PHANEROZOIC SEDIMENTARY HISTORY & PETROLEUM POTENTIAL OF ETHIOPIA[1]

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INTRODUCTION

Phanerozoic sediments in Ethiopia range in age from upper Palaeozoic to Recent. These sediments, which exceed 5,000 metres in thickness in the Ogaden and Red Sea basins, may contain hydrocarbon deposits of major importance to the future development of Ethiopia.

The proximity of the giant oil fields of the Middle East has sharpened interest in the petroleum potential of Ethiopia for many decades. By the 1920s, the discovery of oil and gas seeps along the faulted Red Sea Coast had prompted comparison with the Gulf of Suez region. The discovery of oil seepages in northern Somalia sparked early interest in the Horn of Africa and, since the late 1930s, exploration in the Ogaden Basin has been stimulated by comparison to the petroliferous Mesozoic sequence in Saudi Arabia. The results of drilling in the Ethiopian Red Sea area have been disappointing but recent drilling in the Ogaden Basin has yielded an impressive record of oil and gas shows, highlighting the potential of this vast basin.

The pattern and facies of Phanerozoic sedimentation in Ethiopia was significantly controlled by two main periods of crustal extension. The first period commenced in the Upper Paleozoic, probably the Permian, eventually leading to the formation of the eastern African continental margin. The second period of rifting occurred primarily in the Tertiary causing the separation of Arabia and Africa along the Gulf of Aden and the Red Sea, and the proto-fragmenting of the African plate along the East African rift system.

This paper describes the Phanerozoic sedimentary geology of Ethiopia and discusses the influence of these tectonic episodes on the sedimentation and petroleum potential of the region. Special attention is focussed on the prospects for petroleum exploration in the Red Sea and Ogaden basins.

REGIONAL FRAMEWORK

Figure 1 illustrates the main outcrop units and structural features in Ethiopia and the surrounding region. Four large sedimentary provinces are shown on the map.

1. The Ogaden basin in the southeast, extending into Somalia and Kenya, and divided into Tertiary and Mesozoic outcrop provinces by the northwest-trending Marda Fault (Purcell, 1976). Over 5,000 metres of Palaeozoic to Tertiary sediments occur in the basin.

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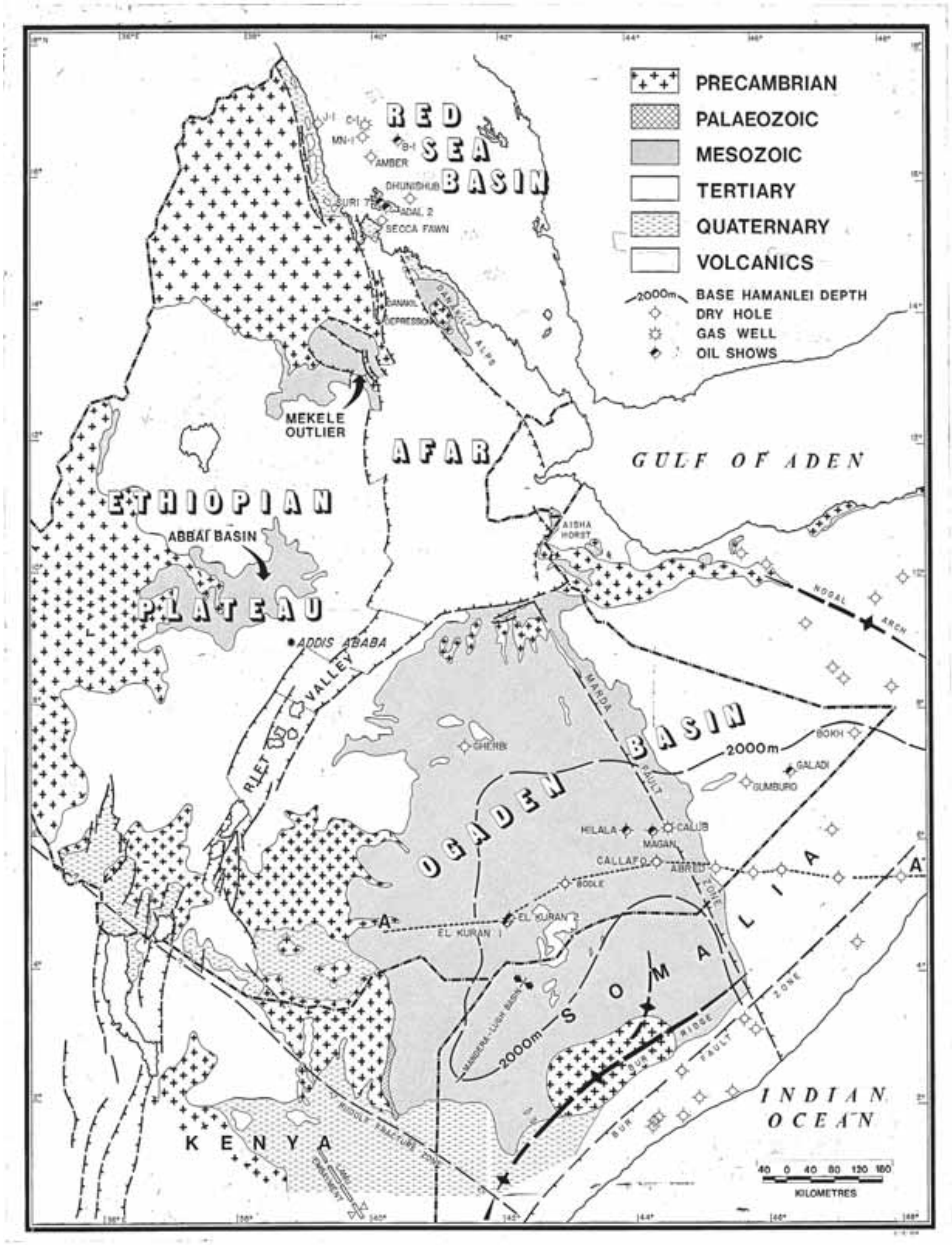

Figure 1: Generalised tectonic map of Ethiopia (Based on Kazmin, 1972; Merla et al, 1973). The Ethiopian rift valley and the Afar region are covered by Tertiary-Recent volcanics and continental sediments.

2. The Red Sea Basin in the northeast, marked onshore by the Tertiary - Recent sediments along the narrow, fault-bounded coastal plain. Mesozoic sediments probably underly the basin but are not generally considered prospective for petroleum exploration.

3. The Mekele Outlier, where down-faulting has preserved Mesozoic sediments which are also exposed to the southeast in the Takkese River Valley.

4. The Abbai Basin where Mesozoic sediments are exposed in the canyon of the Abbai (Blue Nile) River.

Extensive areas of Quarternary sediments occur in the Afar Depression and in southeast Ethiopia. These sediments, including the fluvio-deltaic Mursi and Nkalabong Formations in the Lower Omo River area, are not significant to the petroleum, potential of the region and are not included in this discussion.

STRATIGRAPHY

1. Paleozoic

Upper Paleozoic sediments occur in many areas of Ethiopia. In northern Ethiopia, fluvio-glacial sediments of the Adaga Arbi Glacials overlie the continental to shallow marine sands and silts of the Enticho Sandstone (Garland, 1972; Beyth, 1973). The age of these sediments is probably Permo-Carboniferous, although an older age has been considered (Dow et al, 1971). Elongate outcrops of upper Palaeozoic-Lower Mesozoic sediments, frequently termed Karroo (Mohr, 1962) or pre-Adigrat (Elwerath, 1967) also occur in the Chercher area (Lebling and Nowack, 1939), the Abbai Basin (Jepsen and Athearn, 1961), the Omo Valley region and in Bale Province. These sediments are mainly continental clastics and commonly seem localized to narrow grabens. They are not considered prospective for hydrocarbons.

Exploration wells drilled in the Ogaden Basin have encountered thick pre-Adigrat sediments. At first thought to be part of the weakly metamorphosed Inda Ad Proterozoic basement complex (Kazmin, 1972), they are now interpreted as evidence of a major Palaeozoic depositional cycle (Geological Survey, Ethiopia, 1976). Three formations have been named but considerably more drilling is required to define the age of facies and distribution of these formations. In Calub-1, the only well to encounter the three formations, the section consists of a basal arkosic sandstone (Calub Sandstone) overlain by 1200 metres of shale and siltstone (Bokh Shale) and 400 metres of sandstone with chert pebbles and anhydrite (Gumboro sandstone). In the basin centre the Upper Palaeozoic sediments may be 5,000 metres thick and may include salt deposits.

The discovery of large gas deposits in the Calub sandstone in Calub-1 reveals the hydrocarbon potential of these sediments.

2. Mesozoic

The extent of the Mesozoic sedimentation in Ethiopia is revealed by the outcrops of Mesozoic sediments in the Ogaden basin, in the major river canyons of the Ethiopian plateau and the erosional remnants in north and west Ethiopia. The Mesozoic sedimentation is characterized by three transgressive cycles:

a) the Triassic-Jurassic
b) the Albian-Aptian
c) the Cenomanian-Maestrichtian

The younger cycles are progressively more limited in extent and significance and may be considered secondary to an overall Mesozoic transgression-regression cycle.

The Adigrat Sandstone marks the base of this Mesozoic transgression and is considered Triassic in age in the Ogaden where it consists of sandstones with interbedded silts, shales, dolomites and marls. In northern Ethiopia, the Adigrat is probably Lower Jurassic in age and is mainly cross-bedded sandstones with thin layers of siltstone, conglomerate and laterite. The porous sandstones of the Adigrat Formation, which unconformably overlies either the Precambrian basement or the Permian sediments, are a main objective in petroleum exploration in the Ogaden Basin. The formation grades upward through a transition zone of dolomites and anhydrite into a thick Jurassic carbonate unit which is known as the Antalo group on the Ethiopian Plateau and the Hamanlei Formation in the Ogaden region.

The Antalao Group includes the Antalo Limestone and the Agula Shale (Kazmin, 1972) and appears to be Bathonian-Kimmeridgian in age. The Antalo Limestone consists of yellow to white limestone and marl with local oolites and coquina. In the Mekele Outlier area, sandy oolitic limestones occur in the west and are separated by a reefal facies from deeper water marls and shales in the Afar escarpment area (Beyth, 1973).

The Agula Shale overlies the Antalo Limestone and consists of green to black shales and marls interbedded with black pyritic limestones. In the Abbai Basin the Antalo Group contains intercalations of shale, gypsum and sandstone; the lower section is known as the Abbai Beds and is dominantly clastics with gypsum interbeds (Mohr, 1962).

The Hamanlei Formation is a major objective for petroleum exploration in the Ogaden area. The formation was described in outcrop as 200 metres of Callovian to Oxfordian oolitic limestone (Migliorini, 1948), but in the subsurface includes a thick sequence of carbonates and anhydrite of Liassic to Oxfordian age (Clift, 1956). This section and the overlying Upper Mesozoic units are shown on Figure 2, which is based on the Abred-1 well. Over 400 metres of porous dolomitized limestones in this well identified the Hamanlei as an important potential reservoir unit. The formation is conformably overlain by the Uarandab Formation which regionally consists of dark fissile shales (Mohr, 1962) but in the Ogaden is mainly intercalated marls and oolites. The overlying Gabredarre Formation also consists of oolitic and marly limestones, interbedded in the upper part with gypsum and shale.

A clastic facies of the Upper Jurassic units occurs along the basin margin and is known as the Garbaharre Formation in southwest Ethiopia (Merla et al, 1973) and Somalia (Beltrandi and Pyre, 1973). On the northwest flank of the Ogaden Basin, the basin margin facies is called the Amba Aradam Formation and includes Lower Cretaceous deposits. Cretaceous sediments in Ethiopia are mainly restricted to the Ogaden region where they are mainly carbonates and gypsum.

Several points about the Ogaden Mesozoic stratigraphic column, as shown on Figure 2, should be noted:

a) The Mustahil and Belet Uen formations mark, respectively, the beginning of the Aptian and Cenomanian transgressions.

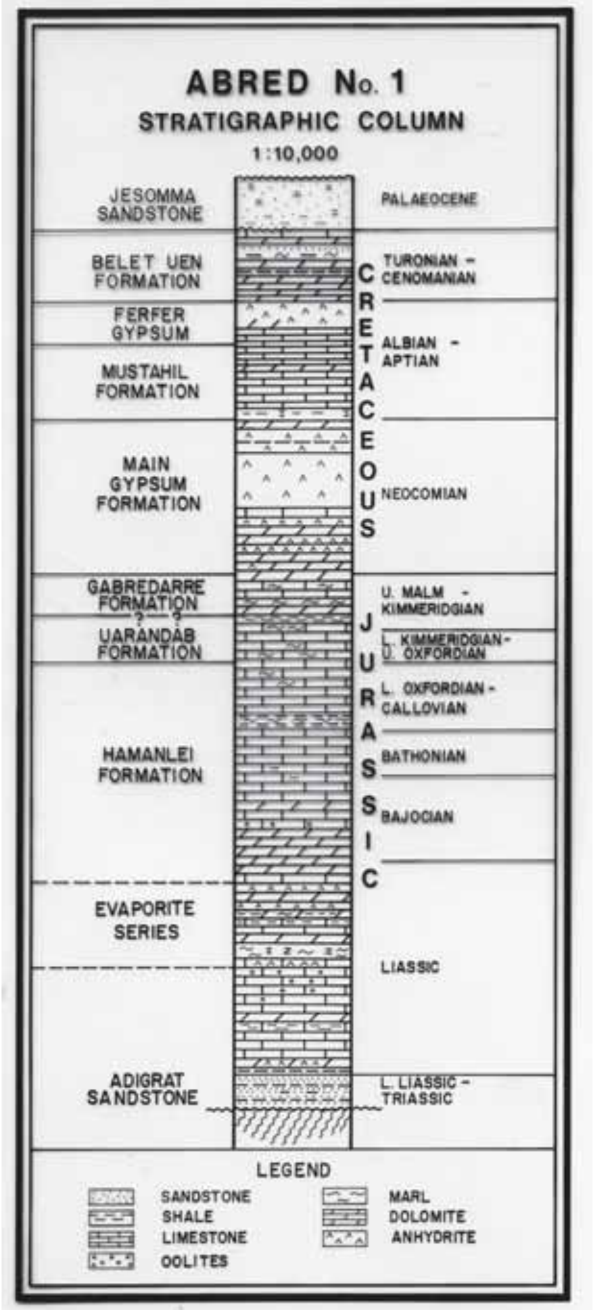

Figure 2: Representative stratigraphic column of the Ogaden Mesozoic section.
Generalised from the lithology log of the Abred well (Elwerath , 1967)

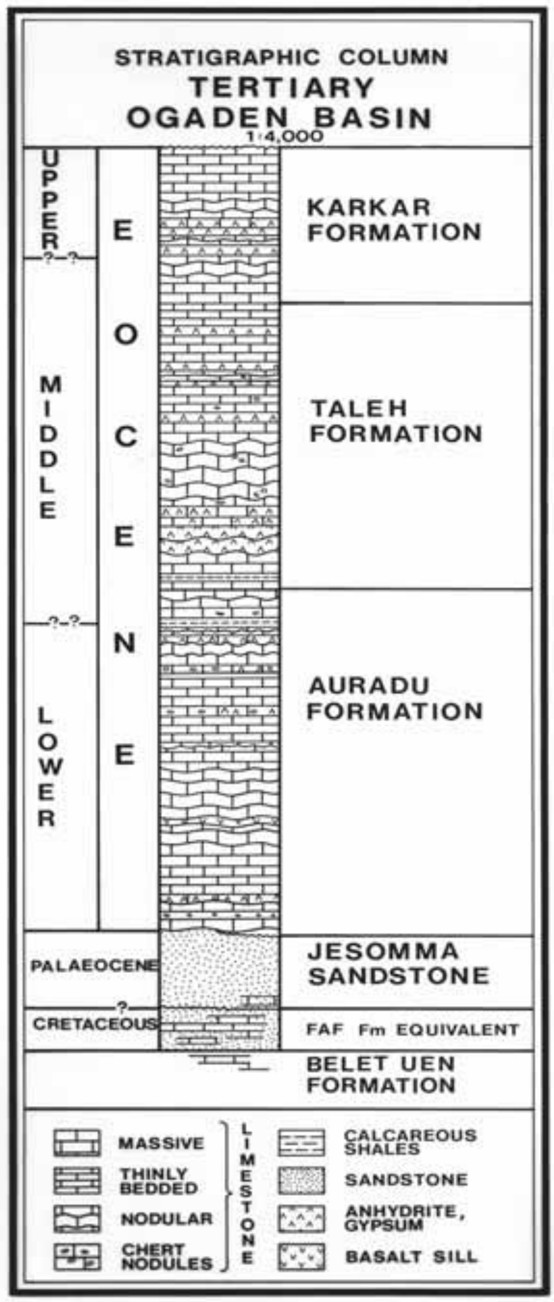

Figure 3: Generalized Tertiary stratigraphic column, Ogaden Basin, Ethiopia. Simplified from Taylor (1947

b) The Belet Uen Formation grades upward from the Ferfer Gypsum in the basin centre but is markedly transgressive over older eroded sediments on the uplifted northern flank.

c) The Abred section does not include the Faf Formation which occurs in the subsurface in the northeastern Ogaden Basin. It is Coniacian to Maestrichtian in age and consists of sandstones and shales with interbedded dolomites and limestones, predominantly limestone in the Maestrichtian.

d) To the east the Mustahill, Ferfer, Belet Uen and Faf Formations grade into dark lignitic shales and the entire sequence is known as the Gumboro Series (Clift, 1956).

3. Tertiary

Marine Tertiary sediments occur only in the Red Sea Basin and in the Ogaden Basin where they are mostly restricted to the region east of the Marda Fault Zone. Four formations have been recognised in the Ogaden Basin and are shown in representative section on Figure 3. It should be noted that while the Jessoma Sandstone is a continental to shallow marine unit of Palaeocene age in Ethiopia, the type section in Somalia included some Maestrichtian sandstones (Migliorini, 1948). In the Ethiopian terminology, these Cretaceous sandstones might be viewed as a shore- line facies of the Faf Formation.

In the Red Sea Basin four Tertiary formations have been defined in outcrop and exploration wells in the offshore area have identified evaporitic and volcanic units of equivalent age. The relationship between these sediments is shown on Figure 4 which is based on the Secca Fawn-1, B-1 and Amber-1 wells, but is not a structural cross-section.

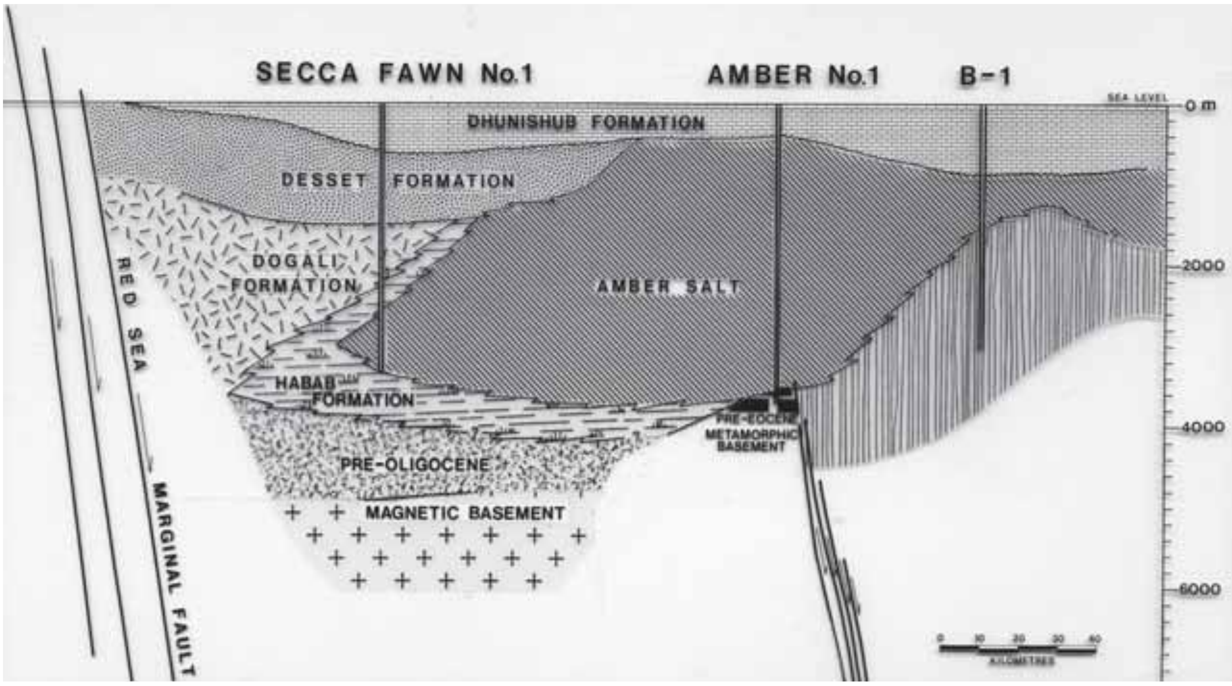

Figure 4: Stratigraphic cross-section, Ethiopian Red Sea Basin. This interpretive section is based on well sections (Geol. Surv. Ethiopia, 1976) and coastal geology (Kazmin, 1972).

The Dogali Formation, dated at 14-24 m.y., is the oldest Tertiary unit recognised in outcrop in the Red Sea coastal plain. It is underlain by either Jurassic limestones or Precambian basement rocks and consists of basalts, locally subaqueous, interbedded with tuffacious sandstones and conglomerates. It is conformably overlain by the upper Habab Formation which outcrops locally along the east and comprises 150-200 metres of sand, shales and marls with minor evaporites. The formation is 500 metres thick in the near offshore area where it is transitional between the Dogali Formation and the Amber Salt. In outcrop, the Desset Formation of Upper Miocene/Pliocene age unconformably overlies the Dogali and Habab formations and consists predominantly of sandstones with local beds of clay, anhydrite and salt. The Dhunishub Formation, of Pliocene to Quartenary age, consists mainly of organogenic limestones and unconformably overlies the older formations.

In the offshore area the Amber Salt is a remarkably uniform sequence of halite varying in thickness to over 5,000 metres and containing only thin interbeds of anhydrite, sand and shale. The Harmil Volcanics consists of interbedded basalts and basic tuffs of Oligiocne/Pliocene age and is associated with the spreading axis of the Red Sea

In the Danakil Depression Mio-Pliocene continental sandstones with interbedded basalts and marine sediments occur on the basin margins with interbedded halite, gypsum,. anhydrite and potash in the basin centre (Kazmin, 1972).

GEOLOGICAL HISTORY

1. Palaeozoic

In the early Palaeozoic, Ethiopia was landlocked in the interior of the ancestral continent of Gondwana, and erosion slowly levelled the Precambrian terrain. By the Lower Permian earth forces had begun to strain the continental crust and normal faulting commenced in response to the regional extension. These faults developed into a major rift system, down the (present) east coast of Africa. This rift system generally consisted of NNE-trending troughs and NW/WNW transverse faults. The main rift valley was located in the present offshore area and the major faults along coastal Kenya and Somalia, with displacements ranging to 6,000 metres, probably marked the edge of this central rift. The presence of marine Permian sediments in the Sakamena Basin of Madagascar (Radelli, 1975) indicates that marine waters penetrated over 1,500 kms into Gondwana along this rift axis, perhaps in a gulf similar to the present Red Sea.

At the same time a series of flanking half graben basins developed on the African mainland. One major trough extended from Tanzania through the Mandera-Lugh basin of Somalia and Kenya into the western Ogaden Basin. This trough was probably silled by the uplifted western margin of the main rift valley, which formed a major basement ridge along the present coast. Evaporites in Tanzania (Kent, 1965), Somalia (Beltrandi and Tyre, 1973), Ethiopia and Kenya reveal that the sea periodically overflowed this ridge, a remnant of which is the Bur Massif.

The structure and stratigraphy of the Palaeozoic rift system in the Ethiopian Ogaden cannot be defined on present data. The Marda Fault appears to have been an important element (Kozerenko and Lartsev, 1976) and the Galadi Fault (Purcell, 1979) may also have been significant. The organic carbon content of much of the rift valley sequence was probably derived from terrestrial plants which, on current thinking, tend to generate gas rather than oil. The presence of gas deposits has been confirmed by the Calub-1 discovery. If the Bokh Shale is a marine unit, indicating a major Permian embayment in the Horn of Africa, the prospect for Upper Palaeozoic oil generation would be significantly upgraded.

2. Mesozoic

The eastern margin of the African continental plate along the (present) central Somalia coast appears to have been isolated by early Triassic time and, as the continental block began to subside, the seas advanced northwest into the Ogaden depositing the shoreline clastics of the Adigrat Sandstone. With increasing subsidence during the Lower Liassic, the shoreline moved progressively inland and the seas deepened in the Ogaden region. Local ponding caused precipitation of anhydrites and the Adigrat sands became increasingly calcareous. By the middle Liassic limestones were forming over most of the Ogaden and the seas extended into central Ethiopia where mixed continental and marine clastics were deposited in the Abbai Basin. During the late Liassic, the Ogaden Basin became hypersaline causing precipitation of anhydrites. This silling of the basin was probably caused by uplift of the coastal ridge, which apparently persisted as a submarine element through the Mesozoic era. Uplift along the Marda Fault Zone may have also been a controlling factor.

In the Bajocian, renewed subsidence caused the seas to overflow the basement sill, again reaching the Abbai Basin, and joining with seas advancing westward from the Yemen, isolating a major basement island along the present southern Afar escarpment. Thick calcarenites, rich in detrital limestone and oolites, formed in the shallow, well agitated waters which flooded the Ogden Basin. Limestones also formed in the Abbai Basin interbedded with gypsiferous layers. This Bajocian transgression appears contemporaneous with the subsidence of the Kenya coastal area, perhaps hinged along the Rudolf Fracture Zone, as crustal spreading developed progressively southward.

By the end of the Bathonian the seas had transgressed as far as Eritrea. Down-warping along the eastern Afar Escarpment caused a deeper water environment in the Afar area, and reefs developed along the hinge zone (Beyth, 1973), separating the shelf limestones on the (present) plateau area from the deeper water facies.

In the Oxfordian, the seas reached their maximum extent over the Horn of Africa and shales were deposited over large areas. At this time, a major tectonic episode appears to have been initiated in the region. Diapiric structures developed in the Mandera-Lugh Basin (Beltrandi and Tyre, 1973) and uplift of the Chercher Massif and Nogal Arch began to cause a shallowing of the Ogaden seas. The entire area north of the Nogal Arch was uplifted and eroded. In the subsurface of northeast Somalia Cretaceous limestones rest unconformably on Hamanlei Formation (Migliorini, 1948). Further east, on Socotra Island, the Jurassic section has been completely eroded and the Cretaceous sequence rests on Precambrian. This pattern of Jurassic sediments has also been interpreted in terms of non-deposition (Azzaroli, 1968). The origin of this uplift is not known but it may be related to the initial rifting in the Gulf of Aden, similar to the contemporaneous doming and rifting in the Ethiopian and Kenyan rifts. Azzaroli (1968) and Kasmin (1976) have previously suggested that rifting occurred in the Gulf of Aden in the Mesozoic.

Widespread regression, which commenced in the Kimmeridgian, is marked in northern Ethiopia by the lagoonal Aqula Shale and, in the southeast, by the shoreline clastics of the Garbaharre Formation. Carbonates were deposited over most of the central Ogaden area. By Portlandian time the seas were restricted to the Ogaden Basin where carbonate deposition continued, grading to clastics on the basin flanks. Near the end of the Jurassic, the shallow Ogaden sea was again silled and over 1600 metres of gypsum had formed in this basin by the end of the Barremian. It is now known if the gypsum is a primary deposit or a diagentic alteration of anhydrite. Limestones formed around the margins of the basin and merged shoreward into the clastics of the Amba Aradum Formation.

This tectonism exposed the Jurassic sediments in north and central Ethiopia, significantly reducing the potential for hydrocarbon generation and entrapment. This destruction of incipient Mesozoic petroleum deposits was furthered by the extensive erosion and volcanism associated with the Tertiary rifting. If sedimentation had continued in the area with, for example, Cretaceous and Tertiary sediments deposited on a stable shelf, the Jurassic section might be prospective over most of Ethiopia. As it developed, these sediments were, except in the Ogaden region, either eroded or buried under the thick Trap Volcanics.

By the Aptian the developing Afro-Arabian rift system had begun to control the depositional pattern in the region. In northwest Somalia, probably Lower Cretaceous sandstones thicken abruptly into the Gulf of Suez, indicating active subsidence of this rift. Alkali basalts along the southern Afar margin are dated as Aptian (Canuti et al., 1972), and tholeitic basalts on the western Agar margin are probably of similar age, as is the down-faulting of the Mesozoic sediments in the Mekele Outlier. Kazmin (1976) related the crustal extension of the Gulf of Suez to a relative sinistral motion of the Arabian block, possibly along the Marda Fault Zone. Contemporaneously a major transgression swept across the Horn of Africa and the Middle East. The clastics of the Amba Aradam Formation in central Ethiopia may be associated with the transgressive cycle but sedimentation in Ethiopia was mainly restricted to the Ogaden Basin, where limestones were deposited. Silling of the basin in the upper Albian led to renewed deposition of gypsum and anhydrite, continuing the cyclic pattern of carbonate and evaporite sedimentation that characterizes Mesozoic sedimentation in the basin.

By the Cenomanian, the uplifting of the western Ogaden region and the coastal downwarping, apparently hinged along the Marda Fault Zone, had significantly altered the pattern of sedimentation in the Ogaden region. Isopachs of Jurassic and Lower Cretaceous formations show that deposition in the basin was controlled by two major troughs (Purcell, 1979): one trending northwest across Somalia into the Ogaden; the second trending north-northeast from Kenya into the western Ogaden. In contract, the isopach map of the Cenomanian shows the Ogaden Basin only as an embayment of a NNE-trending coastal Somalia Basin. This coastal basin deepened to the east and the Cretaceous carbonates and evaporites of the Ogaden grade into the shales and marls of the Gumboro Series. The coastal ridge persisted through this period, marked by a thick sequence of coquinal limestones and dolomites (Barnes, 1976).

It appears probable that sedimentation occurred in the Red Sea area during the late Cretaceous, as evidenced by Cretaceous-Palaeocene marine fossils in the southern Red Sea (Carella and Scarpa, 1966). This may indicate the opening of the Red Sea to the Indian Ocean (Kazmin, 1976) or the Mediterranean (Coleman, 1974).

3. Tertiary

General uplift of the Ethio-Yemen or Arabo-Ethiopian dome (Mohr, 1967) continued in the Paleocene, elevating the flanks of the western Ogaden Basin. At the same time subsidence of the coastal zone caused the Palaeocene seas to advance west across the eastern Ogaden region. This transgression apparently reached its peak in the Lower Eocene when limestones of the Auradu Formation were deposited over most of the eastern Ogaden. Minor changes in sea level caused alternating evaporite and carbonate shelf conditions in the eastern Ogaden through the Eocene but, by Oligocene time, the seas had retreated east of the Ethiopia/Somalia border. This regression may have been relatively abrupt (Dainelli, 1943; Azzaroli, 1968), caused by major uplift of the Ethio-Yemen dome in the late Eocene. Girdler and Styles (1974) suggest that seafloor spreading may have been initiated in the Red Sea at this time, possibly explaining the metamorphism dated at 36 myr in the Amber-1 well. Contemporaneously, extrusion of the Ashangi basalts onto the Ethiopian plateau accompanied the down-warping of the western Agar Margin. Volcanism along the proto-Ethiopian rift may also have commenced in the Eocene but it reached its peak in the Lower Miocene when the Trap Series basalts covered most of the Ethiopian plateau and northwestern Ogaden, burying the Mesozoic sediments and any remnant hydrocarbon deposits.

The nature of sedimentation in the Red Sea basin in the Lower Tertiary is not known but probably included both marine and continental units. By the Lower Miocene crustal attenuation in the Afar had caused a rotation of the Danakil block which apparently silled the Red Sea from the Gulf of Aden across the straits of Bab-el Mandeb (Gate of Tears). Over 5,000 metres of halite precipitated in the restricted, hypersaline ocean, filling the subsiding Red Sea graben. Girdler and Styles (1974) suggest that active plate separation was not occurring in the Red Sea at this time, although basaltic lavas and tuffs were forming in the central rift area. In the Upper Miocene crustal attenuation and volcanism continued in the Afar, and active plate separation began in the Gulf of Aden.

Intensive faulting developed along the Ethiopian rift valley in the Lower Pliocene accompanied by silicic volcanism, which again overflowed onto the plateau margins. The uplifted margins of the rift system were rapidly eroded and poorly sorted sediments were deposited in the rift area. In the Red Sea, the Desset Formation sediments were deposited over the Amber Salt. Under the weight of this overburden the salt mass became increasingly unstable and diaprisim commenced. The main salt diapirs consistently occur on the down-thrown side of major faults (Frazier, 1970), a consequence of the thicker overburden and the triggering effect of movement on the fault zone. Locally, as on Grand Dahlac Island, the salt diapirs reached the surface and the Desset Formation overburden was eroded and redeposited around the salt domes. At this time a narrow seaway passed through the Gulf of Zula into the Danakil Depression and a minor channel may have extended to the east across the Buri-Danakil high. These restricted marine waters in the Afar Depression precipitated thick salt deposits, which thickened to the west towards the hinging fault of the western Afar escarpment (Hutchinson and Engels, 1970).

Late in the Pliocene active plate separation in the Red Sea caused extrusion of the Aden Volcanics and reopened the channel into the Gulf of Aden. Limestone deposition commenced and has persisted to the present day. Increased faulting and crustal attenuation led to the development of oceanic crust in several zones in the Afar (Barberi and Varet, 1975; Kazmin, 1976) where evaporite sediments formed until recent times. The Ethiopian rift faulting also intensified during this period, leading to the development of the Wonji Fault Belt approximately 1.8 m.y. ago (Mohr, 1967).

The extent and magnitude of the Tertiary tectonism significantly reduced Ethiopia's petroleum potential. The domal uplift limited marine sedimentation to the eastern Ogaden while the extensive volcanism precluded the development of petroliferous sediments in the Afar and rift valley, and buried most of the eroded Mesozoic basin. The hypersalinity of the Miocene Red Sea is also a direct consequence of the Tertiary rift cycle. The intensity of this tectonic cycle is commonly explained in terms of anomalous earth temperatures - the so called mantle hot spots - through Mohr's (1976) "hot smudge" appears a more apt term for the Afar.

PETROLEUM POTENTIAL

Early discussions of the petroleum prospects of Ethiopia have ascribed considerable potential to many areas of the country including all the main sedimentary provinces (Caprau, 1966), the Afar Depression and the rift valley (Murdoch, 1947). Most of these areas are now considered relatively unprospective. In the Abbai Basin sediments outcrop only in the rugged canyons of the Abbai (Blue Nile) River and the section is breached to the basement level. Erosion has also been extensive in the Mekele Outlier and only a thin sedimentary section remains. In the Afar Depression and rift valley area the extensive Tertiary faulting and volcanism has certainly destroyed any Mesozoic hydrocarbons and the Tertiary deposits are not petroliferous. Hydrocarbons might occur locally in the Mesozoic sediments underlying the Trap Series on the Ethiopian Plateau but present technology does not permit exploration below this thick basalt layer. Only two areas in Ethiopia may be defined as potential petroleum provinces: the Ogaden Basin in the southeast and the Red Sea Basin in the north.

1. Red Sea Area

In the Gulf of Suez oilfields, Lower Miocene muds of the Gharandal Group, frequently termed the Globerigina Marls, have sourced Miocene reefs and pre-Tertiary reservoirs. This favourable juxtaposition of source and reservoir rocks by Tertiary rift faulting has generally been projected over the entire Red Sea but exploration has revealed several important differences in the petroleum geology of the southern Red Sea Basin (Heybroek, 1965).

Drilling in Ethiopia has shown that the Lower Miocene is predominantly halite; that is, while open marine conditions caused deposition of the Globerigina Marls in the Gulf of Suez, the southern Red Sea was a hypersaline environment. This hypersalinity was caused by several factors: mainly the higher temperatures associated with the seafloor spreading, the distance from the Mediterranean Sea and the silling of the basin across Bab-el-Mandeb from the Gulf of Suez. The Habab Formation is generally accepted as the equivalent of the Globerigina Marls but it is primarily a basin flank facies and occurs mainly in a narrow zone along the coast. Lenses of Habab "facies" extend into, and underlie, the salt but, in Ethiopia, have proven thin by comparison to the offshore Sudan area (Carella and Scarpa, 1962). To date the only encouragement to exploration for pre-salt Habab objectives has been the discovery of gas, mainly Methane, in the C-1 well. The oil shows in Dahlac-7 and Adal-2 on Grand Dahlac Island occur in a Habab lens near the top of the salt.

Interest in the Ethiopian Red Sea basin has been based mainly on the possibility of Habab Formation underlying the salt in local areas. In this regard, however, the thickness of the Amber Salt and the high heat flow rates in the basin are complicating factors. In Dhunishub-1, a temperature of 171ºC was measured at -3,865 metres and a temperature of 193ºC was estimated at -3,363 metres in Secca Fawn-1. Since both measurements were made in the salt and 150ºC is generally considered near the upper limit for oil preservation, it appears unlikely that there are any significant hydrocarbon deposits in the pre-salt sediments in these areas. Where the salt layer is over 2,500 metres thick, the Habab Formation, if present under the salt, will probably be thermally post-mature.

A further complication to exploration of the pre-salt section is the recognition of Eocene metamorphism in the basal sediments of the Amber-1 well. In the Gulf of Suez porous Mesozoic and Palaeozoic sediments are important reservoirs. If the Eocene metamorphism is widespread in the Ethiopia offshore basin, any porosity and hydrocarbons in the pre-Eocene section will probably have been destroyed.

Future exploration in the Ethiopian Red Sea might best be concentrated in the extreme south. The high temperature gradients and the Eocene metamorphism in the northern area may reflect the proximity to the most developed segment of the Red Sea Rift (Frazier, 1970). If the Red Sea spreading axis ends around 15ºN (Kazmin, 1972) heat flow rates in the southern area may be significantly lower, and the area of unprospective volcanogenic sediments in the basin axis may be significantly reduced. Also, the Habab Formation may be better developed in this area - a product of the decreasing salinity near the basin margin and periodic inflow of marine waters across the Bab-el-Mandeb sill. Shell Ethiopia recently drilled a well in this area and the results will be important in an evaluation of the basin.

Exploration anywhere in the Red Sea will require top quality seismic reflection data to permit reconstruction of the Miocene basin, especially in the search for intra-rift horst blocks. In the Gulf of Suez, rapid facies change from salt to limestones occurs over Lower Miocene horst blocks (Heybroek, 1965). Similar structures in the Ethiopian Red Sea Basin may not have been recognised on the seismic data recorded in the sixties and could be prospective.

2. The Ogaden Basin

The Ogaden Basin covers an area of over 350,000 sq kilometres and contains over 5,000 metres of Phanerozoic sediments. During the 1950s, exploration in the eastern Ogaden confirmed the presence of a thick sequence of Mesozoic carbonates and evaporites, which graded eastward into basinal shales. This stratigraphic analogy to Saudi Arabia raised great hopes for the discovery of a major petroleum province in the region. However, surface mapping, shallow core drilling and geophysical surveys - which had been the successful exploration techniques in Saudi Arabia - all proved unsuccessful at defining deep basement structure in the Ogaden. This reinforced the concept that the Ogaden was a "tabular" region (Murdoch, 1947), generally limited in oil potential because of an absence of structures to trap any generated hydrocarbons. This early exploration of the basin was concentrated in the eastern region but aeromagnetic surveys in 1970-71 discovered a deep sedimentary basin west of the Marda Fault Zone. This region had formerly been considered a shallow basement province, largely because of erroneous reports of basement outcrops in the Wabe Shebelle River in the basin centre.

Thirteen wells have been drilled in the Ogaden Basin, yielding an impressive record of oil and gas show, particularly in the western sub-basin. The Calub-1 tested gas from Adigrat and Calub sandstone reservoirs. Total estimated reserves in the field which covers 93 sq. kilometres are 1.6 Tcf, with 75% recoverability. The El Kuran wells on the western flank of the basin yielded "continuous oil and gas shows" through the Lower Cretaceous and Upper Jurassic section, (Geol. Survey Ethiopia, 1976), and significant oil shows were reported in both Hilala-1 and Magan-1. An oil show in the Adigrat Sandstone was also reported from Galadi-1 (Jelenc, 1966). In evaluating the drilling results in the basin, it is significant to note that at least five of the wells were not located on structures (Purcell, 1979). These shows highlight the potential of the Ogaden Bin and should encourage further exploration.

The main clastic reservoir units in the Ogaden Basin are the Adigrat Sandstone and the Calub Sandstone. The best known carbonate reservoir is the porous dolomitized Lower Hamanlei Formation. Clift (1956) and others have suggested that the Uarandab Formation is the main Mesozoic sourcing unit - though limited analyses by Elwerath (1967) did not reveal a high organic carbon content. The Bokh Shale may be the sourcing unit for the Calub Gasfield and interbedded shales could source Adigrat and Hamanlei reservoirs. The evaporites of the middle Hamanlei Formation and the Main Gypsum Formation are important capping units.

The main concern expressed by petroleum geologists about the Ogaden Basin is the absence of significant structures. In Saudi Arabia most producing fields occur in large Upper Mesozoic anticlines which were caused by upwelling salt or major basement faulting. The limited data available on these structures reveals that structural growth was initiated, or renewed, in the Upper Jurassic and continued through the Cretaceous (Beydoun, 1975). Widespread tectonism involving both salt movement and basement faulting also occurred in the Horn of Africa in the Upper Jurassic but apparently did not establish the pattern of stratigraphy and structure that caused the unique productivity of the Saudi Arabian Basin. Salt-related structures drilled in Kenya and Somalia were dry and few major basement structures have been identified in the region. It is possible that the continental-scale forces acting on the Afro-Arabian plate at this time may have involved a compressional component in the "unstable shelf" province of Saudi Arabia while only tensional forces acted on the Horn of Africa, causing fewer and widely separated structures.

In this regard, it may be significant that the Calub Gasfield and the oil shows in both Halala-1 and Megan-1 occur in the Marda Fault Zone. Galadi-1, which had an oil show, also appears to be located in a fault zone. These fault zones are associated with major gravity anomalies which suggests a Precambrian origin but at least the Marda Fault Zone has been active throughout the Phanerozoic (Purcell, 1976). Seismic surveys of the Marda Zone reveal abrupt trend changes at the base Hamanlei level, strongly suggesting basement control (Elwerath, 1967). It is possible that these broad, poorly defined zones of weakness have localised the epeirogenic movements in the basin, with differential adjustment during uplift and subsidence of the region causing drape structures over horst and tilted blocks. Structures may also have forced by local compression of graben fill sediments. This faulted topography along the zones during the Jurassic could also have juxtaposed source and reservoir rocks: that is, porous sands and carbonates could have developed above wave base on the horst blocks while source rocks were forming in the reducing environment of the adjacent deeper water pools.

Figure 5, an interpretive cross-section of the Ogaden Basin, shows the main formations and facies, and reveals the apparent magnitude of the central Marda Fault Zone arch. The data available suggests that the zone is particularly interesting for future exploration in the basin.

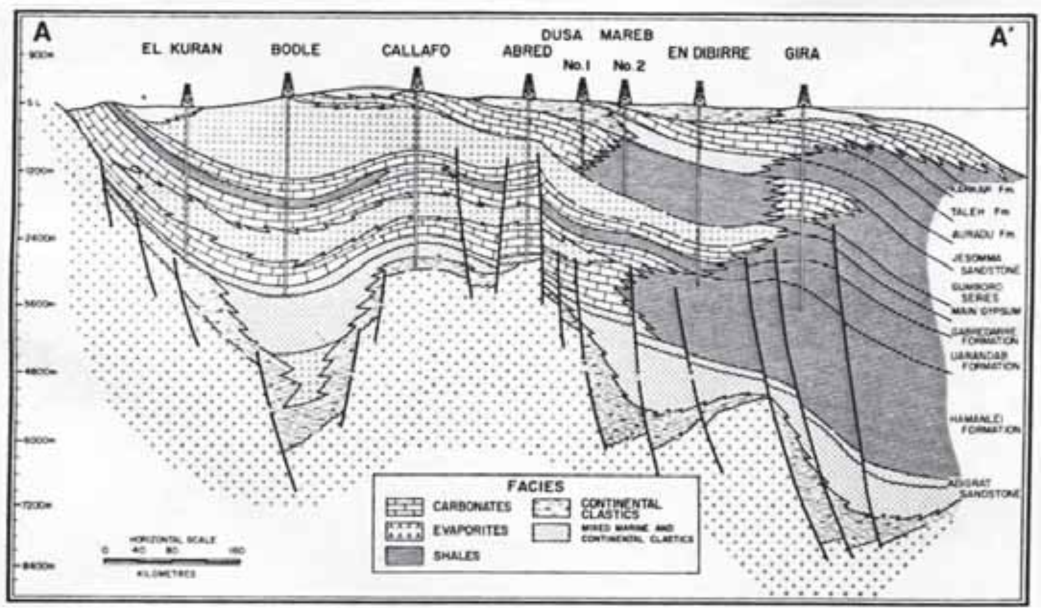

Figure 5: **Interpretive cross-section (E-W) across the Ogaden Basin.**

The interpretation below the wells, specifically the structure and stratigraphy of pre-Adigrat section, is subjective.

It should be noted that the results of exploration in the Ogaden Basin by the Tenneco group were not available to this review and should significantly improve understanding of the area.

SUMMARY

Two phases of rifting and sea-floor spreading have influenced the sedimentary history of Ethiopia. The first phase commenced in the Permian and led to the formation of a linear rift valley across Gondwana. Subsequently this rift developed into a spreading centre which, following a complex history, has expanded into the western Indian Ocean. Mesozoic sedimentation was primarily controlled by subsidence of the newly formed continental margin but differential or isostatic adjustment along the coastal fault zones repeatedly silled the inland basin, causing a cyclic pattern of carbonate and evaporite deposition. The second phase of rifting may have been initiated in the Gulf of Aden in the Mesozoic, but was principally a Tertiary event, involving the formation of the Red Sea, the Gulf of Aden and the Ethiopian rift valley. These tectonic events significantly influenced the petroleum potential of the Ethiopian region.

Rift faulting has established many important oil provinces - the Rhinegraben, the Gulf of Suez, the Sirte Basin (Libya) and the North Sea being useful examples. Intra-rift horst blocks cause drape folds and localize development of porous sandstone and carbonate units, while the adjacent deeper waters favour development of source rocks. Generation is stimulated by the moderately higher geothermal gradients and oil migrates into the contemperaneous or older reservoirs on the horst blocks. The rift faulting in Ethiopia did not produce a major petroleum province for a variety of reasons. The Permian rift only developed into a deep basin in the Ogaden area where it may contain hydrocarbons. However the sediments are now deeply buried under younger rocks over large areas and only one prospective element, the Marda Zone, has been defined. During the relatively stable Mesozoic era, potential source and reservoir units were deposited over most of Ethiopia, but these sediments were subsequently eroded or buried under volcanics, except in the Ogaden region, where exploration is hampered by a general paucity of contemperaneous structure. By contrast, the Tertiary era involved intense uplift, faulting and volcanism, which exposed most of the region, established evaporitic conditions in the Red Sea and precluded the formation of petroliferous deposits in the Ethiopian rift valley and Afar. Only two sedimentary basins with any potential for significant hydrocarbon deposits are present in Ethiopia; the Red Sea Basin and the Ogaden Basin.

Ethiopia is famous for the Tertiary rift system which is expressed so dramatically in the topography of the country. The oil explorers might be forgiven for wishing that the rift was just a little less spectacular. If that had been the case, most of the Mesozoic basin might not have been eroded and covered with basalt, the Red Sea might not have become hypersaline and the rift valley might have filled with thick lacustrinal and marine sediments. The history of petroleum exploration in Ethiopia would have been a different story.

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