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PETROLEUM GEOLOGY OF MUGLAD BASIN, SUDAN

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ABSTRACT

Abstract: The Muglad rift basin of interior Sudan is an integral part of the West and Central African Rift System (WCARS). It has undergone a polyphase development which has resulted in three major phases of extension with intervening periods when uplift and erosion or non-deposition have taken place. The depositional environment is nonmarine ranging from fluvial to lacustrine. The basin has probably undergone periods of transtensional deformation indicated by the rhomb fault geometry. Changes in plate motions have been recorded in great detail by the stratigraphy and fault geometries within the basin and the contiguous basins. The rift basin has commercial reserve of petroleum, with both Cretaceous and Tertiary petroleum systems active. The major exploration risk is the lateral seal and locally the effect of the tectonic rejuvenation as well as tectonic inversion. In some oilfields, the volcanic rocks constitute a major challenge to seismic imaging and interpretation.

PETROLEUM GEOLOGY OF MUGLAD BASIN

1- INTRODUCTION:

The muglad basin is the largest graben structure straddling Sudan and South Sudan Republics (fig.1). The total area of the basin is approximately 120,000 km2 extending 800 km in a NW-SE direction with a maximum width of 200km (fig.2). The basin comprises nine sub-basins oriented in a NW-SE to NNW-SSE direction; with extensional and strike-slip structural histories.

Geophysical and geological data (schull; 1988, Fairhead et al 2012) have pointed to the presence of probably more than 16,000m of non-marine cretaceous-Cenozoic sediments in the deepest parts. The sedimentary successions in several deep wells within the basins consist of thick lower cretaceous to paleogene and neogene strata of claystones, fluvio-lacustrine sandstones and siltstone (schull, 1988). The basin is terminated in the NW against the Central African Shear Zone (CASZ) a regional structure which extends from the Cameroon through chad into Sudan (Browne and Fairhead, 1983; Fairhead 1988). The NW- trending basin has resulted from extensionaltectonics caused by conversion of shear stress via the CASZ (schandelmeir and pudlo,1990).

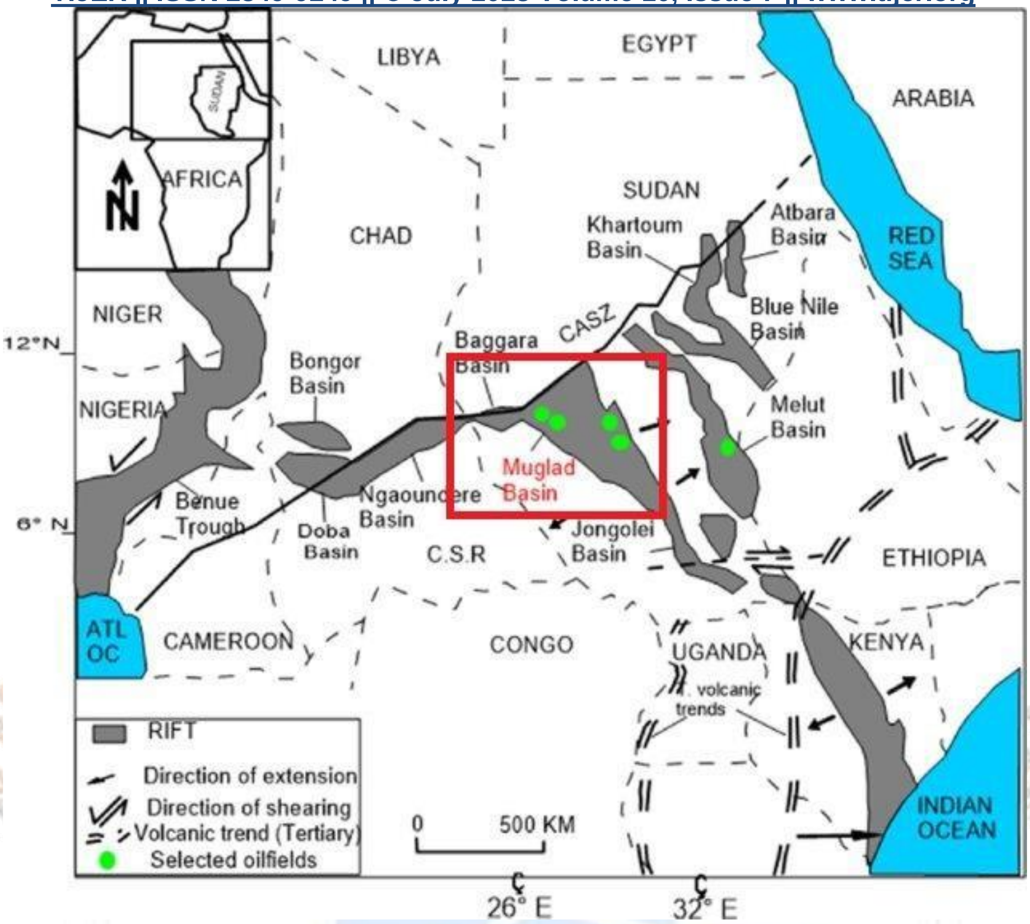


Fig. 1. Map showing the location of the Muglad Basin of Sudan as a part of the Central African Rift System.

The structural development of the basin was marked by three major rift cycles, each characterized by coarsening upward sequences of clastics sediments (schull, 1988).
A study by Fairhead et al, 2012 has compiled the high resolution land and airborne gravity and magnetic data over the basin in which detailed 2D gravity modeling, constrained by wells density logs and depth converted sections have been used to define the representative density depth function for the basin. This density depth function was then used to invert the residual gravity data into a 3D depth to basement model. This 3D model reflects the complex geometry of subsurface basement relief. The defined basement heights are known to central many of the oil field on the northeast side of thebasin.
The images are depth to basement models that represent the culmination of a number of calibration and integration steps. These include integrated structural/kinematic interpretation, geophysical modelling, seismic and well calibration and integration of tectonic events and response. Observations from different areas have been used and jointed together in a GIS environment to construct regionally consistent structural models that provide significant new insights in existing geological models; their evolution and architecture. Such models from the basis for systematic evaluation of exploration strategies.
Exploratory drilling for hydrocarbons in the muglad basin began in October 1977 the first oil was discovered in the basin from the second unity-1 well in May 1979 the first significant flow was found in the fifth well, Abu gabra-1 in August 1979, the first important discovery unity-2 happened in early 1980(schull, 1988).

2- GEOLOGY AND TECTONICS OF THE MUGLAD BASIN:

1.2- Geology of The Muglad Basin:

Basic geology of the Muglad basin essentially comprises a group of rocks and sediments that vary in age from the Precambrian to the Quaternary. Literally, we can classify these rocks and sediments into two main categories:

1.1.2- Basement rocks

As the well-known Sudan's Basement Complex, these are the oldest rock units in the basin, of Precambrian age that furnish the base of the basin, and on top of which a group of sediments and sedimentary rock sequences uncomformably rest. Distinct basement outcrops engulf the country from both the western and eastern boundaries. In general, the Basement Complex of Sudan includes: high-grade metasediments such as

Quartzites and marbles that are found in association with Amphibolite-facies gneisses and metasediments within a low-grade volcanogenic ophiolite assemblages such as in the Red Sea Hills of Eastern Sudan, and high-grade granitoid gneisses that are associated with either inliers of high-grade metasediments (e.g. Bayuda, Nubian desert, North Kordofan belt, Darfur belt, and Nuba Mountains) or a low-grade volcanogenic ophiolite assemblages (e.g. Bayuda, Nubian desert, and Nuba mountains). In the Muglad, the basement has been encountered in the peripheral parts of the basin at different locations. Granitic gneisses were penetrated at several wells throughout the basin, while marble has recently been hit by GNPOC at nearly 3,500 m in one well in block-2 area. Muglad’s basement was proven to be oil bearing (e.g. Block-17) however, no major commercial discovery is made so far.

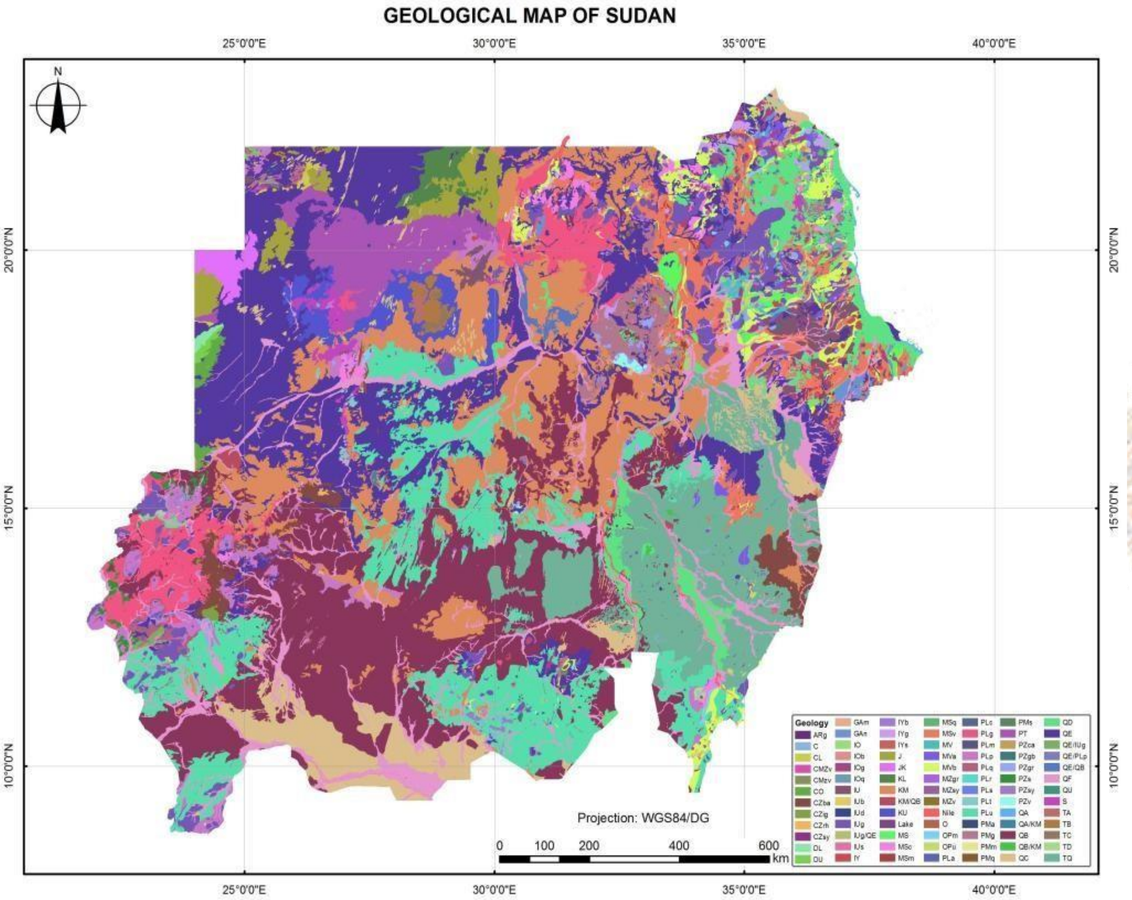


Fig.2: **Geological map of Sudan.**

2.1.2- Sedimentary cover & chronostratigraphy:

A group of sediments and sedimentary rocks of ages ranging from the Late Jurassic??/Early Cretaceous to the Quaternary period that were un-conformably lain on top of the Pre-Cambrian basement rocks. They are all of clastic and continental origin in the study area except for the Late Cretaceous sequence whose organic geochemical and stable carbon isotope data show strong evidence for a marine origin as discussed by the authors in this paper. Sedimentation in the basin took place as a result of three rifting episodes: (I) end Jurassic?/Early Cretaceous, (II) L.Cretaceous, and (III) Tertiary (Fig. 1). The first rift ended with the accumulation of a thick non-marine sandstones and organic-rich shales and mudstones of the Abu Gabra formation (Neocomian- Barremian) representing the major source rock in the basin. Widespread fluvial sandstone of the Bentiu formation (Aptian-Cenomanian) was uncomformably deposited on top of the Abu Gabra and is considered the major reservoir in the basin. A thick reddish brown flood plain mudstone of the Aradeiba formation (Santonian) represent the top seal of the E. Cretaceous petroleum system. The formation comprises some good intraformational sandstones reservoirs. A progradatioanl sequence of intercalated sand-shale units within the Darfur group uncomformably overlie the Bentiu shales and provide good reservoirs for the system. The topmost portion of this sequence provide a good quality source rock rich in algal type-II marine kerogen i.e. Baraka and Ghazal formations (Campanian-Maastrichian) which was followed by a thermal sag phase resulting in the deposition of thick massive fluvial sand stones of the Paleocene Amal formation. The basin again witnessed fluvio-lacustrine conditions during the Tertiary rifting that resulted in thick shales of the Nayil and Tendi sandstone reservoirs(Fig. 3).

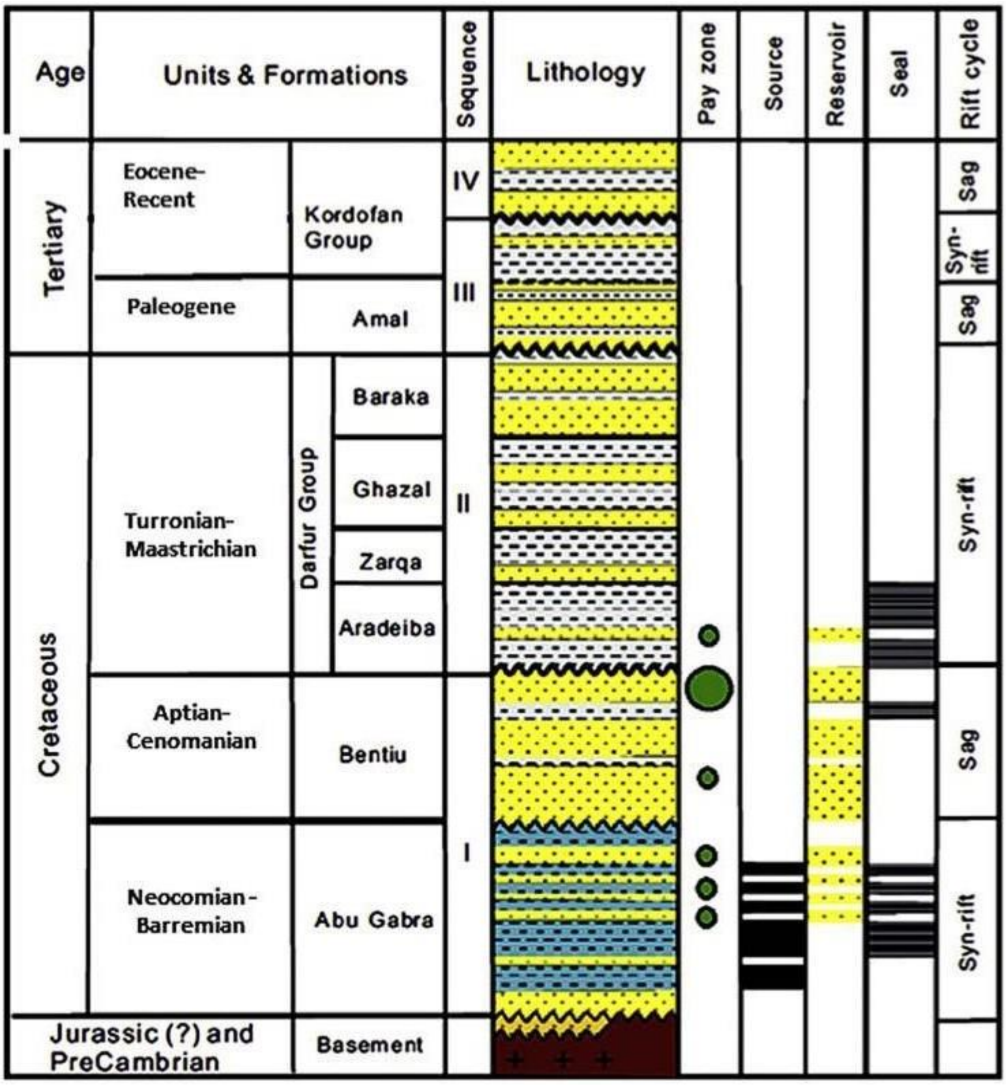


Fig.3. **Muglad's Chrono-stratigraphic chart based on Palynological data.**

2.2- TECTONIC EVOLUTION:

The tectonic development of this area can be divided into a pre-rifting phase, three rifting phases and sag phase. This evolutionary sequence is well documented by geophysical data, well information and regional geology (Schull 1988).

1.2.2- Pre-rifting phase:

By the end of the pan-African orogeny (550± ma 100 m.y.), this region had become a consolidated platform. During the remainder of the Paleozoic and early Mesozoic, this highland platform provided sediment to adjacent subsiding areas. The nearest preserved Paleozoic rocks are continental sediments in northwestern Sudan near the chad and Libyan borders. The general lack of lithic fragments in the oldest rift sediments further suggests that no significant amountof sedimentary section existed in the agreement area prior to rifting.

2.2.2- Rifting Phase:

Three distinct periods of rifting have occurred in response to crustal extension, which provided the isostatic mechanism for subsidence (Browne and Fairhead, 1983). Subsidence was accomplished by normal faulting parallel and sub parallel to the basinal axes and margins. The initiation of rifting cannot be precisely dated. Where basement has been penetrated in two wells of the north- western Muglad block, it is overlain by Neocomian-Barremian lacustrine siltstones and claystones. Seismic data, however, indicate thick sections of older but undated sediment down flank from these wells. In the northern Blue Nile block, the only well bottomed in inter-bedded siltstones, claystones, and salts (halite) of probable Jurassic age. Based on these widely spaced penetrations, rifting is thought to have begun in the Jurassic (?)-Early Cretaceous (130-160 Ma). Well control and seismic data indicate that this initial and strongest rifting phase lasted until near the end of the Albian. In the Sudan, no volcanism is known to be associated with this early rifting phase. The termination of the initial rifting is stratigraphically marked by basin wide deposition of the thick sandstones of the Bentiu Formation. The second rifting phase occurred during the Turonian-late Senonian. Stratigraphically, this phase is seen in the widespread deposition of lacustrine and floodplain claystones and siltstones, which abruptly terminated the deposition of the Bentiu Formation. This rifting phase was accompanied by minor volcanism. In wells, this phase is represented by a 300ft (91 m) dolerite sill in the northwest Muglad basin, dated 82 Ma ± 8m.y., and a Senonian andesitic tuff in the central Melut basin. These occurrences fit well with the approximate 90 Ma date cited as one of two periods of igneous activity in central and northern Sudan (Vail, 1978). The end of this

Phase is marked by the deposition of an increasingly sand-rich sequence that concluded with a thick Paleocene sandstone, the Amal Formation. The final rifting phase began in the late Eocene-Oligocene. This final phase is reflected in the sediments by a thick sequence of lacustrine and floodplain clay-stones and siltstones. The only evidence of volcanism in wells is the occurrence of thin late Eocene basalt flows in the southern Melut block near Ethiopia. However, age dating of widely scattered volcanic outcrops indicates volcanism in the Sudan at this time (Vail, 1978). After this period of rifting, deposition became more sand-rich throughout the late Oligocene-Miocene.

3.2.2- Sag Phase:

In the middle Miocene, the basinal areas entered an intracratonic sag phase of very gentle subsidence accompanied by little or no faulting. Limited outcrops of volcanic rock in the area southeast of Muglad dated at 5.6 Ma + 0.6m.y. and
2.7 Ma + 0.8 m.y. indicate that minor volcanism occurred locally. During this time, however, extensive volcanism did occur in some adjoining areas to the north (e.g., Jebel Marra, Meigob Hills, and in the East African rift system to the east and southeast). Currently, the area is stable with little earthquake or volcanic activity (Browne et al, 1985).

3- STRATIGRAPHIC AND SEDIMENTATION OF THE MUGLAD BASIN:

1.3- STRATIGRAPHY:

All sedimentary rocks penetrated are of non-marine origin. Correlations and age assignments have been established by palynomorph assemblages from which a five part spore/pollen zonation was created. Subsurface floral units have been palynologically defined for Lower, middle, and Upper Cretaceous as well as Paleogene and Eocene/Oligocene. Lower Cretaceous correlations have been confirmed by the presence of ostracods. Because of the scarcity of Cretaceous- early Tertiary outcrops, knowledge of the stratigraphy is limited to well control and the inferences made from the seismic data. Once sufficient well control became available, seismic-stratigraphic analysis techniques became useful in predicting stratigraphic facies and constructing depositional models. The depositional environments are illustrated in Figure 4. Generally, the environments can be grouped as alluvial fan, fluvial-braided stream, fluvial floodplain, and lacustrine. Depositional environments were determined by integrating data from wells, seismic facies mapping, and basin geometry. The well data (logs, samples, cores) provided lithologies, geochemical data, palynological control, sedimentary structure definition, stratigraphic dip information, and a direct tie to seismic data. Seismic facies mapping expanded the interpretation of depositional environments beyond the area of well control. Seismic character within nine time-related sequences was mapped by establishing criteria for each depositional environment relative to reflection configuration, reflection continuity, reflection amplitude, and interval velocity. Finally, the knowledge of basin geometry as determined by aeromagnetic, gravity, and seismic data was also used in defining depositional environment. A high percentage of the well and geophysical control is located in the large Muglad basin, therefore, although our discussion of the stratigraphy includes interpreting all data, it most completely reflects the geology of the Muglad basin. Also, because the well control is located in the more central parts of the basins, knowledge of the stratigraphic section is weighted toward the more distal environments present during any particular period. The generalized stratigraphic column (Figure 5) and the regional Muglad structural-stratigraphiccross section (Figure 6) are referenced throughout the discussion of the stratigraphic section.

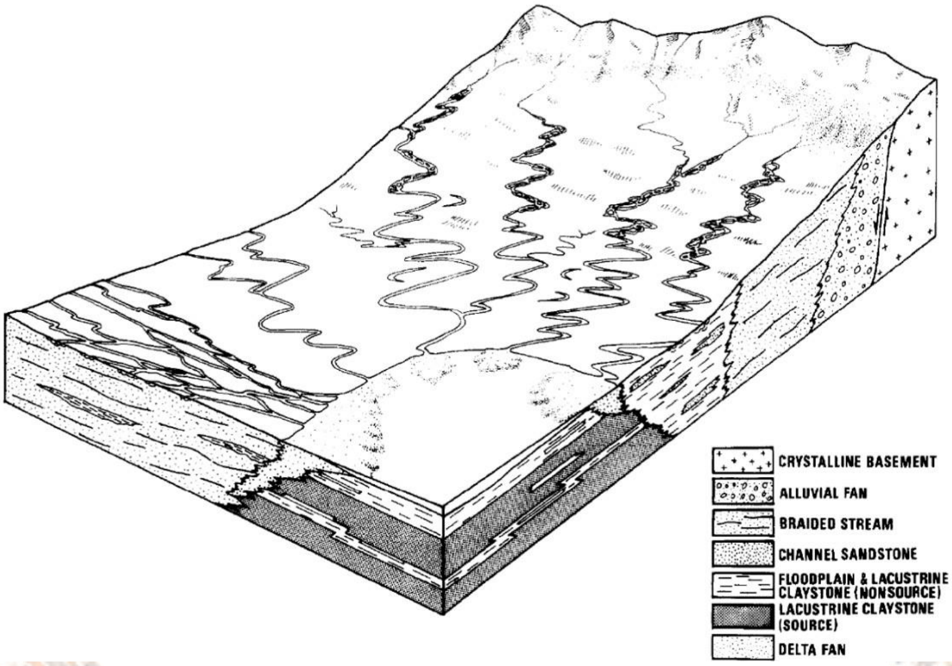


Fig. 4. Generalized depositional model depicting the environments operativeduring the filling of the southern Sudan Rift basin.

1.1.3- Precambrian-Jurassic:

The basement adjacent to the agreement area is predominantly Precambrian and Cambrian metamorphic rock with limited occurrences of intrusive igneous rocks. The primary composition is granitic or granodioritic gneiss. Basement has been penetrated and cored in two wells. At these locations, granodioritic gneiss has been dated 540 Ma + 40 m.y. From the Cambrian into the Mesozoic, the agreement area was the location of an extensive continental platform. The oldest sedimentary rocks penetrated are non-marine Jurassic (?) salts (halite), siltstones, and claystones in the Blue Nile block. One well has penetrated probable pre- rift sediments, a 700ft (213 m) quartzite of unknown age overlying gneissic basement. However, the two wells to reach basement have been drilled on structurally high blocks over which thick pre-rift section may have been removed, (Schull, 1988).

2.1.3- Cretaceous:

The Nubian Sandstone crops out or is covered by surficial deposits over much of northern Sudan. However, most of this outcrop terminates near the northern edge of the exploration area. A few Nubian outcrops exist adjacent to the Muglad block, east and northeast of the town of Muglad (Figure 1). In this area, the rocks are water-laid, non-marine, massively bedded, highly weathered, medium to coarse-grained sandstones. Because of the uncertainty in age determination and the limited and scattered nature of the outcrop, reconstructing the depositional history is difficult. In the subsurface, a thick sequence of Cretaceous sediment has been penetrated (Figure 5). This sequence is believed to be time equivalent too much of the Nubian out-crop.

Based on seismic data and well control, an estimated 20,000ft (6,096m) of Cretaceous sediment has been deposited in the deepest troughs (Figure 6). Cretaceous-Paleocene sediments reflect two cycles of deposition, each represented by a coarsening-upward sequence. These cycles are correlatable basin wide and are directly related to rifting and basin infilling. The first cycle is represented by the Sharaf, Abu Gabra, and Bentiu Formations. The second cycle is present in the Cretaceous Darfur Group and the Paleocene Amal Formation.

Sharaf and Abu Gabra Formations: The early graben-fill clastics are first cycle sediments derived from the gneissic basement complex. During the early phases of rifting, Neocomian and Barremian claystones, siltstones and fine- grained sandstones of the Sharaf Formation were deposited in fluvial- floodplain and lacustrine environments. Toward the basin edges and in the areas of major sediment influx these sediments graded to coarse alluvial clastics. The maximum penetration of this unit is approximately 1,200ft (366 m) in the northwest Muglad basin; however, seismically, the unit is indicated to be much thicker in the deeper troughs.

The Aptian-early Albian Abu Gabra Formation (Figure 5) represents the period of greatest lacustrine development. Several thousand feet of organic-rich lacustrine claystones and shales were deposited with interbedded fine-grained sands and silts. The nature of this deposit was probably the result of a humid climate and the lack of external drainage, indicating that the basins were tectonically silled. The Abu Gabra Formation is estimated to be up to 6,000ft (1,829 m) thick. In the northwestern Muglad block, several wells have recovered oil from sands within this sequence. These sands were deposited in a lacustrine- deltaic environment. The lacustrine claystones and shales of this unit are the primary source rock of the interior basins.

Bentiu Formation: During the late Albian-Cenomanian, a predominantly sand sequence (the Bentiu Formation) (Figure 5) was deposited. The alluvial and fluvial-floodplain environments expanded, probably due to a change from internal to external drainage. The regional base level, which was created by the earlier rifting and subsidence, no longer existed. These thick sandstone sequences were deposited in braided and meandering streams. This unit, which is up to 5,000ft (1,524 m) thick, typically shows good reservoir quality. Sandstones of the Bentiu Formation are the primary reservoirs of the Heglig area (Figure 1).

Darfur Group: The Turonian-late Senonian period was characterized by a cycle of fine to coarse-grained deposition. The lower portion of the group, Aradeiba and Zarqa Formations, is characterized by the predominance of claystone, shale, and siltstone. These initial deposits followed the second rifting phase. The excellent regional correlation of this unit verifies the strong tectonic influence on sedimentation. Floodplain and lacus-trine deposits were widespread. The low organic carbon content indicates deposition in shallow and well-oxygenated waters. These units may represent a time when the basins were partially silled. Although this unit offers little source potential to date, it may develop an organic-rich facies in areas not yet drilled. Throughout the basins, the Aradeiba and Zarga Formations are an important seal. Interbedded with the floodplain and lacustrine claystones, shales, and siltstones are several fluvial/deltaic channel sands generally 10-70ft (3-21 m) thick. These sands are significant reservoirs in the Unity area (Figure 1). The Cretaceous ended with the deposition of increasingly coarser grained sediments, reflected in the higher sand percentage of the Ghazal and Baraka Formations (Figure 5). These units were deposited in sand-rich fluvial and alluvial fan environments, which prograded from the basin margins. The Ghazal Formation is also an important reservoir unit in Unity field. The Darfur Group is up to 6,000ft (1,829 m) thick.

3.1.1- Tertiary

In outcrop, the Tertiary is represented by sequences of unconsolidated sands, gravels, silts, and clays deposited in alluvial, fluvial, and shallow lacustrine environments (Vail, 1978). These sedimentary rocks are difficult to distinguish from the overlying Pleistocene and Holocene alluvium. Few fossils have been found, and no firm age dates have been established for these units. In the subsurface, a thick sequence of Tertiary sediments has been penetrated (Figure 5). The initial deposits of the Tertiary were medium to coarse-grained clastics, followed by a single cycle of fine to coarse-grained sedimentation associated with the final rifting phase. Based on well control and seismic data, over 18,000ft (5,486 m) of Tertiary rock is present in the deepest troughs (Figure 5).

Amal Formation: The massive sandstones of the Paleocene, which are up to 2,500ft (762 m) thick, are composed dominantly of coarse to medium-grained quartz arenites. This formation represents high energy deposition in a regionally extensive alluvial-plain environment with coalescing braided streams and alluvial fans. These sandstones are potentially excellent reservoirs.

Middle and Upper Kordofan Group: These sediments represent a coarsening-upward depositional cycle that occurred from the late Eocene to middle Miocene. The lower portion of this cycle, the Nayil and Tendi Formation (Figure 5), is characterized by fine-grained sediment related to the final rifting phase. The deposits represent an extensive fluvial-floodplain and lacustrine environment. The lake deposits of this interval appear to have only minor oil source potential; however, they offer excellent potential as a seal overlying the massive sand-stones of the Amal Formation.

Upward, this unit is generally characterized by inter-bedded sandstone and claystone with an increasing sand content. The fluvial-floodplain and limited lacustrine environments gave way to the increasing alluvial input reflected in the sand-rich braided stream and fan deposits of the Adok and Zeraf Formations. An exception occurs in the area of the Sudd Swamp where approximately 2,000 ft (610 m) of late Tertiary claystones were deposited (schull, 1988)

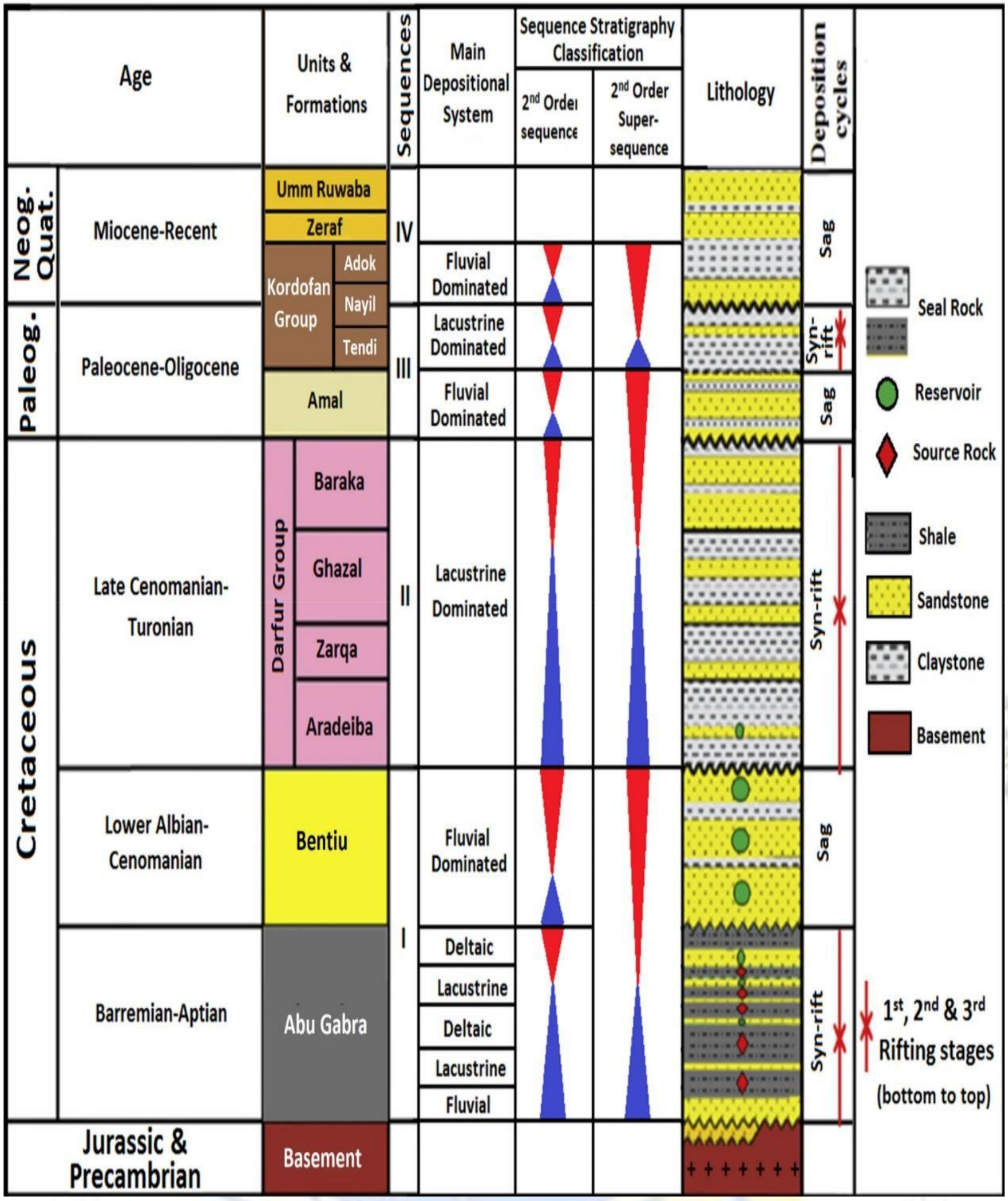


Fig.5. Generalized stratigraphic column based on data collected from 86 wells.

2.3- **RESERVOIR CHARACTER:**

The reservoir rocks of interior Sudan range from quartz arenites and wacke stones to arkosic arenites and wackestones. The reservoir rocks were originally derived from the Precambrian and Cambrian gneissic basement. The primary reservoirs include sandstones deposited in fluvial-channel, lacustrine delta-plain-distributary Channel, and delta-front environments. Generally, the better reservoirs were deposited in the more proximal alluvial and fluvial environments. The more distal lacustrine environment generally lacked the energy necessary to rework and clean up the potential reservoir sands. Typical Cretaceous reservoirs are very fine to medium-grained, moderately sorted, sub rounded to sub angular sandstones. Coarser grained, more poorly sorted sand-stones are common in alluvial intervals. Quartz and feldspar (both potassium and plagioclase) are the dominant minerals. Rock fragments are generally rare and heavy mineral content is low (0-5%). Clay minerals and mica predominate as matrix. Quartz and kaolinite, with lesser amounts of the following conclusions can be drawn from the reservoir data compiled from the study of 3,200ft (975 m) of conventional core taken from 30 wells (Figure 6).

(1) Reservoir quality decreases with depth due to compaction, quartz overgrowths, and other diagenetic changes.

(2) Reservoir quality decreases with decreasing grain size. The coarser grained alluvial and fluvial sandstones are better reservoirs than the finer grained sandstones. This reservoir quality is due to the lower proportion of interstitial mud matrix and is true even though the finer grained reservoirs often exhibit better sorting.

(3) Reservoir quality decreases with increasing amounts of feldspar and lithic grains.

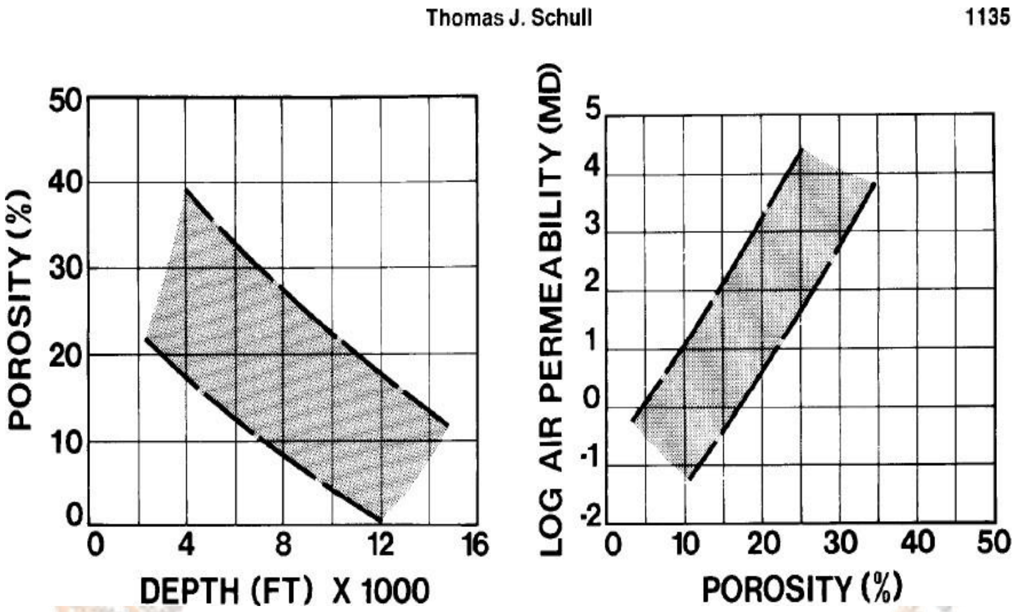


Fig.6. Porosity vs. depth, and permeability vs. porosity plots based on analysis of 3,200ft (975m) of Tertiary and Cretaceous conventional cores. Whole core data only.

2.4- GEOCHEMISTRY:

Routine geochemical analyses, including whole-rock pyrolysis and organic carbon content, have been run on thousands of rock samples from 65 wells. The analytical data derived from this extensive sampling indicate that the dark gray lacustrine claystones and shales of the early rift phase (Neocomian-Albian) are moderately rich oil-prone source rocks. Total organic carbon content of these source rocks averages 1.3% (range 1 to 5%). The regional Muglad structural- stratigraphic cross section (Figure 6) indicates the position of these claystones and shales as well as the Turonian-late Senonian and late Eocene-Oligocene intervals. The depositional environment of the thickest oil-prone source claystones and shales was within large lakes distal from the primary clastic influx. Within these areas, sub-oxic conditions existed preserving much of the organic material deposited on the lake bottom. The primary sources of the kerogen are degraded algal and plant material. During thermal maturation, these hydrogen-rich kerogens generate paraffinic, low sulfur, high pour-point oils. Typically, the oils recovered have 18 °-45° API gravities and 80°-105 °F (45 °- 59°C) pour points. The transition from oil-prone to gas-prone source material often occurs quickly both vertically and horizontally within a formation, reflecting the rapidly changing environments of the lacustrine depositional system. The non-source claystones and shales contain kerogen derived from oxidized terrigenous sources and generally have a TOC of less than 1%.

The geochemical log (Figure 8) shows typical results from the wells that encountered oil-prone Neocomian-Albian source rocks. The various columns indicate the oil-prone nature of these rocks (Hydrogen Index), the source potential (S,), and the maturation level (R,). A thorough discussion of this type of geochemical log is provided by Peters (1986). This diagram also reflects the limited source potential of the younger claystone-shale intervals. Generally, the temperature gradient ranges from 1.0°to 1.8°F/100ft (18 °-33 °C/km) with a 1.4°F/ 100ft (26°C/km) average. Earliest generation typically begins at approximately 10,000ft (3,048 m). The complexity of the geology, both structurally and stratigraphically, and the high sand content of the overall section have created a very leaky system. Vertical migration, particularly along fault planes, is viewed as an important aspect of many accumulations.

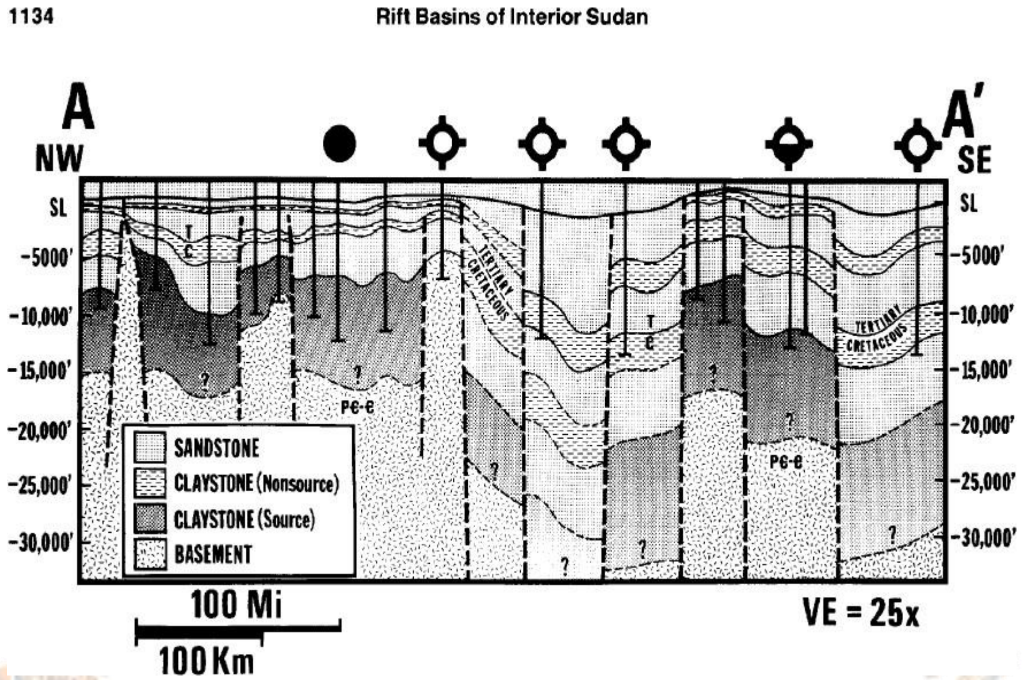


Fig.7. Generalized Muglad basin structural-stratigraphic cross section.Well symbols depict first six wells drilled in agreement area.

2.4- STRUCTURAL STYLE

Extensional Movement: Structurally, the area is dominated by dip-slip normal faults. The three rifting phases resulted in a long complex history of horst and graben development and the formation of a highly complicated fault system. The predominant fault orientation is parallel or sub parallel to the strike of the primary grabens and basin margins. These longitudinal faults mainly strike N40°-50 °W throughout the Muglad, Melut, and Blue Nile basins. In the central and southern Muglad basin, an

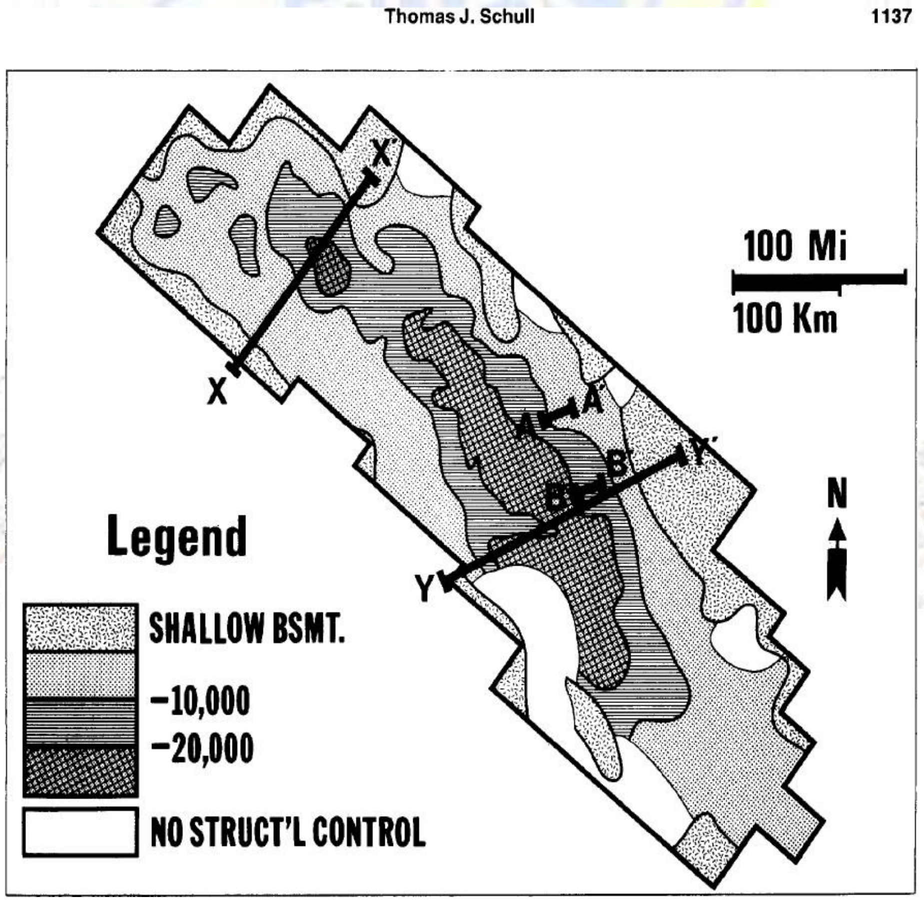


Fig.8. Generalized structure map, top of Albian/ Aptian source sequence, Muglad block. Faulting has been removed for simplification. Mapping horizon not present in areas designated as shallow basement.

apparently older north-northwest trend also exists. The general structure of the Muglad basin is shown in Figure 8. Common within these basins are faults oblique to the primary trends. Relatively few major transverse faults occur. The faulting exhibits great variety in displacement, geometry, and growth history. Representative structural profiles XX ' (Figure 9) and YY

' (Figure 10) reflect this variety and provide a cross-sectional view of the structural style of the Muglad basin. Along the basin flanks the faults clearly involve basement; however, in the deeper troughs many faults appear to sole into the fine-grained early rift sequence.

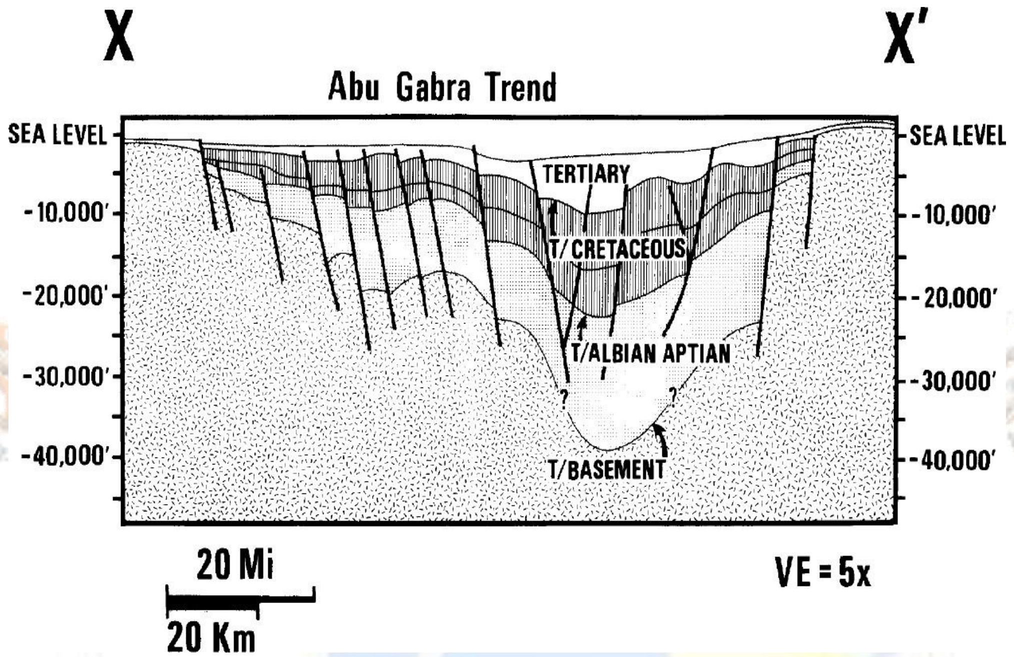


Fig.9. Structural profile across Abu Gabra trend of northern Mugladbasin. See Figure 10 for location of profile. T = top.

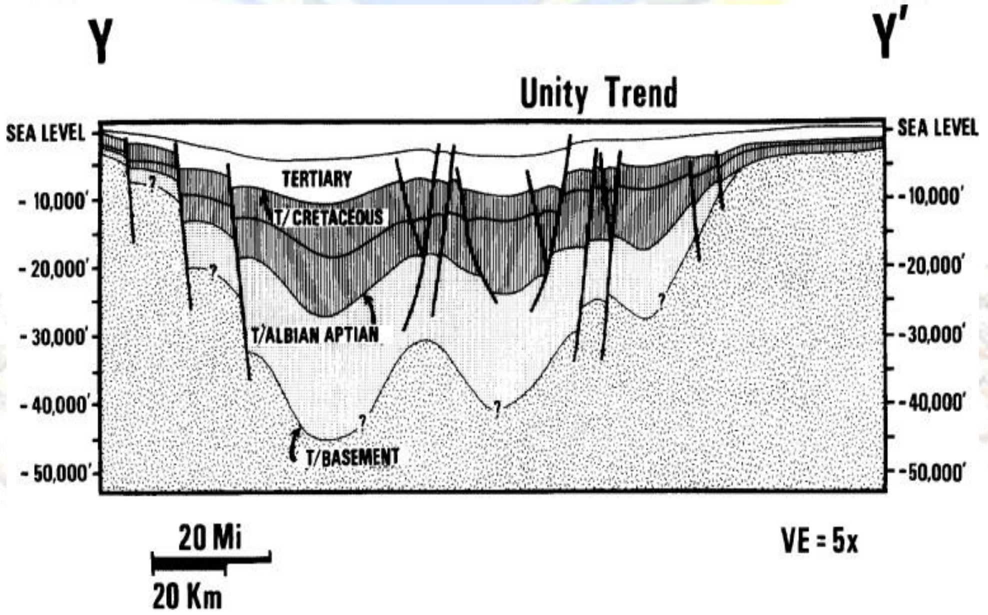


Fig.10. Structural profile across Unity trend of southern Muglad basin. See Figure 9 for location of profile. T = top.

Productive and Prospective Structures: The productive and prospective structures resulting from this complex extensional history have been categorized as rotated fault blocks, drape folds, and reverse drag folds.

Rotated fault blocks are formed by simple block rotation along a normal fault plane. These structures are important producing traps, but entrapment depends upon a seal at or across faults for closure. This type of structure is common throughout the basins and can be seen on seismic lines AA’ (Figure 11) and BB’ (Figure 12). Drape folds are formed in the sediments overlying the up thrown side of deeper normal faults. This type of closure has been found in areas where faults formed during the early rifting phase were not rejuvenated. Closures of this type have trapped oil in the Heglig area. In some locations, downthrown rollover anticlines have resulted from rotation into listric faults. These listric faults are often accompanied by antithetic faults sub-parallel to the primary fault trend. Several anticlinal closures have trapped oil in the Unity area. Seismic line BB’ (Figure 12) depicts this type of structure.

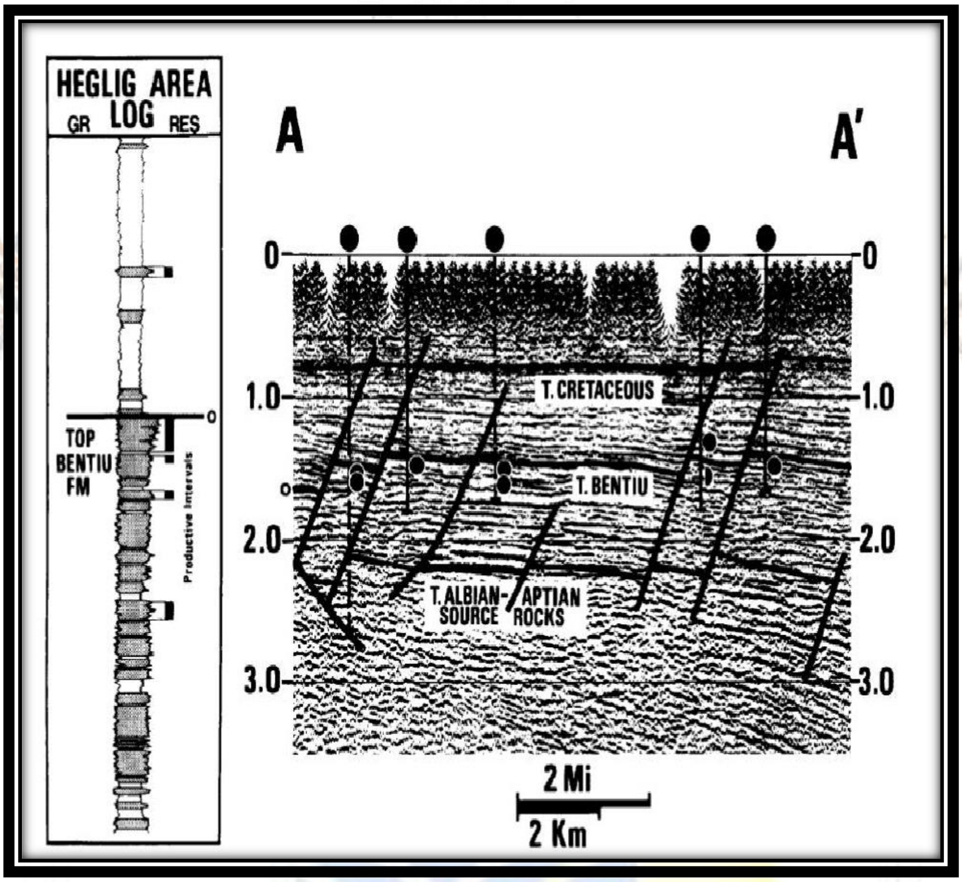


Fig.11. Time-migrated seismic section across Heglig area of southern Muglad block, which passes through several productive fault blocks. See Figure 9 for location of profile. Times shown are two-way travel times in seconds. T = top.

Compression and Strike-Slip Movement: Good evidence for compressional structure and strike-slip movement is confined to the Bagarra block. Seismic data from this area suggest that structures associated with the major basin-bounding faults were formed by Cretaceous and Tertiary compressive forces related to strike-slip movement. These structures are generally en echelon folds associated with reverse faults. The basins of this area are narrow and have a trend similar to basinal areas in eastern Chad and Central African Republic where dextral strike-slip movement is well documented (Browne and Fairhead, 1983).

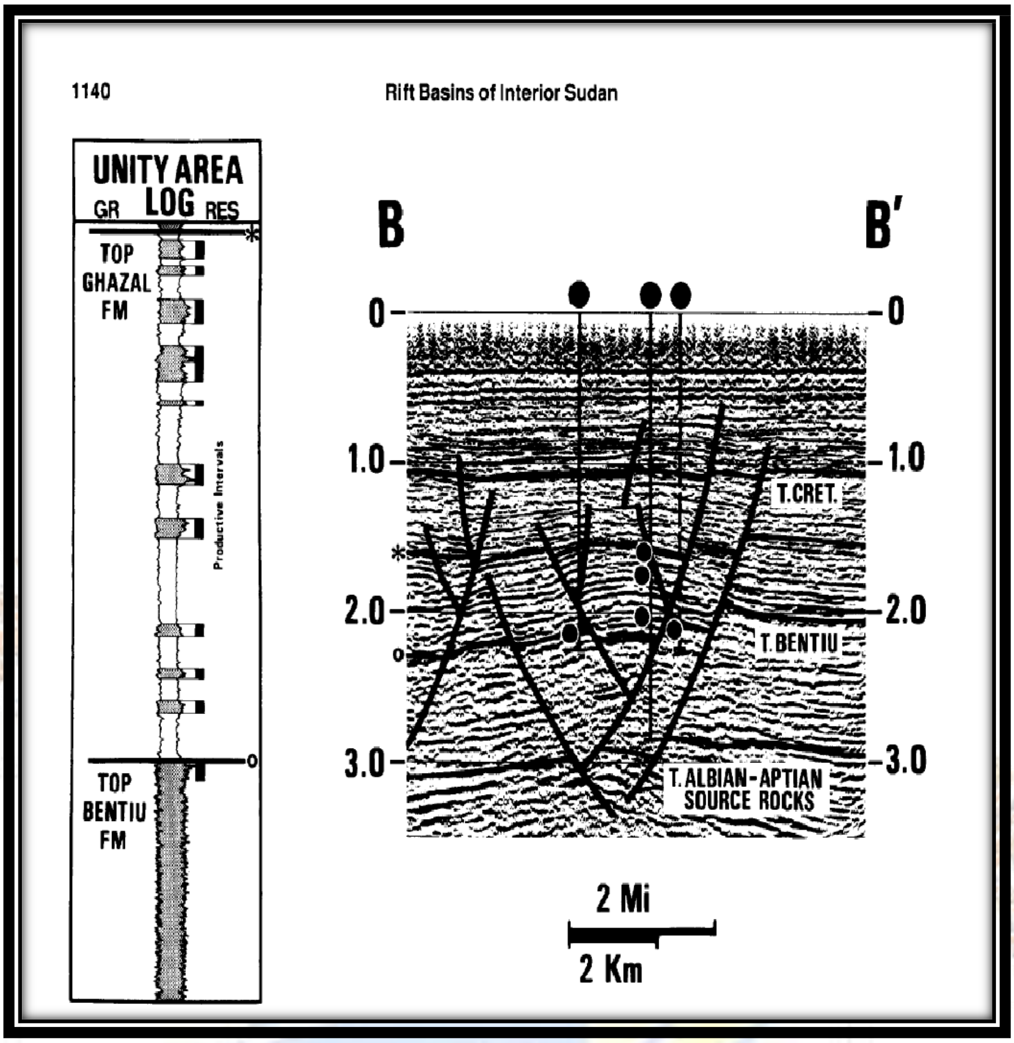


Fig.12. Time-migrated seismic section across Unity area of southern Muglad block. Passes through Unity field. See Figure 10 for locationof profile. Times shown are two-way travel times in seconds. T = top.

IMPLICATIONS FOR AFRICAN TECTONICS: The development of the rift basins of southern Sudan is related to processes that operated not only within central Africa, but also along the western and eastern continental margins. The three periods of rifting creating these basins probably began in the Middle Jurassic(?) and continued to the middle Miocene. Tectonic maps and interpretations have been published (Bermingham et al, 1983; Browne and Fairhead, 1983; Browne et al, 1985; Fairhead, 1986) describing the spatial and developmental relationships of these basins within the regional frame work. These interpretations are based on outcrop geology, extensive gravity coverage, limited well information, and, to a lesser extent, seismic data. The large southern Sudan proprietary data base (Figure 2) generally supports these interpretations. To assist in reviewing the relationship of these rift basins to central African tectonics, a regional tectonic map (Figure 14) is provided. This map is a composite of maps from previously cited authors.

The initiation of rifting in southern Sudan may have been directly related

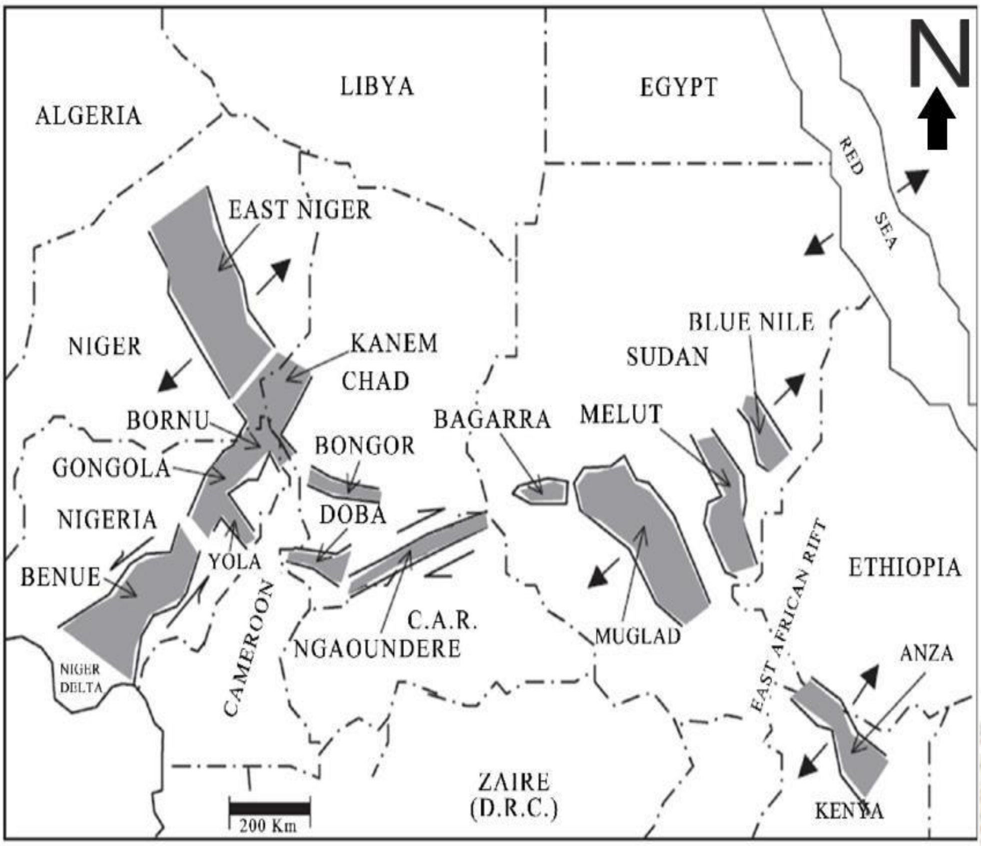


Fig.13. Regional tectonic map of western and central Africa showing relationship of southern Sudan rift basins to selected structural features (stippled areas). Locations of regional shear zones (marked with half-arrow) and major zones of extension (complete arrow) are shown. C.A.R. = Central African Republic.

To Jurassic rifting in the Lamu embayment of Kenya (Reeves et al, 1987). The Anza trough of northern Kenya strikes in the same direction as the Muglad, Melut, and Blue Nile basins. The initial rifting phase in the Anza trough occurred in Middle Jurassic (Reeves et al, 1987). Possible evidence for related early Sudan rift development is the Jurassic (?) sedimentary sequence encountered in the Blue Nile well. Additionally, Jurassic sedimentary rocks are possibly part of the thick seismically defined sequence that lies below well penetrations in the deep Muglad and Melut basins. Any connection between the Anza trough and these basins has been obscured by the Tertiary and Quaternary development of the East African rift system. This primary southern Sudan rifting phase continued into the Albian, corresponding with the initial opening in the South Atlantic and extension in the Benue trough (Wright, 1981). During this period of regionally wide-spread rifting, thick sedimentary sequences were deposited in several developing African basins, e.g., Benue trough, East Niger basin, Doba basin, Ngaoundere Rift basin, and Anza trough (Figure 13). Some of these basins developed within and immediately adjacent to the Cretaceous shear zones and others formed near their endpoints at angles of 90°-120° to the shear movement. Fairhead and Green (in press) suggested that movement on the Central African shear zone translated into the extensional basins of southern Sudan. This relationship is similar to that between the axial shear zone of the Benue trough and the East Niger rift basin. This mechanism could explain rift basin development contemporaneous with movement on the West and Central African shear zones. Within the Muglad basin, well control and seismic data suggest that over 12,000ft (3,658 m) of sediment may have been deposited during this rifting. The second southern Sudan rifting phase began in the Turonian and continued until near the end of the cretaceous. This rifting phase was accompanied by the deposition of up to 6,000ft (1,829 m) of sedimentary rock. Fairhead (in press) has concluded that changes in the opening of the South Atlantic account for a Late Cretaceous period of shear movement on the West and Central African rift system. This movement could explain Late Cretaceous Benue compression and dextral reactivation of the Central African shear zone. The second Sudan rifting phase may be related to this movement. In the east-northeast-west-southwest-trending Bagarra basin, a continuation of the Central African shear zone strike-slip movement has been inferred from compressional features interpreted from seismic data. This continuing strike-slip movement is not seen in the adjoining north- western Muglad basin or further northeast. The east-northeast-west- southwest trend appears to have been terminated and replaced by the northwest-southeast-trending basins interpreted to be extensional in their development, supporting the concept of translation of shear movement into extension. Also during this period, rifting and deposition continued in the northwest-southeast-trending Anza trough (Figure 13).

The thick highly faulted lower Tertiary section of the southern Sudan basins indicates that the final rifting phase was a significant tectonic event. Regional data sug-gest the initiation of this phase was generally time equivalent to the initial phases of the opening of the Red Sea (Lowell and Genik, 1972) and east African rifting (Girdler et al, 1969). The Muglad, Melut, and Blue Nile basins are subparallel to the Red Sea and rifted in response to the African-Arabian extensional forces. A direct relationship between east African rifting and the development of the southern Sudan basins is not apparent. Interestingly, a sharp contrast is seen between the Tertiary development of the southern Sudan basins and the west African basins, which exhibited strong Cretaceous similarities. For example, the East Niger basin (Figure 14) has only a thin relatively unfaulted Tertiary section (Avbovbo et al, 1986). This section indicates that the significant early Tertiary extension affecting southern Sudan, which resulted in the accumulation of over 13,000 ft (3,962 m) of sediment, was inoperative in the west African basins. However, the Anza trough, on trend to the southeast, did experience rifting and thick sedimentary accumulation (Reeves et al, 1987). In the later Tertiary, the regional stress regime changed (Bermingham et al, 1983) resulting in the middle Miocene termination of southern Sudan rifting. To the northeast, the Red Sea rift continued its development. The current lack of seismic activity in the southern Sudan basins, as compared to the seismically active Red Sea area (Girdler, 1983), supports this conclusion. A maximum of 2,500 ft (762 m) of sediment has accumulated in these basins during the postrifting sag phase. Muglad basin extension has been estimated to be 29 mi (48 km) based on gravity modeling (Browne and Fairhead, 1983), compared with 36 mi (58 km) for the East Niger basin (Fairhead, in press) and 40 mi (65 km) for the Anza trough (Reeves et al, 1987). Considering the width and interpreted depth of the Muglad basin, extension of 29 mi (48 km) seems conservative. When the combined extension associated with the Muglad, Melut, and Blue Nile basins is considered, a total estimate of 43-49 mi (70- 80 km) seems more appropriate for southern Sudan.

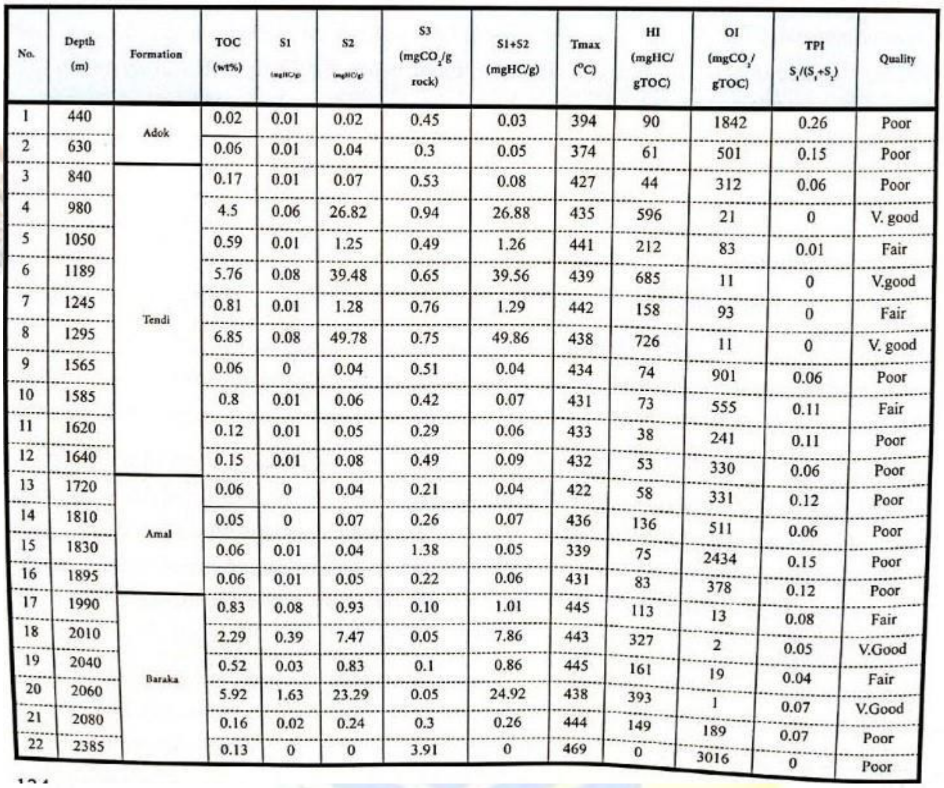
4- HYDROCABON POTENTIAL OF MUGLAD BASIN:

1.4- PETROLEUM SYSTEM OF MUGLAD BASIN:

1.1.4- SOURCE ROCKS:

Three potential source rocks exist in the Muglad Basin namely; Abu Gabra-lower Bentiu Formation(early Cretaceous), Baraka Formation (Late Cretaceous) and Nayil-Tendi Formations Eocene-Early cretaceous), the dark grey lacustrine claystones and shales of the early rift phase (Neocomian-Aptian/ Abu Gabra-Lower Bentiu) are the only proven source rocks which show positive correlations with oils in the northern Muglad Basin(Blevin et al.,2009 Although the younger source intervals have relatively high TOC(up to 10 wt% for Tendei formation), there is limited opportunity for them to reach maturity, except in the deeper parts of the Kaikang Trough where the top of the Baraka Formation may be reached at more than 2.500m (BeicipFranlab, 2004; Blevin et al , 2009). A conforming remark comes from Balulla (2011) who noted that the majority of samples from the Tendi Formation in Kaikang west-1 well are mature with Tmax range from 435-4421C and this fall at the beginning of the oil generative window (Table.1). The source potential and expulsion history of the Abu Gabra formation has been modelled in the Central Muglad Basin by BeicipFranlab (2004). The main source rock is represented by interbedded lacustrine fine-grained clastics containing Type I Kerogen, with TOC values ranging from 1-5 wt% (av. 1.3 wt%), laid down in freshwater lakes in distal depositional settings However, Giedt (1990) noted that the TOC values may reach 7.5wt %. To the north in the Abu Sufiyan Sub-basin, Type I Kerogen with a TOC range of 0.84-3.18 wt % (Fig.14) characterizes the oils discovered in Suf-1 well (RIPED and Sudapet, 2007). Type II Kerogen with TOC ranging from 0.2-0.8 is less potential source rock in the Rakuba, Hiba and West Nugara Sub-basins (CNPC-IRC, 2008). Potential source rock is poorly known to the south due to limited well intersections of the most prospective Abu Gabra Formation. Trend analysis of sand versus shale from wells suggests that the Abu Gabra Formation becomes sandier and less prospective to the south, with palaeocurrent directions to the north (Lundin, 2008). Based on sequence stratigraphic analysis nine seismic stratigraphic units were identified within the Muglad Basin (RIPED and Sudapet, 2007), these are AG-4, AG-3, AG-2, AG-1, Bentiu-2, Bentiu-1, Darfur, Amal and Neogene to Quaternary (N+Q: Fig.15). These units facilitate a better recognition of the petroleum system elements in the basin. Based on information obtained from borehole data and seismic features, the Abu Gabra formation is informally divided into four stratigraphic units: AG-1,AG-2, AG-3 and AG-4 likewise two units were proposed for the Bentiu Formations ‘namely, Beatiu-1 which consists of interbedded sandstone and claystone and Bentiu-2 which is mainly composed of massive blocky sandstone (Riped and Sudapet 2007), AG-2 and AG-4 are composed of interbedded sandstone and claystone whereas AG-3 consists of massive blocky sandstone. According to RRI and GRAS (1991), the upper part of the Abu Gabra Formation at well Abu Sufyan-1 shows fair to good ability of oil generation (Table.2). The S2 exceeding 6mg/g accounts for 28.6% of the total; the average value of S2 is 6.96 mg/g all data show that most of the dark shale of the upper section of the Abu Gabra Formation is a good source rock and AG-2 is the better than AG-1 with abundant organic matter and larger potential for oil generation (fig.14) Suf-1 well, drilled by CNPCIS in 2003, penetrated the Abu Gabra formation which has an average thickness of 679m. According to the geochemical analysis, no source rock has been identified in the Tendi and Bentiu Formation, good source rocks are developed in the Abu Gabra formation and the Darfur Group (fig.16). Geochemical characteristics of the sediments penetrated in Suf c-1 well are penetrated in (fig.16)

Table. 1. Rock Eval pyrolysis results, Kikang west-1 well (Blula, 2011)



No.	Depth (m)	Formation	TOC (wt%)	S1 (mgHC/g)	S2 (mgHC/g)	S3 (mgCO$_2$/g rock)	S1+S2 (mgHC/g)	Tmax (°C)	HI (mgHC/ gTOC)	OI (mgCO$_2$/ gTOC)	TPI $S_1/(S_1+S_2)$	Quality
1	440	Adok	0.02	0.01	0.02	0.45	0.03	394	90	1842	0.26	Poor
2	630		0.06	0.01	0.04	0.3	0.05	374	61	501	0.15	Poor
3	840	Tendi	0.17	0.01	0.07	0.53	0.08	427	44	312	0.06	Poor
4	980		4.5	0.06	26.82	0.94	26.88	435	596	21	0	V. good
5	1050		0.59	0.01	1.25	0.49	1.26	441	212	83	0.01	Fair
6	1189		5.76	0.08	39.48	0.65	39.56	439	685	11	0	V.good
7	1245		0.81	0.01	1.28	0.76	1.29	442	158	93	0	Fair
8	1295		6.85	0.08	49.78	0.75	49.86	438	726	11	0	V. good
9	1565		0.06	0	0.04	0.51	0.04	434	74	901	0.06	Poor
10	1585		0.8	0.01	0.06	0.42	0.07	431	73	555	0.11	Fair
11	1620		0.12	0.01	0.05	0.29	0.06	433	38	241	0.11	Poor
12	1640		0.15	0.01	0.08	0.49	0.09	432	53	330	0.06	Poor
13	1720	Amal	0.06	0	0.04	0.21	0.04	422	58	331	0.12	Poor
14	1810		0.05	0	0.07	0.26	0.07	436	136	511	0.06	Poor
15	1830		0.06	0.01	0.04	1.38	0.05	339	75	2434	0.15	Poor
16	1895		0.06	0.01	0.05	0.22	0.06	431	83	378	0.12	Poor
17	1990	Baraka	0.83	0.08	0.93	0.10	1.01	445	113	13	0.08	Fair
18	2010		2.29	0.39	7.47	0.05	7.86	443	327	2	0.05	V.Good
19	2040		0.52	0.03	0.83	0.1	0.86	445	161	19	0.04	Fair
20	2060		5.92	1.63	23.29	0.05	24.92	438	393	1	0.07	V.Good
21	2080		0.16	0.02	0.24	0.3	0.26	444	149	189	0.07	Poor
22	2385		0.13	0	0	3.91	0	469	0	3016	0	Poor

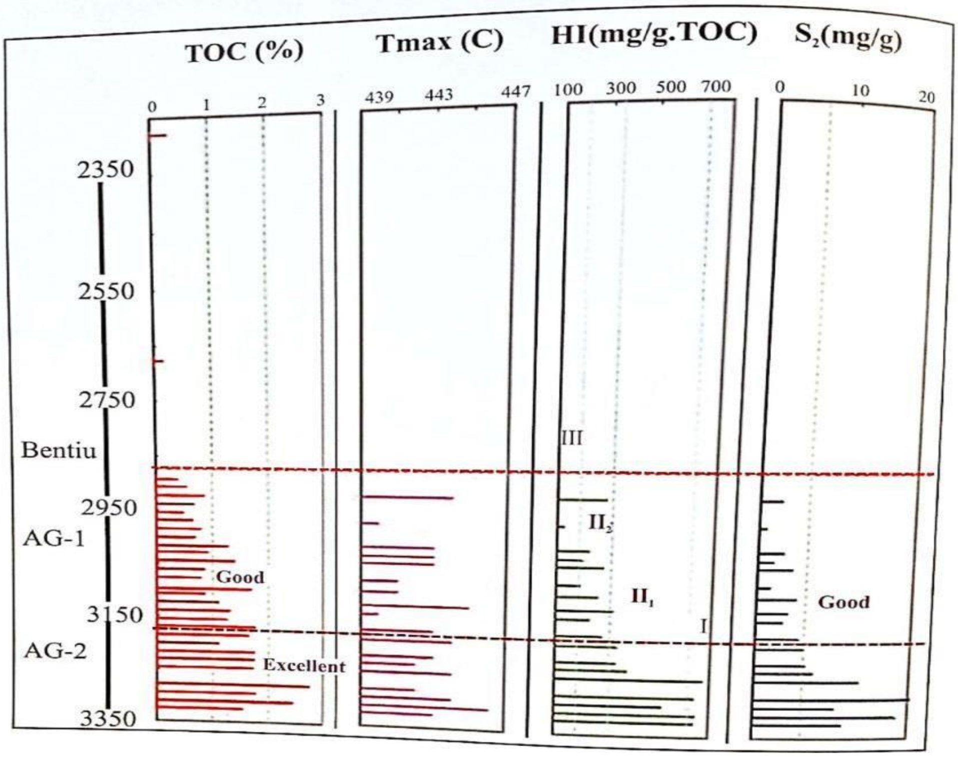


Fig.14. Geochemical profile of Abu Sufyan-1 well NW parts of theMuglad basin.

1.1.1.4- KEROGEN TYPES

Figure (15) provides a summary of the organic matter types at the Abu SuFyan-1 well bused on Hydrogen index (Table 2). Higher oil generative potential is found in AG-2 (mainly Type I and Type 11, Kerogens), while AG-1 is mainly of Type III (Table.3). Likewise, in Suf- well the kerogen is mainly of type III and partly of type II for the Darfur Group(fig.16) and Table.4), The underlying AG-1 unit has a main Type II, kerogen, minor Type II, and Type III, while AG-2 is mainly of Type II, and less Type II, Kerogens (Fig.16). In well Suf C-1, just south of the previous well, the kerogen type of the Darfur and Bentiu Formations are of Type III (Fig.14, and Table.4) In conclusion, it is obvious that the hydrogen index (HI) data (Table.2) are in agreement with the result of kerogen macerals (Tables.3 and .4), which reflects hat the original organic matter of the Abu Gabra source rocks mainly derived from an aquatic land source (RIPED and Sudapet, 2007). Moreover, the source rock of the Abu Gabra Formation in NW Muglad Basin is good and most of the kerogen is of type I or Type II, which has large hydrocarbon potential(Fig.17).

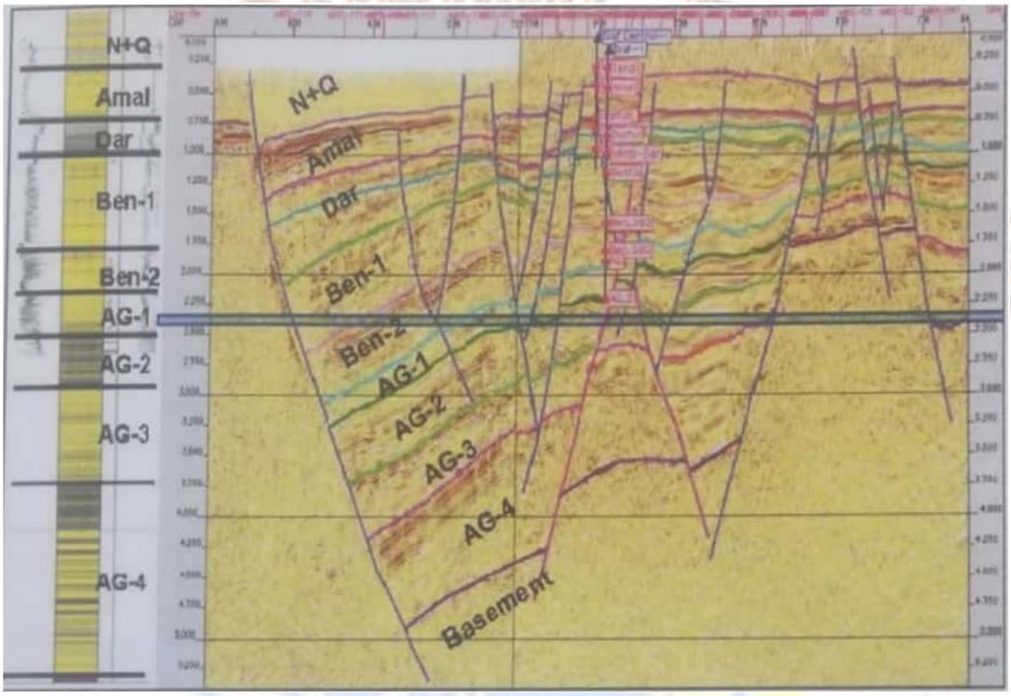


Fig. 15. Seismic-stratigraphic sequences identified in Abu Sufyan sub-basin.

Table .2. Geochemical data of Abu Sufyan-1 well NW part of Muglad basin

Ro (%)	HC/TOC (%)	HC (ppm)	"A" (ppm)	S2 (mg/g)	HI (mg/g)	Tmax (C)	TOC (wt%)	Depth (m)	Fm
	5	150	205				0.3	2279.9-2292.1	Bentiu
	10.31	165	215				0.16	2676.1-2685.3	
				2.74	314	444	0.87	2923-2938.3	AG1
	5.85	385	525				0.66	2938.3-2953.5	
							0.49	2953.5-2968.8	
				0.81	128	440	0.63	2968.8-2984	
							0.79	2984-2999.2	
							0.7	2999.2-3014.5	
				3.12	245	443	1.27	3014.5-3029.7	
0.51				1.95	211	443	0.92	3029.7-3045.0	
				4.33	307	443	1.41	3045.0-3060.2	
							0.86	3060.2-3075.4	
				1.57	201	441	0.78	3075.4-3096.7	
				4.87	287	441	1.69	3096.7-3105.9	

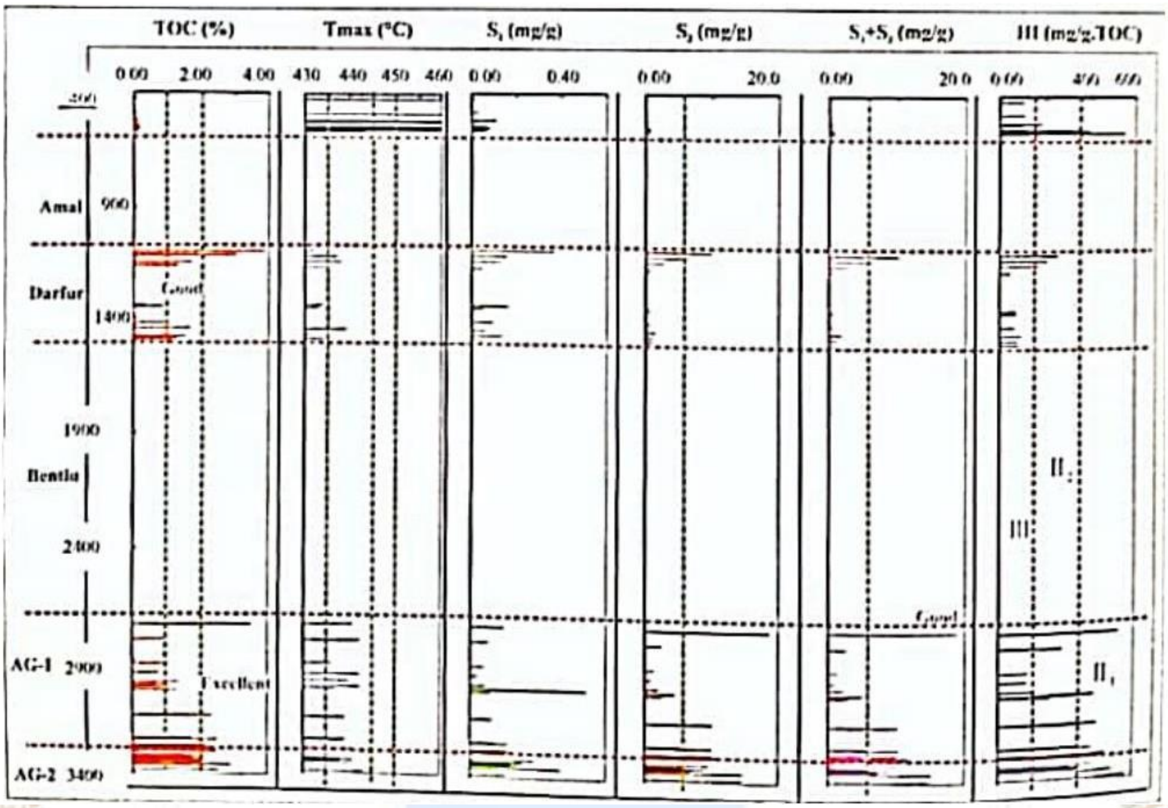
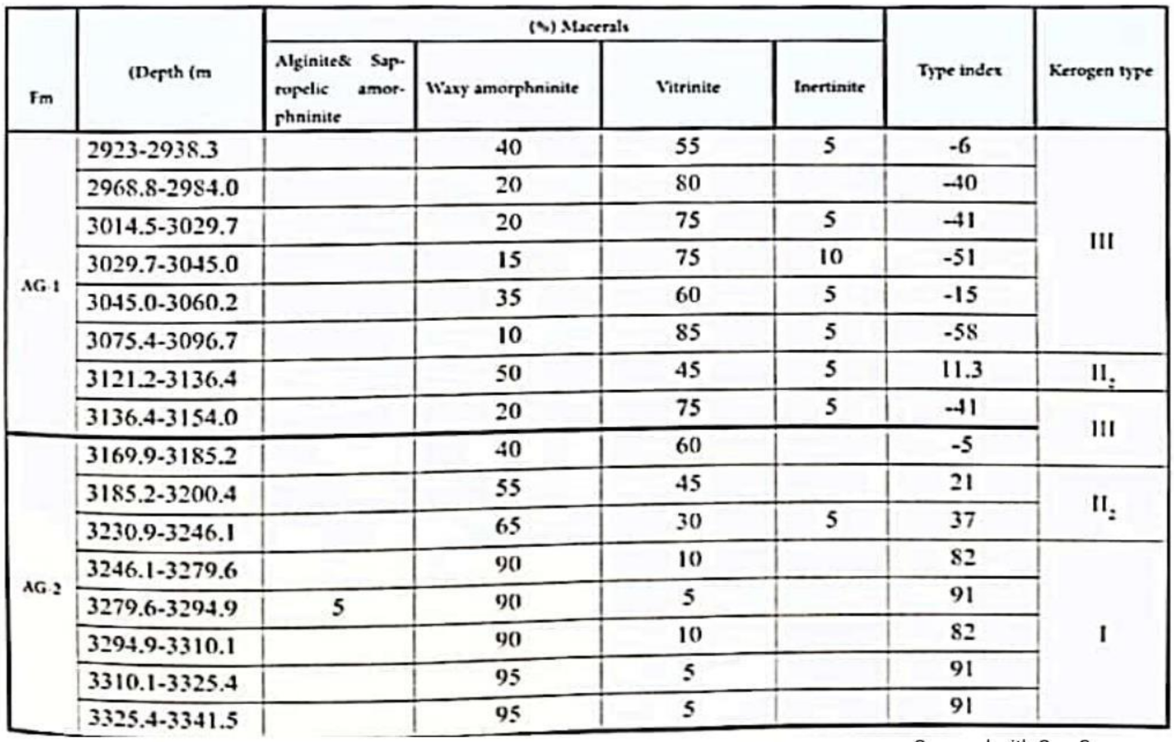


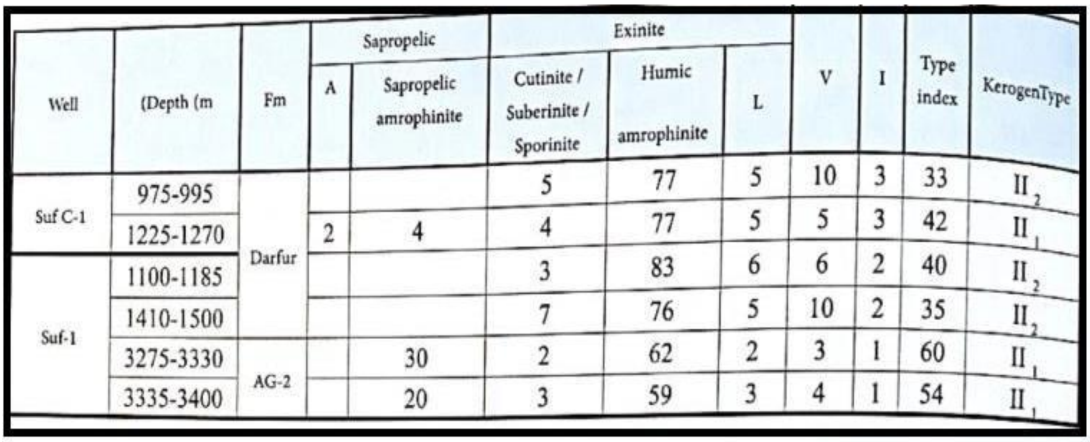
Fig. 16. Geochemical profile of suf-1 well NW part of Muglad basin.

Table.3. Identification of kerogen macerals and types of Abu Sufyan-1 well NW parts of the Mugladbasin.



Fm	(Depth (m	(%) Macerals				Type index	Kerogen type
		Alginite& Sapropelic amorphninite	Waxy amorphninite	Vitrinite	Inertinite		
AG-1	2923-2938.3		40	55	5	-6	III
	2968.8-2984.0		20	80		-40	
	3014.5-3029.7		20	75	5	-41	
	3029.7-3045.0		15	75	10	-51	
	3045.0-3060.2		35	60	5	-15	
	3075.4-3096.7		10	85	5	-58	
	3121.2-3136.4		50	45	5	11.3	II_2
	3136.4-3154.0		20	75	5	-41	III
AG-2	3169.9-3185.2		40	60		-5	
	3185.2-3200.4		55	45		21	II_2
	3230.9-3246.1		65	30	5	37	
	3246.1-3279.6		90	10		82	I
	3279.6-3294.9	5	90	5		91	
	3294.9-3310.1		90	10		82	
	3310.1-3325.4		95	5		91	
	3325.4-3341.5		95	5		91	

Table.4 Identification of kerogen macerals and types of Suf-1and Suf C-1 well Muglad basin.



Well	(Depth (m	Fm	Sapropelic		Exinite		L	V	I	Type index	KerogenType
			A	Sapropelic amrophinite	Cutinite / Suberinite / Sporinite	Humic amrophinite					
Suf C-1	975-995	Darfur			5	77	5	10	3	33	II_2
	1225-1270		2	4	4	77	5	5	3	42	II_1
Suf-1	1100-1185				3	83	6	6	2	40	II_2
	1410-1500				7	76	5	10	2	35	II_2
	3275-3330	AG-2		30	2	62	2	3	1	60	II_1
	3335-3400			20	3	59	3	4	1	54	II_1

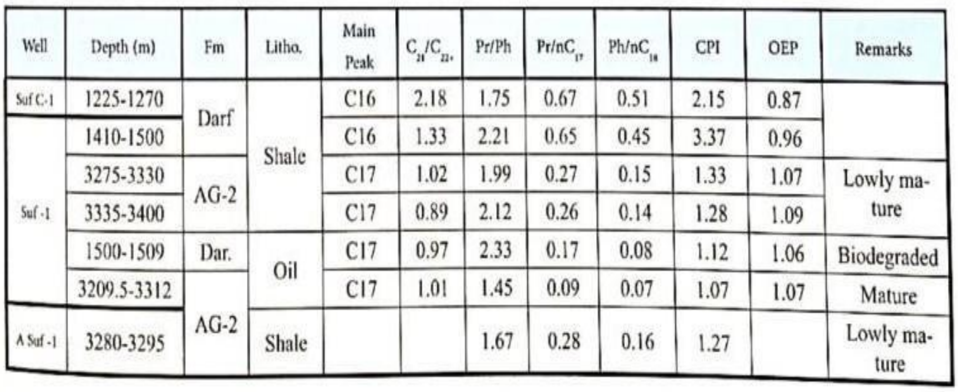
2.1.1.4- MATURITY:

Tmax value (440° and 446°) from Abu Sutyan-1 well show that the source rock of the Abu Gabra Formation; namely AG-1 and AG-2 are mature (table.2). However the vitrinite reflectance (Ro) data from the same interval indicate that AG-1 und AG-2 are of low maturity, which was confirmed by gas chromatographic data (Table.6). In (Table.6), the Tmax values of the Abu Gabra Formation in Suf-1 well are between 436° indicating marginally mature to mature source rocks. The source rocks of the Darfur Group in Suf-1 well, are immature to low-mature, having a Tmax range between 430° and 419° As for the Tendi Formation, no conclusive results could be reached due to the low S2 values which caused the abnormal Tmax values (being higher than those of the Darfur and Abu Gabra Formations) Vitrinite reflectance (Table.6) shows that the Darfur Group reached a low maturity level, whereas the Abu Gabra Formation has already entered the maturity zone and is still at the peak of the oil generation window (Fig.17), However, the gas chromatography data (Table.6) shows that the source rock of the Darfur Group is immature, and that of the Abu Gabra is of low maturity level (RIPED and Sudapet, 2007).

Table.5. Determination of thermal maturity level of source rock.

Stage of maturity for oil	**Ro (%)**	**Maturation Tmax C°**
Immature	0.2-0.60	<435
Mature:		
Early	0.6-0.65	435-445
Peak	0.65-90	445-450
Late	0.90-1.35	450-470
Post mature	>1.35	>470

Table.6. Gas chromatography parameter of saturated HC of oil/extracts Muglad basin



Well	Depth (m)	Fm	Litho.	Main Peak	C_{21}/C_{22+}	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	CPI	OEP	Remarks
Suf C-1	1225-1270	Darf	Shale	C16	2.18	1.75	0.67	0.51	2.15	0.87	
Suf -1	1410-1500			C16	1.33	2.21	0.65	0.45	3.37	0.96	
	3275-3330	AG-2		C17	1.02	1.99	0.27	0.15	1.33	1.07	Lowly mature
	3335-3400			C17	0.89	2.12	0.26	0.14	1.28	1.09	
	1500-1509	Dar.	Oil	C17	0.97	2.33	0.17	0.08	1.12	1.06	Biodegraded
	3209.5-3312	AG-2		C17	1.01	1.45	0.09	0.07	1.07	1.07	Mature
A Suf -1	3280-3295		Shale			1.67	0.28	0.16	1.27		Lowly mature

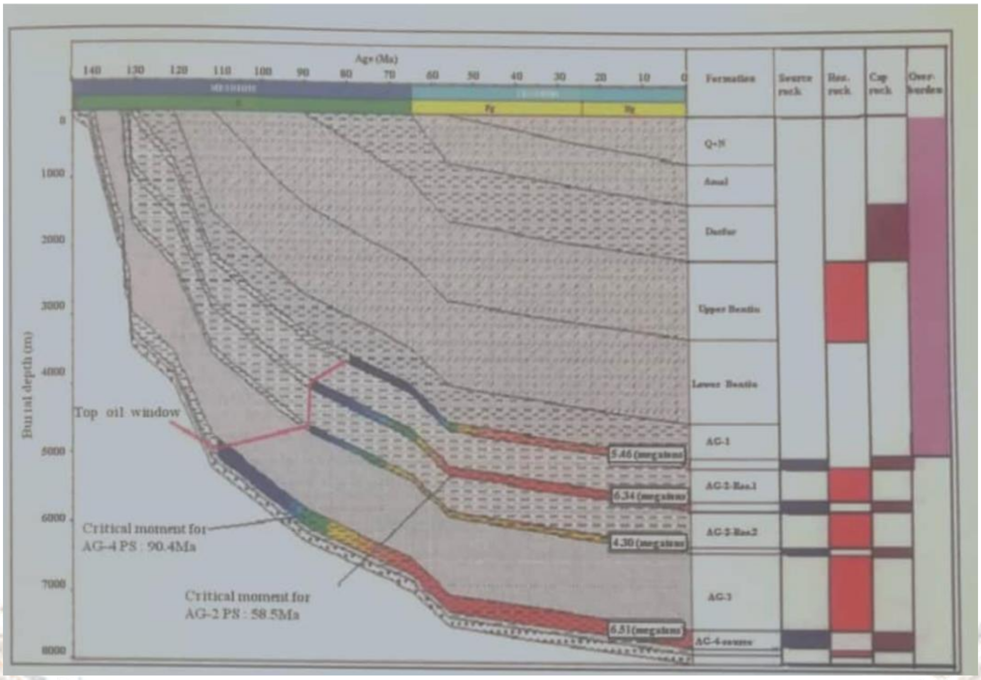


Fig.17. Burial history model based on critical time of pseudo well P3location Muglad basin.

3.1.1.4- MIGRATION:

Hydrogen migration pathways have been modelled by Blevin et al. (2009). In this model, depocenter outlines have been used to constrain the location of potential source deposition from which hydrocarbons are assumed to have migrated. (Fig.18). the fluid pathways at depths shallower than 600m were not considered since oils above this depth would be subject to biodegradation. This migration pattern is only applicable for source rocks that were deposited in the early syn-rift phase (i.e. Abu Gabra Formation and old units). Many fields e.g., Unity, Abu Gabra, Fula, Bamboo show positive relationship to the fluid focus pathways. However, other fields such as the Balome and Diffra do not fit into this model and probably have an alternative mechanism for hydrocarbon migration into these producing fields, based on the model proposed by (Blevin et al. 2009) a number of areas in the northern and central muglad basin lie on potential fluid focus pathways which are indicated by yellow circle in the following figure.

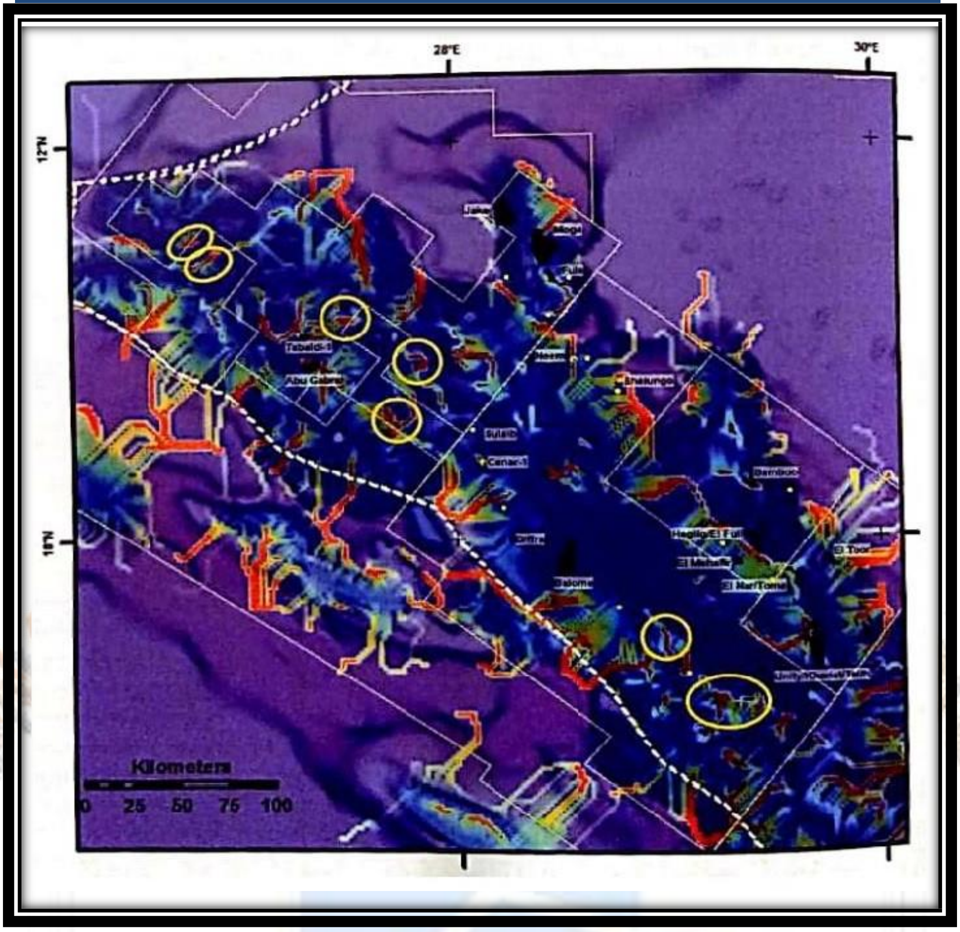


Fig.18. Fluid migration pathways in northern and central Muglad basin.

4.1.1.4- RESERVOIR ROCKS:

According 1o tectonic cycles and sedimentary facies studies in the Muglad Basin, five reservoir assemblages were predicted, these include Cretaceous and Palacogene/Neogene assemblages. The cretaceous assemblages comprise the Abu Gabra Formation (reservoir/cap rock) Bentiu formation (reservoir rock), Aradeiba Formations (cap rock) and Darfur Group (reservoir/cap rock). The Palaeogene/Neogene assemblages include (the Amal formation (reservoir rock), Nayil-Tendi (cap rock) as one assemblage in addition to the Nayil-Tendi as reservoir and cap rocks. Detailed accounts on these assemblages are provided as follows:

Abu Gabra Formation: the reservoirs in this formation arc represented by interbedded sands within the shaley source interval (e.g. Suf-1 and Abu Gabra-1 wells, Neem field). The sandy intervals within AG-2 and AG-4 are considered as the best reservoirs, with all levels predicted to have reservoir potential in the Abu Sufyan Sub-basin (RIPED and Sudapet, 2007). The thickness of the reservoirs within the Abu Gabra Formation is estimated to be more than 800m in the North Kaikang Trough (BeicipFranlab, 2004). Bentiu Formation: forms the main reservoir in the Heglig, Unity, Bamboo, Munga, Toma South, Joknyang, Mala and TharJath fields, in particular, the upper sandy part of the formation which is dominated by braided fluvial and alluvial environments (BeicipFranlab, 2004; IHS, 2006). The thickness of the Bentiu Formation exceeds 1,200m in the central Muglad Basin (BeicipFranlab, 2004) and amount is to 2,000-2,500m in the Heglig field. Aradeiba and Zarga Formations: channel sands encompassed within the shales of the regional seal are locally important in the Unity area, where they are vertically charged along faults (BeicipFranlab, 2004). Moreover, these sands act as secondary reservoirs in the TharJath, Joknyang, and Mala arcas. The three Cretaceous assemblages are comparatively good in oil supply: being close to the oil source of the Abu Gabra Formation, good in reservoir and cap rock quality and has good and effective structures. However, the assemblages are presently buried too deep in most of the central parts of the basin. Therefore, exploration targeting these assemblages should be focused on the relatively higher areas, such as the basement highs located in between the north and south Kaikang depressions and the two flanks of the Kaikang trough. Amal Formation: these are dominantly coarse-grained, massive sandstones deposited in a high energy alluvial plain with coalescing braided streams and alluvial fans environments. They are up to 762m thick forming potentially excellent reservoirs. Nayil Formation:this is predominantly a shaley unit with sandy interbeds that provide minor reservoir intervals.

Both Amal and Nayil Formations are potential reservoirs for hydrocarbons that could be generated from the Baraka formation in the north kaikang trough, where older source rocks are likely to be over- mature. (BeicipFraniab, 2004).

Tendi Formation: the sandstones of the lower part of this formation havegood reservoir qualities:

They represent the reservoir in the kaikang-1 well discovery. However, the age of the hydrocarbons source might be Palaeogene or older. The reservoir is proved to be a secondary pool that resulted from the third rift cycle. In general, this rifting event was Strong in the kaikang trough four dry holes targeting the palaeogene strata have been drilled after kaikang-1 discovery; kaikang-2, malok-1, kaikang-3 (95% water cut) and kaikang-4. Tendi oil pool in kaikang-1 well, Nayil oil pool in Suttaib-1, well, Diffra-3 well and Haraz-1 well are secondary pools related to long-term movement of growth faults which connected the palaeocene reservoir to the Abu Gabra source rock. Although the Palaeogene/Neogene assemblages have good reservoir and seal conditions, yet they are poor as source rocks being relatively at shallow level. Consequently, exploration should be focused on the relatively huge and complete structures that are connected with proper fault conduits to the deep oil source and/or to the underlying reworked original oil pools.

1.4.1.1.4- RESERVOIR UNITS' DISTRIBUTION:

In the 3D block model established for the North and South Kaikang sub- basins four layers have been recognized as reservoirs (BeicipFranlab, 2004). These arc the Amal sand, Aradeiba sand-shale, Bentiu sand and upper Abu Gabra sand unit. The reservoir properties which are accounted for in the trapped hydrocarbons volume calculations include thickness maps (Fig.19) and porosity maps (Fig.21). Other layers identified as sand facies but have not been considered as reservoirs are: Nayil, Baraka upper sand, Zarqa sand and Lower Abu Gabra sand. The layers may act as conduits for the fluids (hydrocarbon and water) during migration. Reservoir thickness distribution maps for the Abu Gabra, Bentiu, Aradeiba and Amal Formations are shown in (Fig.6).

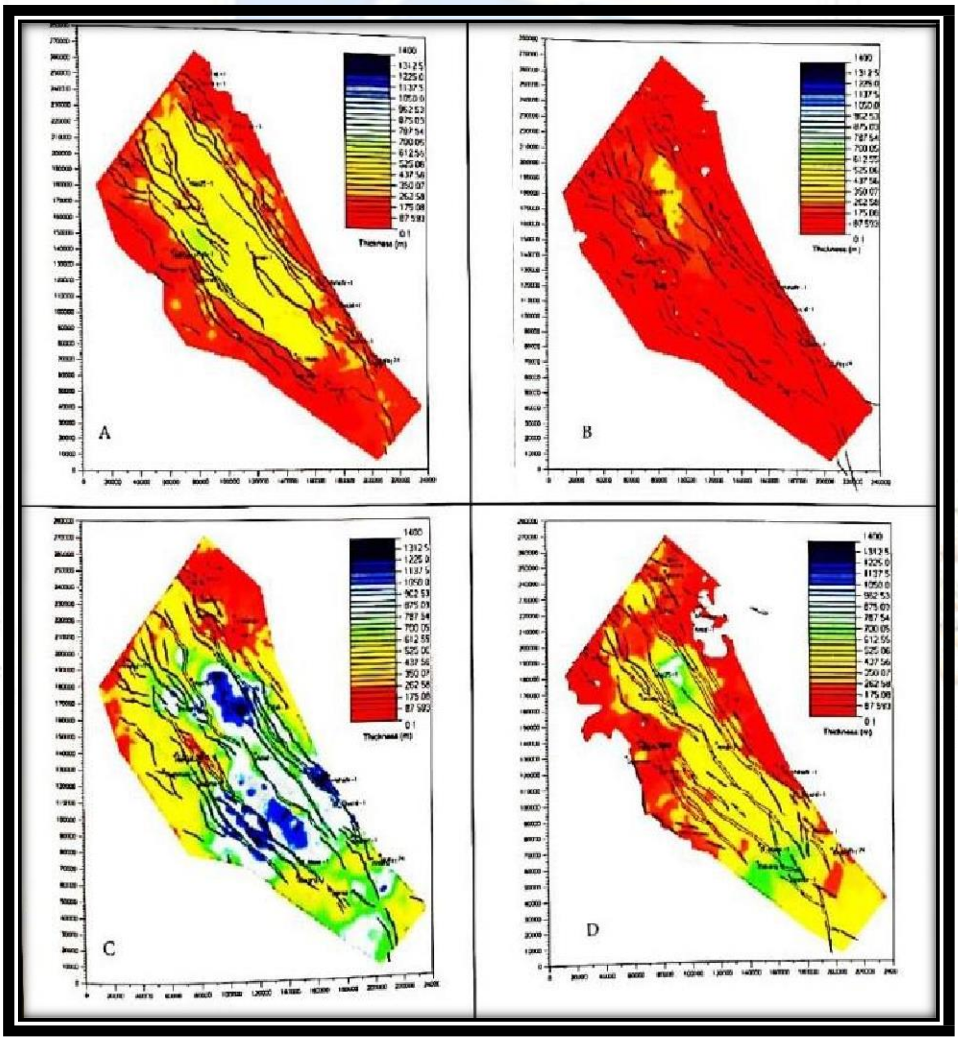


Fig. 19. Thickness distribution maps for the four reservoir layers in the Muglad Basin, A) Amal formation, B) Aradeiba formation, C) Abu Gabra formation.

2.4.1.1.4- RESERVOIR POROSITY

Table 7.8 shows the porosity and nearby well reference for each prospect in the north-western part of the Muglad Basin. The minimum, maximum and average porosity for Khadari-1, Falah-1, Rabah-1, Najah-1, Somagh-1 and Baraka-1 wells are given. Porosity measurements within the basin show a general decrease with depth to reach minimal values below 4 km (Fig.20). At the same time permeability values are in a good accordance with porosity values showing positive trend (Shull, 1988; Fig.6).

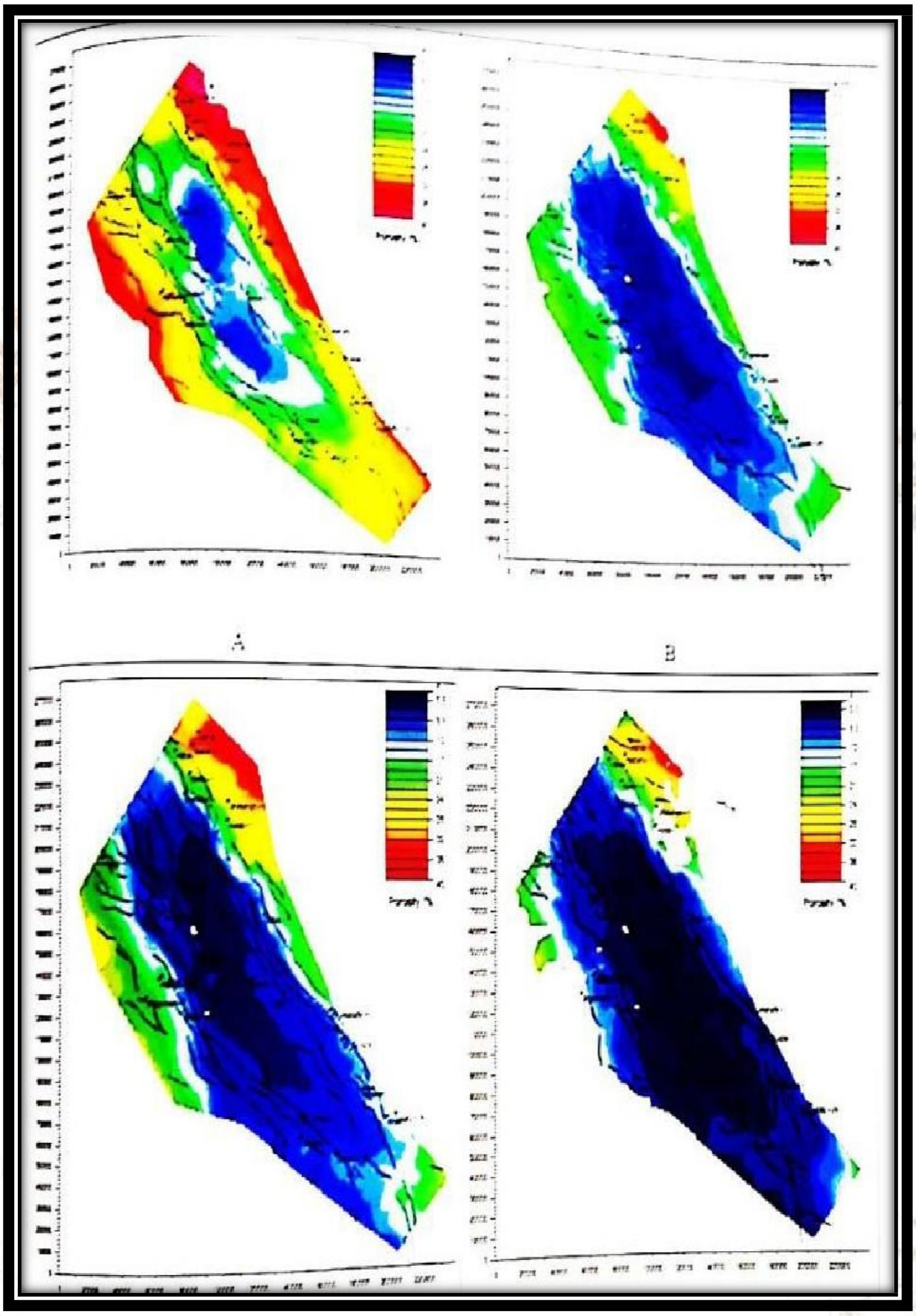
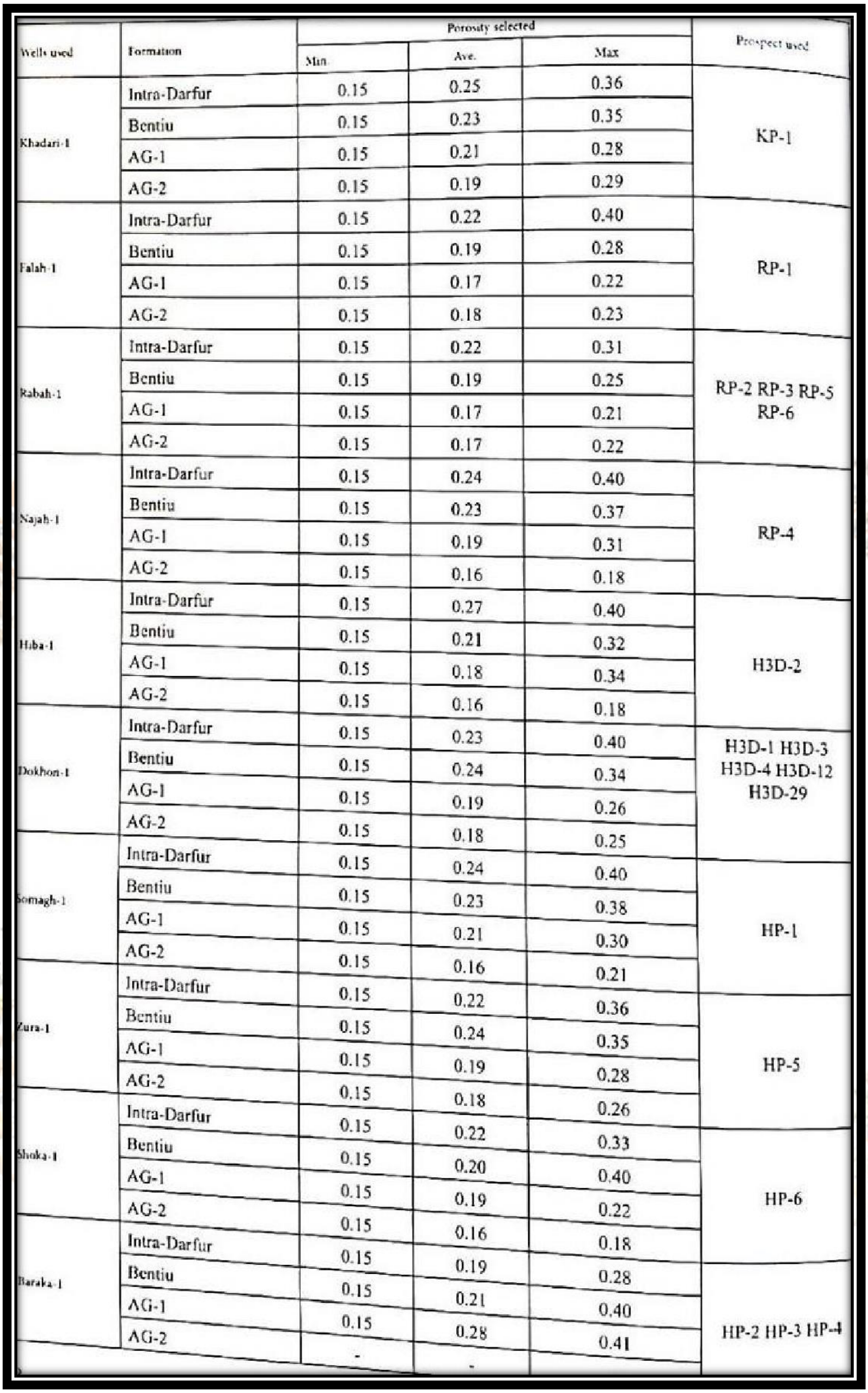


Fig.20. **Porosity distribution maps for the four reservoir layers inthe Muglad Basin, A) Amal formation, B)Aradeiba formation, C)Bentiu formation, D) Abu Gabra formation.**

Table.7. porosity values derived from the nearby wells statistics, Muglad Basin.



Wells used	Formation	Porosity selected			Prospect used
		Min.	Ave.	Max	
Khadari-1	Intra-Darfur	0.15	0.25	0.36	KP-1
	Bentiu	0.15	0.23	0.35	
	AG-1	0.15	0.21	0.28	
	AG-2	0.15	0.19	0.29	
Falah-1	Intra-Darfur	0.15	0.22	0.40	RP-1
	Bentiu	0.15	0.19	0.28	
	AG-1	0.15	0.17	0.22	
	AG-2	0.15	0.18	0.23	
Rabah-1	Intra-Darfur	0.15	0.22	0.31	RP-2 RP-3 RP-5 RP-6
	Bentiu	0.15	0.19	0.25	
	AG-1	0.15	0.17	0.21	
	AG-2	0.15	0.17	0.22	
Najah-1	Intra-Darfur	0.15	0.24	0.40	RP-4
	Bentiu	0.15	0.23	0.37	
	AG-1	0.15	0.19	0.31	
	AG-2	0.15	0.16	0.18	
Hiba-1	Intra-Darfur	0.15	0.27	0.40	H3D-2
	Bentiu	0.15	0.21	0.32	
	AG-1	0.15	0.18	0.34	
	AG-2	0.15	0.16	0.18	
Dokhon-1	Intra-Darfur	0.15	0.23	0.40	H3D-1 H3D-3 H3D-4 H3D-12 H3D-29
	Bentiu	0.15	0.24	0.34	
	AG-1	0.15	0.19	0.26	
	AG-2	0.15	0.18	0.25	
Somagh-1	Intra-Darfur	0.15	0.24	0.40	HP-1
	Bentiu	0.15	0.23	0.38	
	AG-1	0.15	0.21	0.30	
	AG-2	0.15	0.16	0.21	
Zura-1	Intra-Darfur	0.15	0.22	0.36	HP-5
	Bentiu	0.15	0.24	0.35	
	AG-1	0.15	0.19	0.28	
	AG-2	0.15	0.18	0.26	
Shoka-1	Intra-Darfur	0.15	0.22	0.33	HP-6
	Bentiu	0.15	0.20	0.40	
	AG-1	0.15	0.19	0.22	
	AG-2	0.15	0.16	0.18	
Baraka-1	Intra-Darfur	0.15	0.19	0.28	HP-2 HP-3 HP-4
	Bentiu	0.15	0.21	0.40	
	AG-1	0.15	0.28	0.41	
	AG-2	-	-		

5.1.1.4- TRAP TYPES:

In the Muglad basin, the extensional tectonics has created four major structural trap styles: UP thrown fault blocks (horst and tilted fault blocks), faulted anticlines, roll-over anticlines and down-thrown fault blocks. Stratigraphic traps linked to fluviatile sand distribution and flooding shale are expected when the structural deformations are absent, Pinch-outs under the numerous unconformitics all over the basin may form potential traps. Drape folds associated with faults, formed during the early rifting phase, were not rejuvenated such type of structure has trapped oil in the Heglig area. In some locations, downthrown roll-over anticlines have resulted from rotation into Listric faults, that are often accompanied antithetic faults sub-parallel to the primary fault trend. Several anticlinal closures have trapped oil in the Unity area. Two main periods of trap formation in the Muglad Basin are believed to have occurred in the early Cretaceous (130-120 Ma) and Late Cretaceous (90- 65 Ma; Riped and Sudapet, 2007). Both are either before or synchronous, with the main periods of expulsion. Subsequent re-migration of oils may be explained by the progressive increase in API gravity in shallower reservoirs (e.g. Unity field area). One possible explanation is that early generated (heavy) oils had migrated into successively younger reservoirs with reactivation and are replaced by later generated oils in the older reservoirs. The anomalously low GOR of the Muglad fields also supports reactivation of faults, with continued escape of gas to the surface during repeated fault movements (Mohamed et al., 1999; Beicipfranlab, 2004).

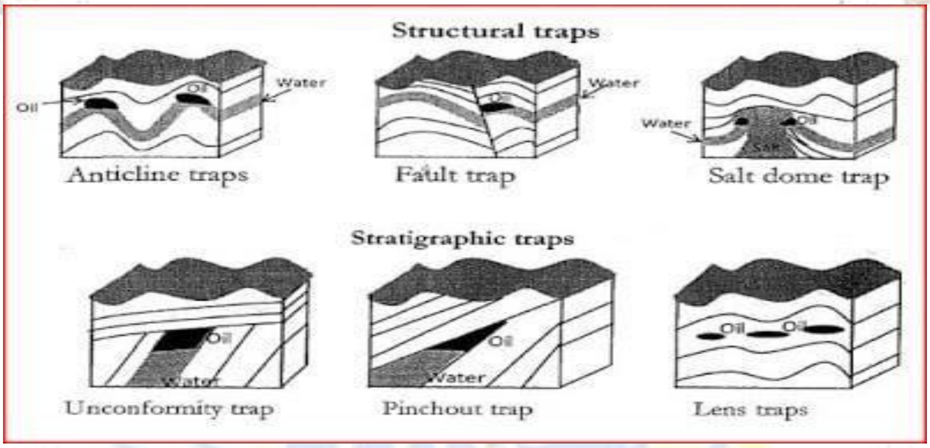


Fig (21): shows petroleum traps.

5- CONCLUSION:

The Muglad Basin is the largest graben structure straddling Sudan and South Sudan republics and covering approximately 120,000 Km. The basin extends 800 Km in a NW-SE direction (terminated in the NW against the CASZ) with a maximum width of 200 km; forming one of the major oil sources in Sudan and South Sudan republics. Geophysical and geological data have revealed the presence of nine sub-basins filled with more than 16,000m of non-marine Cretaceous-Cenozoic sediments in the deepest troughs. The basin fill consists of thick strata of claystones, fluvio- lacustrine sandstones, and siltstones. The tectonic development of the basin is characterized by three major episodes of rifting which initiated during the early cretaceous and continued to the end of the Oligocene. Each rift phase was associated with a coarsening-upward clastic sedimentary cycle. Each cycle is represented by basal sandstone, followed by a succession of lacustrine shales grading through marginal lacustrine mudstones and sandstones into fluvial mudstones and sandstones, and capped by fluvial and alluvial sandstones. Blevin et al. (2009) assigned six basin-forming events (basin phases) spanning the Jurassic to the Neogene and a pre-rift basin phase of Permo-Triassic to Jurassic. However, the presence of rotated fault blocks beneath the Jurassic?-Lower Cretaceous interval in the southern Muglad Basin may embrace Karroo-aged equivalent strata. Up-to-date subsurface data allow the recognition of thirteen informal lithostratigraphic subdivisions within the Muglad Basin, namely: Abu Gabra, Upper Bentiu, Lower Bentiu, the Darfur Group(Aradeiba, Gahzal and Zarqa, Baraka) and Kordofan Group (Amal, Nayil, Tend; Adok, Zeraf and Umm Ruwaba formations). The oldest penetrated unit, is the Abu Gabra Formation (Neocomian-Aptian corresponding to Assemblage Zones I and II), represents the early phase of lacustrine environment with thousands of meters of organic-rich claystones and shale deposits interbedded with fine-grained sandstones and siltstones unconformably overlying the Precambrian basement rocks. The Abu Gabra Formation is unconformably overlain by the lower Bentiu formation (Late Aptian-Cenomanian spanning part of Zone II to

IV). This unit was deposited under alluvial and braided to meandering fluvial environment. Palynofacies association reflects high energy depositional settings. The oldest unit of the Darfur Group, the Aradeiba Formation, corresponds to Zone V and rest unconformably upon the Upper Bentiu Formation. Core data analysis suggests deposition in a fluvial channel complex possibly deltaic distributary channels. The Aradeiba sands are important reservoirs in the Unity and Heglig oilfields. Palynofacies association indicates deposition in high energy settings. The second unit in the Darfur Group is the Zarga Formation which consists of interbedded sequences of mudstones, sandstones and siltstone. Similar to the Aradeiba Formation, the Zarga Formation was deposited in a lacustrine environment with fluvial-deltaic channels. The freshwater algae pediastrum spp. forms the dominant component of the kerogen. The formation is of Santonian age equivalent to Zone V. The Ghazal Formation (Campanian- Maastrichtian) is characterized by high percentage of sand interbedded with shale throughout the reservoir. The lithological composition and palynofacies association and its thicker sands indicate deposition in braided streams. The upper part of the formation is relatively of lower sands content assuming a fining-upward sequence: scour surface and lag deposits suggest deposition in meandering streams. The unit partially corresponds to Zone V and VI. The topmost unit of the Darfur Group,

Baraka Formation consists of sands and sandstones interbedded with thin silty claystones. Palynofacies association suggests deposition in a well- oxygenated environment. The unit is assigned to the Maastrichtian Zone
VI. The Cainozoic strata of the Muglad succession comprise the Kordofan Group which includes the Amal, Nayil, Tendi, Adok, Zeraf and Umm Ruwaba Formations. The thick massive sandstones of the Amal Formation (Paleocene) mark the end of the second rift cycle whereas the claystones- dominant Nayil Formation (Eocene-early Oligocenc) represents the syn- rift unit of the third rifting phasc. The Tendi Formation (late Oligocenc-early Miocene) was deposited during a transitional rifting phase documented by the onset of open lacustrine environment. The sand and sandstones of the Adok Formation (late Miocene-Pliocenc), widely recognized throughout the basin, has been deposited during the final sag phase. The Quaternary strata comprise the Pleistocene Zeraf Formation which is overlain by the Umm Ruwaba Formation, sometimes informally referred to as post Adok Formation. Active petroleum systems have been identified in the Muglad Basin where three potential source rocks exist namely: Lower Cretaceous Abu Gabra-lower Bentiu Formations, Upper Cretaceous Baraka Formation and Oligo-Miocene Nayil-Tendi Formations. Of these, the dark grey lacustrine claystones and shales of the early rift phase (Neocomian-Aptian/Abu Gabra- Lower Bentiu) are the primary source rock (moderately rich oil-prone). Although the younger source intervals (Baraka, Nayil-Tendi Formations) have relatively high TOC, there is limited opportunity for them to reach maturity, except in the deepest parts of the Kaikang Trough. The main source rock is represented by interbedded lacustrine fine-grained clastics containing Type I Kerogen laid down in freshwater lakes. Kerogen Type II with TOC ranging from 0.2-0.8 wt% is less potential source rock. Potential source rock is poorly known to the south of the basin, due to limited well intersections of the most prospective Abu Gabra Formation. Nine seismic-stratigraphic units were identified within the Muglad Basin: AG-4, AG-3, AG-2, AG-1, Bentiu-2, Bentiu-1, Darfur, Amal and Neogene to Quaternary (N+Q).The units introduced facilitate a better recognition of the petroleum system elements in the basin. Fair to good ability of oil generation is documented in the upper part of the Abu Gabra Formation (AG1 and AG2), where good source rocks were associated with the dark shale. AG-2 is better than AG- 1 with higher abundance of organic matter and high potential for oil generation. The main kerogen in the Tendi Formation is of Type III, with subordinate Type II kerogen. For the Darfur Group, the kerogen is mainly of Type III, and partly of Type II. An aquatic land source was identified for the original organic matter of the Abu Gabra source rock as deduced from Hydrogen Index (HI) data and confirmed by the result of the kerogen macerals. The migration pattern for the Muglad Basin is only applicable for source rocks of the Abu Gabra Formation and older units; since oils above this depth, would be subject to biodegradation. Five reservoir-cap assemblages were suggested in the Muglad Basin, which include Cretaceous and Palaeogene/Neogene assemblages. The Cretaceous assemblages comprise the Abu Gabra Formation (reservoir rock and cap rock), Bentiu (reservoir rock) and Aradeiba Formations (cap rock) and Darfur Group (reservoir rock and cap rock). The Palaeogene/Neogene assemblages include the Amal (reservoir rock), Nayil and Tendi (cap rock) in addition to Nayil and Tendi Formations as reservoir and cap rocks. Porosity measurements show a general decrease with depth. Four major structural trap styles were dentificd: up-thrown fault blocks (horst and tilted fault blocks). faulted anticline, rollover anticline and down-thrown fault blocks. The stratigraphic traps, linked to the fluviatile sand disturibution and flooding shale are also known. pinch-out under the numerous unconformities all over the basin represents also potential traps. Two main periods of trap formation are thought to have occurred in the Muglad Basin during the Early and Late Cretaceous, before or synchronous with the main

periods of hydrocarbons expulsion Post- generation/expulsion fault movements, clearly evident till at least the Early Miocene, increase the possibility of late trap breaches in many areas within the basin, Hydrocarbons generated during the Syrian Arc II inversion period would travel up the NW-SE-trending open faults into younger carrier beds and/or reservoir intervals or to the surface, Cross-cutting structures have the potential to be predominantly closed; thus traps are predicted to preferentially localize during this event. As a first pass, where open and closed fractures are cross-cutting, traps may be accessible to migrating hydrocarbons. This orientation of open/closed fractures persiststhroughout most of the Palaeogene and Neogene Periods.

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