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GEOLOGIC ASSESSMENT OF THE FOSSIL ENERGY AND GEOTHERMAL POTENTIAL OF THE SUDAN

By Loren W. Setlow
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GEOLOGIC ASSESSMENT OF THE FOSSIL ENERGY AND GEOTHERMAL POTENTIAL OF THE SUDAN

By

Loren W. Setlow[1]

INTRODUCTION

This preliminary report provides geological input to the consideration of appropriate activities that can enhance the exploration and development of fossil-fuel and possible geothermal energy resources of the Sudan, and is based on study of available literature in early 1982. The project has been supported under Resources Support Services Agreement (RSSA) No. Int/USGS 1-80 by the Agency for International Development as part of its prospective technical assistance to the Sudan in the exploration and development of conventional energy resources.

The Democratic Republic of the Sudan has an area of 2,505,813 km^2 and is the largest country in Africa. It is bordered by eight countries plus the Red Sea; its location in northeastern Africa is shown on figure 1. The physical climate of Sudan is so varied that land type ranges from sandswept desert in the north to swamps and tropical rain forest in the south. Major features of its topography include: the Nile River Valley which drains north from Uganda and runs the length of Sudan and Egypt; the large erosion scarp that borders the Red Sea; the great peneplains and basins of the north and interior of Sudan; the highlands adjacent to Kenya, Uganda, and Zaire; the foothills of the volcanic plateau of Ethiopia; the volcanic highlands of Jebel Marra and Meidob; and the isolated

1/ Now with U.S. Minerals Management Service, U.S. Department of the Interior.

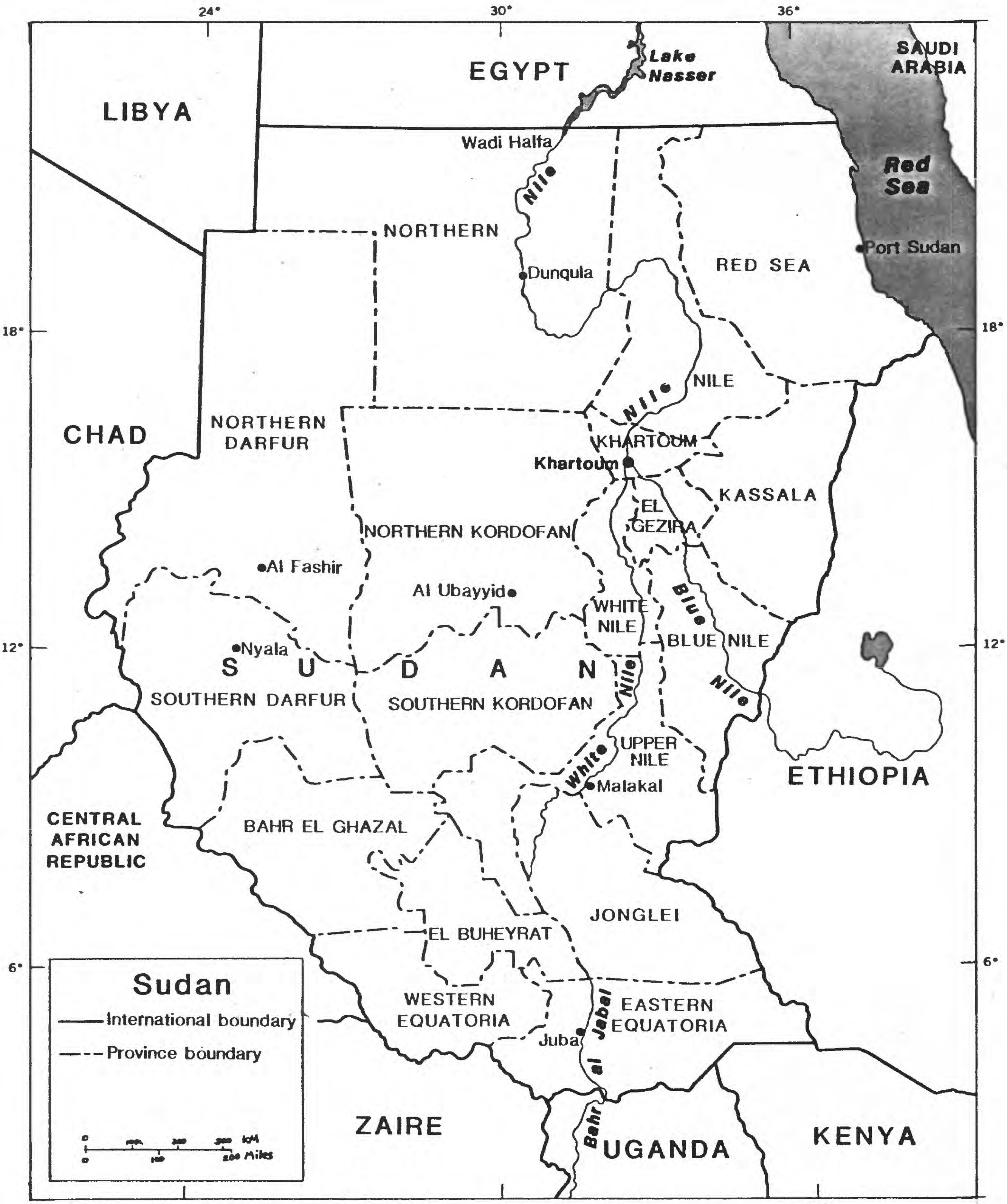


Figure 1. Index map of Sudan.

inselbergs scattered throughout the country (Whiteman, 1971) (fig. 2). The Sudan has a population of 18.8 million people, 1.3 million living in the capital city of Khartoum (Caputo, 1982).

PRESENT ENERGY SITUATION

Sudan, which at present produces no domestic oil or gas, imported 1.1 million metric tons of oil in 1980 in the form of both crude and refined petroleum products. Oil constitutes 27.5 percent of the total energy used in the country; the remainder is derived from domestic firewood, charcoal, and hydropower sources (U.S. Department of State, 1980). Sudan spends 80 percent of all its hard currency earned from exports for high-priced imported oil, thus draining much of the country's capacity to pay for ambitious internal development programs and upgrading of its railroads, ports, and facilities for power generation and telecommunications facilities (Caputo, 1982).

Recent discoveries of oil in Sudan by Chevron Oil Company could make the country self-sufficient by the mid 1980's. Chevron, the Sudanese General Petroleum Corporation, and possibly the World Bank's International Finance Corporation will be building a new pipeline to handle production from the Unity and Talih fields, which would deliver crude oil to a Red Sea port (Anonymous, 1982). Possibilities do exist for finding and utilizing a variety of other energy minerals such as coal, peat, uranium, and geothermal fluids which would further enhance Sudan's economic condition.

In Sudan the Ministry of Energy and Mining coordinates energy minerals exploration and production matters. Within that Ministry, the Geological Survey Administration issues permits and licenses for exploration and production and acquires geological and geophysical data from its own and

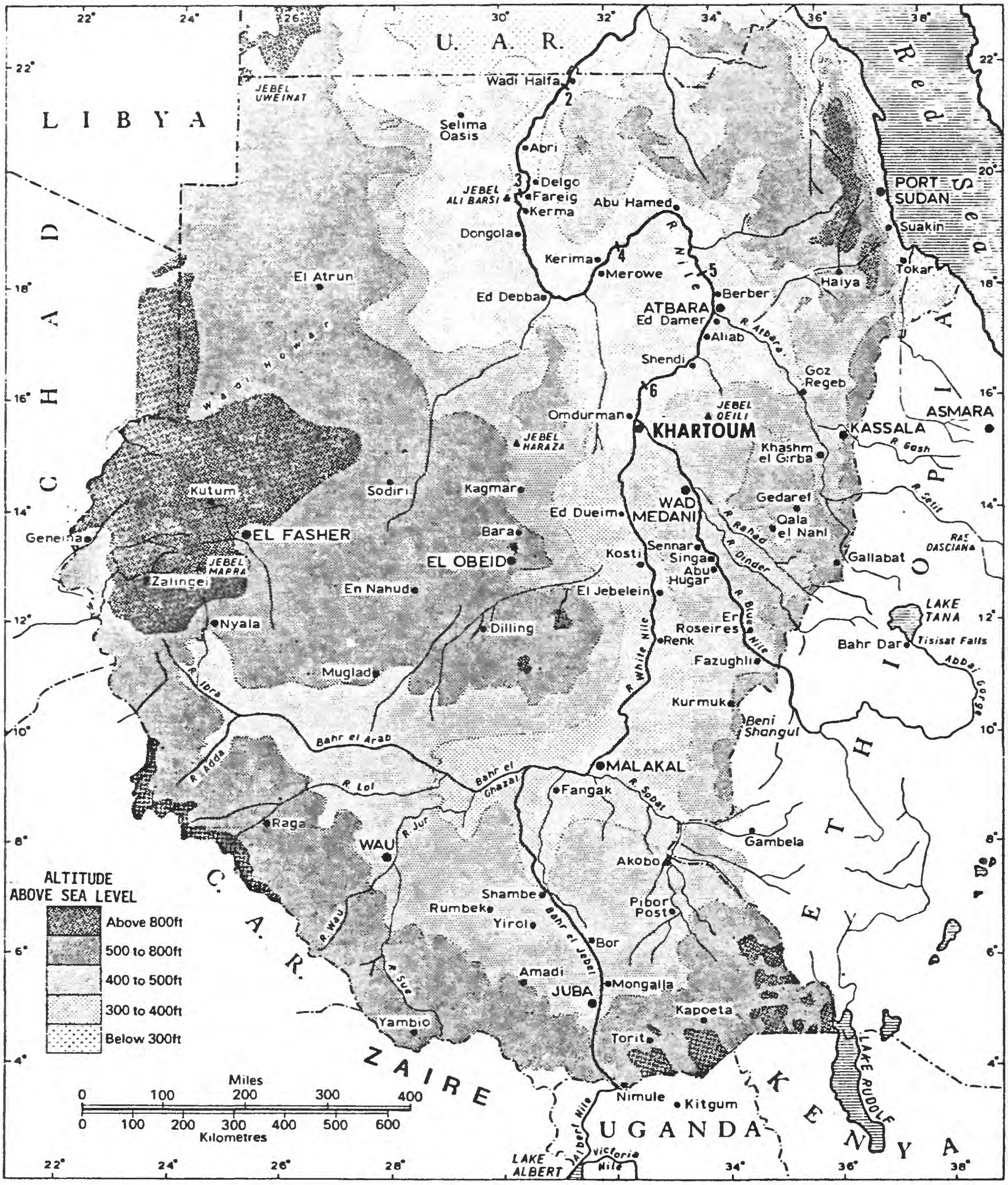


Figure 2. Relief map of Sudan. (From Whiteman, 1971).

data and industry's efforts. The Ministry's National Energy Administration is patterned after the U.S. Department of Energy; it has responsibilities for establishing Sudan's energy policy, though it is still in an early information-gathering mode and is receiving start-up planning assistance from the U.S. Agency for International Development (S. Hale, Jr., Energy/ Development International, Washington, D.C., oral commun., 1982). Under the "Petroleum Resources Act" and the "Mines and Quarries Act," both of 1972, a very encouraging climate for minerals exploration by foreign companies exists in Sudan; however, the Government of Sudan's General Petroleum Corporation or Public Mining Corporation (also of the Ministry of Energy and Mining) may buy into as much as 50 percent of a foreign company's Sudanese subsidiary when mineral production is expected (Sudan Geological and Mineral Resources Department, 1974). Owing to the nature of this overall policy, data on energy mineral exploration results are mostly unavailable to the public.

REGIONAL GEOLOGY

Precambrian

Approximately one half of Sudan is covered by Precambrian igneous and metamorphic rocks (figs. 3 and 4). The geology in much of the "Basement Complex" is still not well understood. Kroner (1977) believed that the oldest part of the Basement Complex, which he called the West Nile Complex, extended from northern Uganda into Sudan and the Central African Republic. He considered this to be a mobile belt of rocks of mixed sedimentary and volcanic origin, now consisting of predominantly gneiss, mica schist, quartzite, and amphibolite, that were deposited on a granite floor approximately 3 billion years ago. Also of similar age may be the foliated

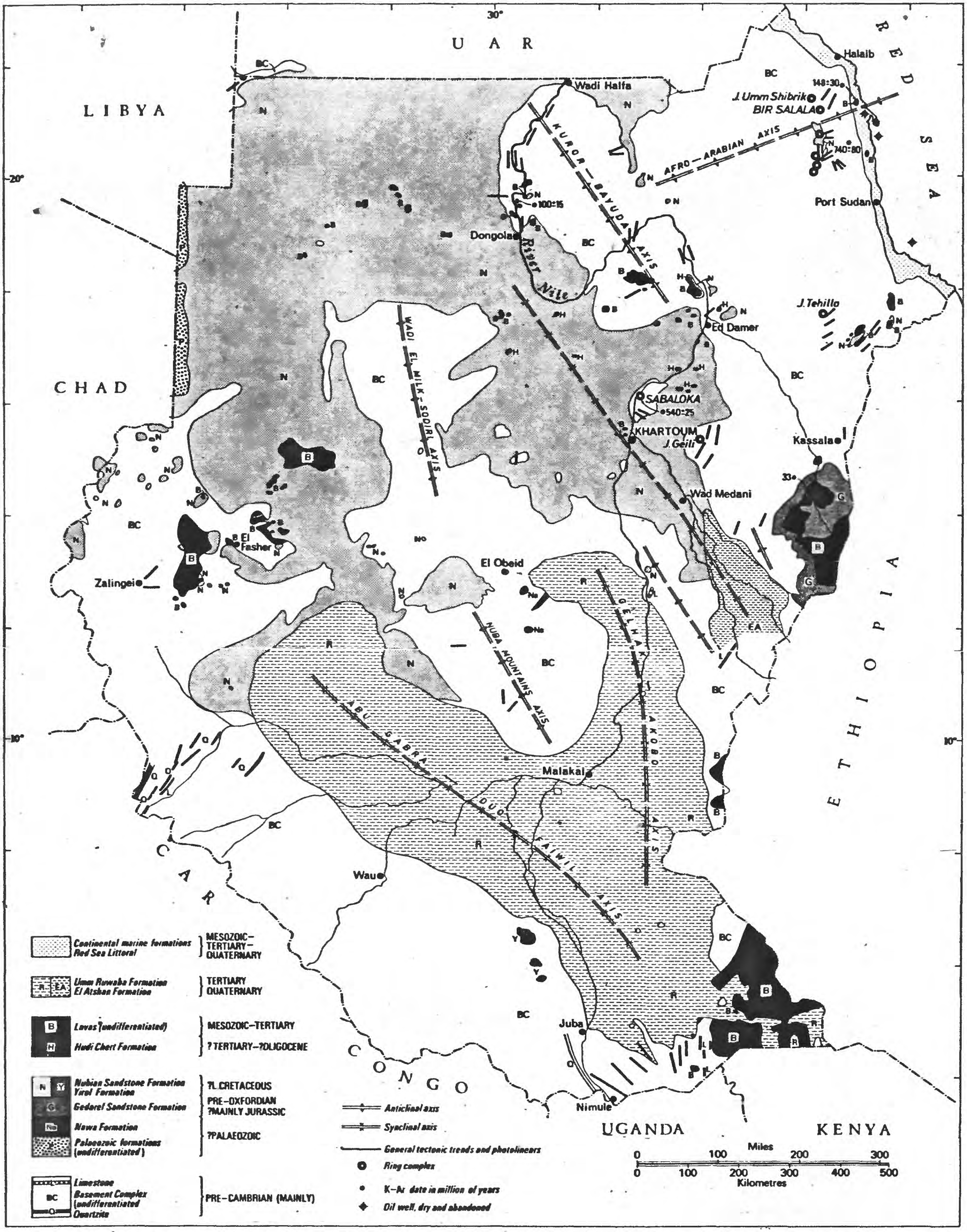


Figure 3. Generalized geologic map of Sudan. (Modified from Whitman, 1971)

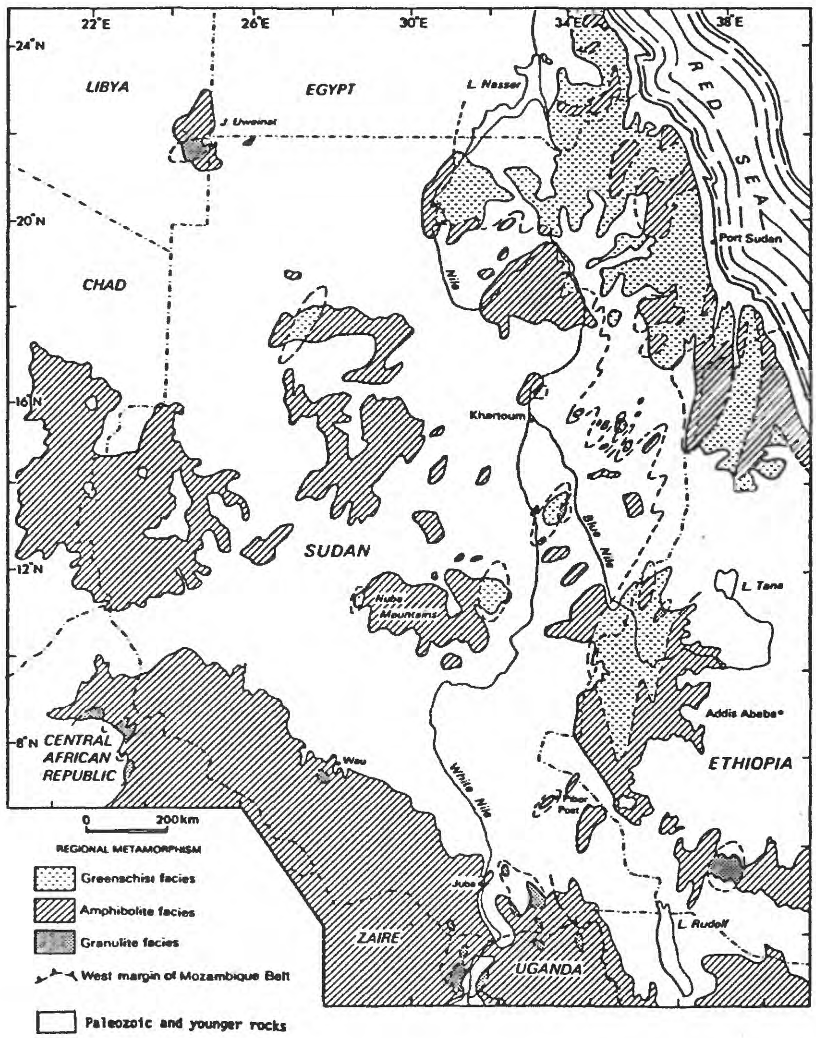


Figure 4. Distribution of Basement Complex rocks, and their metamorphic facies in Sudan. (From Vail 1978).

gneisses and schists, and granitic batholiths of North Kardofan, Darfur, and the Northern Province which adjoin the basement rocks of Chad (see figs. 1 and 3). These rocks were reheated and reworked during the Eburnian tectogenesis of approximately 2 billion years ago and ultimately formed part of a large continental shield area (Sutton and Watson, 1974) in the Proterozoic. S. M. El-Raba' (1978) characterized the Precambrian rocks described above in Sudan as the West/Equatoria unit, and he referred to the Basement Complex metasediments of amphibolite facies present west of the Nile (the Nuba Mountains, the Dar Hamid area of Kardofan Province, and isolated areas in the Northern Province) as the Central Sudan/Nile unit. The Central Sudan/Nile unit and the less metamorphosed volcanics of the greenschist facies of the Red Sea Hills unit probably were derived from an intraocean island-arc complex during the latest Precambrian (Engel, Dixon, and Stern, 1980). The emplacement of these rocks occurred about the same time as the Pan African orogeny. During that period most of the Basement Complex underwent metamorphism, and a variety of igneous rocks (ring complexes, granites, gabbros, volcanics) were emplaced from 650 to 400 million years ago (Vail, 1978).

The structural trends of the major foliation and bedding plane directions of the Basement Complex are shown in figure 5.

Paleozoic formations

As the tectonic events which formed the Basement Complex drew to a close in the late Precambrian and the early Cambrian, a period of widespread erosion took place across northeastern Africa. Sandstone, shale, conglomerate, and some marl of Paleozoic age were deposited

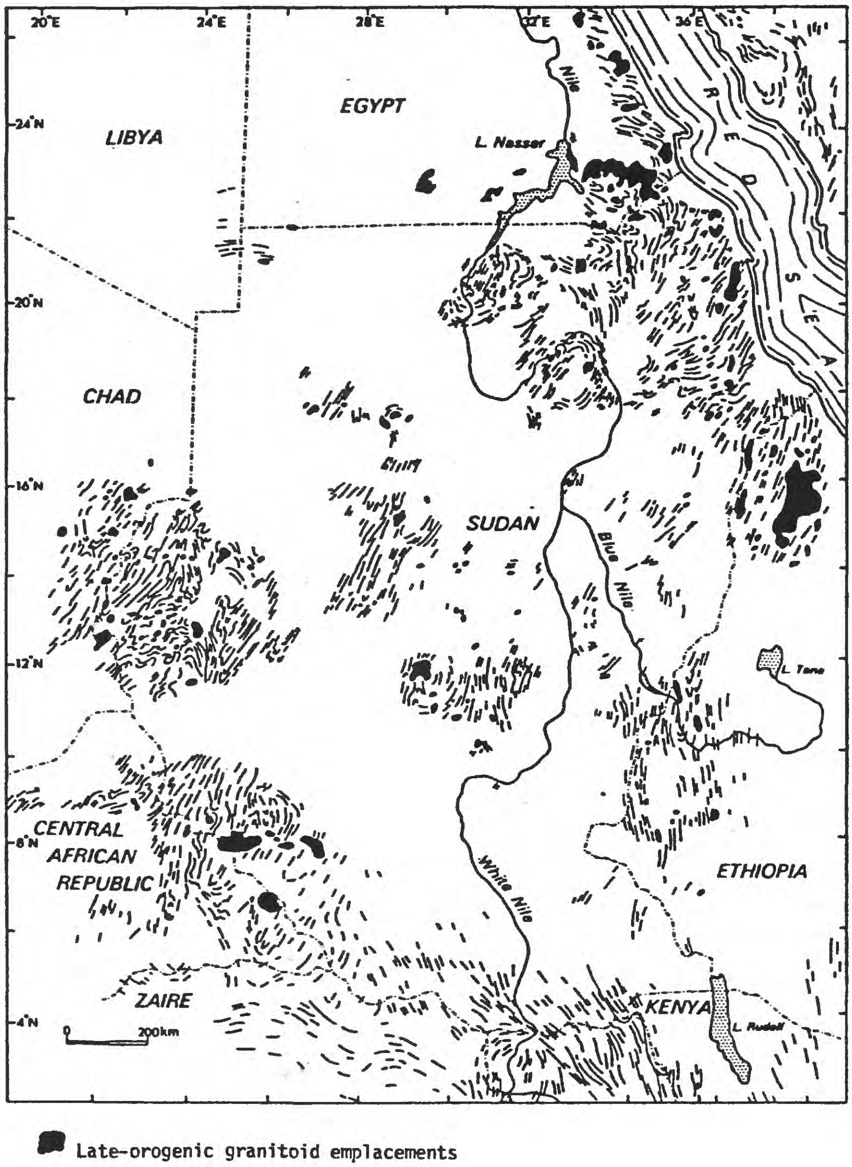


Figure 5. Tectonic trends of Basement Complex rocks of Sudan. (From Vail, 1978).

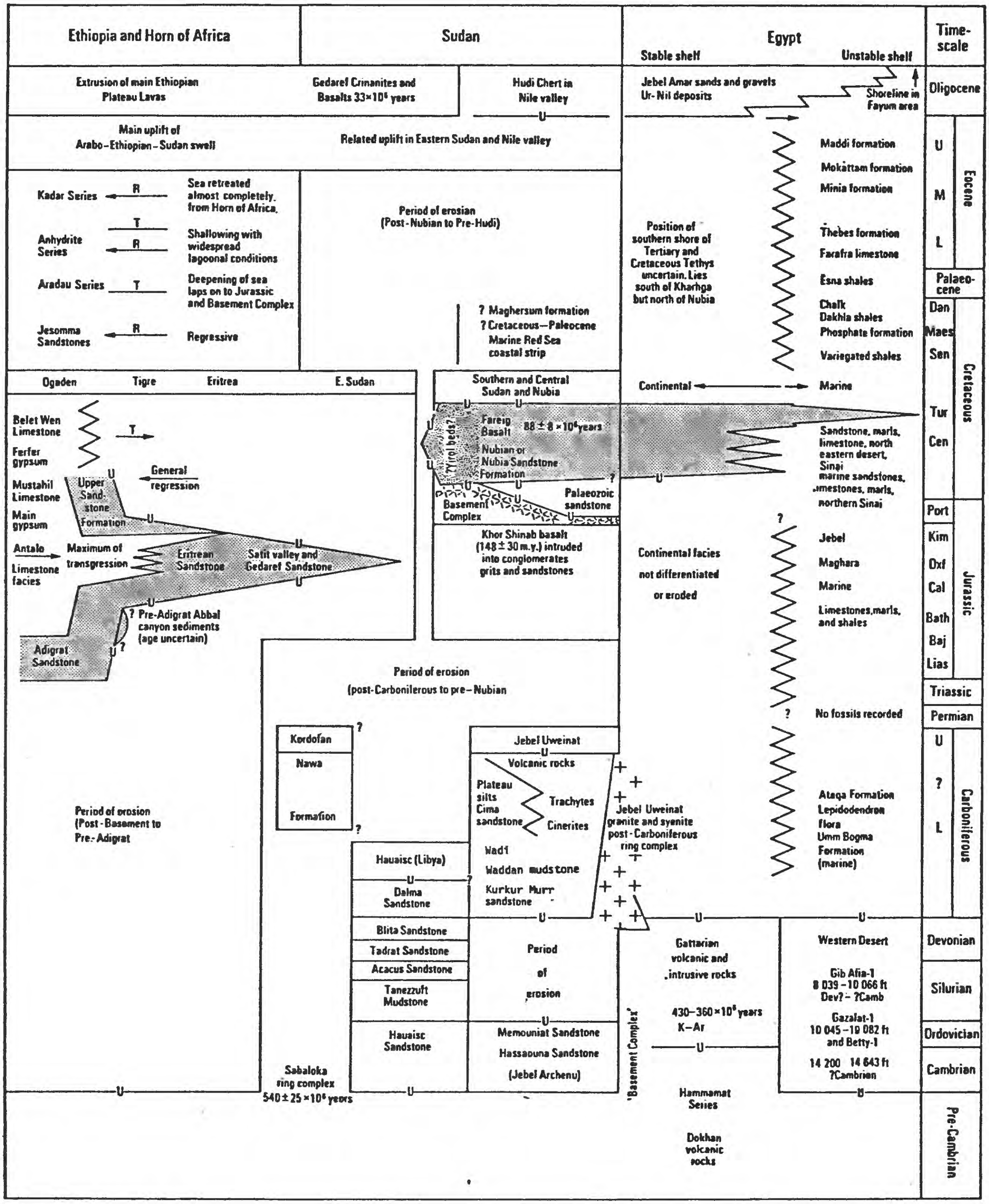
on a peneplained surface. These rocks crop out in the border area of Sudan, Chad, Libya, and Egypt but the magnitude of their extent into the subsurface of central Sudan is not known. On the basis of fossils and lithology these strata have been identified as Cambrian, Orodovician, Devonian, and Carboniferous sequences. One other formation of indeterminate Paleozoic age is found in wells and boreholes of Kardofan Province in Central Sudan. A correlation chart for Paleozoic and Mesozoic formations in Ethiopia, Sudan, and Egypt is shown in table 1.

In Sudan and Chad, Paleozoic sedimentary rocks occur in the Erdi and Ennedi regions (see fig. 3). Sandford (1935, p. 336) gave the following rock descriptions:

Age	Unit No.	Description
MESOZOIC	8	Buff sandstones (Nubian Series)
	7	Variegated white and purple shales and mudstones (Nubian series)
UPPER PALEOZOIC	6	Grey limestones
	5	Soft light grey sandstones
	4	Black sandstones with ripple marks
	3	White sandstones
	2	Hard black shales
LOWER PALEOZOIC SANDSTONES	1	Massive sandstones of the southern side of Murdi, Guroguro, Ennedi, and central Erdi showing fantastic weathering

More detailed studies have been made on the outcrops of Paleozoic rocks in southeastern Libya which continue around Jebel Uweinat into the subsurface of Sudan. According to Whiteman (1971) and Vail (1978) the Hassaouna Formation consists of a basal conglomerate overlain by 100

Table 1. Correlation chart for the Paleozoic and Mesozoic in Ethiopia, the Sudan, and Egypt. (Modified from Whiteman, 1971).



m of sandstone containing Tiggilites and then by an upper 100 m of coarse-grained and conglomeratic sandstone. The Memouniat Formation of late Ordovician age rests unconformably on the Hassaouna. The Memouniat consists of 150 m of fine- to medium-grained sandstone and coarse conglomerate. Burollet (1963) believed these formations were lifted on the flanks of Jebel Archenu in Libya by the post-Carboniferous igneous intrusion of the Uweinat area.

Burollet (1963), Goudarzi (1970), and Said (1962) describe the rest of the Paleozoic succession in the Jebel Uweinat area as including 160 m of Upper Devonian and Lower Carboniferous alternating sandstone, siltstone, and conglomerate beds of the Kurkur Murr Formation unconformably overlying the Memouniat Formation. Above the Kurkur Murr is the Wadi Waddan Shale, consisting of approximately 300 m of fine-grained sandstone, siltstone, and shale, and then approximately 400 m of the Cima Sandstone--a massive quartz sandstone. Both formations are also of early Carboniferous (Mississippian) age.

Burollet recognized the presence of the Plateau Siltstones (as much as 60 m of black silt and mudstone) overlying the Cima Sandstones in the Uweinat area, though Vail did not. Carboniferous rocks (undifferentiated) are shown to crop out in both the Uweinat and Ennedi areas on Vail's Geologic Map of Sudan.

These Paleozoic sediments were most likely deposited by shallow transgressive seas of the Kufra basin, but it is uncertain how far the sea extended into Sudan, as the formations are hidden by extensive exposures of Nubian Sandstone of Mesozoic age.

Boreholes and shallow wells at localities near Nawa village in Kardofan Province have penetrated a maximum of 285 m of purple and green mudstone containing mica, thin limestone beds, and veins of aragonite (Strojexport, 1972). These sediments have been named the Nawa Formation (Andrew, 1945); based on field relationships and the lack of fossils, the rocks have been assigned a Paleozoic-Mesozoic age (Whiteman, 1971). Vail (1978) believed the Nawa to be of local derivation because of the presence of mostly unweathered micas and feldspar, probably eroded from the adjacent Nuba Mountains; the Nawa is preserved by local faulting.

Mesozoic formations

The Mesozoic in Sudan (see fig. 3 and table 1) is represented in surface outcrop by the Nubian Sandstone and its correlatives of Late Cretaceous age. However, the greatest thickness of Mesozoic sediments was deposited in south-central Sudan where as much as several thousand meters of the Yirol Formation (and Nubian Sandstone ?) may be present in the subsurface. Vertical crustal movements and block faulting took place in north Africa during the early middle Cretaceous, followed by major marine transgressions and regressions of the Tethys Sea in the region (Dewey et al, 1973) as shown by carbonate beds deposited in Saudi Arabia, Iraq, and Iran.

Nubian Sandstone

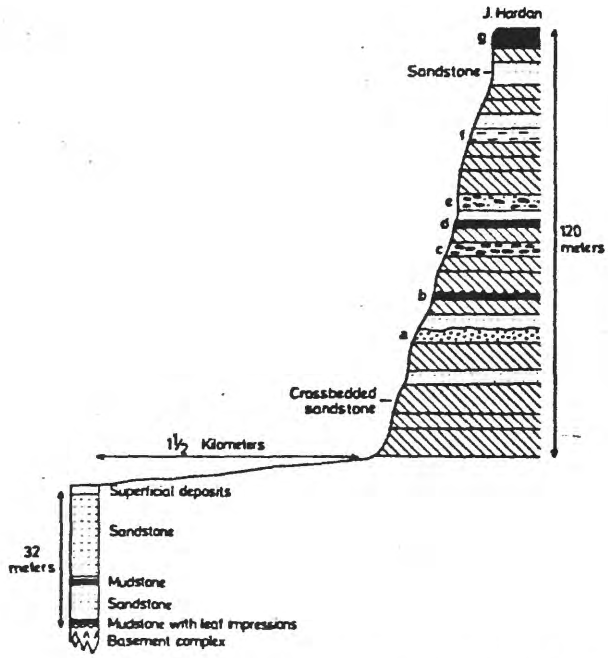
Many articles have been written about the Nubian Sandstone, which crops out extensively in Chad, Egypt, Libya, and Sudan. Owing to paucity of fossil evidence, its origin, whether aeolian, deltaic, estuarine, or marine is controversial.

The Nubian Sandstone was first described in Egypt where it was observed to contain more than 600 m of brown, unfossiliferous sandstone (Whiteman, 1971). In Sudan the Nubian is comprised of predominantly arenaceous and rudaceous beds, and includes some layers of siltstone, mudstone, lignite, limestone, and ironstone. A basal conglomerate unconformably overlies the Basement Complex in many locations and is, in turn, overlain by typically medium grained brown or creamcolored sandstone beds, (and interspersed pebble conglomerates and mudstones higher in the section (Vail, 1978). Figure 6 shows a typical section of the Nubian Sandstone from Jebel Hardan, which is north of Khartoum. Shadul (1980) has postulated that it actually consists of two formations (a Lower Basal Conglomerate and Upper Sandstone).

Most of the fossils collected in Sudan from this formation are plants of the genus Dadoxylon. Other plants, a petrified forest (30 km north of Khartoum), coal beds, and marine gastropods have also been found (Shadul, 1980). Many of the beds have ripple marks, slumps, current bedding, and other features that indicate a depositional orientation of southeast to north, and it is quite likely that the formation was deposited by braided river systems in deltas or flood plains (Vail, 1978).

Yirol Formation

The Yirol Formation crops out at two localities near the village of Yirol in Bahr El Ghazel Province of southern Sudan. It is equated in age to the Nubian Sandstone and consists of semi-consolidated to consolidated sandstone interbedded with shale and conglomerate. The sandstone has



Typical section (not to scale) at Jebel Hardan of Nubian Sandstone Formation composed of thick crossbedded and massive sandstones intercalated with (g) ferruginous sandstone capping hill (5 m), (f) sandy mudstone (2.5 m), (e) intraformational conglomerate (3 m), (d) ferruginous sandstone band (0.5 m), (c) silicified conglomeratic bed (1 m), (b) ferruginous sandstone band with dark conchoidal iron concretions at top (0.5 m), (a) very coarse pebbly sandstone (4 m), and mudstones in a hand-dug well south of hill.

Figure 6. Typical section of Nubian Sandstone from Sudan. (From Medani, 1975).

well-sorted, rounded to subrounded quartz grains held together by siliceous, ferruginous, and/or a clay cement; the shale beds are micaceous and contain some quartz pebbles (Shazly, et al., 1978).

Shazley et al, (1978, p. 28) state that:

> This formation, associated probably with older sediments, underlies Umm Rawaba Formation in some of the deep troughs within the basins of Jonglei Canal Project area. In these troughs Yirol Formation rests unconformably either over the basement or some older sediments.
>
> Yirol Formation was encountered in some deep boreholes at depths ranging from a few meters to 370 m below the groundsurface. In boreholes (of the Jonglei Canal Project)... some 40 m thick of Yirol successions consisting of sandstones with low clayey content, ironstone concretions and mudstone were encountered.
>
> The presence of Yirol Formation was also inferred from the geophysical survey carried out by Strojexport, and it has been interpreted as relatively thick beds with a high resistivity, of more than 20 ohms, underlying the low resistivity successions of Umm Rawaba Formation in the environs of Malakal and southwards. The thickness of these beds has been estimated to be several 100 m. The results of the seismic survey carried out by Chevron Oil Co. south of Malakal included the estimation of the thickness of the sedimentary cover, lying unconformably over the weathered surface of the basement to be in the range of several 1000 m.

The Yirol, Nubian (?) and overlying sediments of the Umm Rawaba Formation fill the Sudan Continental Basin in southern Sudan which was created by Alpine and older tectonic events. The basin is located between the Ethiopian Plateau and the Basement Complex bordering Kenya, Uganda, and Zaire, and is bifurcated by the Nuba Mountains to form a Y and two troughs. Figure 3 shows the left fork of the basin to have been deposited along the Abu Gabra-Duq Faiwil axis and the right fork along the Gelhak-Akobo axis. Chevron's recent oil discoveries are most likely in either the Yirol Formation or Nubian Sandstone where wells have extended as deep as 4,635 m before penetrating into basement. No environment-of-deposition information or complete description of the Yirol formation is presently available.

Gedaref Formation

The Gedaref Formation was described by Whiteman (1971) as the sediments outcropping near Gedaref in Kassala Province and also along the Ethiopian border with Sudan. It is comprised of conglomerate, sandstone, sandy mudstone, and mudstone. Its greatest thickness is 200 m in borehole locations around Gedaref and its sediments resemble those of the Nubian Sandstone, though Whiteman (1971) correlated it with Jurassic rocks in Ethiopia. This hypothesis has not been proven, according to Vail (1978).

Other Mesozoic formations

Other Mesozoic rocks probably are present in the subsurface of Sudan, but until recent deep drilling information is released, their extent will not be known. In the Central African Republic sandstones of Cretaceous (?) age are found within 40 km of Sudan. As well, Upper Cretaceous marine shale beds are located just north of the Sudan border in Egypt near Lake Nasser.

Tertiary formations

Tertiary deposits west of the Red Sea Hills in Sudan consist solely of the lacustrine rocks of the Hudi Chert Formation and various igneous rocks. These igneous rocks were intruded as a result of uplifting of the Red Sea Hills at the end of the Cretaceous and beginning of the Tertiary; a discussion of all igneous intrusive rocks in Sudan is included in a later section of this report.

The separation of the African and Arabian continental plates during the Oligocene by a process of normal faulting along an arm of the Indian Ocean Rift created the Red Sea Graben (Widatalla and Suleiman, 1972; Styles and Hall, 1980). Faults in the Red Sea are aligned in a NNW-SSE direction, and offset by fractures oriented WSW-ENE, E-W, and N-S. Marine sediments have been deposited along the Sudanese coastal plain and in the Red Sea, where as much as 3300 meters of sediments of Tertiary and Quaternary age may be present. Some finds of natural gas have been made in the Tertiary formations of the Red Sea; this is discussed in the section on Energy Resource Identification. A correlation chart of Tertiary formations of Sudan is shown in table 2.

The Hudi Chert, of uncertain age within the Tertiary (Vail, 1978), is found in a variety of locations in Sudan's Northern Province. All the localities are in the Nile Valley and its associated dry water courses (wadis). The type locality is in a wadi near Hudi Station east of Atbara. The Hudi is typically fossiliferous chert boulders, pebbles, and gravel layers that are commonly yellow brown, pitted, contain gastropod casts and shells, and are hard and may be brecciated (Whiteman, 1971). Thickness of the deposits range from 1.5 to 15 meters.

Whiteman (1971) felt that eruptions of the Bayuda volcanoes and associated hot springs northeast of Atbara provided silica to nearby lakes. The silica which was the form of gels then converted to chalcedony and quartz. When the lakes subsequently evaporated, erosion weathered the chert deposits to create the boulder, pebble, and gravel-field outcrops of the Hudi Chert.

Table 2. Correlation chart of Tertiary formations in Sudan. (From Whiteman, 1971).

Nile Valley	Areas east and west of Nile	Red Sea Littoral			Regional tectonic history: Nile Valley etc	Regional tectonic history: Red Sea area	Time-scale
Integration of Nile drainage		Older terrace gravels Khor Eit		Abu Shagara Formation? Quaternary fauna			Pleistocene
Umm Ruwaba Formation and El Atshan Formation	Formation of Jebel Marra, Melit, Meidob, Nakhara, and Bayuda volcanic rocks. Laterite formation age uncertain (Oligocene—Miocene?)	Pleistocene beds Khor Eit?			Subsidence in the Umm Ruwaba and El Atshan depressions	Subsidence in mid-Pliocene Red Sea connected with Indian Ocean Central trough formed	Pliocene
		Dunganab Formation (post-mid-Miocene unfossiliferous)	A member B member	Salt, anhydrite interbedded 658 metres Gypsum interbedded with clays 54 metres		Miocene lagoon extends south from Suez	Miocene: U
Lacustrine and riverain clays and sands, with fossil fish, pigs' teeth etc. Proto-Nile deposits derived from Ethiopian volcanic plateau and East African and Nile Congo divide		Abu Imama formation (mid-Miocene—Tortonian)	A member B member C member	Reef limestone 62 metres Calcarenite 25 metres Conglomerates of igneous rocks and sandstone 50 metres	Tertiary volcanic rocks formed at scattered localities in Sudan	Marine transgression	?
Initiation of proto-Blue Nile, Atbara, Rahad, Dinder, Sobat drainage consequent on formation of Ethiopian plateau		Maghersum Formation (A= mid-Miocene—Helvetian)	*A member (rich fauna) B member (few fossils) C member	Marls, sandstone, conglomerates with gypsum veins 111 metres Gypsum anhydrite with sandstones and shales 859 metres Rock salt anhydrite and marls 465 metres	Downwarping and downfaulting along eastern margin of Ethiopian plateau?	*Globigerina* marl transgression in Suez region and to south; lagoonal conditions poorly developed in Egypt	Middle
					Climax of Rift Phase 2: separation and formation of Red Sea central trough, separation approx. 80 km		?
Hudi Chert with Oligocene molluscan fauna deposits, in an extensive lake in proto-Nile valley	Gedaref erosion surface intrusion of Gedaref crinanites and basalts, 33×10⁶ years K—Ar	Hamamit Formation (?Lower Miocene to? Eocene)		Sandstones, quartzitic conglomeratic; sandstones are badly sorted; contains basaltic lava flow at type-locality 226 metres	Extrusion of main Ethiopian plateau lavas from fissures and vents		L (Miocene) Oligocene
					Main uplift of of Arabo-Ethiopian—Sudan swell and formation of Phase 1: separation 130 - 170 km		Eocene: U, M, L
No deposits. Pre-Hudi and Gedaref basalt time predominantly a period of erosion. Marine conditions extended approximately as far south as Aswan and as far west as Aden and, Somalia Formation of Late Cretaceous—Early Tertiary Shendi and Togni surfaces		Mukowwar Formation (marine) 190 metres 190 metres uppermost Cretaceous or Palaeocene			Regression of sea. Volcanicity started as early as 69×10⁶ years ago, Abbai basalts		Paleocene ? Cretaceous

*[Maghersum A-member may well be Lower Miocene (Burdigalian) (Whiteman and Bell MS)]

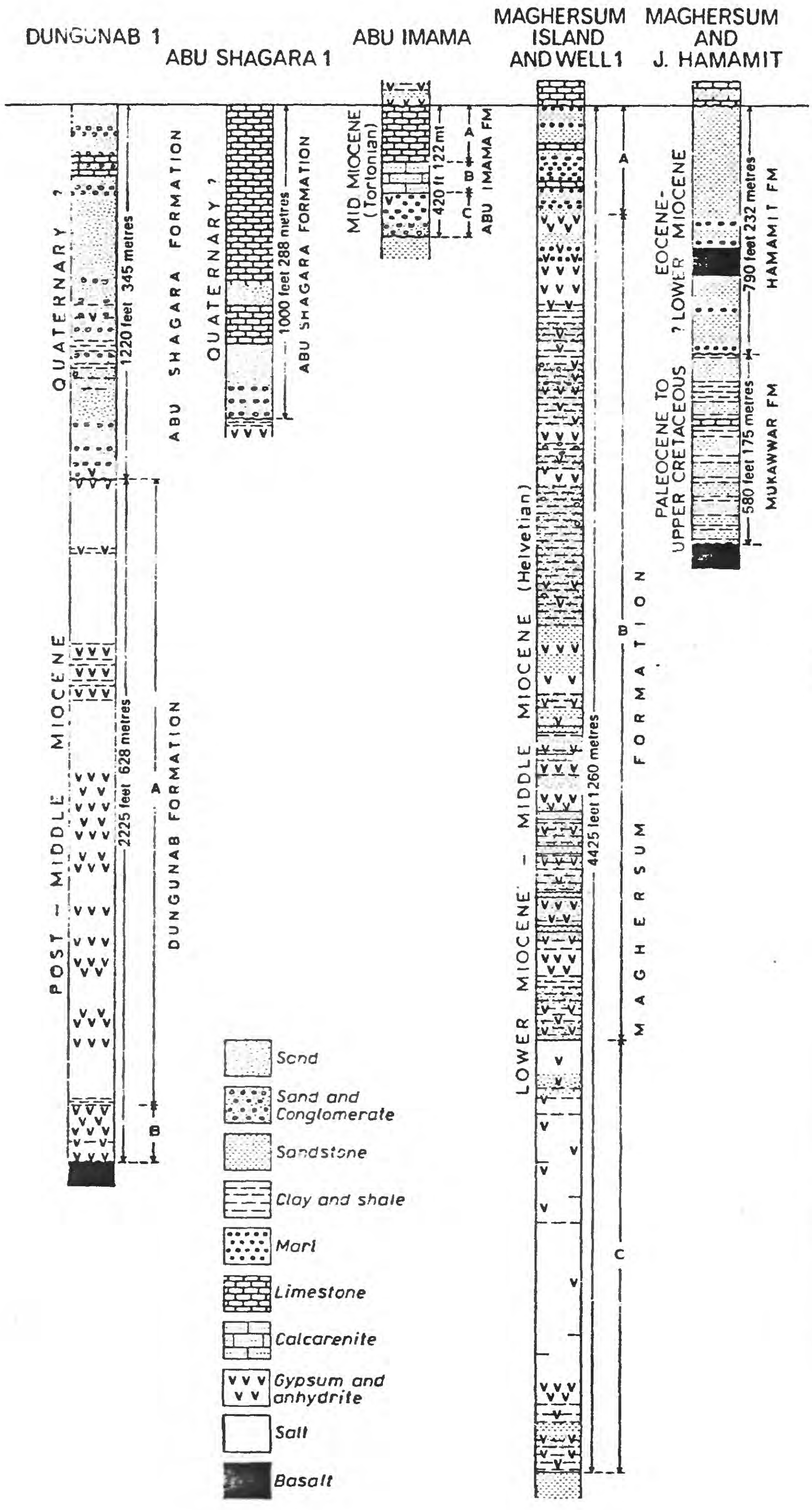


Figure 7. Lithologic sections from oil well tests in the Red Sea area. (From Whiteman, 1971).

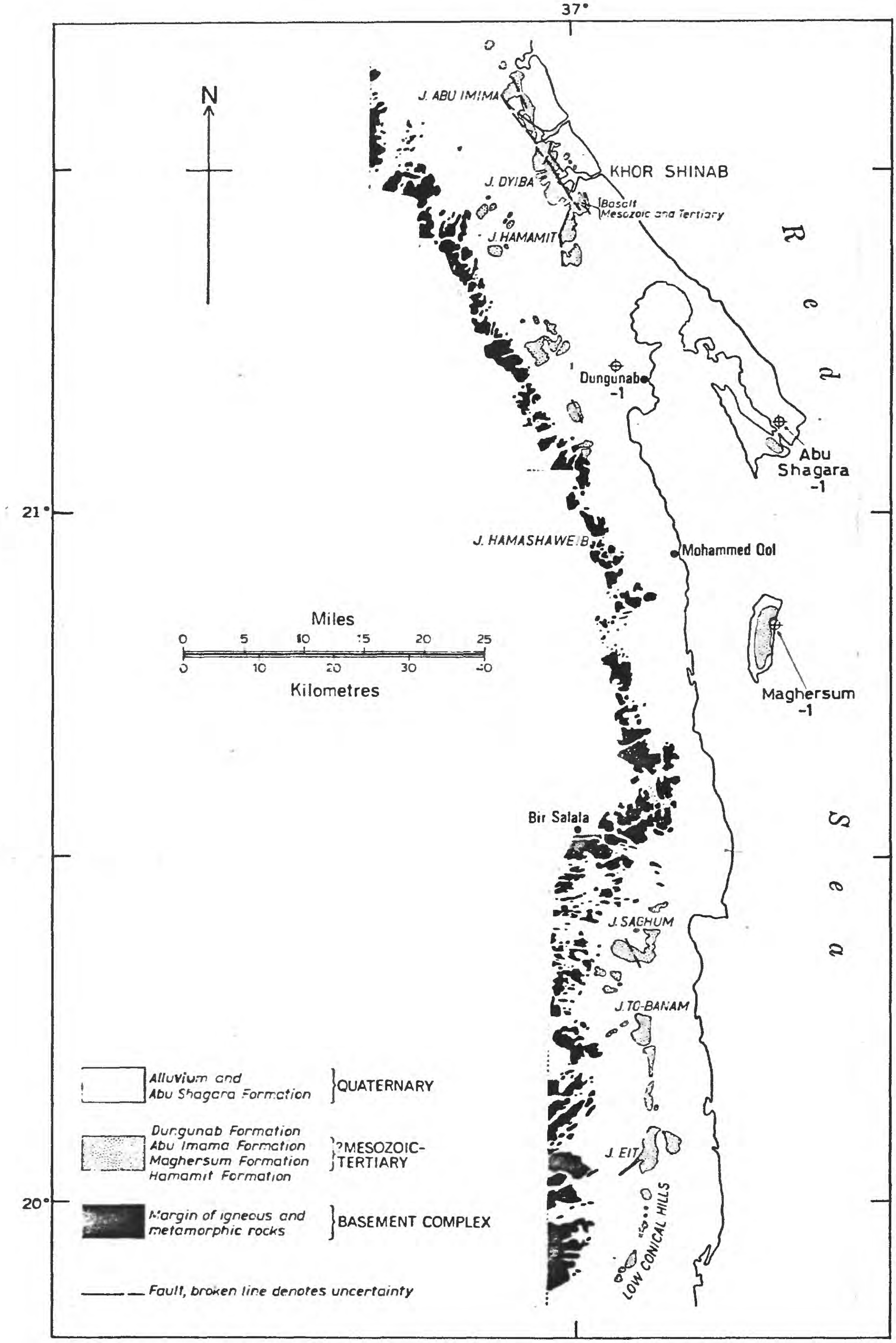


Figure 8. Outcrop of Mesozoic, Tertiary and Quaternary rocks in the Red Sea area. (From Whiteman, 1971).

Red Sea coastal deposits - Mukawwar Formation

The lowermost formation above basement rocks in the Red Sea area, the Mukawwar Formation, was first described by Carella and Scarpa (1962). This formation, found in the Maghersum-1 well on Mukawwar Island in the Red Sea, is comprised of 190 m of shale and sandstone with some marl and limestone. It lies unconformably on basaltic, tuffaceous breccia that in turn overlies basalts and Basement Complex porphryies. No age determination has been made for the basalt or breccia, but ostracod fossils place the Mukawwar in the uppermost Cretaceous transitional to Paleocene time. Depositional environment for the Mukawwar, deposited before the closure of the Tethys Sea and the opening of the Red Sea, is believed to have been brackish to shallow water marine. Lithologic sections from drill holes in the Red Sea area are shown on figure 7 and locations of Mesozoic, Tertiary, and Quaternary outcrops near the Red Sea coast are shown on figure 8.

Hamamit Formation

The Hamamit Formation of (?) Eocene to mid-Miocene (?) age crops out at Jebel Hamamit and Jebel Hokeb along Sudan's coastal plain and was penetrated in the Maghersum-1 well on Mukawwar Island (Carella and Scarpa, 1962). Coarse,and less commonly fine grained, sandstone beds of the Hamamit Formation are 226 m thick at the type locality of Jebel Hamamit. Interspersed in the sandstones are conglomerate and shale lenses, plus a basaltic lava flow 30 m thick at the type locality. The formation conformably overlies calcareous shales there, but unconformably overlies the Makawwar Formation in the Maghersum-1 well. Abu Imama conglomerates of Miocene age truncate the formation at Jebel Hamamit. No fossils have been found in the Hamamit; its age has been determined on the basis of stratigraphic relationships.

Maghersum Formation

Carella and Scarpa (1962) also initally described the Maghersum Formation of early to middle Miocene age. This formation crops out onshore in Sudan and is found in offshore wells. It is as much as 1435 m thick at Maghersum Island, but varies in thickness considerably--being only 66 m thick in the Dungunub-1 well onshore (fig. 8). The Maghersum has been subdivided by Carella and Scarpa (1962) into three members: the lowermost C member composed of as much as 465 m of massive salt beds, including some anhydrite and marly bands; the overlying B member containing as much as 859 m of gypsum and anhydrite interbedded with sandy shale and sandstone; and the uppermost A member consisting of as much as 111 m of marine marl, sandstone, conglomerate, limestone, and gypsum veins and nodules (fig. 7). On the basis of lithology and fossil content, the C and B members were probably deposited in an evaporite lagoonal basin of early Miocene time, whereas the A Member was most likely formed in a more open marine environment (Vail, 1978).

Abu Imama Formation

Like the Maghersum Formation, the Abu Imama Formation also crops out onshore (fig. 7) and is found in Red Sea wells. It reaches 137 m in thickness and has three members (Carella and Scarpa, 1962): the C member, which underlies the B and A members and unconformably overlies the Maghersum Formation, is 50 m thick at the type locality and consists of lenses of marly, sandy conglomerate; the B member contains 25 m of calcarenites and subordinate marly limestones; overlying that is the A member consisting of 62 m of reefal limestone that locally is dolomitized and cavernous. The Abu Imama Formation contains fossil corals, fish, echinoids, and Foraminifera of middle Miocene age (Vail, 1978), indicating a near-shore environment of deposition.

Dungunab Formation

The Dungunab-1 onshore well recorded more than 700 m of the Dungunab Formation which also crops out onshore at Dungunab and farther south toward Port Sudan. Carella and Scarpa (1962) divided the formation into two members, the B member composed of gypsum with interbedded clay and sandstone and the overlying A member, which is 658 m of massive rock salt interbedded with minor anhydrite layers. The formation is unconformably overlain by Quaternary Abu Shagara sands (Whiteman, 1971). On the basis of its stratigraphic position, the Dungunab is probably post-middle Miocene in age.

Quarternary formations

Abu Shagara Formation

Pleistocene and Holocene deposits of gravel, sand, boulders, and reefal limestone varying in extent, age, and thickness overlie Tertiary formations of the Red Sea coastal areas. Carella and Scarpa (1962) postulated a Pliocene age for the 300+ m of mostly unconsolidated sediments found in the Dungunab-1 and Abu Shagara-1 wells. However, fossil and radiocarbon evidence (Berry, Whiteman, and Bell, 1966) indicates a more likely Quaternary age. These sediments, plus fossil and Holocene coral reefs, modern deltas and marshes, and the outcropping

Table 3. Correlation chart of Quaternary deposits and events in Sudan. (From Whiteman, 1971).

Nile valley			Areas East and West of Nile valley		Red Sea Littoral	Age Whiteman MS 1965 *C date in years B.P. × U–Th date	
Nile silts, Wadi deposits and terraces			Desert deltas, reg, hamada, clay plains, dunes and sand sheets, wadi deposits; Jebel Marra, Melit Meidob, Nakharu, Bayuda volcanics	Ooz belt Post-Meroitic wet phase Dry phase As far S as 13°N —3000—	Present-day reefs and lagoonal deposits. Wadi deposits, and terraces 2m Bench raised reef 3·5-4m Bench raised reef	Recent or Holocene	?2100–2600? ?4600–6000?
Esh Shaneinab Neolithic site (av) main Nile				—±7000—			5253 ± 415*
Charcoal 13m above flood plain (afp) Sudanese Nubia				Modification of Ooz during wet phase soils leached	Flooding of Red Sea marsas		7300 ± 250*
Khor Umar gasteropod site main Nile, Khartoum area							7400 ± 120*
382m White Nile Lake deposits sample no.1139							8730 ± 350*
Cleopatra bulimoides 12m afp, Sudanese Nubia							9325 ± 250*
?Esh Shaheinab wavy line pottery, Qeili Station, and Khartoum Hospital sites (mesolithic)	—?—	—?—		Main phase of Ooz formation (phases based on Warren 1964 *a,b*)			
Aetheria elliptica 9-10m afp Nubia	Siltation phase (Sebilian) Nubia	Upper clay member 'Gezira clay' Gezira formations				Pleistocene – Late	11 200 ± 285*
382m White Nile lake deposits sample no 1211 386 White Nile lake?							11 300+400*
Corbicula ertini 15m afp, Nubia							11 600 ± 300*
20m afp, Nubia							14 950 ± 300* ?25 000
Period of deep scour Shambat B.H.Khartoum	—?—			—?— ?Early Ooz phases ?	Cutting of Red Sea marsas		29 000 ± 300*
Singa skull and vertibrates. ?Near base of Gezira clay Blue Nile							?38 27 000–
Khor Abu Anga, Lupemban? Gravels (Cole 1964), Khartoum		Mungata and Gezira member					—?— Lumpemban ?29 27 000–
Khor Abu Anga, Sangoan Gravels (Cole 1964) Khartoum							—30000— Sangoan
Khor Abu Anga, late Acheulian gravels Khartoum					(a) 3·5-4m bench (b) 7–8m Mohd. Qol stage (b) 11–12m Shinab stage (c) –16m Mukawwar stage raised reef Mukawwar early Monastirian 18m 60ft stage (Riss–Lrm int.)		—50 000— (a) 75-80 000 (b) 95 000 (c) 91 000 ± 5000×
50ft terrace Wadi Halla Acheulian imlements	—?— Umm Ruwaba and El Atshan formations						—?—
J.Nakharu, Early Acheulian gravels 100ft terrace, Wadi Halfa					Older Terrace Gravels Khor Eit / Abu Shagara formation		Middle
J.Nakharu, Chellian gravels							
J.Nakharu, Wawa, Nuri Pre-Chelles-Acheul pebble tools							Early
150ft river terrace and platform 200ft river terrace and platform 300 river terrace and platform Wadi Halfa-S.Egypt				—?—	—?— Pliocene beds Khor Eit (Berry and Sestini)	—?— Plio-Pleistocene	

Table 3. Correlation chart of Quaternary deposits and events in Sudan. (From Whiteman, 1971).

Nile valley				Areas East and West of Nile valley		Red Sea Littoral	Age Whiteman MS 1965 *C date in years B.P. × U-Th date	
Nile silts, Wadi deposits and terraces				Desert deltas, reg, hamada, clay plains, dunes and sand sheets, wadi deposits; Jebel Maira, Melit Meidob, Nakharu, Bayuda volcanics	Qoz belt Post-Meroitic wet phase Dry phase As far S as 13°N —3000—	Present-day reefs and lagoonal deposits, Wadi deposits, and terraces	Recent or Holocene	
Esh Shaneinab Neolithic site (av) main Nile					-	2m Bench raised reef 3.5-4m Bench raised reef		?2100–2600? ?4000–5000? 5253±415*
Charcoal 13m above flood plain (afp) Sudanese Nubia					—±7000— Modification	Flooding		7380±250*
Khor Umar gasteropod site main Nile, Khartoum area					of Qoz			7400±120*
382m White Nile Lake deposits sample no.1139					during wet phase	of		8730±350*
Cleopatra bulimoides 12m afp. Sudanese Nubia					soils leached			9325±250*
?Esh Shaheinab wavy line pottery, Qeili Station, and Khartoum Hospital sites (mesolithic)	—?—	—?—				Red		
Aetheria elliptica 9-10m afp Nubia	Siltation phase (Sebilian) Nubia	Upper clay member 'Gezira clay'	Gezira formations		Main phase of Qoz formation (phases based on Warren 1964 a, b)	Sea	Pleistocene: Late	11250±285*
382m White Nile lake deposits sample no 1211 336 White Nile lake?								11300±400*
Corbicula artini 15m afp. Nubia						marsas		11000±300*
20m afp. Nubia								14950±300* ?25000
Period of deep scour Shambat B.H Khartoum	—?—				—?—	Cutting		29000±300*
Singa skull and vertibrates. ?Near base of Gezira clay Blue Nile						of Red		?28 27000–
Khor Abu Anga, Lupemban? Gravels (Cole 1964), Khartoum		Mungata and Gezira member				Sea marsas		—?— Lupemban ?25 27000–
Khor Abu Anga, Sangoan Gravels (Cole 1964) Khartoum					?Early Qoz phases ?	(a) 3.5-4m bench		—28000— Sangoan
Khor Abu Anga, late Acheulian gravels Khartoum						(b) 7-8m Mohd. Qol stage (b) 11-12m Shinab stage (c) ~16m Mukawwar stage		—37000— (a) 75-80 000 (b) 95 000 (c) 91 000±5000 ×
50ft terrace Wadi Halfa Acheulian implements	—?—					raised reef Mukawwar early Monastirian 18m 60ft stage (Riss–Würm int.)		—?—
J.Nakharu, Early Acheulian gravels 100ft terrace, Wadi Halfa	Umm Ruwaba and El Atshan formations					Older Terrace Gravels Khor Eit ≷ Abu Shagara formation	Middle	
J.Nakharu, Chellian gravels								
J.Nakharu, Wawa, Nuri Pre-Chelles-Acheul pebble tools							Early	
150ft river terrace and platform 200ft river terrace and platform 300 river terrace and platform Wadi Halfa-S Egypt					—?—	—?— Pliocene beds Khor Eit (Berry and Sestini)	—?— Plio-Pleistocene	

Tertiary formations mentioned earlier make up a coastal plain 10-40 km wide along Sudan's Red Sea Coast. Table 3 correlates the Quaternary continental and marine events and deposits of the Sudan.

Umm Rawaba Formation

In central and southern Sudan the Umm Rawaba Formation, which is composed mainly of unconsolidated and unsorted, gravelly and clayey sand, overlies the Yirol Formation, the Basement Complex, or the Nubian Sandstone (Shazly et al., 1978; Vail, 1978; Shadul, 1980). The formational name was originally proposed by Andrew and Karkanis (1945) for deposits at Umm Rawaba village in eastern Kardofan Province which are as much as 300 m thick and show abrupt changes in facies. The Umm Rawaba extends continuously from Chad to the eastern Nile valley and may be as much as 500 m thick in down-faulted blocks (Shazly et al., 1978).

Although fossil information is scant, lithology, stratigraphic relationships, and geography suggest that the Umm Rawaba is an alluvial deposit possibly laid down by the early Nile River and its tributaries during Pliocene to Pleistocene time (Shadul, 1980).

Shadul has proposed that the Umm Rawaba Formation and the Gezira Formation (a name aplied to similar deposits located between the White and Blue Nile Rivers) be combined into one formation called the Nile Formation. Additional evidence to support this proposal was obtained by Shadul through analysis of satellite imagery.

Holocene deposits

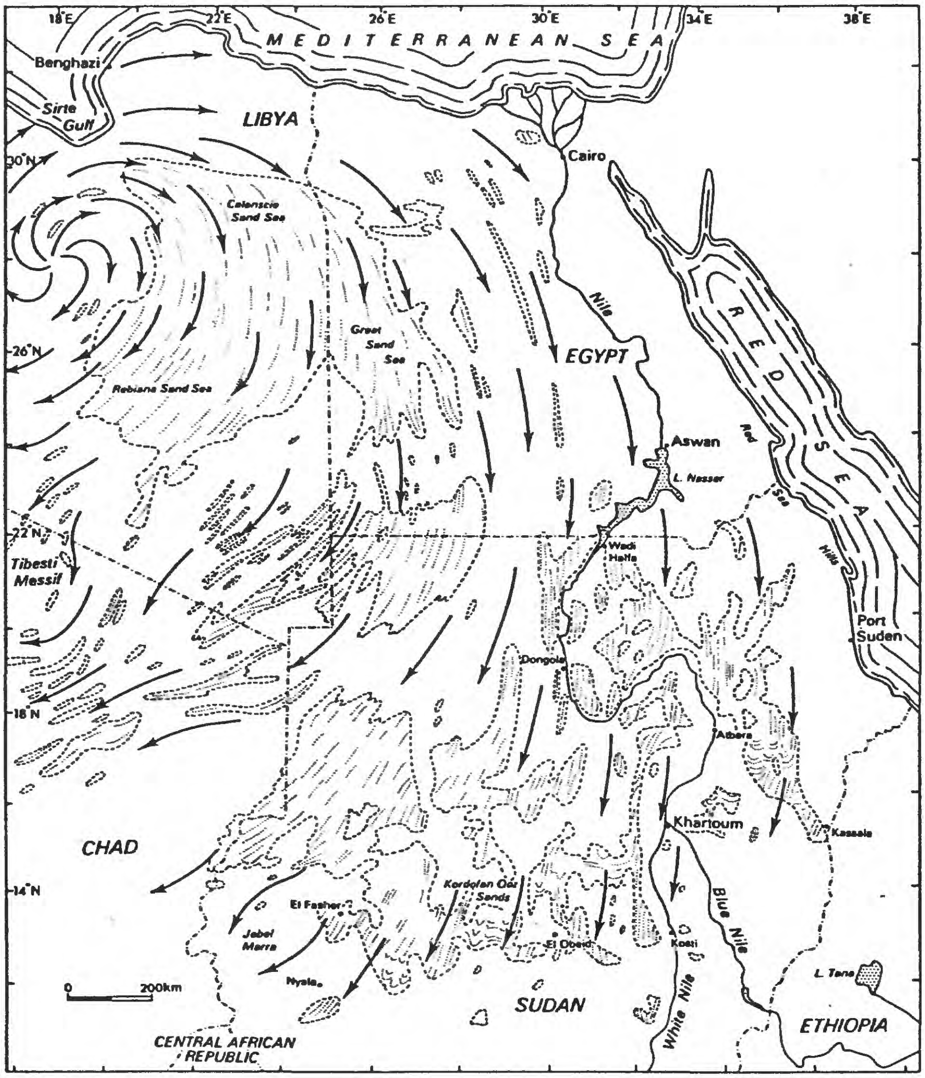
Dunes and sheets of sand are found throughout Sudan, but are most prevalent north of 12° N latitude. The greatest expanse of these modern deposits is in the northwestern desert extending into Libya. In Kardofan Province, a belt of dunes and sand sheets (Kordofan Qoz on fig. 9) has been stabilized in an area having rainfall exceeding 300 mm/year, according to Shadul (1980); iron stain, cover, and occasional layers of silt and clay have helped to stabilize the sand grains there. The sands in Sudan are made up of small, rounded, and frosted, generally well sorted quartz grains, but can contain silt and clay, mica, and feldspar (Vail, 1978). The deposits of windblown sand can be as much as 50 m thick, and were most likely derived from bedrock and reworking of fluvial sediments (Vail, 1978). Figure 9 shows the distribution and trends of major windblown sands in Sudan and adjacent areas in Northeastern Africa.

Alluvial and coastal marine deposits, according to Vail (1978) and Whiteman (1971), comprise the remainder of the Holocene sedimentary cover of Sudan (see table 3). The alluvial deposits are along the main drainages of Sudan, especially the Nile. Several of the smaller rivers and dry riverbeds have alluvial valley fill, whereas the larger rivers have developed delta fans and overflow deposits--especially in southern Sudan where annual flooding has developed swamps on the Umm Rawaba Formation.

Holocene coastal deposits of Sudan include modern beaches, back dunes, offshore and fringing reefs, lagoon-fill, and deltas.

Igneous activity

Igneous events have taken place in Sudan from the Precambrian to the present. The largest amount of igneous rocks are found in



Sand-flow movements

Sand sheets with principal trend directions

Figure 9. Distribution of wind blown sands in Sudan and northeastern Africa. (From Vail, 1978).

Sudan's Basement Complex where there are both extrusive and intrusive types (see the earlier section of the Precambrian). Emplacement of volcanic rocks in the Red Sea Hills and batholiths in other parts of Sudan were all related to the formation of the northeast part of the African plate in the Precambrian.

Vail cites other major igneous rocks in the country as: 1) ring dike complexes of various depositional ages concentrated in the Red Sea Hills, the Nuba Mountains, and the headwaters of the White Nile near Uganda; 2) dike swarms ranging in age from Precambrian to the Tertiary in the Red Sea Hills, along the Nile Valley, in the Nuba Mountains, and in western Darfur Province; and 3) lava flows, and plugs in volcanic vents and craters. The latter date from Late Cretaceous to Holocene and are found throughout the country (see fig. 10), although the most significant are adjacent to the Ethiopian border, along the Nile in the Northern and Red Sea Provinces, and in Darfur Province's Meidob Hills and Jebel Marra.

The distribution of these volcanic rocks has been controlled by the Rift Valley system of east Africa, which extends from Saudi Arabia to Kenya, and by a regional fracture pattern that extends from the Kenya-Uganda border to northern Libya (Vail, 1971). Faults, earthquakes, and hot springs associated with this volcanic activity are also shown in figure 10.

ENERGY RESOURCE IDENTIFICATION

Petroleum

Oil and gas deposits of the world are generally found in association with sedimentary geologic basins. The presence of organic-rich

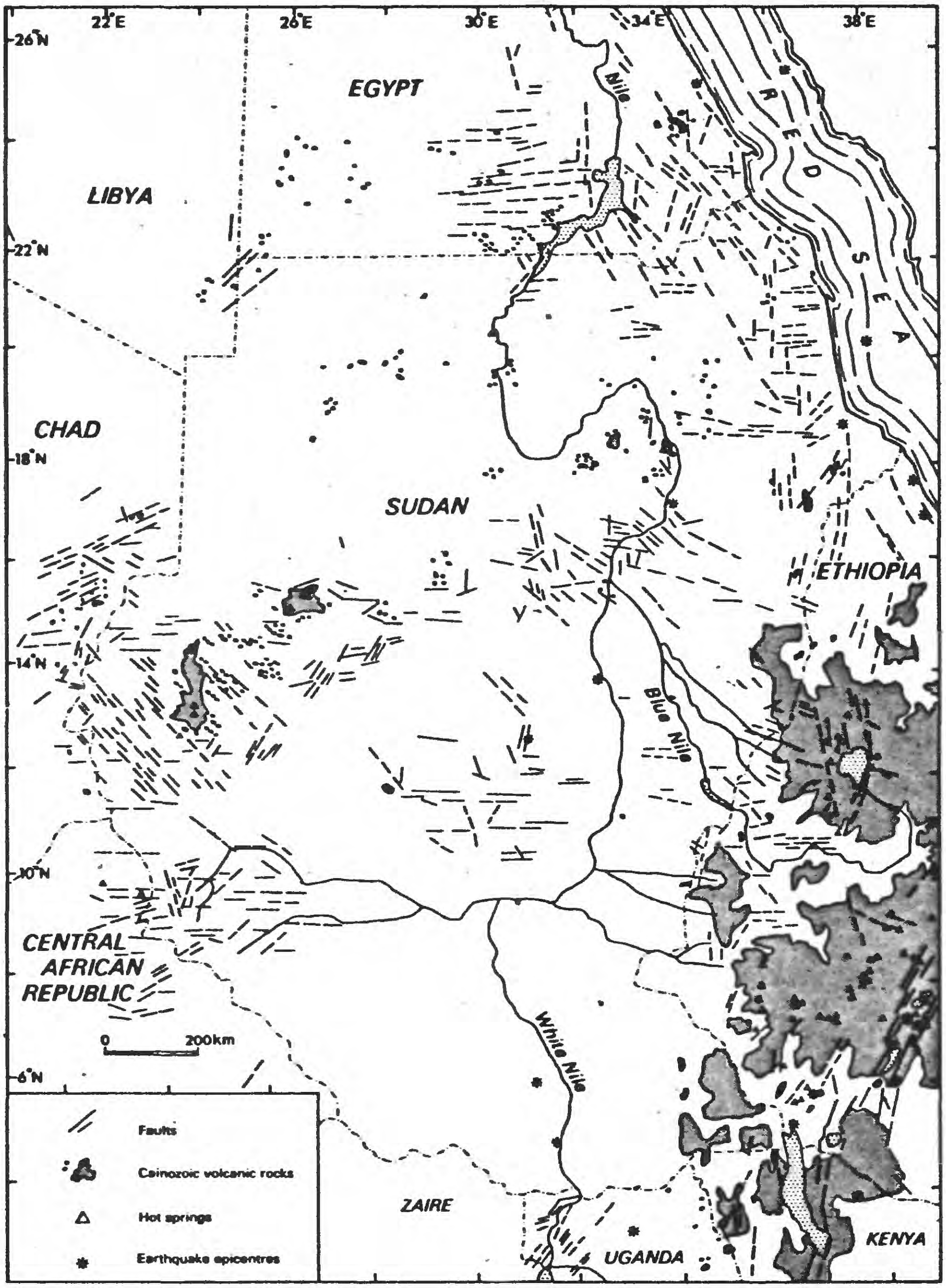


Figure 10. Distribution of Cretaceous, Tertiary, and Quaternary volcanic events, earthquakes, faults, and hot springs. (Modified from Vail, 1971).

source rocks (such as shale) and potential reservoir rock (such as sandstone or limestone) are of high interest in the exploration for petroleum. In general, the stable or moderately mobile parts of the basin are generally favorable for concentration of hydrocarbons. In Sudan this includes the interior basin of the Sudd (the Sudan Continental Basin) and along the Red Sea margin, which are both hinge zones. A hinge zone is a boundary between a stable platform or region and an area which is undergoing downward or upward movement. This zone is marked by relatively rapid changes in thickness of individual formations and sudden changes in sediment facies.

In the Red Sea area natural gas and condensate were generated from marine shales of the lower Miocene Maghersum Formation and possibly from Eocene bituminous limestones where the high temperature gradient favored gas over oil development (Grunau and Moses, 1981). Reservoirs consisting of sandstone with interbedded shale and capped by salt deposits form stratigraphic traps; a variety of structural traps are also present (Grunau and Moses, 1981; Widatalla and Suleiman, 1972). The gas finds have been encouraging, but not prolific enough to permit field delineation or development.

Oil discovered in the south-central interior of Sudan was probably generated from Cretaceous shallow marine shale (?) at burial depths exceeding 3000 m (Grunau and Moses, 1981). Traps are probably in the Yirol Formation or Nubian Sandstone of Late Cretaceous age, though no information has been released on the nature of the trapping mechanism. Two fields have been delineated by Chevron and other exploratory work is continuing.

Table 4 shows the significant events in the history of petroleum exploration in Sudan; table 5 provides a statistical summary of the exploratory activities. Table 6 is a summary of exploratory drilling in Sudan.

Table 4. Petroleum exploration in Sudan--Significant Events (Source: American Association of Petroleum Geologists annual reports on foreign exploration activities; Widatalla and Suleiman, 1972; Whiteman, 1971)

1920's:	Anglo-Persian Oil Company visited Red Sea coast; recommended against further petroleum research in the area.
1950's:	Overseas Geological Survey of Great Britian conducted geophysical research.
1958 :	Petroleum Resources Development Act-1958 signed into law.
1959 :	Petroleum Resources Development Regulations issued. Exploration licenses issued to AGIP Mineraria (Italian State oil company), General Exploration Company of California in the Red Sea area, all later relinguished in the early 1960's. Geological reconnaissance conducted by Shell and British Petroleum in northwestern Sudan desert at request of Sudanese Government.
1960 :	AGIP conducted geophysical and geological reconnaissance in their concession areas.
1961 :	AGIP continued reconnaissance, and drilled one dry well.
1962 :	AGIP continued reconnaissance and drilled 3 dry wildcat wells. Party of French oil company geologists visited Uweinat area, but obtained negative results.
1963 :	AGIP drilled 2 wildcats that yielded some noncommercial natural gas.
1967 :	Digna Petroleum Company granted 14 licenses primarily offshore Red Sea coast. Aeromagnetic surveys were conducted by Digna.
1968 :	Digna awarded additional licenses in the Red Sea and continued aeromagnetic surveys. Continental Oil Company conducted aeormagnetic survey in northwestern desert at request of Sudan Government.

1969 - 1971	:	No activity
1972	:	Romanian geologists advised Government of Sudan on exploration and geological data, with recommendations for research. Government signed into law Petroleum Resources Act, 1972.
1973	:	Government issued Petroleum Resources Development Regulations.
1974	:	Ball and Collins Ltd., Sudanese Resources Development Company, and American Pacific International awarded exploration licenses in Red Sea area. Chevron awarded licenses in interior basins as well as Red Sea. Ball and Collins and American Pacific conducted geologic field work, and a marine geophysical survey was conducted for Sudanese Resources Development Company.
1975	:	All exploration licenses transformed into Government production sharing contracts. Chevron conducted aeromagnetic study over Red Sea and airborne gravity and satellite mapping studies of interior basins. Chevron spudded 1 well in Red Sea.
1976	:	Sudanese Resources licenses cancelled, Chevron released part of interior basin block. Seismic and gravity studies conducted by Chevron in interior basin and seismic studies in the Red Sea. Chevron completed 2 offshore wells that were plugged and abandoned. Bashayer-1 tested 9,500 mcf of gas per day with two gas-bearing sandstones present. Suakin well tested gas and 1,200 b/d condensate, but was also abandoned.
1977	:	Chevron (and its partner Texaco) returned contracts in the Red Sea. Chevron continued onshore seismic studies. Chevron drilled and abandoned one well in the Red Sea and spudded one well in the interior basin.
1978	:	American Pacific and Ball and Collins returned their production-sharing contracts in the Red Sea. Chevron continued onshore seismic studies. Four wells were drilled by Chevron onshore with oil found in the Unity-1 well and source rocks found in the Baraka-1 well, Chevron announced that a major new basin with as much as 6000 m of sediment was found (Sudan Continental Basin). One other well was also spudded in the year.
1979	:	Burmah/Eastern Petroleum, Texas Eastern, and Total granted licenses in the Red Sea. Chevron conducted seismic surveys, aeromagnetic and airborne gravity studies. Chevron completed 6 Continental Basin wildcats and 2 more were spudded in the year. The Abu Gabra-1 flowed 40°API gravity oil at 500 b/d from Cretaceous sediments, and Unity-2 flowed 31° to 38° API low sulphur oil from 6 zones at 7,300 b/d.

1980 : Total and other partners granted an exploration block in Upper Nile Province, while Chevron released part of its concession.

Chevron continued seismic work and Texas Eastern, Burma, and Total shot seismic lines in the Red Sea. Chevron drilled 8 wells, 6 of which had commercial oil shows. Total spudded one offshore well.

1981 : By mid 1981 Chevron, Texas Eastern, and Total were all conducting exploration geophysical work. Total plugged and abandoned an offshore well while Chevron had completed 6 wells, two of which had oil finds and had unspecified results. Union Texas had planned one wildcat onshore on the Red Sea Coast and Sun, Phillips, and Transpacific had applied for exploration licenses. At the end of the year Chevron announced the discovery of the Unity field which had approximately 400 million barrels of oil, and that it was planning a pipeline to a proposed refinery at Kosti; ten reservoir sands had been identified with 610 m of pay sands.

mid 1982 : The Sudanese Government and Chevron announced that plans for building the Kosti refinery were to be suspended (Anonymous, 1982). Instead a 900 mile crude oil pipeline will be built from the Unity and Talih fields to Port Sudan. The pipeline would be completed in 1985 and be designed to carry 50,000 b/d of crude for export, with potential for expansion to 100,000 b/d; the crude line would probably be 22 inches in diameter. Due to waxiness of the crude, a parallel 8 to 10 inch diameter return pipeline would be built to carry Kerosine or naptha from Port Sudan to the discovery fields for blending with the crude.

Table 5. Petroleum Exploration in Sudan (source: American Association of Petroleum Geologists annual reports on foreign exploration activities; Widatalla and Suleiman, 1972; Petroconsultants, S.A., 1981)

Type of Activity	1950 - 1972	1973 - 1981(June)	Remarks
A. Number of wells drilled			
i) Onshore	0	25	
ii) Red Sea onshore and offshore	6	5	
B. Area Surveyed Onshore - Interior of Sudan			
i) Geological (field investigation)	480,000 sq. km.		Incomplete data
ii) Geological (aerial photo)			Incomplete data
iii) Seismic survey		126.5 crew months†	
iv) Gravity survey		4.6 crew months†	Data incomplete
v) Magnetic survey	105,154 sq. km.	1 crew month †	
Red Sea Onshore and Offshore			
i) Geological (field investigation)	9,972 sq. km.	? †	Data incomplete
ii) Geological (Aerial photo and surveys)	59,030 sq. km.	†	
iii) Seismic survey	14,872 km	5077 km †	
iv) Gravity survey	2,859 stations	61,100 km †	Data incomplete
v) Magnetic survey	9,122 km (incl. gravity)	†	

Table 6. Continued

Well Name	Company	Completion data	Total depth	Remarks
Abu Gabra 2	Chevron	9/25/79	1797	D & A
Hiba 1	Chevron	12/12/79	3911	D & A
Adila	Chevron	12/12/79	3122	D & A
Abanus 1	Chevron	Early 1981	4257	D & A oil shows
Abu Gabra 3	Chevron	4/30/80	3292	3200 b/d 34° - 37°API oil, 3 zones
Abu Gabra 4	Chevron	10/19/80	3257	D & A oil shows
Sharaf 1	Chevron	8/16/80	3459	2340 b/d oil, 1 zone
Unity 2	Chevron	4/28/80	3997	7900 b/d 31° API oil, 6 zones
Unity 3	Chevron	5/4/80	2748	2600 b/d oil 1 zone
Unity 4	Chevron	6/30/80	2776	D & A
Unity 5	Chevron	10/19/80	2722	3200 b/d
Unity 6	Chevron	12/12/80	2661	oil well
Unity 7	Chevron	Early 1981	2714	2750 b/d cum 32.9° API oil
Yasmin 1	Chevron	7/8/81	3037	Suspended
Sidra 1	Chevron	Drilling late 1981		
Doleib 1	Chevron	Drilling late 1981		
Talih 1	Chevron	1981	2893	9300 b/d 40°API oil, four zones
Nyang 1	Chevron	1981	2889	D & A

Reserves and production

Natural gas.--No reserves of natural gas have been found yet in Sudan. Exploration is continuing in the Red Sea to further establish the nature and extent of possible Miocene traps in the Maghersum Formation. Figures 11a and 11b show the location of available magnetic survey data for the central Red Sea, and interpretations of that data. Given that the Red Sea has been spreading since the early Tertiary, block faulting associated with the rifting process and salt layers in the overlying marine sediments play a major role in the creation of gas traps. The rapidity with which the salt beds can plasticly form a seal over new faulting determines the possibility of gas accumulating in any one location.

As stated by Ahmed (1972) and Widatalla and Suleiman (1972), the presence of offshore oil seeps and gas shows in wells of the Red Sea, plus all the necessary ingredients for accumulation of gas in traps, are good indicators for furture success in the area. The Durwara-II well had a gas show of 96.79-98.12 percent methane, 1.12 percent ethane, 0.12 percent propane, and 0.05 - 1.02 percent carbon dioxide. The Bashayer-1 well, which tested 9,500 mcf/d gas from two zones, was not of commercial scale to warrant pipeline construction; failure to extend the find from that well with adjacent tests indicates the small area of the trap. Figure 12 shows the location of wells drilled in the Red Sea area.

Oil.--Reserve information for oil in Sudan is still incomplete; however, Chevron has estimated that as much as 10 billion barrels could be present in the interior basin of the country; the Unity Field is estimated to have 400 million barrels of oil (Anonymous, 1982a). Owing to the lack of other discoveries, no production of domestic crude oil

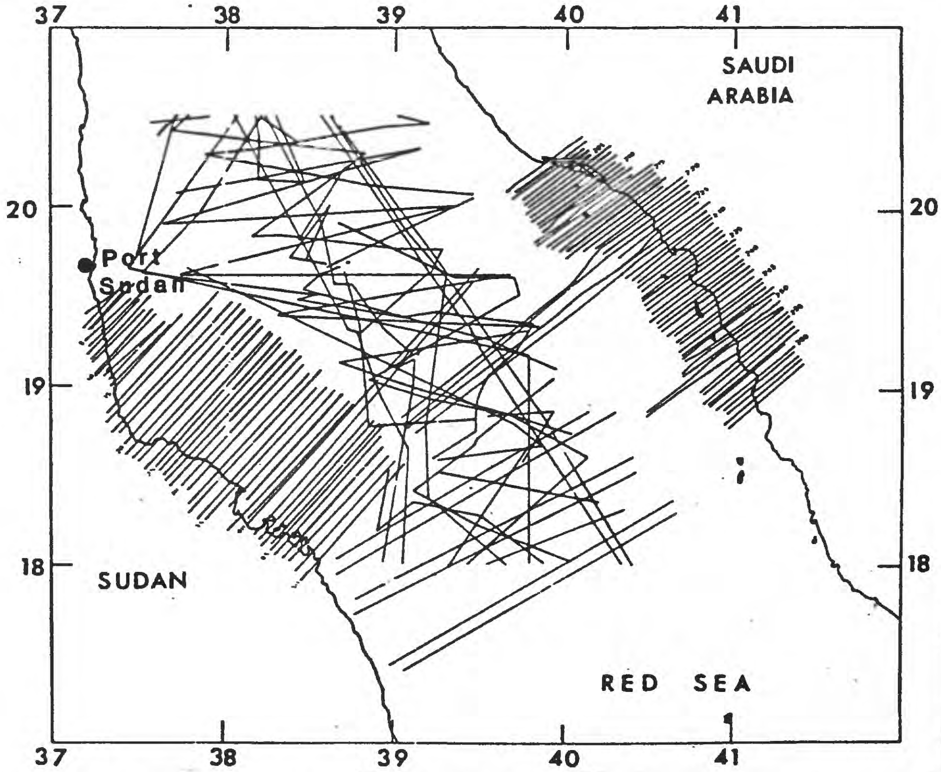


Figure 11a. Location of magnetic data lines in the Central Red Sea. Airborne survey lines adjacent to Sudan obtained by Conoco Oil Company, airborne survey lines adjacent to Saudi Arabia obtained by Sun Oil Company, marine magnetic lines obtained by research ships. (Modified from Styles and Hall, 1980).

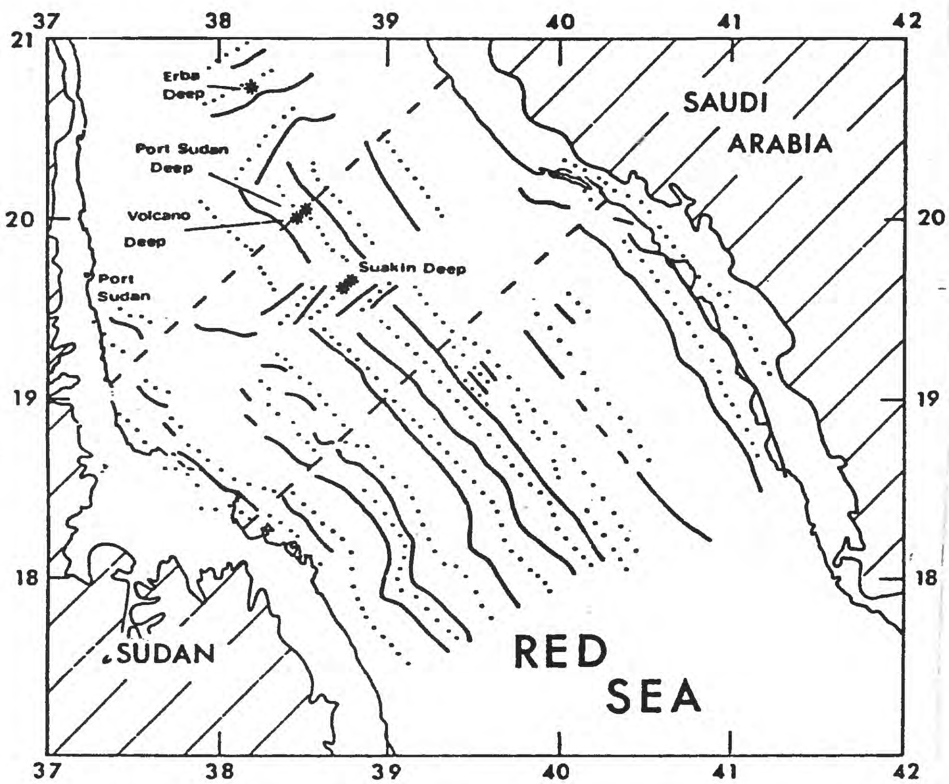


Figure 11b. Interpretation of magnetic data lines in central Red Sea to determine major magnetic features and transform faulting. (From Styles and Hall, 1980).

can occur in Sudan until a 10 inch diameter pipeline is constructed from the remote Unity field in Bahr el Ghazal Province to the 25,000 barrel/day refinery being built in Kosti (some 550 km away). Completion of the refinery is expected in 1984.

Oil produced from the Unity Field will probably be derived from Cretaceous sandstones. The small size of the field is due to Tertiary faulting (F. Ahmed Ibrahim, University of Khartoum, oral commun., 1982). Chevron's exploration has shown that as much as 6000 m of sediment (Quaternary, Tertiary, Mesozoic, and Paleozoic) may exist in the Y-shaped interior basin (Shazly et al., 1978). According to Petroconsultants Ltd., (1982), the productive sandstone horizons tested by Chevron in the Unity Field range in depth from approximately 1829 to 2530 m, with as many as ten zones yielding low API gravity, low-sulphur crude oil (see table 6).

Faulting may limit the size of other potential fields in the area. The discovery wells at Abu Gabra, as an example, were not sufficient to delineate that field although they were found at the same time as the first wells at Unity.

Exploration by Chevron is continuing northwest of the Unity Field and has also extended recently to the east in the Sudd swamps.

Discoveries have been made at Talih and Malhout, as well as Abu Gabra. The wells at Abu Gabra had up to 3 productive horizons that were found at approximately 2745 m depth and yielded from 500 to 3200 b/d of 34°-40° API gravity oil per well. The Talih well had 4 horizons that produced a total of 9,300 b/d 40° API gravity oil. Further information on oil wells drilled by Chevron is not readily available; publicly released data is shown in table 6. Figure 13 shows the location of wells drilled in the

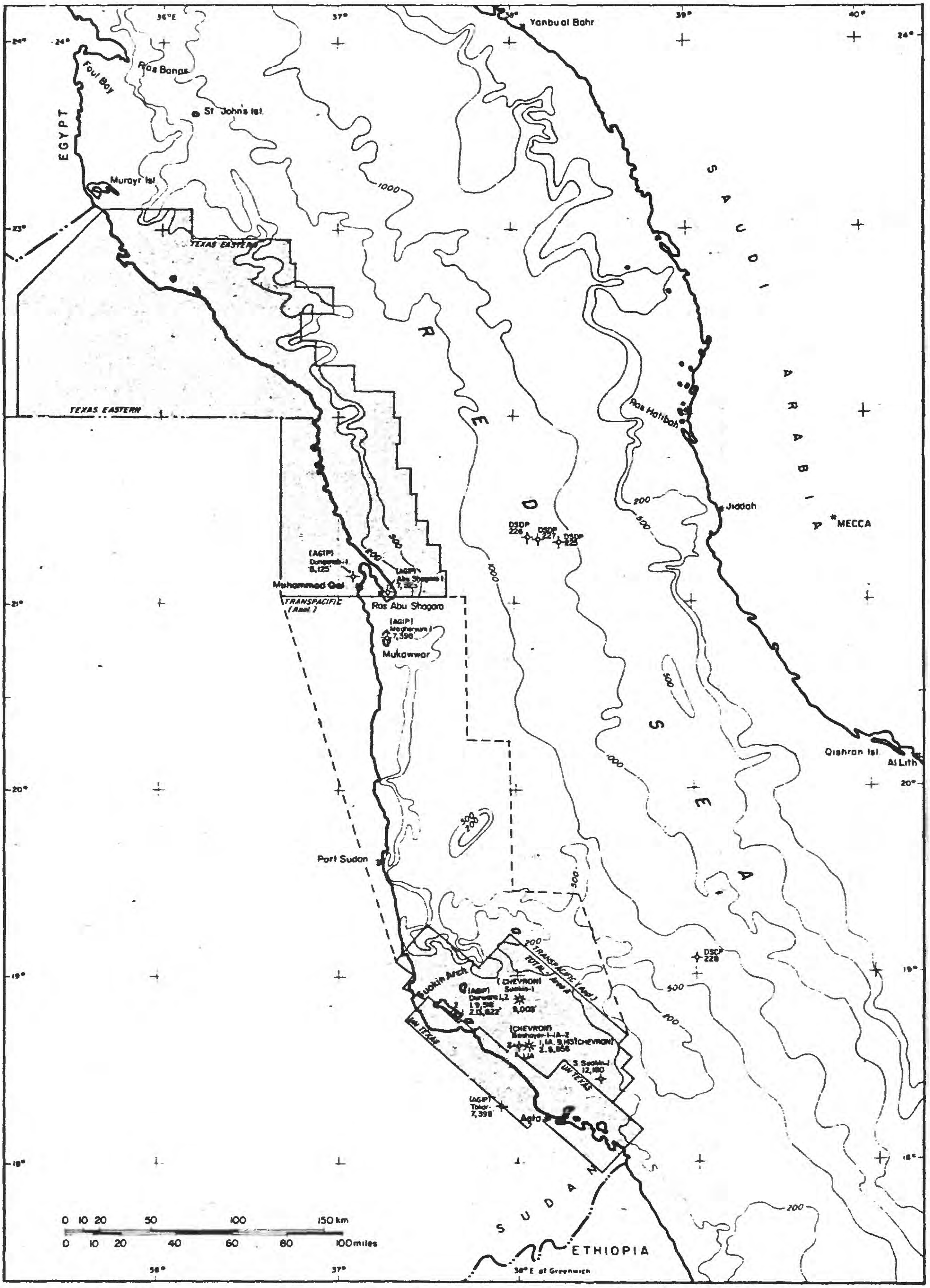


Figure 12. Location of wells drilled along Sudan's Red Sea Coast and existing exploration licenses. (Modified from Petroconsultants S.A., 1981).

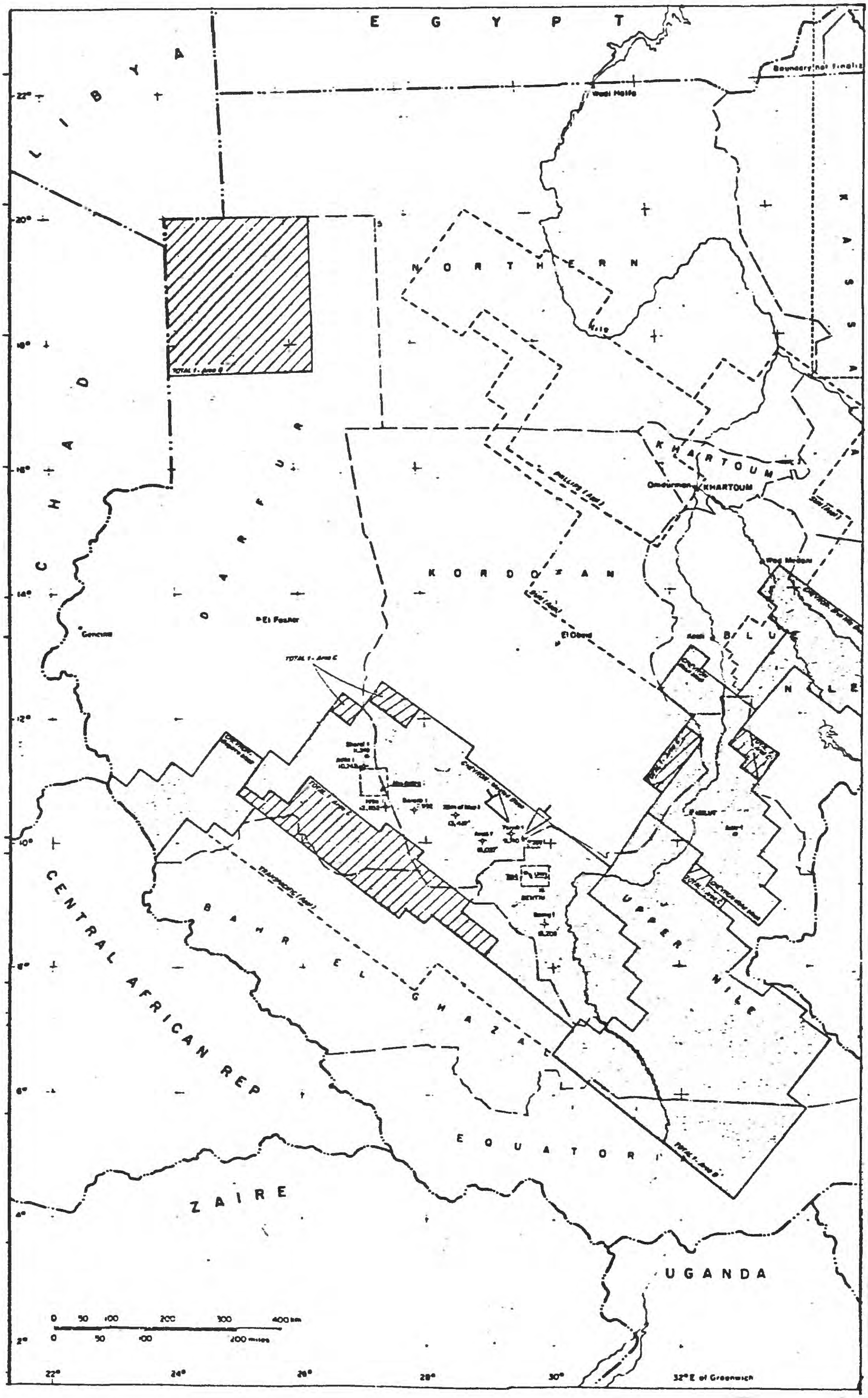


Figure 13. Location of wells drilled in interior basin of Sudan and exploration licenses. (Modified from Petroconsultants S.A., 1981).

Sudan Continental Basin, and existing exploration licenses; figures 14 and 15 show the location of wells drilled in the Unity Field, Abu Gabra, Sharaf, and Talih discoveries.

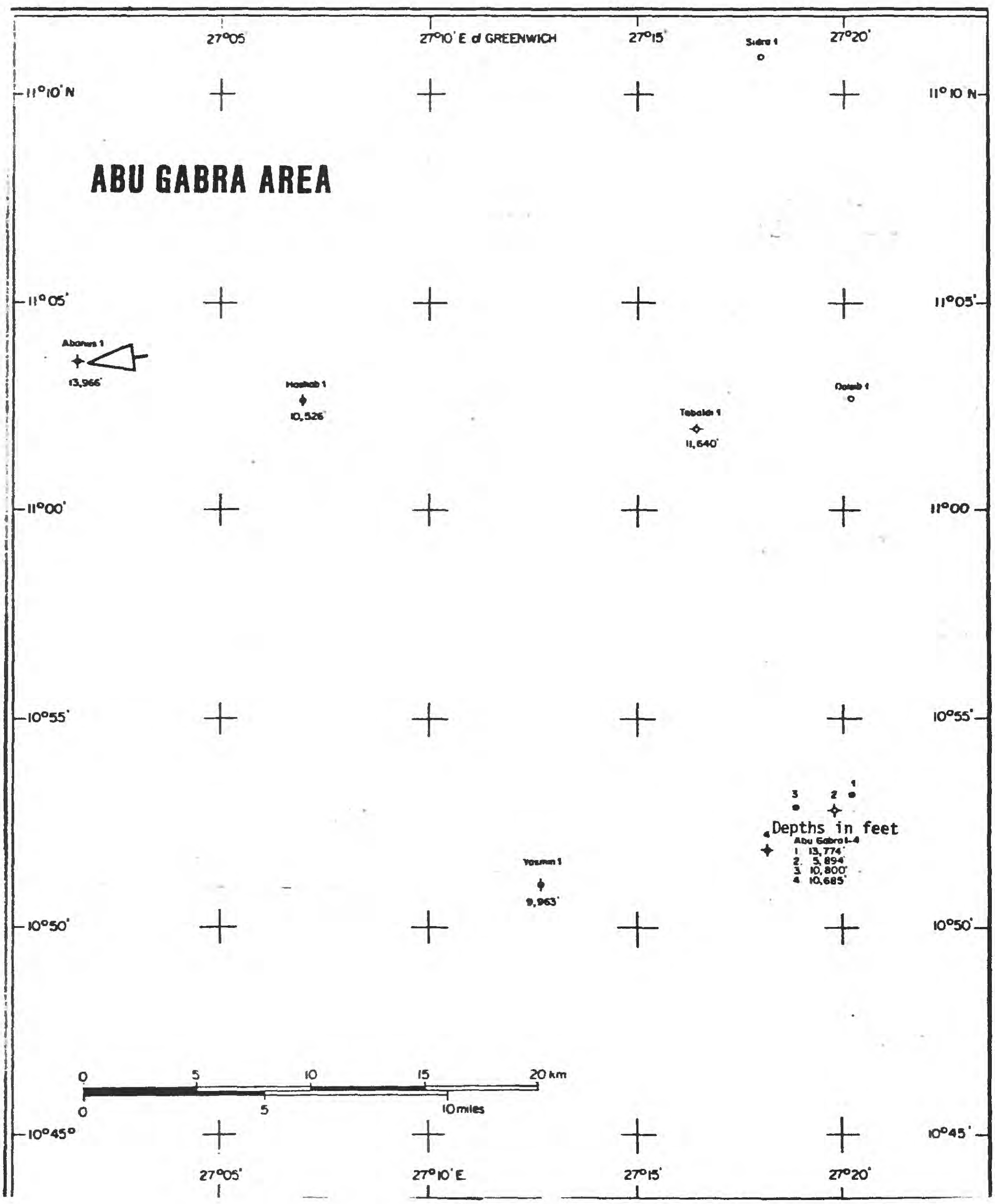
Coal and peat

Coal beds have been reported in Sudan, but investigations to date have not delineated economic deposits. Most of these investigations have been in the area near Dongola along the Nile River in Northern Province where: 1) a 10-cm thick layer of lignite was found at 10 m depth (Dunn, 1911); 2) coal found near Dongola and Hamur Village proved to be one 0.6-m thick bed of poor quality in all but one sample collected (Abdullah, 1955); 3) analysis of a 1.5 m thick coal found in a well in the Gedaref region in 1949 (Whiteman, 1971). The coal beds in the Dongola area are in the Nubian Sandstone.

Anthracite has not been found in Sudan, though graphite beds are present in the Basement Complex in bands up to 4 km wide and 100 km long (Shadul, 1980). Graphite is normally used as an industrial mineral rather than as a fuel.

Possible commercial quantities of coal occur in Tertiary rocks of of Ethiopia, in the Nubian Sandstone of Egypt, and in scattered localities in the Zaire Valley (Grossling, 1979).

Coal may occur in locally workable deposits within the Nubian Sandstone of northern Sudan, especially if Vail (1978) is correct in his belief that the formation was laid down in braided river systems discharging into deltaic areas. Freshwater marshes adjacent to such rivers could have been buried and eventually may have formed lignite beds such as those found in the Nubian sandstone of Egypt.



ABU GABRA

		Test Results		
Wells	TD in feet	BOPD	API gravity	Appr. Depth in feet
1	13,774	500	40°	9,000
2	5,894	—	—	—
3	10,800	3,200 (cumulative)	34 - 37°	—
4	10,685	—	—	—

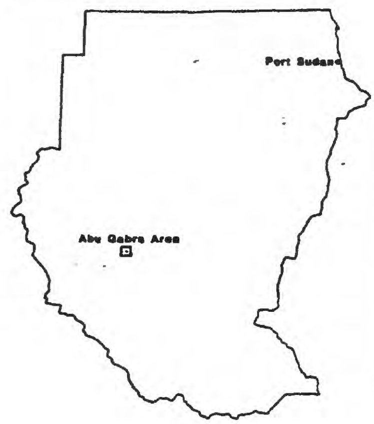
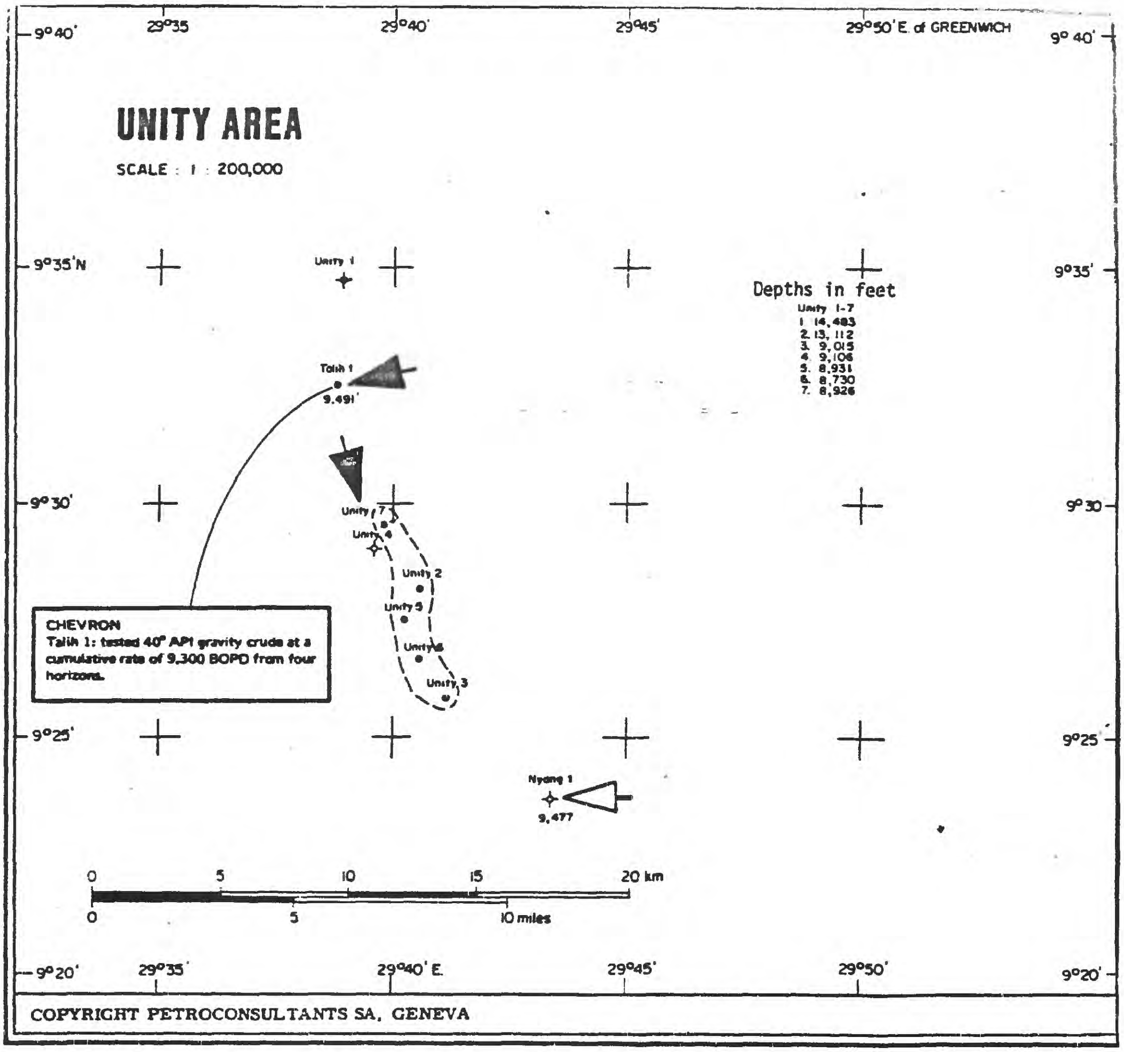


Figure 14. Location of wells drilled in the Abu Gabra area. (Modified from Petroconsultants S.A., 1981).



UNITY

		Test Results		
Wells	TD in feet	BOPD	API gravity	Appr. Depth in feet
1	14,483	small amounts	—	—
2	13,112	7,900 (cumulative)	31 - 38°	
3	9,015	2,600		8,000
4	9,106	—	—	—
5	8,931	3,200		7,400
6	8,730	—	—	—
7	8,926	2,750 (cumulative)	32.9°	7,400 - 8,300

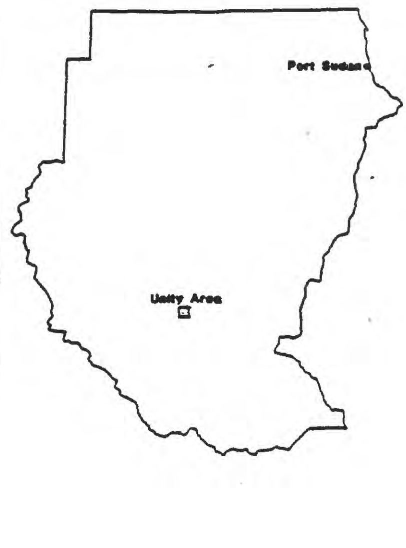


Figure 15. Location of wells drilled in the Unity area. (Modified from Petroconsultants S.A., 1981).

Peat is known to occur in Sudan's great Sudd swamp, but no efforts have been made to identify the extent, thickness, or location of the deposits. The intensity of the tropical climate, presence of the headwater of the Nile River, and topography of the region combine to create vast areas in southern Sudan which are either flooded all year or periodically flooded during the rainy season (May to November). The flood region occupies 240,000 km^2 with vegetation dominated by Papyrus and perennial grasses; organic soils (peat ?) thicker than 1.25 m are present (Barbour, 1961, p. 59).

One effort is apparently under way by a German Government team to collect floating water hyacinths, compress them into dry blocks and use that as a fuel source (A. Abdul, Clark University, oral commun., 1982). The Jonglei Canal Project, which is a joint effort by the Governments of Egypt and Sudan that will be completed in 1986 or 1987, will create a canal that will drain waters from the southern marshes. At present the reclamation of the drained areas will be strictly for agricultural use (M. Medani, Embassy of Sudan, oral commun., 1982).

Exploration and production of peat resources prior to the completion of this canal project could provide an additional source of fuel for southern and central Sudan, though no exploration program is presently contemplated. Further field and laboratory research beyond the scope of this report is needed to evaluate Sudan's coal and peat resource potential. Locations of coal finds, swamps of the Sudd region, and the Jonglei Project are shown in figure 16.

Uranium

Several countries in northeast Africa have likely prospects for uranium discoveries because of the presence of large areas of Precambrian

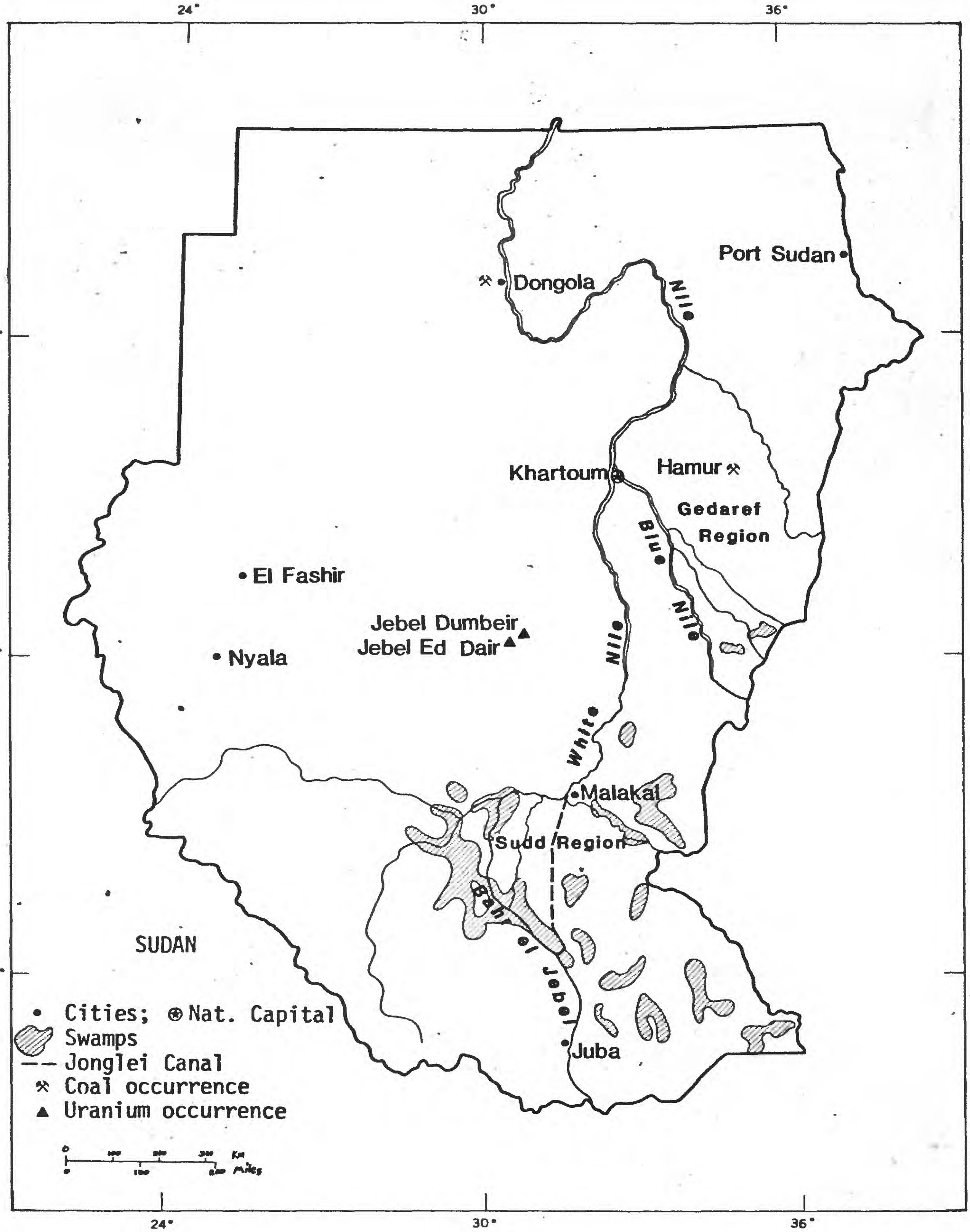


Figure 16. Location of coal and uranium occurrences, swamps of Sudd Region, and the Jonglei Canal Project.

shield areas, igneous activity, and adjacent sedimentary basins. Discovery of uranium, and other radioactive minerals has been reported by the Minex Corporation in Jebel Dumbeir and Jebel Ed Dair (figure 16) in central Sudan (Shekarchi, 1980). No published information is available on that discovery or the reserves located. Several companies were to have furnished reports to the Sudanese Government for exploration projects that they were to complete by the end of 1981. According to Dr. F. Ahmed Ibrahim (Khartoum University, oral commun., 1982) this exploration was carried out by Minex, Chevron Resources, and a joint Sudanese-German Government team. Previous exploration has been performed by AGIP, Westinghouse, the International Atomic Energy Agency, and the United Nations Development Program (S. Hale, Jr., Energy/Development International, oral commun., 1982). No reports are readily available on any of this exploration.

Previous discoveries in countries adjacent to Sudan include uranium-bearing phosphorites near Safaya, Egypt, uranium-bearing sandstones near Jebel Quatrani in Egypt's western desert, uranium-bearing phosphate at Bakouma in the Central African Republic, and vein deposits at Shinkolobwe in Zaire (Byers, 1977; Wilpott and Simou, 1979).

Geothermal

Several hot spring areas in Sudan are shown on figure 10. Most have not been studied to discern temperatures, flow rates, or salinity, with the exception of those near the volcanic complex. Hammerton (1966) found hot springs there in which temperatures range from 65°-85° C; a number of fumaroles are also present. The 60°-65° hot brines in the Red Sea adjacent to Sudan will be exploited in the mid-1980's for metal extraction by the Saudi-Sudanese Red Sea Commission (Anonymous, 1981). Although the temperatures in these offshore brines are only moderately warm, temperatures of 135°C and pressures of 700 atmospheres were encountered at depths of 4000 m in petroleum exploration wells adjacent to Sudan's coast (Widatalla and Suleiman, 1972). Both the Red Sea brines and high temperatures encountered in offshore wells are related to the Red Sea rifting process which brings magma closer to the crust at these locations. It is quite possible that wells drilled onshore of the Red Sea coast of Sudan could provide geothermal steam for power generation, though no effort is underway to explore this possibility. Steam at 150°C is the minimum temperature necessary to support power generation in the U.S.

Field and laboratory research to further evaluate the geothermal energy potential is beyond the scope of this report.

OBSERVATIONS

Energy planning

With the assistance of the Agency for International Development, the U. S. Department of Energy, and a contractor (Energy/Development International), Sudan is developing the skills and capabilities of its National Energy Administration (NEA). Its first major effort to identify the energy balance of the country is to be completed in 1982. Future efforts to identify fossil energy resources and bring about their development will require full cooperation and coordination of the NEA, the Sudan Geological and Mineral Resources Department, the General Petroleum Corporation, and the General Mining Corporation.

Potential for petroleum development

The existing climate for investment in Sudan for oil and gas development is good, and according to Chevron's estimates (discussed previously), petroleum prospects are excellent. Should the estimate of

10 billion barrels of oil reserves be accurate, Sudan could definitely export oil and place 14th in oil holdings worldwide (Anonymous, 1982a). Possibilities for discovering some gas deposits in the Red Sea are also good. Since the Government has the right to buy into the domestic affiliate of foreign petroleum corporations, it will be necessary for Sudanese General Petroleum Corporation personnel to acquire skills necessary to run a major oil company. Many of these skills can be acquired with assistance from the foreign oil companies and professional advisors. Gaining sufficient capital resources to modernize existing facilities and provide salaries sufficient to prevent loss of trained Sudanese personnel to private industry elsewhere in Africa or the Middle East is also important.

Constraints on development of the petroleum resources of Sudan are related to lack of supporting infrastructures. Ports, roads, railways, pipelines, barges, power, and telecommunications all require major investments to modernize and meet the demands that will be placed on Sudan by discovery of oil and gas. Foreign investment and advisors may be needed in all these sectors to allow for rapid development of the resources.

Potential for coal and peat development

At the present time, petroleum constitutes only 27.5 percent of the fuel used in Sudan. The recent finds of petroleum will go to supply motorized vehicles, the few domestic power stations, and the export market. As most of the Sudanese population is found in rural areas subsisting on cattle raising and farming (Caputo, 1982; Barbour, 1961), cooking and heating needs are supplied by the use of firewood, charcoal, or dried cattle manure. The collection of wood for fuel, especially in arid and semi-arid areas of northwestern Sudan has caused deforestation and desertification (A. Abdu, Clark University, oral commun., 1982).

Coal and peat resources, if discovered in workable quantites, and quality, could offset the use of these other fuels. Coal, if found, would be of value to northern Sudan and would assist in its development. Peat resources, although probably located in the same general area as recent oil discoveries, could be of use to the population in central and southern Sudan.

Constraints to exploration and development of coal and peat in Sudan may be related to the low economic values of these fuels in comparison to oil and gas, which may readily attract foreign investment. Given the nature of these resources and the possibility of development for only local consumption rather than export, exploration, in all likelihood, may only be carried out in the future by domestic companies, the Sudanese Government, or foreign advisors. If discovered in economic quantities and quality for development, the marketing of the fuel will be dependent on transportation constraints mentioned above.

Potential for uranium and geothermal development

The possibility of finding uranium in Sudan in addition to the minor discoveries near the Nuba mountains is quite good. However, further information is needed to assess the results of recent exploration activities in Sudan. Use of uranium in Sudan, if economic deposits are found, would probably be for export purposes, given the long lead times and skills necessary to develop nuclear power generation.

Geothermal resources could provide energy for power generation in both the far west and northeast of the Sudan. Development of this fuel is highly dependent on the temperatures and depths of the host rocks, outflow of superheated water and steam, and the costs of installing generating facilities. On the basis of the location only, it is more likely that potential resources could developed in the area of the Red Sea to provide power for coastal towns.

Further research is needed on both uranium and geothermal resources of Sudan to determine their extent and suitability for development.

Geological inputs for optimizing Sudan's indigenous energy supply

Maximizing the known and potential energy resources of Sudan requires the following:

1) An assessment of the oil and gas reserves and resources of Sudan.
2) A program for geologically mapping the Nubian Sandstone, supported by shallow corehole drilling to determine the presence and extent of coal in northern Sudan.
3) A geological field investigation of the Sudd to determine the presence and extent of peat resources. Initial attention should be paid to the area to be drained by the Jonglei Canal Project.
4) A geological mapping and drilling project in the vicinity of the western geothermal springs to determine the extent and potential of this resource for development.
5) A geological, engineering and economic assessment of utilizing geothermal steam from deep coastal wells to provide energy for towns bordering the Red Sea. Additional drilling is necessary.
6) A geological assessment of information obtained by recent exploration for uranium in order to provide direction for future investigations or exploitation of discoveries.
7) Synthesis of information on all these energy minerals with data on energy use (by sectors of Sudan's economy) to develop a national plan for energy development.

REFERENCES

Abdullah, M. A., 1955, Sudan Geological Survey Report 1953-5.

_____, 1966, Annual report-1965, Sudan Geological Survey.

Ahmed, Syed Sirtajuddin, 1972, Geology and petroleum prospects in eastern Red Sea: American Association of Petroleum Geologists Bulletin, v. 56 No. 4, p. 707-719.

Andrew, G., 1945, Sources of information on the geology of the Anglo-Egyptian Sudan: Bull. Geol. Surv. Sudan, No. 3, 36 p.

_____, and Karkanis, G. Y., 1945, Stratigraphical notes, Anglo-Egyptian Sudan: Sudan Notes & Rec., v. 26, p. 157-166.

Anonymous, 1982, Chevron, Sudan to expidite crude oil exports: Oil and Gas Journal, v. 80, no. 38, p. 84.

Anonymous, 1982a, Crude oil potential: Sudan Progress, v. 6., no. 1.

Anonymous, 1981, Two thousand meters under the sea: Mining Magazine, v. 145, no. 2, p. 114-122.

Barbour, K. M., 1961, The Republic of the Sudan--a regional geography; University of London Press, Ltd., London, 292 p.

Berry, L., Whiteman, A. J., and Bell, S. V., 1966, Some radiocarbon dates and their geomorphological significance, emerged reef complex of the Sudan: Z. fur Geomorphologie, Neue folge, v. 10, p. 119-143.

Burollet, P. F., 1963, Reconnaissance geologique dans le sud-est du Bassin de Kufra: Review Institute Francaise Petrologique, v. 18, p. 1533-1545.

Byers, V. P., 1977, World uranium: U. S. Geological Survey Open file report 77-40, sheet #3.

Caputo, R., 1982, Sudan: Arab-African Giant: National Geographic, v. 161, no. 3, p. 346-379.

Carella, R. and Scarpa, N., 1962, Geological results of exploration in Sudan by AGIP Mineraria Ltd.: Rep. 4th Arab Petroleum Congress, Beirut, 23 p.

Civetta, L. et al, 1980, Geological and structural outlines of the Southern Sudan, in Geodynamic evolution of the Afro-Arabian Rift System, Academia Nazionale Dei Lincei, Rome, p. 175-183.

Consiglio Nazionale Recerche Red Sea Cruise Shipboard Scientific staff, 1980, Geology of the Red Sea between 23° and 25° N., preliminary results: in Geodynamic Evolution of the Afro-Arabian Rift System, Accademia Nazionale Dei Lincei, Rome, p. 607-613.

Delaney, F. M., 1954, Recent contributions to the geology of the Anglo-Egyptian Sudan: International Gelogical Congress, 19th Algiers, 1952, Report, part 20, p. 11-18.

Dewey, J. P., et al, 1973, Plate tectonics and the evolution of the Alpine System: Geol. Soc. Amer. Bull., v. 84, p. 3137-3180.

Dunn, S. C., 1911, Notes on the mineral resources of the Anglo-Egyptian Sudan: Anglo-Egyptian Sudan Geol. Survey Bull. 1, Government of Sudan, Khartoum, 70p.

El-Raba'a, S. M., 1978, Structural and metamorphic evolution of the basement complex of Sudan: Precambrian Research v. 6, p. A17.

Engel, A. E. J., Dixon, T. H. and Stern, R. J., 1980, Late Precambrian evolution of Afro-Arabian crust from ocean arc to craton: Geol. Soc. Amer, Bull., part 1, v. 91, p. 699-706.

Goudarzi, G. H., 1970, Geology and mineral resources of Libya-- a reconnaissance: U.S. Geological Survey Prof. Paper 660.

Grossling, Bernardo, 1979, World coal resources: Financial Times Ltd., London, 154 p.

Grunau, Hans, and Moses, Hans-Jorg, 1981, Overview of source rocks for oil and gas--A worldwide survey, Source Rocks of Africa, Vol. 2: Petroconsultants, Ltd, Dublin, p. Sud. 1-11.

Hagemeier, M. E., 1965, Petroleum developments in north Africa 1964: Amer. Assoc. Petrol. Geol., Bull., v. 49, no. 8, p. 1232-1256.

Hammerton, D., 1966, Hot Springs and fumaroles at Jebel Marra, Sudan: Nature, v. 209, p. 1290.

Heatzig, Grant, and Michel, Roland, 1968, Petroleum developments in North Africa in 1967: Amer. Assoc. Petrol. Geol., Bull., v. 52 no. 8, p. 1489-1511.

_______, 1969, Petroleum developments in North Africa in 1968: Bull. Amer. Assoc. Petrol. Geol., v. 53, no. 8, p. 1700-1727.

Kroner, A., 1977, The Precambrian geotectonic evolution of Africa: Plate accretion versus plate destruction: Precambrian Res., v. 4, p. 163-213.

Medani, A. H., 1975, Nubian Sandstone Formation (Sudan): distribution and typical section: Amer. Assoc. Petrol. Geol. Bull., v. 59, p. 345-347.

Menchikoff, N., 1926, Observations geologiques faites an cours de l' expedition de S.A.A. le Prince Kemal el Din Hussein dans la Desert de Libye: Academy Science Comptes Rendus, Paris, v. 183, p. 1047-1049.

Moody, J. P., 1962, Petroleum developments in Africa in 1961: Amer. Assoc. Petrol. Geol. Bull., v. 46 no. 7, p. 1693-1440.

_____, 1964, Petroleum developments in Africa in 1963: Amer. Assoc. Petrol. Geol. Bull., v. 48, no. 10, p. 1622-1665.

_____, and Parsons, M. C., 1963, Petroleum developments in Africa in 1962: Amer. Assoc. Petrol. Geol. Bull., v. 47, no. 7, p. 1348-1396.

Nicod, Marc - Andre, 1974, Petroleum developments in North Africa in 1973: Amer Assoc. Petrol. Geol. Bull., v. 58, no. 10, p. 2025-2054.

_____, 1975, Petroleum developments in north Africa in 1974: Amer. Assoc. Petrol. Geol. Bull., v. 59, no. 10, p. 1871-1903.

_____, 1976, Petroleum developments in North Africa in 1975: Amer. Assoc. Petrol. Geol. Bull., v. 60, no. 10, p. 1767-1812.

_____, 1977, Petroleum developments in North Africa in 1976: Amer. Assoc. Petrol. Geol. Bull., v. 61, no. 10, p. 1698-1745.

_____, 1978, Petroleum developments in North Africa in 1977: Amer. Assoc. Petrol. Geol. Bull., v. 62, no. 10, p. 1796-1843.

_____, 1979, Petroleum developments in North Africa: Amer. Assoc. Petrol. Geol. Bull., v. 63, no. 10, p. 1636-1679.

_____, 1980, Petrolem developments in North Africa in 1979: Amer. Assoc. Petrol. Geol. Bull., v. 64, no. 11, p. 1739-1775.

_____, 1981, North Africa: Amer. Assoc. Petrol Geol. Bull., v. 65, no. 10, p. 2047-2075.

Petroconsultants, Ltd., 1982, Sudan Unity Field Report: Petroconsultants Ltd, Dublin.

Petroconsultants S.A., 1981, Petroleum Exploration Synopsis first half of 1981-Sudan: Petroconsultants S.A., Geneva.

Said, R., 1962, The Geology of Egypt: Elsevier, New York, 377 p.

Sandford, K. S., 1935, Geological observations on the northwest frontiers of the Anglo-Egyptian Sudan and adjoining part of the southern Libyan desert: Geological Society of London Quarterly Journal, v. 91, p. 232-281.

Shadul, Shadul Ahmed, 1980, Integrated geology of central Sudan, in Proceedings of Sudan Symposium and Workshop on Remote Sensing Oct. 1-11, 1979: Government of Sudan, U.S. Agency for International Development, and South Dakota State University, p. 520-574.

Shazly, E. M., et al, 1978, Satellite mapping-Regional Geology, Geomorphology, Structure, drainage, and Hydrology of Bahr El Gebel Area, Southern Sudan: Remote Sensing Center, Egypt Acad. Sci. Res. and Tech., Cairo, 48 p.

Shekarchi, E., 1980, The mineral industry of Sudan, in Minerals Yearbook 1978-1979, V. III, Area Reports: International: U.S. Bureau of Mines, Washington, D.C. p. 867-872.

Strojexport, 1972, Ground Water Research, SW Part of Kardofan Province, Second Stage, Final Report: Sudan Ministry of Natural Resources and Rural Development, Khartoum, 169 p.

Styles, P. and Hall, S. A., 1980, A comparison of the seafloor spreading histories of the western Gulf of Aden and the central Red Sea, in Geodynamic Evolution of the Afro-Arabian Rift System: Accademia Nazionale Dei Lincei, Rome, p. 585-606.

Sudan Geological and Mineral Resources Department, 1974, Mining and Oil Exploration Laws in Sudan: Sudan Ministry of Industry and Mining, Khartoum, 103 p.

Sutton, J. and Watson, J. V., 1974, Tectonic evolution of continents in early Proterozoic times: Nature, v. 274, p. 433-435.

U.S. Department of State, 1980, Quantity and Value of Minerals produced in Sudan Calendar year 1979: U.S. Embassy-Khartoum, unpub. doc., 5 p.

_____, 1981, The power sector in Sudan: U.S. Embassy, Khartoum, unpub. doc., 18 p.

Vail, J. R., 1978, Outline of the Geology and Mineral Deposits of the Democratic Republic of the Sudan and adjacent areas: Inst. Geol. Sciences, Overseas Geol. and Mineral Resources, no. 49, London, 68 p.

VanHouton, Franklin B., 1980, Latest Jurassic-Early Cretaceous regressive facies, Northeast Africa craton: Amer. Assoc. Petrol. Geol. Bull., v. 64 no. 6, p. 857-867.

Whiteman, A. J., 1971, The Geology of the Sudan Republic: Clarendon Press, Oxford, 290 p.

Widatalla, Abdel Latif and Suleiman, Yousef, 1972, Guide to Oil Exploration in Sudan: Sudan Geological Survey Department, Khartoum, 19 p.

Wilpott, R. H., and Simou, S.D., 1979, Uranium deposits in Africa, in Uranium Deposits in Africa: Geology and Exploration: International Atomic Energy Agency, Vienna, p. 3 - 20.