Journal of Science and Technology vol. 13
ISSN 1605 – 427X
Engineering and Computer Sciences (E C S No. 1)
www.sustech.edu

June 2012

Sequence Stratigraphy and Sedimentary Facies of Fula Subbasin, Muglad Basin (Sudan)

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Abstract: Sedimentary analysis and Facies Associations may enhance accuracy of sequence stratigraphic correlation of Fula Subbasin, Muglad Basin, Sudan. According to core (very 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. The origin of Fula Subbasin is related to the first rifting cycle (+ synrifting cycle?) that took place during the Early Cretaceous associated with an increase in tectonic activity and the opening of the Central African rift system (Late Jurassic- Middle Miocene). Synsedimentary tectonic activity and succeeding restructural regime of the subbasin were clearly reflected in the sedimentary records. Two sets of faulting in Fula oil field were detected. The first set was striking NW-SE, as in five zones the Fula 1 fault, Fula 2 fault, Fula 3 fault, eastern fault of well Fula 1 and the western fault of well Fula North 2, which dominate the evolution and sediments of the Fula structure. The second set was striking EW, as the north fault of well Fula 1, which controls the evolution of the trap. Three seismic horizons, i.e. the top of Aradeiba, the top of Bentiu and the top of Abu Gabra formations were chosen for interpretation according to their geological significance. Infill of that Early Cretaceous subbasin began with continental deposits that were alluvial and lacustrine in origin.

***Keywords**: Fula subbasin- Muglad Basin- Sudan, Sequence Stratigraphy, Sedimentary Facies,*

مستخلص:

التحليل الرسوبي والعلاقات السحنية يمكن ان تحسن تدقيق مضاهاة التتابع الطبقي لتحت حوض الفولة بحوض المجلد, السودان. تم عمل المضاهاة الطبقية بناءً علي بيانات سجلات الجس وبيانات اللباب (قليلة جداً). تم تقسيم تكوين أبوجابرة وتكوين بانتيو وتكوين عرديبة الي وحدات. تم تنظيم الانظمة الترسيبية الاساسية في منطقة الدراسة علي اساس تقدم السحن الرسوبية. أصل تحت- حوض الفولة ينتسب الي الدورة الاخدودية الاولي (+ اثناء الدورة الاخدودية؟) والتي اخذت مكانها اثناء العصر الطباشيري الباكر مرتبطاً بزيادة في النشاطات التكتونية وفتح لنظام اخدود افريقيا المركزي (الجوري الباكر- المايوسيني الاوسط). النشاطات التكتونية الاثناء-ترسيبية والبرنامج التركيبى تحت الحوضي اللاحق انعكست جلياً في السجل الترسيبي. تم التعرف علي طقمين من الفوالق في منطقة الفولة. يضرب الطقم الاول في اتجاه شمال غرب- جنوب شرق, كما في خمس مناطق في فالق الفوله1, فالق الفوله2 , فالق الفوله3 , الفالق الشرقي لبئر الفوله1 والفالق الشرقي لبئر الفوله شمال2 , والتي تسود تطور وترسيب تركيب الفوله. يضرب الطقم الثاني في اتجاه شرق غرب, كما في الشمالي لبئر الفوله1 , الذي يسيطر علي نمو المصيده. تم اختيار ثلاث مناطق زلزالية وهي اعلي تكوين عرديبه, اعلي تكوين بانتيو واعلي تكوين ابوجابره وذلك لتفسيرها طبقاً لخصائصها الجيولوجية. ابتدأت حشوة تحت الحوض الكريتاسي المبكر برسوبيات قارية ذات الاصل الغريني والبحيري.

Introduction:

Muglad basin is the largest of the NW-SE oriented rift basins in the Sudan comparing to the smaller ones Melut, White Nile, and Blue Nile rift basins which are parallel to Muglad trend. Muglad basin extends from Western and Southern Kordofan in the southern-central of Sudan to the southern part of Sudan, covering an area of ~ 160,000 sq. km (800 km in length and 200 km in width). Fula sub-basin is situated in the NNE part of Muglad basin covers an area of 100 sq. km Figure 1. It trends northwest- southeast in the same general trend of Muglad basin. The surface elevation of the area is moderately medium to low varies from 480 to 580 m. Nonmarine Cretaceous sequences underlie surficial Cenozoic deposits and overlie basement rocks.

The research intention was to come out with detailed sedimentology and facies sequence stratigraphic framework for Fula Subbasin, characterize the depositional system of the study area, and to figure out the time span for the basin fill with regard to the opening of the Central African Rift System (CARS).

Geological Context:

Mugald basin represents one of the major rifting systems in the world, sequentially, a main component of West and Central African Rift System (WCARS) Figure 2.

Some previous studies considered Muglad Basin as shallow intracratonic sag filled with Tertiary and Cretaceous sediments but detailed studies by Schull [1] suggested that it is intercontinental rift system. McHargue et. al, [2] and Craig Mann, [3] suggested half-graben. This study deals with it as intercontinental rift basin. The onset of intercontinental rifting within West and Central Africa was synchronous with gradual breakup of Gondwana, particularly, with separation of South America from Africa [4]. Precambrian to Cambrian basement crops out at the surface above 100m to the northeast of the field in Nuba Mountains between Muglad basin and White Nile basin. Shallow basement is lower than 1km in depth. It extends into parts of the study area

Materials and Methods:

Data set from Fula wells including 3D seismic data, wireline and master logging data, sidewall core data, and conventional core analysis data (from wells fula-1 and Fula-North-2) were used to gain optimum results for the suggested objectives in this study.

Tectonic and Structural Setting:

The deep Cretaceous-Tertiary basins of southern Sudan associated with regionally linked intercontinental rifting system that crosses Central Africa. Benue Trough was suggested to be as sinisterly wrench-fault zone made up of series en echelon basins in filled with marine Cretaceous sediments of Albian and younger age. [5, 6, 7, 8] Maurin et. al .[6] acknowledged the Cretaceous strike-slip faulting for fracture zones within two basement inliers those located in the middle- upper Benue Trough.

Further to the northeast the Benue Trough becomes the Gondola Rift which extends to Lake Chad (Figure. 2). In this zone and to the north-northwest of Lake Chad in eastern Niger the Cretaceous rift system is blanketed by thick Cainozoic sediments cover [9,10]. The Central African shear zone extends for at least 2000 km across Africa from the Atlantic coast in the Gulf of Guinea through Cameroon, Chad, and the Central African Republic then into Sudan. Farther to the east-northeast, the shear zone is covered by Cretaceous-Recent deposits. The shear zone has an origin similar to the Benue shear zone [7]. The dextral shear movement was documented by Ngangom, [11] in Cameroon and by Cornacchia and Dars, [12] in the northern Central African Republic. These basins were structurally developing during Early Cretaceous times [7]. The idea that can be supported by the continuation of Lower

Cretaceous sediments within the basins. In Western Sudan the Central African shear zone transforms most of its dextral displacement into the southern Sudan Rift [13, 14]; a major extensional basin extends in a southeastern direction through southern Sudan into northern Kenya [15]. Hussein [16], Fairhead [7], Browne and Fairhead, [13] assumed that the southern Sudan Rift was opened by extensional tectonics. It was indicated that [2,,17,18] this rift developed in three rifting phases in Early Cretaceous, Late Cretaceous and Early-middle Tertiary times.

Faulting Pattern in Fula:

There are two sets of faulting in Fula area. The first set striking NW, as in five zones the Fula 1 fault, Fula 2 fault, Fula 3 fault, eastern fault of well Fula 1 and the western fault of well Fula North 2, which dominate the evolution and sedimentary of the Fula Structural Play. The second set striking EW, as the north fault of well Fula 1, which controls the evolution of the trap Figure 3.

The Fula 1 fault is located in the middle of the study area. It is striking NW direction and dipping SW direction and extending 14 km in the area. It dominates the Fula Structural Play. It developed from the crystalline basements to Quaternary. The vertical displacement is 70- 870m.

Western Fault of Well Fula North-1:

This fault is located about 0.5 km east of well Fula North-1. It is striking NWW and dipping SW and extending 2.5 km in the area. The vertical displacement of the fault is 0- 150 m. The maximum vertical displacement is less than 170 m i.e. it represents the thickness of Darfur group which is acting as a sealing mudstone.

Eastern Fault of well Fula North-1: This fault is located about 0.5 km east of well Fula North - 1. It is striking NWW and dipping NE and extending 9.9 km in this area, cutting from Abu Gabra formation to Aradeiba and up to the upper formations.

Western Fault of well Fula North-2: This fault is located 0.7 km west of well Fula North-2. It controls the well Fula North-1 structure with the eastern fault of well Fula North-1. It is striking NWW and dipping SW and extending 9.5 km in the area, cutting from Abu Gabra formation to Aradeiba and above formations. In seismic data, the vertical displacement is 0- 300 m. The displacement of the western fault of well Fula North- 2 is 170 m increasing towards NW.

Western Fault of well Fula North-3: This fault is located between the eastern fault of well Fula North-1 and the western fault of well Fula North- 2 and parallel to them. The well Fula North- 3 fault- nose structure is controlled by the western fault of well Fula North- 3. It is striking NWW and dipping SW, and extending 2.5 km in the area. The vertical displacement is 0- 40m, cutting from Abu Gabra formation to Aradeiba formation.

Eastern Fault of well Fula- 1: This fault is located 0.5 km east of well Fula-1. The eastern fault of well Fula-1 cuts the Fula 1 structure into two blocks. It is striking NNW and dipping NE, and extending 4.5 km in the area. In seismic data, the vertical displacement is 0- 160 m.

Facies Associations: The lithological description and facies analysis of Fula Subbasin focused mainly on Upper Abu Gabra sand, Bentiu 1 sand, Aredeiba D sand and Aradeiba E sand.

Upper Abu Gabra Sand: The sandstone is composed of medium to coarse sands interbedded with thin mudstone. Mud logging data in well Fula North show that the sandstone is grey colored, sub-angular to sub-rounded, to some extent well sorted, fine to medium grained, and of a poor consolidation. The mineralogical composition is mainly quartz with minor argillaceous matrix. The major cementing material is kaolinite clays; however, the sandstone is of good porosity.

Upper Abu Gabra is relatively thick. It is about 400 m in the middle area and thinner in the east and south area i.e. ~ 350 m. Based on sequence stratigraphic study Upper Abu Gabra deposited in the contraction period of the basin. The type of sediments suggests that they were supplied mainly from the east.

Bentiu 1 sand: Bentiu 1 consists of sandstone interbedded with small amount of shale and siltstone. The sandstone is composed of light gray color, friable and poorly consolidated, medium to coarse grained, sub- angular to sub- rounded sands and rarely with some megascopic quartz grains reflecting bad winnowing in some zones Figure 4. The mineral constituents are quartz, feldspar and mica with some lithic fragments cemented mainly by kaolinite clays.

Bentiu 1 is relatively thinner than abu Gabra. It is about 70 m in the middle area but thicker in the south ~ 85 m and to some extent in the north. The sedimentary facies and depositional evolution suggest that Bentiu 1 sand is dominated by braided stream. The sediments were supplied mainly from the southeast in addition to northwest.

Aradeiba D sand: Aradeiba D sand of Cretaceous Darfur group is very near to the top of the Bentiu Formation in the Fula area. It is predominantly composed of thick gray to dark gray and purplish red shale interbedded with thin lenses of gray to light gray fine sandstone. It is loosely consolidated exhibits significant oil shows. The composition of Aradeiba D sand is mainly quartz and the major cementing material is Kaolinite. The sand is sub-rounded to sub-angular and medium to moderately sorted as shown in Figure 5.

Aradeiba D sand varies in thickness, thinner (about 26 m) in the middle of the area than in the north and the south where it is ~ 35 m. Review of distribution of sedimentary facies and depositional evolution of the sub-basin manifests that the contraction of the basin and meandering streams are well developed with sediments probably from those uplift areas of southeast and north- northwest.

Aradeiba E sand: Aradeiba E is thin sand deposited in the same environment of Aradeiba D sand and has the same properties but is distributed locally in the area near well Fula North-2 and Fula North-3.

Sand Bodies Identification and Distribution: Logging and core data were used to carry out inter well sand identification. But the core data available were not enough.

Five sand units were identified for Bentiu 1 those were: B1A, B1B, B1C, B1D, and B1E and two units for Aradeiba: D and E sands.

B1E: The B1E sand seems laterally stable in the Fula area and is the thickest bed among Bentiu 1. But it has relatively lower porosity (~25.4 %) and lower permeability compared to the oil- bearing sands in the above zones. Logs interpretation confirmed that this sand body is of high water saturation reaches to 100 %. The oil water contact can't be easily determined. Accordingly, almost all the tests were focused on the top of Bentiu 1.

B1D: The B1D is also massive sand distributed widely. The thickness of B1D varies from Fula- 1 Block (10m) to Fula North Block (27m). Both the porosity (28.3 %) and permeability are higher than that of B1E. Oil saturation of B1D is higher in Fula- 1 Block (71.6 %) than in Fula North Block (55.8).

B1C: The thickness of B1C varies from 14.5 to 21.6 m. This sand is widely distributed and has good reservoir properties with high porosity (29.9 %) and high permeability. Oil is prolifically accumulated in this sand with hydrocarbon saturation up to 78.2 % in Fula 1 Block and 68 % in Fula North Block.

B1B: It is widely distributed as the sand below. Sand body is about 13- 19.5 m thick with high porosity (30.8 %) and high permeability. This sand body is oil- bearing with high hydrocarbon saturation (69.4 % and 75.7%) in Fula- 1 Block and in Fula North Block respectively.

B1A: This sand body is distributed widely in the Fula area. It is thicker in Fula- 1 Block (13.2 m) than in Fula north Block (~ 3- 9 m). The whole sand in the Fula area is oil- bearing.

Aradeiba E sand: Aradeiba E sand is thin sand body with a local thickness of about (1.5– 3.4 m) in the west, pinching out in the east of the Fula North Block and absent in the entire Fula- 1 Block. Although high porosity (~ 31 %) and high permeability are seen in Fula North Block, a low commercial volume of oil is still inferred here since the distribution area of this unit is limited. The understanding on this sand might be enhanced when more development wells are drilled in the future.

Aradeiba D sand:

It varies in thickness (6.5- 20 m). It is widely distributed throughout the entire area. It has the highest porosity (~ 33 %) and the highest permeability among all the sand bodies along the entire Fula area. The hydrocarbon saturation is (58.6 %) in Fula- 1 Block and (60 %) in Fula North Block, lower than that of Bentiu 1 sands.

Sequence Stratigraphy:

Regional stratigraphy confirms that the time span for the formation of East Africa rift basin extends from Late Jurassic to Early Cretaceous. The Central African Trans-current Slip Zone (CATSZ) occurred as a result of the breakup of the upper continent Pangaea which controlled the orientation of the faults within the basin. The faulting system in the area is deep-seated normal faults trending NW-SE perpendicular to the CATSZ. The early rift in filled by sediments with interbeds of coarser rift clastics derived from surrounding basement rocks.

Wells and logging data from the south- central Sudan basins verified thick continental environment existed in different areas essentially including fluvial and lacustrine facies of Cretaceous and younger age.

Based on previous studies and the geological understanding, the stratigraphic sequence of the Fula – Sub Basin can be suggested as in Figure 6 which explains the tectonostratigraphic development of the Fula subbasin and shows the formations and rifting cycles.

Depositional Systems:

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 [19]. The role of sequence stratigraphy is to provide a way of analyzing how sedimentary basins fill. The major factors that influence facies patterns and stratal architecture within a sedimentary basin fill are sediment accommodation (space), the nature and rate of sediment supply (sediment flux), and the physiography of basin (basin geometry).

In Fula subbasin Yan Junsheng et al, [20] recognized six sedimentary facies in the Lower Cretaceous of the Fula subbasin, based on the well logs and seismic data analysis. Those sedimentary facies are: (A) fluvial facies, (B) fan delta facies, (C) braided delta facies, (D) delta facies, (E) nearshore subaqueous fan facies, and (F) lacustrine facies. This study maximized the targeted area to take over the entire sequence through Fula Subbasin to give a generalize idea about the area and detailed depositional system for Fula Subbasin was established. Abu Gabra Formation, Bentiu Formation, and Aredeiba Formation were the major tools for depositional sequence.

Abu Gabra Formation: The sandstone in Abu Gabra Formation was interpreted to be deposited in shallow lacustrine and meandering stream environment. Logs show that only mid-upper Abu Gabra Formation can be considered as two separated oil pools. Accordingly, three sequences have been recognized in mid-upper Abu Gabra Formation, SC, SD, and **SE. SC sequence:** the type of lithology is mainly composed of dark to light brown to light grey, blocky mudstone and shale which indicates a shallow to semi- deep lacustrine environment.

SD sequence: the type of lithology is mainly composed of dark grey blocky mudstone interbeded with white sandstone and oil shale. There are some minor local coal layers. The sandstone deposited in delta front facies. The mudstone is deposited in semi-deep lacustrine environment.

SE sequence: It is light-grey siltstone, coarse sandstone interbeded with grey claystone layers. The sandstone deposited in meandering stream environment. The upper part was eroded.

Bentiu Formation and Aradeiba Formation: Based on logs and cores, the prolific formations, Bentiu, and Aradeiba Formations exhibit the following outlines: The maximum lacustrine flooding surface which is in turn the main sequence boundary was identified at the base of Aradeiba formation, where more than 170 m of claystones/ siltstones and sandstones was identified at the top of Bentiu Formation. The Aradeiba claystones were interpreted to be deposited in shallow lacustrine to lakeshore environment.

The sand sequences of Aradeiba Formation were interpreted to be deposited under meandering stream or distributed channel in delta plain due to: **1)** the presence of typical positive pace sequence Figures 7a, and b, **2)** intercalation of thin fine sandstones with thick beds of shale, **3)** fine to medium sandstones (Figures 5a and b), **4)** sedimentary structure including low angle cross- bedding, planar tabular cross-bedding, and trough cross- bedding.

Bentiu thick sand sequences were interpreted to be chiefly deposited in braided stream environment due to the following rationale points: **1)** logs curves are in Box- shape or Bell- shape (Figure 7 c and d), **2)** main sandstones are interbedded with little shale or siltstones, **3)** bad winnowing which is confirmed by ill sorted sandstones and angular to sub-angular sand grains (Figure 4), **4)** the main cementing material is kaolinite, **5)** lack of organic assembly in the associated mudstones or red/ green color, **6)** sedimentary structure including trough, planar- tabular cross- bedding (Figure 8) and/ or massive structure.

Bentiu 1 sands are internally well connected due to the migration of braided chnnels. The interbedded siltstones and claystones are more likely to be deposited in a shallow lacustrine to lakeshore environment as flooding surfaces in five to six- order sequence boundaries (forced by lacustirne regressions) were easily identified within the Bentiu Formation. These surfaces are argued to be influencing the vertical connectivity of the reservoir.

Conclusions:

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.

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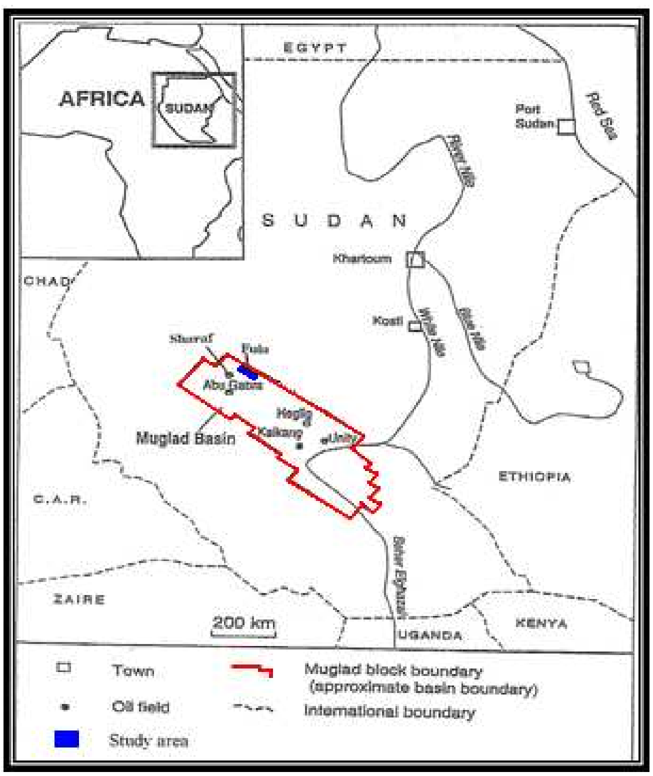

Figure 1: Location Map of Fula Subbasin, Muglad Basin, Sudan

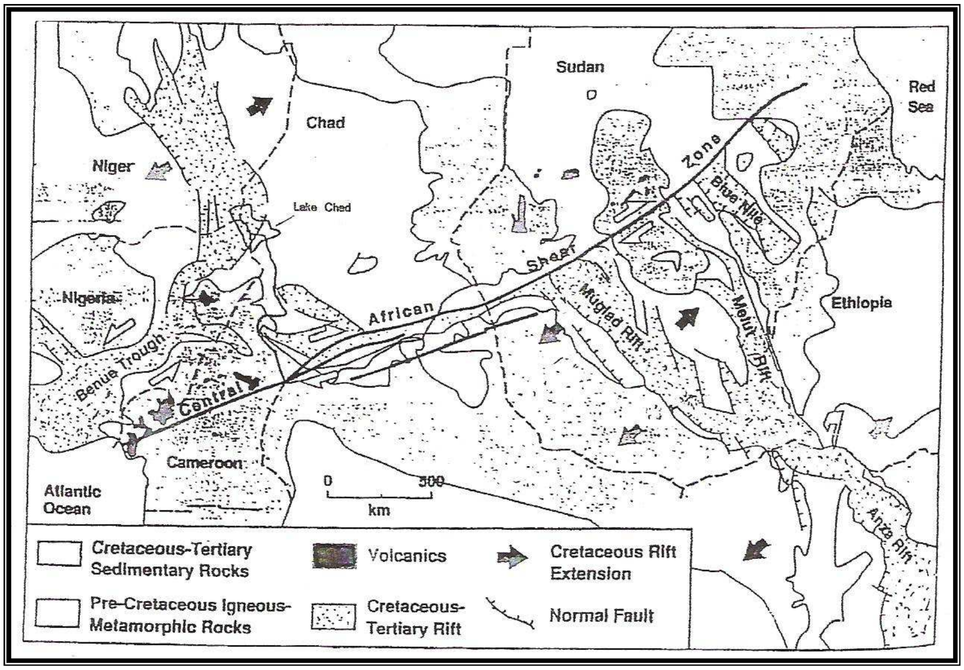

Figure 2: Muglad Basin, Sudan as One of the West and Central African Rift System's (WCARS) Components. (Modified from Firhead, 1988).

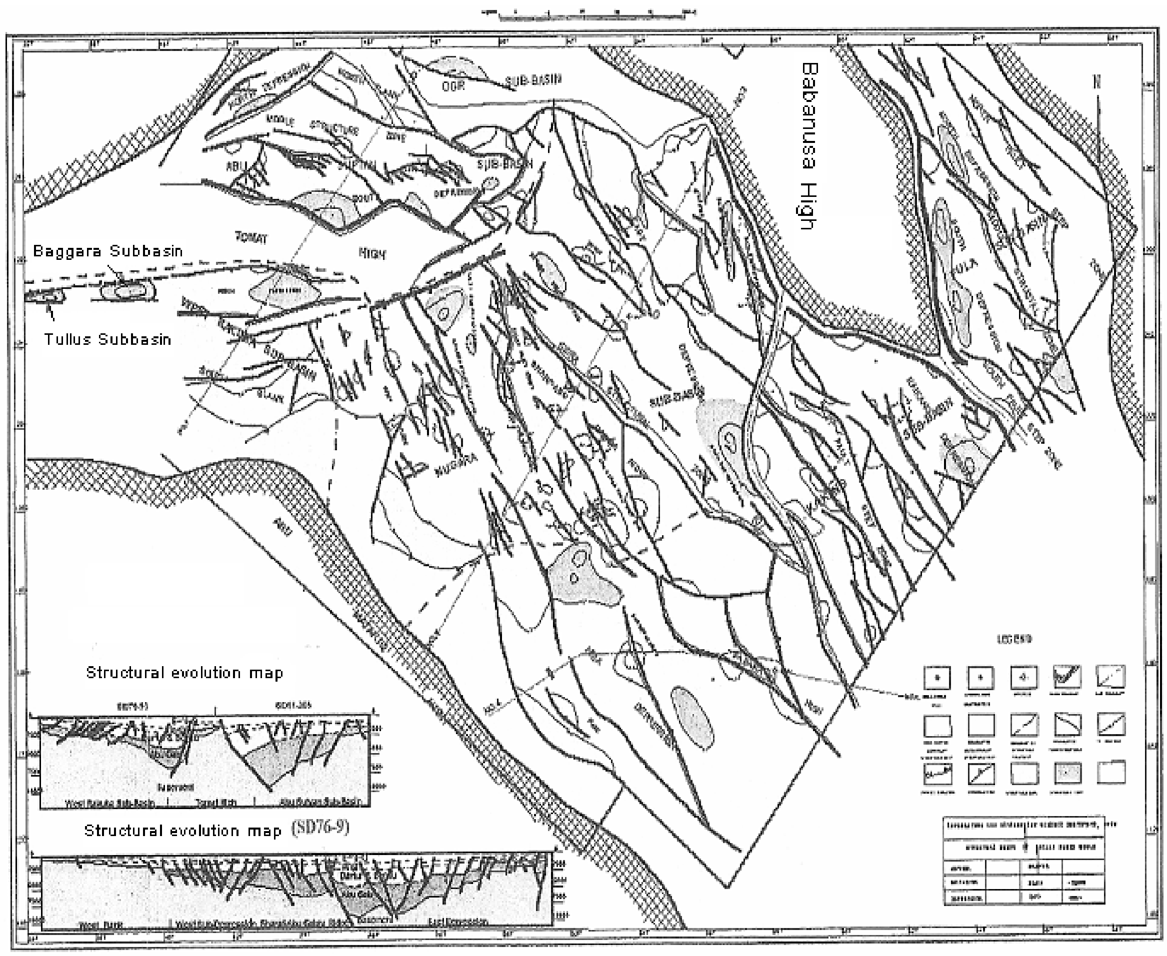

Figure 3: Fulting Pattern in Fula Subbasing, Muglad Basin, Sudan

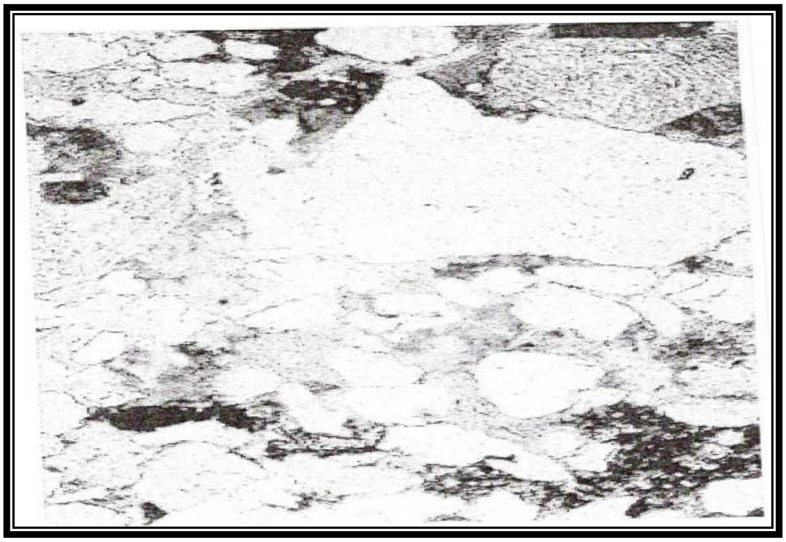

Figure 4: Bad Winnoing and Sorting of Quartz Sandstone at Depth 1258.67m. well Fula - 1 in Fula Subbasing , Muglad Basin, Sudan.

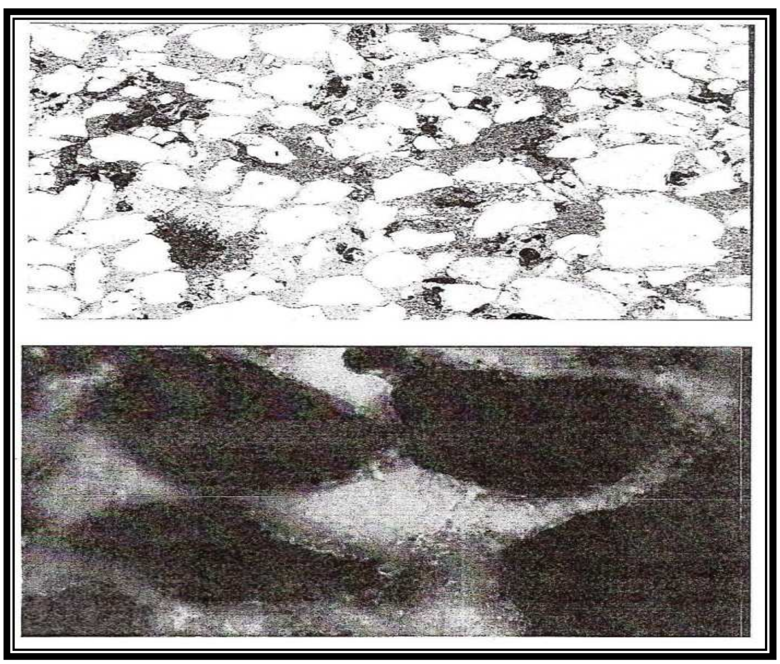

Figure 5: Top Photomicrograph, Bottom: Fluoresecence Slide: Showing grain size: fine to medium, roundness: sub-angular to sub-rouned, sortning: sorted, grain contact: point contact, composition: quartz with arrgilleceous matrix in Fula North (well Fula North 2).

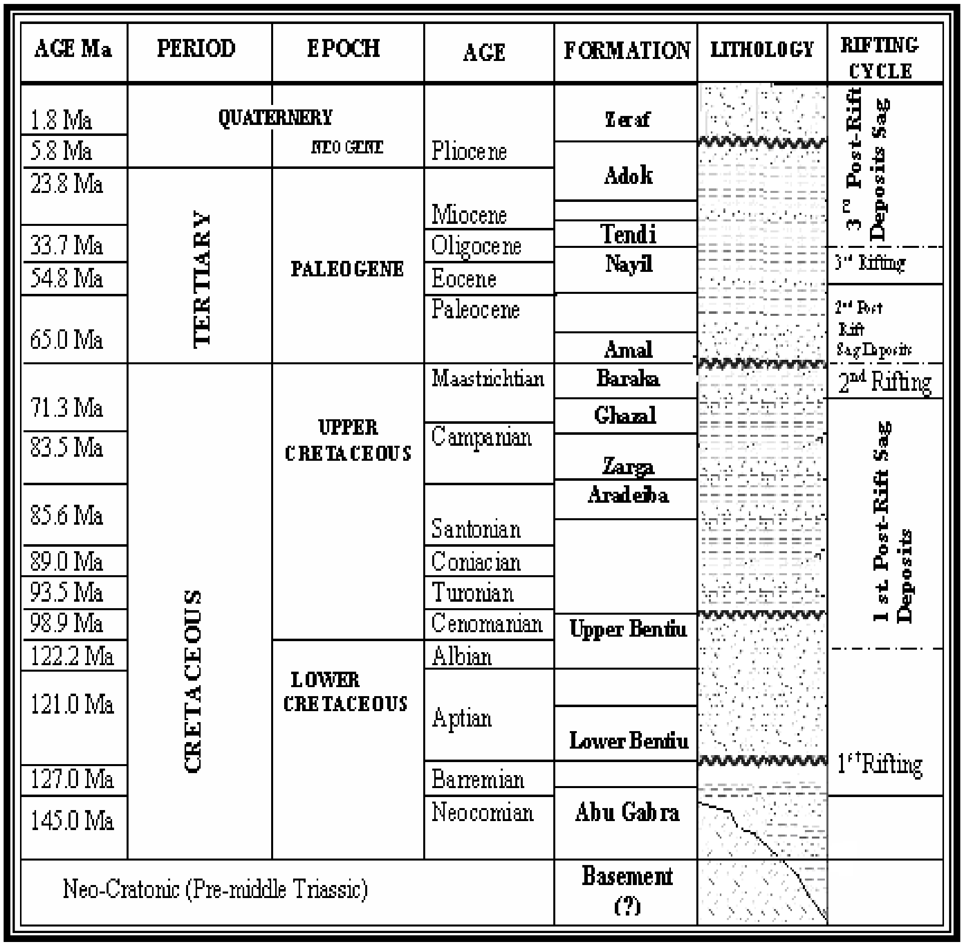

Figure 6 : A Sugesstd Tectonostratigraphic Column for Fula Sub-basin.

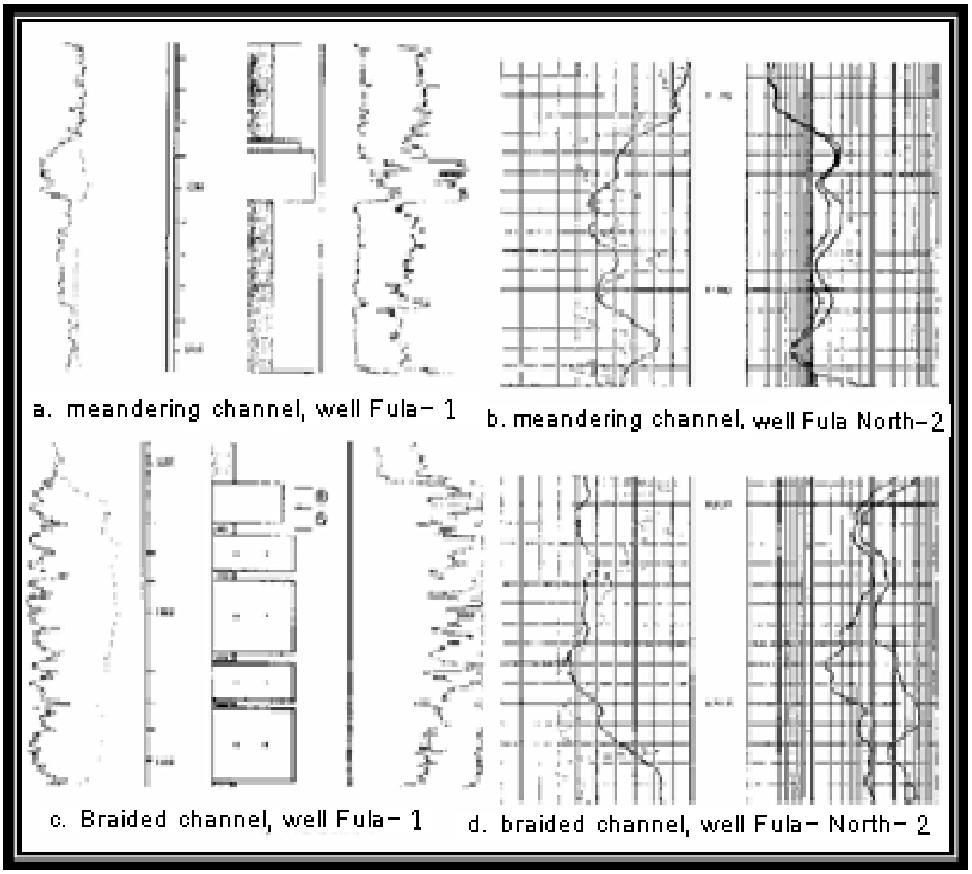

Figure: 7 (a, b, c, and d) : Log Characters of lacustrine Deposits in Fula Subbasin

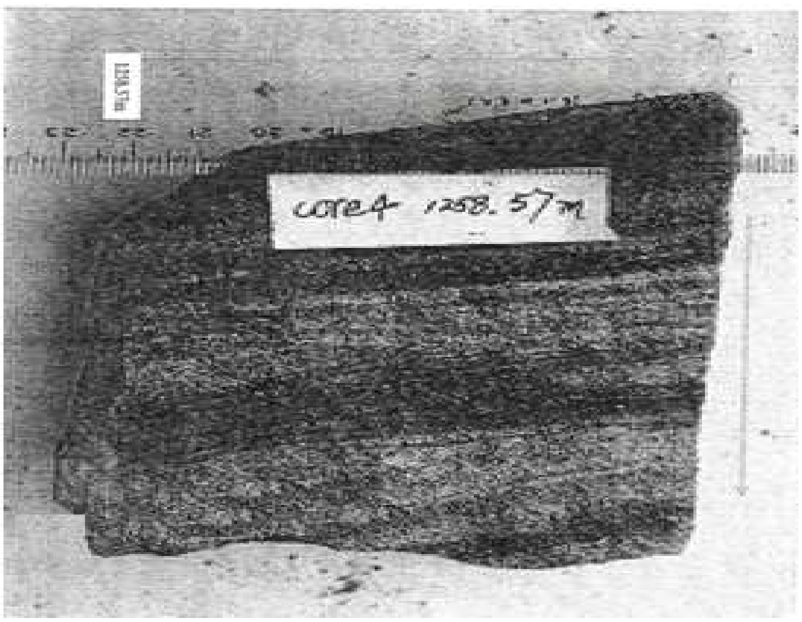

Figure 8: Cross- beddeing of Bentiu 1, well Fula 1