Chapter One:-

Introduction

1.1 Location and accessibility:-

The Muglad Basin Complex is the main petroliferous sedimentary basin in Sudan and represents the western flank of its interior rift basins which are parts of the Central African rift system (Fig1.4) (Fairhead, 1988). Fula oil field from this basin which are investigated in the present study. The Muglad Basin Complex, which is about 200 km wide and more than 800 km long, covering an area of at least 120,000 km², is predominantly trending NW–SE. It extends from its northern part at the Southern Darfur Province, passes southwards through the Southern Kordofan, the Upper Nile and the Equatorial Provinces to link with the Anza Trough in northwestern Kenya (Fig 1.4). The northern end of the Muglad Basin terminates against the metamorphic and igneous complexes of the Darfur Dome, whereas the northwestern part ends at the Baggara Basin which is an E–W trending sedimentary basin, that formed synchronous with the Muglad Basin and the other Cretaceous sedimentary basins of West and Central Africa (Fig. 1.4). Geophysical studies indicate a sedimentary section up to 13,720 m (45276 ft) thick in the deepest part of the Muglad Basin, which is Kaikang Trough. However, the maximum drilled thickness of sediments in the Muglad Basin does not exceed 15,000 ft, which consists mainly of lacustrine and fluvial sediments of Early Cretaceous to Tertiary age (Schull, 1988). This basin is bounded approximately by the longitudes 26° 00´ and 30° 00´ E and latitudes 8° 00´and 12° 00´ N (Fig. 1.1).

The area is linked with Khartoum by a railway line which passes through Sennar, Kosti, Er Rahad to Babanusa and then runs southward through the Muglad city to Wau. Also from Babanusa a line runs westward via the NW Muglad Basin up to Nyala. A paved road runs from Khartoum to Kadugli through El Obeid, but from El Obeid many unpaved roads can be followed to different towns and villages in the area. These passage-ways cross thick forest and mountainous areas and are passable only during the dry season.

1.2 Topography:-

Generally the Muglad Basin area is a flat plain of low relief surrounded by hilly metamorphic and igneous terrain of the Nuba Mountains in the NE, isolated Basement and Nubian outcrops in the North and Basement Complex terrain in the SW, along the Sudanese and Central Africa Republic border (Fig. 2.4). With the exception of some isolated sandstone outcrops of Miocene to Pliocene age east of the Muglad town (El Shafie, 1975), the Muglad area is covered by stabilized sand dunes locally veneered by silt or clay in the northern part. In the southern and southeastern parts, the surface sediments tend to be clayey and silty soils commonly referred to as black cotton soils. Moreover, alluvial and wadi sediments as well as swamp deposits of the White Nile tributaries border the eastern side of the area.

1.3 Drainage :-

The drainage is sparse, and the streams are seasonal flowing during the rainy seasons which generally starts in May and continue for almost five months. The average annual rain fall in the area ranges from 600 to 800mm. The White Nile's tributaries considered as the main drainage system in the area.

The most significant drainage system of this kind in the area are Khor Abu Habel and Wadi Khadari. Some of the small spring-fed streams and of the ephemeral wadis and khors which carry run off, reach the White Nile or its perennial tributaries. The White Nile and its tributaries are largely affected by evaporation and infiltration.

1.4 Climate and vegetation :-

The southern Central Sudan is generally considered to have Savannah-type climate where the average annual precipitation ranges between 120 and 800 mm. This Savannah-type climate shows a gradual change from the very humid southern equatorial climate to the semi-arid northern zone. The majority of the rainfall happens normally during July, August and September. The annual rainfall is irregular especially during the last decades when more dry seasons than expected occurred, causing a regional drought and desertification. The prevailing winter wind comes from the North while that during the rainy season comes from the Southwest. Wind velocities are usually less than 8 km/h. The average daytime temperature reaches approximately 38°C in May and September. In winter (December–March) the temperatures are lower, around 20°–25°C. The mean humidity ranges from about 21% in the dry season to an average of 75% during the rainy season.

The natural vegetation ranges from a sparse cover of drought resistant grasses and shrubs in the arid north through a belt of open woods and grass land in the semi-arid central region, to thick forests in the well-watered south. Considerable parts of the area are covered by the genus Acacia such as <u>Acacia verek</u> (Hashab) which form one of the economic resources by producing Gum Arabic; <u>Balanites aegyptiaca</u> (Heglig); <u>Borassus flabellifer</u> (Daleib palm); <u>Adansomia digita</u> (Tebeldi or the Baobab tree);

Tamarindus indica (Aradeib); as well as Acacia nilotica (Sunut); etc. In the flood plains, swamps and lagoons of the Sudd area a typical equatorial vegetation is prevalent.

1.5 Population :-

The population is sparse in the region. The area is inhabited by a diversity of ethnic groups, but most of them belong to the Baggara tribes like Misseriya, beside Dinka, Daju and Nuba (El Badi, 1995). In recent years, the drought in the northern Kordofan has forced other groups such as Kababish to migrate with their sheeps to the south. Ten percent of the population settle in the towns and villages, but the rest are nomads who migrate seasonally in search of water and pasture for their herds which are mainly of cattle, sheep and goats. The main activity of the population is animal breeding. However, some people grow sorghum (dura), millet, cotton, sesame, groundnut, Arabic Gum, besides some vegetables and fruits. All crops are grown depending on episodic rainfalls.

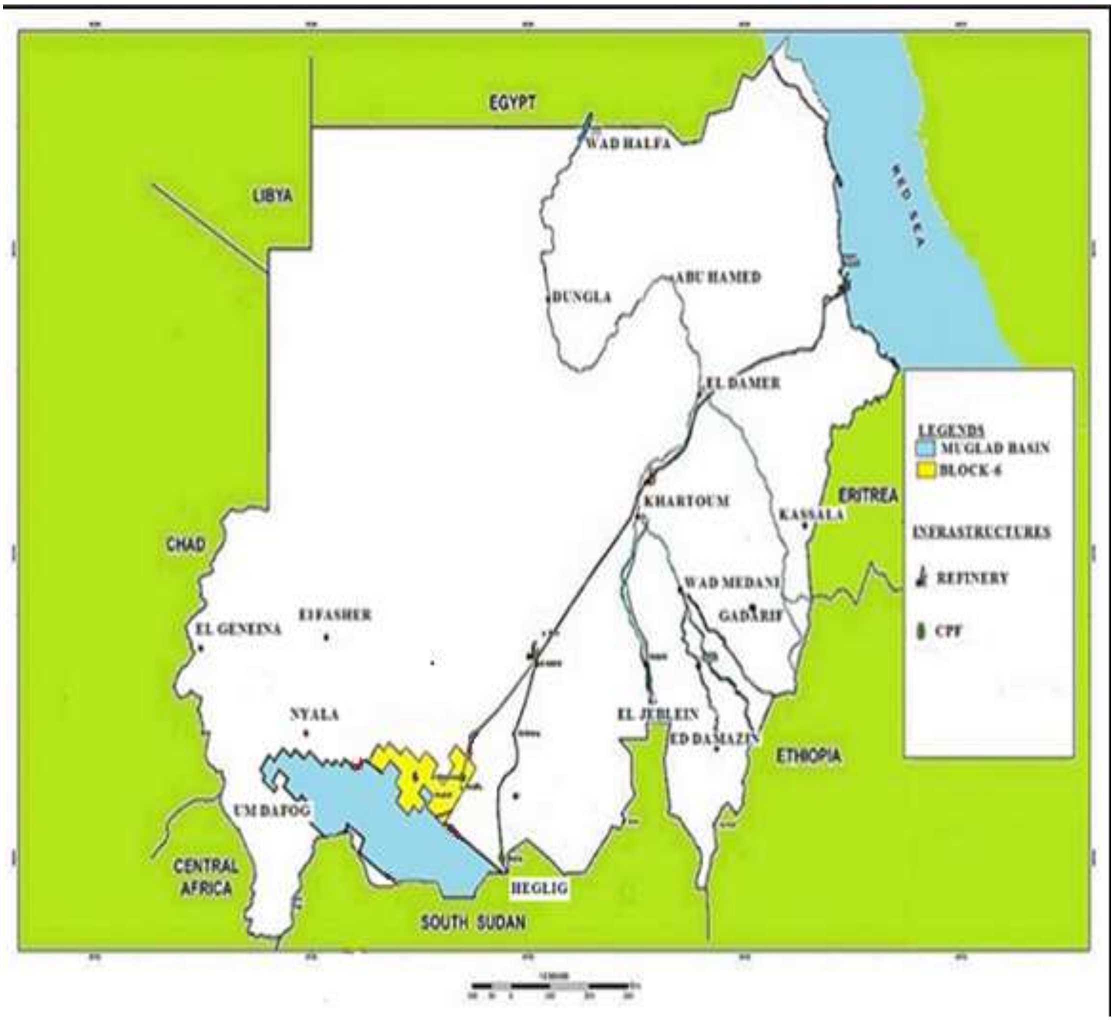


Fig 1.1: Location map for the study area (from Mohammed et al., 1999).

1.6 Historical background:-

The shear zone dates to at least 640 MA (million years ago). Motion occurred along the zone during the break-up of Gondwanaland in the Jurassic and Cretaceous ages. Some of the faults in the zone were rejuvenated more than once before and during the opening of the South Atlantic in the Cretaceou era.

The Pernambuco fault in Brazil is a continuation of the shear zone to the west In Cameroon, the CASZ cuts across the Adamawa uplift, a post-Cretaeous formation. The Benue Trough lies to the north, and the Foumban Shear Zone to the south. Volcanic activity has occurred along most of the length of the Cameroon line from 130 MA to the present, and may be related to reactivation of the CASZ. The lithosphere beneath the CASZ in this area is thinned in a relatively narrow belt, with the asthenosphere upwelling from a depth of about 190 km to about 120 km. The Mesozoic and Tertiary movements have produced elongated rift basins in central Cameroon, northern Central African Republic and southern Chad.

Fig1.2: illustrate Motion occurred along the zone during the break-up of Gondwanaland in the Jurassic and Cretaceous ages.

The CASZ was formerly thought to extend eastward only to the Darfur region of western Sudan. It is now known to extend into central and eastern Sudan, with a total length of 4,000 km. In the Sudan, the shear zone may have acted as a structural barrier to development of deep Cretaceous-Tertiary sedimentary basins in the north of the area. Objections to this theory are that the Bahr el Arab and Blue Nile rifts extend northwest beyond one proposed line for the shear zone. However, the alignment of the northwestern ends of the rifts in this areas supports the theory.

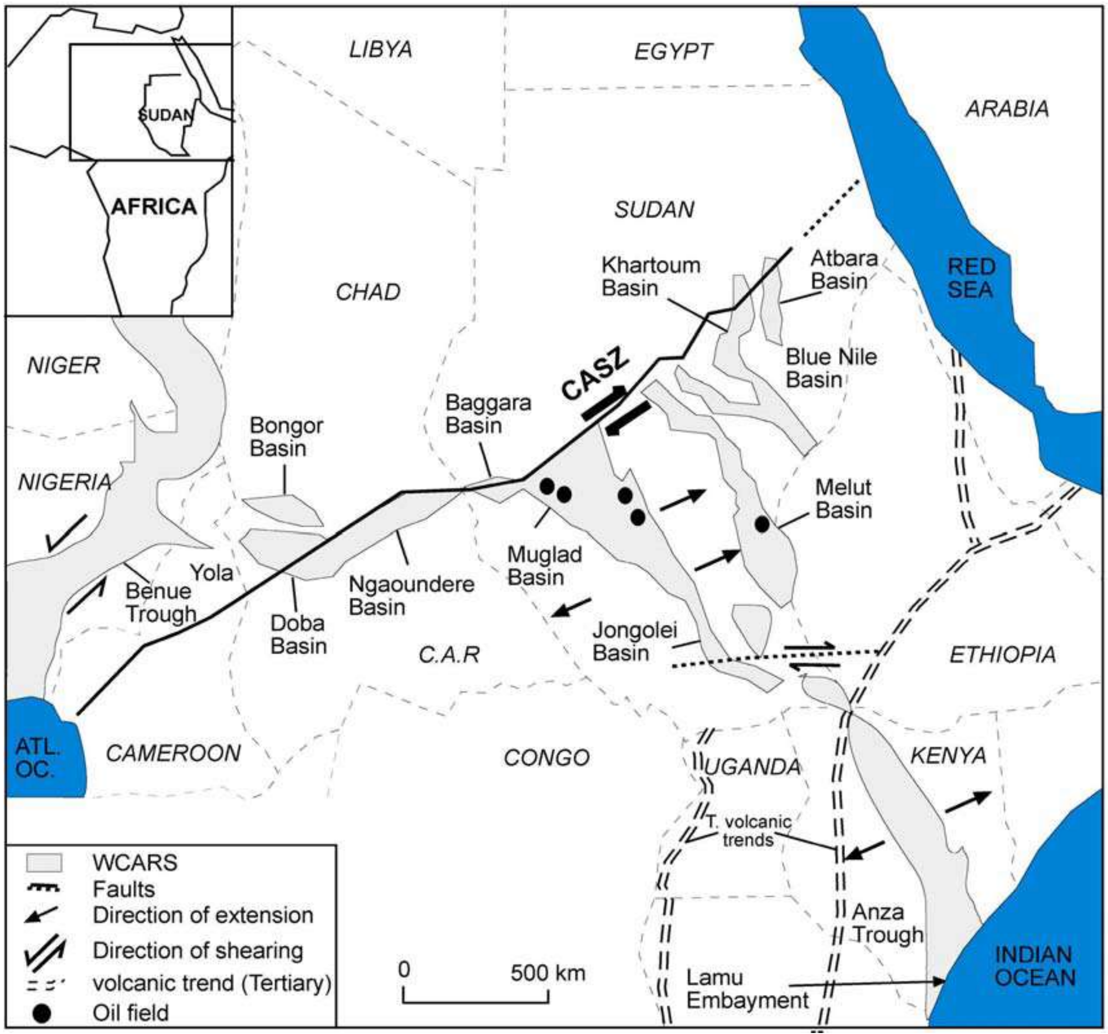


Fig 1.3: Tectonic model of the West and Central African Rift System from Fairhead (1988).

In I994, the Government divided the Darfur region into blocks for exploration. Block 6 was operating by CNPC Company. It area is about 38468 SQ.km. Only Block 6 (it calls also Abu Gabra) is producing oil in the Abu Gabra and Sharaf Fields as explained above.

Oil exploration and production in war-torn areas I95 production from the nearby Baleela field with 30,000 bpd. This increased the total production of Block 6 to 70,000 bpd, permitting the export of oil from this block for the first time. Before that it was used to supply the Khartoum refinery for local consumption. The CNPC built a pipeline from the Fula field in Block 6 to the middle of southern Kordofan, which produces approximately 45,000 bpd to Khartoum.

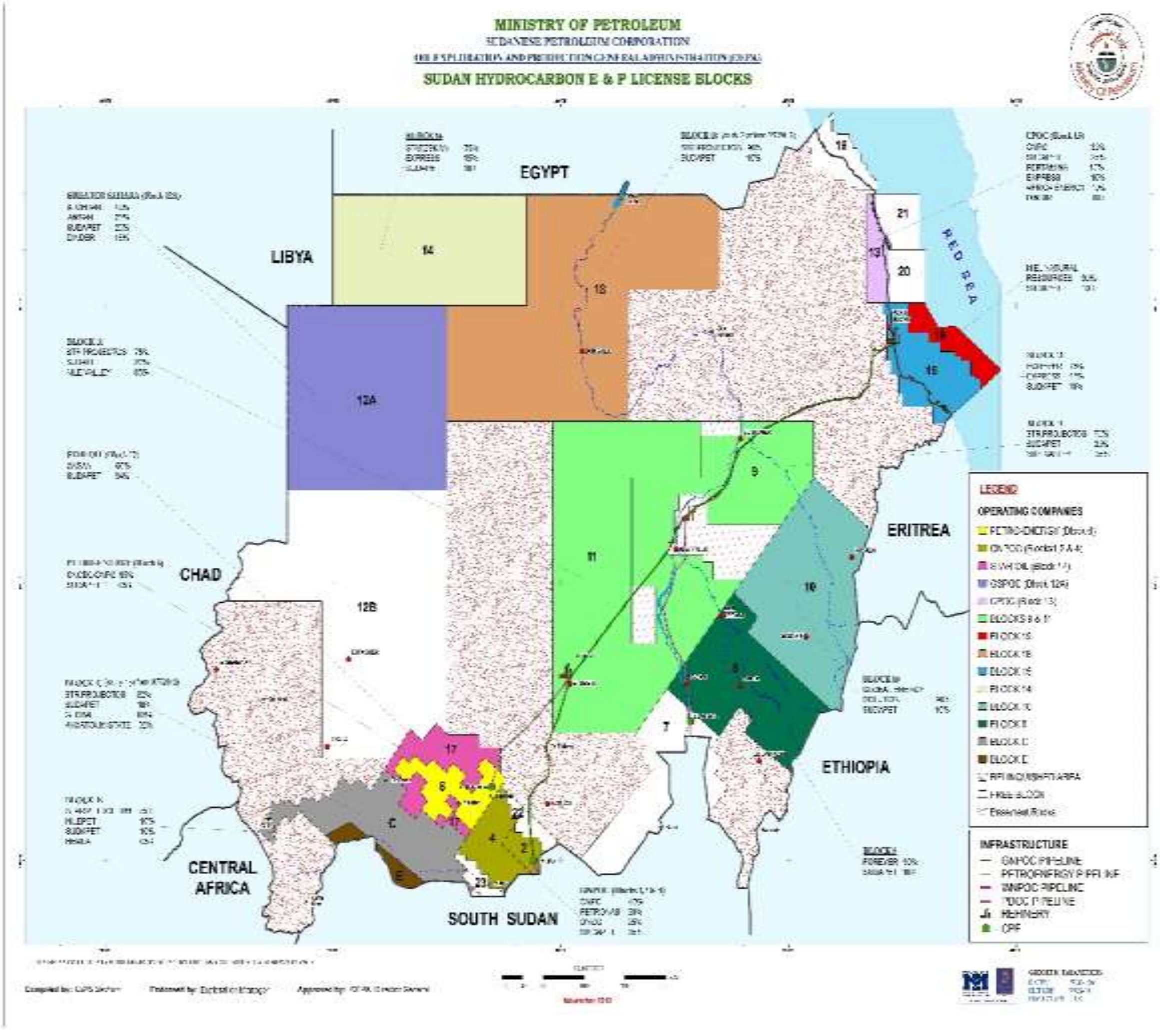


Fig1.4: Sudan hydrocarbon E & P licence blocks.

FORMATION		LITHOLOGY AND ENVIRONMENTS	AGE	
KORDOFAN GROUP	Zeraf Fm.	predominantly iron - stained sands and silts with minor claystones interbeds. braided streams / alluvial fans.	Recent - Middle Miocene	TERTIARY
	Adok Fm.		Oligocene - Late Ecocene	
	Tendi Fm.	predominantly claystone / shale interbedded with sandstones. fluvial / floodplain & lacustrine.		
	Nayil Fm.			
	Amal Fm.	predominantly massive medium to coarse sandstones sequences. braided streams / alluvial fans.	Paleocene	
DARFUR GROUP	Baraka Fm.	predominantly sandstones with minor shales and claystones interbeds. fluvial / alluvial fans.	Late Senonian Turonian	CRETACEOUS
	Ghazal Fm.			
	Zarga Fm.	predominantly sandstones, shales with interbeds of siltstones and sandstones. floodplain / lacustrine with fluvial / deltaic channel sands.		
	Aradeiba Fm.			
Bentiu Fm.		predominantly thick sandstones sequences. braided / meandering streams.	Cenomanian Late Albian	
Abu Gabra Fm.		predominantly claystones and shales with fine sandstones and siltstones. lacustrine / deltaic.	Albian - Aption	
Sharaf Fm.		claystones, shales with interbeds of fine sandstones and siltstones. lacustrine / fluvial - floodplain.	Barremian - Neocomian	

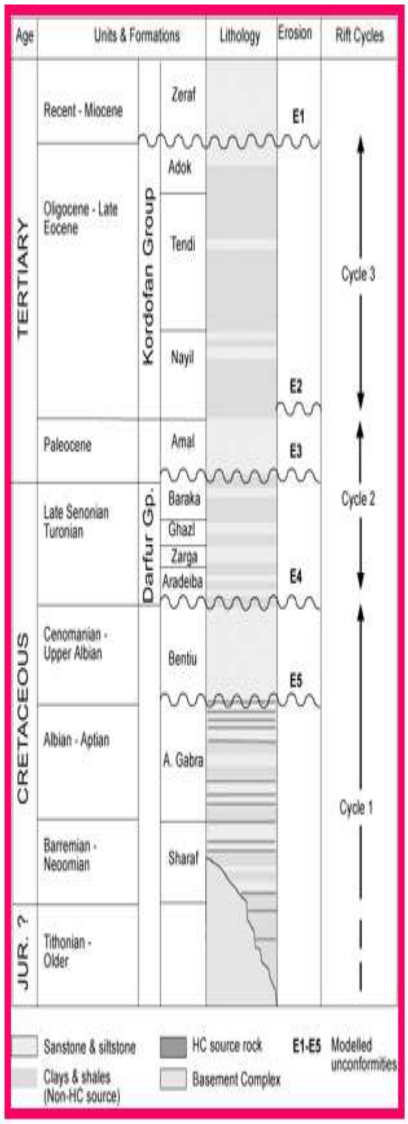


Fig1.5: show lithological column of Muglad Rift Basin.

1.7 The purpose of the study:-

- To evaluate and characterize the sedimentary facies and depositional paleo environments in block-6 region in Muglad rift basin.
- To infer the effect of the depositional regime and the diagenetic processes on reservoir and source rocks quality of the study intervals.
- Calculate the primary and secondery porosity from core analysis.
- Integrate and compare between the information obtained from well log interpretation and core analysis.

Chapter Two:-

Literature review

- ## Ali Sayed Mohamed Ibrahim (1997)

He investigated the depositional environment, source area and paIeogeography of the early Cretaceous (Neocomian .Albian) strata of Sharaf and Abu Gabra formations 1 in the N-W. Muglad rift Basin of interior Sudan. Methods of study included lithofacies analysis, heavy minerals, clay minerals and geochemical analyses. The lithofacies analysis reveals that Sharaf and Abu Gabra formations can be divided into three major units namely fluvial dominated, fluvial lacustrine and lacustrine dominated units. The heavy minerals analysis allowed the subdivision of Sharaf and Abu Gabra Formations into three heavy minerals zones. He suggested that the source rocks of Abu Gabra are mixed igneous and metamorphic rocks of granitic and granodioritic composition whereas, the source rocks of Sharaf Formation are mainly metamorphic of granitic and granodioritic composition.

The clay minerals associations and abundances reveal two distinct zones: upper and lower, which can be correlated laterally across Sharaf and Abu Gabra Formations. The upper zone consists of kaolinite, mixed - layer Smectite/ illite, Smcctite, illite and / or chlorite, while the lower zone consists of kaolinite, mixed-layer smectite/ illite, illite and diagenetic processes. Geochemical investigations reveal preferential enrichment and depletion of certain chemical elements in the lacustrine / fluvial environments. The multivarite analysis of the chemical elements of the Sharaf and Abu Gabra Formation, show two clusters; cluster one is dominated by samples from Abu Gabra Formation and cluster two is dominated by Shamf Formation. Inspite of their different source rocks, the similarity in the chemical composition shown by source samples in these cluster may be due to similar environmental condition within the lacustrinel fluvial system. The heavy minerals, feldspars and clay minerals contents suggest a relationship with facies types and their distribution

- ## Hanan Abd El Mutaal Hussein (1997)

She investigated in her study Cenomanian-Late Albian continental fluvial Bentiu formation based on data obtained from three exploration wells, in. W Muglad basin. Various methods have been used in the present work including lithofacies, reservoir quality, heavy mineral and clay mineral analyses. The lithofacies analysis allowed the subdivision of Bentiu Formation into lower, middle and upper parts.

The stratigraphic change of lithological facies and depositional patterns of Bentiu formation reflect mainly both allocyclic and autocyclic controls such as the tectonic activity, climate, drainage system, dispersal pattern and sediment load. Reservoir quality of Bentiu formation is controlled by grain-size and sorting and hence by depositional facies and environments. The facies analysis of Bentiu formation suggests a change in fluvial architecture and sand body geometry, from isolated, vertically stacked, narrow channels, in lower Bentiu formation, to vertically stacked broad channels and sand sheets, in middle and upper Bentiu Formation. It has been found that higher porosity and permeability values are associated with the coarse-grained sandy bedload dominated facies of upper and middle Bentiu Formation. In contrast, relatively lower porosity and permeability values are associated with the high sinuosity, mixed-load meandering stream of lower Bentiu Formation.

The heavy mineral analysis which was carried out on the whole penetration thickness of Abu Sufyan well reveals four distinct zones. The metamorphic rocks are the main contribtional source rock, in addition to the volcanic, plutonic igneous rocks and older sedimentary rocks. The heavy mineral assemblages were affected mainly by tectonism, weathering, transportation, abrasion and intrastratal solution. The clay minerals of Bentiu formation mainly consist of kaolinite, smectite, illite, mixed layer s/i and minor chlorite. The clay mineral assemblages of lower, middle and upper Bentiu Formation show a relationship with lithofacies types and depositional systems.

- **Abu Obeida Aamir Babiker (2000)**

He investigated the facies, depositional environment, source area and paleogeography of the Upper Cretaceous outcropping sediments at the NE margin of the Muglad Rift Basin of the south western Sudan. Methods of investigation included lithofacies analysis, grain size, petrography, heavy minerals and clay minerls analysis. The lithofacies analysis reveals the presence of massive to crudely trough cross-bedded pebble conglomerate facies (Gm, Gt) large and small scale trough cross-bedded sandstone facies (Stl. Sts), planar cross-bedded sandstone facies (Fl/Fm).

These facies belong to four major facies association, namely alluvial fan, major channel/bars, minor channel and overbank/ flood plain facies.

The facies associations show tabular to sheet geometries made of braided channels and bar sequences. The laboratory analysis shows that these sediments are generally poorly sorted, coarse to very coarse grained sandstones. The sandstones are mainly quartz arenites with minor arkosic arenites. These sandstones were cemented by ferruginous and/ or siliceous materials and kaolinitic clays, and all appear to have reduced sandatone porosity significantly. The heavy minerals analysis revealed the dominance of the ultras stable assemblage zircon, tourmaline and rutile over the metastable assemblage staurolite and kyanite. Kaolinite dominated over the other clay minerals smectite illite and chlorite. The facies, heavy and clay minerals contents of sediments in the study area show similsrity to those of the Albian- Cenomanian Bentiu Formation.

- **Ayad Mohamed Idriss Abass (2001)**

He investigated the penetrated part of Bentiu Formation in order to characterize the facies and depositional environments, to characterize the sandstone composition, diagenetic properties and reservoir quality, and to identify the paleogeographic setting and basin development. The methods followed in this study include subsurface facies analysis based on wireline logs, cuttings and core analyses, and laboratory analyses consisting of heavy mineral analysis, petrographic analysis, clay mineral analysis and scanning electron microscopy (SEM). The lithofacies analysis resulted in dividing the penetrated part of Bentiu formation into three parts: upper, middle and lower according to the difference in the recognized lithofacies. The geometry of these three parts was found to be sheet sandstone bodies. The heavy mineral analysis revealed that kyanite and garnet are the most widely spread heavy minerals in the study area indicating that the source rock are of metamorphic origin.

The petrographic analysis revealed that the sandstones are generally quartzarenite with some subarkoses. They are very fine to very coarse grained, sub-angular to well-rounded and moderately to well sorted. The mean porosity value was found to be 30% and it ranges from 21-35%. Diagenetic features affecting the sandstones are quartz overgrowth, clay infiltration and authigenesis, feldspar alteration and calcite cementation, and dissolution. The clay minerals of the penetrated part of Bentiu Formation consist of kaolinite, smectite, illite, mixed layer S/I and chlorite.

The reservoir quality of Bentiu Formation seems to be controlled by large-scale heterogeneties such as facies architecture, geometry and depositional styles recognized in lower, middle and upper Bentiu Formation small-scale heterogeneties of influence included sandstone detrital composition, texture, grain size and diagenetic features mentioned earlier.

- **Mohamed Abaker Abdalla (2001)**

He investigated the facies depositional environment, subsurface facies analysis, source area, petrographical characteristics of reservoir, of Upper Cretaceous (Campanian-Maastrichtrian) Ghazal Formation in the Muglad rift basin of interior Sudan. Method of this study included subsurface lithofacies analysis, heavy and clay minerals analysis, petrographical analysis and reservoir evaluation from five wells in Heglig and Unity Field. The lithofacies analysis revealed that Ghazal formation could be divided into three major units, namely fluvial dominated unit, fluvial-lacustrine dominated unit and lacustrine dominated unit. These units are divided into several single-story and multi-story sandstone bodies.

- **Saida Osman Mohamed Mustafa (2001)**

She studied the subsurface sedimentary facies, depositional environments and reservoir quality of the Turonian-Late Senonian Zarga formation of Darfur group in Unity and Heglig fields in the Muglad rift basin, Sudan. The principal objective of this study is to characterize the facies, paleoenvironments and reconstruct a facies depositional model, to characterize the sandstone petrography and provenances and to investigate the reservoir geology and quality. The methods of study included lithofacies analysis based on conventional cores and wireline logs, and sandstone petrographic analysis, heavy and clay minerals analysis. The core lithofacies analysis shows the cross trough-bedded sandstone, ripple cross-laminated sandstone, low-angle planner crosssbedded sandstone, laminated sandstone, siltstone and mudstone, laminated to massive siltstone, mudstone and massive to laminated shale. Based on the lithofacies analysis it reveals that Zarga formation compnses, from top to bottom, of three majors units, fluvial-dominated, fluvial-lacustrine and lacustrine-dominated unit.

The heavy minerals zone indicates that the main source area rock are metamorphic, igneous and recycled sedimentary rocks. The clay minerals recognized in Zarga formation include smectite, kaolinite, smectite/illite, illite and chlorite. Reservoir quality of Zarga formation seems to be controlled by macro-scale of facies, sub-environment, geometry, depth, and diagenetic alteration such as compaction, cementation and diagenetic alteration and dissolution are of prime importance. Zarga formation sandstone represents fair to good quality oil reservoir in Unity and poor in Heglig fields.

- **Ali Sayed Mohammed Ibrahim (2003)**

He investigated the depositional environment, source area, sandstone composition, diagenetic properties, reservoir quality and palaeogeography of the Middle–Upper Cretaceous strata at the Unity and Heglig Fields in the SE Muglad Rift Basin, Sudan. In this study, the subsurface Cretaceous sediments were investigated essentially by seven sedimentological techniques. These included subsurface facies analysis, which was based on 1500 cutting samples and seven conventional cores description as well as on wire line logs and three seismic section analyses, petrographic analyses that included heavy mineral analysis, thin sections and scanning electron microscopic investigations, clay mineral as well as geochemical analyses.

The Middle – Upper Cretaceous strata in Unity and Heglig Fields can be classified into three different units of first-order sequences that represent: fluvial-dominated unit, lacustrine-dominated unit and deltaic-dominated unit.

- **Abuzeid Abdall (2005)**

He investigated the depositional, geochemistry, and the diagenesis of the Aptain-Albian Abu Gabra Formation in the Muglad rift basin, which is one of the largest basins in the Sudan, in which the evolution and trend was controlled by tectonic activity. The facies analysis for the formation has made possible the establishment of a depositional model with three main sub-environments, fluvial, fluvio-lacustrine, and lacustrine sub-environments.

Seismic sections showed that normal faults controlled deposition of Abu Gabra Formation with fining upwards sequences associated with low stand of the lake, and or floodplain and coarsening upwards sequences associated with the deltaic sub environment.

From the seismic facies analysis it was found that the fluvial subenvironments were associated with the pre-rifting phase, the fluvio-lacustrine subenvironments were associated with the early rifting phase, and the deep lacustrine environments was associated with the high rate of subsidence. Clay mineral analysis using XRD showed a vertical downward increase in diagentic minerals, mainly illite and chlorite, through an intermediate clay mineral Illite/Smectite.

The above finding was supported by XRF, and SEM. SEM studies showed a vertical downward increase in diagentic clay minerals, mainly authigenic illite and chlorite, and authigenic kaolinite. Diagenesis in Abu Gabra formation played a major role in the accumulation and the transportation of the hydrocarbon to its reservoirs. In the three wells diagenesis associated with the disappearance of smectite mineral, started at depth 9800 feet (2956m) approximately. The three types of diagenesis were, diagenesis with burial depth, diagenesis due to fluid migration, and the geothermal diagenesis, all might have been active during the history of diagenesis in Abu Gabra formation.

- **Elmahi Musab Mohamed (2007)**

In his study The Campanian- Maastrichian continental fluvial Ghazal Formation has been investigated based on data obtained from (10) wells in the Unity field, Muglad Basin. Various methods have been used in the present study including different sedimentological, petrographical and petrophysical techniques using conventional cores, polarized microscope, X-ray diffraction analysis, Scanning electron microscopy, mudlogs and wireline logs.

The lithofacies analysis allowed the sub-division of Ghazal Formation into lower and upper parts. The stratigraphic thickness of the formation was measured from logs and found to be ranging from 213m -182m. The clay minerals of Ghazal Formation mainly consist of kaolnite, smectite, illite and chlorite. Therefore, the reservoir quality was mainly controlled by the original framework composition, cementation and to a lesser extent by compaction.

- **Hassan Abdalla Eltom (2007)**

Abu Gabra formation is interpreted to be deposited within a lacustrine system and is composed of fluvial; shallow and deep lacustrine and fluvio-deltaic environments. Bentiu formation is interpreted to be deposited within a fluvial system and composed of braided; meandering and minor shallow lacustrine environments. The study objective is to characterize the facies, depositional environments and the sequence stratigraphy of Abu Gabra and Bentiu formations in the Muglad rift basin, Sudan.

Lithofacies analysis revealed six lithofacies associations in Abu Gabra formation and four lithofacies associations in Bentiu formation.

- **Abdelhakam E. Mohamed and Ali Sayed Mohammed (2008)**

According to his research, Muglad Basin is recognized to be a major part of Sudanese interior rift basins. It trends northwest-southeast covering an area of over 1200 km long and in excess of 300 km wide. The major segment of the faulted strata in this basin lies beneath the Late Tertiary sediments.

According to his study Rift tectonic phases have controlled the geological settings of the African rift basins and their associated sedimentary cycles. Fractures of South African plate in early Mesozoic era was led to creation of deep troughs, this, together with sediment accumulations and faulting across the successively deposited beds formed structural and sedimentary conditions ideal for trapping of oil.Muglad trough was filled with non-marine sediments of upper Jurassic [1] derived from North African plate.

- **Rashid A. M. Hussein (2012)**

He suggested that Sedimentary analysis and Facies Associations may enhance accuracy of sequence core (very stratigraphic correlation of Fula Subbasin, Muglad Basin, Sudan. According to little) and log data, stratigraphic correlation was set. Abu Gabra Formation, Bentiu Formation, and Aradeiba Formation were subdivided into units. Essential depositional systems were recognized in the study area on the basis of the evolution of sedimentary facies. Tectonic and climatic fluctuation controlled the evolution of the syn-rift fill of Fula Subbasin. The deep Cretaceous- Tertiary Fula subbasin associated with regionally linked intercontinental rifting system that crosses Central Africa. Thick continental environment existed in different areas essentially including fluvial and lacustrine facies of Cretaceous and younger age. A framework of tectonostratigraphic development and rifting cycles of the Fula subbasin was constructed. Lacustrine Deposits in Fula Subbasin were characterized. The components of the depositional sequences are systems tracts. Systems tracts are divided into three groups according to relative sea level at the time of deposition: lowstand at low relative sea level, transgressive as the shoreline moves landward, and highstand at high relative sea level.

- **Dou Lirong et.al (2013)**

As he observed, In contrast to other parts of the Muglad Basin, the Fula sub-basin underwent three episodes of rifting. Sandstones in the Aradeiba, Bentiu and Abu Gabra Formations are major reservoir units, characterised by high porosity and high permeability for the Aradeiba and Bentiu reservoirs, and medium-low porosity and permeability for the Abu Gabra reservoirs.

Oil-source correlation in the Fula sub basin indicates that the present-day top of the oil generation window lies at a depth of 2100 m. The similarity between oil maturation at different depths and source rocks confirms that oils in different pay zones were sourced from the middle Abu Gabra interval.

Four play fairways are present in the Fula subbasin. That in the central oblique anticline zone is the most favourable for hydrocarbon accumulations.

- **Dong Wu et al (2015)**

He described the spatial distribution and temporal evolution of clastic depositional systems based on integrated analysis of seismic, core and well logging data. In the Abu Gabra Formation of the Fula Sub-basin, a variety of depositional systems are recognized, namely, fan delta, braided delta, delta, sublacustrine fan and lacustrine system.

The following three types of sequence architectures from northern to southern part of the Fula Sub-basin have been identified: simple dustpan-shaped sequence architecture in the north, transfer-zone sequence stratigraphic architecture in the middle and graben-shaped sequence architecture in the south.

According to the study of petrology, log-phase, seismic facies, and sandstone distribution, the distribution of the Cretaceous rift sedimentary system in Fula sag of the Muglad Basin have been predicted, and the sedimentary models in two rift periods have been established. There developed eight 3rd-order sequences in the two rift periods in the Cretaceous of Fula sag, which have 5 types of sedimentary facies, namely, braided river delta, meandering river delta, fan delta, lacustrine, and turbidite fan.

- **Ali Yasir Abdalla Abass (2015)**

He investigated the Santonian continental fluvial Aradeiba Formation based on the lithological data obtained from five (5) wells in the Heglig field, Muglad Basin. Various methods have been used including different sedimentological, petrographical and petrophysical techniques, conventional cores investigation, polarized microscope is used for petrograhy, X-ray diffraction analysis, Scanning electron microscopy, mudlogs and wireline logs inspection.

The lithofacies analysis indicate that Aradeiba Main Sand is composed of coarse sandstone that reveal coarsening upwards deltaic mouth bar with minor fining upwards sequences of distributary channels. The dominant sandstone intercalated by fine sandstone, siltstone and claystone that reveal coarsening upward sequence of prodelta and delta front. The stratigraphic thickness of the formation was measured from logs and found to be ranging from 10m to13.5m. The clay minerals of Aradeiba Main Sand consist mainly of kaolnite, smectite, illite and chlorite.

The sand bodies are extended in the northern part of the area, the economic value of Aradeiba Main Sand is considered in 2006 after exploring the hydrocarbon by Greater Nile Operating Company (GNPOC).

- **Eldegial Tarig Gumaa Adam (2016)**

He investigated the Santonian Aradeiba Formation in order to configure out facies distribution and suggest model for depositional environment. The study is based on data obtained from three (3) wells drilled in the Unity Field, Muglad Basin. Various methods have been used in the present study including sedimentological and petrophysical techniques using conventional cores, polarized microscope, X-Ray diffraction analysis, mud logs and Wireline logs.

The lithofacies analysis suggests that the Aradeiba Formation is divisible in to three parasequences. The parasequences-1 (PS-1) is mainly shaly at the base with limited sand bodies. This is followed by (PS-2), which is composed mainly sandy coarsening upward parasequences of deltaic nature. The (PS-3) ends with continuous shale to silt lithology, the data suggests that deposited in lacustrine or floodplain environment.

The lithofacies and depositional patterns of the Aradeiba Formation reflect mainly allocyclic and autocyclic controls such as tectonic activity, climate, drainage system and sediment load. Three heavy mineral zones, Zircon- Tourmaline- Rutile; Hornblend- Garnet and Staurolite- Kyanite are recognized in the Aradeiba Formation. The sources of heavy minerals in the Aradeiba Formation are metamorphic with minor igneous and some extent sedimentary source from outcrops in adjacent area. The clay minerals of the Aradeiba Formation mainly consist of kaolinite, smectite, illite, chlortie and mixed layer (illite/smectite). The thin section investigations of the core samples revealed that the quartz is the main mineral in the Aradeiba sand, its ranging between 19 -37%, the feldspar percentage ranging between 3 -16 % with low amounts of mica and rock fragments .

Chapter Three:-

Methods of Investigation

3.1 Introduction:-

In this study, the subsurface sediments in Muglad rift basin (block 6) have been investigated by using different types of analysis from Bentiu formation, these analysis include wirelines logs interpretation, conventional core description, petrography, x-ray analysis and scanning electron microscopy.

3.2 Wire line logs:-

The interpretation of wire line logs as subsurface techniques is now widely used in sedimentology, a wide range of physical parameters can be measured using tools lowered down a petroleum exploration hole. These give information on lithology, porosity and oil and water saturation (Cant 1984; Allen and Allen 1990; Emery and Myers 1996). In this study the gamma-ray, sonic, spontaneous potential (SP), density, neutron and caliper wire line logs from the above mentioned wells at the field were interpreted to identify the lithologies and the lithofacies types along the wells profiles.

3.2.1 Gamma ray:-

Gamma ray (GR) logs measure the natural radioactivity in formations and can be used for identifying lithologies, correlating zones and for the determination of shale (clay) volumes. Shale-free sandstones and carbonates have low concentrations of radioactive material and give low gamma ray readings. As shale content increases, the gamma ray log response increases because of the concentration of radioactive material in shale. However, clean sandstone (i.e., with low shale content) might also produce a high gamma ray response if the sandstone contains potassium feldspars, micas, glauconite, or uranium-rich waters.

The spectral gamma ray log records not only the number of gamma rays emitted by the formation but also the energy of each, and processes that information into curves representative of the amounts of thorium (Th), potassium (K), and uranium (U) present in the formation.

3.2.2 Spontaneous potential:-

The spontaneous potential (SP) log was one of the earliest measurements used in the petroleum industry, and it has continued to play a significant role in well log interpretation. Most wells today have this type of log included in their log suites. Primarily, the SP log is used for determining gross lithology (i.e., reservoir vs. non-reservoir) through its ability to distinguish permeable zones (such as sandstones) from impermeable zones (such as shales). It is also used to correlate zones between wells. However, as will be discussed later in this chapter, the SP log has several other uses that are perhaps equally important. The SP log is usually recorded on the left track of the log (track 1).

3.2.3 Sonic log:-

The sonic log is a porosity log that measures interval transit time (Δt, delta t, or DT) of a compressional sound wave traveling through the formation along the axis of the borehole. The sonic log device consists of one or more ultrasonic transmitters and two or more receivers. Modern sonic logs are borehole-compensated (BHC) devices. These devices are designed to greatly reduce the spurious effects of borehole size variations (Kobesh and Blizard, 1959) as well as errors due to tilt of the tool with respect to the borehole axis (Schlumberger, 1972) by averaging signals from different transmitter-receiver combinations over the same length of borehole .

3.2.4 Density:-

Density is measured in grams per cubic centimeter, g/cm3 (or Kg/m3 or Mg/m3), and is indicated by the Greek letter ρ (rho). Two separate density values are used by the density log: the bulk density (ρb or RHOB) and the matrix density (ρma). The bulk density is the density of the entire formation (solid and fluid parts) as measured by the logging tool. The matrix density is the density of the solid framework of the rock. It may be thought of as the density of a particular rock type (e.g., limestone or sandstone) that has no porosity. Since the late 1970s, the density log has also been used for the photoelectric-effect measurement (Pe, PE, or PEF) to determine lithology of a formation.

3.2.5 Neutron log:-

Neutron logs are porosity logs that measure the hydrogen concentration in a formation. In clean formations (i.e., shale-free) where the porosity is filled with water or oil, the neutron log measures liquid filled porosity (ϕN, PHIN, or NPHI).

3.2.6 Resistivity logs:-

The resistivity logs are generally used to determine hydrocarbon-bearing versus water-bearing zones indicate permeable zones determine porosity By far the most important use of resistivity logs is the determination of hydrocarbon-bearing versus water-bearing zones. Because the rock's matrix or grains are nonconductive and any hydrocarbons in the pores are also nonconductive, the ability of the rock to transmit a current is almost entirely a function of water in the pores. As the hydrocarbon saturation of the pores increases (as the water saturation decreases), the formation's resistivity increases. As the salinity of the water in the pores decreases (as Rw increases), the rock's resistivity also increases.

3.2.6 Caliper log:-

The caliper log is a well logging tool that provides a continuous measurement of the size and shape of a borehole along its depth and is commonly used in hydrocarbon exploration when drilling wells. The measurements that are recorded can be an important indicator of caving or shale swelling in the borehole, which can affect the results of other well logs.

3.3 Core analysis:-

Retrieval and analysis of cores is essential to all phases of the petroleum industry. Cores offer the only opportunity to obtain intact, vertically continuous samples that allow the visual examination of depositional sequences and variations in reservoir character. Properly analyzed cores provide data available from no other source; these data should provide direct evidence of the presence, quantity, distribution, and deliverability of hydrocarbons. Cores are essential to understanding the nature of the pore system in the potential reservoir unit. The knowledge gained from cores enhances our ability to predict reservoir performance and to select procedures to maximize profitable hydrocarbon recovery.

3.3.1 Thin sections:-

The samples were prepared by using a vacuum impregnation with blue dyed resin to facilitate the recognition of the porosity. Each sandstone thin section was counted by the counter (250 p), the specific characteristics of most of the studied samples are illustrated by two photomicrographs for each sample.

3.3.2 Scanning Electron Microscope (SEM):-

Scanning Electron Microscopy (SEM) analysis provides valuable and highly detailed information on clay and cement distribution, pore geometries and on the microstratigraphy of the mineralogical phases. The SEM is further equipped with a backscatter facility which enables recognition of different mineral phases.

The samples were first cleaned in a cold chloroform to remove the hydrocarbon residues, and then fixed on standard aluminium tape, the SEM analysis involved a detailed investigation and description for the sample material with special focus on clay minerals composition and morphology.

3.3.3 X-ray Diffraction (XRD):

The samples were analyzed using XRD- technique with size fraction less than (2 micron), this procedure after Chamley, (1989) and Reynolds, (1997). A quantity estimation of the clay mineral constituents were computed mainly from the ethylene-glcol solvated X'RD patterns as suggested by Schwertman et al. (1993) a.

Chapter Four:-

Calculations and Results

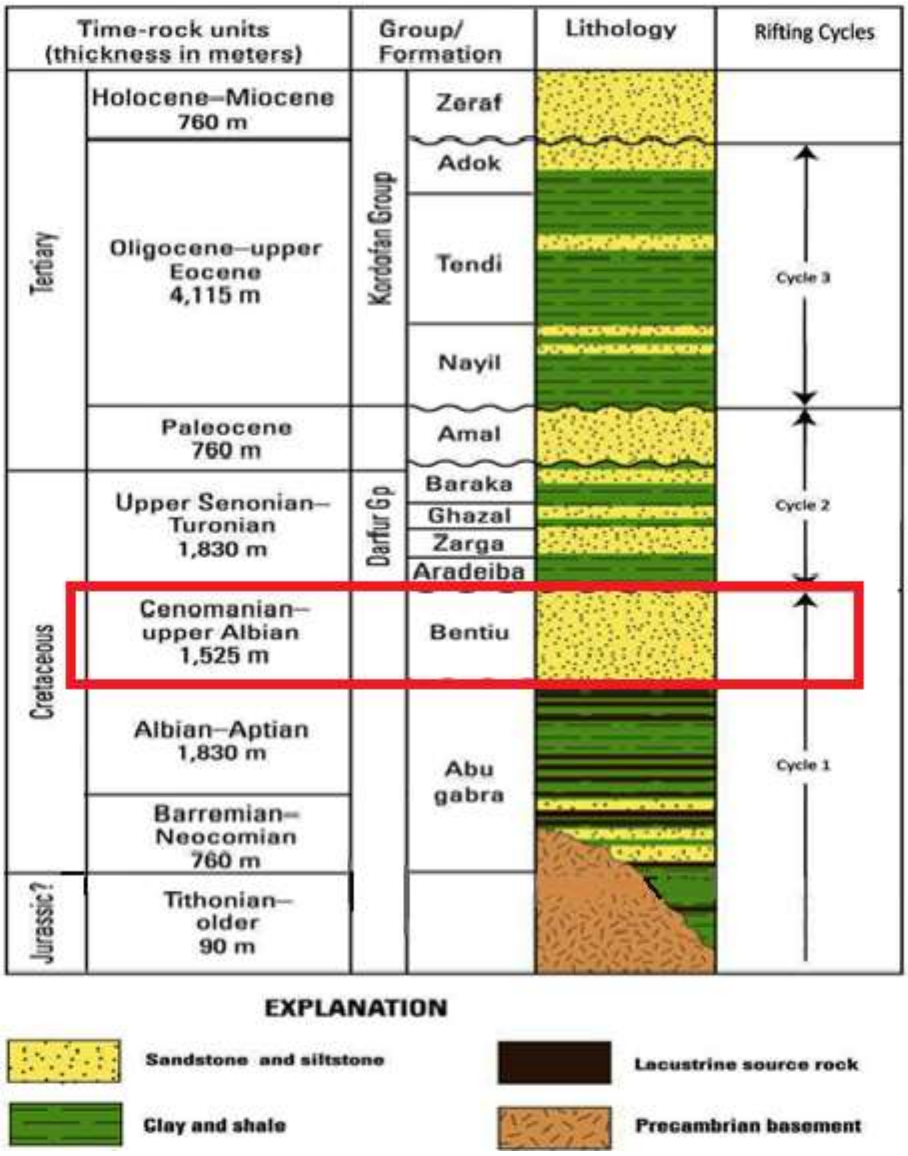
4.1 Wire line logs interpretation of Bentiu formation:-

In Bentiu Formation the gamma ray readings showed some deflections to the right side (high readings) in different parts, which means those parts are clay, beside the Gamma ray pattern giving a bell shape with long neck at the upper and the middle parts in Fula-1 well. ,and showed low readings in the other parts (Fig 4.2), while in Fula-2, the gamma ray readings dominated with low readings (Sandstone), and the pattern is bell shape with long neck, that means the fluvial system is braided channel (Fig 4.3).

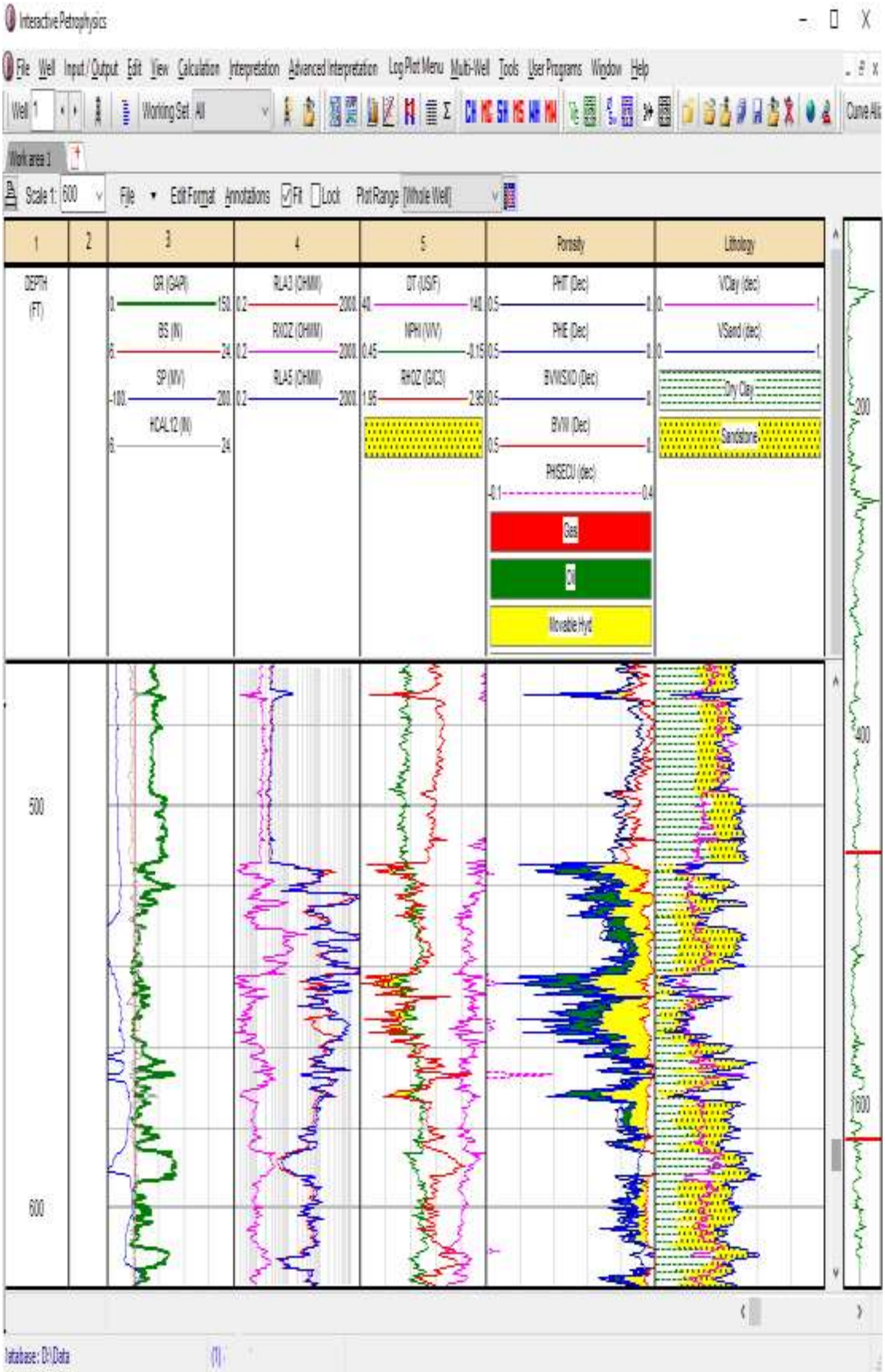
The Caliper and Bit size readings showed (no shifts), that is in Fula-1, while in Fula-2 here are some crossed readings between Caliper and Bit size. That means there is a mud cake in the upper and lower parts, and also there are some shifts between the Caliper and Bit size, that gives a clear understanding that; these zones have exposed to washout (caving), in the upper and middle parts.

The Density, Sonic, and Neutron logs were ran together to recognize the rock type and to calculate the porosity. The Density and Neutron logs readings in Bentiu Formation through Fula-1 and Fula-2 wells, the readings going parallel, overlapped and crossed in some parts as shown in (Fig 4.2) and (Fig 4.3),that means the rock type is Sandstone, and same parts the readings going separately, that reflects the zones of clay.

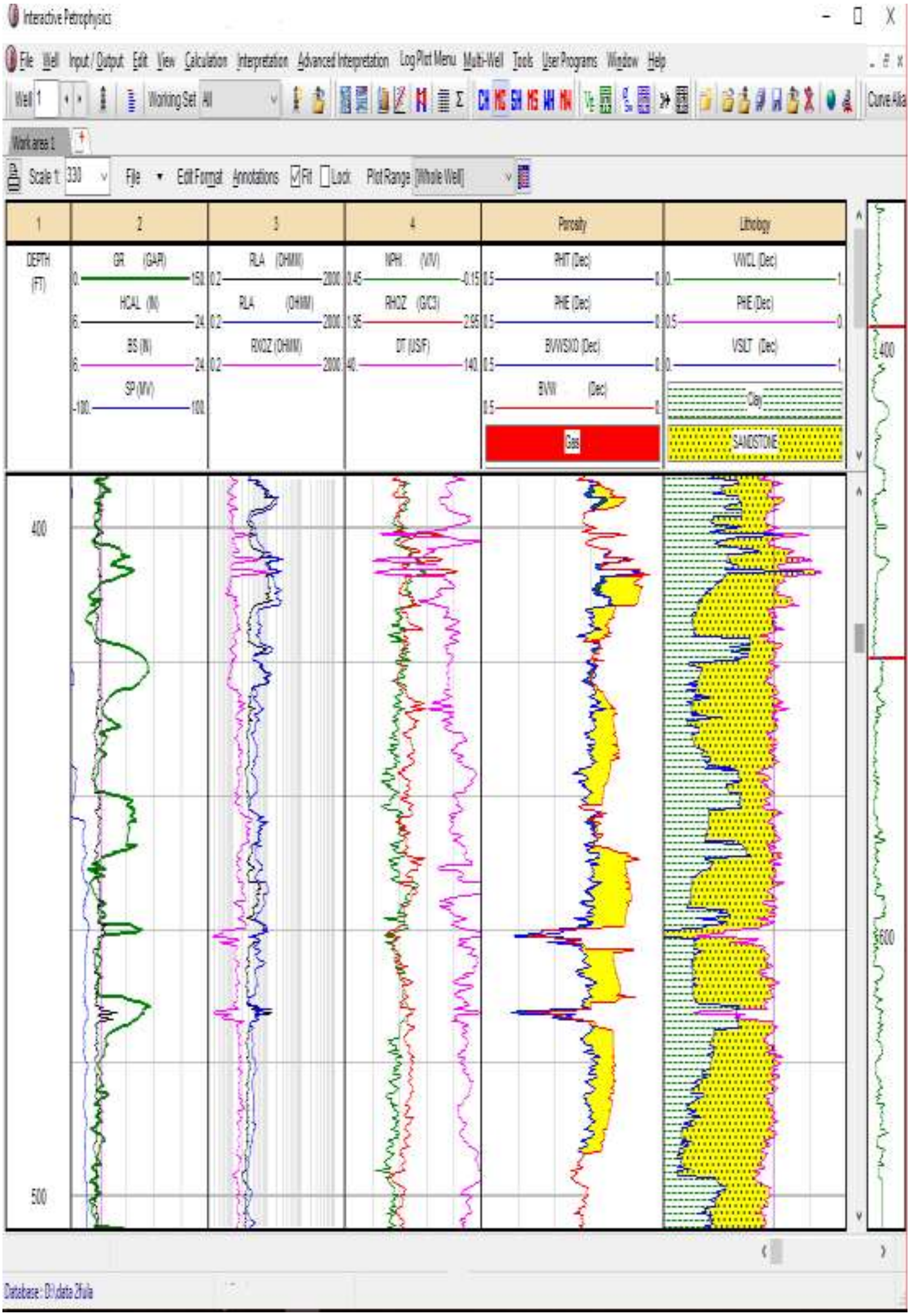
The Resistivity log (Deep, Shallow and Micro), used to detect fluids, and they showed that, most of the Sandstone layers in Fula-1 containing hydrocarbons, and the Sandstone layers in Fula-1 is more contain hydrocarbons than Fula-2 (Fig 4.2) and (Fig 4.3).



(Fig 4.1): showed the paleo-strategraphy column of Muglad rift basin.



(Fig 4.2): showed the wire line logs from Fula-1 using IP software.



(Fig 4.3): showed the wire line logs from Fula-2 using IP software.

Depths(m)	Total porosity %	V clay %
521.0	15.6	19.99
527.4	21	19.76
576.5	14.26	29.48
579.4	19.52	28.91

Table 4.1 showing the readings from Fula-1 calculated from IP (Interactive Petrophysics) software.

Depths(m)	Total porosity %	V clay %
412.0	21.3	17
436	25	22.4
454	20.6	15.1
480	18	25.6

Table 4.2 showing the readings from Fula-2 calculated from IP (Interactive Petrophysics) software.

4.2 Subsurface Facies Analysis

4.2.1 Introduction:

Megascopic core description and observation of sedimentary sequences were done before any other detailed analyses. Standardize procedures by the major oil companies for core description by means of check lists, uniform legends and symbols as well as with other measures.

Conventional cores are the best mean to obtain direct information on all aspects of sedimentary sequences and its hydrocarbon content. The core samples are cleaned after recovery and to mark the bottom of a core by an arrow.

Cores are described as one unit; however, if it is heterogeneous, each lithological unit requires separate description.

This study is based on cores from two wells from Fula oil fields, the samples analyzed were selected to represent all of the facies types, the main types of facies are Conglomerates, Sandstones, Siltstones, Mudstones and Shales, which are representing the main facies of lower Bentiu formations (Table 4.3).

Well	Facies Type & Percentage %									
	Sm	**St**	**Sp**	**Sr**	**Sh**	**Fl**	**Gm**	**Fm/Fcf**	**GAP**	**Total**
Fula-1	4.97%	1.65%	4.30%	0.42%	*	0.39%	0.74%	1.06%	44.92%	100%
Fula-2	16.35%	1.38%	3.03%	*	*	1.64	2.38%	0.33%	72.62%	100%

Table (4.3): The main facies of Bentiu formations from Fula-1 & Fula-2.

Sm= Massive Sandstone.

St= Cross bedded Sandstone.

Sp= Planner bedded Sandstone.

Sr= Ripple laminated Sandstone.

Sh= Horizontal bedded Sandstone.

Fl= Fine laminated Sandstone.

Gm= Conglomerates.

Fm/Fcf= Massive Mud and Siltstone.

4.2.2 Facies Distribution in Bentiu Formation:

Bentiu Formation represented through two wells from Fula oil field, which are: Fula-1 have a total length of the core 10.17m and Fula-2 have a total length of the core 42.01m; the establishment of a complete lithofacies classification for the study intervals is based mainly on the full megascopic description and analyses of the conventional core samples.

From the lithofacies analysis of the conventional cores, seven (7) different major lithofacies types have been recognized from Fula-1 and six (6) different major lithofacies types have been recognized from Fula-2.

4.2.2.1 Fula-1:

Trough Cross-bedded Sandstone:

This facies is present in the core samples reaching a total thickness of 1.65m. The colour of this facies is grey to yellowish. The grain size is medium grained. The grains are rounded to sub rounded in shape and are moderately to well sorted. The observed porosity is high. However, some siliceous, and some few iron oxide cements have also been observed. Kaolinite represents the dominant matrix material. Oil shows have also observed. This facies could be classified as **"St"** type according to Miall (1978) and could be interpreted as the deposits of migrating 3-D dunes in fluvial channels or in small delta distributary channels.

Planar cross-bedded sandstone:

This facies is present in the core samples reaching a total thickness of 2.53m (Table 4.2). The colour of this facies is grey to yellowish. The grain size is medium-grained (mL). The grains are sub rounded to sub angular in shape and are well sorted. The observed porosity is fair|. However, some siliceous, some few carbonate and some few iron oxide cements have been observed. Carbonate has been confirmed by acid (HCl con. 10%) test. Kaolinite represents the dominant matrix material. Oil shows have also been observed. This facies could be classified as **"Sp"** type according to Miall (1978) and could be interpreted as linguoids, transverse bars or sand waves deposited in a fluvial channel or a small delta mouth bar.

Ripple Laminated Sandstone:

The total thickness of this facies is a bout 0.42m, (Table 4.4). The colour of this facies is grey to dark grey. The grain size is fine the grains range from sub rounded to round and are well sorted. Kaolinitic matrix is present. Moreover, some iron oxides and some amounts of micaceous mineral occur as cements. This facies resembles the **"Sr"** facies type in Miall's (1978) classification and can be explained as ripples that were deposited on the top of the fluvial bars or in the floodplain or as natural levee deposits.

Massive Sandstone:

This facies type has been observed in the core samples with a total thickness of 2.92m (Table 4.4). The colour of this facies is light grey. The grains size range from medium to coarse, with dominant gradual fining upward trend. The grains are subrounded to round and moderately to well sorted. Some iron oxides, silica and some amount of imbedded mud clasts. Kaolinite is disseminated throughout the facies. Oil shows were also observed. Locally the massive-looking beds have faint bedding planes. This massive sedimentary facies, which resembles the **"Sm"** facies type in Miall's (1978) classification, was formed by very rapid sedimentation, probably by high-discharge events such as sheet-floods.

Mud Conglomerate:

This facies is present in the core samples with a total thickness of 0.44m (Table 4.4). It is grey to yellowish in colour. The grain-size is very coarse grained. The grains are subrounded to round in shape embedded in silty mudstone matrix and are poorly to moderately sorted. Few Kaolinitic matrix. Some oil shows was observed. This facies resembles the **"Gm"** facies type in Miall's (1978) facies classification. The deposition of this facies may have taken place in a fluvial channel or in the mouth bar of the crevasse splay.

Fine Laminated to Massive, Siltstone and Mudstone:

The above facies type has total thickness of about 0.62m in all of the studied cores (Table 4.4). The colour of this facies varies from light grey, reddish to dark grey in colour. The sedimentary structure of this facies is fine laminated. Furthermore, the above facies is classified as **"FI"** according to Miall (1978). It can be interpreted as overbank or waning flood deposits or crevasse splay distal bar deposits.

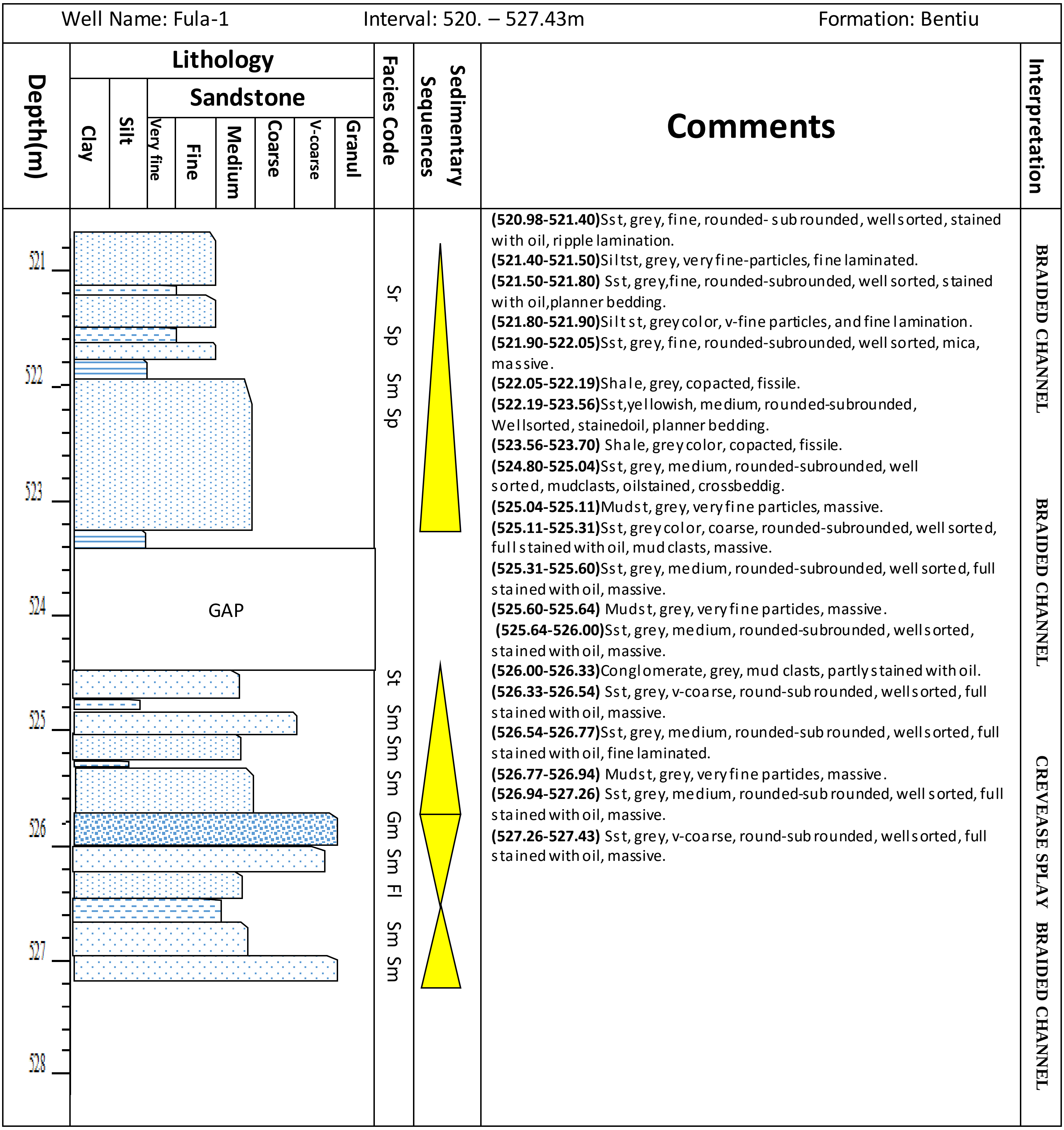
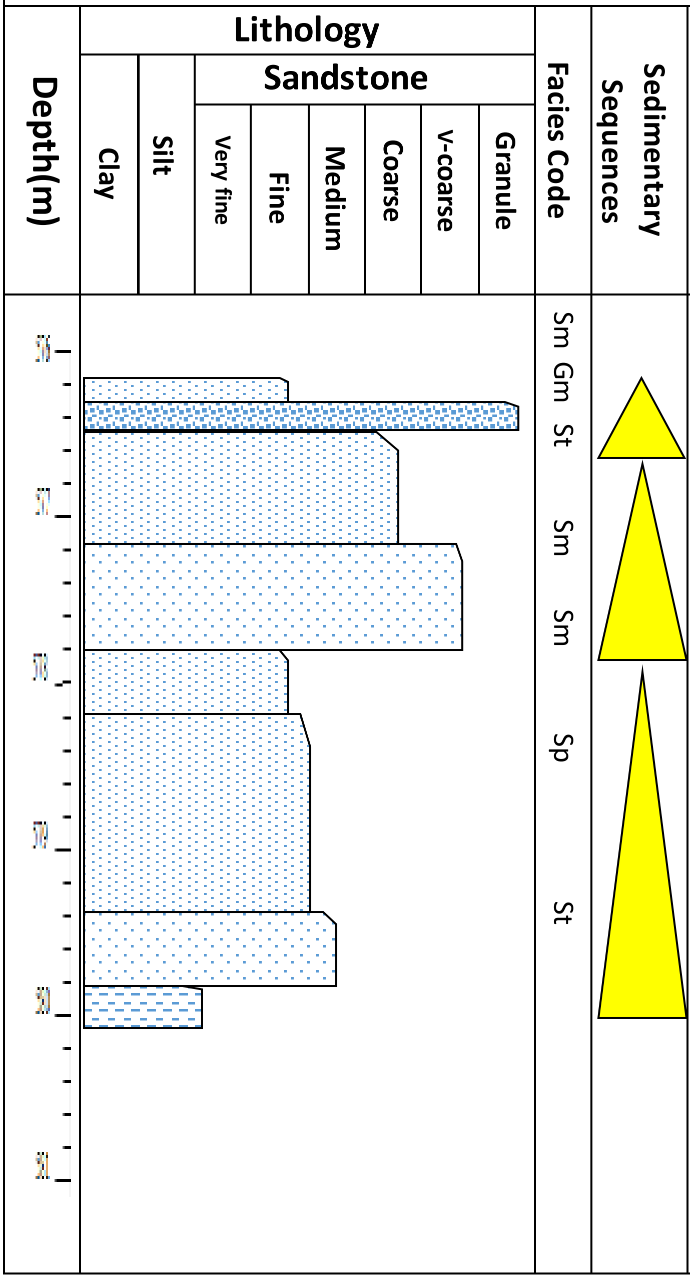


Fig (4.4): Fula-1 Core description.

Well Name: Fula-1 | Interval: 576 – 579.72m | Formation: Bentiu



Comments

(576.00-576.16) Sst, grey, mediume- grained, rounded-sub rounded, well sorted, stained with oil, mud clasts, massive.

(576.16-576.27) Conglomerate, grey, mud clasts.

(576.27-577.00) Sst, yellowish, coarse grained, rounded- subrounded, well sorted, and full stained with oil, cross bedding.

(577.00-577.62) Sst, grey, very coarse, grained, rounded-sub rounded, moderately sorted, some granules, massive.

(577.62-578.00) Sst, grey color, fine grained, rounded-sub rounded, well sorted, mica, massive.

(578.00 -579.20) Sst, grey, mediumgrained, rounded-subrounded, well sorted, stained with oil, planner bedding.

(579.20-579.66) Sst, grey, coarse grained, rounded-subrounded, well sorted, stained with oil, cross bedding.

(579.66-579.72) Mudst, grey, massive.

Interpretation

BRAIDED CHANNEL

BRAIDED CHANNEL

Fig (4.4): Cont-Fula-1 Core description.

General Sedimentological Characteristics:

The sedimentary succession retrieved in the cored intervals from Fula-1 well consists almost of continental derived siliclastic sediments. The succession composes of both fine-grained and coarse-grained lithofacies. Most of the studied units display fining upward sequences starting from coarse grained facies (sandstone beds) then pass to the medium-grained sandstone facies and ending with the fine-grained sediments (siltstone, mudstone or shale). The length of the Fining upward sequences ranges between 0.10m to 1.51m. However, at the top of core 1, stacked fining upward sequences occur, which are characterized by short length of fining upward sequences. Furthermore, the coarsening upward sequences are dominantly begun with fine laminated mudstone and end with mud conglomerate (cf., sedimentological core log summaries in (Fig.1).

Depositional Environment:

The composition and the internal arrangement of the lithofacies types distinguished in the studied core intervals from Fula-1 well, suggest deposition in a complex depositional paleoenvironment. This sedimentary succession includes dominantly fining upward sequences of fluvial system and small coarsening upward sequences of crevasse splay and/or levee deposits. The fining upward sequences, which start with coarse and medium-grained, cross-bedded to massive sandstone beds as well as fine-grained and ripple laminated sandstones facies association and alternate with finer-grained laminated siltstone and mudstone facies association are likely to represent a sequence of braided paleoenvironment. Whereas, the small coarsening upward sequences which, start with mudstone and/or shale beds and end with mud conglomerate facies are likely to indicate crevasse splay paleo-environment. However, according to this facies model, the conglomerate bed, the coarse to medium-grained, cross-bedded to massive sandstone facies can be interpreted as continental sediments that were emplaced under relatively high energy conditions, while the very fine laminated sandstone, siltstone and the fine laminated mudstone facies group is also belonging to continental deposits that were deposited under relatively low energy conditions.

Facies Code	Lithofacies	Total thickness(m)	Percentage%	Interpretation
St	Trough cross bedded sandstone.	0.97	1.65	Dunes (fluvial channel or small delta distributary channel).
SP	Planar cross-bedded sandstone.	2.53	4.30	Linguoids, transverse bars, sand waves (fluvial channel or small delta mouth bar).
Sm	Massive sandstone.	2.92	4.97	Rapid sedimentation (high-discharge event).
Sr	Ripples marked sandstone	0.42	0.71	Ripples (top fluvial bar or small delta mouth bar or floodplain or levee.
FI	Fine laminated sandy siltstone, siltstone and mudstone.	0.23	0.39	Overbank or waning flood deposits or small delta distal bar deposits.
Gm	Mud conglomerate	0.44	0.74	Scour fills, washout dunes, antidunes (fluvial channel or small delta distributary channel).

Table (4.4): Summary of facies description and interpretation of the conventional studied cores from Fula-1 well.

4.2.2.2 Fula-2:-

Trough Cross-bedded Sandstone:

This facies is present in the core samples reaching a total thickness of 0.58m (Table 4.5). The colour of this facies is grey. The grain- size is fine-grained. The grains are rounded to sub rounded in shape and are well sorted. The observed porosity is high. However, some siliceous, and some few pyrite cements have been observed. Kaolinite represents the dominant matrix material. Oil shows have also been observed. This facies could be classified as **"St"** type according to Miall (1978) and could be interpreted as the deposits of migrating 3-D dunes in fluvial channels or in small delta distributary channels.

Planar bedded Sandstone:

This facies is present in the core samples reaching a total thickness of 1.27m (Table 4.5). The colour of this facies is grey. The grain size is coarse grained. The grains are sub rounded to rounded in shape and are well sorted. The observed porosity is high|. This facies could be classified as **"Sp"** type according to Miall (1978) and could be interpreted as linguoids, transverse bars or sand waves deposited in a fluvial channel or a small delta mouth bar.

Fine laminated Sandstone:

This facies type has been observed in the core samples with total thickness of 1.64m (Table 4.2). The colour of this facies is light grey. The grain-size is fine. The grains are subrounded to rounded and moderately to well sorted. Traces of pyrite have observed. This sedimentary facies, which resembles the **"Fl"** facies type in Miall's (1978) classification, was formed by over bank deposits of braided river.

Massive Sandstone:

This facies type has been observed in the core samples with total thickness of 6.87m (Table 4.3). The colour of this facies is light grey. The grain-size ranges from medium to coarse, with dominant gradual fining upward trend. The grains are subrounded to rounded and moderately to well sorted. Some amount of imbedded mud clasts and oil shows are also have observed. Locally the massive-looking beds have faint bedding planes. This massive sedimentary facies, which resembles the **"Sm"** facies type in Miall's (1978) classification, was formed by very rapid sedimentation, probably by high-discharge events such as sheet-floods.

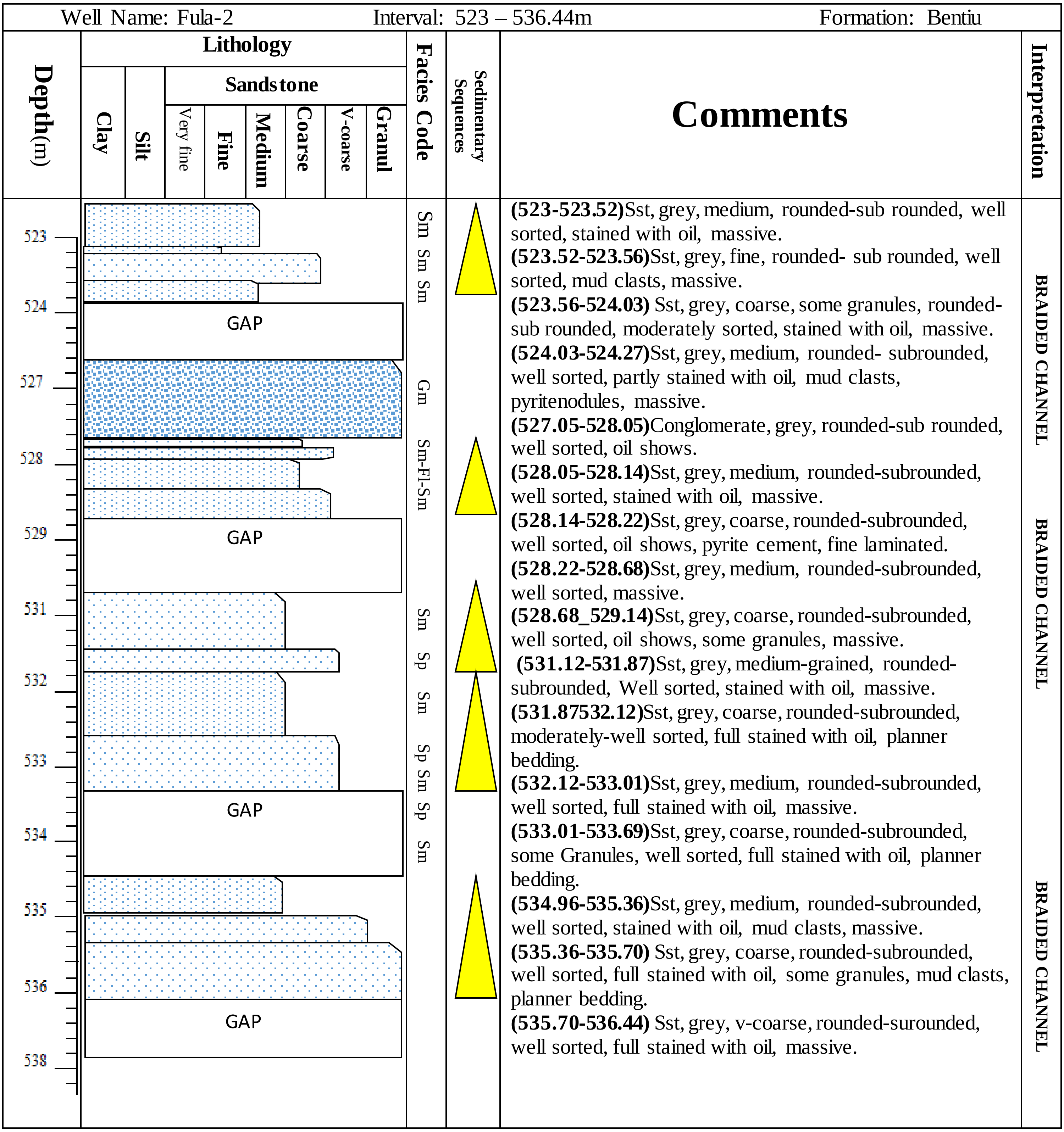


Fig (4.5): Fula-2 Core description.

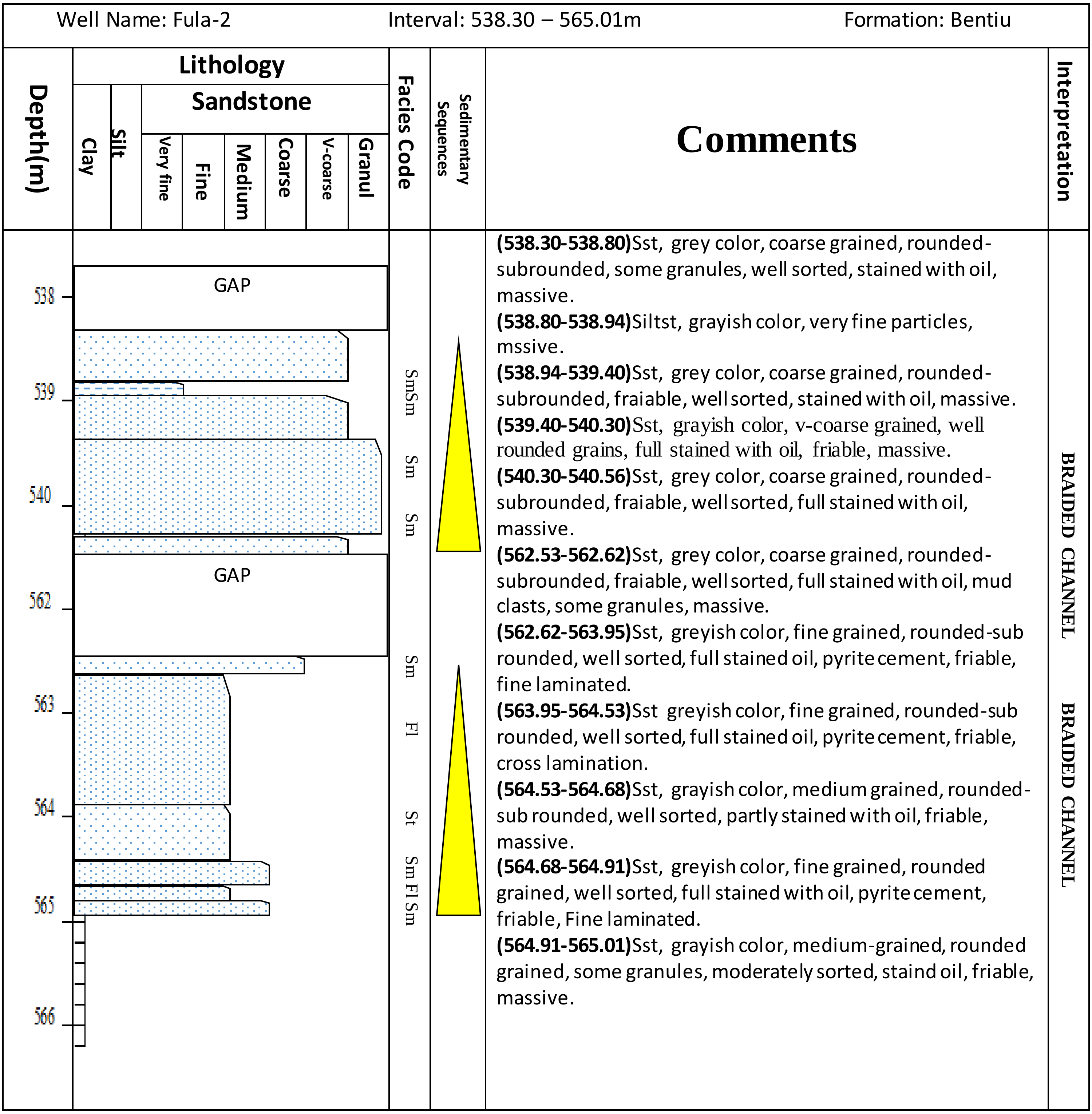


Fig (4.5): Cont-Fula-2 Core description.

Faies Code	Lithofacies	Total thickness(m)	Percentages (%)	Interpretation
St	Trough cross-bedded sandstone.	0.97	1.38	Dunes (fluvial channel or small delta distributary channel).
SP	Planar cross-bedded sandstone.	1.27	3.03	Linguoids, transverse bars, sand waves (fluvial channel or small delta mouth bar).
Sm	Massive sandstone.	6.87	16.35	Rapid sedimentation (high-discharge event).
Fl	Fine laminated sandy siltstone, siltstone and mudstone.	1.64	3.90	Overbank or waning flood deposits or small delta distal bar deposits.
Fcf/Fm	Fine laminated silt &mudstone.	0.14	0.33	Overbank or waning flood deposits or small delta distal bar deposits.
Gm	Mud conglomerate	0.44	0.74	Scour fills, washout dunes, antidunes (fluvial channel or small delta distributary channel).

Table (4.5): Summary of facies description and interpretation of the conventional studied cores from Fula-2 well.

Mud Conglomerate:

This facies is present in the core samples with a total thickness of 1.00m (Table 4.5). It is grey in color. The grain-size is very coarse grained. The grains are subrounded to round in shape embedded in silty mudstone matrix and are poorly to moderately sorted with few Kaolinitic matrix. Some oil shows is observed. This facies resembles the **"Gm"** facies type in Miall's (1978) facies classification. The deposition of this facies may have taken place in a fluvial channel or in the mouth bar of the crevasse splay.

Fine Laminated to Massive, Siltstone and Mudstone:

This facies is present in the core samples with a total thickness of 1.64m. (Table 4.5). The colour of this facies varies from light grey to dark grey in color. The sedimentary structure of this facies is fine laminated. Furthermore, the above facies is classified as **"FI"** according to Miall (1978). It can be interpreted as overbank or waning flood deposits or crevasse splay distal bar deposits.

General Sedimentological Characteristics:

The sedimentary succession retrieved in the cored intervals from Fula-2 well consists almost of continental derived siliclastic sediments. The succession composes of both fine-grained and coarse-grained lithofacies. Most of the studied units display fining upward sequences starting from coarse grained facies (sandstone beds) then pass to the medium-grained sandstone facies and ending with the fine-grained sediments (Sandstone & Siltstone).The length of the fining upward sequences ranges between 0.10m to 1.51m. However, at the top of core, stacked fining upward sequences occur, which are characterized by short length of fining upward sequences. Furthermore, the coarsening upward sequences are dominantly begun with fine laminated mudstone and end with mud conglomerate.

Depositional Environment:

The composition and the internal arrangement of the lithofacies types distinguished in the studied core intervals from Fula-2 well, suggest deposition in a complex depositional paleoenvironment. This sedimentary succession includes dominantly fining upward sequences of fluvial system and small coarsening upward sequences of crevasse splay and/or levee deposits. The fining upward sequences, which start with coarse and medium-grained, cross-bedded to massive sandstone beds as well as fine-grained and ripple laminated sandstones facies association and alternate with finer-grained laminated siltstone and mudstone facies association are likely to represent a sequence of braided paleoenvironment. Whereas, the small coarsening upward sequences which, start with mudstone and/or shale beds and end with mud conglomerate facies are likely to indicate crevasse splay paleo-environment. However, according to this facies model, the conglomerate bed, the coarse to medium grained, cross-bedded to massive sandstone facies can be interpreted as continental sediments that were emplaced under relatively high energy conditions, while the very fine laminated sandstone, siltstone and the fine laminated mudstone facies group is also belonging to continental deposits that were deposited under relatively low energy conditions.

4.3 Sandstone Petrography

4.3.1 Introduction:

This chapter is concerned with the study of the thin sections. There are some types of techniques that have been applied to study the thin sections from Bentiu formation, which is to recognize the different constituents of reservoir rocks and its classification, textural maturity, and impact of diagensis.

Thin section analysis has been carried out on 4 core samples from Fula-1, from different existing sandstone facies types. The samples were selected after the core description and the lithofacies analysis.

The prepared thin sections were studied using a polarized microscope with different colour, form, relief, extinction angle, paleochroism, twining and birefringence. Counting was conducted using a point counter machine in order to account the minerals percentages in each slide.

4.3.2 Mineralogical Description

The composition of the sandstone depends mainly on the nature of the source rocks and on the weathering processes. The minerals and components which are recognized in the thin sections include: **Detrital components** and **authigenic components**. Here we're going to discuss any component of these and their presence in the sandstone samples.

4.3.2.1 Detrital Mineralogy:

- **Quartz:** The most common mineral in the studied sandstones is quartz. It appears in thin sections as relatively clear colourless grains having weak birefringence and low refractive index that is only slightly higher than that of the mounting medium (Kerr, 1977; Adams et al., 1995). Both of the two quartz types, which are the polycrystalline quartz (QP) and the monocrystalline quartz (QM), were observed. Some of the polycrystalline and monocrystalline quartz crystals exhibit undulose extinction. Moreover, some of the composite quartz grains (polycrystalline quartz grains) are granular grains and within some of them, the crystals boundaries are point, concavo-convex, elongated and sutured. Many of the quartz grains incorporate mineral inclusions such as rutile, zircon, iron oxides and tourmaline. Fractured quartz grains are also common.

- **Feldspars:** Like quartz, feldspars in thin section are typically clear, colourless and having low birefringence, but they can be distinguished from quartz by their cleavage, twining and refractive indices. Nevertheless, distinguishing between untwined orthoclase and quartz can be difficult but in a stained slide with a sodium cobalt nitrate solution, it is easily distinguished. However, feldspar grains may sometimes be partly decomposed, and then they appear cloudy or turbid in contrast to quartz grains, which are invariable unaltered and relatively clear (Adams et al., 1995).
- **Micas:** Biotite (Bi) and muscovite (Mu) were identified by their platy shape and parallel extinction. Biotite has a brown to green pleochroism, which masks the interference colours whereas, muscovite is colourless in the plane-polarized light, but has bright second-order colours under crossed polars (Kerr, 1977). They were observed with different concentrations in most of the investigated samples.
- **Lithics:** Rock fragments form a subordinate detrital component in some samples, where relative abundances between trace quantities and 2% in Fula-1. Rock fragment are dominated by mudstones, while granite and chert clasts occur in minor abundances.
- **Detrital clays:** Detrital clays have been recorded in most of the studied samples, where their relative abundances about 14.2% in Fula-1. However, the thin section and the SEM analyses suggest that the vast majority of the interstitial clays are authigenic in origin particularly the kaolinite.

4.3.2.2 Authigenic Components/ Cements

- **Carbonates:** Calcite (Ca) and siderite (Sid) were observed as patchy cements in some of the examined samples, where the concentration of the calcite and siderite reaches 2.8% and 3% respectively, which is from Fula-1. Both siderite and calcite can be identified by their perfect rhombohedral cleavage and a pearl grey or white of higher orders interference colour. Calcite is colourless, but it is often cloudy, usually anhedral whereas, siderite resembles calcite but may often be distinguished by the brown stain around the borders of the grains and along cleavage cracks, Kerr (1977).
- **Quartz overgrowths:** Well developed syntaxial quartz overgrowths are recorded in most of the analyzed samples with lesser amounts ranging between

trace values and 2% from Fula-1. Thin section and SEM observations revealed the presence of well-developed euhedral, smooth-faced, pyramidal quartz overgrowths, which commonly enclose kaolinite plates.

- **Iron oxides cement:** Iron oxides are not widely spread in the examined samples and they were recorded as a cementing material.
- **Pyrite:** Authigenic pyrite as cementing and replacive agent has been noticed in few samples and where it occurs with a very minor amount reaching.

4.3.3 General Textural Characteristics:

Grain Roundness: The grain roundness in all of the studied samples is less variable as sub-rounded grains are relatively common in almost all of the samples.
Sorting: In thin section, the analyzed samples show all variations from poorly to well sorted.

Compaction: The majority of the studied sandstone samples are poorly to moderately compacted and display point, concavo-convex and long grain contacts, while sutured grain contacts, which reflect a higher degree of compaction are relatively minor.

Porosity: the analyzed samples from Fula-1 shows counted porosity values range between 2.00% to 22.6%.

Classifications of the studied Sandstone:

This classification is based on the scheme of Dott (1946) which depends on Quartz: Feldspar: Lithic ratios (QFL) on the sandstone.

The analyzed samples from Fula-1 Well are displayed in QFL sandstone composition diagram. The studied samples are relatively rich in quartz and feldspars, while the lithics are generally of very minor abundances. However, the significant quantities of the kaolinite were also considered in the classification of these sandstone samples. In summary, Fula-1, the 4 sandstone samples from the different lithofacies types can be classified as kaolinitic Sub-feldspathic Arenite and Kaolinitic Feldspathic Arenite.

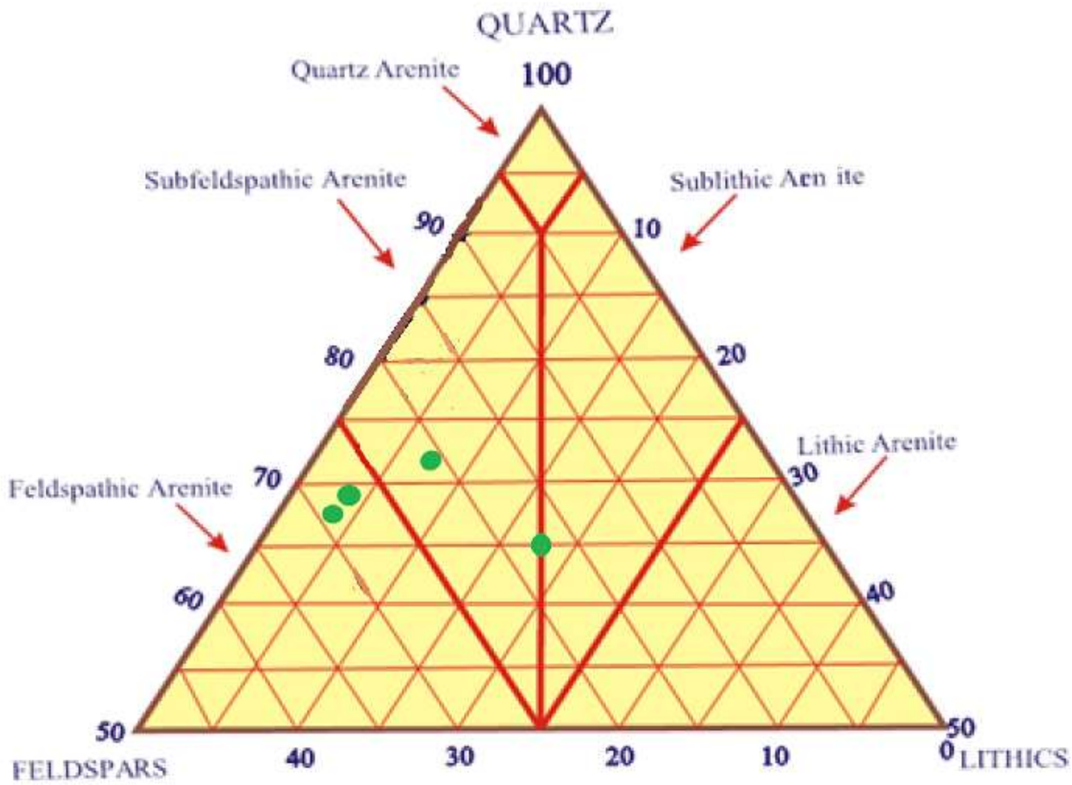


Fig (4.6): Sandstone Classification plot of the studied samples, (after Dott, 1964). Samples from Fula-1 represented as (Green spots).

Plate 1.1: WELL: Fula-1 Depth: 579.4m Facies Type: St

ROCK TYPE: Sub-feldspathic Arenite medium grained (average mU), moderately to well sorted, patchy cemented and moderately to week compacted with point, long, and concavo-convex grain contacts.

DETRITAL GRAINS: Common polycrystalline quartz with also common amount of monocrystalline quartz (Photo A & B: B-I 1-4, A-D 10-15) and abundant quantities of K-feldspar mainly microcline (Photo A & B: C-I 7-11), minor plagioclase feldspar (Photo A & B: E-H 5-6), some lithic fragment and minor grains of heavy minerals are incused inside the quartz grains (Photo A & B: C 14).

DETRITAL CLAYS: Some patchy pore filling detrital clays (Photo A and B: D-E 12-13).

AUTHIGENIC MINERALS: Some patchy pore filling with considerable amount of smectite, minor of authigenic kaolinite (sharp peak in XRD chart). Few illite and chlorite (from the XRD result) and quartz overgrowths (Photo A and B: A-D 10-15).

PORE NETWORK: Primary interparticle pores (PBP, Photo A: impregnated with blue dyed resin), secondary intraparticle porosity (SWP) mainly through the partial dissolution of K-feldspars and secondary interparticle porosity (SBP), with good pore interconnectivity.

PORE COUNTED POROSITY: 20.60%.

RESERVOIR QUALITY: Good.

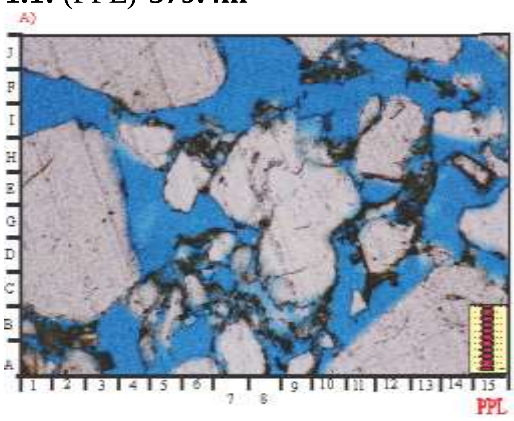
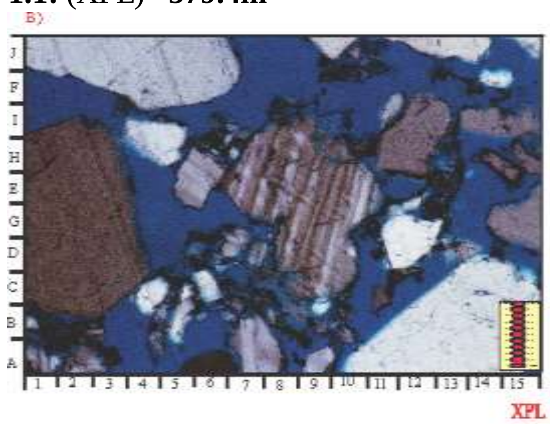
1.1: (PPL)-**579.4m**	**1.1:** (XPL)- **579.4m**
	

Plate1.2: WELL: Fula-1 Depth: 576.50m Facies Type: St

ROCK TYPE: Feldspathic Arenite, fine to medium grained (average fL-mL), moderately to well sorted, patchy cemented and moderately compacted with point, long, concavo-convex and float grain contacts.

DETRITAL GRAINS: Common monocrystalline quartz (Photo B: G-F, 1-4 & E-J 12-15), with lesser amount of polycrystalline quartz, abundant K-feldspar mainly microcline (Photo B: B-J 4-13), as well as some plagioclase, some lithic fragment and minor heavy minerals occurring as inclusions inside the quartz grains.

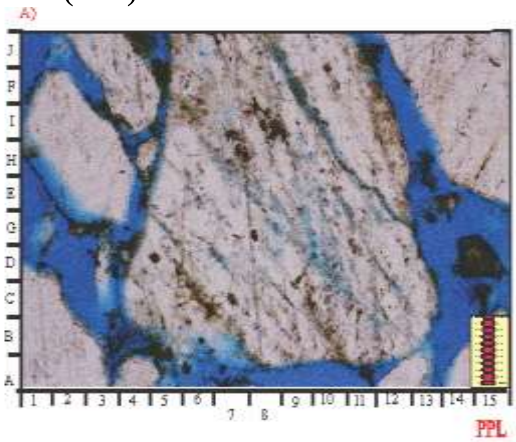
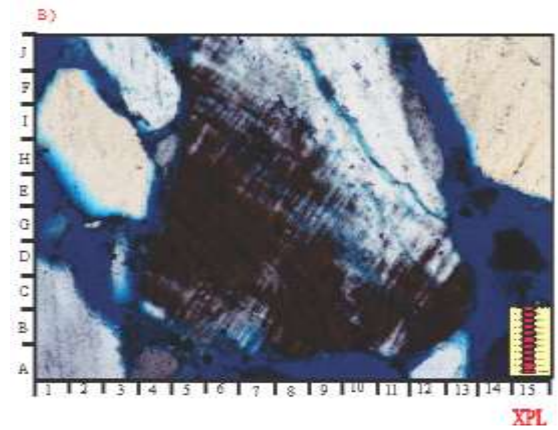
DETRITAL CLAYS: Many amounts of detrital clays occur inside the pores.

AUTHIGENIC CEMENTS: Some patches of quartz overgrowths (euhedral crystal termination around detrital quartz grains, Photo A & B: A-D 1-3) and minor iron oxides.

PORE NETWORK: Common primary interparticle pores (PBP, Photo A: impregnated with blue dyed resin), amount of secondary inter- and intraparticle pores (SWP) and (SBP) mainly through the partial dissolution of K-feldspars. Pore interconnectivity is fair to good.

PORE COUNTED POROSITY: 14.4%.

RESERVOIR QUALITY: Fair to good.

1.2: (PPL)-**576.50m**	**1.2:** (XPL)-**576.50m**
	

<u>Plate 1.3;</u> WELL: Fula-1 Depth: 527.40m Facies Type: Sm

ROCK TYPE: Sub-feldspathic Arenite, fine to medium grained (average fL-mL), moderately to well sorted, patchy cemented and moderately compacted with point, long and concavo-convex grain contacts.

DETRITAL GRAINS: Considerable quantities monocrystalline quartz (Photo A & B: I-F 4-6 & D-E 13-15) with lesser amount of polycrystalline quartz (Photo B: J 12-14 & G-H 8-9) as well as some quantities of K-feldspar (Photo A & B: E-I 12-14), subordinate quantities of plagioclase, mica flaks mainly muscovite (Photo A & B: B-G 4-6), lithic fragment as well as minor traces of heavy minerals enclosed inside the quartz grains.

DETRITAL CLAYS: some of detrital clays occupying more pore spaces (Photo A & B: A-C 9-12).**AUTHIGENIC CEMENTS:** Some patches of quartz overgrowths (euhedral crystal termination around detrital quartz grains) and few iron oxides.

PORE NETWORK: Primary interparticle pores (PBP, Photo A: impregnated with blue dyed resin), secondary intraparticle porosity (SWP) mainly through the partial dissolution of K-feldspars and secondary interparticle porosity (SBP), with good pore interconnectivity.

PORE COUNTED POROSITY: 21.6%.

RESERVOIR QUALITY: Good.

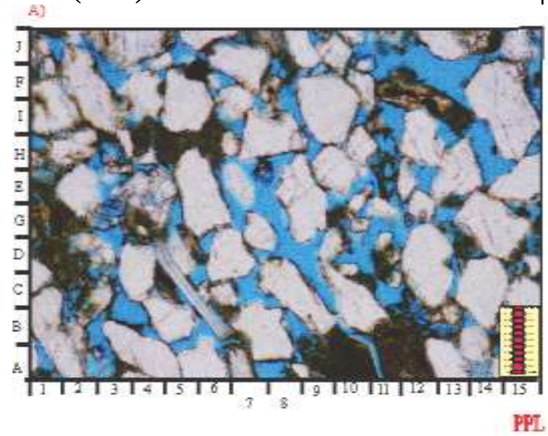
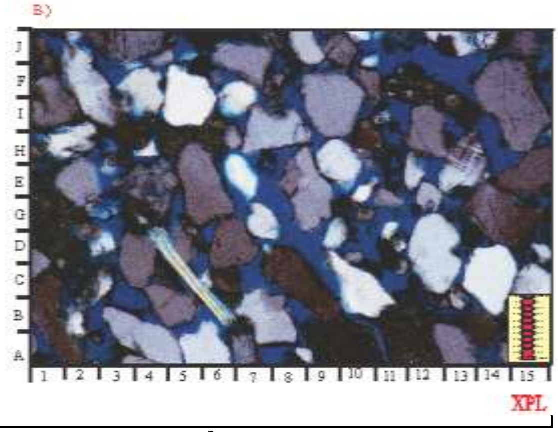
1.3: (PPL)- 527.40m	1.3: (XPL)- 527.40m
	

Plate 1.4: Well: Fula-1 Depth: 521.00m Facies Type: Fl

ROCK TYPE: Sub-feldspathic Arenite, fine grained (average fL-fU), well sorted, patchy cemented and weakly compacted with point, long and concavo-convex grain contacts.

DETRITAL GRAINS: Common monocrystalline quartz (Photo A & B: E- I 7-8 & G-E 9-10). With some amount of polycrystalline quartz (Photo B: H-I 3-5), considerable quantities of K-feldspars, less amount of plagioclase (Photo A & B: B 5-6), some micas (muscovite and biotite photo A & B: I 9-13 & E-H 9-11) which arranged due to the hydraulic faction of the mica flakes). Inclusions of heavy minerals inside the quartz grains.

DETRITAL CLAYS: Some of detrital clays occupying more pore spaces.

AUTHIGENIC CEMENTS: Patches of siderite (Photo A & B: B 9-10 & A 3) and less amount of carbonaceous depress occur as pore filling.

PORE NETWORK: Commonprimary interparticle pores (PBP, Photo A: impregnated with blue dyed resin), amount of secondary inter, and secondary intraparticle pores (SWP) and (SBP) mainly through the partial dissolution of K-feldspars, with fair to good pore interconnectivity.

PORE COUNTED POROSITY: 14%.

RESERVOIR QUALITY: Fair to good.

(1.4): (PPL)- 521.00m

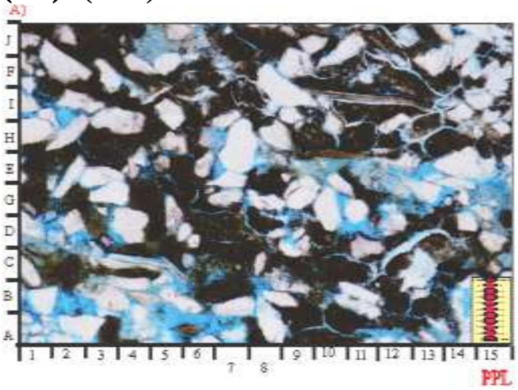
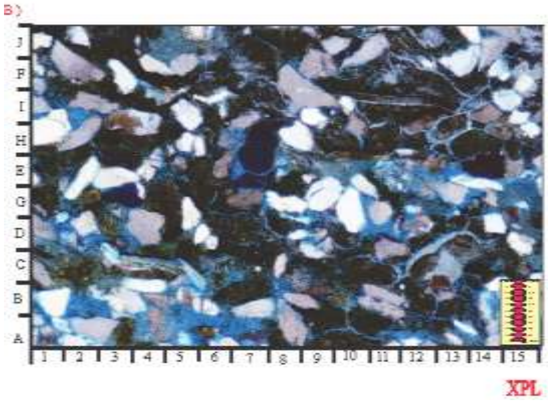


Plate (1.4): (XPL)- 521.00m



	Textural Data				Detrital Mineralogy							Authigenic Mineralogy					Porosity		
Depth(m)	Grain sorting	Grain contact	Grain roundness	Pore connectivity	Poly QTZ%	Mono QTZ%	Lithic fragments%	K-feldspar%	Plagioclase%	Micas%	Clay matrix%	Calcite cement%	Siderite cement%	QTZ over growth%	Pyrite cement%	Iron oxide cement%	Primary porosity%	Secondary porosity%	Rock name
579.4	MS -WS	PLC	SR-SA	Good	21.6	20.8	2.00	12.4	2.00	0.00	8.00	0.00	0.00	2.00	0.00	0.00	18.6	2.00	Sub-Feldspathic Arenite
576.5	MS-WS	PLCF	SR-SA	Fair	19.6	28.0	1.00	13.6	5.20	0.00	13.4	0.00	0.00	2.00	0.00	2.00	10.0	4.40	Feldspathic Arenite
527.4	MS-WS	PLC	SR	Good	18.2	32.0	1.00	5.40	5.20	0.80	12.8	0.00	0.00	2.00	0.00	1.00	13.4	8.20	Sub-Feldspathic Arenite
521.0	WS	PLC	SR-SA	Fair-Good	6.8	35.6	2.00	10.4	1.20	9.20	13.0	2.00	2.80	0.00	0.00	0.00	8.00	6.00	Sub-Feldspathic Arenite

Table (4.6): Petrographic Data for the Studied Samples From Fula-1 Well.

4.4 Clay mineralogy

The study of the clay minerals has involved two analytical techniques, X-ray diffraction and Scanning Electron Microscopy (SEM). Two clay rich samples from the studied intervals from the well mentioned above have been analysed with the XRD technique. In addition two mudstone, siltstone and sandstone core samples from the studied cores have been examined by the SEM. Five clay mineral species were identified from the size fraction less than 2 micron using the procedures of Chamley (1989) as well as Moore and Reynolds (1997). A Quantitative estimation of the clay mineral constituents were computed mainly from the ethylene-glycol solvated XRD patterns as suggested by Schwertmann et al. (1993). The results obtained are shown in Table (4.3), for Fula-1 well. In addition the XRD graphical charts are shown in plate (7.4) from Fula-1 well in order to give a general impression about the degree of crystallinity for these clay minerals. Furthermore, seven SEM micrographs are shown in plates, in order to clarify the diagenetic effects of the clay minerals on the reservoir quality.

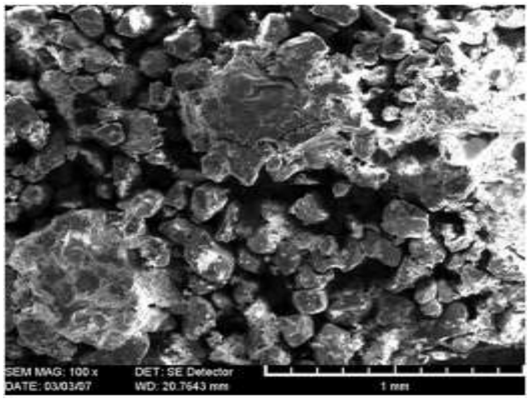
Depth(m)	**Clay Minerals %**				
	Kaolinite	**Smectite**	**Illite**	**Chlorite**	**Illite/ Smectite**
526.50	15.70	74.90	0.00	2.36	0.00
579.40	90.90	0.00	0.00	4.12	4.92

Table (4.7): Showing the percentages of the clay minerals in the analyzed samples From Fula-1 well.

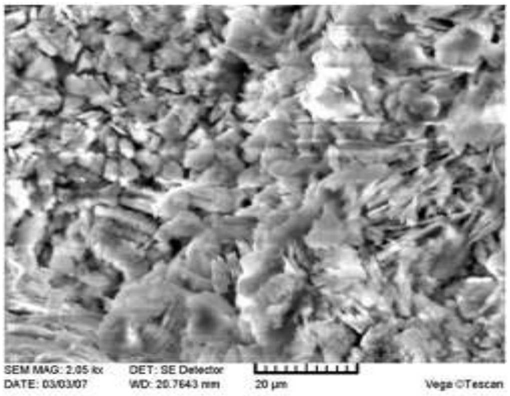
<u>**PLATE 2.1:**</u> Well: Fula-1 Depth: 526.50m Photo Type: SEM

Mudstone dominantly consolidated and blocky. The holes that appear in the micrograph photo -A comes as a result of the breaking of the sample. Much scatter of pseudohexogonal basal plates of kaolinite were leached (Photo B: A-D 3-7 & D-H 12-15). Some scattered cluster of disc-like shape of chlorite (Photo B: H-I 3-4).

(2):**SEM Photomicrograph**
526.50m



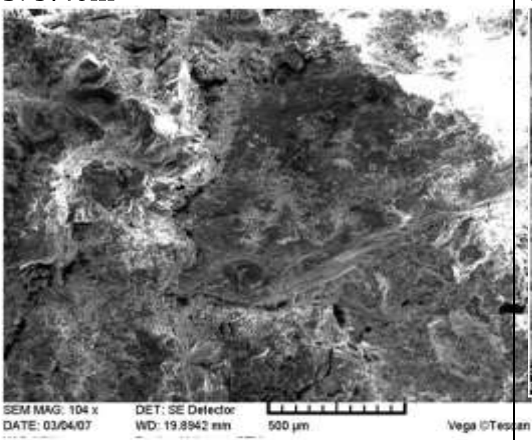
(2):**SEM Photomicrograph**
526.50m



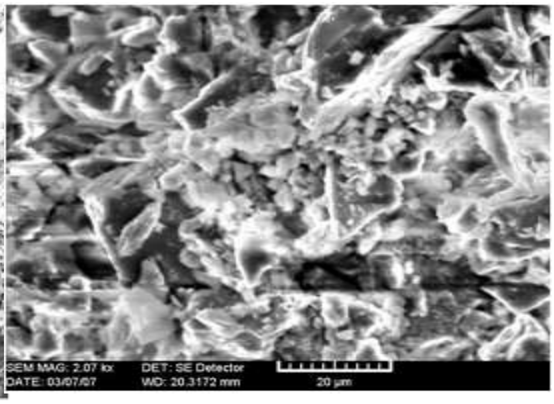
<u>PLATE 2.2:</u> Well: Fula-1 Depth: 579.40m Photo Type: SEM

Sub-feldspathic arenite, moderately to well sorted, medium grained, moderately cemented and blocky with relatively open grain packing and good degree of primary intergranular porosity (Photo A: F 6/7 & E 5-7). Authigenic kaolinite formation from K-feldspar (Photo B: I-F 2-4 & G-E 9-11). Detrital kaolinite (Photo B: H-F 6-8).

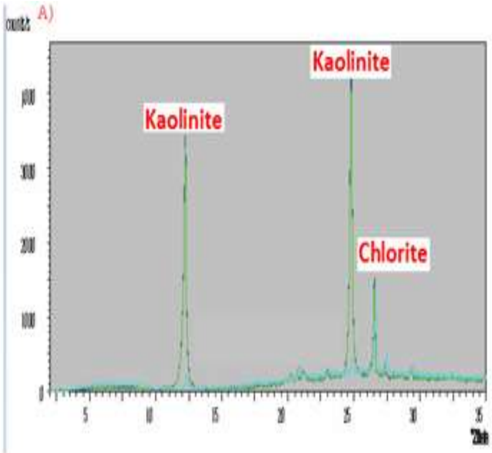
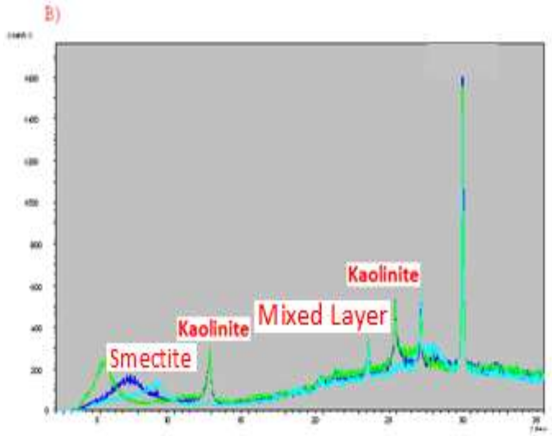
(4):**SEM Photomicrograph**
579.40m



(4):**SEM Photomicrograph**
579.40m



<u>PLATE 2.1 & PLATE 2.2</u>: XRD Graphical chart giving a general impression about the degree of crystallinity of the clay minerals in the studied depths from Fula-1 Well.

<table>
<tr>
<td>(1):XRD Graphical chart
526.50m

</td>
<td>(2):XRD Graphical chart
579.40m

</td>
</tr>
</table>

Chapter Five:-

Conclusions & Recommendations

5.1 Conclusions:

- **Porosity** have been calculated from well logs and laboratory analysis at the same depth intervals, we observe that the porosity values was approximately indicates to similar results.

Depths(m)	Total porosity %	V-clay %
521.0	15.6	19.99
527.4	24	19.76
576.5	14.26	29.48
579.4	19.52	28.91

Table (5.1): showing the log readings from Fula-1.

Depths(m)	Primary porosity%	Secondary porosity%	Total porosity %
521.0	8.00	6.00	14
527.4	13.4	8.20	21.6
576.5	10.0	4.40	14.4
579.4	18.6	2.00	20.6

Table (5-2): Petrographic Data for the Studied Samples from Fula-1.

Depths(m)	Total porosity %	V clay %
412.0	21.3	17
436	25	22.4
454	20.6	15.1
480	18	25.6

Table (5.3): showing the log readings from Fula-2.

- **Depositional environment** observed from gamma ray log of the two wells gives the pattern of bell shape with long neck, which means the fluvial system is braided channel. And the pattern is bell shape with long neck, which means the fluvial system is braided channel. Depositional environments distinguished in the studied core intervals from Fula-1and Fula-2 wells, suggest deposition in a complex depositional paleo environment. This sedimentary succession includes dominantly fining upward sequences of fluvial system and small coarsening upward sequences of crevasse splay and/or levee deposits.

- ## Diagenetic Processes:

The detailed petrographical analysis of samples from Fula-1 well showed that the sedimentary succession was affected by several types of diagenetic processes (Physical, Chemical & Biological processes); these diagenetic processes have a positive and negative impact to the reservoir quality in term of porosity and permeability.

Some of these Factors and processes reduced the porosity and some of them increased the porosity as listed below:

The main processes, which have decreased porosity include:

a) Kaolinite Precipitation.

b) Compaction and Quartz Overgrowths.

c) Presence of Detrital Clays.

d) Carbonate Cementation (Calcite and Siderite).

e) Pyrite Precipitation.

The main processes, which have increased porosity include:

f) Dissolution of Feldspars and Micas.

g) Partial Dissolution of Carbonate Cements and Clays.

5.2 Recommendations:

As a result of integrating and correlating the previous analysis, this study gives a good description of potential reservoirs in Bentiu formation, block-6, Muglad rift basin. The study found from fula-2 well core samples, that the formation in this block is very friable (no or lack of cementing material), which is the main reason behind the problem of sand production from this field that could be solved by other studies in the future.

References

Adams, A. E., Mackenzie, W. S. and Guilford, C. (1995) "*Atlas of sedimentary rocks under the microscope*". 104 p., Longman, Harlow.

Cant, D. J. (1984) "Subsurface *facies analysis". In Facies Models* (Ed. by R. G. Walker).Geoscience, pp. 299-308, Canada.

Chamley, H. (1989) "Clay *sedimentology* ".Springer-Verlag, 623 p., Berlin, Heidelberg.

DOTT JR, R. H. (1964) *"Wacke, Graywacke and Matrix--What Approach to Immature Sandstone Classification*?**".** Journal of Sedimentary Research, 34.

El El Badi, S. (1995) "Sudanese *ribes*". M.Ar. Thesis, University of Khartoum, 121 p., Khartoum, Sudan.

El Shafie, A. A. (1975) "Lithology *of the Umm Rawaba Formation and its paleageography in connection with water problems, Sudan*". Ph.D. Thesis, 130 p., geological Exploration Institute, Moscow.

Fairhead, J. D. (1988)" *Mesozoic plate tectonic reconstruction of the central South Atlantic Ocean: The role of the west and central African rift system*". Tectonophysics, **155**, pp. 181-195.

Miall, A. D. (1978)" *Lithofacies types and vertical profile models in braided river deposits: a summery"*. In: Fluvial sedimentology (Ed. by Miall, A. D.). Memoir, **5**, pp. 597-604, Ottawa.

Mohammed, A.Y., Pearson, M.J., Ashcroft, W.A., Illiffe, J.E., Whiteman, A.J. (1999).

"Modeling petroleum generation in the Southern Muglad rift basin, Sudan". Am.

Assoc. Pet. Geol. Bull. 83, 1943e1964.

Moore, D. M. and Reynolds, R. C. (1997) "X-*ray diffraction and the identification and analysis of clay minerals (second edition*)". Oxford University Press, Inc., 371 p., Oxford.

Schwertmann, U. and Niederbudde, E. (1993) " *Tonminerale in Böden*". In: Tonminerale und Tone (Ed. by Lagaly, G.). 490 p., Steinkopff Verlag, Darmstadt.