THE GEOLOGY AND PETROLEUM POTENTIAL OF THE OGADEN BASIN, ETHIOPIA

P G PURCELL

1979

Author's Notes

"The possibilities of the occurrence of petroleum in Ethiopia is a subject of considerable interest in connection with any plan for the development of the country. The exploration of such resources, if they exist, would solve the problem presented by the lack of fuel for industrialisation; this would be only one advantage. The benefits of being able to export such a community in the world market and of having an industry which would provide employment to thousands of workmen would be far-reaching".

Murdoch (1947b)

Thirty years later this observation is even more accurate. Exploration for petroleum is a matter of national importance, and the Ogaden Basin, with an impressive record of oil and gas shows, provides the main possibility of establishing commercial production in Ethiopia.

It is an unfortunate reality that several decades of unsuccessful exploration in the Horn of Africa have sponsored a bias against this region, including the Ogaden Basin of Ethiopia. To counter this bias and encourage interest in the area, the potential of the vast Ogaden Basin must be advertised by publication of the results of exploration surveys in the basin. The recent publication of the report "Oil and Gas in Ethiopia" is an excellent beginning. It is hoped that this review will be a useful second step and that it will be followed by other publications on the basins of Ethiopia.

The work is dedicated, as a gesture of gratitude, to the people in the Ministry of Mines, and Whitestone Ethiopia Petroleum Company that it has been so pleasing to know and work with these last few years.

P. G. Purcell
Addis Ababa
December 1976

Addendum #1

Plans to finalise this volume after the writer's return to Australia in 1977 did not proceed because security restrictions regarding the Ogaden region precluded export of the original maps and figures from Ethiopia. Since that material was unlikely to be available in the foreseeable future, this report was distributed in final draft form, with a number of figures missing. In response to recent requests for a copy of the paper, the 1979 draft has been retyped and edited, and several figures, missing or incomplete in that draft, have been redrawn from old prints and included. Minor text changes have been made for clarification. There are no changes to the original conclusions and recommendations.

Perth, WA
November 2003

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ABSTRACT

The Ogaden Basin is located in southeast Ethiopia and covers an area of over 350,000 square kilometres. The basin extends into Somalia and Kenya and contains over 7000 metres of Permian to Tertiary sediments. Mesozoic and Tertiary sediments outcrop in the basin with a linear contact along the northwest-trending Marda Fault, which divides the basin into western and eastern sub-basins.

The basin developed in the Permian when extensive rifting occurred in eastern Africa. The Permian basin was controlled by northwest- and north/northeast-trending faults and accumulated an estimated 4000 metres of partly marine sediments. On the Marda Fault Zone deep wells have identified three distinct units: the basal Calub Sandstone, the Bokh Shale and the Gumburo Sandstone.

In the Triassic, subsidence of the newly formed continental margin caused a major transgression across the region, lead by the shoreline Adigrat Sandstone. This unit grades upward into the Liassic-Oxfordian Hamanlei Formation, primarily limestones and dolomites, with a marked Liassic evaporite zone. The Mesozoic transgression reached its maximum extent in the Oxfordian, when the dark shales of the Uarandab Formation were deposited. It is overlain by the Gabredarre Formation which marks the beginning of the upper Jurassic regression. In the lower Cretaceous the Main Gypsum Formation was precipitated in the basin centre, with limestones and shoreline clastics of the Amba Aradam Formation deposited on the basin margin.

A major transgression occurred in the Aptian and deposited the Mustahil Formation. Withdrawal of the seas in the Albian is evidenced by Ferfer Gypsum, but tilting of the coastal area caused a renewed transgression in the Cenomanian and superimposed the coastal Somalia Basin onto the Ogaden Basin. A Palaeocene transgression was followed by minor transgressive and regressive cycles in the Eocene. Younger sedimentation was confined to the coastal and offshore areas of Somalia. During most of the Mesozoic era, bathyl to abyssal facies formed in coastal Somalia, controlled by the abrupt continental 'margin' along the Bur Fault.

Thirteen deep exploration wells have been drilled in the Ogaden Basin in Ethiopia and have yielded numerous oil and gas shows. The drilling record is particularly impressive along the Marda Fault Zone where the Calub-1 well discovered a gas field with an estimated 1.6 trillion cubic feet of reserves and two other wells tested free oil.

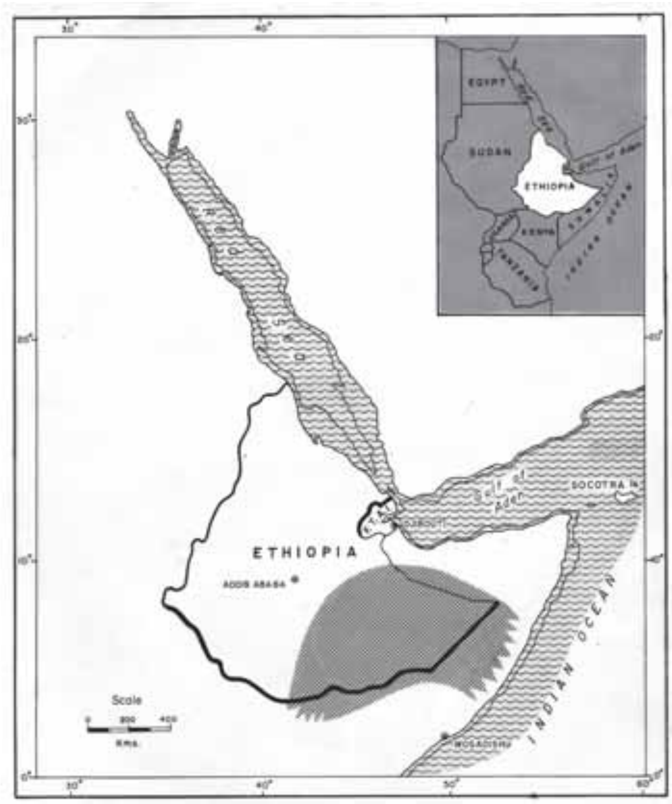
Good reservoirs have been identified in the Calub Sandstone, the Adigrat Sandstone and the Hamanlei Formation. The Adigrat Sandstone frequently shows up to 20% porosity and the Abred-1 well, located off-structure, penetrated over 400 metres of porous Hamanlei oolites and dolomites, which tested salt water.

Faulting appears to be important in the formation of structures in the basin. Specifically, rejuvenation of Precambrian fault zones during uplift and subsidence of the basin has determined major structural trends. Drilling in the Marda and Galadi fault zones suggests that drape folds and 'compressed graben' structures along these fault zones are prospective. Potential development of reservoir facies on the horst blocks, adjacent to local sourcing grabens, makes the Ogaden an exciting - and neglected - basin.

The hydrocarbon potential of the basin is clearly evidenced by its structure and stratigraphy and the success of future exploration is confidently predicted.

INTRODUCTION

The Ogaden Basin covers an area of over 350,000 square kilometres in southeast Ethiopia (Figure 1) and contains over 7000 metres of Palaeozoic and Tertiary sediments. It is one of the largest basins in eastern Africa and, with an excellent record of oil and gas shows, remains one of the most interesting wildcat basins in the world.



Interest in the petroleum potential of the basin dates from the early twenties but major exploration did not commence until after the Second World War. Then, the proximity of the giant Saudi Arabia oil fields sponsored great interest in the entire Horn of Africa area, where a similar geologic province was expected.

The early drilling in coastal Somalia identified an abyssal Jurassic facies but the first well drilled in the Ethiopian Ogaden Basin revealed a thick sequence of interbedded Jurassic carbonates and anhydrite. This suggested that the prospective shelf carbonate sequence of Saudi Arabia did indeed extend south into the Horn area and was present at favourable depths in the Ogaden area of Ethiopia and western Somalia (Bush, 1957). The second well drilled in Ethiopia, Galadi-1, (Figure 2) recovered oil from a porous basal sand and seemed to confirm the potential of the basin (Taylor, 1948a).

Figure 1. Location Map. Ogaden Basin, Ethiopia

However, exploration in the basin was greatly hampered by the incapacity of available geophysical techniques to define subsurface structure and, after two more wells failed to prove major oil deposits, interest in the area waned. In recent years, Tenneco Inc. has demonstrated that modern seismic reflection techniques permit detailed mapping of the basin. They also extended exploration into the western Ogaden and discovered a large petroliferous sub-basin in an area formerly considered a shallow basement region. The first wells drilled in this sub-basin, El Kuran-1 and 2, had numerous oil shows and the third well discovered a large gas deposit.

This note, expanding a lecture to the Geologic Survey of Ethiopia, utilises the results of exploration, mainly pre-1970, to describe the general geology of the area and comment on the petroleum potential of the basin. Some more recent data is also available: the Whitestone and Voyager companies have released the results of some of their surveys and the Ministry of Mines has recently published brief descriptions of the results of the Tenneco wells. However the results of the extensive geological and geophysical surveys by the Tenneco Group are still classified and the conclusions and predictions of this review are derived without those data.

Much of the information discussed is available in other publications (especially Mohr, 1962; Jelenc, 1966: Kazmin, 1972; Geol. Survey Ethiopia, 1976) but this compilation was intended to integrate all these earlier studies with other available information. Hence an attempt is made to fully document the stratigraphy and geological history of the area, while providing some subjective comments on the petroleum potential of the basin

Physiography

The Ogaden Basin underlies the extensive semi-arid region of southeast Ethiopia known as "the Ogaden". It covers parts of four administrative regions, Hararge, Bale, Sidamo and Arussi, but most of the basin lies within Hararge and Bale provinces, which are administered from the provincial capitals, Harar and Goba respectively.

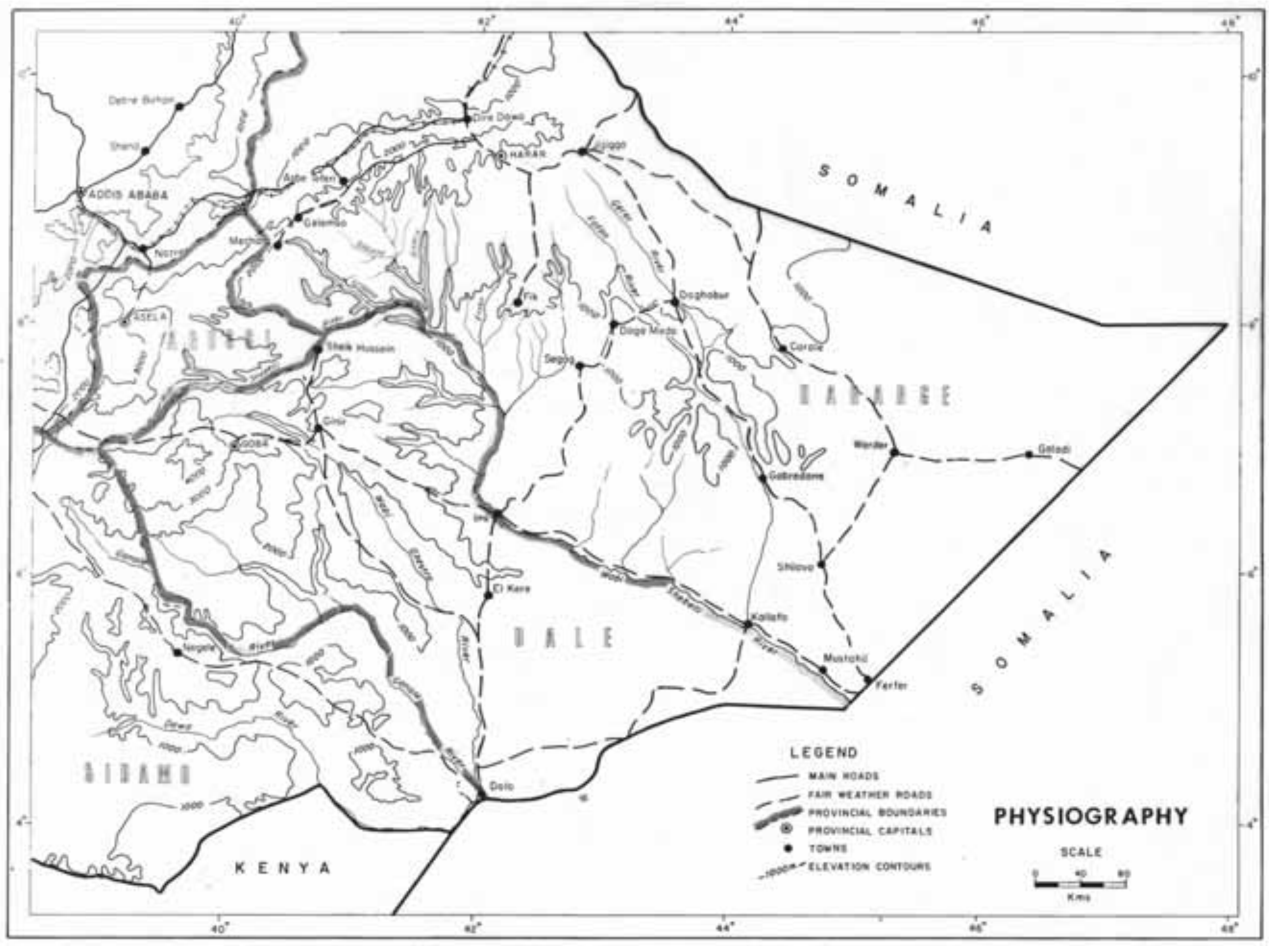


Figure 2. Physiography, Southeast Ethiopia

Elevation of the region generally decreases south and east from the highland plateau along the margins of the rift valley. This high plateau is deeply dissected in the north and west by tributary rivers of the Wabi Shebelli which drains most of the basin; in the southwest the Ganale Doria River system also drains southeast into Somalia. The decreasing elevation is reflected in the changing climate, vegetation and culture across the region. In the highlands good rainfall and rich soil supports an extensive agricultural community, but the land becomes increasingly arid below about 1500 metres. Most of the central and southern regions are rolling sandy and rocky plains, with some dune topography in the east. The population of the lowland region is essentially nomadic but agricultural settlement schemes are being developed in the Wabi Shebelli valley by the Ethiopian Government.

Rainfall in the region also varies from north to south. The highland areas have rainy seasons in March-May (Belg) and July-September (Kerempt). The Kerempt rains move slowly south across the region into Kenya in the last quarter of the year. The small rains occur over the desert area in April-May. Travel in the area during the rainy seasons is frequently difficult.

Access to the basin area from the capital, Addis Ababa, is via Harar or Shashamene, both of which are connected by bitumen roads. Good dirt roads extend from Harar (via Jijigga) and from Shashamene (via Goba) into the basin centre. These towns are served by regular DC-3 airline service. Smaller towns in the Ogaden have developed for trade or administrative purposes and are connected by fair, dry-weather roads; many have a weekly air service.

Regional setting

The Ogaden Basin was first described by Clift (1956) as "the sedimentary province of the Ogaden district" and delimited by the 44º 20'E meridian at the "gently dipping cuesta of upper Cretaceous continental sandstones". This excluded the entire western sub-basin area from the basin: and was probably based on early reports (Daniel, 1943; Murdoch, 1947a) of a thin, mainly non marine, sedimentary sequence in the western area Recent work has proved a deep sedimentary basin the western area (Figure 3), separated from the eastern sub-basin by a major northwest-southeast arch related to the Marda Fault Zone (Purcell, 1976a). This subdivision is reflected on geologic maps of the basin by the linear contact of outcropping Mesozoic and Tertiary units. The western and eastern depocentres of the Ogaden basin (Figure 3) are referred to in this volume as the Western Ogaden Sub-basin and the Eastern Ogaden Sub-basin respectively.

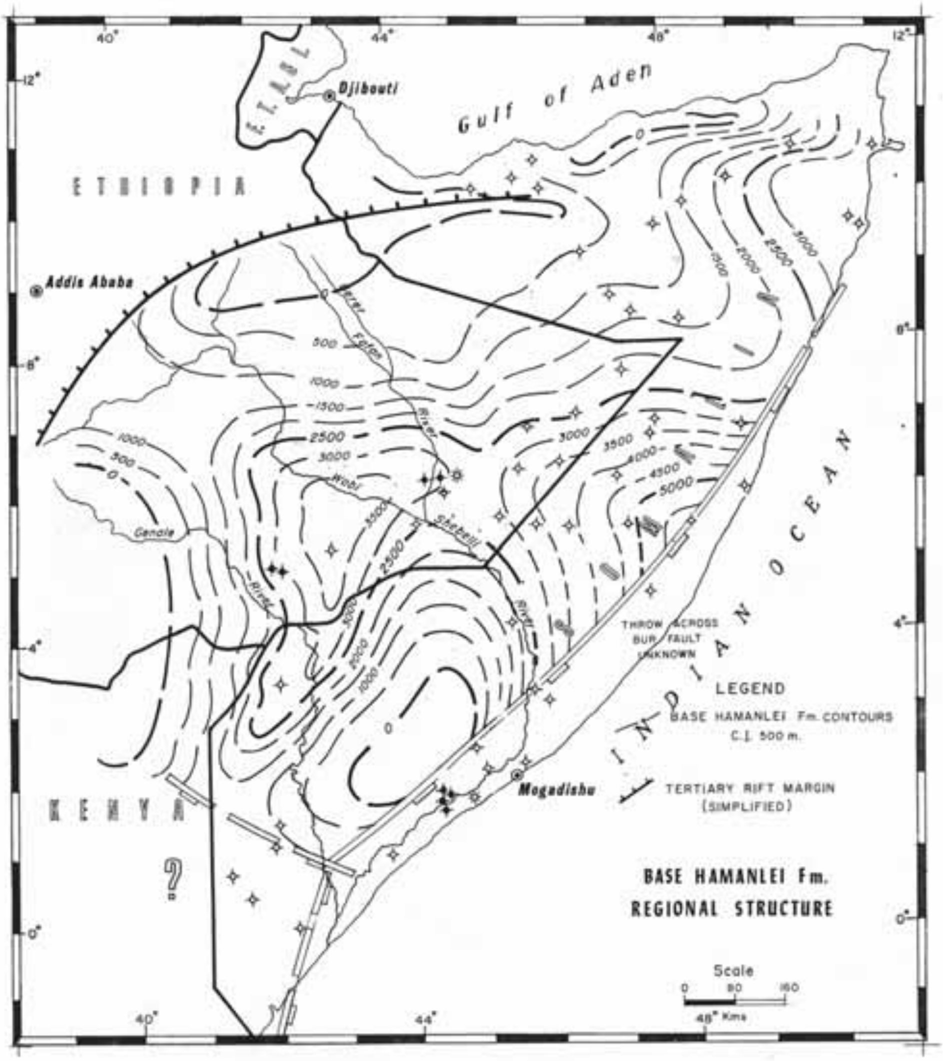


Figure 3. Base Hamanlei Formation Regional Structure Map

The basin is bounded by three major basement massifs: the Chercher Massif in the north, the Negele Block in the southwest and the Bur Massif in the southeast. The Nogal Arch, sometimes called the Los Anod Arch, extends southeast from the Chercher Massif and separates the Ogaden Basin from the northern Migiurtinia Basin. This arch was a subsurface feature until Cretaceous time (Mason, 1957) when major uplift elevated the northern region. These basement blocks are bounded by major fault/hinge zones (Figure 4) that formed in the Upper Palaeozoic and define two depositional axes, trending north-northeast and northwest respectively.

The north/northeast-trending element of the Ogaden Basin is part of a major trough that extended north from Tanzania through Kenya and Somalia where it has been referred to as the Mandera-Lugh basin. It contains an estimated 4600 metres of pre-Jurassic sediments and 3,000 metres of Mesozoic sediments near the Ethiopian border (Beltrandi and Pyre, 1972). The northern continuation of this trough beyond the Ogaden Basin is not clear. Beltrandi and Pyre (1972) suggested that the Jurassic hinge zone is coincident with the Afar margin near Mekele, where the warp fault scarp described by Mohr (1962) and confirmed by facies studies (Beyth, 1972) may be part of this system. Alternatively, Kazmin and Purcell (1977) extend the trough northeast across the western Ogaden Basin.

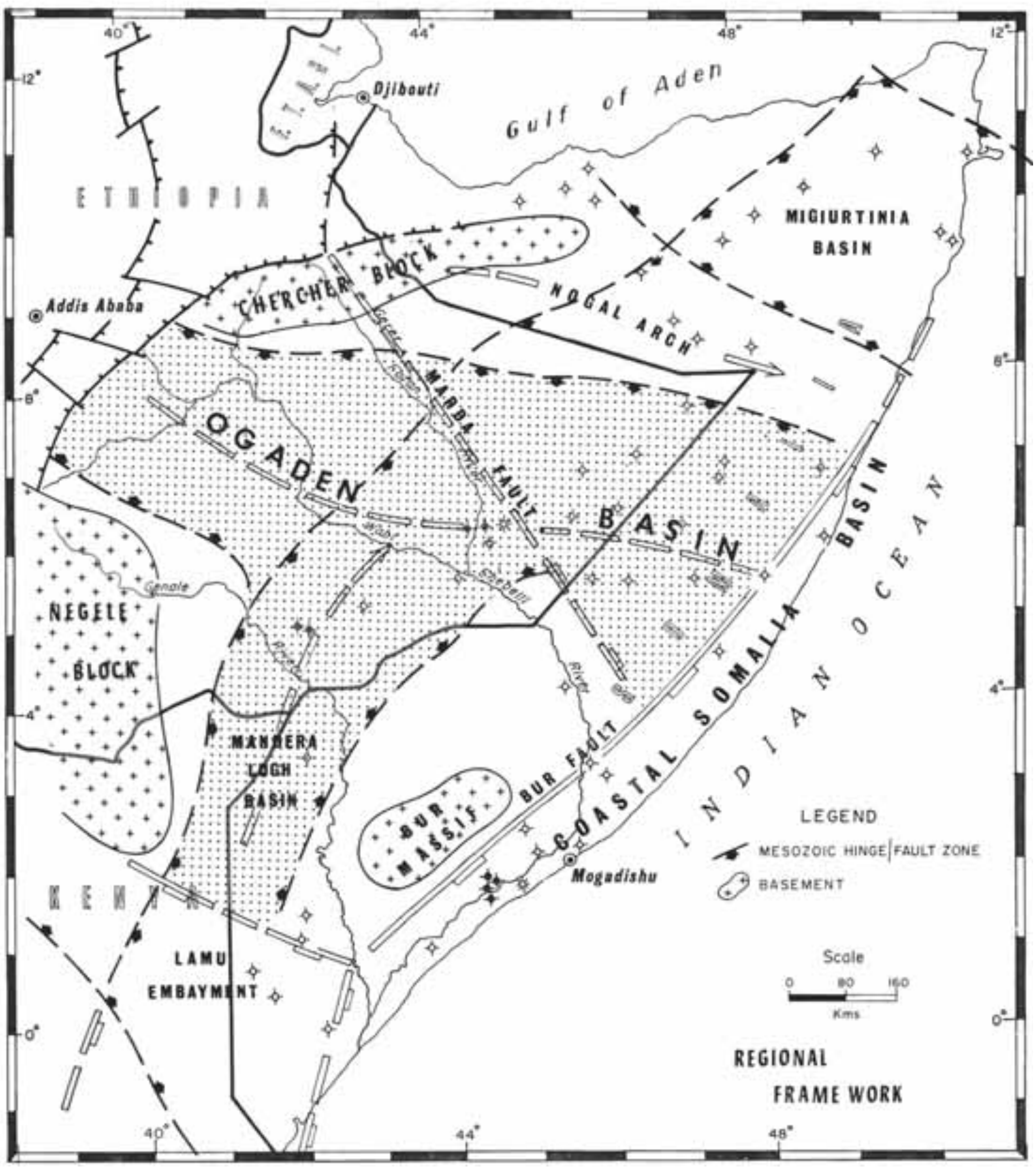


Figure 4. Regional Structural Framework, Ogaden Basin and Horn of Africa

The northwest-trending trough extends from coastal Somalia through the Ogaden and into the Abbai Basin in central Ethiopia. The eastern section has been called the Somalia Embayment by Barnes (1976) but, in Ethiopian terminology, is referred to as the Eastern Ogaden Basin (or Sub-basin, as in this volume).

The Upper Cretaceous to Tertiary sequence in the eastern Ogaden region unconformably overlie the Ogaden sequence and is sensu stricto part of a separate basin system, herein called the Coastal Somalia Basin. This distinction defines the Ogaden Basin as an Upper Palaeozoic-Lower Cretaceous feature.

Exploration History

The exploration for petroleum in Ethiopia has been a long and fascinating adventure. It begin in the 1920s when seeps were magic, boomed in the 1940s and 1950s when proximity to Saudi Arabia raised great hopes for the region and, more recently, has peaked and declined with the international trends of the 1970s. Wells drilled in the region (to 1977) are shown on Figure 5.

The first oil seep in Ethiopia was reported in 1860, and by the 1920s the prolific seeps of the Red Sea coast were widely known. Early reports (Molly, 1928; Belluigi, 1937) also refer to seeps in the Ogaden Basin: in the Gara Mulatta Mountains near Harar, in the Fafan and Gerer river valleys, and near Jijigga.

The first exploration licence for Hararge Province was granted in 1915 and subsequently transferred to the Anglo American Company, a London subsidiary of Standard Oil Company, ultimately incorporated into Esso. In 1920 this company organized a survey party, the so-called Dudley Expedition, to conduct geologic surveys in northern Hararge Province between Harar and Jijigga, and in the Afar Depression (Brown et al, 1943). In interim reports, two possible drilling sites were noted but the final geologic report on the concession was negative and the concession was cancelled (Brown, 1921).

During the next decade, exploration in Ethiopia focussed on the Red Sea coastal area and it was not until 1936, during the Italian Occupation, that systematic geologic mapping of the Ogaden Basin began. This work was performed by AGIP and their records were later used extensively by Sinclair Petroleum in early studies of the region (Taylor, 1947). In 1939 the Standard Vacuum Company (now Mobil) considered the offer of a concession over the Ogaden but declined in order to avoid acknowledging the Italian Occupational Government. (Anonymous, 1939) The company maintained its interest in the basin, apparently intending to apply for a concession after the war.

As it developed, that privilege went to Sinclair Petroleum Company who were granted an oil exploration licence covering all Ethiopia in July 1945. Preliminary work on the regional geology and detailed discussions with AGIP geologists focussed interest on the Ogaden region, (Taylor, 1947; Cecioni, 1945) and field surveys begin in that area. The influence on this work of the idea that the Horn of Africa was a similar geologic province to Saudi Arabia is revealed clearly in the company's Final Report (Bush, 1957), which stated that the first priority was to quickly scan the countryside for the presence of ‘Middle East type structures’.

After three years of photogeology and field surveying (Taylor, 1948b), a small structure near Gumburo was recognised as the best lead. Although this closed dome in the Eocene limestones covered only 6 square kilometres, with only 15 metres of 4-way dip-closure, it was still larger than the Ghawar surface structure. Reasoning that Gumburo might also develop at depth, Sinclair spudded Gumburo-1 in May 1949, but quickly discovered that two shallow volcanic sills were the cause of the surface structure. However, the well encountered a porous basal sandstone and a thick sequence of Jurassic carbonates, with some analogies to the Saudi Arabia section, demonstrating the presence of a prospective basin.

Subsequent seismic and potential method surveys focussed interest to the east, and Galadi-1 was spudded on February 5, 1952. It was finally abandoned three years later at a depth of 2769.5 metres. Several "oil impregnated sandstone" were encountered in the upper Adigrat Sandstone and testing is reported to have yielded some free oil (Straub, 1957). Stratigraphic boreholes offset from the well proved that Galadi was not on structure and the site was abandoned.

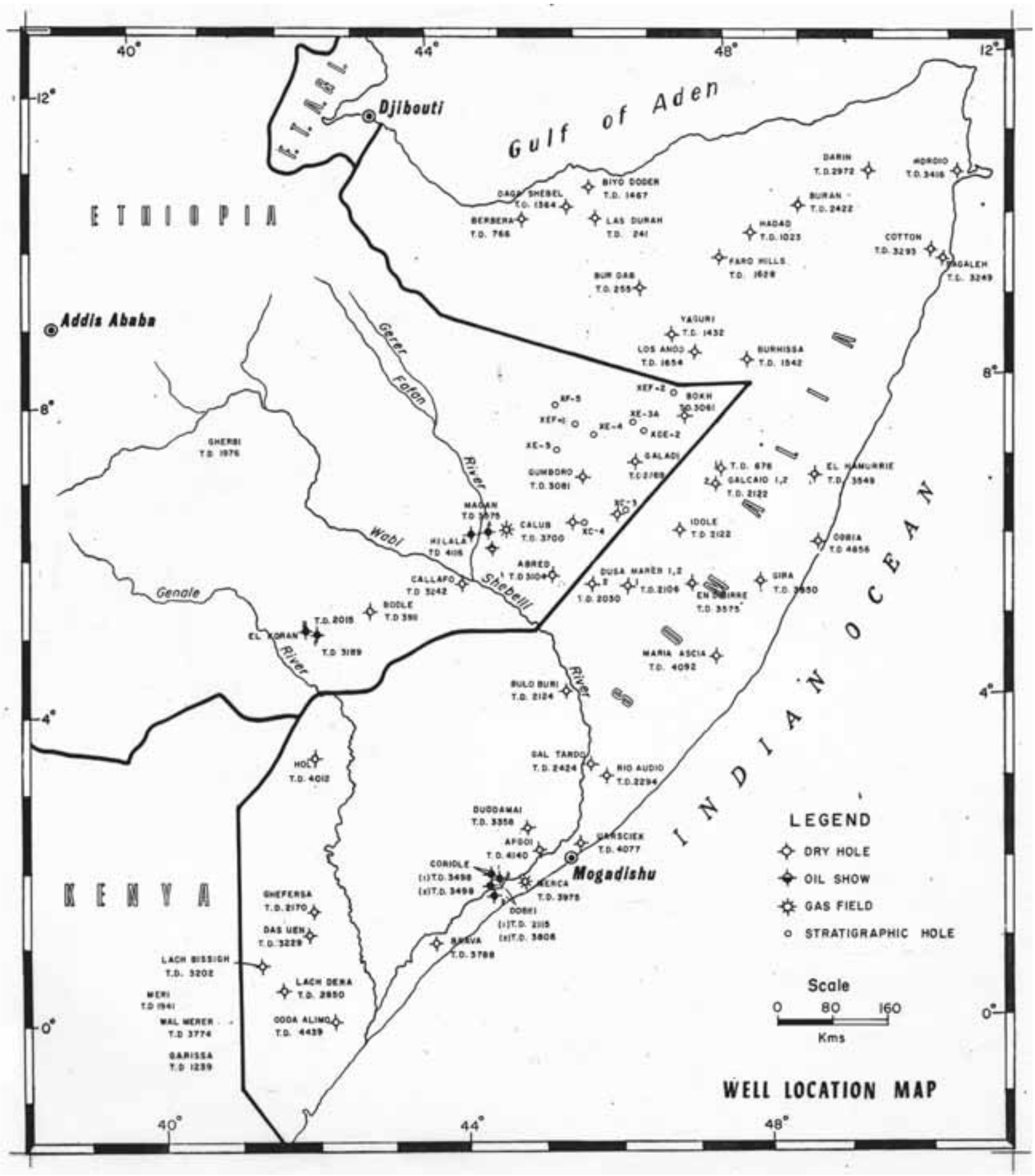


Figure 2. Well Location Map

Convinced of the basin's potential, but unable to map subsurface structures with available seismic techniques (Straley, 1954), Sinclair then drilled a grid of shallow wells in search of regional structure - a technique being utilised successfully in Saudi Arabia, where geophysical techniques were also proving inadequate. However the 19 holes drilled in eastern Ethiopia revealed only basinward dip and, having exhausted all available exploratory techniques in their efforts to locate structures, Sinclair relinquished the concession in December 1956.

In March 1959 Gewerkschaft Elwerath, of Hannover, Germany, signed a concession agreement covering the eastern Ogaden region. Geology and photogeology focused attention in the lower Wabi Shebelli area where seismic and gravity surveying commenced in 1960. As a result of this work, Abred-1 was spudded in June 1963. It was plugged and abandoned without significant hydrocarbon shows five months later, at a depth of 3104 metres. The Cretaceous section tested fresh water but the Hamanlei and Adigrat sections yielded salt water. Elwerath concluded that the structure was Cretaceous but it seems probable that the well was located off structure: gravity surveying, now recognized as useful in locating major basement structures in the area, locates the crest of the Abred structure over 20 kilometres to the east (Purcell, 1975b).

Reasoning that the oil show in Sinclair's Galadi-1 may indicate favourable structures in that region Elwerath moved its attention to the northeast and spudded Bokh-1 in November 1964 on a small structure up-dip from Galadi. This well was abandoned at a depth of 3062 metres in June 1965, without any shows of oil or gas being reported. The Upper Jurassic and Lower Cretaceous section was missing at unconformity, the Middle Jurassic reservoir was flushed and the Adigrat Sandstone tested salt water. Elwerath concluded that this structure was also of Cretaceous age.

Further seismic reflection surveys in 1965 and 1966 identified few structures: two were compromised by magnetic evidence of subsurface volcanics and a third was considered remote from the sourcing section. Again, it was an inability to locate drillable structures that was the main issue in the company's decision to relinquish the concession in 1967.

In 1969, ahead of the early seventies boom in the Horn of Africa, Tenneco Oil Company obtained an exploration licence over the Ogaden Basin. Photogeology and aeromagnetic surveys led to the drilling of El Kuran-1 early in 1972. This well was located on a surface structure but subsequent seismic surveying showed that the structure was not present in the subsurface. The well had near continuous oil shows through the Gabredarre and upper Hamanlei section and oil and gas shows in the Lower Hamanlei and Adigrat sequences. A step-out well, El Kuran-2, perhaps seeking more favourable porosity and permeability conditions, also had oil and gas shows "through the entire section" (Geol. Survey Ethiopia, 1976).

The seven other wells drilled during 1972-73 by Tenneco Group, by then consisted of Tenneco, Texaco and Chevron, were based on detailed seismic reflection surveys utilising the Vibroseis system.

The third well, Calub-1, discovered a gas field, with pay zones in the Adigrat Sandstone and a basal (?)Permian sandstone which Tenneco called the Calub Sandstone. This well tested over 35 MMcfd on a one inch choke, with a surface pressure of 1500 psi, and condensate at about 28 bbl/MMcf, The field is reportedly estimated to have reserves of 1.6 trillion cubic feet.

Magan-1 and Hilala-1, both west of Calub-1, yielded uncommercial free oil (32^{o} API) from the Hamanlei Formation. These two wells and Calub-1 are located in the complex Marda Fault Zone and define the zone as a principal exploratory objective for future work. Bodle-1, in the basin centre, and Callafo-1, up-dip towards the Bur Massif, had no significant shows. Gherbi-1, on the northwest flank, tested fresh water from Adigrat; the Upper Hamanlei section showed weak fluorescence but tested salt water.

The Tenneco Group relinquished the concession in 1975.

Subsidiaries of Whitestone International, Inc. and LL&E International, Inc. signed an agreement with the Ethiopian Government in March 1973 for a permit over the north and northeast margins of the Ogaden basin, partly covering areas relinquished by Tenneco (Stilley, 1973). The presence of Jurassic outcrops over most of the area qualified use of photogeological studies, with subsequent gravity and magnetic surveying of the main areas of interest. Structural leads in the Marda Fault Zone near Daghabur and to the west near Ginir were defined by these surveys (Purcell, 1975a) but aeromagnetic surveying subsequently revealed a thin sedimentary section in these areas, and the company relinquished the concession in 1977.

Voyager Petroleum Company, operator for a Joint Venture of Canadian companies, also commenced exploration of an area on the west flank of the basin in 1973 but after photographic and detailed gravity surveys, relinquished the concession in December 1974.

STRATIGRAPHY

General

. The surface geology of the Ogaden Basin is shown on Figure 6. The basin is subdivided into Mesozoic and Tertiary outcrop provinces by the Marda fault lineament (Purcell, 1976a,).

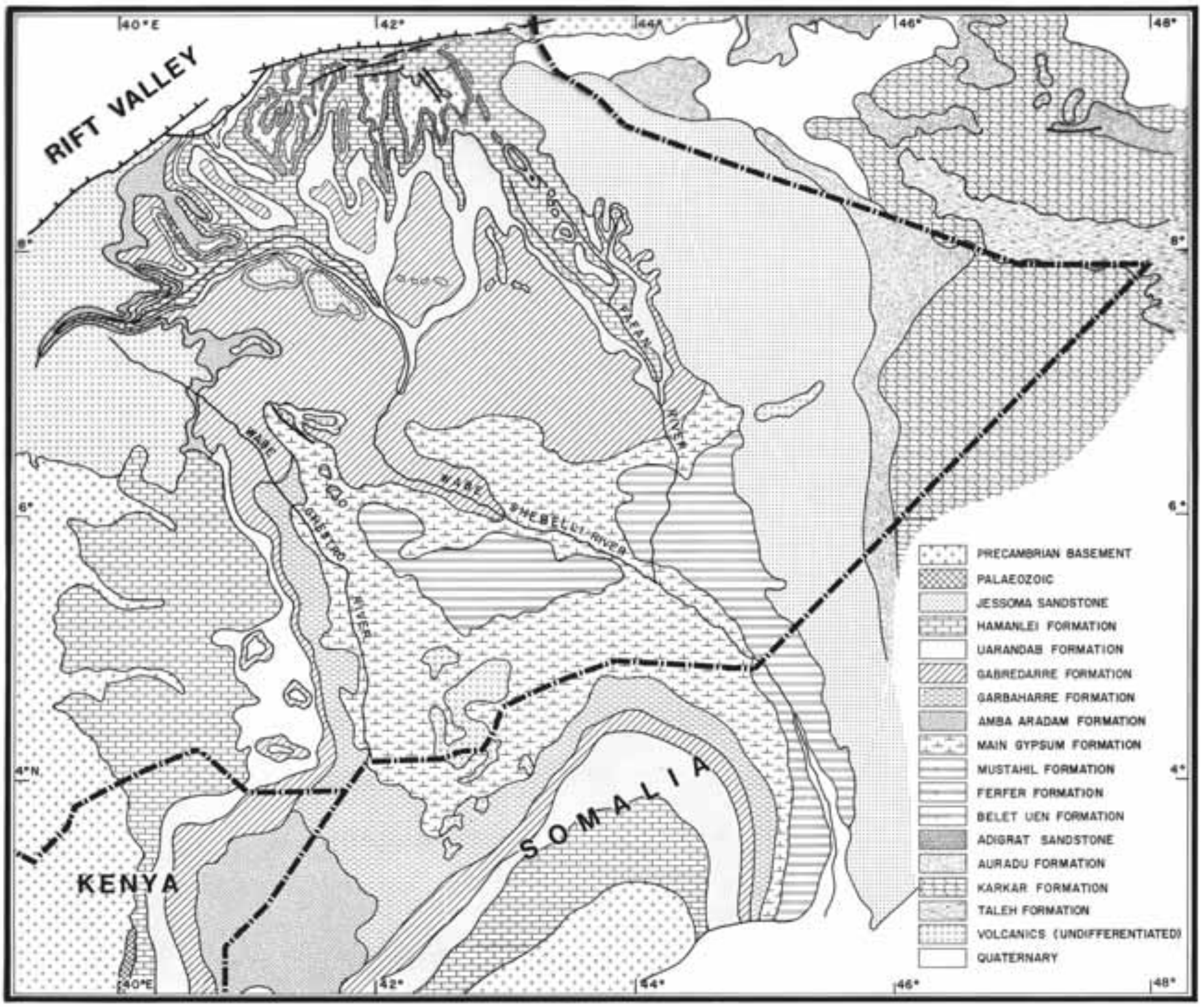


Figure 6. Geological Map, Ogaden Basin

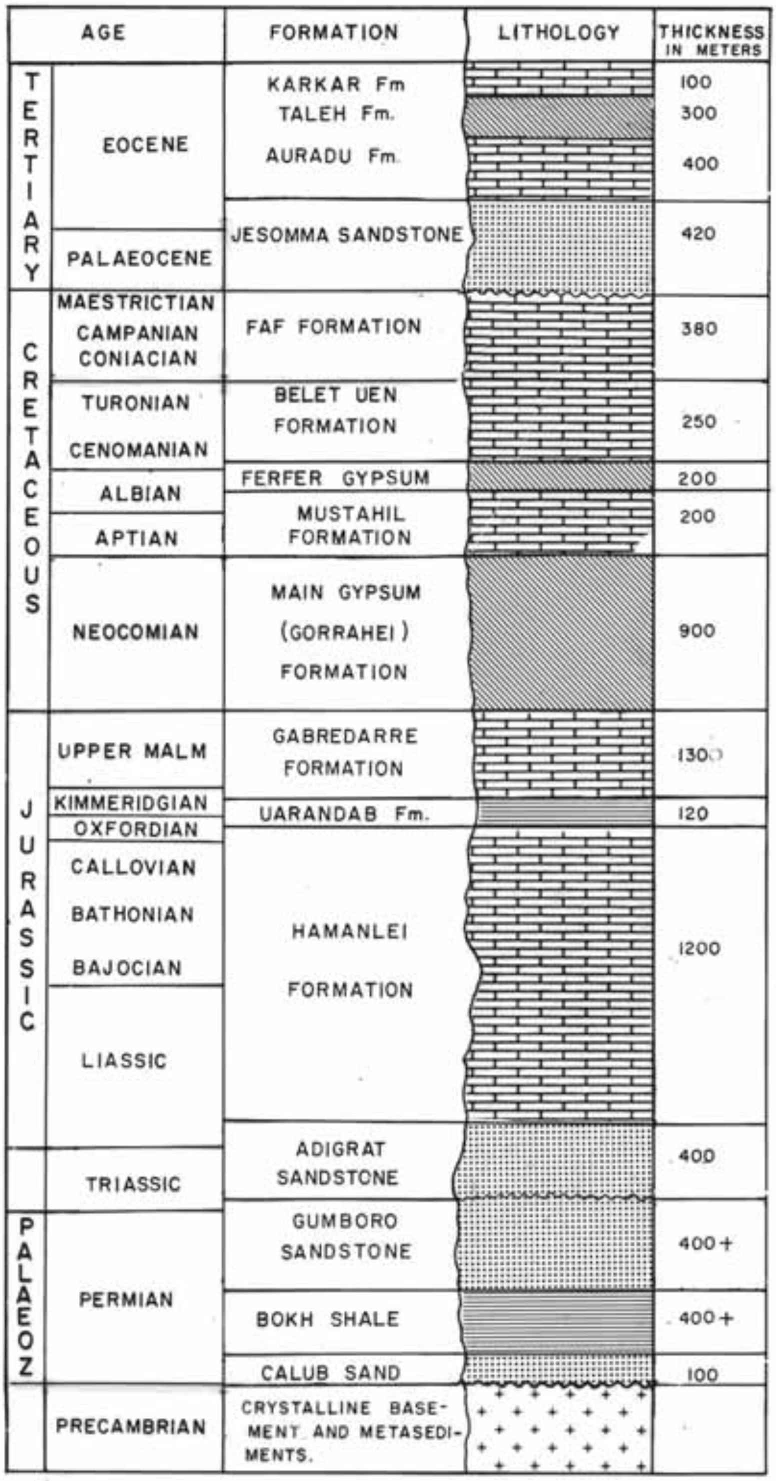


Figure 7. Generalized Sedimentary Column, Ogaden Basin

Tertiary sediments cover the entire eastern region, and the outcrop pattern reflects the north-northeast orientation of the Coastal Somalia Basin. In the Western Ogaden Sub-basin, Jurassic sediments outcrop over most of the region and are overlain by Cretaceous rocks around the basin margin and in the basin centre. The southeast and southwest areas are based mainly on Merla et al (1973); the northern area draws considerably on extensive photogeological studies by Tasfai Gebre Hanna (1975) and field checking by Whitestone Ethiopia Petroleum.

Figure 7 is a generalized stratigraphic column for the basin, using the stratigraphic terminology favoured in this report. The relationship of to other terminology defined for the Ogaden basin and surrounding region is shown in Figure 8.

As discussed below, there are several ambiguities in the stratigraphic nomenclature of the Ogaden Basin. It is recommended that the formations be accepted as named and defined informally in this report. Future work may modify the dating and provide better descriptions or definitions of various formations, but the nomenclature outlined in this note would provide a useful framework for that work. This will be especially important in field mapping in the southwestern basin margin area.

The individual formations in the Ogaden Basin are discussed separately below.

Precambrian Basement

The basement rocks of the Ogaden Basin are of Precambrian age. Three basement massifs bound the basin and are clearly visible on geological maps of the region (Figures 4 and 6): the Negele

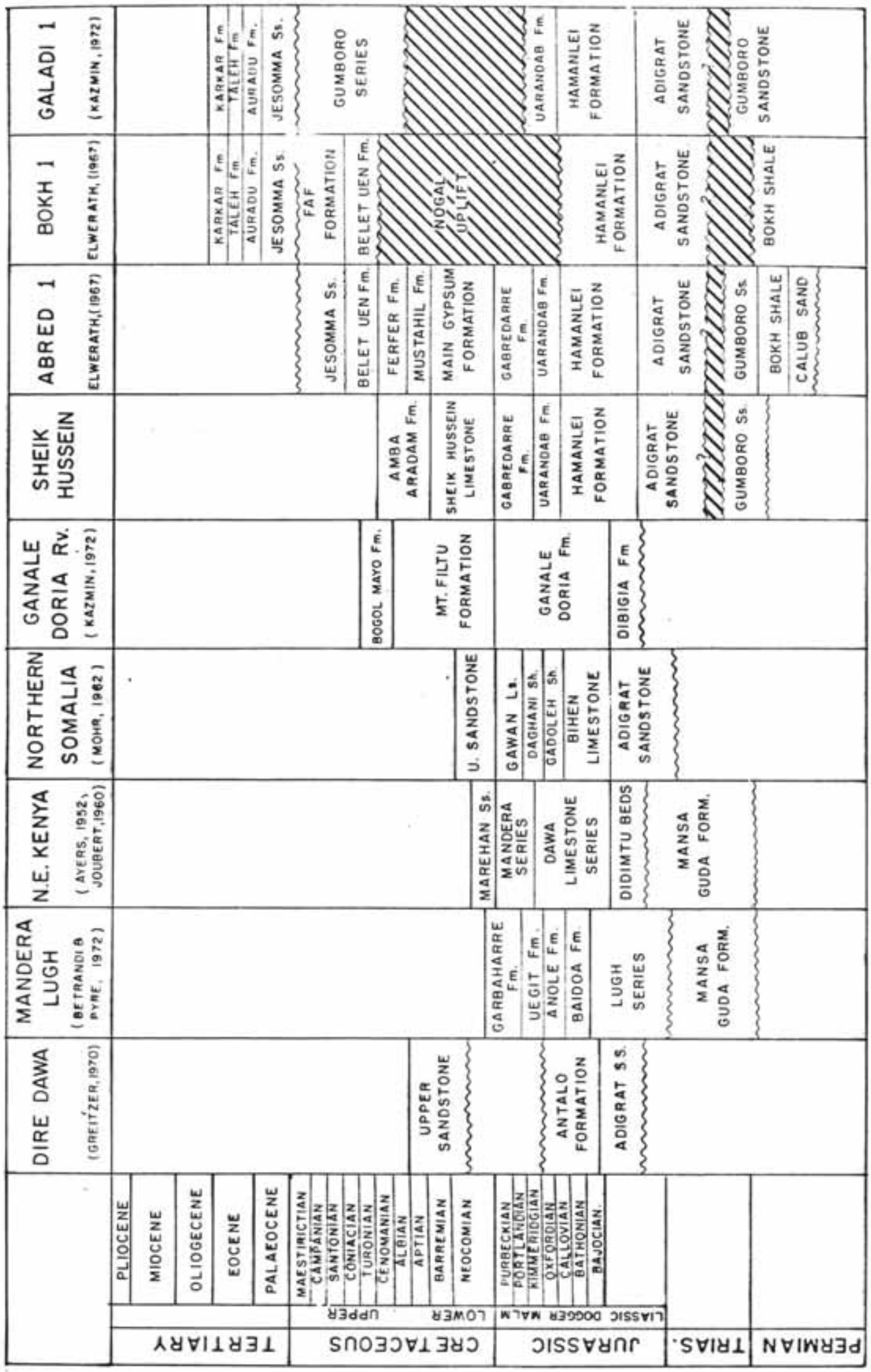


Figure 8. Stratigraphic Correlation Chart, Ogaden Basin and surrounding region

Block extends south into Kenya and marks the edge of the Permo-Jurassic marine incursion; the Chercher Block in the north extends into Somalia, and is part of the complex elevated zone along (what is now) the southern side of the Gulf of Aden; the Bur Massif is located entirely in Somalia.

Kazmin (1972) subdivided the Precambrian of Ethiopia into Lower, Middle and Upper complexes. The Lower Complex consists of a variety of granites, gneisses and migmatites, and forms the bulk of the Negele and Chercher massifs. The Middle Complex is relatively insignificant and is known only in the Negele Block as a low grade metamorphic succession filling troughs in the Lower Complex. The Upper Complex originated as Upper Proterozoic basinal sediments which, now predominantly greenschist facies, are markedly unconformable on the Lower Complex units.

Both the Upper and Lower complexes have been considered part of the Mozambique Belt (Unesco, 1969) but Kazmin (1972) included only the Lower Complex within the Mozambique Belt and considered the younger Precambrian fold belts in the Ogaden and Northern Ethiopia as part of the Upper Proterozoic Red Sea Geosyncline.

A general north-south trend, with variations trending to northeast and northwest, characterises the basement complex. This trend is marked in the younger fold belts and is superimposed an older trends, including east-west, in the granite-gneiss blocks. Faults of this submeridional trend were important in the formation of oil bearing structures in the Saudi Arabia Basin and may also prove important in the structural development of the Ogaden Basin.

The Upper Complex basement is predominant in the eastern region, where it may be correlated in Somalia with the Inda Ad Formation, which consists of weakly metamorphosed, folded and foliated mudstone and greywacke with local bands of slate, quartzite and limestone.

PALAEOZOIC

The Palaeozoic era has traditionally been described as a period of denudation in the Horn of Africa (Dainelli, 1943; Mohr, 1962). This concept has been sufficiently accepted to obscure the significance of local and regional indications of a major Upper Palaeozoic sedimentary cycle in the region. The presence of extensive Permian sedimentation in the Ogaden region is now well established and has been discussed by Purcell (1977) who estimates, by analogy to the Mandera-Lugh Basin (Beltrandi & Pyre, 1972), about 4000 metres of Permian sediments in the western Ogaden Sub-basin axis.

While Upper Palaeozoic sediments may be widespread in the subsurface, only two areas of outcrop are known in the Ogaden: near Negele (Kazmin and Purcell, 1977) and in the Ramis River valley (Lebling and Nowack, 1939). Both outcrops comprise cross-bedded sandstones, intercalated with silts, grits and shales, above a basal conglomerate, and occur in linear faulted depressions in the basement surface.

In the subsurface, pre-Adigrat sediments (as the Palaeozoic sediments are commonly called in Ethiopia), were first discovered in Gumburo-1 where an anomalous thickness of the ‘basal sand unit’, nominally the Adigrat Sandstone, occurred. There is no description of the contact of the Adigrat with the underlying unit, which was termed the Gumburo Sandstone, but, by analogy to outcrops in northern Ethiopia, it is probably a slight unconformity. The absence of a marked unconformity suggests that deposition was interrupted only briefly and that the Gumburo Sandstone is mainly of Permian age. Locally, the two units are indistinguishable and appear to be part of a continuous depositional cycle.

The Gumburo Sandstone has been recognised in other wells in the basin, including Calub-1, where it consists of 400 metres of sandstone, with chert pebbles and anhydrite. Calub-1 penetrated the most complete Palaeozoic section known to date in the Ogaden Basin: the Gumburo overlies 1200 metres of shale and a basal arkosic sand unit, 85 metres thick It may be correlated regionally with the Karroo sequences of east and southern Africa – though the 'Pre-Adigrat' term remains more commonly used in Ethiopia. The middle shale unit has been correlated with the Bokh Shale, and the basal arkose was named the Calub Sandstone.

The Bokh Shale is named for the 400 metres thick shale unit in the Bokh-1 well, where it overlies 300 metres of dolomite greywacke, arkose and conglomerate, with no simple equivalent of the Calub Sandstone recognized.. In early unpublished company reports, Elwerath suggested that the entire pre-Adigrat section in Bokh-1 was of Permian age, but later (Elwerath, 1967) interpreted the sequence as Precambrian 'dynamometamorphics'. There is a definite lithologic similarity to the Inda Ad Formation, but dips measured in cores in the shale units were only 20º, whereas the Inda Ad Formation characteristically dips nearly vertically.

The data available at this time do not resolve this uncertainty. Nor do they demonstrate a continuity of the shale unit from Bokh-1 to the Calub area. Hence, while it is reasonable to assign the Bokh Shale of Calub-1 to the Permian depositional cycle, clarification of the Bokh-1 section will require more subsurface control.

This Bokh Shale unit has proven gas-condensate source potential and the discovery of gas-condensate in the Calub Sandstone identifies the Permian sediments as a new objective in the basin.

MESOZOIC

Adigrat Sandstone

The Adigrat Sandstone was first defined in northern Ethiopia near the town of Adigrat (Blanford, 1870) and included sediments now described, in common usage, as pre-Adigrat (that is, Gumburo Sandstone equivalent). The Adigrat Sandstone is now accepted as the basal unit of the major Mesozoic transgression across the Horn of Africa and, in Ethiopia, varies in age from Triassic in the southeast to Middle Jurassic in the north. In the Ogaden Basin it is thought to overlie the Palaeozoic sediments with slight unconformity and it grades upward through a transition zone into the carbonate Hamanlei Formation.

Outcrops on the north and northwest flanks of the basin consists of intercalated sandstones, calcareous sandstones, dolomites, shales and marls (Kazmin, 1972). In the southwest a thin sequence of interbedded limestones and sandstones at the base of the Dibigia Formation probably represent the Adigrat Formation (Mohr, 1962) but this unit occurs only locally (Kazmin, 1972). Farther south, in Kenya and Somalia, the Adigrat cycle is also poorly developed. In the Ogaden Basin, shale and evaporites occur as interbeds in the formation, and in the eastern area subdivide the Adigrat into lower and upper sand members. The thinning towards the north, which occurs at the expense of the lower member illustrates the transgressive nature of the Adigrat unit. Elsewhere on the basin flanks, the thickness also varies, but a basin average thickness of 110 metres is a reasonable estimate. The facies is generally shallow marine to littoral.

In the past, the failure to recognise the Permian sedimentary cycle in Ethiopia, and the presence of Triassic continental sandstones in Kenya, have complicated regional and local correlations of this unit. For example the type section near the village of Adigrat is now considered primarily pre-Adigrat sediments! (W. Morton, pers. comm). Similarly it is now being realised that in many areas of the Ogaden the mapped Adigrat Sandstone incorporates Palaeozoic sediments, e.g. the Chercher Mountains (V Kazmin, pers. comm). The usual correlation of the Wajir Sandstone of Kenya with the Adigrat Sandstone is not valid: the former is a continental sandstone unconformably overlain by Jurassic limestone, and may sensu stricto be the Gumburo equivalent; the Adigrat is a transgressive marine shoreline facies and has a gradational contact with the overlying limestones.

The Adigrat Sandstone has good porosity in most locations and is a primary objective in the basin. In Galadi-1 oil was recovered from the Adigrat and major gas deposit were discovered by the Calub-1 well.

Hamanlei Formation

The type section of the Hamanlei Formation was originally defined as 210 metres of Callovian-Oxfordian, white to buff, oolitic limestone exposed on the Marda uplift near the village of Hamanlei (Migliorini, 1956). Outcrops of the formation or its equivalents fringe most of the western sub-basin and represent a deepening of the seas behind the transgressive shoreline sands of the Adigrat Sandstone. The contact between these two units is gradational through a series of shales, marls and calcareous sandstones, with some gypsum in the lower part. A correlation of surface sections of the Hamanlei and overlying Jurassic formations from the Ogaden Basin is shown on Figure 9.

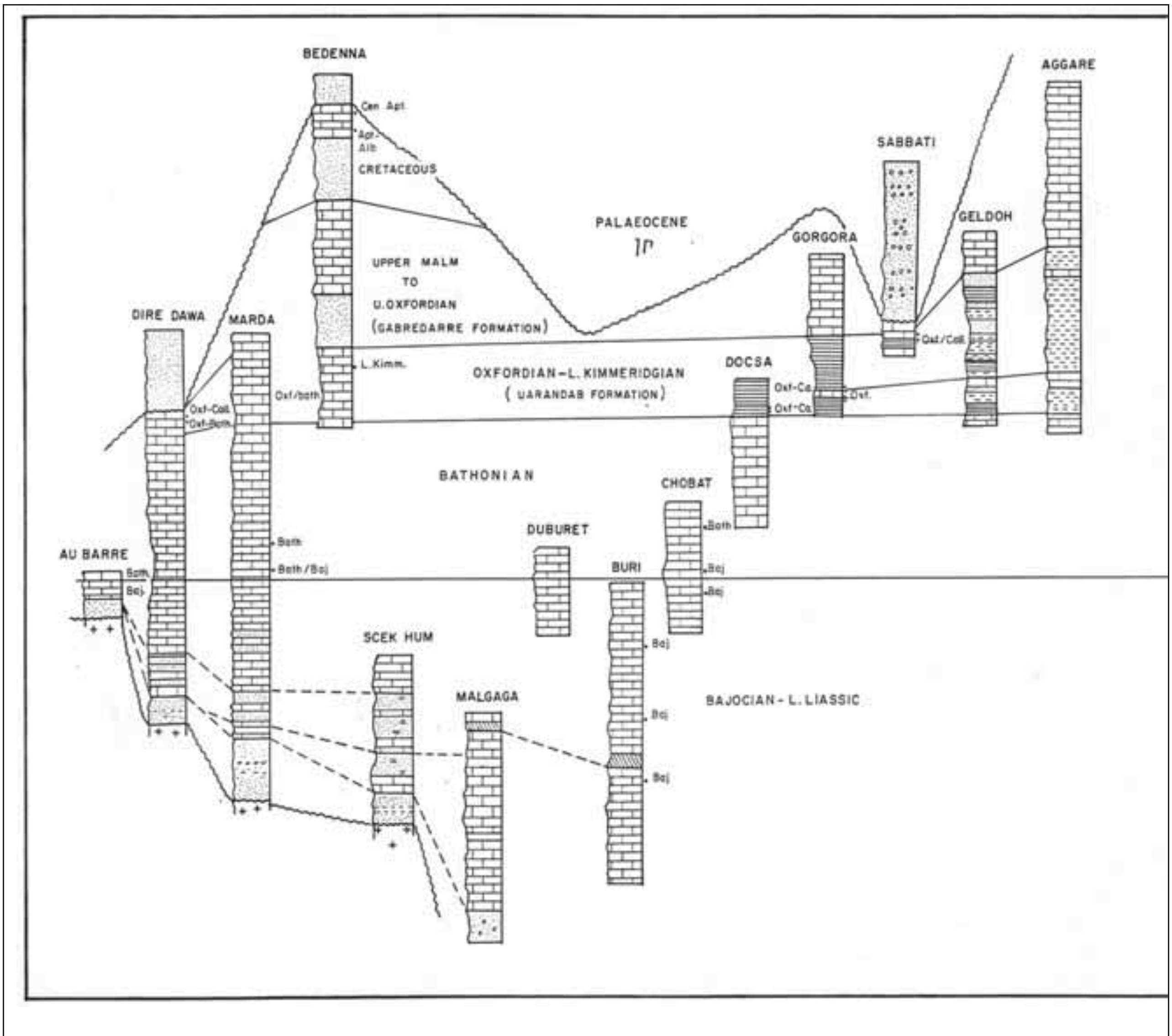


Figure 9. Correlation of Jurassic Outcrop Sections, Ogaden Region

The Hamanlei Formation is the rock unit equivalent of the Upper Jurassic Antalo Formation, defined in northern Ethiopia (Blanford, 1870), but the AGIP geologists who described the Hamanlei Formation recognised the need for independent nomenclature in the Ogaden Basin. The limited mapping of the Jurassic units of the Ogaden led Mohr (1962) to apply the term Hamanlei Formation in the eastern Ogaden but retain "Antalo Formation" for the entire Jurassic carbonates sequence between the Adigrat Sandstone and the Amba Aradam Formation in the western area.

A similar terminology was used by Merla et al (1973). It is recommended that the terminology should follow Kazmin (1972) and use the nomenclature specifically defined for the Ogaden Basin area. Most limestone outcrops south of 9º N are better termed the Hamanlei Formation, rather than Antalo Formation (Black et al 1974).

In the basin area, Elwerath (1967) subdivided .the Hamanlei into several units (Figure 10):

1. Calcarenite Series: Oolitic and pelletal limestones and dolomites, light brown to grey in colour:

2. Evaporate Series: 150-375 metres of grey and brown lutitic dolomites, intercalated with white to pink anhydrite:

3. Calcilutite Series: 170-215 metres of light grey and cream limestone, partly dolomitic and containing abundant organic detritus:

4. Basal Dolomite: Grey lutitic dolomite, locally clayey or gypsiferous, and interbedded with shales and sands. This unit, 30-70 metres thick, is frequently viewed as the Transition Zone (Geol. Survey Ethiopia, 1976).

This sequence is Liassic-Bathonian in age in the basin axis, and is overlain by a series of light-coloured limestones and dolomites, with intercalations of marls and clays in the lower part. This overlying sequence, Callovian to Lower Oxfordian in age and containing clastic beds in basin marginal areas, corresponds to the type section described by Migliorini (1956)! In recent decades, the term Hamanlei Formation has, by common usage, come to mean the entire Liassic-Oxfordian carbonate units. It is recommended that a new type section for the Hamanlei Formation be established, based on the sequence intersected in either the Abred or Calub wells, the latter probably preferable because of the availability of modern logs and seismic control. If the definition by Migliorini (1956) is to remain in effect, the Ogaden sub-surface section should be redefined as the Hamanlei Group, with sub-units redefined as formations.

On the northern flank of the basin the entire pre-Bathonian section is missing, a product of the high elevation of the Chercher Massif. Greitzer (1970) termed a sequence of Oxfordian-Bathonian limestones near Harar the Antalo formation but, as discussed above, this is better called the Hamanlei Formation.

On the western flank of the basin, the Jurassic outcrops have been mapped as Hamanlei, Gabredarre and Uarandab formations on the basis of early work by the Italian geologist, A Marchetti. Because this work was unpublished until recently (Merla et al, 1973), a separate nomenclature has developed for the Sidamo and Bale areas, where 850 metres of microcrystalline limestones and dolomites, with some interbedded shales and marls, are known at the Dibigia and Ganale Doria formations. The Ganale Doria Formation conformably overlies the Dibigia Formation and both units were considered Lower-Upper Jurassic (Kimmeridgian) by Kazmin (1972), consistent with the earlier identification as Hamanlei Formation in this area. Comparison with the Baud Formation and the Ugh Series on the eastern side of the Mandera-Lugh Basin and the Lower Awa Series of northern Kenya supports this proposal.

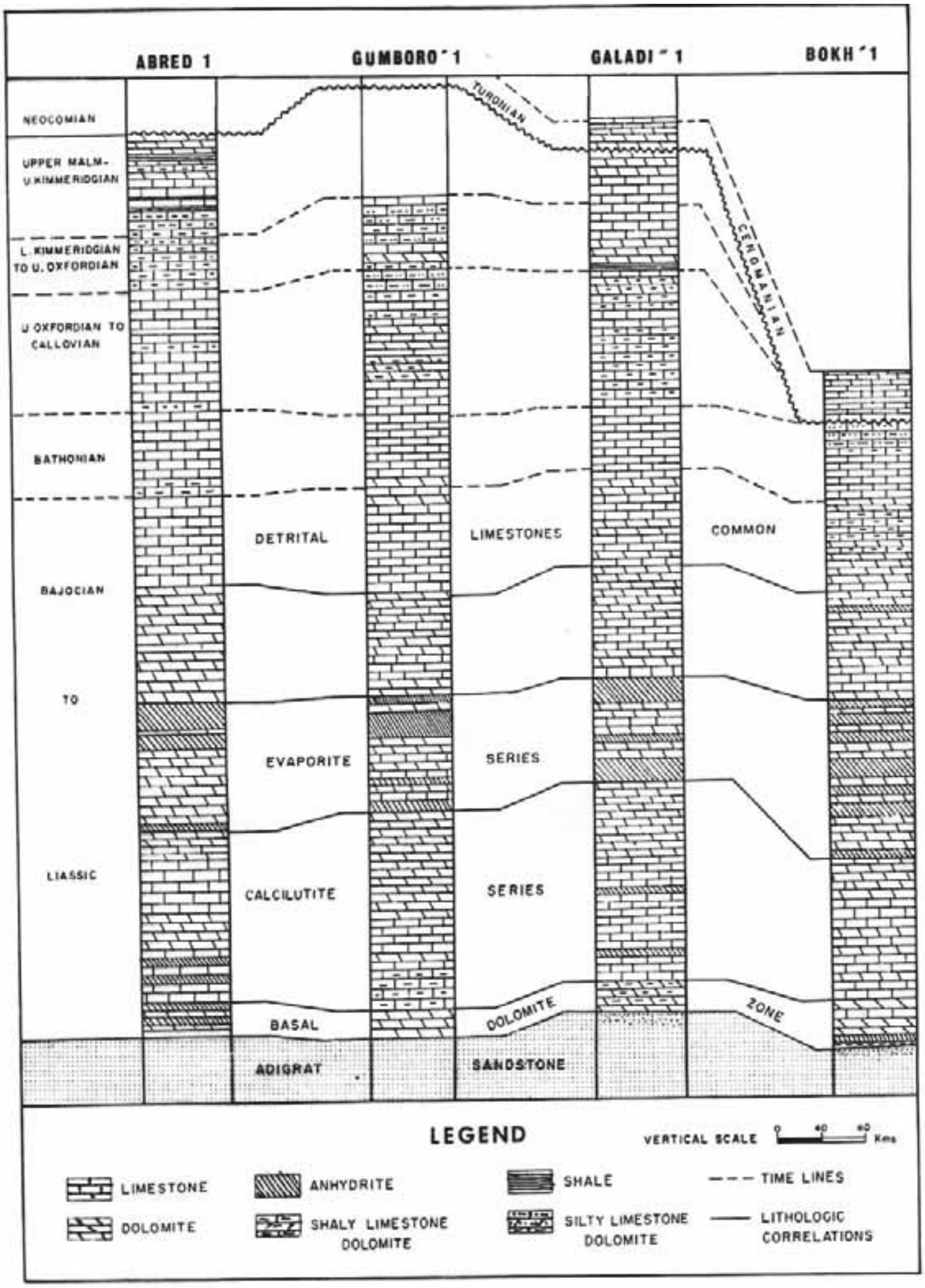


Figure 10. Subsurface Correlation of Jurassic sediments in the eastern Ogaden

The Bur Massif apparently had a silling effect on the Mandura Lugh Basin area, since shallow marine shelf conditions did not develop there until Bajocian time, and the littoral sediments of the Lower Lugh Series formed during the Liassic (Thomson and Dodson, 1960). By contrast, drilling east of the Bur Fault and along the central Somalia coast has revealed a bathyl-abyssal Hamanlei facies (Barnes, 1976). This deep water environment extended along the basin axis, almost to the Ethiopian border, as shown by the Bathonian facies superimposed on the Hamanlei isopach on Figure 11, and may have been fault controlled.

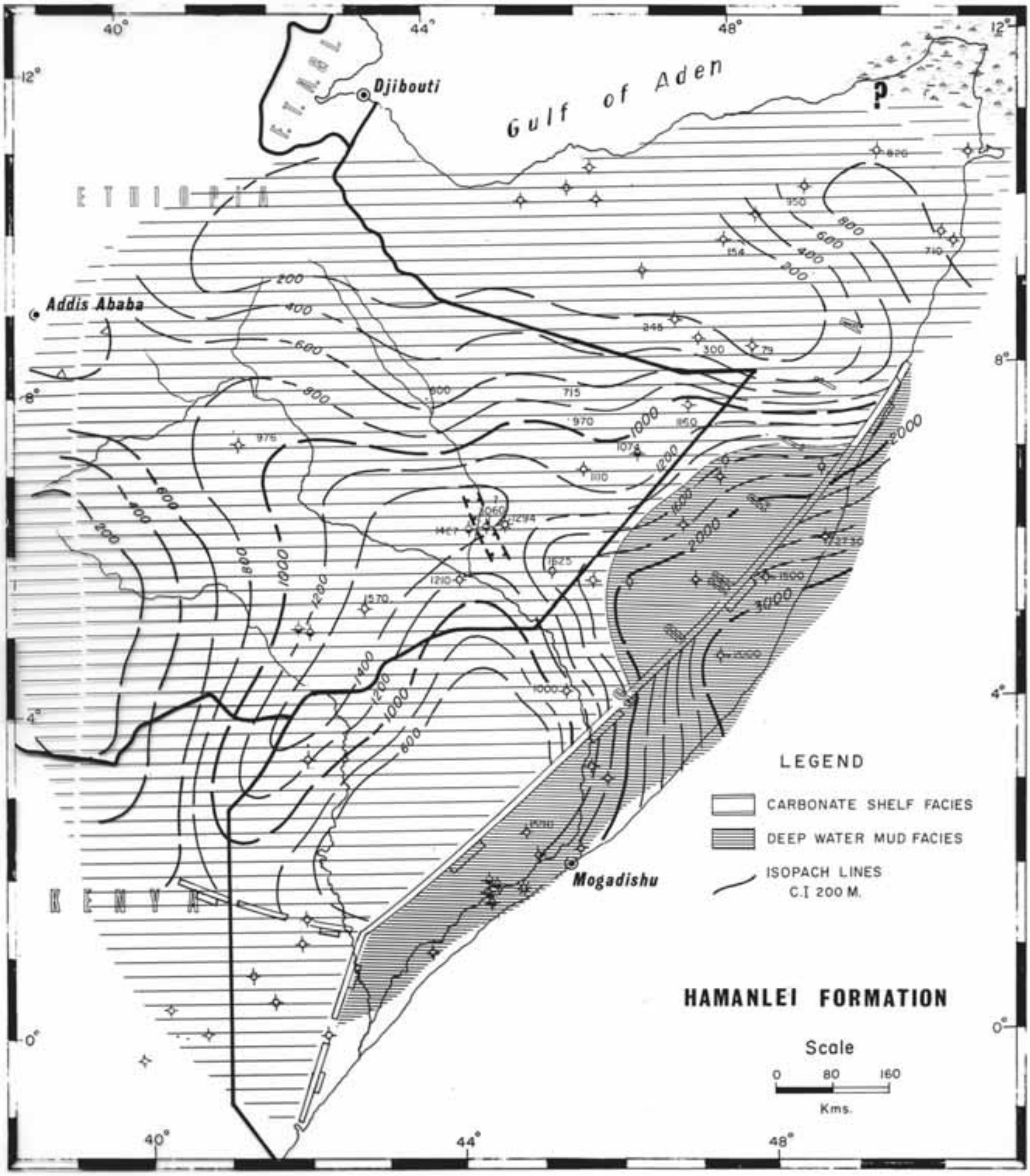


Figure 11. Hamanlei Formation isopach and facies

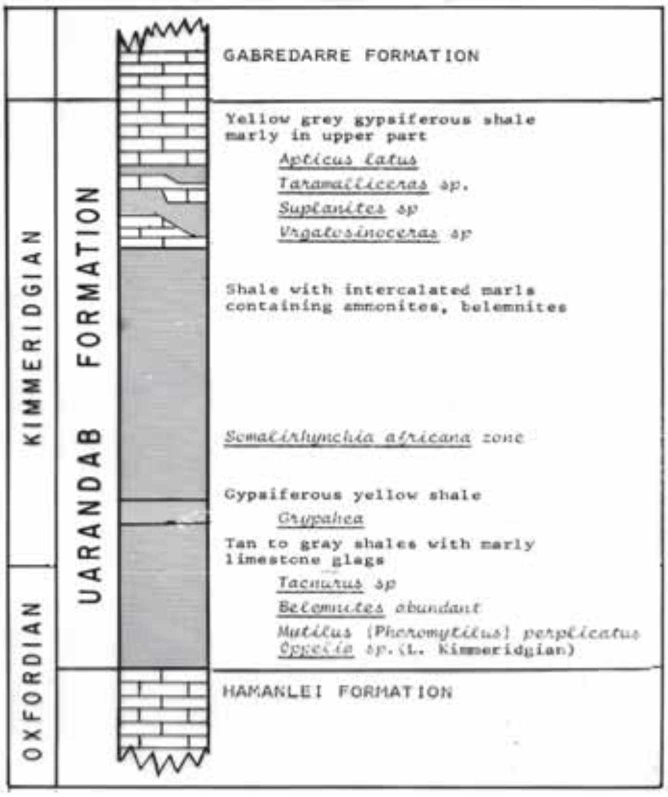
The isopach map of the Hamanlei formation shows a separation of the eastern and western sub-basins by the arch of the Marda Fault Zone, despite the presence of a local faulted (?) trough in the zone. This subdivision is also clear on the structure map of the base of the Hamanlei, as shown in Figure 3.

The sub-basins reveal quite different facies. The carbonate shelf that prevailed over the western area extends only a short distance east of the Marda zone, perhaps influenced by the Nogal and Bur basement blocks. Most of the eastern basin shows a deep water lime mud facies. This facies change is quite abrupt and may have been controlled by faulting along the sinistrally displaced Bur Ridge (Kozerenko and Lartsev, 1976a). The Nogal Arch was a positive feature in the basin but most of the dramatic thinning shown by the map is erosional. In the Migiurtinia Basin, the Hamanlei is mainly a shallow water limestones facies; the area of Cape Gardafui and Socotra Island was apparently exposed at this time.

The Hamanlei Formation has yielded numerous oil shows in the western Ogaden Basin and is a major objective in the region.

Uarandab Formation

The Uarandab Formation conformably overlies the Hamanlei Formation and is characteristically a dark fissile shale unit approximately 400 metres thick. The *Belemnopsis tanganesis* and *Subplanites* fauna define an Oxfordian-Kimmeridgian age in the Ogaden basinal area. Locally in the basin (e.g. the Fafan Valley), a carbonate facies develops and is also present on the basin flanks (e.g. the Oxfordian limestones near Harar). The facies of the Uarandab Formation in the eastern sub-basin are shown in Figure 10; Figure 12 shows a representative surface section. In general the shale facies predominates over large areas of Ethiopia and northern Somalia and marks the quiet water conditions that prevailed near the peak of the Jurassic transgression.



Belemnopsis tanganensis also characterises the Daghani Shales of Somalia and the Upper Shales of northwest Kenya. The Oxfordian Anole Formation (Beltrandi and Pyre, 1972) of southern Somalia is correlable with the Uarandab Formation, but the Agula Shale of northern Ethiopia mark the beginning of the regression of Jurassic seas.

The Uarandab grades into the overlying Gabredarre Formation in the western Ogaden but the contact is abrupt in the eastern area. This probably reflects uplifting on the Nogal Arch, which caused more abrupt regression in the eastern sub-basin.

The Uarandab Formation was considered a good source rock by Taylor (1947), Clift (1956) and others.

Figure 12. Uarandab Formation Section

Gabredarre Formation

The Gabredarre Formation was defined in outcrop near the village of Gabredarre (Figure 13), as 150 metres of oolitic and marly limestones, interbedded with gypsum and shale (Clift, 1956). The formation closely resembles the Gawan Limestones and Uegit Formation of Somalia and the Upper Limestone of northeast Kenya. In Northern Somalia the formation is predominantly limestone but has a distinct sandstone facies at the top (Macfadyen, 1935).

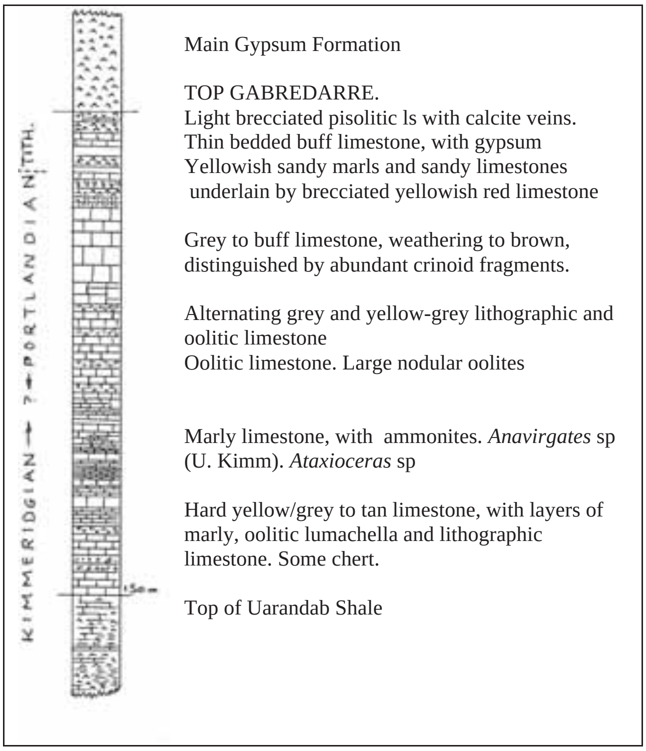


Figure 13. Gabredarre type section in outcrop near Gabredarre (after Taylor, 1947

The Gabredarre was described as Kimmeridgian-Portlandian by Kazmin (1972), while Elwerath (1967) defined the upper age limit as Upper Malm, in agreement with the Tithonian age determined for the sandstone facies in northern Somalia. Over most of the central Ogaden Basin, deposition was continuous into the Lower Cretaceous and the contact of the Jurassic and Cretaceous units is gradational. The definition of the top of the Gabredarre as Portlandian and the Main Gypsum as Lower Cretaceous omits the Tithonian carbonates from the basin nomenclature, and it is recommended that the Gabredarre Formation be accepted as Kimmeridgian to Tithonian in age.

In the basin areas, the Gabredarre Formation consists mainly of grey argillaceous and calcareous marlstones, with interbedded argillaceous limestones and dolomites.

Some shales occur in the upper section, with thin anhydrite layers and occasional fine grained sandstone.

In basin margin areas, the clastic content of the Gabredarre Formation increases markedly in the upper section. A sandstone facies in the Goja-Imi area has been termed the Goja Series and dated as Upper Malm to Kimmeridgian. It is equivalent to the Garbaharre Series of Somalia (Beltrandi and Pyre, 1972) and the Mandera Series of Northern Kenya. These units are uppermost Jurassic in age and evidence the beginning of the regression from the Mandera-Lugh Basin. The limestone facies encountered in Tenneco's Gherbi-1, apparently shelfward of the Goja area, probably results from the deeper water conditions in a northwest-trending trough extending through this area.

In coastal Somalia deep wells encountered dark basinal shales with thin finely crystalline limestone (Barnes, 1976).

The regional facies and isopach of the Gabredarre Formation are shown in Figure 13. The influence of the Marda Arch and the consequences of epeirogenic uplift of the Nogal Arch and northern Somalia are clearly revealed. Subsidence in the Mandera Lugh trough was apparently more rapid than elsewhere in the basin: the 600 metres of outcropping Kimmeridgian limestone on the western flank of the Bur Massif are markedly thicker than the 350 metres encountered in the Bodle-1 well in the centre of the western sub-basin.

Oil shows were reported in the Gabredarre Formation in the El Kuran wells on the western basin margin (Geol Survey, Ethiopia, 1976) and this formation is a potential reservoir in this area, and probably elsewhere along the basin margin.

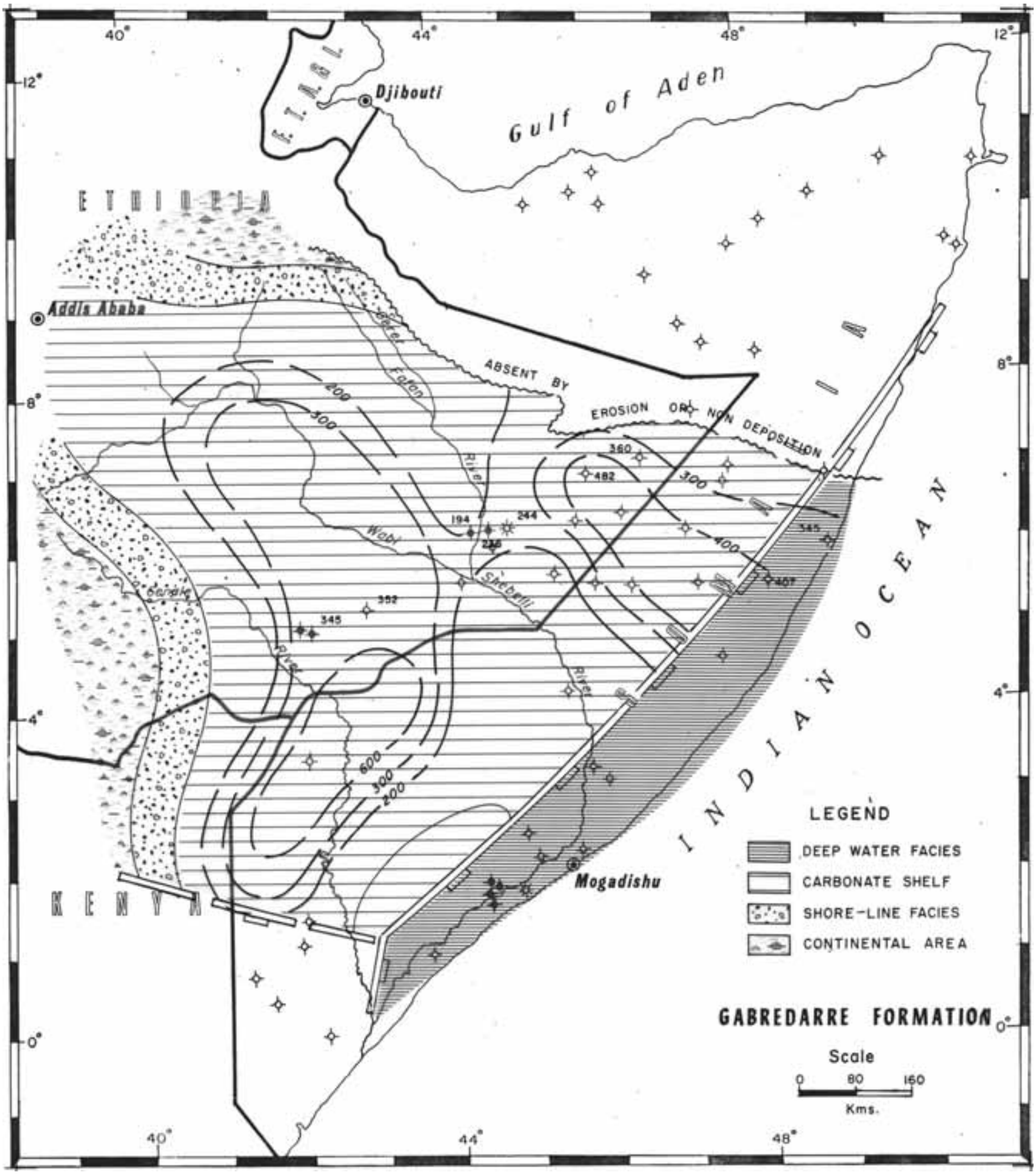


Figure 14. Gabredarre Formation Isopach and Facies Map

CRETACEOUS

Main Gypsum Formation

The type section of the Main Gypsum Formation, also known as the Gorrahei Formation, is near Gabredarre in Ethiopia and comprises 200 metres of gypsum intercalated with limestones, marls and shales. Migliorini (1956) dated this section as Portlandian-Barremian and noted a thickening to the east and southeast at the expense of the Gabredarre Formation. In Somalia the Main Gypsum has been dated as Lower Cretaceous (Barnes, 1976) and it is probable that

Migliorini's definition includes some rocks of the Gabredarre Formation. As noted above, the contact between the Jurassic and Cretaceous sediments is gradational in the basinal areas and separation of the units is difficult. A correlation of selected outcrops of the Cretaceous sediments in the basin is shown in Figure 15.

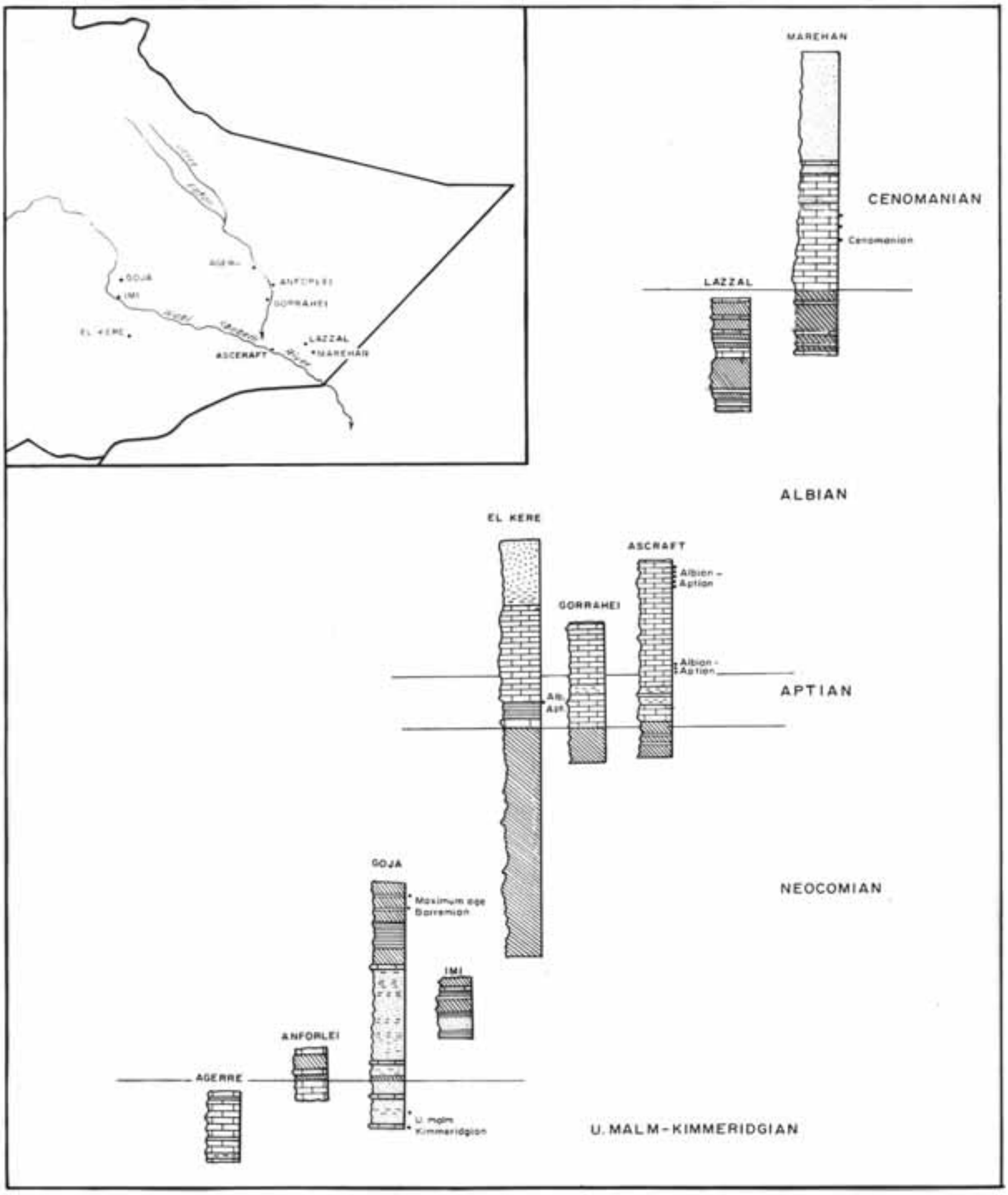


Figure 15 Correlation of Cretaceous Outcrops (after Elwerath, 1967)

The Main Gypsum Formation outcrops over large areas of the western basin and extends into the Mandera-Lugh trough where it consists of gypsum and limestone with interbedded shales. In the western Ogaden, the formation is thickest in the basin centre where Bodle-1 encountered 1680 metres of interbedded shales, sandstones, limestones and dolomites with anhydrite and salt. To the west, the El Kuran wells encountered a thick section of shales, limestones and sandstones, increasingly clastic in the upper part, which is characterised by interbeds of red shales and gypsum. The isopach and facies of the Main Gypsum Formation are shown on Figure 16.

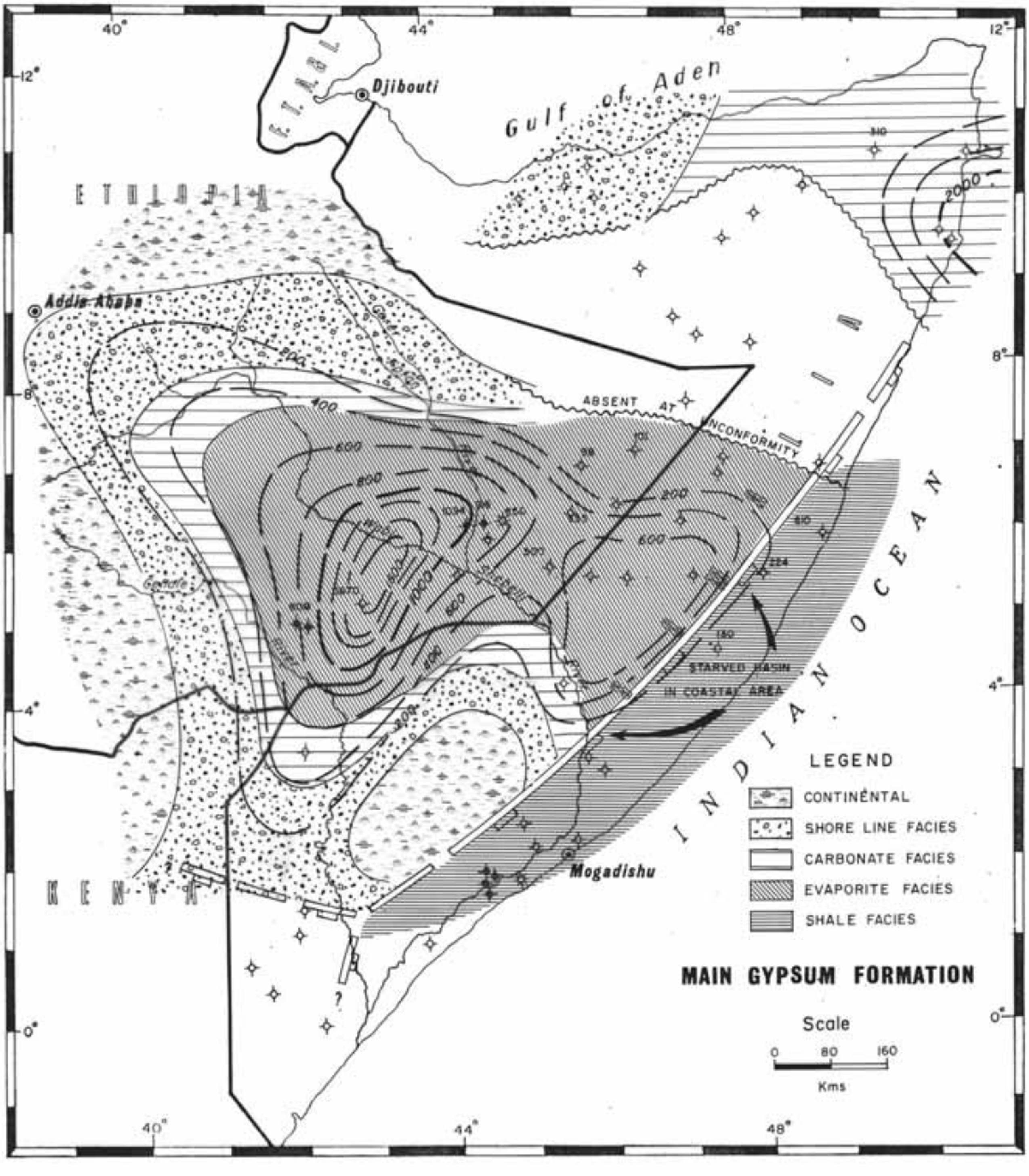


Figure 16. Main Gypsum Formation Isopach and Facies Map

On the southwest flank of the basin, the Main Gypsum Formation was defined during early mapping of the area (Marchetti, 1939) but, as noted above, this work was unpublished until recently and independent nomenclature developed. The thick sequence of limestones and anhydrites overlain by interbedded sands and shales has been called the Mt. Filtu Formation. It is reported to rest unconformably on the Ganale Doria Formation, and was considered by Teitz and Blakely (1970) to be equivalent to part of the Gabredarre, Main Gypsum and Faf (Upper Cretaceous) formations.

The reported unconformity at the base of the Mount Filtu Formation is not known elsewhere in the basin and requires field checking. It is difficult to reconcile with the established sedimentary history of this area and it may be only an intraformational feature, as observed in the Gabredarre Formation in Somalia (Beltrandi and Pyre, 1972). In northeast Kenya, an unconformable relation between the Dawa Limestone Series and the Mandera Series is frequently described (Ayres, 1952; Jaubert, 1960) and would be equivalent, but in an early draft of his 1952 report Ayers describe this contact, in detail, as gradational! This contradiction of draft and final reports has not been resolved. It is recommended that future regional mapping in this area by the Geologic Survey of Ethiopia discontinue use of the "Mount Filtu Formation" terminology, and focus on detailed mapping of the Main Gypsum (or Gorrahei) Formation.

Wells drilled in west-central Somalia defined a local evaporitic basin centred near the Dura Mareb wells (Kozerenko & Lartsev, 1976) The depocentre in coastal Somalia, effectively the Eastern Ogaden Sub-basin, seem to be separated from the Western Ogaden Sub-basin by a ridge along the Marda Fault Zone (Figure 16). The Calub well, located on the Marda zone, encountered anhydrite and gypsum intercalations with interbedded dolomites near the base. The gypsum has also been converted to anhydrite in other areas of the basin. In Gumburo-1 and Abred-1, gypsum occurs interbedded with dolomites and shales, and the Sinclair stratigraphic well XC-3 encountered 165 metres of anhydrite.

On the northwest flank of the basin, Neocomian and Aptian limestones outcrop in the canyon of the Wabi Shebelli River (Reck and Dietrich, 1923). This carbonate facies of the Main Gypsum Formation has been considered (Mohr, 1962) evidence of deeper water persisting in the area from the Jurassic period. Alternatively these limestone may be basin-flank carbonates developed around the basin-centre evaporites as a result of salinity distribution or the desalinising effect of inflowing streams. It is suggested that this limestone be termed the Sheik Hussein Limestone.

In northern Somalia the Lower Cretaceous sequence is known as the Cotton Formation and consists of fore-reef limestones and neritic shales. In central coastal Somalia the Obbia and Gira well encountered abyssal Lower Cretaceous mudstones (Barnes, 1976) on the downthrow side of the Bur Fault.

Mustahil Formation

In the type section near Mustahil, the Mustahil Formation consists of alternating limestones and marls with thin shales, rudistid layers and gypsum in the upper part. Outcrops of the formation are found in the lower Wabi Shebelli valley and in the centre of the western sub-basin. A correlation section based on outcrops in the Wabi Shebelli valley south from Mustahil is shown on Figure 17.

Migliorini (1956) described the formation as Barremian to Cenomanian in age but Elwerath (1967) determined an Aptian-Albian age in the western sub-basin. This slight age difference may reflect the transgressive nature of the formation. Alternatively, the Barremian limestones may be *sensu stricto* the basin margin facies of the Main Gypsum Formation. This may also be the case with Barremian limestones in the Wabi Shebelli valley south of Mustahil. However field mapping by AGIP geologists (Taylor, 1947) suggested that evaporitic conditions persisted in this area into the Aptian, with only a thin overlying Aptian Mustahil sequence (Figure 17).

In regional terms, the formation merges at the base by intercalation with the Main Gypsum Formation, but mainly overlies it, and marks a major transgression across the Horn of Africa, part of the regional Aptian transgression over eastern Africa and the Middle East. The identification of Aptian limestones on the margins of the Ogaden Basin at Sheik Hussein (Reck and Dietrich, 1923), Grau (Brown et al, 1943), and other locations in Gara Mulatta mountains near Harar shows the significant expansion of the Lower Cretaceous seas. In several places in this area, the limestones overlie a thick sandstones unit which is the shoreline facies of Main Gypsum Formation.

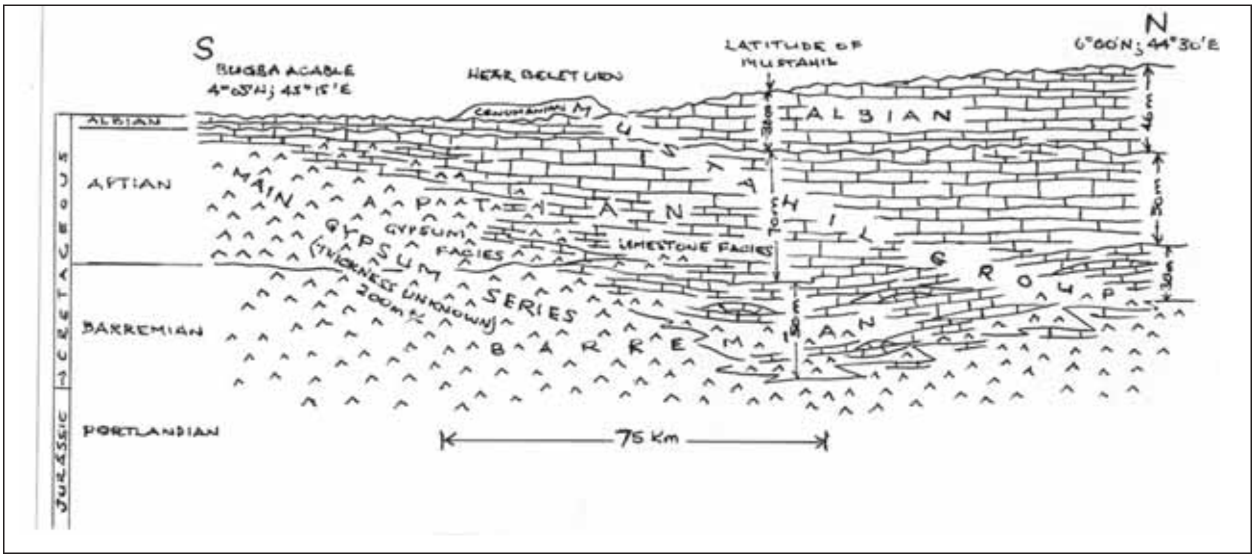


Figure 17. Generalised section of Mustahil and Main Gypsum Formations, Wabi Shebelli Valley, Southern Ogaden and Somalia (after Taylor (1947))

The Mustahil Formation is absent at an unconformity in Galadi-1, Bokh-1 and probably Gumburo-1, where a thin limestone section was interpreted by Elwerath (1967) as Mustahil Formation but is probably part of the Main Gypsum Formation.

The formation is also missing over most of northern Somalia. This unconformity is associated with the epeirogenic uplift of this region. It is probable that the Mustahil sea extended across part of the Nogal Arch and that the deposits were subsequently removed during the upper Albian-Cenomanian erosion. The formation merges at the top with the Ferfer Gypsum which marks a re-establishing of regressive sedimentation in the basin.

In central Somalia, the Mustahil Formation merges into the Gumburo Series and cannot be distinguished from this Aptian-Upper Cretaceous sequence of lagoonal muds. For this reason, the Mustahil Formation is frequently discussed with the Upper Cretaceous Ferfer Gypsum and Belet Uen formations, which outcrop in the same area of the Wabi Shebelli valley. However, , the Mustahil Formation represents a distinctly separate sedimentary episode. The Upper Cretaceous sediments are part of the Coastal Somalia Basin and unconformably overlie the Mustahil Formation.

Upper Cretaceous

The Upper Cretaceous depositional cycle is *sensu stricto* part of the Coastal Somalia Basin rather than the Ogaden Basin This has complicated understanding of the basin stratigraphy and history, and led to a rather confused nomenclature for the Upper Cretaceous sequence .

Upper Cretaceous sediments outcrop only in the lower Wabi Shebelli valley, and are subdivided into two formations, the Ferfer Gypsum and the Belet Uen Formation.

The Ferfer Gypsum is lithologically similar to the Main Gypsum Formation and consists of alternating dolomites, limestones marls and gypsum. It was considered by Migliorini (1956) to be Cenomanian in age near Ferfer village but Elwerath (1967) identified it as Albian. It is approximately 200 metres thick in outcrop, and merges by intercalation with the overlying Belet Uen Formation.

The type section of the Belet Uen Formation near Belet Uen in Somalia is composed of light coloured limestones, sometimes reefal, with intercalations of grey-green glauconitic shale and green and brown sandstones. Gypsum interbeds are common in the upper section, which grades into the Jesomma Sandstone in the southern area. At the type locality (Figure 18) the Belet Uen grades conformably up from the Ferfer Gypsum but, farther north, it is markedly transgressive over eroded Jurassic sediments. It is Cenomanian to Turonian in age.

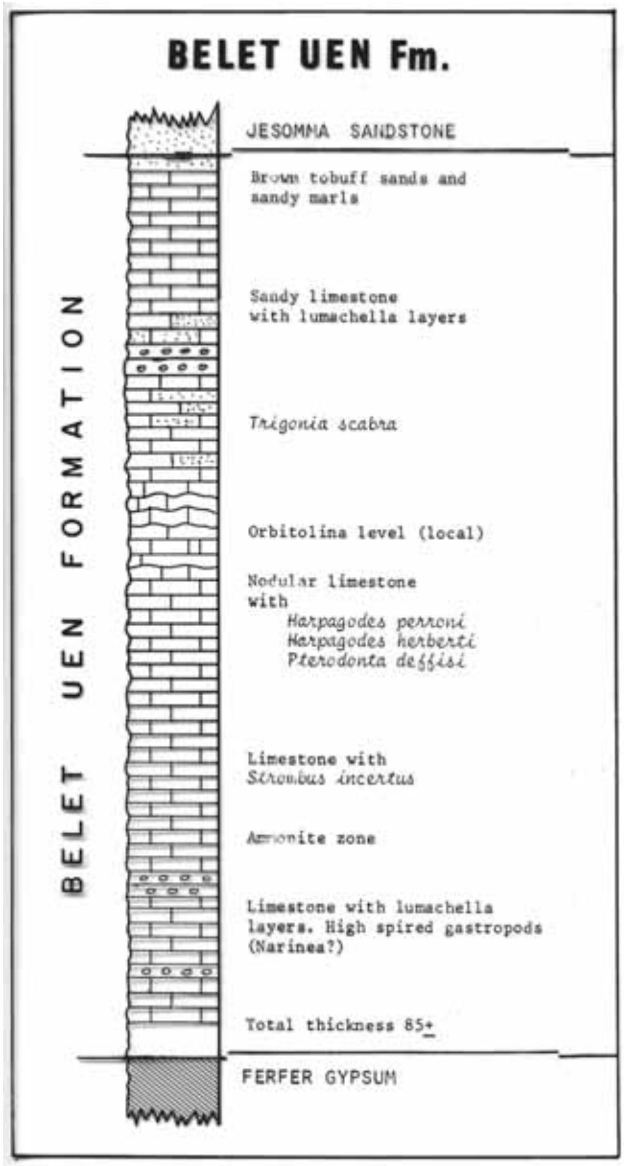


Figure 18. Type section, Belet Uen Formation (after Taylor, 1947)

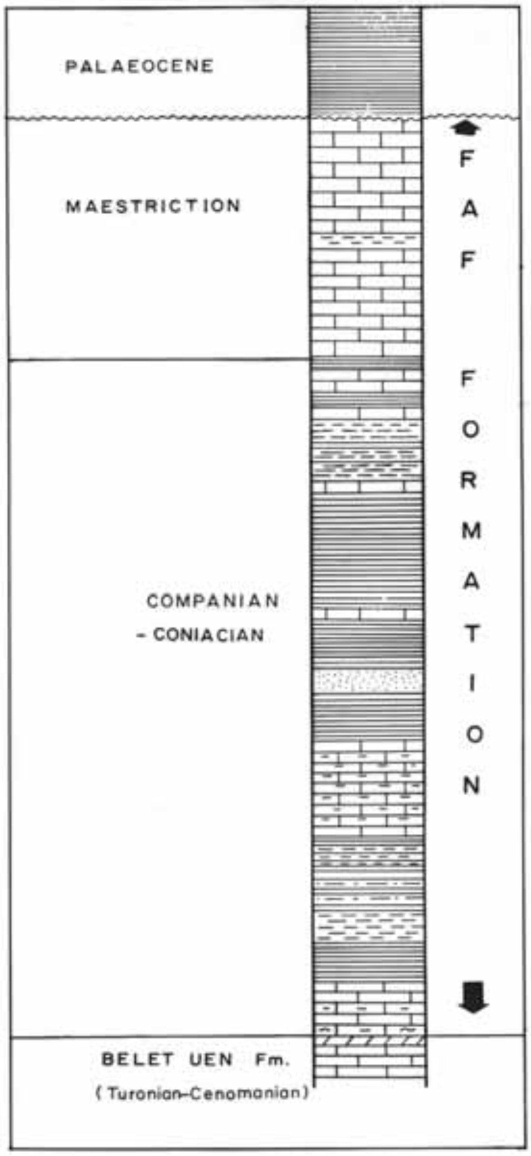


Figure 19. Type Section, Faf Formation (after Elwerath, 1967)

Neither of these formation could be recognised in the sub-surface in Gumburo-1, the first well in the Ogaden Basin, and the entire Upper Cretaceous was called the Gumburo Series, which Clift (1956) described as a "thick accumulation of fossiliferous lignitic and pyritic dark grey marine shales and limestones". The base of the Gumburo Series is Cenomanian-Albian in age. It is only in the Abred well, close to the outcrop area, that the Upper Cretaceous formations can be separately recognized - though the Belet Uen Formation is recognised widely in wells on the northeastern flank of the basin.

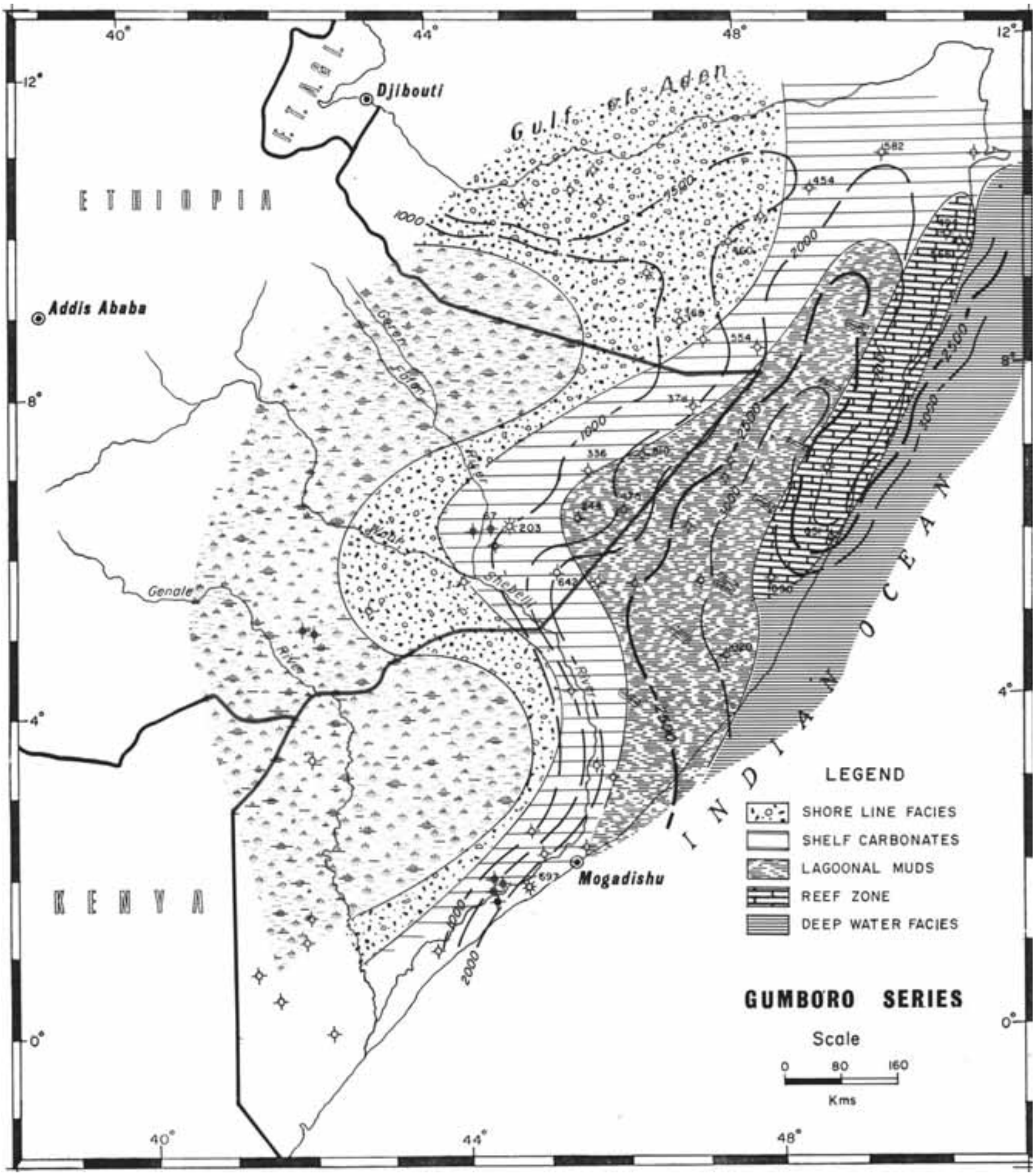


Figure 20. Upper Cretaceous isopach with superimposed and Cenomanian Facies

In the Bokh well, the Belet Uen Formation is overlain by Coniacian-Campanian sandstones and shales, interbedded with dolomites and limestones, and then by Maastrichtian limestones. This entire Coniacian - Maastrichtian unit was designated the Faf Formation by Elwerath(1967). Adding further confusion, this term has also been applied to the entire Aptian to Upper Cretaceous sequence, with Faf 1, 2, 3 and 4 referring to the Mustahil, Ferfer Gypsum, Belet Uen and "Faf" formations respectively (Greitzer, 1970). In the central Ogaden Basin, the Calub, Magan, Hilala and Callafo wells encountered a limestone and shale unit overlying the Main Gypsum Formation. This unit has been termed the Faf Series by the Geologic Survey of Ethiopia (1976) but is probably equivalent to the Mustahil Formation – or, if you will, Faf 4!

It is recommended that the Faf Formation be accepted as defined by Elwerath (1967) and the term not be used for the older formations which have full definition in the literature. The type section of the Faf Formation in the Bokh well is shown as Figure 19.

In coastal Somalia, the Upper Cretaceous in Geri-1 and Maria Ascia-1 is a thick sequence of porous coquinal limestones and dolomites, interbedded with green to grey foraminiferal and ostracod-rich shales. In the Obbia well, porous fossiliferous limestones were found interbedded with dark grey shales.

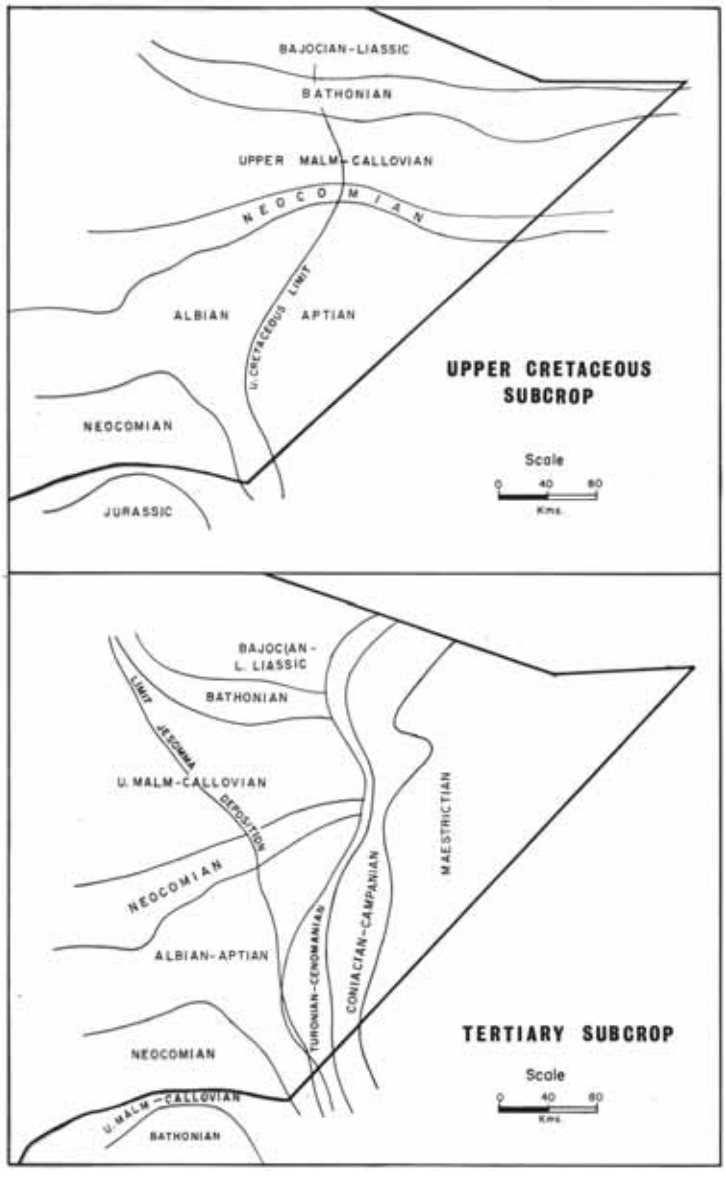


Figure 21. Upper Cretaceous and Tertiary Subcrop Map, Eastern Ogaden (after Elwerath, 1967)

The depositional pattern of the Upper Cretaceous basin results from the interaction of the minor transgressive and regressive cycles in the Ogaden axis, epeirogenic uplift of the Chercher Massif and eastward tilting of the basin area. On Figure 20, the Upper Cretaceous isopach is superimposed on the Cenomanian facies to show the main pattern of sedimentation in this period. Following the Aptian-Albian transgression, the seas withdrew in the early Cenomanian. Evaporites formed in the basin and the extensive erosion occurred on the Nogal Arch and Chercher Massif. Later in this period, the eastward tilting of the eastern area caused the seas to overflow the Nogal Arch depositing limestones over eroded Jurassic and Cretaceous sediments.

Water depths increased eastward and a distinct shale facies developed between the shelf carbonates in the west and a barrier reef complex, probably associated with uplift on the Bur Fault. Deep-water sediments formed east of the reef zone which because of continuing subsidence, was buried in deeper water muds by Maastrichtian time.

This tilting of the region, superimposing the Coastal Somalia Basin onto the Ogaden Basin sediments is clearly revealed on the subcrop maps for the Upper Cretaceous and Tertiary shown in Figure 21

Amba Aradam Formation

On the western flank of the Ogaden Basin, a thick arenaceous sequence separates the Gabredarre Formation and the Trap Series Volcanics. This unit was first called the Upper Sandstone but has lately been termed the Amba Aradam Formation (Kazmin, 1972; Purcell, 1977), following Mahdi Shumburo's (1968) re-definition of the Upper Sandstone in Tigre.

Near Bedessa, the Gabredarre Formation limestones grade conformably upward, through calcareous sandstones and marls, into sand/shale interbeds and, finally, a massive sandstone (Purcell and Tasfai Gebre Hanna, 1977). This section is shown in Figure 22 and is clearly the closing regressive facies of the Mesozoic sedimentary cycle. No palaeontologic work has been done on this outcrop but it is thought to be mainly Lower Cretaceous, possibly extending down into the Upper Malm.

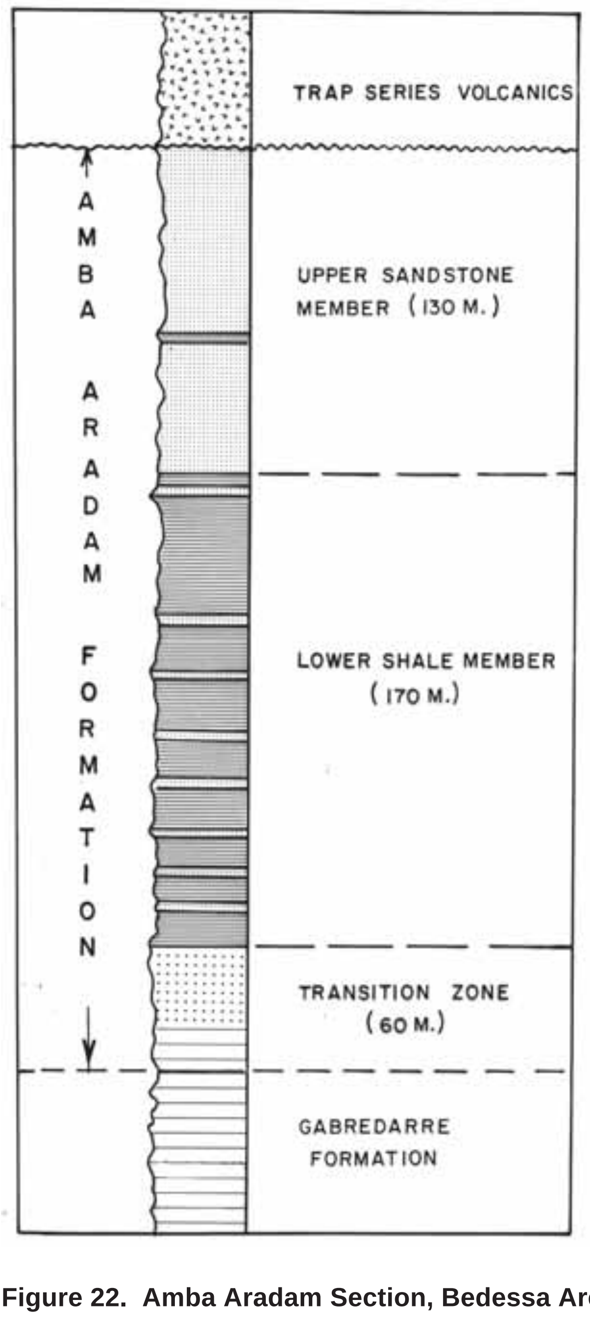


Figure 22. Amba Aradam Section, Bedessa Area

These outcrops may be traced continuously down the west flank of the basin, at least to the Web River near Ginir, where interbedded limestones and marls grade through yellow calcareous sandstone and thin dolomite bands into white and red sandstone. This unit also occurs under the isolated outcrops of Trap Series basalts along the Wabi Shebelli River.

Near Mt. Abul Cassim, Aptian limestones grade upwards into sandstones dated as Aptian on the presence of *Trigonia picteti* (Reck and Dietrich, 1923). At Grawa and Mt Mammuski, the Aptian-Albian nautiloid *Heminautilus* dates the formation. At Gara Mulatta, west of Harar, the overlying Mustahil limestones contain Aptian foraminifera and pelecypods. Near Gokti, Upper Jurassic limestone grade into sandstones of Tithonian to Early Cretaceous age (Mohr, 1962).

On the southwest basin margin, a thick unfossiliferous sandstone unit appears to be the equivalent of the Amba Aradam Formation but it is known locally as the Bogal Mayo Formation. This unit grades conformably down into the Mt. Filtu Formation (Main Gypsum Formation equivalent). Teitz and Blakely (1972) considered the formation to be Upper Cretaceous, perhaps as old as Cenomanian-Turonian, while Kazmin (l972) has correlated most of these sandstones with the Jesomma Sandstone. Merla et al (1973) correlated the unit with the Garbaharre Formation of Upper Jurassic-Lower Cretaceous age. In the absence of definitive fossils no precise correlation is possible but the unit is clearly the shoreline facies of the retreating seas and the geology of the Mandera-Lugh Basin suggests that it is not younger than Lower Cretaceous.

In Somalia and Kenya, the regressive Garbaharre Formation is the rock unit equivalent of the Amba Aradam Formation but is mainly Upper Jurassic in age, marking an earlier withdrawal of seas from the Mandera area. The lower part is alternating dolomitic limestones, fossiliferous calcarenites and red, ripple-marked sandstones.

The upper part comprises dolomitic limestones interbedded with siltstones gypsum, green shales and sandstones. Several intraformational unconformities are present at the base of the sandstone beds (Beltrandi and Pyre (1972).

Near Dire Dawa an unconformity separates Cretaceous sandstones from the underlying limestones (Greitzer, 1970). This unconformity results from uplift of the Chercher Mountains and prompts correlation with the Jesomma Sandstone outcrops to the east.

The Amba Aradam Formation has frequently been described as the shoreline facies of the retreating Mesozoic seas (Mohr, 1962; Purcell, 1977). However Kazmin (1972) has noted the Albian-Aptian age of part of the formation and suggested that it may also be partly the shoreline facies of the Mustahil Formation transgression. This is probably the case on the northwestern flank of the basin. However, the gradational contact of the Amba Aradam Formation with the underlying limestones clearly relates to shallowing and withdrawal of the seas. The Albian-Aptian transgression is clearly marked in areas on the Chercher Massif, where a limestone unit overlies the clastic Amba Aradam Formation.

In northern Ethiopia, the Amba Aradam Formation unconformably overlies the Antalo Formation and the regressive Agula Shale. This suggests that the usual correlation of the 'Upper Sandstone' units from (say) the Mekele area and the Ogaden Basin may be imprecise. (Kazmin (1972) suggested that the Mekele area sandstones may be the continental facies of Mustahil Formation with the littoral sands and shales of the Ogaden marking the transition facies.

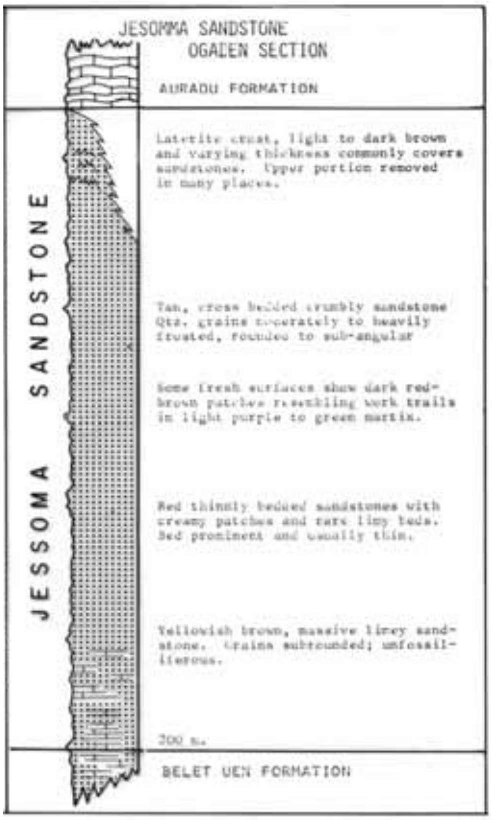


Figure 23. Jesomma Sandstone representative Section

Alternatively, the regressive nature of the Amba Aradam Formation in the Ogaden Basin, suggests that the equivalent unit in northern Ethiopia is the Agula shale. This is supported by the recognition of the thick lower shale member of the Amba Aradam Formation near Bedessa (Purcell and Tasfai Gebre Hanna, 1977).

This uncertainty specifically compromises the use of the term Amba Aradam Formation, as defined in northern Ethiopia, in the Ogaden Basin. The writer would prefer to see this formation in the Ogaden Basin renamed (say) the Arussi Formation, and recommends that this point be considered in future mapping of the area by the Geological Survey.

TERTIARY

Jesomma Sandstone

The type section of the Jesomma Sandstone (Figure 23) is near Jesomma village in Somalia and consists of 400 metres of unfossiliferous cross-bedded sandstones, with gypsum layers in the lower part. The gradational contact with the underlying Belet Uen Formation as well as the intercalating of these two units south and northeast of Jesomma led Migliorini (1956) to assign a Turonian-Senonian age to the formation. A laterite crust at the top of the Jesomma Sandstone (Taylor, 1947) and local disconformity with the overlying Auradu Formation indicates local sub-aerial exposure prior to the Lower Eocene transgression.

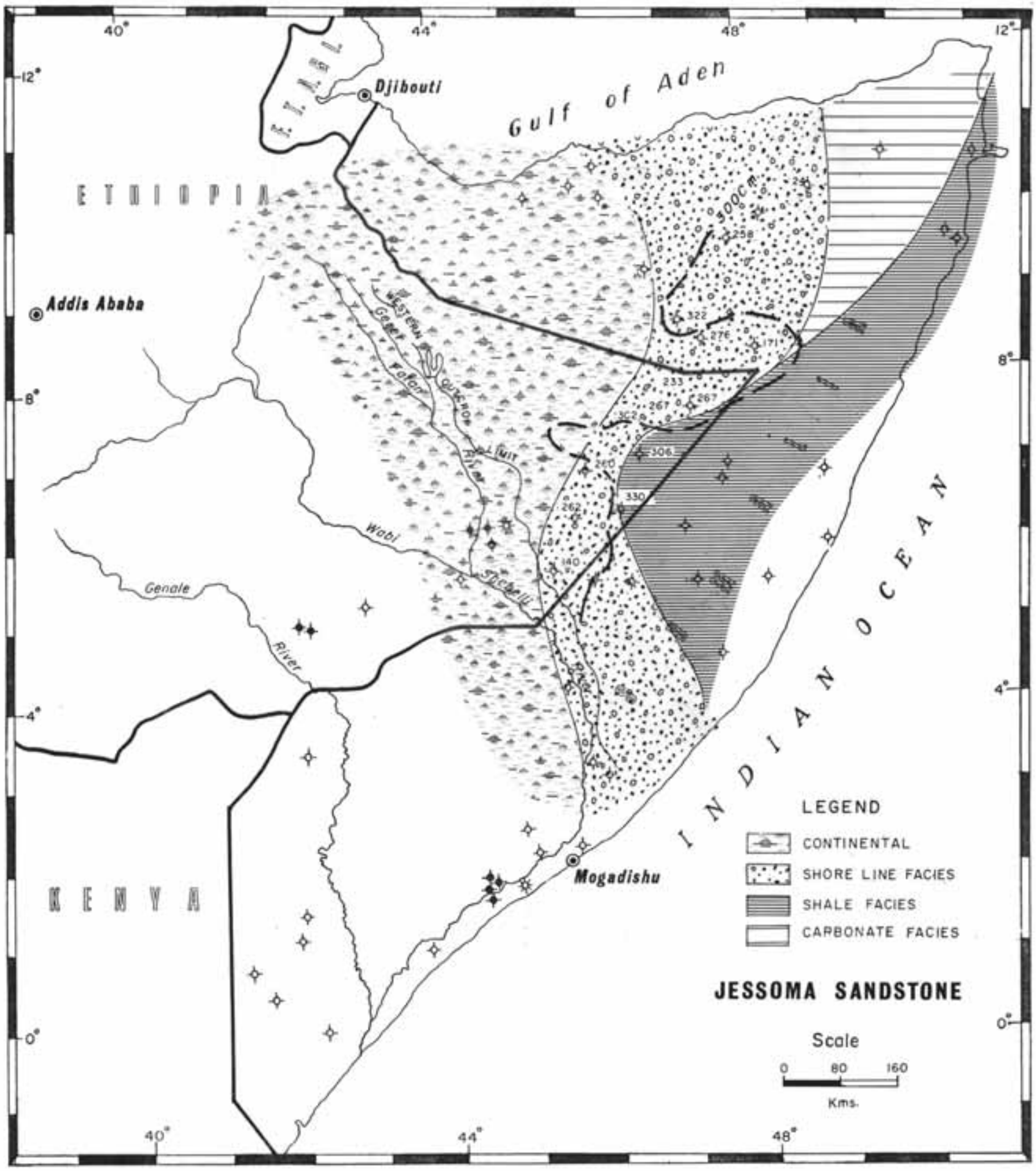
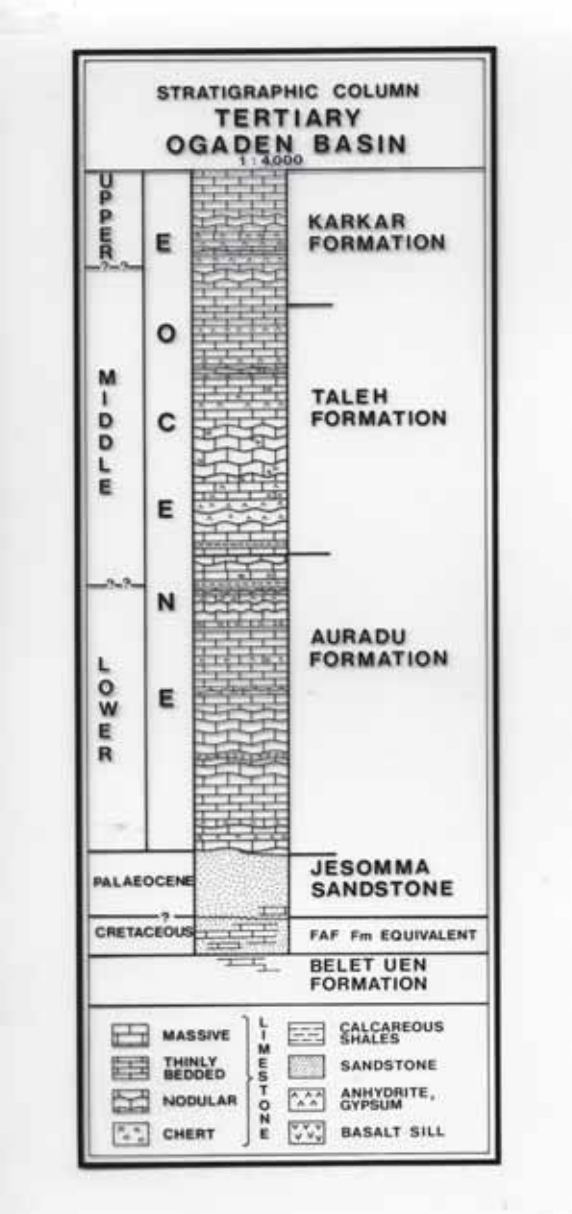


Figure 24. Jesomma Sandstone isopach and facies map

By contrast, the Jesomma Sandstone in the eastern Ogaden is sharply unconformable on Cretaceous and Jurassic sediments, and grades upward into the Eocene Auradu Formation carbonates. In this area it was considered Palaeocene by Clift (1956) and Elwerath (1967).The formation is variously described as the end-Cretaceous regressive facies (Mohr, 1962) and the basal sand of the Tertiary transgression (Kazmin, 1972). That both descriptions are locally true illustrates the broad definition of the Jesomma Formation and the difficulty of making a simple formation description. It also suggests that future work will result in subdivision into two or more formations.

Kazmin's (1972) description of the formation as a major transgression is based on identification of sandstones on the western flank of the basin as the Jesomma Sandstone. As discussed above, these sandstones might be better correlated with Amba Aradam Formation of Arussi.

Similarly the sandstones occurring below the Tertiary (?) volcanics near Dolo, Ethiopia, overlie the Cretaceous Main Gypsum and Mustahil Formations, and represent the final stage of the Cretaceous regression; they are not evidence of a Palaeocene transgression. By contrast, in the area east of the Marda Fault Zone, the Jesomma Sandstone overlies progressively older formations from south to north and the Jesomma-Auradu sedimentation overlaps the Upper Cretaceous. This transgressive aspect of the Jesomma Formation is a result of the regional tilting of the area.



The pattern of the Jesomma Sandstone is, like that of the Upper Cretaceous rocks, a consequence of the superposition of the Coastal Somalia Basin onto the Ogaden Basin. On the uplifted northern flank of the Ogaden Basin erosion continued into the Tertiary while seas slowly withdrew from the basin axis causing a gradation from the Belet Uen Limestones into near-shore clastics. This is a phenomena of the basin centre and is one more example of a type section being a somewhat anomalous example of the unit it represents. While this facies developed in the basin centre, the western sub-basin and the northern flank of the eastern sub-basin were exposed and being actively eroded.

By Palaeocene time continental sedimentation predominated over the present Jesomma outcrop area but the regional tilting down to the east caused submergence of the coastal area and the Jesomma facies becoming increasingly marine from west to east. In Galadi-1 the Jesomma facies is the lignitic and pyritic shales, rich in *Globoritalia velascensis* (Cush) and *Globigerina trilloculinoides* (Pluum). In coastal Somalia, Gira-1 and Obbia-1 encountered an abyssal mud facies from Upper Cretaceous into the Eocene, part of which is equivalent to the Jesomma Sandstone. This sedimentary pattern is shown on Figure 24.

Figure 25. Stratigraphic column, Tertiary formations, Eastern Ogaden Basin

The basin centre facies of the Jesomma is the rock unit equivalent of the Amba Aradam in that it marks the shore-line facies of the retreating seas. However, focus on this section provides an inaccurate concept of the Jesomma basin. Indeed there seems to be some benefit to redefining the Jesomma Sandstone by accepting the type section as a clastic facies of the Faf Formation.

Sandstones occur in the upper Belet Uen in several wells in the basin and represent a shallowing of the seas prior to the Campanian transgression. This suggestion might be considered by the Geologic Survey of Ethiopia when their regional mapping programme provides a useable Jesomma Sandstone type section from the Ogaden Basin area.

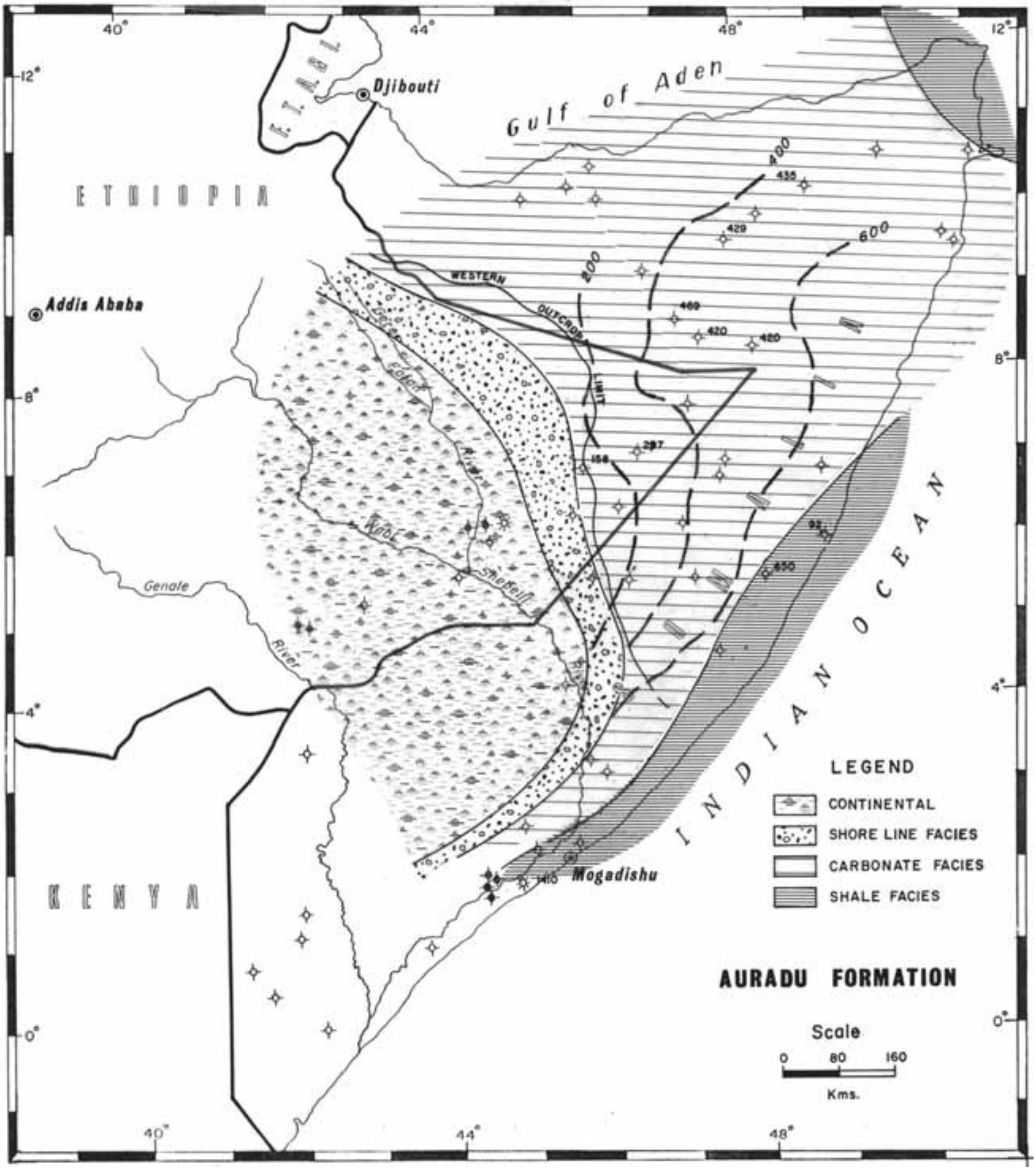


Figure 26. Auradu Formation isopach and facies map

Auradu Formation

The Auradu Formation was first described by Gregory (1921) who assigned the name "Urade" to a sequence of fossiliferous limestones in northern Somalia. The unit was first described as Cretaceous but, in subsequent work, was recognised as Eocene and the name changed to Auradu. A representative section from the eastern Ogaden showing the Jesomma Sandstone and the overlying Auradu, Taleh and Karkar formations is shown on Figure 25.

Wyllie (1925) subdivided the formation into the Allahkajid Beds and the Auradu Limestone. The

Allahkajid Beds were described as limestone, locally chalky, interbedded with shales. Clift (1956) considered that this upper unit did not occur in Ethiopia but the two units are now recognised as, in part, equivalent. In Ethiopia outcrops of the Auradu Formation are composed of grey to pink, dense massive limestones with chert concretions (Mohr, 1962). A similar facies occurs in the Bokh and Galadi wells.

In coastal Somalia, the Eocene is a deep-water facies. In Merca-1 the Lower Eocene and Palaeocene are dark grey to brown shales, with local limestones and sandstone beds. In southern Somalia, the Lach Dera well penetrated Eocene continental sandstones which thickened to 2750 metres in the coastal zone and included a marked marine intercalation (Beltrandi and Pyre, 1972)

The isopach and facies of the Auradu Formation are shown in Figure 26.

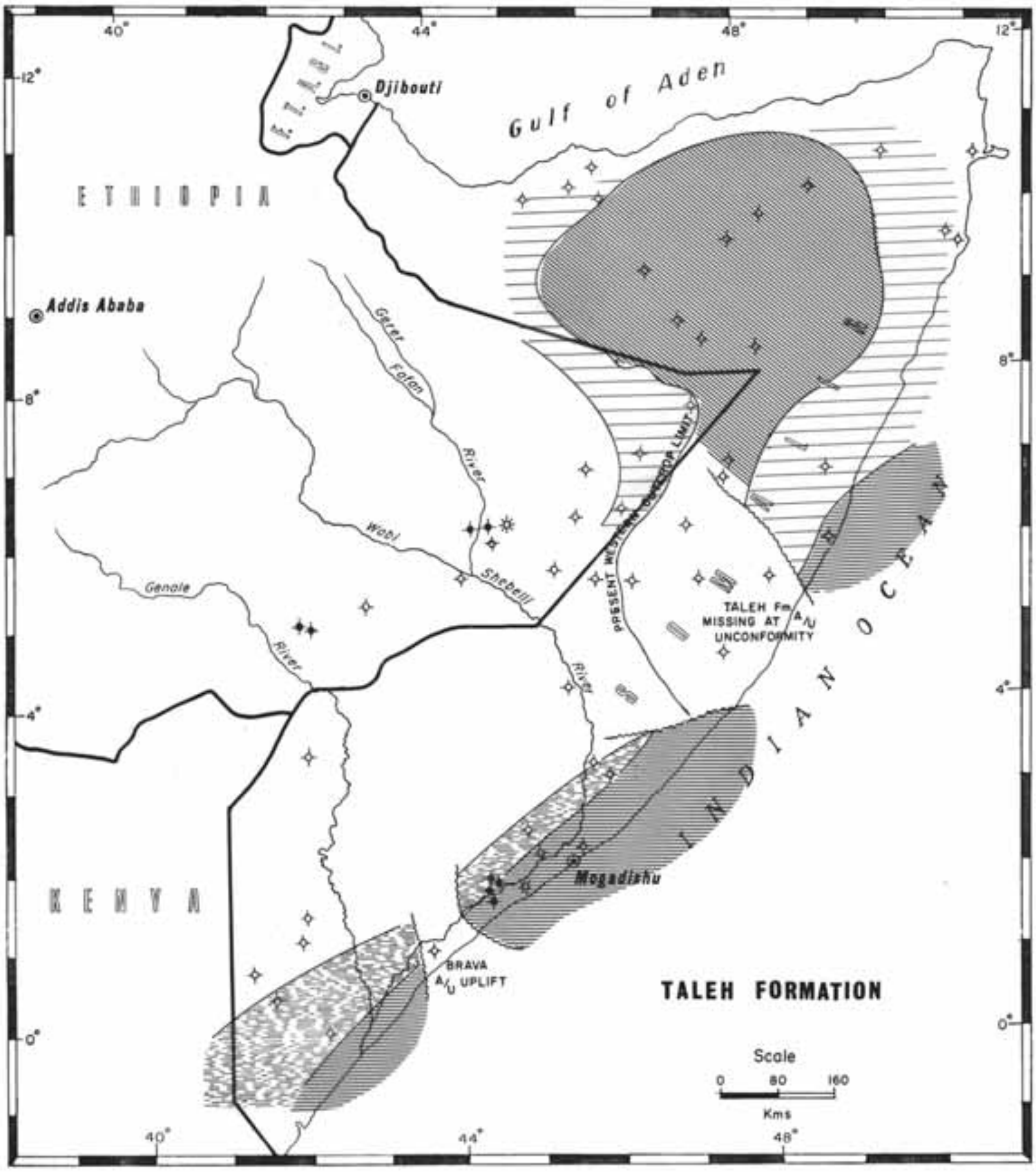


Figure 27. Taleh Formation isopach and facies map

Taleh Formation

This unit, also called the Anhydrite Series (Mohr, 1962), is Middle Eocene in age (Migliorini, 1956). It was defined near the village of Taleh in Somalia, where it consists of 450 metres of massive banded anhydrites superficially altered to gypsum and interbedded with fossiliferous cherty limestones. The formation merges by intercalation into the overlying Karkar Series. In the coastal region, a dolomite facies occurs in several wells. The regional character of the Taleh Formation is shown in Figure 27.

The Taleh Formation facies indicates a regional shallowing of water depths, partly related to the prograding continental margin but also to regional uplift. The formation is absent at an unconformity in the subsurface in central Somalia. The cause of this uplift is not yet understood.

Karkar Formation

The Karkar Formation outcrops only in isolated areas along the Ethiopia-Somalia border. It consists of white chalky limestones with thin shales and gypsum interbeds, and is Middle to Upper Eocene in age. In coastal Somalia, the Merca well encountered quartz sandstones and glauconitic pyritic shales that Barnes (1976) correlated with the Karkar Formation but which appear better correlated with the Oligo-Miocene Somal Series. Similar to the Taleh Formation, the Karkar Formation is apparently absent at an unconformity in the central coastal Somalia. The formation marks a transgressive cycle in the Coastal Somalia Basin and is the last marine sequence in the Ethiopian Ogaden area.

VOLCANICS

Volcanics outcrop along the northwest margin of the basin and locally within the basin area, as shown in Figure 28. Volcanics sills occur in the Adigrat Sandstone in northern Somalia (Azzaroli, 1957) and possibly in northern Ethiopia (Abbate et al., 1969), but no equivalent occurrences have been reported from the Ogaden area. The oldest known volcanic rocks in the basin are Aptian and occur in the Amba Aradam Sandstones near Harar. All other outcrops are believed to be Tertiary in age and are related to the main Trap Series outpourings or to local structural features.

The linear outcrops marking the Marda Range and near Fik are both related to faulting: the Marda Fault is a major zone in the basin (Purcell, 1976) and the Fik volcanics appear to be associated with a Tertiary graben structure in this area (Photogravity, 1974).

Outcrops near Werder appear to be the surface expression of a large basaltic layer that has been identified in the subsurface to the east, as shown on Figure 28. The origin of the outcrops north and west of Dolo is not known. They are 300 kilometres from the nearest Trap Series outcrops, which suggests a local structural cause. Similar to the Werder outcrops, they occur in the area of the Mesozoic basin axis, but the significance of this coincidence is not understood.

Volcanics rocks have been encountered in the subsurface in Gumburo-1, Dura Mareb-1, Idole-1, En Dibire-1 and El Hamurre-1. In all wells except Gumburo a lens of basalt, 45 to 90 metres thick occurs in the Oligocene-Miocene sediments. Contours on the top of the volcanics

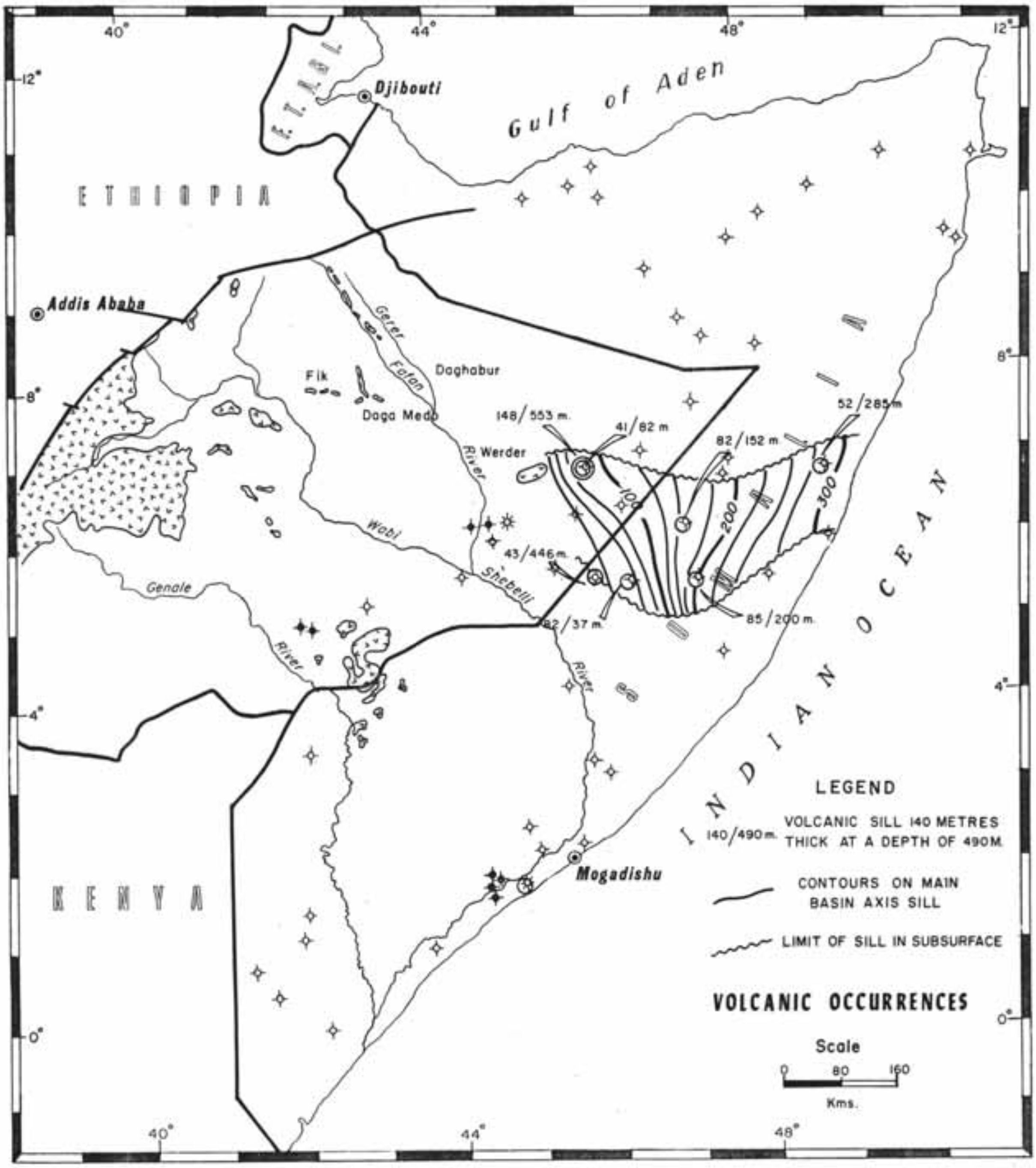


Figure 28. Volcanic occurrences, Ogaden Basin and surrounding region.

show a eastward dipping surface, suggesting that the volcanics have been poured out onto the Eocene-Oligocene unconformity that resulted from local uplift of this area. The cause of the uplift and volcanic episode may be related to rejuvenation of Mesozoic faults. In Gumburo-1 the basalt occurs in the Eocene Auradu Formation but enigmatically appears, on the basis of the contoured surface (Figure 30), to be part of the same body. Clarifying this discrepancy will require additional subsurface control

In Dura Mareb-2, a basalt lens was found in the Jesomma Sandstone and a 150 metre thick sill is interbedded with Upper Cretaceous limestones in Gumburo-1.

TECTONICS

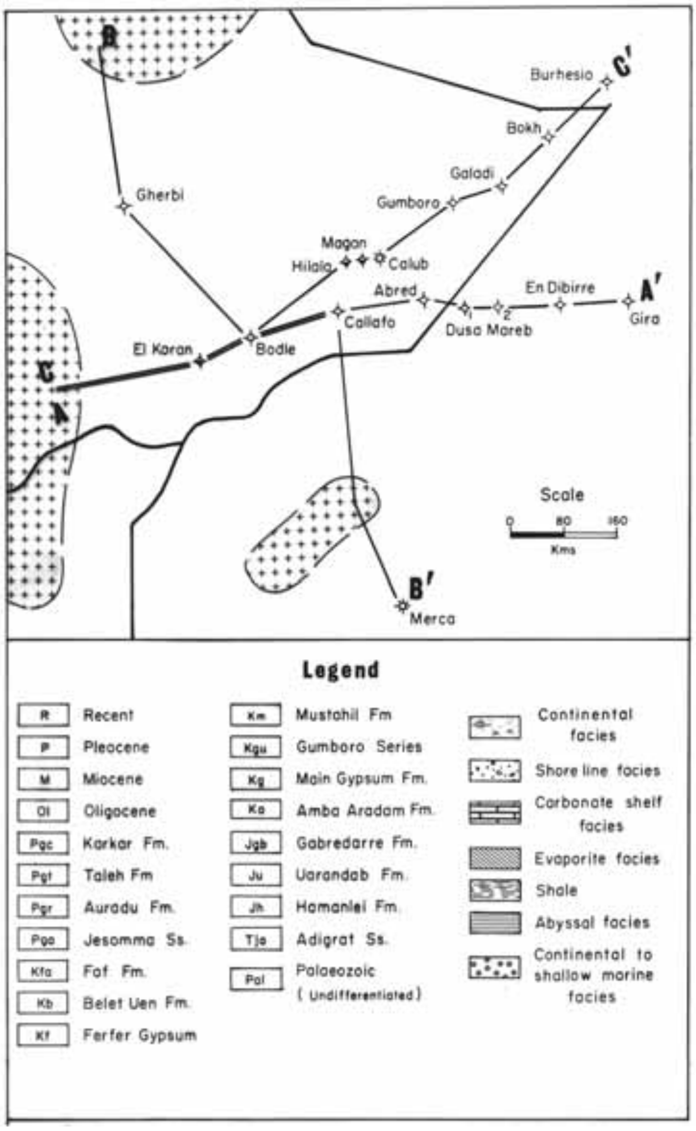


Figure 29. Location map and legend, Ogaden Basin cross-sections

The structure of the Ogaden Basin is clearly revealed on three cross sections, which have been constructed using sub-surface data published in recent years (Barnes, 1976; Geol. Survey. Ethiopia, 1976; Kozerenko and Lartsev, 1977a). The locations of the profiles are shown in Figure 29, which also presents the legend for the generalised facies presented on the cross sections.

Figure 30 extends from the craton area of the Negele basement block eastward across the Western Sub-basin and Marda Fault Zone to coastal Somalia. It reveals the character of the Ogaden Basin and shows definite stratigraphic analogies to many major producing basins.

Most of the characteristic elements of an Atlantic-type margin basin are represented, including the main coastal fault, reef growth along the faulted continental margin, a reversal of orientation of the basin after continental break-up, and an 'interior' basin (the Western Ogaden Sub-basin) that formed in a rift system that was subsidiary to the main rift where continental rupture and spreading subsequently occurred.

Extensive evaporite deposits are also present, though it is interesting that the distinct salt layer characteristically separating the rift-stage and drift-stage basins in the West Africa coastal basins is not developed.

This section shows clearly the thick Mesozoic carbonate-evaporite sequence in the Western Ogaden Sub-basin, across the Marda Arch into the Eastern sub-basin where it changes to a predominantly argillaceous, deeper-water facies.

The large Western Sub-basin, not previously described in the literature, is also shown clearly in Figure 31. Until Tenneco's work in the early 1970s, this area was shown on maps as breached to basement in the river valleys. This misconception appears to have originated with syenite samples collected from the Mt Abul Cassim intrusion by early Italian explorers being assumed by early and even recent map-makers (Dainelli, 1943; Kazmin, 1972) to come from the floor of the Wabi Shebelli river valley!

The bounding Bur Massif in the southeast, and the abrupt 'continental margin' determined by the Bur Fault are also shown on this profile: thick abyssal Jurassic muds are present within 50 Km of the basement outcrop. The profile also illustrates the dramatic uplift of the northwestern

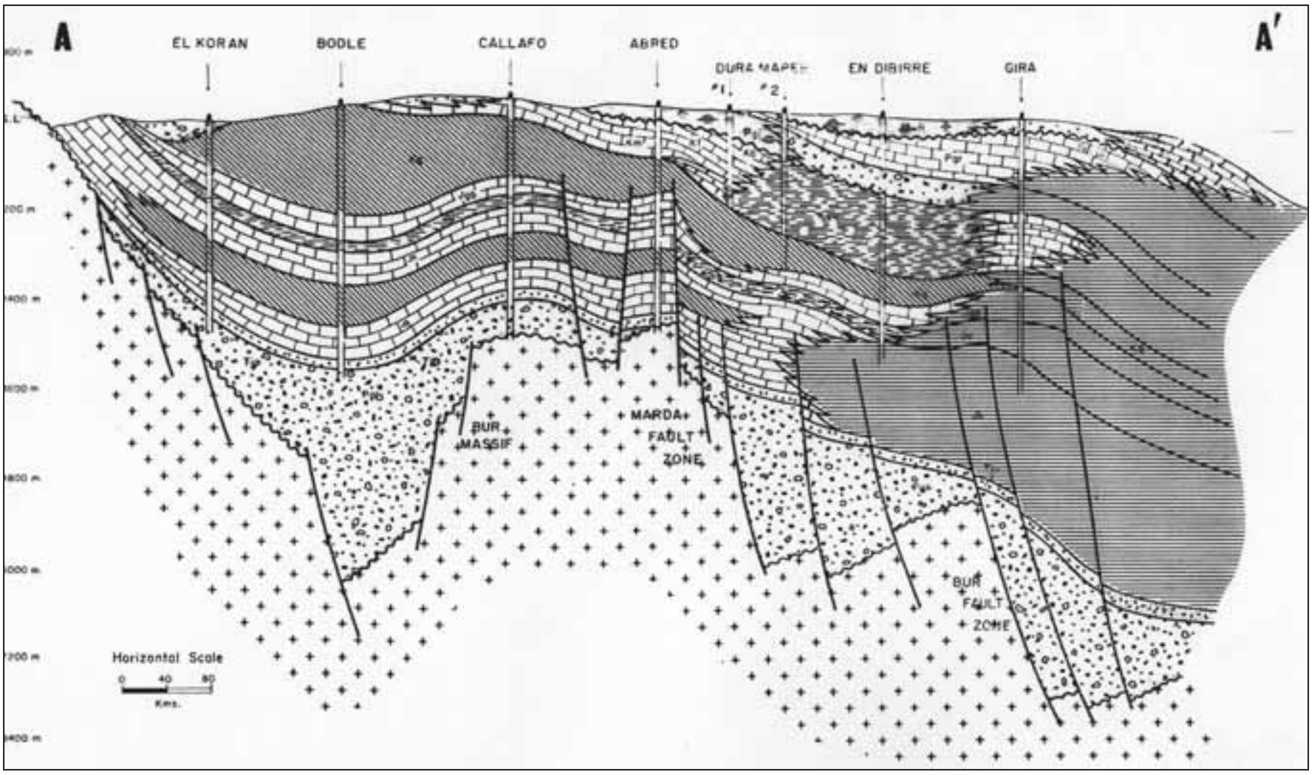


Figure 30 – East-west cross-section, Ogaden Basin

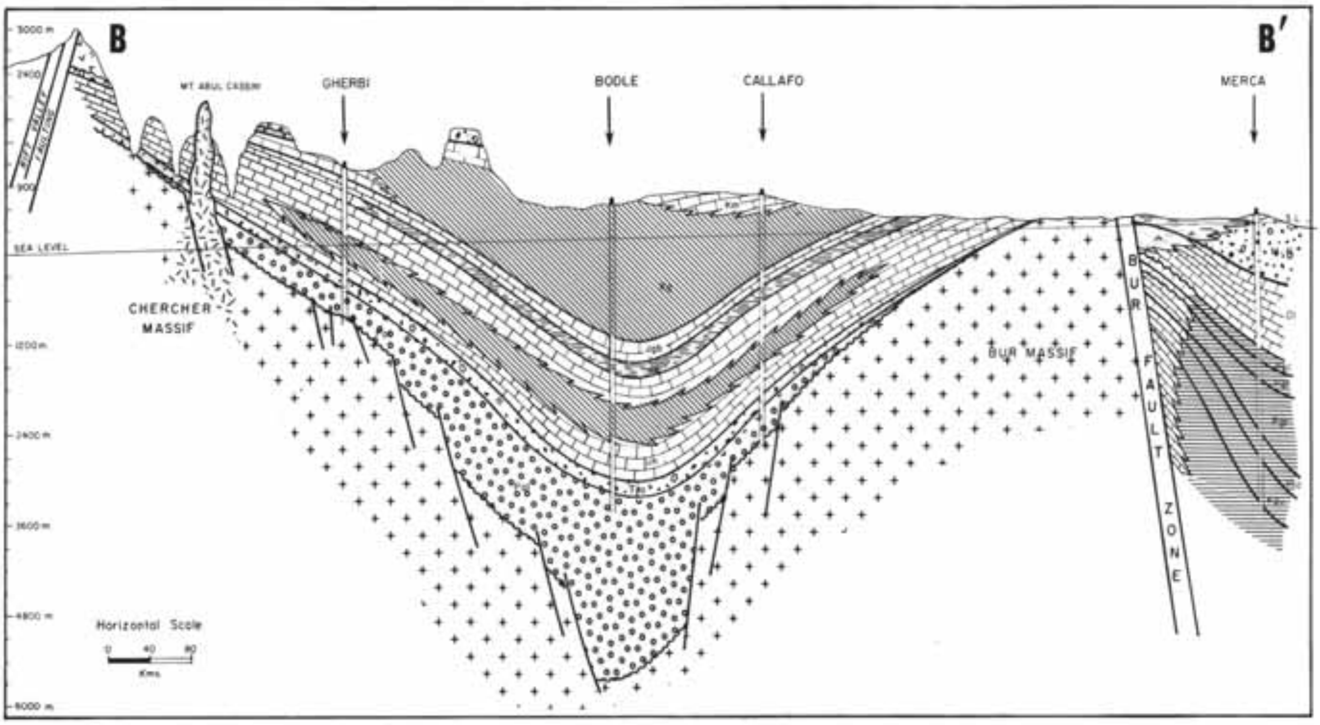


Figure 31 - Northwest Southeast cross-section, Western Ogaden Sub-basin

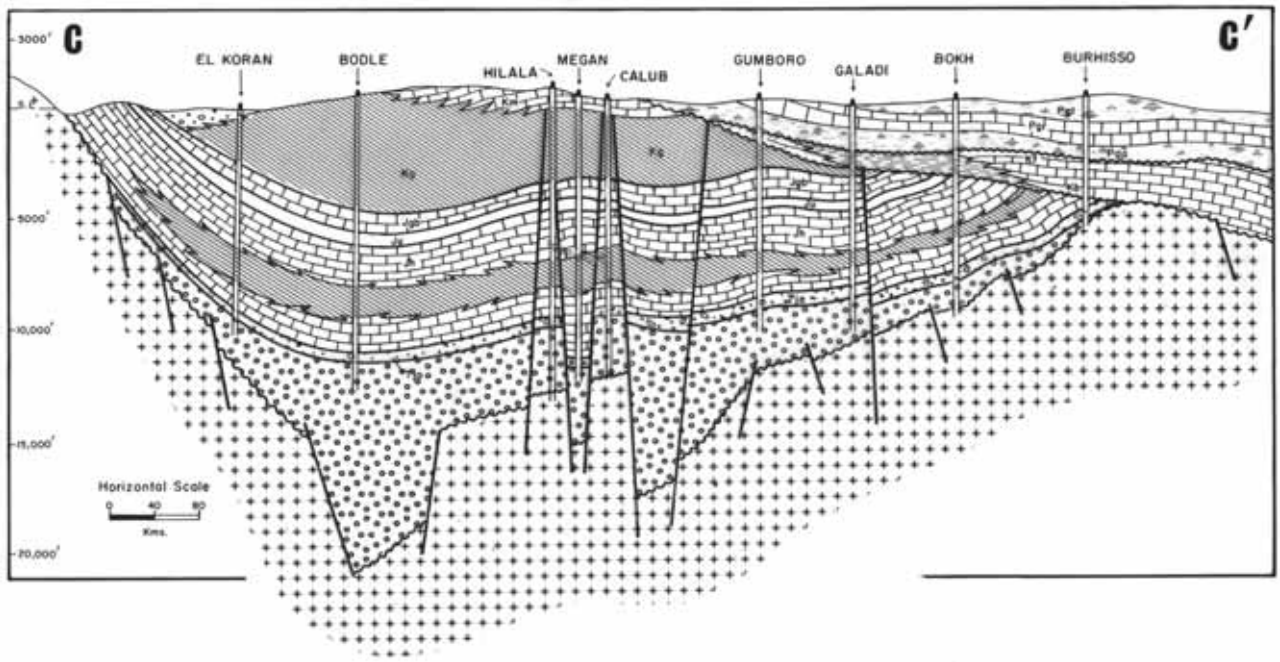


Figure 32. Northeast-Southwest cross-section, Ogaden and Coastal Somalia basins

margin of the basin in association with the Tertiary rifting of the area. Thinning of the Jurassic sediments onto the Chercher Massif is clear. In the southwest, the thickness of the Jurassic sediments suggests that a thin Jurassic sequence originally covered the Bur Massif.

Figure 32 extends northeast across the Western and Eastern Ogaden sub-basins, showing clearly the effect of the Nogal Uplift in the northeast, and the consequent superposition of the Coastal Somalia Basin onto the Ogaden Basin.

On all sections, the Permian basin are subjectively drawn, and the sequence is shown undifferentiated. The depths are comparable with aeromagnetic basement depths determined in the Mandera-Lugh Basin (Beltrandi and Pyre, 1972). The geometry of the basins follows the model of rifted margins discussed by Purcell (1976b).

The development of the Ogaden Basin has been significantly influenced by the development of two of the world's major rift zones. On the western side is the Tertiary rift valley that extends from south of Tanzania through Kenya into Ethiopia, where it opens into the Afar Depression. Isostatic uplift of the eastern margin of the rift has accentuated the relief on the basin-bounding basement blocks, with dramatic elevation of the entire northwestern and western flank of the basin. Early uplift associated with this rift system influenced the end of sedimentation in the basin. On the eastern side of the basin, is the margin of the African continental block which was determined by a major Permian rift system.

This region has been tectonically active from early times. Kazmin (1975) suggested that a major convective cell developed under the area about 1000 million years ago, at the end of the Precambrian, causing contemporaneous rejuvenation of the older basement of the Mozambique Belt and post-orogenic magmatism of the Red Sea geosynclinal belt. Continued activity of this zone is reflected in the formation of the Permian rift system, the subsidence of the Ogaden Basin and the Tertiary rifting. The interrelationship of these features is both complex and controversial, but is it not considered significant that these macro-elements are not locally co-incident. Their progressive superposition is a demonstration of a basic earth cause and co-incidence of such structures on a local scale seems unlikely.

The following discussion is concerned with the tectonic activity important in the formation of the Ogaden Basin. Detailed discussions of the Precambrian tectonics and the Tertiary rifting can be found in Kazmin (1975) and Mohr (1962) respectively, and others.

In the Permian, an extensive rift system developed down the down the eastern side of (what is now) the Horn of Africa (Kazmin and Purcell, 1977), isolating Madagascar and the African mainland, and funnelling marine waters out of the Tethys Sea. A period of vertical tectonics preceding the onset of drifting (that is, horizontal tectonics) is a characteristic development in the formation of an Atlantic-type continental margin (Dewey and Bird, 1972).

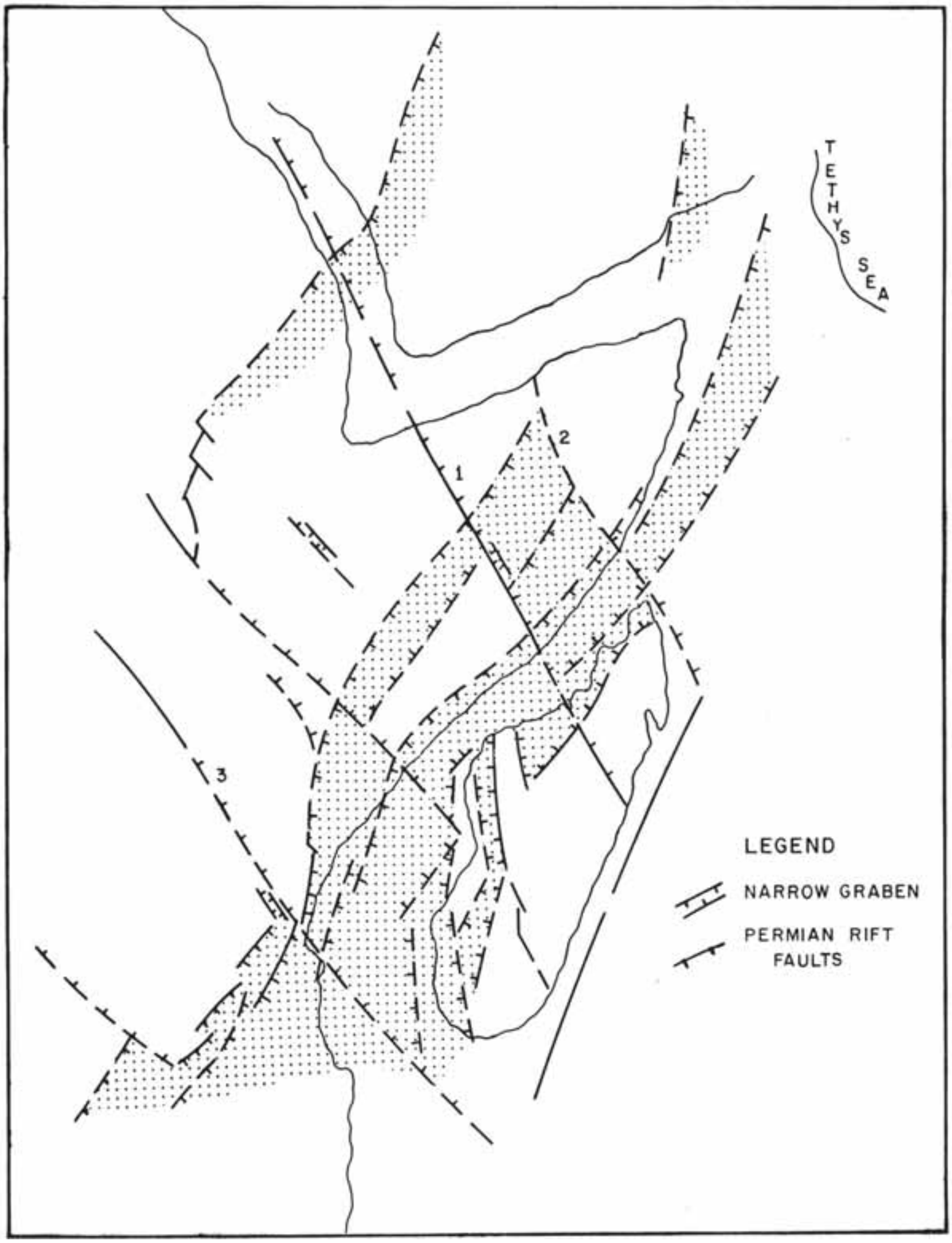


Figure 33. Schematic diagram of Permian rift system, east Africa region of Gondwana

The main rift was located east of the current coastline but a series of flanking half-grabens developed on the African mainland. The trends, and perhaps the location, of these faults seems related to the fabric of the Precambrian basement. The main basin bounding faults trend north-south to north-northeast; the Bur Fault and the Mandera Basin faults (Beltrandi and Pyre, 1972) are part of this trend. Major northwest-trending faults are also important in this system and might be described as proto-transform faults. These faults, which originated as Precambrian wench faults (Kazmin, 1976b), are characterised by narrow grabens, but vertical displacements are sometimes important (e.g. the Marda Fault) in defining the basin area. Part of the eastern side of this Permian rift basin complex occurs on Madagascar (Radelli, 1975) where the main faults are downthrown westward, so that the eastern Africa and Madagascar coastal basin are, in general terms, mirror images of each other. The structural framework of this period, as described by Kazmin and Purcell (1977), is shown in Figure 33.

A sill in the Adigrat Sandstone in Somalia, described by Mohr (1976) as 'an omen of crustral instability' is the only known evidence for volcanism associated with the Karroo rifting episode in this region. This rift developed progressively from north to south and, similarly, the , spreading axis which separated the continents seems to have developed first in the north. The isolation of a rifted margin is followed closely by subsidence of the new margin as decreasing temperatures result in higher density crustal rock types (Falvey, 1974). Regional transgressions flow over the continental region as a consequence of this subsidence and are a guide to the approximate age of the margin.

In central Somalia and the Ogaden, this transgression is marked by the Triassic Adigrat Sandstone. In Kenya, the oldest known marine Mesozoic sediments are Upper Liassic. Farther south in Tanzania, the carbonates overlying the Karroo sediments are Middle to Upper Jurassic in age. Similarly the transgression is of Lower Jurassic age in northern Madagascar but is Middle to Upper Jurassic in the southern Madagascar. This correspondence has been cited as evidence of the palaeolocation of Madagascar adjacent to Somalia and Kenya (Smith and Hallam, 1970), a position recently confirmed by palaeomagnetic data (Embleton and McElhenny, 1975).

The age of the oldest marine Mesozoic sediments along the southern shore of the Gulf of Aden also decreases eastward, but this progression is anomalous. The oldest known Jurassic rocks along the Gulf of Aden coast occur at Ras Hantara and are probably Bathonian-Oxfordian (Azzaroli, 1968). On Socotra Island, Cenomanian limestones overlie basement and arguments about post-Jurassic drift of this mini-continent do not seem to resolve the problem. Other explanations have been proposed: a regional shore-line in the east (Arkell, 1956), an extensive east-northwest trending landmass (Azzaroli and Fois, 1964) and an extensive pre-Cretaceous erosional cycle (Somaliland Oil Exploration Co., 1954).

Subsequent exploration has indicated that the "emergent landmass" concept, especially that of Azzaroli and Fois (1964), requires modification (compare their Figure 2 with Figure 11 of this paper) but appears the best explanation of the Jurassic basin limits. Uplift of the area did occur in the Upper Jurassic, evidenced by the Lower Cretaceous limestones unconformably overlying the Hamanlei Formation in the Migiurtinia Basin, but this does not fully explain the anomaly. In the tectonic scheme described in this paper, subsidence of the Cape Gadafui region would be expected to precede that of the Mogadishu area, but the reverse is true: the outcrops at Ras Hantara show that this area was not submerged until Bathonian time yet Triassic transgression occurred farther south in the Ogaden Basin. As Swartz and Arden (1960) have proposed, it appears that a locally high region was present in this area, similar to the Chercher Massif, which remained above sea level until Bathonian time. This elevated element in the Cape Gadafui area might be the upper end of the ramp zone of a northwest-trending half graben basin bounded by the Marda Fault.

The Marda Fault Zone also appears to be important in the Mesozoic subsidence of the Ogaden Basin. Kozerenko and Lartsev (1976b) reported a throw of 4-8 kilometres across this fault in coastal Somalia. By comparison, displacement across the zones in the northern Ogaden Basin appears very minor. It is possible, therefore, that subsidence took place by rotation along this and other fault zones. It is interesting to note that the extreme Horn area is underlain by the Inda Ad basement complex and independent adjustment of this block to tensional and isostatic forces is probable.

Early rifting in the Gulf of Aden is difficult to date but the zone appears to have been a tensional feature in the Afro-Arabian continent since the Mesozoic, perhaps as early as late Triassic (Kazmin, 1976). Isostatic uplift of the rift margins may have caused the extensive Upper Jurassic to Lower Cretaceous uplift of the Horn of Africa region. The commencement of this uplift may be dated as Oxfordian. The Oxfordian-Upper Malm interval is missing at an unconformity in the Migiurtinia Basin and a marked shallowing of the seas occurred during Gabredarre deposition in the Ogaden Basin.

The rift faulting in the Gulf of Aden, possibly an arm of an Indian Ocean triple junction (Kazmin, 1976), intensified in the Lower Cretaceous. Associated tholeiitic basalts can be dated as Aptian-Albian near Harar (Canuti et al., 1972), faulting of Lower Cretaceous age caused a marine re-entrant into the Migiurtinia Basin, and uplift on the Bur Fault silled the Ogaden Basin in the Neocomian and again in the Albian. During this period, the Bur Fault Zone determined an abrupt continental edge and the upthrown block was tilted westward into a rapidly subsiding basin centre. The term "upthrown" is appropriate: much of the influence of the Bur Fault on the basin history is related to positive movement of the Bur Massif and its extensions, rather than subsidence of adjacent basin areas..

Crustal movement in the Gulf of Aden may have involved transcurrent motion on the Marda Fault Zone. Shear zones have been mapped near Jijigga (Black et al., 1974) and other authors have noted associated folding (Brown, 1921; Purcell, 1976a). In the Mandera Lugh Basin, major faulting occurred in this period and is thought to be controlled by ancient fractures (Beltrandi and Pyre, 1972). Two major anticlinal trends, the Garbaharre and Sengif anticlines, were formed by a combination of basement horst faulting and, at least local, diapiric tectonism, probably associated with pre-Jurassic evaporites. These structures are controlled by northwest-trending faults and began to form in Oxfordian time, probably in response to isostatic uplift of the region. No diapiric structures have been reported in the Ogaden Basin, though the anomalous structural complex near Rendo may be associated with diapirism.

In the Upper Cretaceous, a major change in orientation of the Indian Ocean spreading axis occurred (McKenzie and Slater, 1973). Marine fossils (Carella and Scarpa, 1962) in the coastal Sudan evidence opening of the Red Sea rift at this time, perhaps best explained by north-south separation of the African and Arabian continents (Kazmin, 1976. These regional forces had a marked effect on the sedimentary pattern of the Ogaden Basin. Most significant was downwarping of the coastal zone, perhaps involving hinging along the Marda Fault Zone, causing a marine transgression westward across the eastern Ogaden. Baker et al, (1972) and other suggest that the Ethiopian dome, precursor and companion to the Tertiary rifting, began to form in the Upper Cretaceous.

The Tertiary rifting in the region resulted in major uplift of the northern and western margins of the Ogaden Basin. This uplift continued through the Tertiary and basalts overflowed large areas of the northwestern basin margin (Juch, 1972). The main effects of the Tertiary rifting on sedimentation in the region are manifest in the (now) coastal areas. Northeast-trending faults developed in the Eocene as a result of rotation of the direction of opening of the Red Sea and Gulf of Aden. Deeper water shales in the Cape Gardafui area are related to this faulting.

Extensive uplift occurred in the Eocene in central Somalia and extreme eastern Ogaden region of Ethiopia, accompanied by volcanism of Eocene-Oligocene age. Volcanism also occurred in the axis of the Mandera Lugh Basin. In both areas it is probably related to re-activation of old Mesozoic faults. Oligocene-Miocene faulting was not significant in the Ethiopian Ogaden area.

SEDIMENTARY HISTORY

PALAEOZOIC

The sedimentary history of the Ogaden Basin commenced in the Upper Palaeozoic, probably in the Permian. At that time, Africa was part of Gondwanaland and the southern shore of the Tethys Ocean extended down the (current) east coast of Africa and provided access for marine waters far into the ancient landmass. Marine Permian sediments are well documented in Madagascar (Radelli, 1975), over 1500 kilometres from the main ocean area. This Permian rifting has been viewed as the rift-stage basin of the eastern Africa continental margin (Purcell, 1976b) and is described in detail by Kazmin and Purcell (1977).

In general, the main sedimentary basins are controlled by north/northeast-trending faults while northwest-trending faults appear as quasi-transform elements of the system. Marine waters in the central rift zone periodically overflowed into the landward troughs, but the data are inadequate to describe a detailed geological history. In the central and eastern areas the existence of a basal sand overlain by a thick shale unit that is, in turn, overlain by sandstone with siltstones and gypsum, suggest a transgressive-regressive cycle. However, the Bokh Shale of Calub-1 may be near-shore swamp muds and the significance of the shales in Bokh-1 requires clarifications. Beltrandi and Pyre (1972) and Purcell (1977) cited evidence of evaporitic sediments in Somalia and Kenya respectively, and similar sediments probably occur in the western Ogaden region. The Permian history of the basin will only be resolved when additional subsurface information becomes available.

MESOZOIC

Triassic

Just as the rifting of the African continent and the consequent marine incursion had proceeded from north to south, so also the onset of drifting of the Indian and Madagascar continents and eustatic subsidence of the African continental margin commenced earliest in the north. (The absence of pre-Cretaceous sediments on Socotra Island probably indicates a positive block in northern Somalia, as discussed in the previous section). As the continental plate submerged, tiling down to the east, a marine transgression commenced across the region. This transgression was led by a shoreline sand unit, the Adigrat Sandstone. Perhaps limited by a northwest-trending- trending fault/hinge zone, the seas penetrated from southeast to northwest through the eastern Ogaden and only later, in Upper Liassic time, expanded southwest around the Bur Massif ‘island’ to join waters entering through the Lamu Embayment. Hence, while the marine Adigrat Sandstone was forming in the Ogaden in the Triassic, the continental Wajir Sandstone was being deposited in the Mandera-Lugh Basin in Kenya. This explains the controversial relationship of the Adigrat Sandstone to the Karroo deposits of Tanzania and Kenya. As Mohr (1962) recognised, the Adigrat cannot be correlated with the Wajir Sandstone as a rock unit, though they are contemporaneous.

Jurassic

As the seas advanced farther into Ethiopia, the water depth increased in the eastern Ogaden and carbonate shelf sedimentation was established. Most of the present-day Somalia Plateau was flooded but islands remained in the Chercher Mountains near Harar as well as in northern Somalia and the Bur region. A basal sandy facies developed around these islands and over central Ethiopia. Gypsiferous lagoonal sands were deposited in Arussi but most of the Ogaden basinal area was covered with shallow warm water which precipitated thick calcarenite deposits.

In the Liassic, silling of the Ogaden Basin lead to the formation of an evaporitic basin. The

Marda Arch may have accentuated development of this facies in the western Ogaden Basin but it appears that regional uplift occurred on the Bur Fault at this time, the first of several epeirogenic and compensatory isostatic adjustments that influenced the sedimentary history of the basin. Marine water overflowed these sills by Bajocian time and shallow, well agitated water flooded the region, depositing thick calcilutes over the basin.

By the Bathonian, the transgressive basal sand facies was being deposited over northern and western Ethiopia and limestone deposition was extended from the southeast towards Tigre and Yemen, covering Shoa and parts of Hararge. Over much of Somalia and the Ogaden, the waters were clear enough for development of reefs by the end of the Bathonian and the sea had transgressed as far as Eritrea, where littoral sands were deposited; while limestone facies formed over Tigre and the southern Afar regions. The hills of the Danakil Alps were fully submerged but local islands remained in Hararge, Somalia and Socotra (Jordan, 1976).

In the Oxfordian basinal conditions prevailed over most of the Ogaden region. Here and extensively to the east, dark muds were formed but reefs developed on high platforms such as along the Marda Fault Zone. The Jurassic seas had reached their maximum extent over the Horn of Africa and began to withdraw in the Kimmeridgian, evidenced by the lagoonal muds in the Mekele area. In the Ogaden Basin, uplift of the Chercher Massif commenced late in the Oxfordian, accentuating the regression. In the shallow clear Kimmeridgian sea, reefs abounded and thick oolitic beds developed. Deeper water conditions persisted only in Danakil region, where large ammonite fossils are common.

The shallow marine carbonate shelf conditions that prevailed over most of the region is evidenced by the fauna of pelecypods, brachiopods and corals, and the common occurrence of coquinal layers. Cephalopods in the Ogaden indicate locally deeper waters. In coastal Somalia, major faulting along the eastern side of the Bur Massif determined an abrupt continental edge and lime muds formed in the deeper waters. This facies extended a short distance west (Figure 11), up the axis of the Eastern Ogaden Sub-basin, defining what Barnes (1976) called the Somalia Embayment.

A regressive cycle commenced In the uppermost Jurassic and continued into the Cretaceous.

Cretaceous

The Cretaceous history of the Ogaden Basin, and of eastern Africa generally, is one of regression. Minor transgressions occurred, interacting with major epeirogenic uplift of the region to cause a complex depositional system.

From the peak of the transgression in Kimmeridgian time, the seas retreated to the southeast, depositing a shoreline facies. This unit is probably Tithonian in Tigre while in Arussi the clastic succession is Albian-Aptian. Locally, as in the Chercher Mountains and the Mekele Outlier, the retreating seas exposed areas of erosional or structural relief, and continental beds developed. Seas also withdrew to the north from the Mandera-Lugh basin during this period.

Shallowing of the seas in the Ogaden Basin continued from the Portlandian into the Neocomian, accentuated by uplift of the northern basin flank. In the basin centre, carbonate banks separated evaporitic ponds early in the Neocomian, but the basin became progressively more evaporitic and decreased in size. By the Barremian, anhydrite precipitation was concentrated in two subsiding basin areas apparently separated by a basement ridge associated with the Marda Fault and Bur Massif (Figure 16).

Later in this period, marine waters began to transgress across the basin and, during the Albian and Aptian, deposited limestones over most of the area. This major transgressive cycle ended in the upper Albian and the seas began to withdraw from the region. Continental conditions prevailed in the Mandera-Lugh basin and evaporite ponds covered most of the Ogaden region, though the northern flank was subaerially exposed and activity eroded. In coastal Somalia a linear reef zone formed along the Bur Fault, separated from the central Ogaden region by a trough of quiet water muds. East of this zone which probably marked the continental edge, abyssal lime muds formed.

By the Cenomanian the progressive downwarping of the coastal area had caused an extensive transgression. The seas flooded the entire basin, moving up the eroded basin flanks and across the Nogal Arch depositing shallow water limestones. Oscillatory movement occurred in the Coniacian and Maastrichtian but the basin was now a coastal feature, prograding over the continental margin. The Ogaden Basin *sensu stricto* had "filled".

In the coastal Somalia area the rising Maastrichtian seas flooded over the reef zone, burying it in dark fissile muds which extended inland to the Gumburo longitude. Shoreline sands in the Ogaden "bay" marked the final withdrawal of seas into the Coastal Somalia Basin, and most of the Ogaden region was subaerially exposed by the late Upper Cretaceous.

TERTIARY

Erosion of the western and northern Ogaden Basin areas continued into the Paleocene and was accentuated by renewed epeirogenic uplift. Continental sediments, locally aeolian, overlie progressively older formations towards the basin margins. To the east, open marine conditions prevailed in coastal Somalia.

In Paleocene-Lower Eocene times, the seas advanced westward and shoal limestones developed over most of the Horn of Africa. Hinging on the Marda Fault appears significant in limiting this transgression. Uplift of central Somalia in the Eocene caused a general shallowing of the seas, and lagoonal limestones and evaporites formed over the eastern Ogaden. Dolomite banks developed in deeper water in coastal Somalia except near Obbia and Cape Gardafui where muds, possibly littoral rather than deep-water, formed.

At the end of the Middle Eocene renewed subsidence led to deepening water conditions and a shallow carbonate shelf covered part of north-eastern Somalia, extending slightly into easternmost Ethiopia. This transgressive pulse was less extensive than the Auradu transgression and shows the overall regressive nature of the basin, as sediments prograded over the continental margin. Shallow marine clastics developed north and south of the central Somalia uplift proving that non-deposition, rather than subsequent erosion, caused the absence of lower tertiary sediments in the zone. In the deep-water environment adjacent to the Bur Fault thick lime muds accumulated. A shale facies is also developed in the Cape Gardafui region.

At the end of the Eocene the seas retreated and a period of erosion followed. This uplift is related to the regional tectonism, associated with rifting in the Red Sea and Gulf of Aden.

An Oligocene-Miocene transgression was limited to the Somalia Embayment axis and was apparently bounded on the east by a structurally high block. Shoal limestones settled in a small pond in the Gira area but paralic conditions prevailed on the coast. The carbonate basin dried through the Miocene-Pliocene into a small evaporite pond.

PETROLEUM PROSPECTS

The accumulation of large petroleum deposits involves both structural and stratigraphic factors. The presence of both reservoir and source rocks, and of structures to provide local trapping of hydrocarbons, are essential to the development of exploitable petroleum deposits in a remote basin such as the Ogaden (Weeks, 1960). Historically, the main difficulty perceived in exploring the Ogaden Basin has been the structural aspect (Belluigi, 1941): both Sinclair and Elwerath cited the problem of locating drillable prospects as a principal factor in their respective relinquishment decisions.

Elwerath (1967) also expressed concern about the influence of the basin structure on source rock development, noting that the carbonate shelf that prevailed over the Ogaden region during the Jurassic was generally a shallow water environment. In that basin environment, current activity removes carbon dioxide from solution, causing precipitation of fine-grained limestones, which are usually recrystallised soon after deposition and are commonly dolomitised, and can provide excellent reservoirs. However, this environment is not conducive to the formation of petroliferous sourcing rocks which form in the reducing environment below wave base. Structural relief on the sea floor or moderate structural mobility, alternatively raising and lowering the effective wave base, are necessary to generate a close association of reservoir and source rocks. In this regard, the relative stability of the Ogaden has been considered a negative criterion.

The Ogaden Basin and the entire Horn of Africa is also commonly described as a gas province, apparently referring to the influence of high heat-flow rates associated with the Tertiary-Recent rifting in the region.

These points are the main reasons noted for the lack of success to date in discovering large oil deposits in the basin and are discussed in more detail below. It is appropriate, however, to first review the impressive record of oil and gas shows, some only recently published, in wells drilled in the Ogaden Basin. This record is, in itself, a significant counter- arguments to concerns about both the temperate and sourcing problems in the basin.

OIL AND GAS SHOWS

Seepages of petroleum near Harar and Jijigga on the northern flank of the basin are described in the early literature (Molly, 1928) but several attempts to relocate these occurrences have not succeeded. The most famous seep in the region is near Daga Shebelli in Northern Somalia.

Two oil seeps have been recently reported in the Ogaden, and the oil seepage near Galemso on the northwest edge of the basin is especially interesting. While quarrying the dense Gabredarre limestone for road surface material, the Ethiopian Highway Authority discovered a large seepage in 1974. The oil occurs in fracture zones in the limestone, and is highly viscous in freshly broken vugs in the limestone. It is thought to be migrating up faults and fractures from the underlying Hamanlei Formation. A small gas seep, with a minor oil slick, has recently been described in the Ganale Doria River (Kitachew, 1974).i

The oil and gas shows recorded in the wells in the Ogaden Basin are shown on Figure 34. It is an impressive record. Of thirteen wells, several known to be located off-structure, seven wells have encountered oil or gas shows. Calub-1 tested over 35 MMcfd on a 1-inch choke from Adigrat and Calub sandstone reservoirs, with a reported 28 bbl/MMcf. Total estimated reserves in the field, which covers 93 square kilometres, are 1.6 trillion cubic feet (Tcf), with 75% recoverability, and about 45 MMbbl of condensate.

The El Kuran wells yielded "continuous oil and gas shows" through the Lower Cretaceous and Upper Jurassic section, and free oil was recovered from the Hamanlei Formation in Hilala-1 at a rate of 200 barrels/day (Mahdi Shumburo, pers. comm).

On Figure 35, these shows have been plotted against the sedimentary section in the Calub-1 well. It is stressed that these shows are not all from the Calub well; rather, a show in (say) Hilala-1 in the Middle Hamanlei is plotted against the Middle Hamanlei of Calub-1. The potential of the Mesozoic and Palaeozoic section is clearly revealed: oil and gas shows occur almost continuously through the Lower Cretaceous to Triassic section, and the basal Calub Sandstone also tested gas.

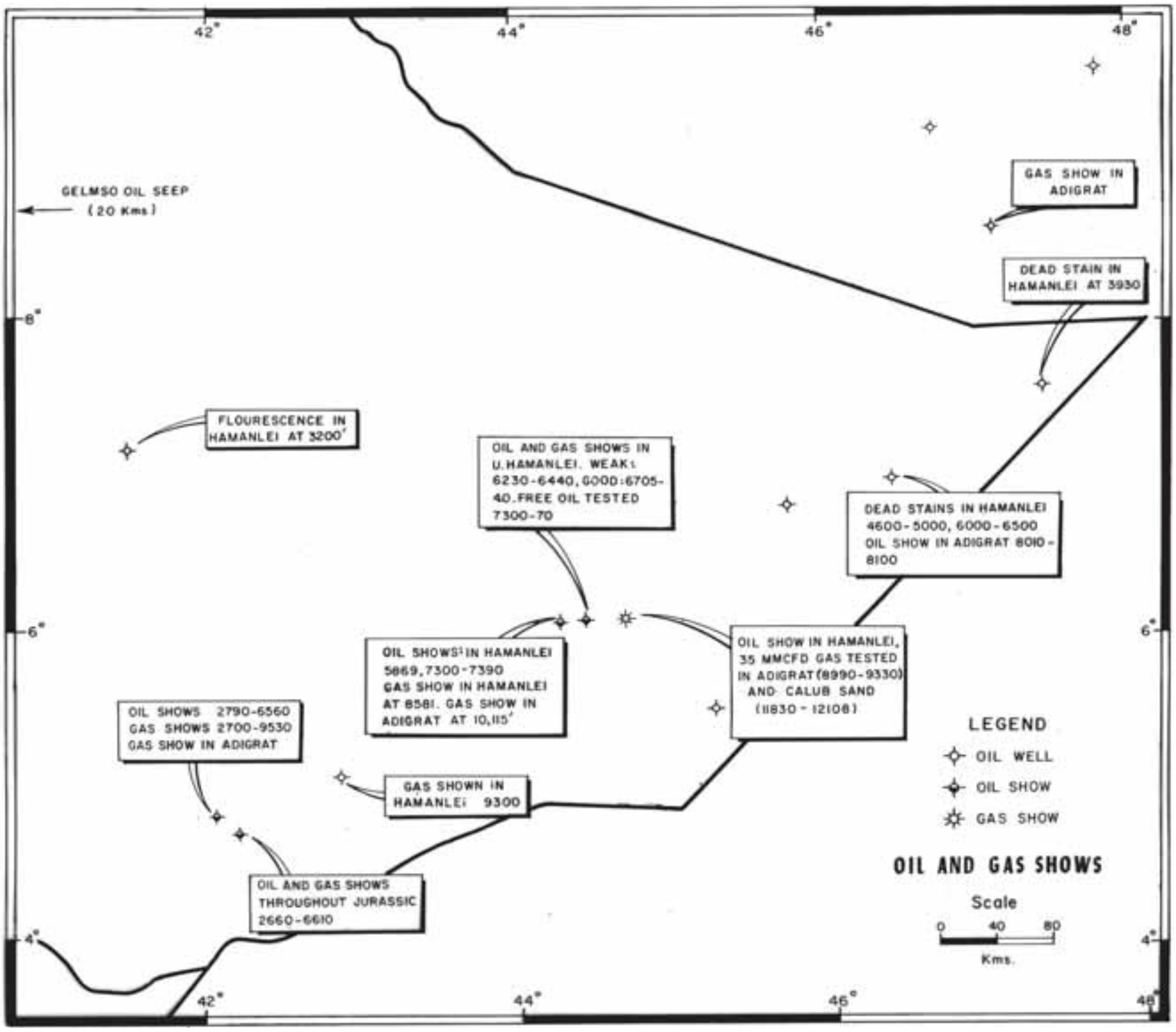


Figure 33 - Oil & gas shows, Ogaden Basin

Several points about the distribution of the oil and gas shows are significant.

1. The oil and gas shows in the El Kuran wells reveal the potential of the western flank of the basin - especially when it is noted that these wells are not located on structure.

2. The gas discovery in Calub-1 and the oil shows in Magan-1 and Hilala-1 indicate a local structural complex that warrants further attention.

3. More regionally, the shows in Calub-1, Magan-1 and Hilala-1 and the salt water recovered from probably unstructured Hamanlei and Adigrat reservoirs in Abred-1, identify the Marda Fault as a zone with interesting exploration potential.

4. The oil show in Galadi-1 suggests that the Galadi Fault Zone deserves attention and, in association with the record of shows in the Marda Fault zone, suggests that fault zones in the basin may determine prospective trends. This point is considered further in a following section.

5. It may be significant that many of the wells are located near the axis of deposition of the basin. More favourable porosities may be developed in the basin flank facies.

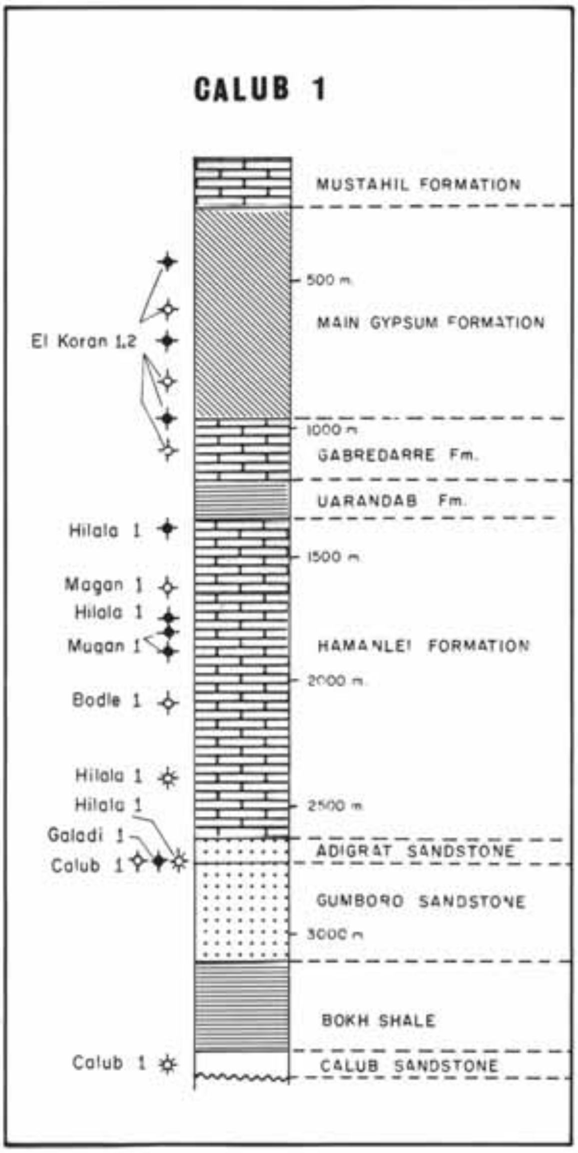


Figure 34 - Oil & Gas Shows in the Ogaden Basin

TEMPERATURES

Description of the Ogaden Basin as a probable gas province is currently very common. In part, this has been sponsored by the paucity of oil shows in the Horn of Africa region, despite the drilling of over sixty wells. Prior to the recent work in the Ogaden by the Tenneco group, the most significant shows were in Merca-1 which tested uncommercial gas deposits. The Calub gas discovery seems to have reinforced this bias and overshadowed the record of oil shows in the basin.

The definition of the area as a gas province is usually attributed to high subsurface temperatures in the basin having destroyed any pre-existing petroleum deposits. Data from only three wells in the Ogaden Basin are available to this study. They show a present day gradient of 1.1-1.2ºF/100ft in the eastern area. These gradient indicates that the 250ºF (120ºC) isotherm, marking the top of the gas zone, is currently located near 4,250 metres over most of the area, well below the main prospective section in the basin. Conversely, the top of the oil window is nearer 2000 m. Similar gradients may be expected in the western sub-basin.

This suggests that the Uarandab shales and intra-Hamanlei Formation source beds have only reached thermal maturity for oil generation and expulsion in the centre of the basin. Algal interbeds in the Main Gypsum formation may not have reached maturity

Data on palaeotemperatures in the basin are not available. However it is reasonable to suggest that the volcanism and rifting of the Tertiary to Recent era has had the maximum temperature effect on the basin, not necessarily by way of heating, but rather the cooling effect of the regional uplift. The Permian rifting does not seem to have been associated with extensive volcanism in the Ogaden area but was almost certainly associated with a heating event.

The Mesozoic formations over most areas of the basin axis do not appear to have been subjected to significantly greater depths of burial in the past. However the flanks of the basin, especially along the western and northern margins, have been uplifted substantially and will have had significantly higher palaeotemperatures.

Temperature data from Tenneco wells, when available, will provide far more useful comment on the thermal maturity of the basin. It seems likely, however, that the basin temperatures have not been high enough to preclude significant oil accumulations in the basin, except perhaps in the basin axis, especially in the Permian section.

SOURCE ROCKS

In early work in the Ogaden Basin the thick black shales of the Uarandab formation were considered the principal sourcing section in the basin (Taylor, 1951; Clift, 1956). A second massive shale unit, the Bokh Shale, has been recognised in the subsurface and may have sourced the gas-condensate in the Adigrat and Calub sands in Calub-1. Elsewhere, this shale may be a source of liquid hydrocarbons.

After drilling two wells with no oil or gas shows, Elwerath (1967) conducted source rock studies and concluded that a sourcing section was present only in the basin axis. Data on these studies, presumably based on both surface and subsurface samples are not available at present and should, with more recent studies, be considered in any future review of the basin. Two comments on the Elwerath conclusion are significant. Firstly it may be noted that source rock analysis was only a developing technique at the time. Secondly, the results of the study, utilizing only two subsurface control point wells, over 300 kilometres apart, should not be generalized over the entire basin area.

The Ogaden Basin is one of the major evaporitic basins in the world (Barnes, 1976) and evaporites are widely recognized for their association with source rock development. Immediately prior to, and sometimes following, the evaporitic phase, stagnant and euxinic conditions in deeper water pools determine a reducing environment which ensures the preservation of organic material settling on the sea floor. Oil shows in Hilala-1 and El Kuran-1 occur in the evaporitic Jurassic sequences, presumably in interbedded porous oolitic limestones, and must be associated with local sourcing. Also the recent drilling has revealed a pattern of oil shows immediately above the anhydrite of the Hamanlei Formation. This suggests potential for oil-prone source beds in the Hamanlei and Main Gypsum units.

It is possible that source rocks in the basin may be more intimately associated with reservoir beds than the few wells drilled to date have suggested. Most structures in the basin appear to be associated with fault zones, providing for abrupt facies changes between horst and graben areas. This may be especially important in defining the prospectivity of the Hamanlei Formation. On structurally elevated areas, dolomite and oolite reservoirs can develop, while lime muds with a high sourcing capability are deposited in adjacent quiet water pools - an association reportedly important in the development of many of the prolific Saudi Arabian fields (Baker and Henson, 1952). Also, these faults are zones of maximum structural activity, subjected to rejuvenation through the basin history, and provide the optimum chance for the interfingering of reservoir and source sediments. These points are discussed further in a following section,

Any basin with this record of oil shows must be considered as petroliferous. Simply, the Ogaden Basin has the potential of associating favourable sourcing and reservoir rocks. The search for local areas where that association occurs is a well-justified exploratory objective.

RESERVOIR ROCKS

Drilling in the Ogaden Basin has proved the presence of excellent reservoirs in both the clastic and carbonate units.

Figure 36 shows porosities of 11-18% in the Adigrat sandstone on the northern flank of the eastern basin. Similar porosities have been observed in other wells in the western area (Mahdi Shumburo, pers. comm).

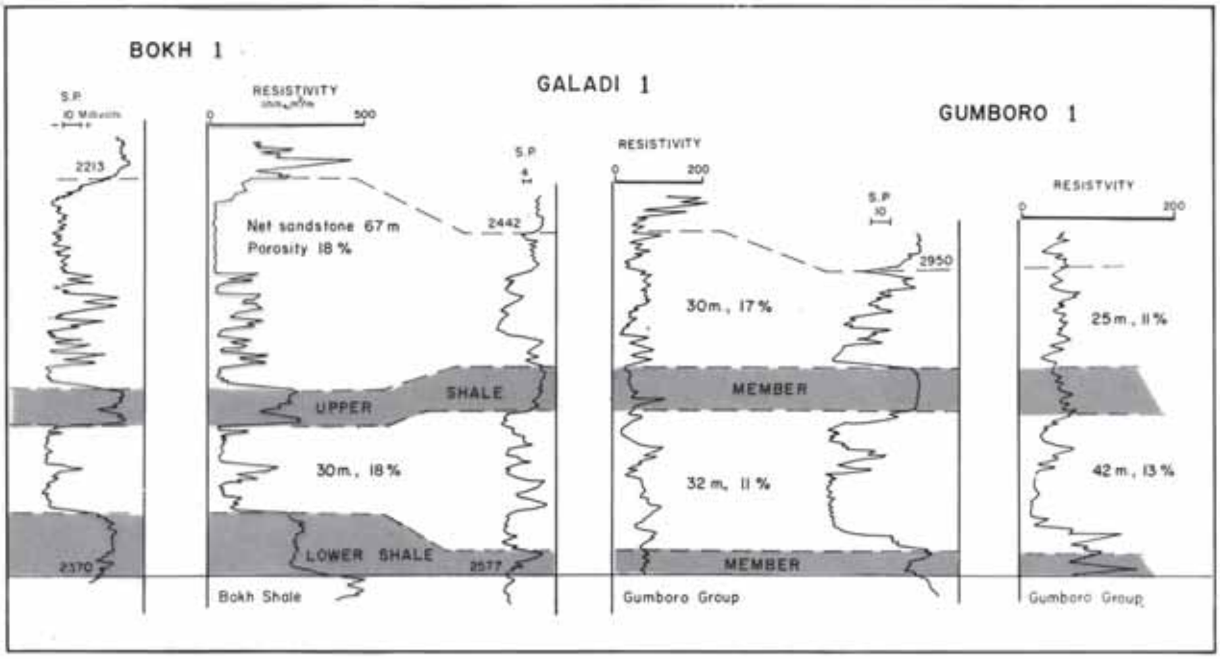


Figure 35. Adigrat Sandstone reservoir data, Eastern Ogaden (after Elwerath, 1967)

Figure 36 shows the SP and resistivity logs from the Hamanlei Formation in the Abred well. The thick calcarenite - dolomite zone with good porosity is a principal reservoir in the basin but the entire Jurassic section could develop porosity in a structured position such as a basin centre arch.

No data are available on the porosities of the Palaeozoic sediments. However, the gas flow at Calub-1 testifies to at least fair porosity and permeability.

Several wells drilled in the basin have revealed disappointing porosities but this may relate to both the structural position in the basin and to a lack of local structure at the well-site. The discussion above, about fault zones and structures controlling local facies, is relevant here: facies changes from calcarenites to shales are frequently abrupt on and off structure in this type of basin.

STRUCTURE

Photogeological studies have revealed numerous structures in the Jurassic outcrops on the basin flanks. Some of these structures near Fik have a surface closure covering 100 square kilometres and may result from erosional relief on the basement or be drape folds over minor dislocations in the basement. These structures appear too shallow to be prospective but suggest that structures may be more common in the deeper basin areas than early exploration indicated.

Structures have also been mapped in the Mandera-Lugh trough near the Ethiopian border. They have been interpreted as drape structure over basement uplifts and reefs are apparently associated with faulting (Ayres, 1952). Elsewhere local ripple structures in the Jurassic carbonates probably result from leaching and differential compaction and, adjacent to the rift margin, from locally compressive forces resulting from the major Tertiary uplift of the region.

In general, however, an association of structures with fault zone, frequently of regional dimensions characterises this entire region. In northern Somalia large north-south anticlinal structures have been mapped in the Eocene limestones and are considered to be the result of

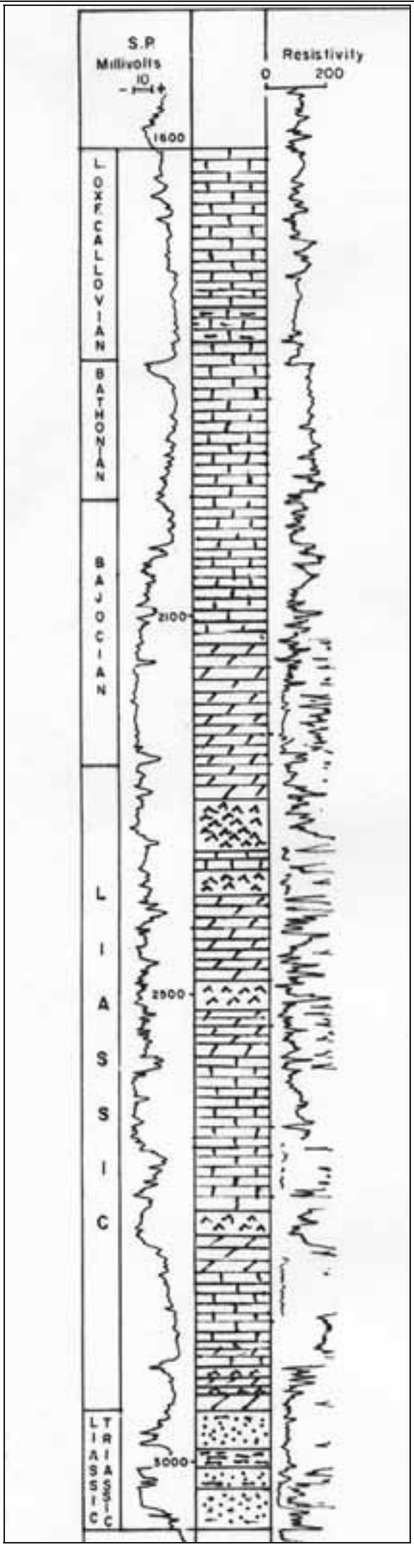


Figure 37. SP and resistivity logs, Abred-1

rejuvenation of pre-existing fault blocks, perhaps as compensatory adjustment to Jurassic epeirogenic uplift of the area (Schwartz and Arden, 1960).

Similar structures have been identified by oil exploration surveys in southern Somalia and Kenya (Walters and Linton, 1972), and may also be related to older structures. Uplift of nearly 300 metres have been suggested for faults controlling the Hapura anticline, south of Mandera, Kenya (Ayers, 1972). Further north, oil-producing anticlines in Saudi Arabia, also appear to be rejuvenated structures.

In the Ethiopian Ogaden, the Marda and Galadi fault zones are both associated with zones of structuring and both have tested hydrocarbons in deep wells. It could be suggested that early exploration in the Ogaden Basin, concentrating in the eastern area and handicapped by inadequate geophysical techniques, was seeking "conventional" structures, remote from the fault zones. The reverse approach may be the more appropriate: the search for petroleum in the Ogaden Basin may need to focus on the fault zones. They provide maximum "mobility" in a rather immobile basin and can result in drape structures over both horst and tilted blocks. Locally, at Magan-1, compression of trough sediments may also cause structural growth.

Barnes (1976) has concluded that "only a stratigraphic approach to oil finding in Somalia will achieve success". This statement has definite implications for exploration in the Ogaden Basin but it seems a little premature. It is based on the assumption that "all or nearly all of the anticlinal features in Somalia have been drilled in the last 20 years with negative results". The difficulties of obtaining useful geophysical data in the Ethiopian Ogaden (Elwerath, 1967) make it unlikely that all the early drilling in Somalia was based on good quality reliable data. It seems more likely that many of the wells in Somalia, by analogy to Gumburo-1, Galadi-1 and Abred-1 in Ethiopia, will prove to be off-structure at the objective levels. As an example the Merca structure in Somalia has been attributed by Barnes (1976) to the influence of spilitic basalt flows about 600 metres thick in the upper Cretaceous and Palaeocene.

Available data do not permit a detailed description of structures in the basin. However a structural map of the eastern area provides some useful implications and ERTS-1 (LANDSAT) imagery reveals the main trends of the basin area.

Figure 38 is an interpretation by the writer of a 1:2,000,000 mosaic of Band 7 imagery compiled by Hunting Geology and Geophysics Ltd, of London. Northwest- and northeast-trending faults and lineaments dominate the map. These trends are known as the Red Sea and Rift Valley trends respectively and are usually considered to be of Tertiary origin. However, it seems likely that the Tertiary trends reflect pre-existing structural zones and fabric.

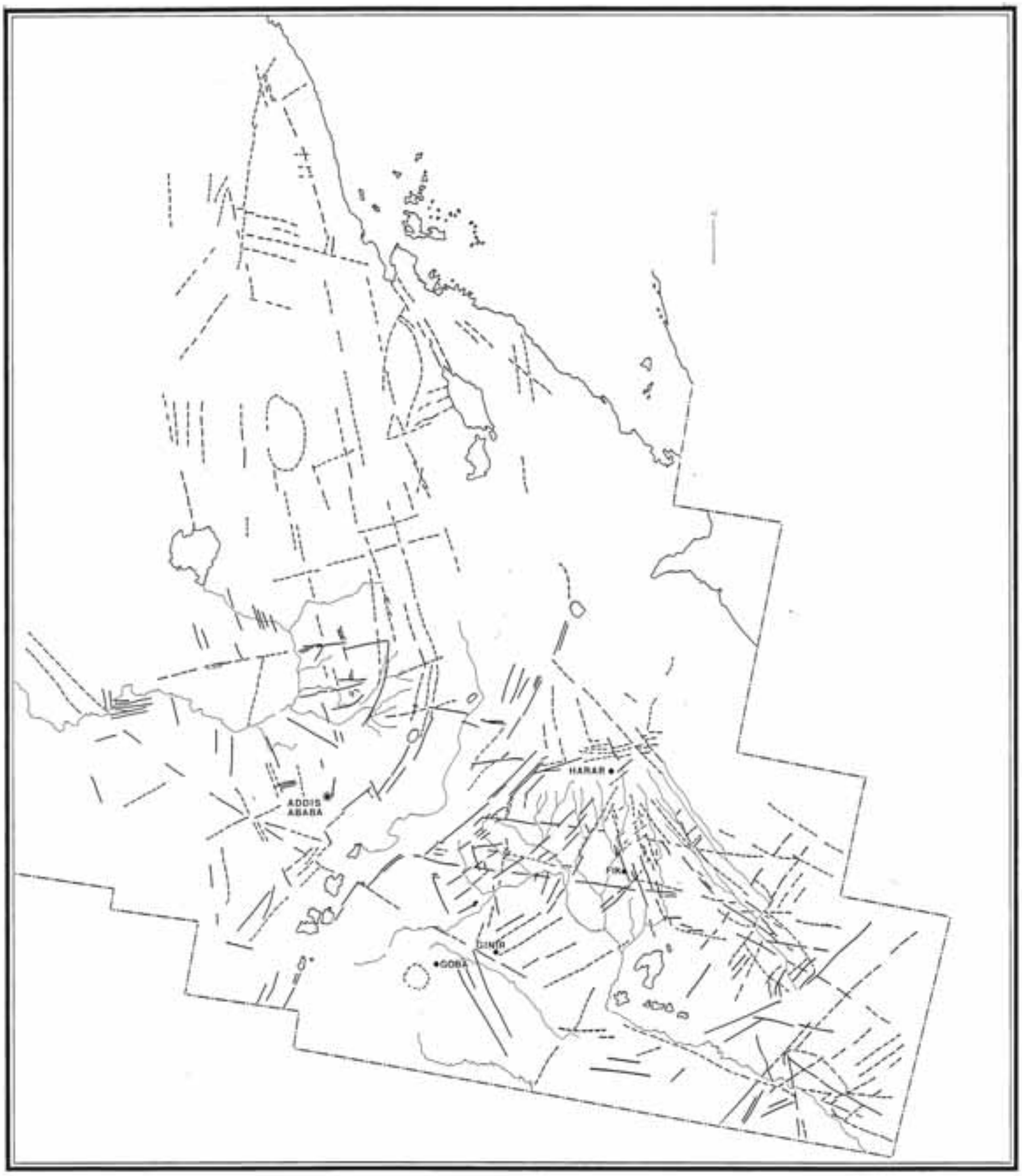


Figure 38. ERTS-1 (Landsat) lineaments, eastern Ethiopia

This is a controversial subject, especially in relation to local features, but the regional influence of older structural elements on the Tertiary rift system seems fairly well demonstrated (McConnell, 1974). In Ethiopia, Mohr (1962) has described Mesozoic warping of the Afar margin, Kazmin (1976) projected the Marda Fault into the Red Sea, and Kazmin and Purcell (1977) noted the influence of Precambrian faulting of the formation of the southern Afar margin.

Several trends in the basin are known to predate the Tertiary period:

1. The northwest- trending Marda Fault has been significant in the history of the basin since the Permian and has proven hydrocarbon potential. Other faults of this trend are revealed on ERTS-1 imagery and have been identified in the subsurface.

2. North/south- to north/northeast-trending lineaments appear to control offsets in the rift margin. This trend is characteristic of the Mozambique Belt and is the dominant trend of the major oil-bearing structures of Saudi Arabia.

3. West/northwest-trending faults are known in the basement of Eritrea and deserve attention in the Ogaden Basin.

Faults of these various trends may have been active in the development of the basin and require careful examination for possible exploratory significance. The extensive subsidence and uplift that occurred in both the Permian and the Mesozoic may have caused differential movements along old faults zones, with consequent development of trapping structures.

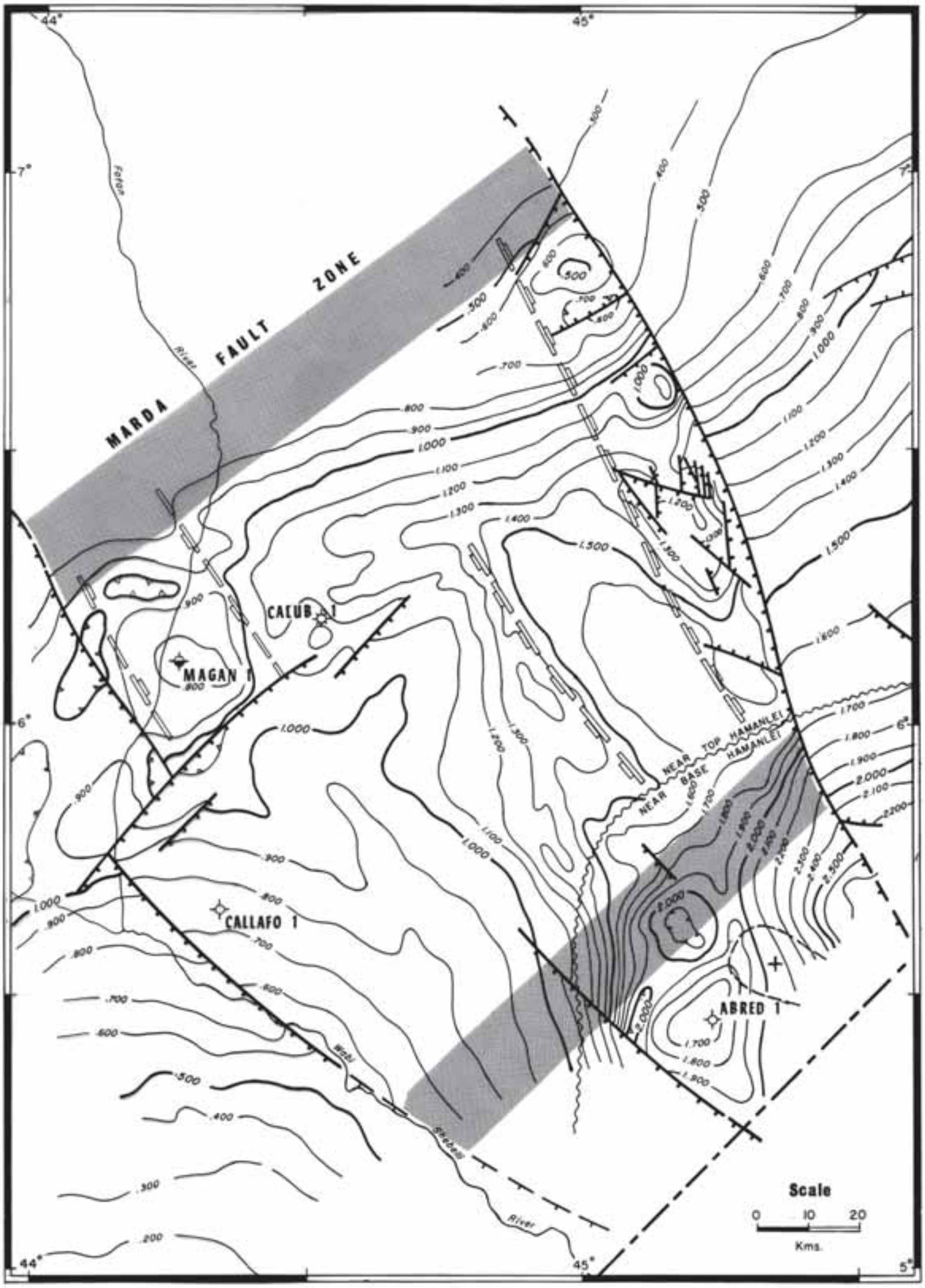
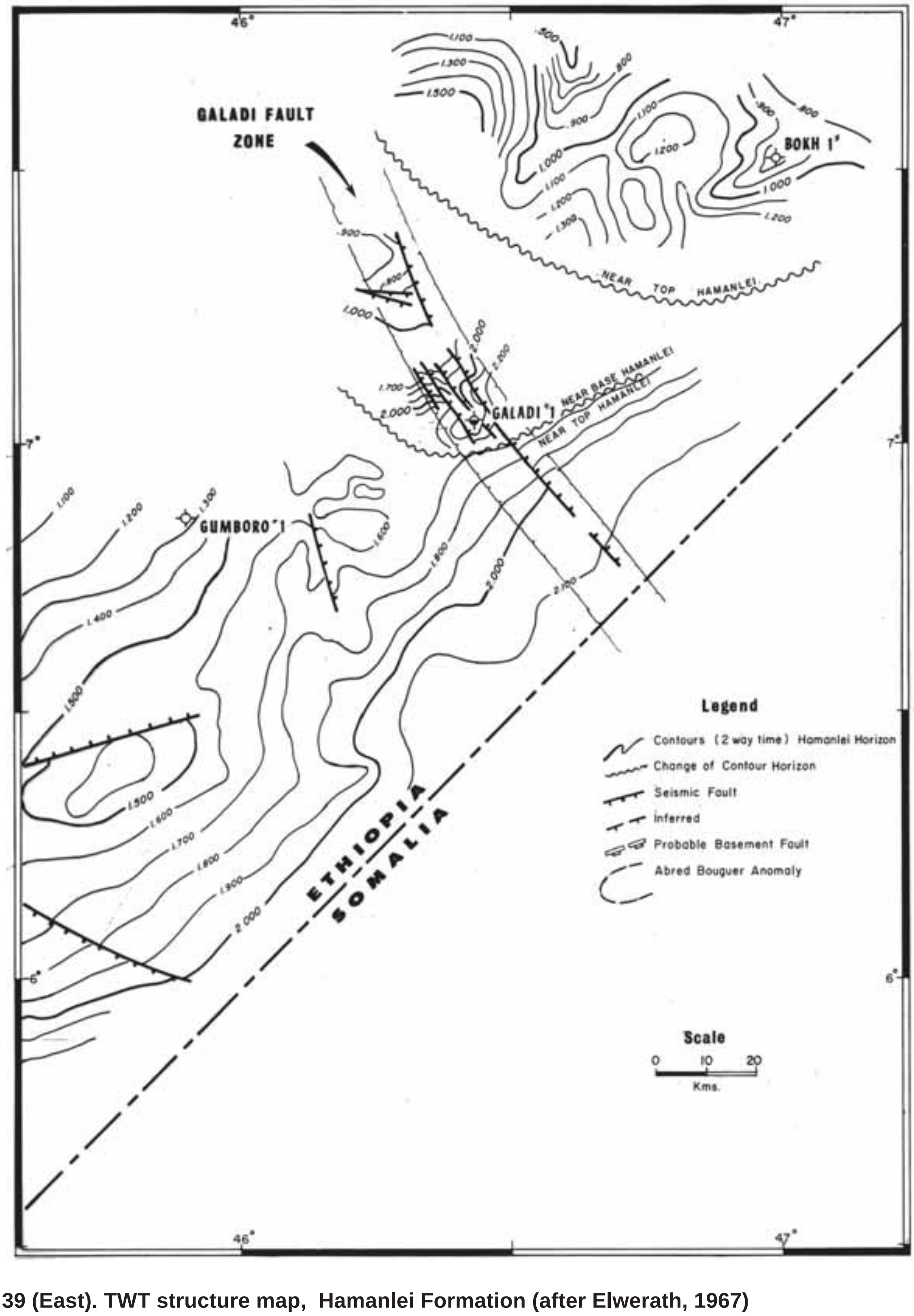


Figure 39 (West). TWT structure map, Hamanlei Formation (after Elwerath, 1967)

A structural map of the eastern Ogaden (Figure 39) provides some comment on local structures and structuring in the basin. The map, reproduced from Elwerath (1967), was based on seismic reflection data and considered to be depicting structure near the top of the Hamanlei Formation. However, comparison of the contours with the stratigraphic section drilled at Calub-1 and Abred-1 suggests that the horizon is not consistent from north to south. Assuming an average velocity of 8000ft/sec the horizon is near the top of the Hamanlei in Calub but is close to the base of the unit in Abred-1. It is possible also that there is a change in the velocity profile



a)

Figure 39 (East). TWT structure map, Hamanlei Formation (after Elwerath, 1967)

between the Abred and Calub areas. Correspondingly, the structures should be viewed only as trends and no significance should be ascribed to their relative depths.

Large areas show monoclinal dip: in the southwest, the north-plunging nose of the Bur Massif; in the central region dipping southeast toward coastal Somalia. The influence of faulting on structure formation is clear, especially the abrupt termination of the basinward dip in the central area. This fault may be part of the Marda system but is clearly distinguished as a separate zone in Somalia by Kozerenko and Lartsev (1976b). The linear zone of structures along the fault is striking and does not appear to be related simply to basement faulting. Kazmin and Purcell, (1977) have noted that narrow grabens characterize major northwest-trending faults in the eastern Africa, including the Marda Fault. It is probable that this zone of structures results from compression of these graben sediments, as well as from drape over horst blocks. This is apparently the case with the Magan structure, where a distinct dome at the top of the Hamanlei Formation has reportedly developed above a graben.

The map also reveals a zone of structures associated with the Galadi Fault and other local structures are fault-related. The Bokh area shows more structural development than other areas of the map. This difference in structural style in this area is thought to be related to the change in basement composition in this area.

In the southwestern area, a complex structural pattern is revealed within the Marda Fault Zone. The geometry of the contours suggests basement block faulting with independent movement on the faults causing abrupt dip-zones in the sedimentary section. The Calub and Magan wells are located on a northeast-trending structure that is controlled by northwest- and northeast-trending faults, and is associated with a positive gravity anomaly of intrabasement origin (Purcell, 1975b). Subsurface data reveal individual elements of this arch: the Calub structure is a basement horst block relative to the Magan graben (refer to Figure 30). Abred-1 is shown to be located on a closed seismic structure but the interpretation is suspect.

This general review of structure in the basin clearly suggests that the description of the Ogaden on the basis of early work as a "flat monoclinal stable shelf with little relief and cut only by some faults" need not be accepted as a negative comment on the petroleum potential. Firstly the available geophysical data, entirely pre-1965, appear to have been inadequate to reliably define the regional or local basin substructure. Secondly, even if this description proves substantially correct, then exploration in the basin should be directed to the loci of structural formation in the basin - the fault zones.

PROSPECT SUMMARY

The petroleum prospect summary map, shown as Figure 40, presents several areas and zones in the basin which appear, on the basis of the data available, to be prospective. Necessarily, the map is general and subjective, being limited by the non-availability of the 1973-6 Tenneco data. The Tenneco data will, when released, provide significant comment on, and doubtless criticism of, many of the concepts outlined in this review.)

In constructing the map, Bouguer gravity data have been used selectively to describe structural elements in the basin. This correlation follows the recognition of the co-incidence of many basement structures with major Bouguer gravity anomalies. However, the large anomaly co-incident with the Calub structure cannot be explained solely by the structure mapped by Elwerath (1967), and the anomaly near Daghabur is not simply related to the basement fault block recently proved in the area by an aeromagnetic survey. Major changes of basement composition or crustal thickness must be coincident with the structural axes. A similar situation has been noted in Saudi Arabia where the large gravity anomaly associated with the El Nala axis, cannot be generated by the structure itself (Aramco, 1959). This complex association of structure with intrabasement anomaly appears to indicate that zones of Precambrian tectonic weakness have, with re-activation or differential movement across the ancient fault zones, determined major structural trends in the basin.

Several regions and regional structures with definite potential for hydrocarbon exploration may be outlined. This does not imply that other zones are not present; only that they are not defined by the available data.

Marda Fault Zone

The Marda Fault Zone trends northwest/southeast across the Horn of Africa (Morton, 1974; Purcell, 1976a) and is expressed in the subsurface as a major basement uplift. The horst plunges south from the basement outcrops bear Jijigga: at Daghabur basement is about 500 metres deep, at Calub-1 it is over 3500 metres. At Abred-1 the basement depth is only 3070 metres and the Palaeozoic section is missing. This uplift is thought to relate to the proximity of the Bur Massif which is limited by, and probably offset by sinistral movement along, the fault (Kozerenko and Lartsev, 1976a).

Displacement on the fault is not clearly understood. In coastal Somalia, Kozerenko and Lartsev (1976a) report a throw of 2-4 kilometres across the zone. The displacement across the zone in Ethiopia is not of this magnitude, suggesting a rotational movement on the fault. Shear zones have been mapped in the zone and probably are re-activation of Precambrian wrench faults.

Four wells have been drilled in the zone: Calub-1 tested 35 MMcfd from Triassic and Permian sandstones, Magan-1 and Hilala-1 both tested non-commercial oil from the Hamanlei Formation, and Abred-1 recovered salt water from Hamanlei and Adigrat reservoirs. The correlation of gravity anomaly and basement structure at Calub and Daghabur suggest that the crest of the Abred structure is located east of the well site, which was positioned on poor quality seismic data (Purcell, 1975b).

The Calub, Magan and Hilala structures are coincident with a large Bouguer anomaly trending normal to the zone. A similar anomaly occurs at Daghabur and is associated with a basement horst block. The negative anomalies flanking these features suggest the presence of a third structure north of Gabredarre. The intervening grabens could be local sourcing basins to porous zones on the flanks and crests of the horst blocks.

The Elwerath seismic structure map (Figure 39) shows numerous leads in the zone. The Calub structure, at least in general, is shown on the map, and investigation of the other leads may prove equally rewarding.

The Marda structural trend, with proven oil and gas potential, should be given the highest priority in future work in the basin. Indeed, this arch may prove to be the major structure that explorers have long sought in the basin.

The Galadi Fault Zone

Galadi-1, drilled in a faulted plunging nose within the Galadi Fault Zone, tested free oil from the Adigrat Sandstone (Straub, 1957). Limited seismic surveying north of the Galadi location revealed structures on trend with the zone and the feature may have similarities to the Marda Fault Zone. A positive Bouguer anomaly near the zone may, by analogy to the Marda anomalies, be associated with basement structure.

The Galadi Fault zone lies close to the axis of the Mesozoic basin, and it could prove to be the first trapping element for hydrocarbons migrating from the basin centre.

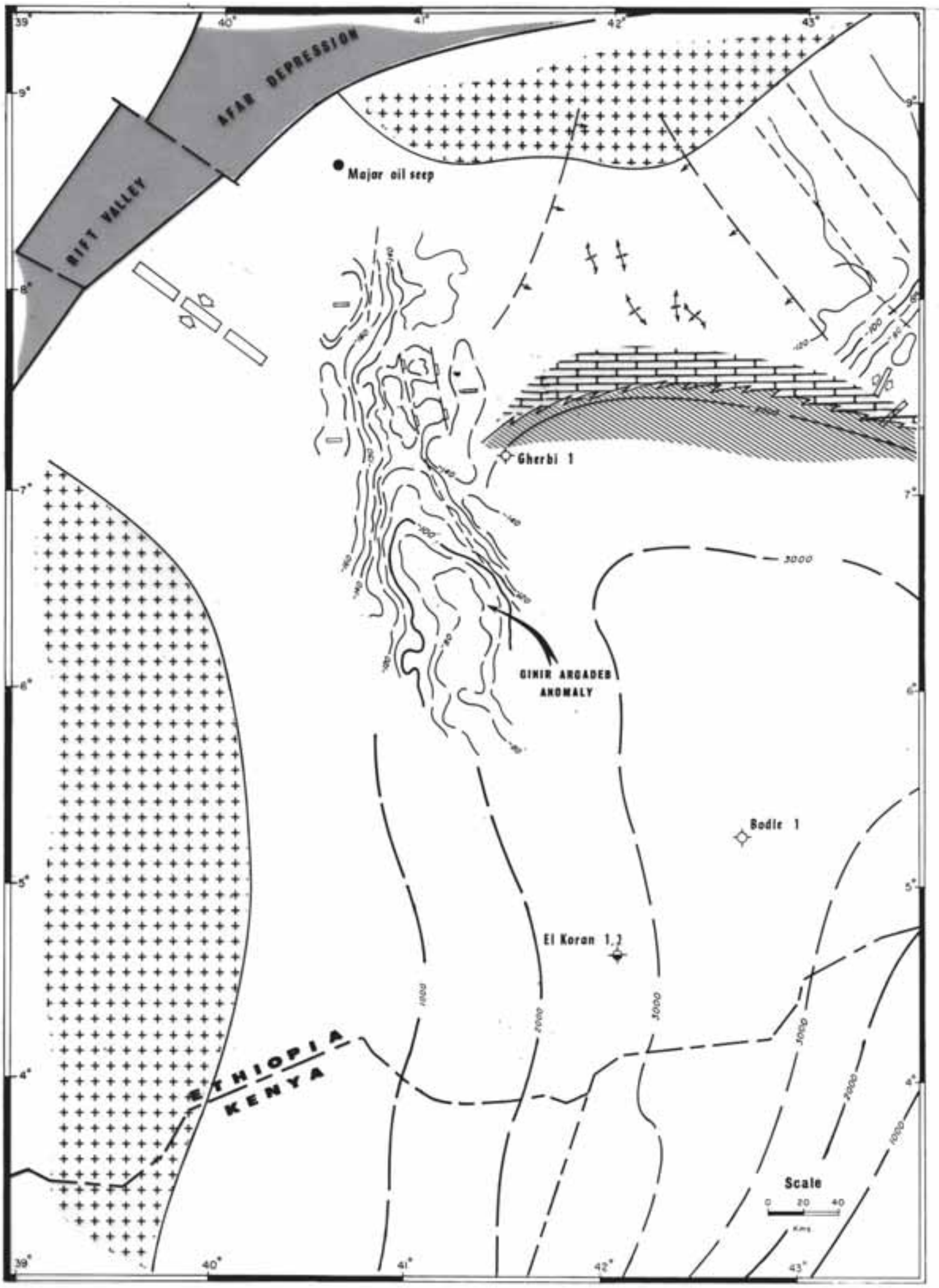


Figure 40. Ogaden basin exploration concepts summary map- western area

The Ginir-Argadeb Anomaly

This major positive Bouguer gravity anomaly located on the western flank of the basin may be related to a linear Precambrian basement element. This feature may have localized a zone of suprabasement structure along the flank of the basin, which has been shown to have potential

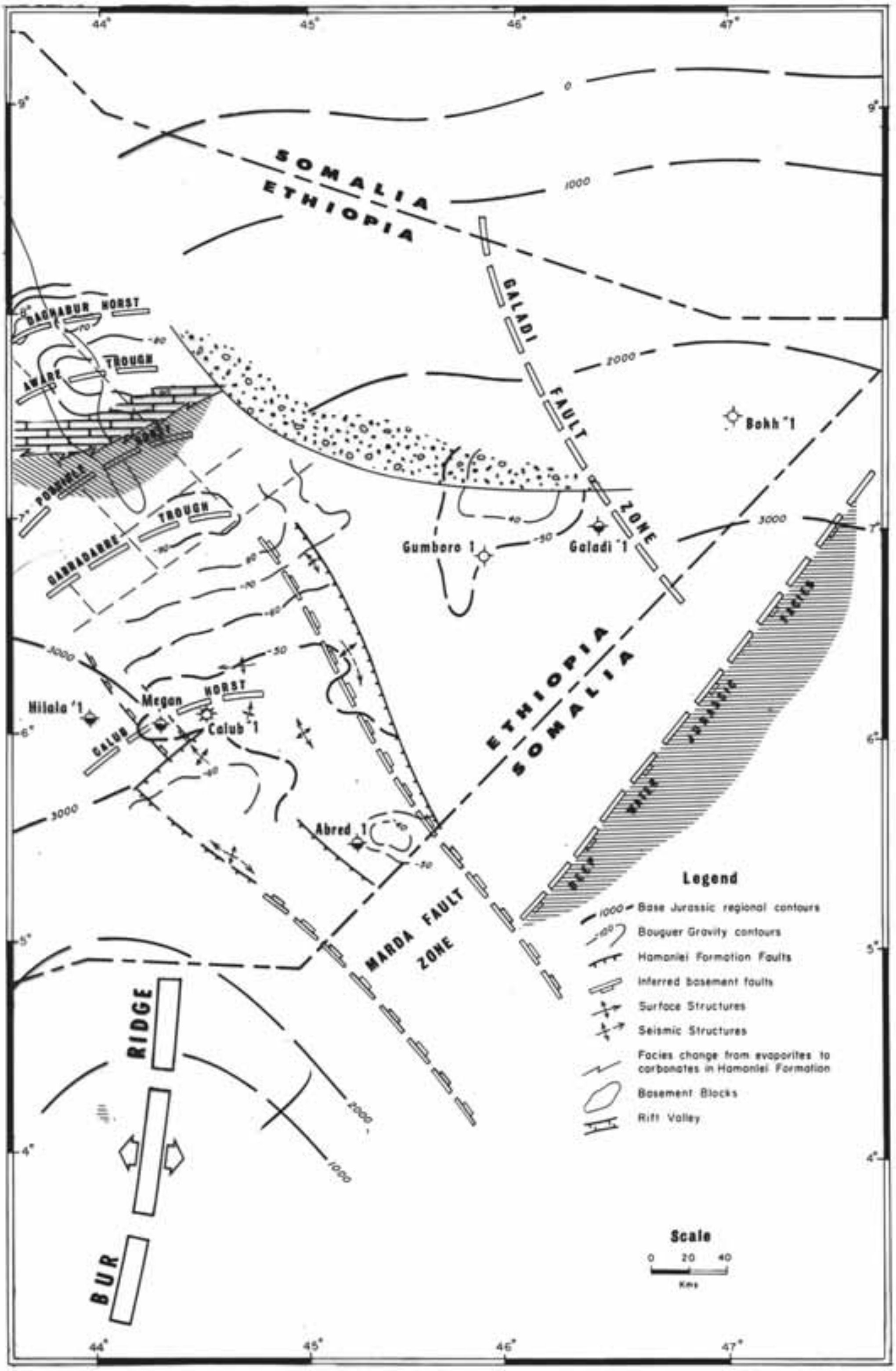


Figure 40 (cont.). Ogaden basin exploration concepts summary map- eastern area

by the oil and gas shows of the El Kuran wells.

Purcell (1975a) noted a residual gravity anomaly on the northern end of the axis, compared it to the El Nala gravity anomaly in Saudi Arabia (Aramco, 1959) and suggested an interpretation in terms of basement structure. Aeromagnetic surveying has recently proven major faults coincident with gravity anomaly.

The Northern Flank

Eastern Sub-basin

The Nogal Arch was a positive element in the early history of the basin, and structures on the basin flank are ideally located to trap hydrocarbons migrating from the basin centre. Uplift resulted in erosion of the Upper Jurassic and flushing of the Middle Hamanlei but the Lower Hamanlei and the Adigrat remain potential objectives. Adigrat reservoirs might be tight in the extreme east, being derived from erosion of the fine-grained Inda Ad metasediments, but elsewhere can expected to show adequate porosity, as observed in Bokh-1 and other wells. Structures may be related to both faulting and erosional relief.

Western Sub-basin

The Adigrat Sandstone is also an interesting reservoir in the northern flank of the western sub-basin. Salt waters recovered from water wells near Jijigga indicate that this basal unit has not been regionally flushed and, with porosities of 12-18% in the subsurface, this sand is a principal objective. Oil shows in this sub-basin consistently occur at the top of the Evaporite Series of the Hamanlei Formation. This evaporitic facies is not present in outcrop to the north and the possibility of facies change to porous carbonates could create a regional stratigraphic trap.

Bur Massif

Favourable Adigrat and Hamanlei reservoirs may occur on the plunging nose of the Bur Massif in the south central area. Callafo-1 seems well located to test this hypothesis but no information is available on the local structure.

SUMMARY

The Ogaden Basin of Ethiopia is one of the most interesting wildcat basins in the world. With only 13 wells drilled in an area of 350,000 square kilometres, several known to be off-structure, the basin is hardly tested at all. The record of oil and gas shows in these few wells highlights the petroleum potential of the basin. The stratigraphy reveals good carbonate and sandstones reservoirs; the Adigrat sandstone blanketing the basin is over 100 metres thick with porosities of 10-20%; the Hamanlei formation has revealed thick oolitic and dolomite zones and the Permian Calub sand has also been shown to be prospective.

Structural development in the basin is apparently influenced by basement fault zones which have been re-activated during uplift and subsidence of the region. These structural zones may have determined abrupt facies changes from porous sediments on the uplifted structures to source beds in the adjacent grabens and synclines.

It is reasonable to predict that future exploration in the basin will result in the discovery of petroleum deposits.

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APPENDIX I

BRIEF SUMMARY OF DEEP WELLS DRILLED IN THE OGADEN BASIN, ETHIOPIA

Name: **Gumburo-1**

Company:	Sinclair Petroleum Company
Location:	N 6º52' 44", E 45º 52' 48"
Elevation (RT):	536 m (1760 ft)
Date:	June 1949-April 1950

DEPTH (m)	FORMATION	THICKNESS (m)
3	Auradu Formation	79
82	Basalt	46
128	Auradu Formation	125[1]
171	Jesomma Sandstone	256
427	Gumburo Series	129
552	Basalt[2]	150
706	Gumburo Series	193[1]
770	Main Gypsum Formation	123
883	Gabredarre Formation	488
1381	Uarandab Formation	116
1497	Hamanlei Formation	1069
2566	Transition Zone[3]	42
2608	Adigrat Sandstone and Gumburo Sandstone (undifferentiated)	479
3,087	TD	

Testing:		
	695-714 m	Fresh Water
	1497-1551 m	Salt Water
	1657-1729 m	Brackish water
	1743-1874 m	Brackish water

1. These formation thicknesses are totals for the formations.
2. This volcanic rock is described as "Gumburo" in Sinclair reports.
3. This zone is properly part of the Hamanlei Formation.

Name: **Galadi-1**

Company: Sinclair Petroleum Company
Location: N 7º 1' 15", E 46º 25'
Elevation: 404 m (1362 ft)
Date: February-September 1952

DEPTH (m)	FORMATION	THICKNESS (m)
4	Auradu Formation	293
297	Jesomma Sandstone	308
605	Gumburo Series	224
829	Main Gypsum Formation	104
933	Gabredarre Formation	362
1295	Uarandab Formation	72
1367	Hamanlei Formation	1029
2369	Transition Zone	46
2442	Adigrat Sandstone and Gumburo Sandstone (Undifferentiated)	327

Shows: Oil shows in Adigrat Sandstone at 2440 - 2450 m

Name: **Abred-1**

Company: Sinclair Petroleum Company
Location:
Elevation: 523 m (1716 ft)
Date: June-November 1973

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Jesomma Sandstone	170	Sandstone, locally calcareous, with thin shales
170	Faf Series	232	Limestone and dolomite, with intercalated sand and shale
402	Mustahil Formation	413	Limestone with shale and marl and intercalated anhydrite
815	Gorrahei Formation	502	Anhydrite with shale in upper part, limestone and dolomite with thin shales in lower part
1317	Gabredarre and Uarandab Formations	6	Limestone and dolomite, locally oolitic
1325	Hamanlei Formation	1425	Limestone and dolomite, locally oolitic, with minor shale and anhydrite
2950	Adigrat Sandstone	120	Sandstone with shale partings
3070	Crystalline basement		
3104	TD		

Name: **Bokh-1**

Company: Elwerath

Location:

Elevation: 551 m (1808 ft)

Date: November 1964-June 1965

DEPTH (m)	FORMATION	THICKNESS (m)
0	Quaternary	13
13	Auradu Formation	417
430	Jesomma sandstone	248
678	Gumburo Series	374
1052	Hamanlei Formation	1161
2213	Adigrat Sandstone	157
2370	Bokh Shale	
3061	TD	

Name: **El Kuran-1**

Company: Tenneco
Location: 4º 43' 14º N, 42º 05' 04"E
Elevation: R.T. 218 m (716 ft)
Date: July-August 1972

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Not identified		Gypsum, red shale, then sandstone
49	Not identified		Silty sands and shales, crystalline argillaceous limestone
383	Not identified		Fossiliferous limestone with interbedded sandstone siltstone and shale
1756	Hamanlei Formation	1149	Limestone and Anhydrite
2905	Adigrat Sandstone[3]	284	Sandstone, with shales and evaporites
3189	TD		

Shows: Fair to poor oil shows and good to poor gas shows occurred through the entire section (Geol. Surv. Ethiopia, 1976)
Oil Shows: Good - trace oil shows 825-2000 m
Gas shows: Several gas-bearing zones 825-2819 m.

1. These sediments are probably part of the Main Gypsum formation.
2. This unit includes parts of the Main Gypsum formation as well as the Gabredarre and Uarandab formations.
3. This unit comprises sands, shales and evaporites and may include some pre-Adigrat sediments (Gumboro Sanstone).

Name: **El Kuran-2**

Company: Tenneco
Location: 4º 41' 33'N, 42º 04' 13" E
Elevation: 221 m (725 ft)
Date: March-June 1972

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Main Gypsum Formation		Red shale and interbedded Gypsum
58	Main Gypsum Formation		Sandstone, siltstone and limestone with interbedded shale
232	Main Gypsum Formation	811	Shale with interbedded limestone and sandstone
811	Gabredarre Formation	347	Limestone, locally argillaceous
1158	Uarandab Formation	189	Shale and sandstone with interbedded limestone
1347	Hamanlei Formation	668	Fossiliferous fine-grained limestone, minor shale and sandstone
2015	TD		

Shows: Fair to poor oil shows and good to poor gas shows occurred through the entire section (Geol. Surv. Ethiopia, 1976)

Name: **Calub-1**

Company: Tenneco
Location: 6º 9' 12"N, 44º 31' 54"E
Elevation: R.T. 463 m (1518 ft)
Date: November 1972-March 1973

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Mustahil Formation	204	
204	Main Gypsum Formation	1101	Anhydrite-gypsum intercalation, dolomitic at base
1058	Gabredarre Formation	254	Limestone with shale and evaporite stringers
1303	Uarandab Formation	143	Pyritic shale, calcareous at top
1446	Hamanlei Formation	1294	Limestone with evaporite
2740	Adigrat Sandstone	105	Sandstone with minor anhydrite
2845	Gumburo Sandstone	398	Sandstone with chert pebbles and anhydrite
3243	Bokh Shale	363	Shales with fine silty sandstone
3606	Calub Sandstone	95	
3691	Crystalline basement.		
3700	TD		

Tests: The Adigrat Sandstone and the Calub Sandstone tested a flow of over 35 MMcfd. Individual flow data not available to this report.

Name: **Magan-1**

Company: Tenneco
Location: 6º 06' 11"N, 44º 17' 41"E
Elevation: R.T. 454 m (1489 ft)
Date: March-June 1973

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Mustahil Formation	87[2]	
87	Main Gypsum Formation	923	
1010	Gabredarre Formation	269	
1279	Uarandab Formation	103	Argillaceous limestone grading to marl
1382	Hamanlei Formation	1973	Limestone, locally oolitic with evaporites
3355	Transition Zone	86	Limestone and shale stringers with thin sands
3441	Adigrat and Gumburo sandstones (undiff)	104	Quartz sand with anhydrite cement and thin siltstone interbeds
3545	Bokh Shale	30[1]	Shale and siltstone
3575	TD		

Shows:	1899-1945 m	Weak Oil and gas shows
	1963 m	Weak gas show
	2044-2045 m	Fair oil and gas shows
	2225-2246 m	Good oil and gas shows with free oil (32º API) recovered on testing thin oolite zone

Name: **Callafo-1**

Company: Tenneco
Location: 5º 39' 11"N, 44º 20' 59"E
Elevation: 565 m (1755 ft)
Date: August-September 1973

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Mustahil Formation	258	Limestone with calcareous shale
258	Main Gypsum Formation	815	Interbedded dolomite anhydrite and shale
1073	Gabredarre Formation	213	Limestone with oolites
1286	Uarandab Formation		Shale
1431	Hamanlei Formation		Limestone and dolomite with interbedded anhydrite
2603	Transition Zone		Interbedded limestone, shale and sandstone
2640	Adigrat Sandstone		Micaceous sandstone with thin shale partings
2757	Gumburo Sandstone		Micaceous sandstone with many thin shale interbeds
3216	Crystalline basement.		
3242	TD		

Shows: No oil or gas shows were encountered

Name: **Bodle-1**

Company: Tenneco
Location: 5º 08' 30"N, 42º 05' 00"E
Elevation: 526 m (1725 ft)
Date: January-April 1974

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0-1681	Main Gypsum Formation	1681	Interbedded shale, sandstone, limestone and dolomite with anhydrite and salt
-2035	Gabredarre Formation	354	Limestone with occasional shale
-2163	Uarandab Formation	128	Interbedded limestone and shale with traces of siltstone
-3633	Hamanlei Formation	1570	Limestone, locally oolitic with anhydrite shale and sandstone near base
-3734	Transition zone	101	Interbedded limestone shale and sandstone
-3911	Adigrat Sandstone	177[1]	Dense argillaceous sandstone

Shows: Gas show at 2835 m
No shows of oil reported.

Name: **Hilala-1**

Company:	Tenneco
Location:	6º 06' 18"N, 43º 53' 30"E
Elevation:	610m (2000ft)
Date:	May-August 1974

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Mustahil Formation	165	
165	Main Gypsum Formation	1101	
1266	Gabredarre Formation	194	
1460	Uarandab Formation	160	
1620	Hamanlei Formation	1462	
3082	Adigrat Sandstone	103	
3185	Gumburo Sandstone	799	
3984	Bokh Shale	132	
4116	TD		

Shows: 1618 m - Oil
2247-2252 m - Oil
2615 m - gas
3095 m - gas

Testing Testing yielded free oil from the 2247-2252 m zone in the upper Hamanlei, but the deposit was uncommercial.

Name: **Gherbi-1**

Company: Tenneco
Location: 7º 22' 55"N, 41º 26' 02"E
Elevation: 1057 m (3468 ft)
Date: September-October 1974

DEPTH (m)	FORMATION	THICKNESS (m)	LITHOLOGY
0	Not identified	131	
131	Not identified	390	Limestone, commonly argillaceous
521	Hamanlei Formation	976	Limestone and anhydrite with occasional dolomite and shale
1497	Adigrat and Gumburo sandstones (undiff)	565	Sandstone with shale and rare clay and coal
1958	Crystalline basement.		
1976	TD		

Shows: No significant shows were encountered. A weak fluorescence occurred at 960 metres within the top of the middle Hamanlei Formation.
A po rous zone at the top of the Lower Hamanlei yielded super-saline water

1. This unit has been identified as the Uarandab Formation (Geol. Surv. Ethiopia, 1976) but is probably equivalent to the Mustahil and Amba Aradam Formations.
2. This unit is probably the Gabredarre Formation and may include parts of the Uarandab and even upper Hamanlei formations.