

concluded that the rank threshold for oil generation in coals is indicated at Tmax of 420–430°C (Ro 0.55–0.6%), and the threshold for oil expulsion at Tmax 430–440°C (Ro 0.65–0.85%).

Plots on the modified Van Krevelen diagram by Obaje et al. (2004) for samples from the Anambra Basin showed a mixed range of type I–III organic matter with a dominance of type II (Fig. 11.3). A corresponding plot on the HI – Tmax diagram based on the values given by Peters (1986) indicates an oil and gas generative potential for some of the samples from the Anambra Basin (Fig. 11.4). GC and GC-MS analyses of the lipid extracts reported biomarkers with a dominance of long-chain n-alkanes (C_{24}–C_{31}) with obvious odd-over-even predominance (OEP) (Fig. 11.5). This points to high inputs of terrestrial humic / higher plants organic matter as well as maturity levels below the conventional begin of oil generation (Ro 0.6%). Pristane/phytane ratios range from 5.58 to 16.88 and steranes are mainly of the C_{29} forms (Fig. 11.5) all of which confirm a considerable input of terrestrial organic matter and fully aerobic conditions. The low Ts/Tm and relatively high m/αβH ratios indicate maturity below the conventional begin of oil generation (Waples and Machihara, 1991). With increasing maturity, 17α(H)-trisnorhopanes (Tm) normally transform to 18α(H)-trisnorneohopanes (Ts) and moretanes to 17α(H)21β(H)-hopanes (αβH) (Meyers and Snowdon, 1993). However, the trend observed in that study shows that the Ts is dependent on the lithology and is generally suppressed in the coals compared to shales of the same the vitrinite reflectance maturity. Ts does not appear in the coaly facies until a vitrinite reflectance maturity of about 0.9 (Ro%) is attained, whereas in the shales the Ts begins to appear already as early as Ro% maturity of about 0.5.

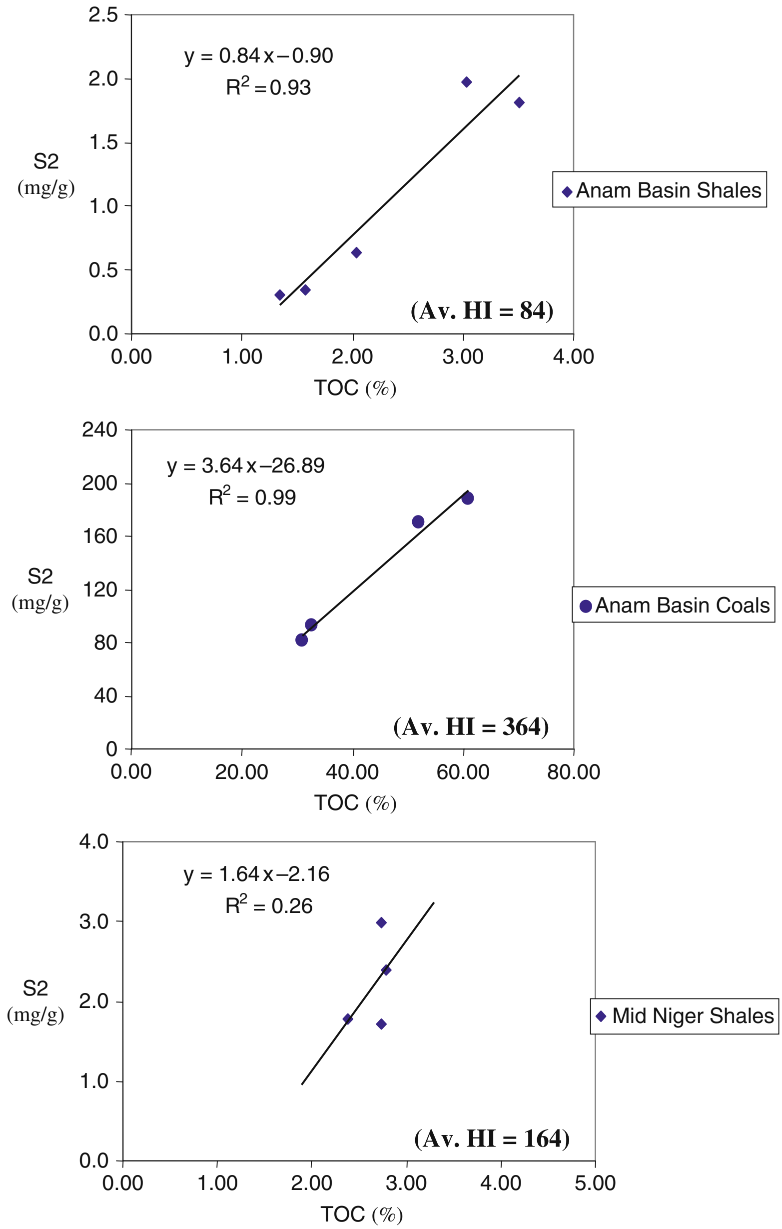


Fig. 11.2 S2 vs. TOC plots of Campanian-Maastrichtian samples from the Anambra and the Mid-Niger (Bida) Basins with the regression equations which gave the average hydrogen indices (Av. HI)

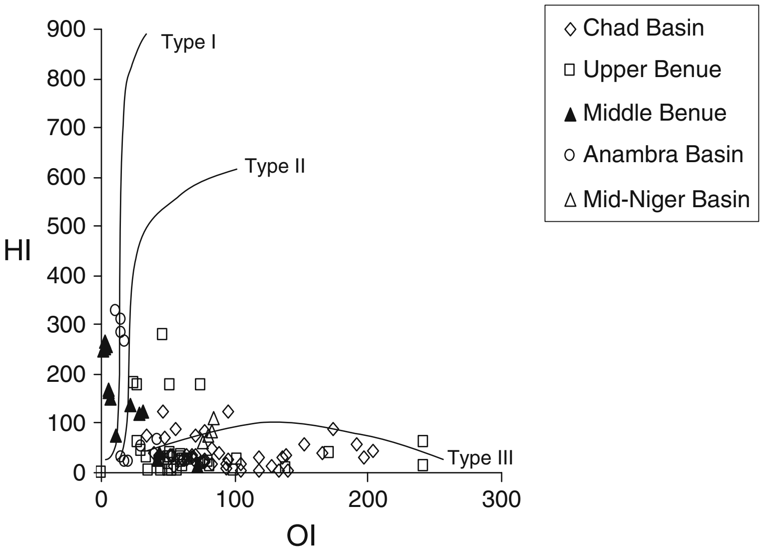


Fig. 11.3 HI vs. OI plots on the modified Van Krevelen diagram of samples from the inland basins of Nigeria

Middle Benue Trough

In the Middle Benue Trough, TOC contents of up to 79.1 wt% (Table 11.2) and a mean HI value of 281 mgHC/gTOC (Fig. 11.6) characterize the coals of the Awgu Formation (Obaje et al., 2004). Tmax and Ro values in Tables 11.2 and 11.3 indicate maturity in the peak to late oil window. Plots on the modified Van Krevelen diagram of samples from the Middle Benue Trough showed a mixed range of type I–III organic matter (Fig. 11.3), similar to the Anambra Basin. A corresponding plot on the HI – Tmax diagram indicates potentials in the oil and gas phase and a gas phase for some of the coal samples from the Middle Benue Trough (Fig. 11.4). Chromatograms and mass fragmentograms of the lipid extracts show biomarkers with a unimodal distributions of short and long-chain n-alkanes (C_{15}–C_{28}) with no obvious odd-over-even predominance (Fig. 11.7) indicating that organic matter were contributed from both algal and terrestrial higher plants sources or are in an advanced stage of maturity. Pristane/phytane ratios range from 4.53 to 7.33 and steranes are mainly of the C_{29} forms with C_{27}/C_{29} ratios ranging from 0.1 to 1.0 (Table 11.4). These values indicate oxic depositional milieu that frequently changed between continental, marine and lacustrine environments. The relatively high values of Ts/Tm and low moretane/hopane ratios validate the vitrinite reflectance maturity of 0.8–1.1 Ro% recorded for these samples.

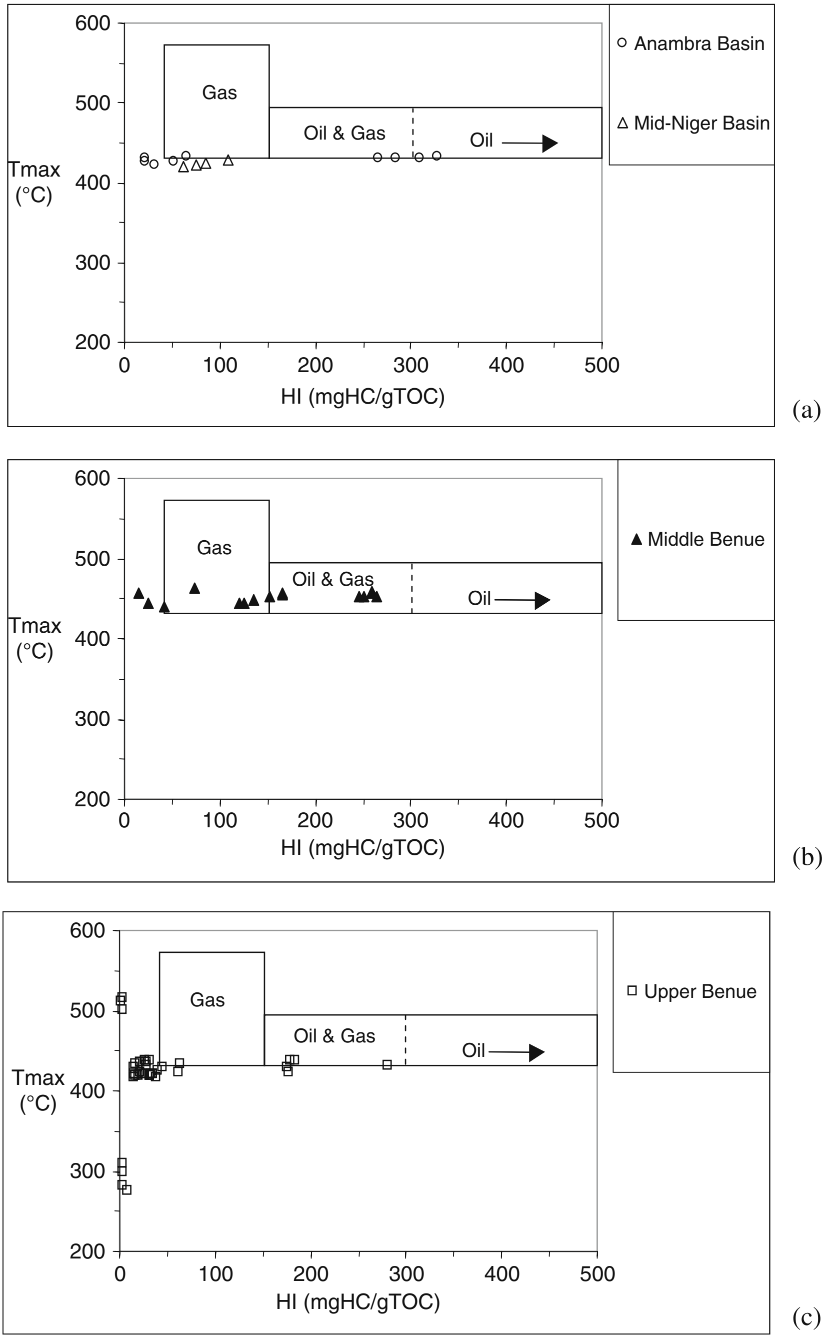
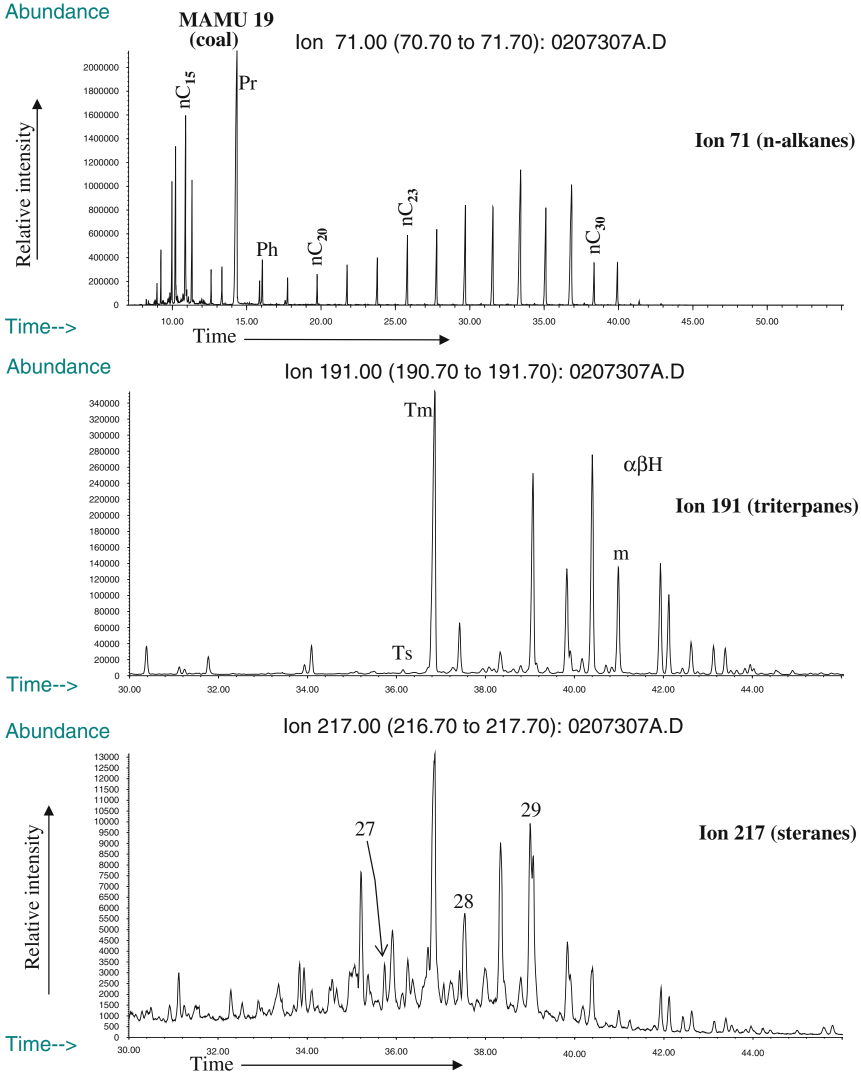


Fig. 11.4 HI-Tmax plots of samples from the Benue Trough (Anambra Basin inclusive)



Pr = Pristane, Ph = Phytane, Ts = 18α(H)–trisnorneohopane, Tm = 17α(H)–trisnorhopane, m = 17β(H)21α(H)–moretane, αβH = 17α(H)21β(H)C_{30}–hopane; 27, 28, 29 = 5α(H)14α(H)17α(H)C_{27}–C_{29}–steranes (20R)

Fig. 11.5 Mass Chromatograms of ions 77 (n-alkanes), 217 (steranes) and 191 (hopanes) of Mamu coal (Mamu Formation), Anambra Basin

Upper Benue Trough

The formations from the Upper Benue Trough have generally low TOC and HI contents (Table 11.5) , except the coals of the Lamja Formation (LAMCO) and those from Doho and Gombe (UBDJ, MGMC) within the Gombe Sandstone as well as

Table 11.2 Rock Eval pyrolysis data of samples from the Middle Benue Trough (Courtesy: Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover, Germany)

Middle Benue Trough									
Sample ID	Locality	Formation	TOC (wt%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI*	OI**
OBIC 6	Jangwa	Awgu	17.40	0.41	21.76	5.37	444	125	31
OBIC 5	Jangwa	Awgu	75.60	2.6	192.77	2.69	457	255	4
OBIC 4	Jangwa	Awgu	76.30	3.04	203.84	2.52	452	267	3
OBIC 3b	Jangwa	Awgu	26.40	0.84	43.51	1.48	457	165	6
OBIC 3	Jangwa	Awgu	79.10	3.16	207.3	2.50	459	262	3
OBIC 2b	Jangwa	Awgu	70.60	2.27	171.54	2.31	453	243	3
MBJJ 9	Jangwa	Awgu	27.00	3.93	41.20	1.65	452	153	6
MBJJ 8	Jangwa	Awgu	44.20	0.26	18.42	19.13	441	42	43
MBJJ 7	Jangwa	Awgu	43.10	0.19	10.81	18.12	445	25	42
MBJJ 6	Jangwa	Awgu	61.10	1.93	83.05	13.60	449	136	22
MBJJ 5	Jangwa	Awgu	18.50	0.38	22.18	5.32	444	120	29
MBJJ 4	Jangwa	Awgu	23.80	0.72	39.58	1.23	455	166	5
MBJJ 3	Jangwa	Awgu	2.69	0.02	1.99	0.30	463	74	11
MBJJ 2	Jangwa	Awgu	66.70	4.38	164.29	1.33	452	246	2
MBJJ 1	Jangwa	Awgu	17.40	0.08	2.49	12.49	457	14	72

* mgHC/gTOC; ** mgCO_2/gTOC

some Dukul Formation samples, all of which have very good to good source rock qualities. Akande et al. (1998) and Obaje et al. (1999) had independently reported TOC values of up to 12.5 wt% from the Yolde Formation and 2.4 wt% from the lower Pindiga Formation, respectively. In the Lamja Formation, TOC contents attain values of up to 50.7 wt% and a mean HI of 183 mgHC/gTOC for the coals in the Upper Benue combined (Fig. 11.6). Tmax and Ro values in Tables 11.3 and 11.5 indicate maturity in the middle/peak oil window for the coals of the Lamja Formation. Samples from the Bima, Yolde, Pindiga and Gongila formations used in the study by Obaje et al. (2004) yielded poor source rock quality. Plots on the modified Van Krevelen diagram for samples from the Upper Benue Trough show mainly type III organic matter with some type II attributable to the Lamja coals (Fig. 11.3). The corresponding HI – Tmax diagram indicates some potentials between oil and gas with gas dominating. Majority of the samples fall into fields that have no hydrocarbon generative potential (Fig. 11.4). The Lamja and Gombe coals are of special attention, especially the Lamja which yielded the highest amount of soluble organic matter during solvent extraction (Fig. 11.8). Biomarkers show a dominance of both short and long-chain n-alkanes (C_{14}–C_{31}) with negligible OEP (Fig. 11.9). Pristane/phytane ratios range from 0.84 in the Pindiga Formation to 6.65 in the Lamja coals. C_{27}/C_{29} ratios range from as low as 0.2 in the Lamja coal to 1.9 in the Pindiga Formation (Table 11.4) indicating rapidly changing depositional conditions. The very low Ts/Tm ratio (0.03) and the moderate moretane/hopane ratio (0.18) validate maturity lower than 0.9% Ro.

Organic petrologic studies by Obaje et al. (2004) presented moderate to high contents of liptinite macerals for most of the coal samples from the Benue Trough

Table 11.3 Vitrinite reflectance values and some petrographic remarks on samples from the Benue Trough and Mid-Niger (Bida) Basin. (Courtesy: Bundesanstalt für Geowissenschaften und Rohstoffe, Hanover, Germany)

	Sample ID	VR (Ro%)	Remarks
Anambra	MAMU 25	0.56	Very high content of liptinite; V = L > 1
	MAMU 22	0.54	“ “ “ “
	MAMU 16	0.56	Very rich in liptinite (sporinite, resinite, cutinite, liptodetrinite); V, L, I in approx. equal amounts
	NKPO 4	0.49	Liptinite well represented (approx. 20%); V > I > L
Mid-Niger	AHOK 3	0.62	
	AHOK 2	0.56	About 40% Inertinite, 35% Liptinite, 25% Vitrinite (I > L > V)
Middle Benue	OBIC 5	1.00	Very rich in maceral constituents with V > L > I
	OBIC 3	0.96	” ” ” ”
	MBJJ 9	1.07	
	MBJJ 8	0.99	
	MBJJ 7	1.00	Rich in maceral constituents with V > I > L
	MBJJ 6	0.96	Very rich in maceral constituents with V > L > 1
	MBJJ 5	1.06	
	MBJJ 4	1.08	
	MBJJ 3	0.83	Not very rich in maceral constituents, mainly vitrinite
	MBJJ 2	0.99	About 70% Vitrinite, 25% Liptinite (lost fluorescence), 5% Inertinite
	MBJJ 1	0.990	
Upper Benue	UBWJ 2	(1.36)(0.73)0.48	A mixture of very different types of vitrinite macerals; probably highly reworked; I > V > L
	UBHJ 4	0.86	Difficult to distinguish whether organic matter are vitrinite or inertinite, VR measurements probably reflects those of inertinite
	UBHJ 3	0.89	” ” ” ” ” ” ”
	UBHJ 2	0.50	Organic constituents very scanty; more than 90% of matter is inertinite
	UBHJ 1	0.49	Abundant inertinite (> 80%), few liptinite, very few vitrinite
	UBDJ 2	0.53	High content of liptinite; corpohuminite abundant; V > L > I
	UBDJ 1	0.53	Moderately good content of liptinite; V > L > I
	LAMCO 7	0.73	Rich in liptinite. Abundant micrinite associated with sporinite in desmocollinite; V > L > I
	LAMCO 1	0.70	” ” ” ” ” ”
	DUKL 8	0.62	Abundant pyrites; poor in maceral constituents
	GONG 3	0.82	
	PIND 1	0.84	Organic constituents very scanty; possibly the measured macerals (VR) were those of inertinite

V = Vitrinite, L = Liptinite, I = Inertinite

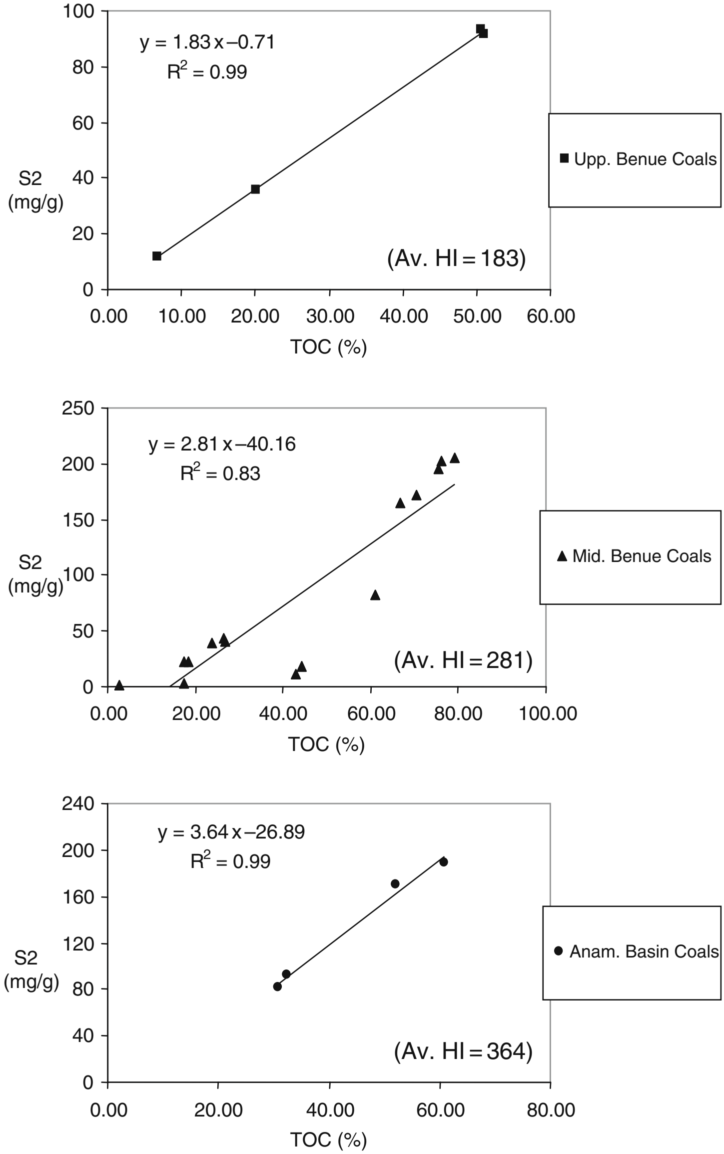


Fig. 11.6 S2 vs. TOC plots of coal samples from the Benue Trough with the regression equations which gave the average hydrogen indices (Av. HI)

(up to 40% in the Lamja Formation). The liptinites comprise mainly resinite, sporinite, cutinite and bituminite from which the abundant micrinite macerals in all the coal samples must have been generated. The origin, nature and significance of micrinite maceral to oil and gas generation have attracted much attention. In a detailed

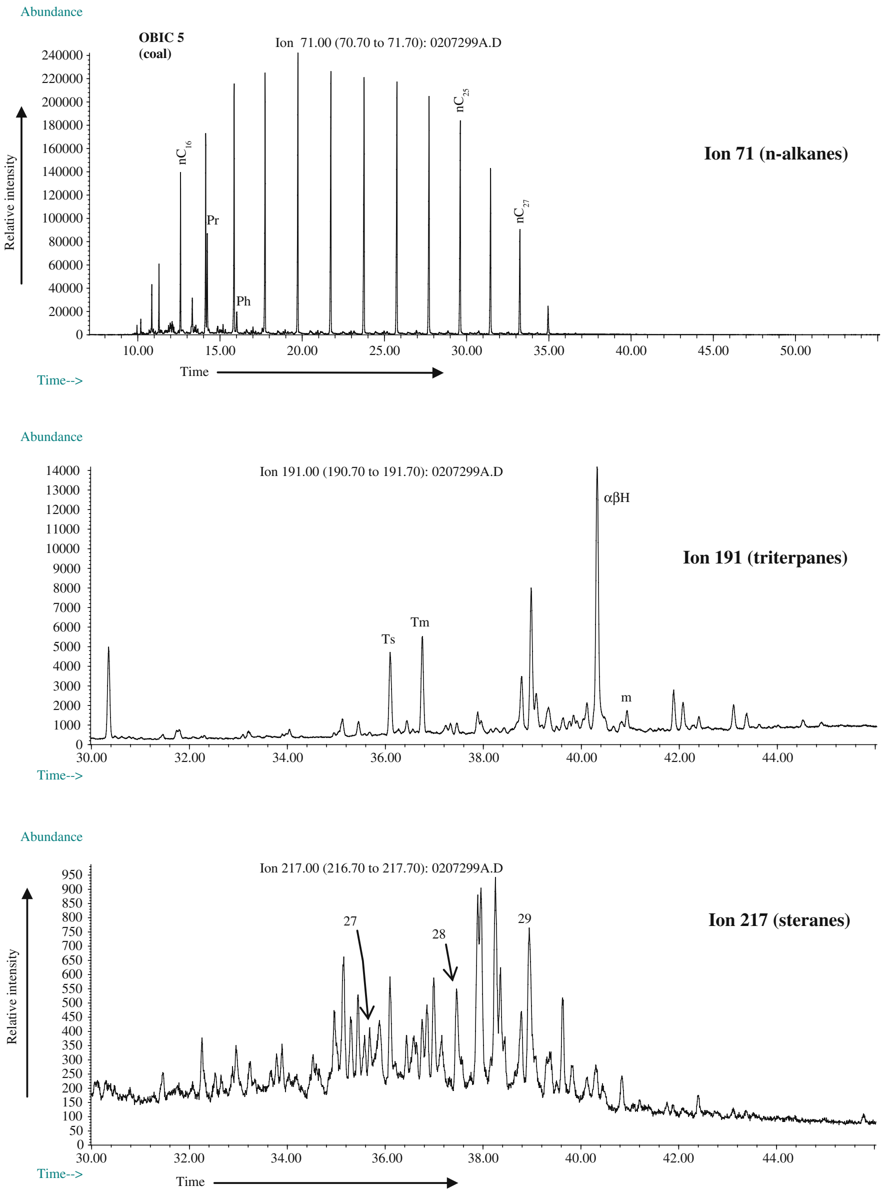


Fig. 11.7 Mass chromatograms of ions 77 (n-alkanes), 191 (hopanes) and 217 (steranes) of OBIC 5 (Obi coal) from the Awgu Formation in the Middle Benue Trough

Table 11.4 Biomarker parameters of samples from the inland basins of Nigeria

	Sample ID	Formation	Pr/Ph	Ts/Tm	m/αβH	C27 (%)	C28 (%)	C29 (%)	C27/C29
Anambra Basin	MAMU 22	Mamu	16.88	0.01	0.48	14.0	26.3	59.6	0.2
	MAMU 19	Mamu	5.58	0.02	0.49	13.6	29.2	57.1	0.2
	ENUG 13	Enugu	11.08	0.09	0.52	39.8	17.6	42.6	0.9
	NKPO 5	Nkporo	9.57	0.25	0.27	32.7	21.7	45.6	0.7
	NKPO 4	Nkporo	7.39	0.23	0.24	36.7	19.5	43.8	0.8
Mid-Niger Basin	AHOK 5	Patti	2.79	0.36	0.42	44.4	18.4	37.2	1.2
	AHOK 2	Lokoja	1.55	0.31	0.36	31.6	20.9	47.6	0.7
	AHOK 1	Lokoja	2.88	0.28	0.52	42.8	16.9	40.3	1.1
Middle Benue	OBIC 5	Awgu	4.70	0.95	0.07	16.1	32.3	51.6	0.3
	OBIC 2b	Awgu	4.53	0.84	0.08	27.8	25.3	46.8	0.6
	MBJJ 7	Awgu	4.89	1.23	0.07	40.0	20.0	40.0	1.0
	MBJJ 4	Awgu	7.33	3.21	0.05	12.5	33.8	53.8	0.2
	MBJJ 2	Awgu	4.95	0.92	0.06	7.8	39.1	53.1	0.1
Upper Benue	UBWJ 1	Gombe	1.22	0.71	0.12	41.4	21.4	37.1	1.1
	UBHJ 4	Gombe	0.94	0.81	0.10	8.9	32.2	58.9	0.2
	UBDJ 2	Gombe	3.44	0.00	0.14	13.7	44.9	41.4	0.3
	MGMC 3	Gombe	2.67	0.25	0.14	35.8	20.2	44.0	0.8
	LAMCO 1	Lamja	6.65	0.03	0.18	14.7	21.7	63.6	0.2
	DUKL 8	Dukul	2.05	0.74	0.21	42.7	19.2	38.0	1.1
	DUKL 1	Dukul	3.91	0.32	0.27	39.3	23.0	37.7	1.0
	GONG 3	Gongila	1.00	0.61	0.12	39.7	25.0	35.3	1.1
	PIND 10	Pindiga	0.84	0.36	0.36	51.0	22.6	26.4	1.9
Chad Basin	KM-1 680	Gongila	0.80	0.33	0.15	46.6	21.1	32.3	1.4
	KM-1-1620	Gongila	1.66	0.85	0.10	41.7	18.9	39.4	1.1
	MS-1-1005	Gongila	1.01	0.38	0.18	47.2	19.2	33.6	1.4
	MS-1-1155	Gongila	0.72	0.38	0.13	17.8	18.8	63.4	0.3
	TM-1-2605	Gongila	1.30	0.83	0.10	44.7	22.0	33.3	1.3
	ZY-1-885	Gongila	2.83	0.22	0.31	52.2	22.8	25.0	2.1
	ZY-1-1210	Gongila	2.85	1.25	0.11	46.8	18.8	34.4	1.4
	ZY-1-1325	Gongila	2.97	0.97	0.10	49.1	20.8	30.2	1.6
	ZY-1-1880	Gongila	2.98	0.92	0.10	46.2	18.5	35.3	1.3
	ZY-1-2840	Gongila	0.98	0.94	0.09	48.6	18.9	32.4	1.5

study on the genesis of micrinite, Teichmueller and Wolf (1977) concluded that it is related to liptinites (although micrinite comes under the inertinite maceral group), and may have been generated from them (liptinites); pointing out that it appears first in the bituminous coal stage as a product of the coalification of liptinites, especially bituminite, with a close link to the generation of petroleum. Taylor and Liu (1989), however, are of the opinion that although micrinite is more common in bituminous coals, it occurs also in sub-bituminous coals (confirmed in this study), within an overall Ro range of 0.3–1.3%. The amount and density increased with rank and was thus inferred that oil generation proceeds over a considerable range at varying rates. The concentration of micrinite particles may thus offer a useful means of trailing the process of hydrocarbon generation and expulsion within the Benue Trough.

Table 11.5 Rock Eval data of samples from the Upper Benue Trough

Upper Benue Trough									
Sample ID	Locality	Formation	TOC (wt%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI*	OI**
UBWJ 2	Wuro	Gombe	2.63	0.01	0.06	2.60	511	2	99
UBWJ 1	Wuro	Gombe	1.26	0.01	0.05	0.67	515	4	53
UBHJ 4	H/Gari	Gombe	1.05	0.01	0.03	0.37	310	3	35
UBHJ 3	H/Gari	Gombe	0.96	0.01	0.03	0.43	502	3	45
UBHJ 2	H/Gari	Gombe	0.83	0.01	0.03	0.47	300	4	57
UBHJ 1	H/Gari	Gombe	0.92	0.01	0.03	0.47	282	3	51
UBDJ 2	Doho	Gombe	20.20	0.62	35.95	10.53	423	178	52
UBDJ 1	Doho	Gombe	6.84	0.13	12.01	5.08	429	176	74
MGMS 1	H/Gari	Gombe	0.12						
MGMC 3	H/Gari	Gombe	3.43	0.08	9.62	1.58	432	280	46
LGMCO 7	Lamja	Lamja	51.10	1.47	91.70	14.15	438	179	28
LAMCO 1	Lamja	Lamja	50.70	2.15	93.25	12.62	438	184	25
MFS 3	Fika	Fika	0.07						
MFS 1	Fika	Fika	0.07						
DUKL 8	Lakun	Dukul	0.61	0.02	0.27	0.18	429	45	30
DUKL 5	Lakun	Dukul	0.34	0.01	0.05	0.83	429	15	242
DUKL 3	Lakun	Dukul	0.36	0.01	0.10	0.17	436	28	47
DUKL 1	Lakun	Dukul	0.72	0.03	0.46	0.20	433	64	28
MDS 13	Lakun	Dukul	0.53	0.01	0.09	0.39	434	17	74
MDS 11	Lakun	Dukul	0.91	0.02	0.26	0.60	432	28	66
MDS 4	Lakun	Dukul	0.45	0.01	0.10	0.36	435	22	81
GONG 4	Ashaka	Gongila	0.55	0.02	0.14	0.33	421	26	61
GONG 3	Ashaka	Gongila	0.53	0.01	0.08	0.32	417	15	61
GONG 2	Ashaka	Gongila	0.52	0.01	0.09	0.26	420	17	50
GONG 1	Ashaka	Gongila	0.59	0.02	0.12	0.35	419	20	60
MGS 24	Ashaka	Gongila	0.09						
MGS 7	Ashaka	Gongila	0.16						
MGS 5	Ashaka	Gongila	0.42	0.01	0.06	0.34	421	14	81
MGS 2	Ashaka	Gongila	0.50	0.01	0.11	0.22	423	22	44
MGS 1	Ashaka	Gongila	0.37	0.01	0.15	0.64	425	40	171
PIND 10	Pindiga	Pindiga	0.71	0.02	0.22	0.36	418	31	51
PIND 1	Pindiga	Pindiga	0.12					0	0
MPS 77	Gombe	Pindiga	0.23	0.01	0.02	0.32	276	9	139
MPS 74	Gombe	Pindiga	0.07						
MPS 72	Pindiga	Pindiga	0.64	0.02	0.21	0.33	421	33	52
MPS 70	Pindiga	Pindiga	0.47	0.01	0.15	0.28	419	32	59
MPS 63	Pindiga	Pindiga	0.52	0.02	0.20	0.27	417	38	52
MPS 50	Pindiga	Pindiga	0.57	0.02	0.20	0.34	421	35	60
MPS 20	Pindiga	Pindiga	0.30	0.06	0.08	0.31	421	26	102
MYS 3	Gombe	Yolde	0.21	0.01	0.13	0.51	424	62	242
MYS 2	Gombe	Yolde	0.05						
YOLD 6	Futuk	Yolde	0.12						
YOLD 4	Futuk	Yolde	0.30	0.01	0.08	0.19	437	26	63
YOLD 2	Futuk	Yolde	0.35	0.01	0.11	0.12	438	31	34
BIMA 5	Bambam	Bima	0.07						

* mgHC/gTOC; ** mgCO_2/TOC

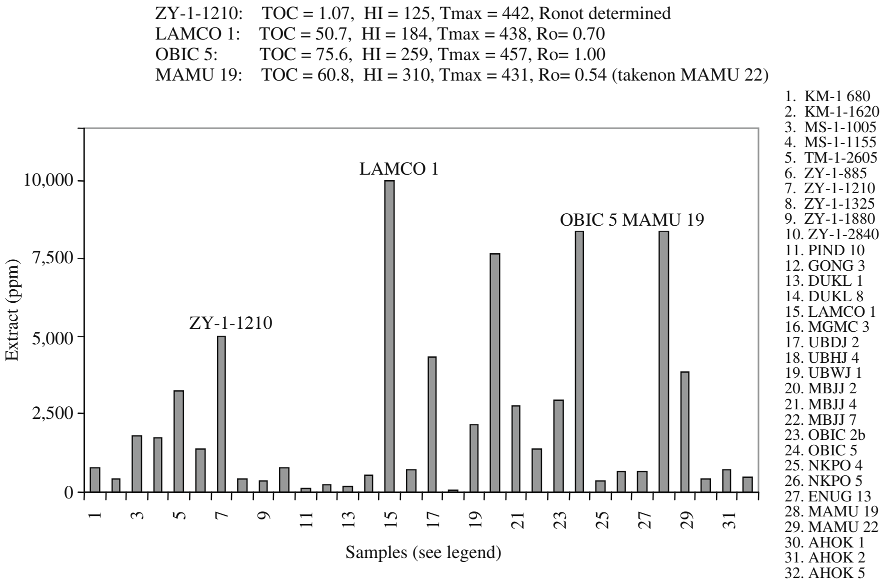


Fig. 11.8 Extract yield per sample (in a 9:1 isohexane-acetone solvent mixture) indicating LAMCO 1 with Tmax 438°C/Ro 0.70% to be within the maturity threshold of peak oil explulsion

Chad Basin

Eighty percent of the shale samples from the Chad Basin studied by Obaje et al. (2004) have TOC values > 0.5 wt%, the minimum limit for hydrocarbon generation (Table 11.6). The HI values all indicate gas-prone Type III organic matter with possibilities to generate gaseous hydrocarbons when juxtaposed against the Tmax (Figs. 11.3, 11.10). S_2 vs. TOC plots (Fig. 11.11) indicate a possible oil generating potential in source rocks from Ziye-1 well (oil was not discovered in this well, but there is such a possibility in prospects that have source rocks correlatable to those in Ziye-1 well). Biomarkers show a dominance of short-chain n-alkanes with no obvious OEP and are very similar to what an oil show or oil sample would look like (Fig. 11.12). A plot of the soluble organic matter (extract yield) against the TOC as proposed by Landais and Connan (1980) in Jovancicevic et al. (2002) for Ziye-1-1210 (depth: 1,210 m) indicate that some oils have actually migrated (oil show/oil impregnation) in Ziye-1 well (Fig. 11.13). This diagram, however, is not suitable for determining expelled/migrated hydrocarbons in coals and coaly samples, and for this reason only plots of the Chad Basin samples can be considered reliable. Pristane/phytane ratios range from 0.80 to 2.98 that indicate anoxic to oxic depositional environments. Steranes are dominantly of the C_{27} forms (Fig. 11.12, Table 11.4). The predominance of type-III organic matter in this basin with dominantly marine

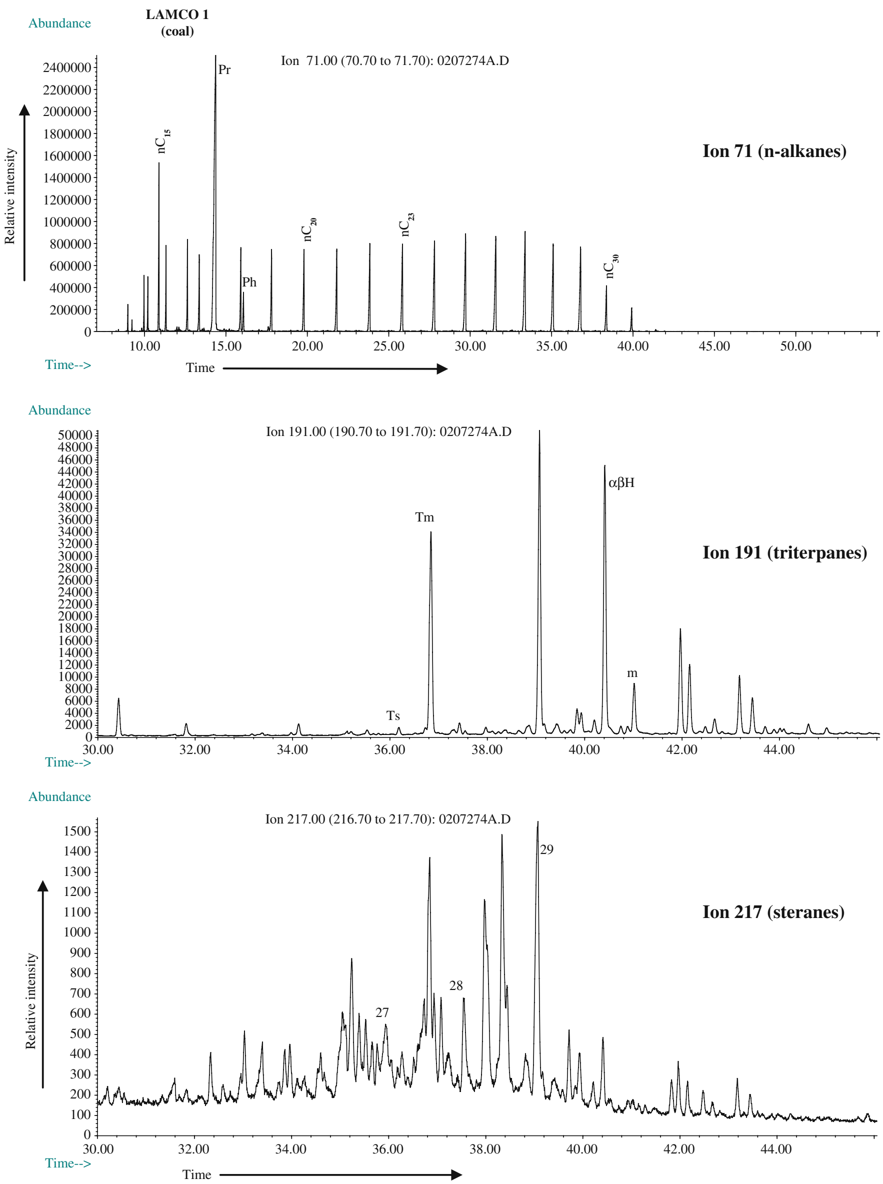


Fig. 11.9 Mass chromatograms of ions 77 (n-alkanes), 191 (hopanes) and 217 (steranes) of LAMCO 1 (Lamja coal) from the Lamja formation in the Uper Benue Trough

depositional environments (as confirmed by the high contents of C_{27} steranes) may be attributed to high oxic level (high Pr/Ph ratios) in the marine system. The relatively high Ts/Tm and low moretane/hopane ratios validate maturity levels that have entered the main phase of oil generation.

Table 11.6 Rock Eval pyrolysis data of samples from the Chad Basin

Chad Basin									
Sample ID	Locality	Formation	TOC (wt%)	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	HI*	OI**
KM-1 680	Kemar-1 well	Gongila	1.13	0.03	0.84	0.39	435	74	35
KM-1-770	Kemar-1 well	Gongila	1.11	0.02	0.43	0.44	433	39	40
KM-1-855	Kemar-1 well	Gongila	0.60	0.01	0.22	0.42	434	37	70
KM-1-975	Kemar-1 well	Gongila	0.86	0.02	0.32	0.45	437	37	52
KM-1-1070	Kemar-1 well	Gongila	0.80	0.02	0.20	0.55	440	25	69
KM-1-1290	Kemar-1 well	Gongila	0.76	0.02	0.22	1.03	431	29	136
KM-1-1385	Kemar-1 well	Gongila	0.72	0.02	0.12	0.75	441	17	105
KM-1-1480	Kemar-1 well	Gongila	0.77	0.02	0.18	0.59	438	23	76
KM-1-1620	Kemar-1 well	Gongila	0.72	0.04	0.64	1.24	447	90	173
KM-1-1720	Kemar-1 well	Gongila	0.59	0.02	0.08	0.75	437	14	128
MS-1-640	Murshe-1 well	Gongila	0.96	0.02	0.22	0.74	419	23	77
MS-1-735	Murshe-1 well	Gongila	0.89	0.02	0.23	0.54	421	26	61
MS-1-820	Murshe-1 well	Gongila	0.78	0.02	0.21	0.61	429	27	78
MS-1-1005	Murshe-1 well	Gongila	0.96	0.03	0.69	0.46	435	72	48
MS-1-1155	Murshe-1 well	Gongila	0.97	0.04	0.84	0.54	439	87	56
MS-1-1260	Murshe-1 well	Gongila	1.05	0.04	0.38	0.67	437	36	64
MS-1-1365	Murshe-1 well	Gongila	0.69	0.03	0.21	0.81	438	31	118
MS-1-1440	Murshe-1 well	Gongila	0.83	0.02	0.27	0.57	443	32	68
MS-1-2035	Murshe-1 well	Gongila	0.66	0.02	0.07	0.61	444	11	93
MS-1-2375	Murshe-1 well	Gongila	0.79	0.02	0.04	0.93	330	5	118
MS-1-2445	Murshe-1 well	Gongila	0.69	0.02	0.04	0.96	322	6	139
MS-1-2515	Murshe-1 well	Gongila	0.55	0.01	0.02	0.73	311	4	133
MS-1-2755	Murshe-1 well	Gongila	0.78	0.01	0.02	0.82	330	3	105
TM-1-935	Tuma-1 well	Gongila	0.33	0.01	0.10	0.64	429	31	197
TM-1-1125	Tuma-1 well	Gongila	0.93	0.01	0.31	0.41	431	33	44
TM-1-1515	Tuma-1 well	Gongila	0.79	0.05	0.28	0.42	441	35	53
TM-1-1685	Tuma-1 well	Gongila	0.57	0.02	0.15	0.54	445	27	95
TM-1-1780	Tuma-1 well	Gongila	0.92	0.03	0.24	0.59	446	26	64
TM-1-1810	Tuma-1 well	Gongila	0.69	0.02	0.11	0.57	440	16	83
TM-1-1985	Tuma-1 well	Gongila	0.77	0.03	0.09	0.42	452	12	55
TM-1-2190	Tuma-1 well	Gongila	0.60	0.03	0.10	0.56	443	17	93
TM-s-2285	Tuma-1 well	Gongila	0.92	0.06	0.33	0.62	451	36	68
TM-1-2605	Tuma-1 well	Gongila	0.37	0.15	0.22	0.57	290	59	152
ZY-1-885	Ziye-1 well	Gongila	0.71	0.02	0.54	0.50	431	76	71
ZY-1-990	Ziye-1 well	Gongila	0.66	0.02	0.32	0.55	430	48	83
ZY-1-1210	Ziye-1 well	Gongila	1.07	0.06	1.34	0.50	442	125	47
ZY-1-1325	Ziye-1 well	Gongila	0.72	0.03	0.61	0.55	441	85	77
ZY-1-1880	Ziye-1 well	Gongila	0.59	0.06	0.34	1.13	457	58	192
ZY-1-2085	Ziye-1 well	Gongila	0.34	0.02	0.15	0.69	457	44	204
ZY-1-2205	Ziye-1 well	Gongila	0.23	0.01	0.09	0.38	452	39	166
ZY-1-2405	Ziye-1 well	Gongila	0.35	0.02	0.12	0.48	482	35	139
ZY-1-2685	Ziye-1 well	Gongila	0.67	0.02	0.26	0.59	437	39	88
ZY-1-2840	Ziye-1 well	Gongila	0.84	0.12	1.04	0.80	448	124	96

* mgHC/gTOC; ** $mgCO_2$/gTOC

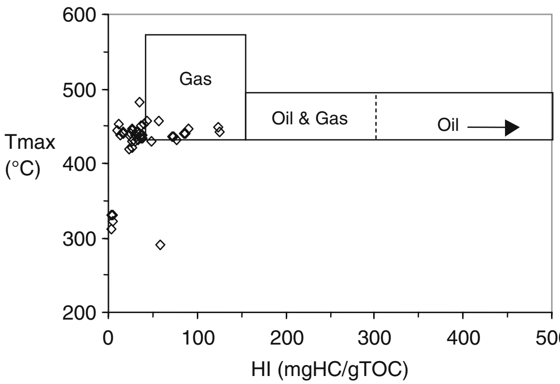


Fig. 11.10 HI-Tmax plots of samples from the Chad Basin

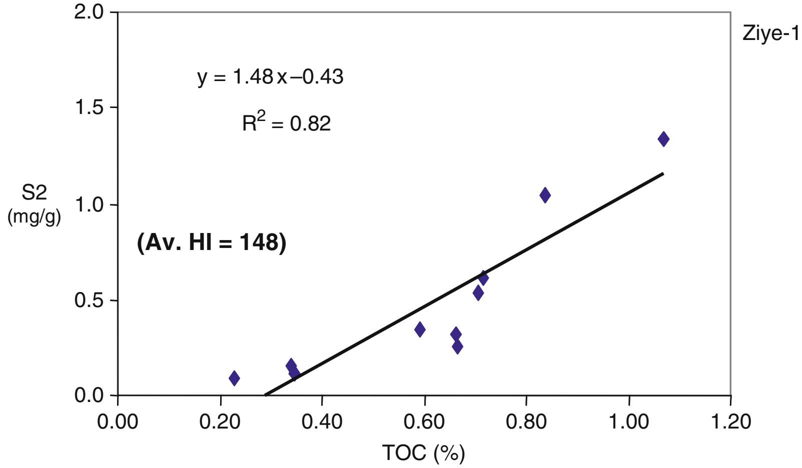


Fig. 11.11 S2 vs. TOC plots of samples from Ziye-1 well in the Chad Basin with the regression equations which gave the average hydrogen index (Av. HI) of source rocks in the well

Mid-Niger / Bida Basin

Although TOC values (Table 11.1) and liptinite contents are relatively high in the Mid-Niger Basin samples, the Tmax values, Ts/Tm and moretane/hopane ratios (Table 11.4) are indicative that hydrocarbons of mainly gaseous composition are probably just being generated in the basin and may not yet have been expelled nor migrated in large quantities. However, it is important to note at this stage that some hydrocarbon seepages have been reported along the bank of River Niger around Pategi and Mokwa in the Niger State of Nigeria (Philip Shekwolo, personal communications).

Organic petrological and geochemical (Rock-Eval pyrolysis) investigation of twenty shales collected from the Patti Formation by Akande et al. (2005) indicate a

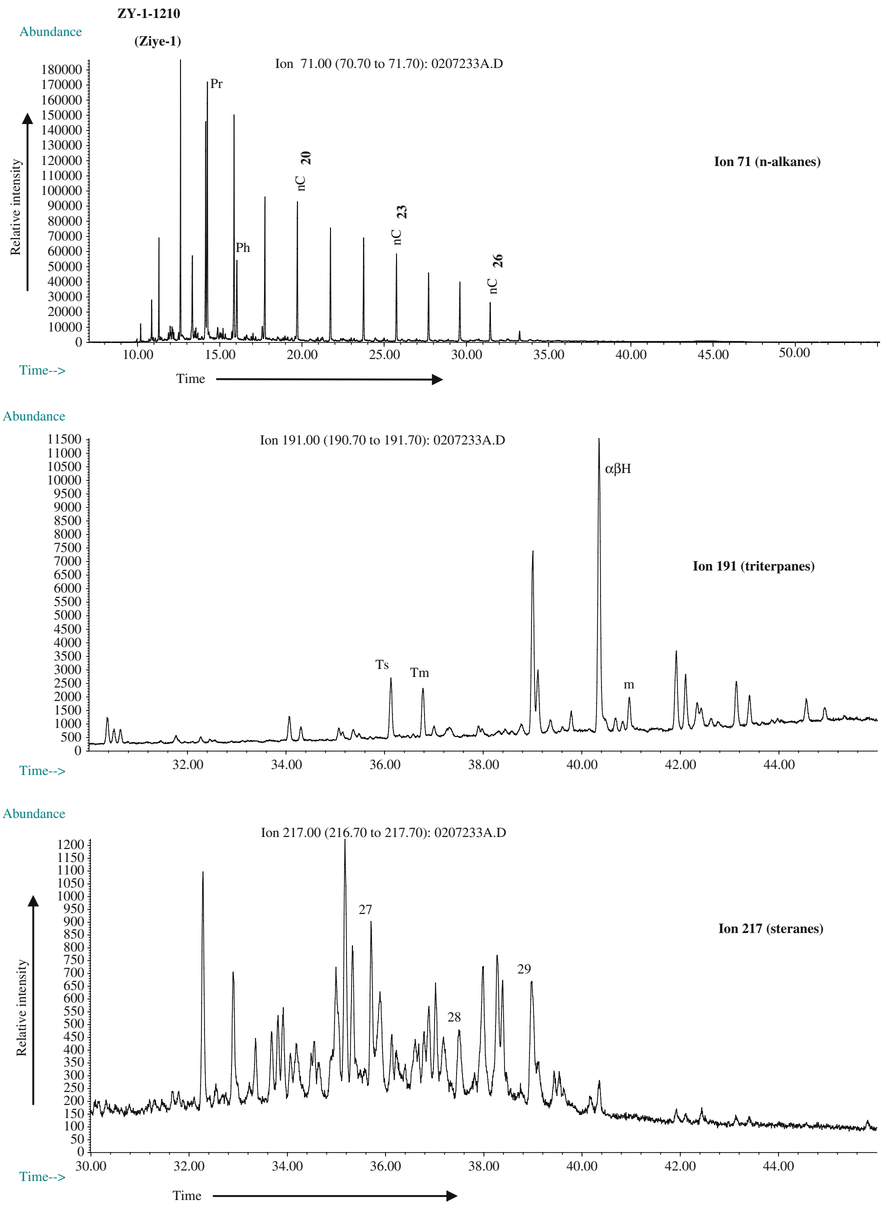


Fig. 11.12 Mass chromatograms of ions 77 (n-alkanes), (hopanes) and 217 (steranes) of Ziye-1-1210 (Ziye-1 well) from the Chad Basin (probably Gongila formation)

large abundance of vitrinite, moderate liptinite and lesser amounts of inertinite. Total organic carbon (TOC) values of the samples average 2 wt.% with most samples (ca. 60%) having greater than 2 wt.% TOC. Vitrinite reflectance (Ro%) and Tmax data

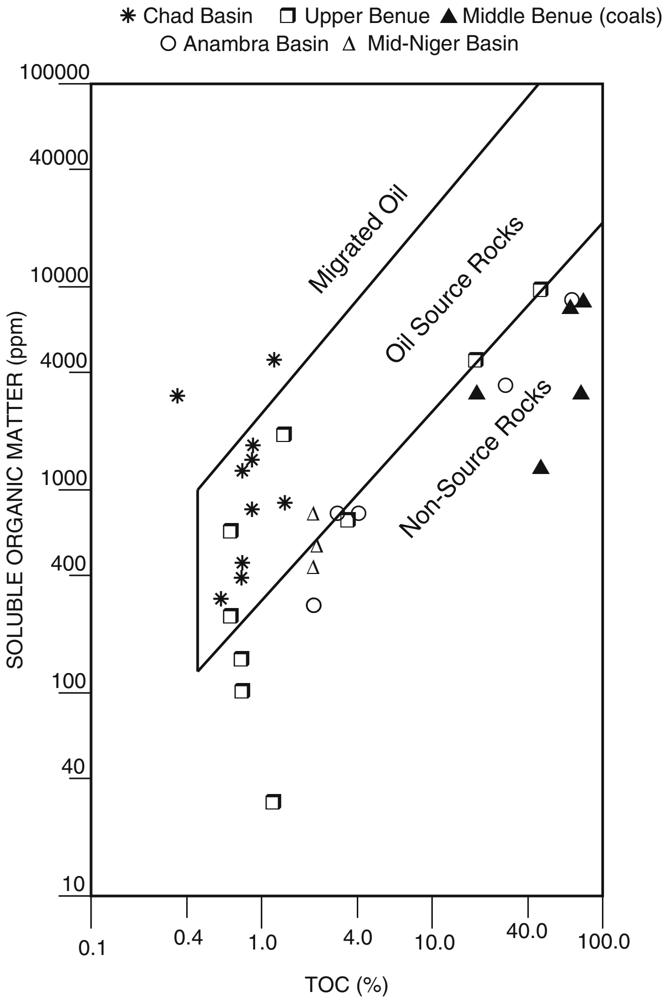


Fig. 11.13 Soluble organic matter vs. TOC plots (based on Landais and Connan in Jovancicevic et al. (2002)) of samples from the inland basins of Nigeria indicating migrated oil in Ziye-1 well. This diagram does not recognize the oil source rock potential of coals and coaly samples and cannot therefore not be used to evaluate such samples

of the sediments all indicate thermal immaturity to marginally mature status for the shale beds, these being at the threshold of the oil generation window. Rock-Eval data for the shales (TOC, Tmax, HI, Yield Potential) suggest the prevalence of a humic Type III kerogen. Generally, the genetic potential of these source rocks is low and free hydrocarbons are absent. Indeed only three of the samples studied by Akande et al. (2005) yielded greater than 2 kgHC/ton of rock suggesting a fair source rock potential. Given the prevalence of Type III kerogen, maturity levels and hydrocarbon potential yields, Akande et al. (2005) concluded that source rocks of the Patti Formation have some moderate to fair potential for gaseous hydrocarbons which have not yet been generated at the present outcrop levels.

Coal Deposits in the Benue Trough as Potential Hydrocarbon Source Rocks

The subject of coal as a major source of oil and gas in many parts of the world has been extensively reviewed and succinctly discussed by Hunt (1991) and many other authors. Coal has long been recognized as a source of gas, primarily methane and carbon dioxide but its importance as a source of economic accumulations of oil has been difficult to prove as coals are often interbedded with shales which are always assumed to be the source beds. Increasing evidence, however, suggests that coals and associated type III kerogens can yield not only gas or condensate (e.g. Tissot and Welte, 1984), but also significant quantities of oil (Murchison, 1987; Hunt, 1991; Hendrix et al., 1995). The traditional view that coals are largely gas-prone may be the result of historical bias in the study of North American and European Paleozoic coals, prior to the study of Mesozoic-Cenozoic coals containing contributions from resinous conifers and angiosperms (Obaje and Hamza, 2000).

Pyrolysis data have revealed that the hydrocarbon richness of sedimentary rocks is dependent on the amount and nature of liptinite and some vitrinite macerals (Hunt, 1991; Hendrix et al., 1995). The abundance of liptinite macerals is therefore the major criterion when considering any sedimentary rock (including coal) as a potential source for liquid hydrocarbons. A minimum of 15–20% liptinite content (by volume) of total macerals in shales, carbonates, or coals is considered an important criterion for a rock to be characterized as a potential oil source rock (Hunt, 1991). Although the concentration of long-chain aliphatic constituents has also been considered as a primary determinant of the oil generation potential of coals (Curry et al., 1994), the factors which govern their occurrence in different coals are poorly understood. Permian coals from the Cooper Basin in Australia, which have sourced commercial accumulations of oil (Curry et al., 1994), were deposited in high latitude bogs and contain 40–70% inertinite. Pristane/phytane ratios range from 2.15 to 6.00 and HIs are moderate (up to 243 mgHC/gTOC). The extracts and pyrolysates both contain high relative concentration of aliphatic groups. These aliphatic groups were found to be derived from microbial biomass (bacterial and algal degradation products). The Taranaki coals of New Zealand, which also are the source of commercial oil accumulations, were deposited in temperate fluvial-deltaic environments (Collier and Johnson, 1991). HI values range from 236 to 365. Extracts have high pristane/phytane ratios and variable abundances of hopanoid and other non-hopanoid terpanes. The extracts and pyrolysates both contain high relative concentrations of aliphatic groups $>nC_{20}$ which were interpreted to be derived directly from higher plant materials. The geochemical results from the studies of Cooper Basin and Taranaki Nasin coals show that long-chain aliphatic groups in coals can be derived directly from higher plant materials, from microbial activity in the depositional environment, or from a combination of both. The geochemical data of our Benue Trough coals are very similar to those of the Cooper Basin and the Taranaki Basin.

Coals and related continental strata with type III kerogen provide the source for commercial oil accumulations in many other sedimentary basins around the world: e.g. in the Mahakam Delta of Indonesia (Huc et al., 1986), the Karoo Basin in Tanzania (Mpanju et al., 1991), the Junggar and Tarim Basins in northwestern China (Hendrix et al., 1995) and in the Harald and Lulita fields in the Danish Central Graben of the North Sea (Petersen et al., 2000). And in the Niger Delta of Nigeria, source rocks of dominantly type III kerogen produce the vast amounts of hydrocarbons that have accumulated in that part of the West African continental margin. The major problem with hydrocarbons generated from coaly source rocks is the fact that most of such hydrocarbons are adsorbed in the interstices of the coal matrix which has made effective expulsion, migration, accumulation and producibility very difficult (Barker et al., 1989). This is probably the case with the envisaged coaly-sourced hydrocarbons in the Nigerian Benue Trough. Exploration for hydrocarbons in these coals, therefore, must target deep coal seams that have been subjected to local and regional tectonics.

Charcoal is one of the most widely used adsorbent for taking bitumens and other organic matter contaminants out of a flowing water system. Laboratory experiments have shown that as you go from high volatile bituminous coal to anthracite, the adsorption of hydrocarbons increases. Increasing pressure also increases the adsorption. Wyman (1984) slowly desorbed coal samples obtained at a depth of 2,835 m in the deep Western Canadian basin and found that after 15 days only the hydrocarbons, methane, ethane and propane were desorbed. By 34 days he was able to obtain isobutane, n-butane and isopentane. Extraction of these coals released up to 30 mgHC/gTOC which apparently was strongly adsorbed on the coal surface. Landais and Monthioux (1988) carried out open and closed pyrolysis of coals. The same coal samples followed different maturation pathways using open, confined and closed system pyrolysis. Comparing these results with extraction data, they concluded that natural coals keep free hydrocarbons trapped in the pores of their structures and that these hydrocarbons are in turn released when these coals have been fractured.

Some Remarks on Potential Petroleum Systems in the Inland Basins

No conclusion was drawn from the work of Obaje et al. (2004) on the build up of any specific prospect nor of any petroleum system in the Benue Trough, which must consider, apart from the identified source rocks, the stratigraphic position of the source rocks, the availability of good quality reservoir and seal lithologies, timing of hydrocarbon generation, favorable regional migration pathways and trapping mechanisms. However, the Anambra Basin presents the best natural petroleum system in terms of formational source rock, reservoir and seal lithologies. Apart from interbedded marine sandstone facies within the Nkporo/Enugu shales, petroleum generated from the Nkporo/Enugu Shale and Mamu coal source rocks have good reservoirs in the overlying clean quartz arenites of the Ajalli Sandstone. Sandstones of the Mamu Formation will provide additional reservoirs. The overlying shales of the Imo and Nsukka formations are expected to provide regional seal for hydrocarbons that may have been generated and migrated into reservoirs in this part of the Benue Trough. Santonian and Maastrichtian deformations were quite intense in this area, and rapid facies changes are also characteristics of the successions. Traps are therefore likely to be a combination of structural and stratigraphic.

In the Middle Benue Trough, juxtaposition of sandstone facies (Fig. 11.14a) of the Keana and Awe formations against the Awgu Formation source rock can lead to some petroleum trappings in this region. Time equivalent marine and paralic sandstones (e.g. the Makurdi Sandstone) and other sandstone bodies within the Awgu Formation are expected to constitute additional reservoirs. Prospects in the overlying Lafia Sandstone will be too shallow and may lack adequate seals, but the possibility of some traps within the Lafia Formation cannot be ruled out. In the Upper Benue Trough, a similar juxtaposition of sandstone facies against shaley and coaly source rocks as a result of block faulting that produced numerous horst and graben structures in this basin can provide good drainage for generated hydrocarbons. In this way, younger shaley and coaly source rocks can generate hydrocarbons that can be trapped in the underlying (but now juxtaposed) very thick and laterally extensive (but compartmentalized as a result of the block faulting) Bima Sandstone (Fig. 11.14b). Shelf sandstones within the Pindiga, Dukul, and Gongila formations may also constitute additional reservoir lithologies. Just like in the very shallow Paleocene Amal Formation in which significant volume of oil has been discovered in the Muglad Basin of Sudan (Schull, 1988; Mohamed et al., 1999), possibilities of shallow prospects within the Paleocene Kerri–Kerri Formation in the Upper Benue Trough cannot be ruled out. Volcanic activities locally occur in this basin, but none of the studied samples from this area has produced an overcooked facies ($Ro>2.5\%$). In the Chad Basin, source rocks are mainly in the Gongila Formation and in the Fika Shale. Reservoirs may be provided by sandstone facies in the same Gongila and Fika formations and in the Gombe Sandstone, where deposited. Most of the hydrocarbons in the Nigerian sector of the Chad Basin may have been lost as result of the Tertiary hiatus (non-deposition). Source rocks, reservoirs and seals in the Mid-Niger (Bida) Basin are in the Lokoja Sandstone and in the Patti Formation (if hydrocarbons had been generated). Prospects in this basin get better towards the center of the basin in the Bida area.

With respect to the exploration and drilling campaigns so far undertaken, Maastrichtian tectonism has tilted and shifted the center of sedimentation in the Upper Benue Basin to the west in the so-called Gombe-Kerri–Kerri or Gongola sub-basin (Fig. 11.14b). The Gongola sub-basin therefore contains the thickest pile of sediments in the Upper Benue Basin and constitutes the more favorable sub-sector for exploration in that region. This is confirmed by Shell's subcommercial success in

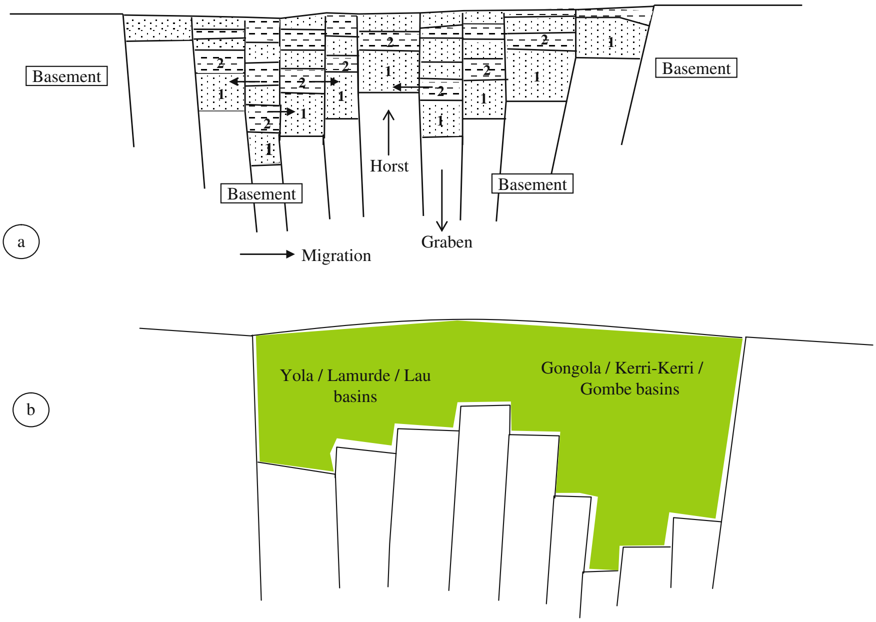


Fig. 11.14 Schematic illustrations of (**a**) Block faulting and the formation of horst and graben structures; juxtaposition of older reservoir facies against younger source rock facies; (**b**) Down-warping, subsidence and tilting in the Maastrochtian making provision for more sediment accomodation in the Gongola / Kerri–Kerri / Gombe sub-basin

Kolmani-River-1 well. Chevron's *Nasara-1* well was too shallow and was located on an anticlinal core of the Pindiga Formation that was supposed to be the source rock for hydrocarbons that would have been generated for the targeted prospect (Fig. 11.15). This is probably responsible for the dry hole encountered in that campaign.

Oil seepages have been widely reported from the Awgu Formation in the south-east. Oil has been struck in the Ezeaku Formation of the Anambra Basin of the Lower Benue. Indications of petroliferous residues were also found in the lime-stones of the Ezeaku Formation in the Middle Benue (Offodile, 1976). The Muri Sandstones, from which oil seepages were reported (Adeleye, 1975), are lateral equivalents of the Keana and Makurdi Formations. The sandstones are porous in places and could provide excellent reservoirs. There are very good indications of the existence of Cretaceous oil in the Benue Valley, the Lower Benue being apparently the most favourable area. Several anticlinal structures arising from the Santonian folding episode are of special interest in the search for oil in the Benue Trough. The most important, the Abakaliki and Keana anticlinoria, present an interesting structural stratigraphical trap setting. The cores of the anticlines comprise of highly compact shales of the Asu River Formation, with a possible predepositional base-ment ridge indicated by Jones (1965). The overlying younger formations flank both

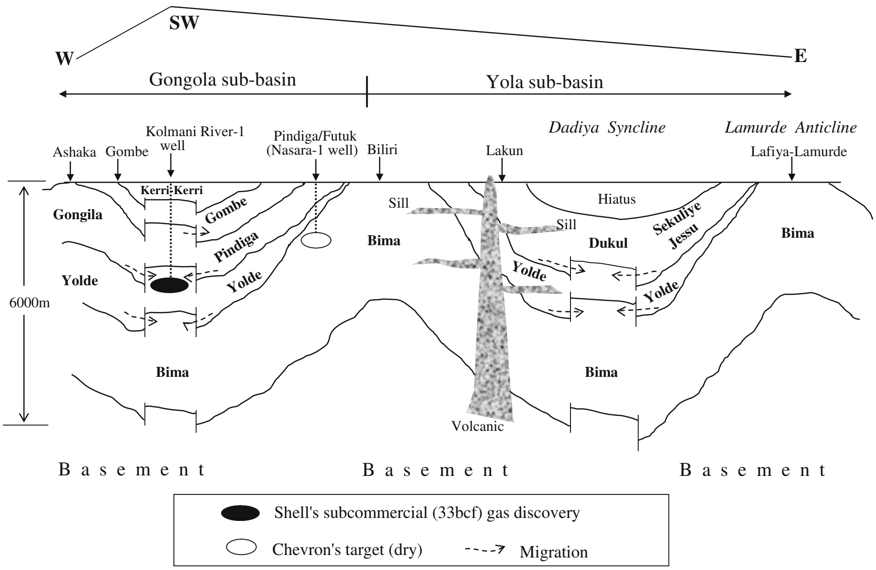


Fig. 11.15 Stratigraphy, structures, possible migration patterns and trapping mechanisms in the Upper Benue Trough (for the indicated section and *horst* trap) in relation to some exploratory wells drilled in the area

sides of the major fold, lying unconformably and wedging out against the structures. The possibility of oil and gas accumulating on either side of these structures is high. The connate or evaporitic brines issuing from the flanks of these anticlinal features are of potential interest. As regards possible oil occurrences, there is, however, the intensive igneous activity which is believed by some workers to have dissipated any hydrocarbons that could have accumulated. The negative effect of this factor on oil accumulation has placed a low-key on the investigation of the mineral in the Middle and Upper Benue areas where igneous activity appears to have been much more intense. More interest appears therefore to be directed to the Lower Benue and the Chad Basin, where the geological environment is, apparently, much more ideal for the accumulation of hydrocarbons (important occurrences are currently being exploited in adjoining Chad Republic).

Chapter 12
Policy Issues and Development Options

Solid Minerals

Prior to the emergence of petroleum in the mid nineteen seventies as a major foreign exchange earner, the solid minerals subsector ranked second only to the agricultural sector as a source of export earnings. The subsector also contributed substantially to national output, accounting for about 10% of the GDP in 1970 (Kogbe, 1976). The annual average output in the subsector was put at some 130.8 thousand metric tonnes over the years 1970–1973. It employed, on the average, about 49 thousand workers per annum over the period 1958–1970. However, with the exit of foreign multinational mining companies and their expatriate professionals in the wake of the 1972 Indigenisation Decree, the performance of the subsector began to dwindle. Annual production declined considerably, particularly in metallic minerals. The tempo of mining activities shifted to industrial non-metallic minerals needed for construction, building and industrial applications in domestic industries.

Policy Evolution and Governance of the Sector

To a large extent, the performance of the solid minerals subsector has depended on the evolution of government policies over the years. Organised mining activities began in Nigeria between 1902 and 1923 following the commissioning in 1903 and 1904 of mineral surveys of the Southern and Northern Protectorates by the then British Secretary of State for the colonies. Modern mining of tin ore (cassiterite and associated minerals) was initiated by the Royal Niger Company in 1905. The mining of gold began in 1914 in areas located within present day Niger and Kogi States. Coal mining began at Enugu in 1916. By 1919, the Geological Survey of Nigeria was established as a department of government to take over and continue mineral surveys of the country.

The Minerals Ordinance of 1946 and the Coal Ordinance No. 29 of 1950 provided the legal basis for the development of solid minerals in Nigeria. The former vested ownership of all minerals in the British crown. It provides that "the entire property in land and control of minerals and mineral oils, in or under or upon any

N.G. Obaje, *Geology and Mineral Resources of Nigeria*, Lecture Notes in Earth Sciences 120, DOI 10.1007/978-3-540-92685-6_13,

lands in Nigeria, and of rivers, streams and water courses throughout Nigeria, is and shall be vested in the state". The Minister of Mines and Power was empowered to grant prospecting and mining rights and leases to individuals and/or corporate organizations on application and payment of appropriate fees.

From the foregoing it is clear that the original cardinal principle of government's policy on prospecting and extracting mineral resources of the country on commercial basis was non-investment of public funds in the risk of mining investment. It was believed that investment in mining activities involved large sums of money on prospecting without any certainty of remunerative returns. The policy engendered a situation whereby large-scale foreign companies and small-scale indigenous miners concentrated their efforts on the production of minerals with export potential, neglecting minerals meant for local industries. Apart from coal which was mined by a government department, the mining of solid minerals was entirely in the hands of private expatriate and indigenous companies and entrepreneurs.

Prior to 1971, British mining companies dominated the scene with up to 120 companies at the peak of tin mining. These companies were well equipped. They employed qualified staff and paid detailed attention to efficiency considerations. All these combined contributed to large-sized output and employment. The Minerals Ordinance of 1946 and allied regulations which were re-enacted as the Minerals Act of 1959 applied globally to the exploration and exploitation of minerals without any particular distinction to special sets of minerals singly or in groups. However, as years passed, the development of mining particular minerals necessitated special regulations and led to the enactment of special Acts to govern the exploitation of special minerals. Such Acts included the Nigerian Coal Mining Act of 1950, the Gold and Diamond Trading Act, the Explosives Act of 1964, the Tin Act No. 25 of 1967, and the Quarries Act and Allied Regulations of 1969.

In 1971 the government policy on solid minerals was drastically reviewed. Government decided to act as catalyst in the mining sector through the establishment of mining corporations which would use government funds for mining. The main policy thrust was the rejection of the concept of private-sector-led development of the solid mineral subsector. Government was of the opinion that the objective of that ensuing mining policy would be to secure the development, conservation and utilisation of the mineral resources of Nigeria in the best possible manner so as to bring about economic benefit for the largest possible period, and that there was no reason to suppose that the private investor was the best instrument with which to achieve the objective. It thus meant that if prospecting and exploitation of minerals were to remain solely in the private sector, the country would be at a disadvantage.

To achieve the objectives of the new policy, government which had hitherto refrained from direct participation decided to participate directly in the mining industry. It established the Nigeria Mining Corporation (NMC) in 1972 to engage in direct investment in the exploitation of known economically viable minerals other than coal and marble. Through subsidiaries, the NMC engaged in the exploitation of kaolin, barytes, cassiterite, columbite, limestone and clays. The Nigerian Coal Corporation (NCC) was responsible for mining coal. Later the Nigerian Uranium Mining Company (NUMCO) was incorporated to mine and develop uranium.

Government direct involvement in the solid minerals subsector has been conducted through three parastatal organizations and an agency. Minerals like coal, iron ore and bitumen have always been under the complete control of government both in exploration and exploitation. In addition to the above parastatals (under the Ministry responsible for solid minerals) through which government exercised control and direct involvement, there are other parastatals whose activities interface with those of the former but which report to other Ministries. These include the Nigerian Iron Ore Mining Company (NIOMCO) which mines iron ore at Itakpe, the National Steel Raw Materials Exploration Agency (NSRMEA) which concentrates on exploration of iron ore and coking coals, the National Metallurgical Development Centre (NMDC) whose focus is on research in mineral processing and downstream utilization studies on minerals, all of which report to the Ministry of Power and Steel, and the Raw Materials Research and Development Council (RMRDC) located in the Ministry of Science and Technology to source local raw materials – agricultural, forest, minerals and chemical – for domestic industries.

Despite the heavy public expenditure involved in the maintenance and operations of the above corporations, the expected economic advantages that informed the 1971 review of mining policy were still far from being realized.

With the exit of multinational companies and their expatriate professionals following the Indigenisation Decree of 1972, the bulk of mining operations by the private sector rested on the shoulders of small-scale indigenous miners. The surface, near surface and shallow depth deposits of the minerals had by then been variably depleted. These factors were largely responsible for production decline particularly in the metallic minerals. As a consequence, there was a shift of the tempo of mining activities to industrial non-metallic minerals needed for construction, building and industrial application for domestic industries. Furthermore, the downturn of the country's economy adversely affected the exploration as well as exploitation of even the non-metallic minerals. The Inspectorate Department of the Ministry of Mines and Power (as it was then known) was ill-equipped. It lacked adequate and suitable manpower to carry out surveillance of the minefields with a view to ensuring compliance to safety standards and to man the exit points to identify mineral commodities being exported. Illegal mining and speculative pegging by legal title holders were rife. These problems were further compounded by administrative bottlenecks which included cumbersome procedures in processing mining applications leading to long delays, difficulties in obtaining consent to enter land for the purpose of prospecting and mining, and procedural reports necessary for the approval of applications.

Current / Ongoing Reforms in the Solid Minerals Sector (As at 2008)

Below is a numerated summary of the ongoing reforms in the solid minerals sector (or subsector), which started since early 2005.

1. The Nigerian government considers the exploitation of Nigeria's mineral resources to be among its highest priorities, and it has said it is committed to the orderly development of these resources in a manner that guarantees the wealth and peace of all Nigerians.
2. The government also recognizes that the successful exploration and exploitation of Nigeria's mineral resources requires both technical expertise and financial strength that to a large extent can be provided by foreign investment capital.
3. A central platform for the new policy is the transformation of the role of government from that of owner-operator to administrator-regulator. This is to allow the private sector to take a pivotal role in the growth of the mining sector.
4. To attract overseas investors, the government has said it is committed to fostering a stable regulatory, economic and political environment that encourages investors to make long-term commitments to exploration and development.
5. The principal legislation regulating mining activities in Nigeria is the Minerals and Mining Act 1999, which is currently administered by the Ministry of Mines and Steel Development. The 1999 Act has been reviewed and amended to ensure security of tenure of a mining title and greater transparency in licensing procedures.
6. Ownership of minerals is still vested in the Federal Government of Nigeria as custodian on behalf of the citizens of the country. The government will grant titles to allow suitable entities to explore for, mine and market mineral resources.
7. Fixed-term mineral titles over a specified area may be granted to entities committed to approved programmes of exploration or mining.
8. Applications for mineral titles and licences will be considered on a first-come, first-served basis and may be made by any person, at any time, over any area not covered by an existing title, or not otherwise reserved by the government.

It is therefore clear that government is making a return to privatization and private sector-driven operations. Government and stake-holders in the solid minerals sector identified the contraints in the implementation of the immediate previous policy to include:

1. Lack of adequate data on mineral deposits up to bankable status.
2. Inadequate capital investments for private sector investors to co-participate in mining operations alongside the government operators (Nigerian Mining Corporation – NMC, Nigerian Iron Ore Mining Company – NIOMCO, Nigerian Coal Corporation – NCC, Nigerian Uranium Mining Company – NUMCO, etc).
3. Lack of in-depth technological knowledge to develop and process the minerals.
4. Undue delay in the processing of mining applications, even by the small-scale miners who were interested in co-participating.
5. Problems of air and water pollution as well as erosion and other ecological problems arising from mining activities.
6. Absence of a Mineral Resources and Environmental Management Committee in the States.

7. Basic infrastructures such as roads, electricity, and communication facilities at mining sites are grossly inadequate to attract the private sector.
8. Lack of market channels for processed mineral products.
9. Absence of a Solid Minerals Development Bank or a window within the banking sector to support investments in the mining sector.

The following points can further be deduced from the current reforms in the sector:

The principle of derivation has been restressed as ownership of minerlas will continue be vested in the Federal Government. A competitive business environment is to be created so that the private sector will be the driver of the operations. The role of government will be limited to regulation. Security of tenure for leasees will be garanteed while discretionary allocation will be abolished. The interest of the community will be protected. Government will continue to develop the political environment that will attract investors. Everybody will have a role to play: Local Governments, State Governments, the Federal Government and the private sector. The Federal Govenment may go into joint ventures with some private sector investors and above all the qualification criteria shall be "come one come all". It is further to deduce that Community Development Agreements will be entered into between the government, the community and the operator, which shall ensure adequate environmental protection and rehabilitation programmes. Furthermore it is expected that an Environmental Protection Fund will be established to ensure adequate Reclamation and proper Decommissioning. At the end of it all, government and stakeholders seem to have noted that mining of solid minerals may not be so volatile or crises-ridden as is the case with oil at the moment, but it can be if not properly handled.

Suggested Policy Modifications

Despite some noted setbacks in the policies guiding the exploration and production of oil and gas in Nigeria, government may still have to adopt a similar model to enable it derive maximum economic benefits from the solid minerals subsector. Below is a numerated summary of suggested inputs to that will guarantee a sustainable policy to the benefit of all stake-holders.

1. The Federal Government (on behalf of the Federation) should continue to retain ownership of all minerals (solid, liquid and gaseous) in and under the land in the territory of the Federal Republic of Nigeria.
2. The Joint Venture (JV), Production Sharing Contract (PSC) and Sole Risk Operation (SRO) models as obtained in the oil and gas sector should be extended to the solid minerals sector.
3. The JV model should comprise the Federal Government (40%), the State Government (20%), the Local Government (5%), and the private sector (core investor) (35%). There may be cases of straddled mineral deposits (i.e. those covering more than one state or more than one local government). In this case,

the 20 or 5% as the case may be will be contributed by the respective states or local governments. The JV model shall only be for the basis of raising initial capital and offsetting operational costs (cash calls). The private sector core investor shall be the operator. It should be noted that private sector core investor does not necessarily mean a foreign company, but it can also be.

4. All monies accruing from the operation (sales of the minerals / profits) shall go into the Federation Account from which a derivation of 50% should be retained in the Federation Account while the remaining 50% shall be returned on the basis of equity (40:20:05:35), after tax, if tax holidays had not been granted. Investments shall be for a specific mineral deposit in a particular locality which shall be ring-fenced in every particular case or for a leased area which may cover several minerals or for several leases but for which more than one contracts have to be signed.
5. It would be noted in (4) above that a different derivation regime of 50% for the Federation Account is set for the solid minerals sector as against the current 87% (and 13% to the derivation-earning state) for oil and gas. It should however be noted that these are two different cases. The 50% going to the solid mineral producing state is not a derivation of any type but for equity participation for which the state is entitled to only 20%. The 50% in the Federation Account is for the Federal Government and all the states of the federation including the Federal Capital Territory as well as the State from which the mineral is derived. This should be so at the initial stage to attract investments into the sector while encouraging state governments to be proactive in seeking out investors themselves. When any solid mineral has attained a contributory quota of up to 30% of the nation's export earning or 10% of the Gross Domestic Product, the derivation to the Government of the Federation should be graduated upwards.
6. A National Solid Mineral Investments and Development Commission (NASCOM) should be set up to supervise the joint venture operations and shall have a state office in all states where JVs are in operation. The Federation Account Allocation Committee (FAAC), calling the attention of the NASCOM, shall ensure the return of the equity shares to the co-investors while the remaining 50% in the Federation Account will be shared between the Federal Government, the States and the Local Governments in line with the existing formula normally derived from the Revenue Mobilization, Allocation and Fiscal Commission (RMAFC).
7. Joint Ventures should initially be for specific minerals. It is recommended that at the initial stage they should be for *gold, marble, limestone, baryte, lead-zinc, iron ore, coal and granite*, but where these co-exist with other minerals, as is the case in many geological environments, the agreement should cover all the minerals in the leased area.
8. All other operations should come under the PSC or Sole Risk models, for which the operator shall be on his own and shall fund the exploration and production. On deduction of initial capital (which shall be graduated over a specified period, e.g. 20 years) and periodic operational cost under the supervision of NASCOM,

rest profit shall be shared between the operator, the Federal Government (on behalf of the Federation), the State Government (in this case derivation) and the Local Government (derivation) in a ratio that shall continue to encourage the operator to continue with investments.

9. For the purpose of Sole Risk agreements, the operator shall be solely responsible for all costs and shall be charged lincensing fees, royalties and profit taxes.
10. A State Government may wish to set up its own company to mine the mineral resources in its territory or any other territory in Nigeria for that matter. It should be allowed to do so but under the arrangement of either the JV or PSC as would be guided by NASCOM.
11. To make profits, there must be sales in the form of export or supply to local industries. It would be left for the operator and/or the joint venture partners to decide whether they want to establish downstream industries or identify downstream industries, belonging to a third party, that will absorb the mined raw materials. For example, what do you do with so much limestone where there is no nearby located cement factory? Or what do you do with so much iron ore where there is no nearby located iron and steel company? But both are dependent one upon the other and each will determine the fate of the other which market forces will work out. However, export potentials are considerably large for all the mineral resources of Nigeria.

The suggested inputs are meant to serve as a mid-way between total privatization and total government control of the solid minerals sector, attract investors who may not have the abilty to bear all the financial burden alone (mining is a capital intensive venture), generate funds for all the tiers of government, expand the economy, generate employment, pacify communities but as well assisting them to take economic benefits of their resource endowments, reinforce federal ownership rights while dousing resource control agitations.

Specific Development Options Based on the Occurrence of Some Mineral Deposits in Nigeria

Based on the JV, PSC or Sole Risk models, the followings, amongst many others, are suggested options for the development of additional mineral-based industries in Nigeria to enhance economic growth and social transformation.

1. The development and recapitalization of the Ajaokuta Iron and Steel Company and the Associated Iron Ore Mining Company at Itakpe in Kogi State.
2. The establishment, or causing to be established, of additional Cement Manufacturing Companies at Ugya and Awe in Nasarawa State, Itobe in Kogi State, and Abuja in the Federal Capital Territory.
3. The establishment, or causing to be established, of Gold Mining Companies in Maru and Anka in Zamfara State, Zungeru in Niger State, Egbe in Kogi

State, Birnin Gwari in Kaduna State, Bin Yauri in Kebbi State and Ilesha in Osun State.
4. The establishment, or causing to be established, of Salt Mining and Beneficiation Companies at Ribi and Awe in Nasarawa State.
5. The establishment, or causing to be established, of Small and Medium-Scale Tantalite and Associated Minerals Mining Enterprises at Wamba-Keffi-Nasarawa in Nasarawa State, Isanlu-Egbe in Kogi State, and Ijero-Aramoko-Ilesha areas in Ekiti and Osun States.
6. The establishment, or causing to be established, of Gemstone Mining, Collection, Processing and Marketing Centres at strategic localities in Kaduna, Plateau, Taraba, Bauchi, Nasarawa, Oyo, Ogun, Kogi, Kwara and Niger States.
7. The establishment, or causing to be established, of Coal Briquetting Companies at Obi (Nasarawa State), Enugu (Enugu State), Okaba and Ogboyaga (Kogi State), Orukpa (Benue State), and Gombe (Gombe State) to supply coal briquetters for domestic cooking all over Nigeria.
8. The establishment, or causing to be established, of Independent Power Projects in above-listed coal localities, to use the coal deposits for power generation for local consumption and/or supply/sale to the national grid.
9. The establishment, or causing to be established, of Barite Processing and Marketing Companies at Azara in Nasarawa State, Ugep in Cross River State, Wase in Plateau State and other localities in Benue, Taraba and Zamfara States.
10. The establishment, or causing to be established, of Sanitary Wares and Ceramic Industries in selected localities in Akwa Ibom, Anambra, Bauchi, Ekiti, Imo, Katsina, Kebbi, Kogi, Ogun, Ondo, Plateau and Rivers States to use the abundant clay deposits in these areas as raw material.
11. The revival of the Cassiterite-Columbite Mining Company in Jos and the establishment, or causing to be established, of new ones in Bauchi, Cross River, Kaduna, Kano, Kwara and Nasarawa States.
12. The establishment, or causing to be established, of Glass Manufacturing companies in Delta, Jigawa, Kano, Lagos and Ondo States.
13. The establishment, or causing to be established, of Phosphate Processing Plants in Sokoto and Ogun States.

Petroleum

Historically, petroleum exploration began in Nigeria as far back as 1908, when a German company, the Nigerian Bitumen Corporation, was attracted to what is now known as the south-western Nigerian Tar Sand deposit. After World War I, Shell-D'Arcy, a consortium of Shell and Royal Dutch, resumed oil exploration in 1937, this time in Owerri, on the northern fringe of the Niger Delta. On June 5, 1956, after drilling 28 wells and 25 core holes, all dry, the new operator, Shell-BP, struck oil at Oloibiri in what is now Bayelsa State.

Thenceforth, exploration activities started earnestly in the Niger Delta region. From an initial output of 5,100 barrels per day in 1958, the nation steadily rose to the sixth position on the export scale of the Organisation of Petroleum Exporting Countries. By the mid 1970s, Shell, the leading producer had exceeded the one million barrels a day production mark.

After over three decades during which the oil industry was dominated by foreign companies, a private indigenous oil company, Consolidated Oil, recorded its first discovery, Bella – 1, in 1991. Since 1992, following the release of new concessions in the Niger Delta to indigenous exploration and production companies, the number of indigenous companies has continued to increase steadily. So far, out of more than 400 oil fields discovered in Nigeria, only about 150 fields are producing. Most of the other fields are not producing because the country has to abide by OPEC's production quota that has been swinging between 1.8 and 2.2 million barrels per day for Nigeria. Violence in the oil-producing communities has also disrupted production, causing the shut-in of most land and swamp wells. Production is generally now sustained by offshore fields.

In order to raise the country's proven petroleum reserves from 23 billion barrels to the target 25 billion barrels set for 1995, the Federal Government opened up new acreages for exploration and also offered a package of fiscal incentives to petroleum companies. Among the incentives was the reduction of petroleum tax to boost exploration in the deeper offshore. Potential reserves in billion barrels were estimated for the new blocks which held good prospects for smaller fields with less than 50 million barrels. Generally, in the Niger Delta, about 73% of crude oil discoveries are in fields having less than 50 million barrels of proven reserves. The overall wildcat success ratio is 42%. However, in some years the success ratios of exploratory and appraisal/development wells are substantially higher (83.5% in 1989). In the early years 52% of the exploration wells were successful and in the latter years the success rate increased to 68%. However, during a period of 1966–1976 only 40% of the wells were considered successful. The increased success during the later years is attributed to improved seismic technology. The sizes of the fields have decreased over the period.

Petroleum prospects in the offshore Niger Delta are most attractive, with a potential 1.10 billion barrels of crude awaiting discovery in awarded Oil Prospecting Licences (OPLs). Oil Prospecting Licences in the deeper offshore (beyond 200 m water depth) have received highly competitive bids, which extensive regional seismic and geochemical surveys have shown to be quite attractive. A new development in Nigeria's petroleum prospecting is the unitisation scheme. Under this arrangement, petroleum prospecting companies, in order to reduce cost, conduct joint exploration and development of undeveloped oil fields which straddle their common concession boundaries.

The Shell Petroleum Development Company (SPDC) of Nigeria and Chevron Nigeria formed such an alliance. Apart from reducing operating cost, the intention is to maximise the exploitation of adjoining fields. The first SPDC-Chevron initiation scheme involved Shell's Belema field and Chevron's Belema North field, which were developed with Shell as the operator, while utilising the facilities of both companies. Under the Unitization Development Statement of Principles of Co-operation, funds would be contributed by both companies based on the size of petroleum reserves found in each of the companies' sector of the fields. The equity share of production allocated would also depend on the reserve held.

New exploration technology has also made substantial impact on Nigeria's petroleum potential. High resolution seismic technology involving enhanced 2-D seismic and the advent of 3-D and 4-D seismic technologies have revealed petroleum prospects at greater depths than before. Consequently, subtle traps and deep-seated structures have been discovered, which in many cases, are larger reservoirs than their shallower and more structurally complex counterparts.

Also, Shell has successfully conducted 3-D seismic surveys over swampy terrain. Similar improvements in drilling technology have been beneficial. Wells can now be drilled in less than half the time it took in the fifties and sixties. Also, with Shell blazing the trail, horizontal drilling is now possible in Nigeria. This involves the use of top drive drilling and flexible drill pipes. Drilling through deep, high temperature overpressured shale into deeper reservoirs is now also feasible. Chevron has embarked upon secondary oil recovery from fields where the reservoir pressure is too low to lift crude oil to the surface. Secondary recovery is through the injection of water into the reservoirs. In Delta South and Meren fields where the natural pressures have declined, Chevron conducted successful secondary recovery. The Delta South Water Injection facility raised the level of recoverable oil reserves by 51.8%.

A major boost in crude oil production was the coming on stream of Mobil's Oso Condensate Project. Discovered in 1967 by the then Mobil Exploration Nigeria Inc., the predecessor of Mobil Producing Nigeria Unlimited, the Oso field holds a gigantic reserve of 500 million barrels of recoverable condensate. The Oso field is located in the NNPC/Mobil Joint Venture Oil Mining Lease No. 70, some 35 km offshore of Akwa lbom State in the eastern delta. Joint venture finance agreement to develop the Oso field was concluded in April 1991, after long and complex negotiations and detailed investigation.

Conservation of the associated gas that was produced from Mobil's fields was an important feature of the Oso project. About 100 km of a gas gathering pipeline system collected associated gas from Mobil's Edop, Etim, Inim, Ubit and Utue production platforms to the Oso Gas Compression platform. Here, the low-pressure associated gas is compressed and re-injected into the Oso reservoir, thereby minimising gas flaring. The Edop field is of the largest offshore platform in Nigeria, producing 165,000 barrels a day, with a daily production target of 250,000 barrels.

In spite of its enormous crude oil reserves and substantial production by world standard, in 1992, Nigeria spent about 216 million pounds sterling importing heavy crude from Venezuela, at the rate of 50,000 barrels per day. Heavy crude is needed in the Kaduna refinery where it is used as base oil for production of lubricants and greases. Harnessing Nigeria's heavy crude from some Niger Delta oilfields and especially from the Tar Sand deposit in Ondo State (with 31 billion barrels of heavy crude), Nigeria will go a long way to provide the needed feedstocks for the Kaduna Refining and Petrochemicals Company.

Natural Gas

Gas utilisation has remained the top-most priority of Nigeria's petroleum and energy policies over the years. This is because, with a proven reserve of 180 trillion cubic feet of natural gas, Nigeria's gas reserve is triple the nation's crude oil resources. Hitherto, associated gas encountered during the normal course of oil production has been largely flared. Nigeria is reputed to be the largest gas-flaring country in the world. By not fully harnessing its gas resources, Nigeria loses an estimated 18.2 million US dollars daily.

On its part, the Nigerian Ministry of Petroleum Resources / Ministry of Energy, in addition to imposing penalties which were intended to end gas flaring by 1994, has offered incentives to potential investors who are interested in gas exploration. Since the 1980s, there has been increasing utilisation of gas in Nigeria, for power generation, industrial heating, fertiliser and petrochemical manufacturing and as feedstock for direct steel reduction. But the largest gas users now are the Liquefied Natural Gas (LNG) Project and the Aluminium Smelting Industry.

Established in 1992, the Nigerian Liquefied Natural Gas Company commenced execution of the project in 1993. The shipment of gas from the Bonny Plant to overseas buyers in Europe commenced in late 1999. The Nigerian Gas Company, the gas marketing subsidiary of the NNPC, signed a 10 billion Naira gas sale agreement with Shell, involving the later marketing gas from its Utorogu gas plant. To augment Government's gas commercialisation efforts, Chevron embarked upon the Escravos Gas Utilisation project in which it would process about 160 billion standard cubic feet (MSCF) of gas daily from the company's Mefa and Okan fields. The project entailed the installation of gas gathering and extraction facilities at the Escravos terminal. About 130 billion standard cubic feet of dry gas residue would be available daily from this project to the Nigerian Gas Company for commercial and domestic use.

Liquefied Petroleum Gas was expected to be produced from the four local refineries, which have a total refining capacity of about 200,000 tonnes yearly. Transportation is, however, a major handicap in LPG marketing. As part of gas conversion, the Nigerian Agip Oil Company has constructed two gas recycling plants at the Obiafu/Obrikom and Kwale/Opai oil fields. At Obiafu/Obrikom, there are gas re-injection wells capable of injecting 200,160 billion standard cubic feet per day, while Kwale/Okpai can handle 73 billion standard cubic feet per day.

Apart from the above projects aimed at ending the flaring of associated gas in Nigeria, the Federal Government also offered incentives to investors in natural gas development under the Associated Gas Framework Agreement (AGFA). The establishment of the Oil and Gas Export Free Zone at Onne was also meant to enhance operations in the industry.

Petroleum Legislation and Policy Evolution

Nigeria's petroleum legislation evolved piecemeal through what can be classified as the colonial, post-colonial, and post boom phases. Prominent among the colonial legislations were the Mineral Oils Act No. 17 of 1914; the Mineral Oils Act No. 17 of 1925; the Mineral Oils Act (Amendment) Ordinance 1959; and the Petroleum Profits Tax Ordinance 1959. Not only did these laws cede Nigeria's mineral rights to the British crown; they also reserved exploration and production rights to only British companies which for the mere payment of token rental due and royalties, acquired proprietary rights over all mineral deposits in the country.

Upon attaining sovereignty in 1960, ten petroleum-related laws were enacted within the first decade of independence. The most significant of these laws was the Petroleum Decree of 1969 (Decree No. 51). This was the nation's first comprehensive petroleum legislation, which covered among other things the definition of petroleum, land surface rights, rents, and compensation.

Apart from reducing the duration of an oil mining lease from the previous 30–40 years to 20 years, the 1969 decree was still, to a large extent, a bonanza to foreign operators. But after entering into membership of OPEC in 1971 and having established its own national petroleum corporation (the Nigerian National Oil Company) in 1972, Nigeria began to establish joint venture participation, production sharing and risk service interests with the oil companies. Between 1973 and 1974, the NNOC, which was later changed to the Nigerian National Petroleum Corporation (NNPC) in 1977, negotiated participation in all the major companies, thus acquiring large percentages in the operations of these companies.

The crash of oil prices in the world market in 1986, to below 10 dollars per barrel, rendered further exploration totally unprofitable to the foreign operators. The need, therefore, arose to offer them a new package of generous fiscal incentives to maintain the momentum in this strategic sector of the economy. This package is the Memorandum of Understanding which guaranteed to the oil companies a notional margin of 2.30–2.50 U.S dollars per barrel and a royalty of 2 US dollars per barrel. Oil companies that operated under the various agreements include Shell, ExxonMobil, Chevron, Elf, Nigeria Agip, Texaco Overseas, Express Petroleum/Conoco, Addax, Atlas, Amni International, Consolidated Oil, Pan-Ocean, Nigeria Petroleum Development Company, and Dubri Oil.

As an oil-exporting Third World nation, Nigeria's economic development has witnessed trials and tribulations, as the nation's fortunes have risen and fallen in the stormy seas of the international oil market. Nigeria's vulnerability to oil price shocks stems from the nation's over dependence on crude oil export. This is amply evident from the drastic decline in non-oil exports over the past three decades of petroleum production in Nigeria.

Crude oil accounted for 7.1% of total exports in 1961, which was dominated at that time by cocoa, groundnut and rubber, in that order. In 1965, oil had climbed to 13.5% of the nation's export earnings, and by 1970, it had become the leading source of foreign exchange, accounting for 63.9%. The 1973 Arab oil embargo against the United States of America earned for Nigeria the windfall revenue of an oil boom.

By 1979, petroleum sales had completely overshadowed non-oil exports, as it then contributed about 95% of the country's export earnings and has remained so uptil date. During the peak of the oil boom, Nigeria's premium crude, the Bonny Light (37° API), fetched the commanding price of 40 dollars a barrel.

But by 1982, as a result of sustained recession in the western industrialised nations, stringent conservation and substitution measures, as well as increased crude production of non-OPEC countries, there was a glut in the international oil market. Consequently, the official price of the Bonny Light tumbled through 35 dollars a barrel in 1982 to 29.5 dollar per barrel in 1983 and then dipped below 10 dollars a barrel. Down too went the Nigerian economy, crashing along with petroleum prices. In spite of efforts to revamp the economy through the Structural Adjustment Programme, an economic package that included comprehensive non-oil export diversification initiatives, petroleum still held onto the level of 95% of the nation's external earnings.

In 1990, following the Gulf War and the United Nations trade embargo on Iraq and Kuwait, not only did the Organisation of Petroleum Exporting Countries (OPEC) re-allocate the production shares of both nations to other producers such as Nigeria, there was also a sharp momentary increase in crude oil prices. From the low spot price of 15.49 dollars in June 1990, the average spot price of the Bonny Light soared to 36.78 dollars a barrel in August 1990. In 1993, the spot price of the Bonny Light, on the average, was about 18 US dollars per barrel. As a result of expansions in the economies of China, India, and some other Asian countries, war in Iraq, apprehensions in Iran (over its nuclear programmes), restiveness in the Niger Delta region of Nigeria, average crude oil price in the international market as at June 2008 stood at 135 dollars.

So strategic is the petroleum sector to the Nigerian economy that crucial aspects of this sector such as exploration, production, gas utilisation, conservation, and petroleum policy and legislation are sensitive economic issues. Also sensitive politically is the refined product pricing policy, especially subsidising energy prices.

The Federal Government's Policy goals for the upstream petroleum sector over the years, therefore, have been targeted at: Increaseing crude oil output; Increasing associated gas utilisation and consequently to end flaring; Encouraging greater foreign investment to finance E&P; Deregulation of petroleum products pricing; Encouraging indigenous participation through the marginal fields and local content policies and Restoration of peaceful and cordial relations with Niger Delta oil-producing communties.

Current Policy Thrusts and Reforms in the Oil and Gas Sector

In April 2000, the Federal Government of Nigeria inaugurated a Committee, the Oil and Gas Sector Reform and Implementation Committee (OGIC), to advise it in the formulation of a new policy for the oil and gas sector of the economy. Government noted that its national oil company, the NNPC, had grown over the years to assume multiple and often times conflicting roles, including those of policy formulation, regulation, commercial operations and national assets management. It was also observed that the NNPC as a corporation had over the years evolved into a huge cost centre without the required strategic commercial focus. The corporation had been slowed down from performing its role as an integrated, commercial oil and gas company, especially as sister national oil companies were effectively competing against international oil companies in all spheres of the industry. It was also noted that the legal and governance structures that were designed for the sector since the 1970s could no longer cater for the requirements of a contemporary Nigerian industry. All government institutions in the industry were ill-equipped to carry out their functions in the complex and sophisticated oil sector-industry. The most problematic, however, remains the NNPC. It has become simply a typical Nigerian parastatal that operates as huge amorphous cost centre with little or no sensitivity to the bottom line. The thrust of the new policy, therefore, was to revolve around the need to ensure separation and clarity of roles between the different public agencies operating in the industry. Equally important was the need to infuse strict commercial orientation.

The current structure of the industry is attached in the power point lay-out on the following pages. On the basis of government concerns and premised on the recommendations by the OGIC, government is in the process of unbundling the Nigerian National Petroleum Corporation and creating new agencies or strengthening some of its existing agencies as follows:

1. The National Petroleum Directorate (NPD) – May replace the Ministry of Petroleum Resources. Shall be the Secretariat of the Minister of Petroleum or Energy and shall be responsible for policy formulation in the sector.
2. The National Oil Company (NOC) – May take up any other name and shall replace the NNPC but shall be wholy capitalized to operate on strict commercial orientation.
3. The Petroleum Inspectorate Commision (PIC) – This will be an upgraded DPR (Department of Petroleum Resources) which shall be responsible for monitoring and regulation of operators in the industry.
4. The Petroleum Products Distribution Agency (PPDA) – Shall concentrate on downstream operations, distribution and marketing on purely commercial basis.
5. The National Oil and Gas Asset Holding Company (NOAHC) – Shall replace the current NAPIMS (National Petroleum Investments Management Services) and shall continue the management and supervision of government interests in the joint ventures and production sharing agreements.
6. A National Petroleum Research Centre (NPRC) – Shall be established to handle and domesticate high-tech research and development and innovations derivables in the sector.

It is important to stress here that the establishment of the proposed National Petroleum Research Centre that will enable the nation to derive maximun economic benefits from the oil and gas sector is long overdue. Nigeria experiences huge economic lost as a result of poor R&D culture in the industry (on the Nigerian side). Nigeria is currently the world's 8th largest producer of petroleum. Petroleum accounts for more than 90% of Nigeria's foreign exchange earnings; yet it has national research centres for everything but not for petroleum. R&D is the engine room on which every other business plan is based.

Upstream operations uptil now have been largely dominated by multinationals E&P companies (Shell, Chevron, Mobil, Elf, Agip, etc) and to a large extent have been liberalized and partly commercialized. The state (Nigeria) participates only through Joint Venture operations (JVs), Production Sharing Contracts (PSCs), Sole Risk Agreements (SRAs), rent collections and direct exploration by the NNPC through the NPDC (Nigerian Petroleum Development Company).

It is general knowledge that the Government never got its returns on investments on any of the JVs correctly because its company has never been the operator and the computations of taxes and accruable profits have been made so complex in some algebraic formulae that are understood only by a few persons in the industry. All the oils produced in Nigeria since 1958 have been produced by the multinational companies. NNPC has participated through JVs but it was never an active partner there. NNPC on its own has never been able to produce any significant amount of oil.

The exploration arm of our national oil company, NPDC in Benin (which should have been the core of NNPC) has been swinging in production level of between 5,000 to 7,000 barrels of oil per day compared to Shell's average of 500,000 bbpd and least of 100,000 bbpd by any of the other multinationals. NNPC is not able to produce at home, even in the prolific Niger Delta, so it can seemingly not make any in – road into the international arena in the near future unless it embraces strong R&D policies.

In all, there is a big gap in research and development (R&D) on the Nigerian side in its quest to optimally exploit the petroleum resources of the nation for economic growth and social transformation. PDVSA of Venezuela has an engine room comprising 34 internationally renowned professors and industry experts (as at 2006), which acts as the strategic intelligent unit for its business decision. Information and data obtained from series of simulations, modeling, regional and acreage studies are normally passed over to its national oil and gas policy formulation agency and regulatory commission.

Shell has a very large R&D Centre in Rieswijk, the Netherlands. Chevron has an indomitable R&D Centre in San Ramon, USA. Ditto Mobil in Dallas, Total in Pau and Agip in Italy. Ironically, NNPC's R&D Centre is a shadow of itself in Port Harcourt.

To strategically place the NOC to be a successful exploration and production company in Nigeria and for it to make foray into other countries like other national oil companies such as Petrobras (Brazil), Petronas (Malaysia), PDVSA (Venezuela), Statoil (Norway), Saudi Aramco (Saudi Arabia) are doing, its R&D must be re-invigorated. This is normally a business decision but to cover for overall national interest, a National Petroleum Research Centre (NPRC) if established should work closely with the National Petroleum Directorate and the Petroleum Inspectorate Commision to assist these agencies in policy formulation and regulation of the industry. Some case studies as given below are suffice to support the establishment of a National Petroleum Research Centre.

Case Study 1: Sometime ago (around 1993), a block was won by Famfa Oil Company, an indigenous oil and gas exploration company. Famfa eventually sold off the block to then Texaco (later incorporated into Chevron) at a give away price. Texaco discovered that the block was very rich in oil (what the DPR did not know at the time it traded it off to Famfa). Texaco went ahead to discover the giant field of *Agbami* within the block. Later, NNPC (Government) wanted to buy in as a JV partner, what was not in the original agreement. A lot of controversies ensued and later resolved in some ways not very clear to industry watchers. A background simulation on the block through a strong research component would have assisted Government to derive value from the block during the bidding round process and avoided the unnecessary controversies that eventually trailed the operation of Agbami.

Case Study 2: There was the case of the sale of a block (OPL 245) to Malabu Oil who later invited Shell to act as its technical adviser. On the discovery by Shell that OPL 245 held vast amount of oil in reserve it eventually took over the block through some back-door arrangements. Series of legal tussles followed between Malabu Oil, the Government and Shell and it is still not clear how it ended and whether the case is now out of court. Who didn't know that OPL 245 was very prolific? Except DPR!!. Uptil now, has government gotten the economic value for OPL 245, even at the price offered by Shell? The Research Centre should have been able to advise DPR (Government) approriately of the potentials of OPL 245 prior to the bidding round processes and many regional and specific acreage studies that would have been carried out by the Research Centre would have given a rough estimate of the value of OPL 245. Just like Shell did and refused to revert back to Malabu Oil.

Case Study 3: NNPC went into the Chad Basin on the Nigerian side and found nothing. Shell (through SNEPCO) went to the Upper Benue Trough, a trough structurally, geologically and geographically similar to the Chad Basin, and discovered some 33 billion standard cubic feet of gas and a little oil under a team led then by Dr. Edmund Daukoru (then Shell's Exploration Manager and until recently, Nigeria's Energy Minister). Dr. Daukoru once told the author about how oils in horst and graben structures as in the Benue Trough and the Chad Basin could be very elusive compared to the easy-to-find oils in roll-over anticlines and growth-fault structures in the Niger Delta and that it would take a lot of technology know-how and intense R&D to discover such oils as in the Chad Basin and Benue Trough. Uptil today the Kolmani-River-1 discovery in the Gongola Basin of the Upper Benue Trough has remained the only moderate find in Nigeria's inland basins and that was by Shell.

All the above enumerated problems could easily have been overcome through studies on the regional sand migration patterns over time using available well log data as well as the bomarker evaluation of the regional migration pathways across the acreages by the Department of Petroleum Resources. In this way, it is easy to estimate the prolificity of most of the acreages under consideration before the bidding-round process. Rigorous and sustained innovative research and development is an inevitable catalyst to improving performance and deriving maximum economic benefits from our national oil and gas sector business.

In the following attachments in power point lay out, the current structure of the industry is summarized (Fig. 12.1) and a brief introduction on the socio-political economy of the nation's oil and gas resources has been attempted in explanatory notes 5–8.

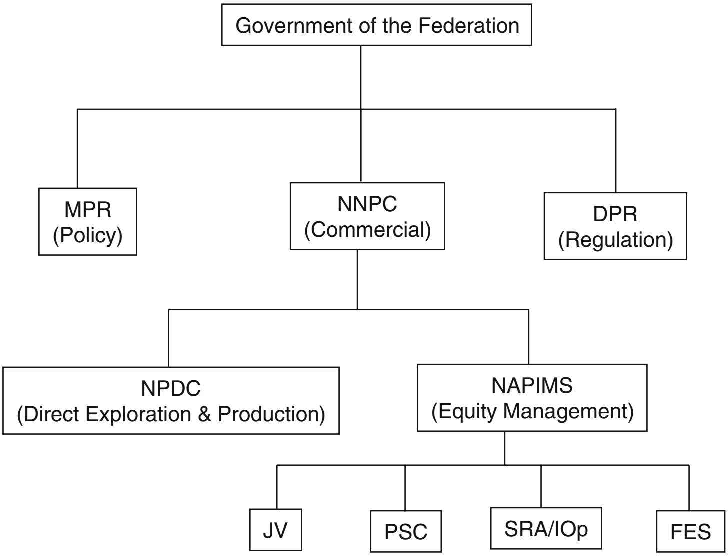


Fig. 12.1 Organizational structure of the oil and gas sector in Nigeria. Please note that the boxes are not necessarily departments but operational structures. FES = Frontier Exploration Services. The diagram is also not a presentation of the NNPC organogram

Explanatory Note 5:
Petroleum

NIGERIA: World No. 6 exporter

Current Reserves:

- 35 billion barrels - oil
- 180 trillion standard cubic feet - gas

Current Production:

- Entirely from the Niger Delta:
  - onshore
  - shallow offshore
  - deep offshore
  - ultra-deep offshore

Explanatory Note 6: Inland Basins Exploration

Nigerian Sector of the Chad Basin

: 23 wells drilled by the Nigerian National Petroleum Corporation (NNPC)

: 2 wells (Kanadi-1 and Wadi-1) contain sub-commercial gas

Benue Trough

: 3 wells drilled (one each) by Shell, Chevron, Elf

:only Kolmani River-1 encountered 33 billion standard cubic feet of gas

: other two wells (Nasara-1 and Kuzari-1) were dry

Recent studies have indicated that the inland basins of Nigeria constitute a stretch of gas shores with possibilities of some oils derivable from deep-seated lacustrine source rocks and coaly materials.

1. Petroleum, like all other mineral resources in Nigeria, belongs to the Government of the Federation; comprising the Federal Government, the Federating States (36 in number + the Federal Capital Territory), the Local Governments (774 in numbers) and the Producing Communities.

2. The Government of the Federation manages and participates in the Upstream and Downstream sectors of the petroleum industry through:
   a) Its national oil company – The NNPC – Commercial
   b) The Ministry of Petroleum Resources - Policy
   c) The Department of Petroleum Resources (DPR) – Regulation and Monitoring.

3. Major Roles of NNPC:
   a) Direct Exploration through the Nigerian Petroleum Development Company (NPDC).
   b) Joint Venture Operations and Equity Management through the National Petroleum Investments Management Services (NAPIMS) in the forms of:

   bi) Joint Ventures (JVs) – 60% NNPC (Nigerian Government), 40% Joint Venture Partners (Currently Shell, Mobil, Total, Chevron, Agip). Joint Venture Partners uptil now have been the Operators. Cost of operations and profits are shared according to equity interest.

   bii) Production Sharing Contracts (PSCs) – The company funds the operations until oil is found. Produced oil and profits are shared according to agreed formula.

   biii) Sole Risk Agreements / Indigenous Operators (SRA/IOp) – Usually a Nigerian owned company – The company will fund the operations and produce the oil and will pay for royalties and petroleum profit tax.

Explanatory Note 7: Petroleum Resources

1. All monies accruing from the sale and other commercial activities of petroleum in Nigeria are paid into the Consolidated Revenue Account or the Federation Account

2. Such monies are shared on monthly basis between the Federal Government, the State Governments and the Local Governments on determined ratios (usually determined by the Revenue Mobilization, Allocation and Fiscal Commission (RMAFC)

3. Presently 13% of the revenue derived from the receipt of oil produced from any State of the Federation is paid to that State. Currently there are nine (9) States enjoying such derivation revenue, namely: Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo, Rivers.

4. Nonetheless, there is still some restiveness in the Niger Delta with some groups asking for an increase in the amount of derivation and some asking for outright resource control.

5. Whichever way, all tiers of government should work toward finding a lasting solution. This may not necessarily need increase in derivation but allowing some equity stake-holdings by the State and Local Governments as well as some indigenes of the locality where the petroleum is won and where the operating company is located. These stake-holdings should be built in the joint operating agreement to be operated by the core private sector investor (Shell, Mobil, Chevron, Total, etc).

Explanatory Note 8: The political economy of oil in Nigeria

1. Oil accounts for 95% of the national foreign exchange earnings and about 80% of the GDP.

2. Current daily production stands at about 2.5 mbpd x current price of averagely $100 = $250 million.

3. There are 140 million people in Nigeria (as at 2008).

4. Poverty line is drawn to include all those living on less than $1 a day.

5. For Nigeria, all things being equal, every citizen can only earn $1.80 per day during good oil prices.

6. Deducting the monies needed to run governments and bureaucracies, Nigerians are still by all standards very poor.

Solution: Divest from oil and invest more in solid minerals, agriculture and technology development.

But Is Nigeria actually a rich country?

About the Author

Nuhu Obaje is currently Professor of Geology at the Nasarawa State University, Keffi, Nigeria. He was formerly the Dean of the Faculty of Natural and Applied Sciences and the Head of the Department of Geology and Mining (Jan. 2004–April 2008). He is a member of the Governing Council of the institution.

Professor Obaje was selected by the Alfried Krupp Foundation in 2007 as one of five Senior Research Scientists selected on a world-wide competition for scientists who have made significant contributions to scientific research in their specialized fields to spend time at the Alfried Krupp Institute for Advanced Studies in Greifswald, Germany to complete a selected major research work.

Professor Obaje was born on the 15th December 1961 at Ajaka in Igalamela Local Government Area of Kogi State (Nigeria). He attended Barewa College Zaria in the period from 1974 to 1979 and obtained the West African School Certificate (WASC/GCE) in Division One in June 1979. He later graduated B.Sc. (2nd Class Upper Division) and M.Sc. Geology from the Ahmadu Bello University, Zaria in 1984 and 1987 respectively; and the Ph.D. Geology from the University of Tuebingen (Germany) in 1994.

Professor Obaje was later awarded the Royal Society of London postdoctoral fellowship in petroleum geochemistry at the University of Aberdeen, Scotland in 1997; the German Academic Exchange Service (re-invitation) postdoctoral fellowship in biostratigraphy at the University of Tuebingen in 1998; and the Alexander von Humboldt research fellowship in organic geochemistry and organic petrology at the Federal Institute for Geosciences and Natural Resources in Hanover/Germany in 2002–2003. (for one year) and 2005–2006 (for 3 months). Professor Obaje also held research tenures in the Exploration Departments of Chevron Nigeria Limited, Lagos (1997–1998) and the Shell Petroleum Development Company of Nigeria Limited in Portharcourt (2000–2001). He has served as a Lecturer at the Ahmadu Bello

University, Zaria (1985–1997) and was Associate Professor at the Tafawa Balewa University Bauchi up to December 2003. He also served as an Assistant Director and Special Assistant to then Executive Chairman and former Head of Service (Alhaji Adamu Fika) at the Federal Character Commission of the Presidency in Abuja briefly between 1999 and 2000, before leaving for Shell.

Nuhu was a recipient of the American Association of Petroleum Geologists' Grants-in-Aid (maximum cash awardable) for parts of his Ph.D. research on the petroleum geology of the Benue Trough and was two times first prize award winner for the best papers presented at the 28th and 33rd annual conferences of the Nigerian Mining and Geosciences Society (NMGS) in 1993 and 2000 respectively (which respectively entailed a one week visit to Elf Petroleum laboratories in Pau, France). His biography is cited in the 19th edition of Marquis Who's Who in the World of 2002. He was also nominated by the American Biographical Institute as Man of the Year for 2004.

Professor Obaje was a member of the Nigerian government Presidential Committee on Oil and Gas Sector Policy Reform for the National Council on Privatization (2000–2008). He has been a resource person on several occasions to the Geological Survey of Nigeria Agency on the review of different segments of the geological map of Nigeria. He is also a member of the Steering Committee and Assessor of the Petroleum Technology Development Fund (PTDF) Annual Research Grants Competition programme and resource person in the Peer Review of the PTDF Professorial Chair Endowment programme. He has served as assessor for professorial appointments in several Nigerian universities including ABU-Zaria, University of Ado-Ekiti, FUT-Minna and University of Jos. He has been a longstanding reviewer for scientific papers in the Journal of Mining and Geology, Global Journal of Geological Sciences, Petroleum Training Journal, African Journal of Microbiology Research, etc; and has himself published over 50 articles in reputable international journals. He has served and still serving as external examiner to many Nigerian universities for undergraduate and postgraduate examinations in the geosciences. Widely traveled and cosmopolitan, Nuhu has visited Algeria, Belgium, Benin Republic, France, Germany, Italy, Niger Republic, Qatar, Switzerland, The Netherlands, Tunisia, United Kingdom, and the United States of America.

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