Sequence Stratigraphy and Depositional Systems of Lower Cretaceous in Fula Subbasin, Muglad Basin, Sudan

By

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ABSTRACT:

Abu Gabra Formation in Fula Subbasin is closely linked in space and time to the first rifting cycle of the Cretaceous in West and Central Africa. Based on integrated analysis of seismic and well logging data, the distribution of sedimentary facies and the prediction of depositional systems were constructed. In this study Abu Gabra Formation is divided into three second-order sequences, namely, sequence K_1SSA, sequence K_1SSB and sequence K_1SSC. They could correspond separately to the strata deposited in the early, middle and late rift periods. Sequence K_1SSA and sequence K_1SSC were subdivided into two third-order sequences, where as sequence K_1SSB was subdivided into three third-order sequences. In this study six types of sedimentary fac- ies were recognized, namely, fluvial deposit facies, delta facies, fan delta facies, braided delta facies, nearshore-subaqueous fan facies and lacustrine facies. On the basis of the evolution of those sedimentary facies, five essen- tial depositional systems were established in the Fula Subbasin. They were fan delta system in the northeast part, delta system in the northwest part, nearshore-subaqueous fan system in the west part, braided delta system in the southeast part and alluvial-fluvial system exposed in different parts of the study area because it had developed in the early period. The distribution and evolution of the depositional systems were controlled by tectonics and to some extent influenced by eustacy paleotopography and paleogeography.

ملخص:
تكوين أبوجابره المتواجد في تحت-حوض الفوله يرتبط مباشرة زماناً ومكاناً بالدورة الأخدودية الأولي الحادثة في العصر الطباشيري في غرب ووسط أفريقيا . إستناداً إلي التحاليل المتكاملة للبيانات الزلزالية (السيزمية) وتسجيلات الآبار , تم بناءُ توزيع السحنةِ الرسوبية والأنظمة الترسيبية لتكوينِ أبوجابرة . في هذه الدراسة تم تقسيم تكوين أبوجابرة الي ثلاثةِ تتابعات ذات الدرجة الثانية وهي تتابع K₁SSB وتتابع K₁SSA وتتابع K₁SSC وهي قد تتناسب كلٌ علي حدا مع الطبقاتِ المترسبة في الفترات المبكرة, المتوسطة , والمتأخرة للأخدود. تم تقسيم تتابع K₁SSA ، K₁SSC إلى ثلاثةِ تتابعات، وتم تقسيم K₁SSB الي تتابعين من الدرجةِ الثالثة في هذه الدراسة تم تقسيم السحنة الرسوبية الي ستة أنماط وهي سحنة رواسب نهرية, سحنة دلتاوية, سحنة دلتا مروحية, سحنة دلتا متشعبة, سحنة دلتا شاطئية (قريبة من الشاطئ) تحت-مائية وسحنة بحيرية. بناءً علي النشؤ أو التطور الحادث في تلك السحنات الرسوبية تم انشاء خمسة أنظمة رسوبية رئيسة تحت-حوض الفوله، وهي نظام الدلتا المروحية في الجزء الشمالي الشرقي, نظام الدلتا في الجزء الشمالي الغربي, نظام دلتا مروحية شاطئية (قريبة من الشاطئ) تحت-مائية في الجزء الغربي، نظام دلتا متشعبة في الجزء الجنوبي الشرقي, ونظام الرواسب النهرية-الطمية التي تكونت في فترات الارساب المبكرة. توزيع وتطور الأنظمة الرسوبية محكوم بالعمليات التكتونية وإلي حدٍ ما تؤثر عليه التساوية , التضاريس القديمة , والجغرافية القديمة.

INTRODUCTION:

The Muglad Basin is the largest rift basin discovered in Sudan (Abdalla Y. Mohamed et al., 2002). It is located in the south- Central Sudan. Fula Subbasin occupies the northeast part of the Muglad Rift Basin with total area of about 4500 km^2 (Fig.1). It is a graben (half graben) trends NNW. Fula subbasin can be subdivided into 5 tectonic units: the northeastern fault zone, the central fault zone, the southwestern fault zone, the northern sub-depress- ion and the southern sub-depression (Fig.1). It consists of a thick Mesozoic and Cenozoic continental syn-rift sequence buried by a Miocene-Recent post-rift sedimentary cover (Abdalla Y. Mohamed et al., 2001; Atalay Ayele, 2002). The opening of the Central African rift system is believed to have begun in the Late Jurassic and continued up to the Middle of the Miocene (Bosworth, W., 1992; Fairhead, J. D and Green, C. M., 1989)· The Muglad rift basin began almost in the same time span of the Central African rifting system. Schull, 1988; and Mc Hargue et al., 1992 recognized three major episodes of rifting concomitant subsidence and non-marine sedimentation. These three rifting periods (140-95 Ma, Cycle-1; 95-65 Ma, Cycle-2; and 65-30 Ma, Cycle-3) resulted in the accumulation of up to 5400m of sediments in Muglad rift basin (Abdalla Y. Mohamed et al. 2001; Bermingham, P. M. et al., 1983; Mohamed, A.Y.et al.,1999) as shown in Table.1. Abu Gabra Forma- tion is composed of syn-rift strata and the above Bentiu Formation is comp- osed of post-rift stratum. They were deposited during the first rifting cycle of Muglad Basin (T. Pletsch et al., 2001; Gian Battista Vai, 2003). Abu Gabra Formation can be divided into three members: upper Abu Gabra, middle Abu Gabra, and lower Abu Gabra. The sedimentological studies in Muglad Basin were mainly concerned with outcrops in the Unity and Heglig fields (Abdullatif, O. M., 1989; Kaska, H. V., 1989). The sedimentary facies and depositional systems studies in Fula Subbasin had rarely carried out before this study.

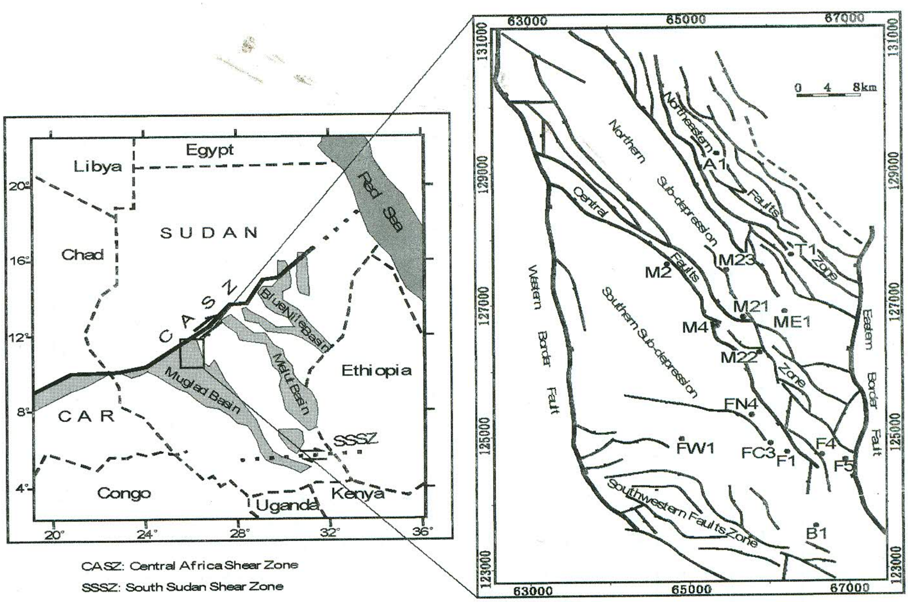


Fig.1- The location and tectonic settings of Fula Subbasin, Muglad Basin, Sudan

The initial exploration in Muglad Basin was conducted by Chevron in the 1960s and 1970s, which led to several oil finds in the basin. Chevron company drilled a disappointed well in Fula Subbasin in 1970s and the exploration in Fula Subbasin was suspended till the China National Petrol- eum Corporation (CNPC) acquired the concession of Fula Subbasin in 1996. They discovered huge reserves of viscous paraffinic crude in Bentiu Forma- tion and Darfur Group, and also high-volume withdrawal of thin oil in Abu Gabra Formation. The main objectives of this paper are (1) to study the depositional character of Abu Gabra Formation, (2) to predict the most ratio- nal reservoir bed, and (3) to provide sedimentological reference for further thin oil exploration. This study is supported by China's National Oil & Gas Exploration & Development Company (CNODC). According to the termination pattern of seismic reflection lithologic association on well logs, stacki- ng pattern of parasequence sets, the Abu Gabra Formation of Fula Subbasin was divided into seven sequences and the sequence framework about systems tracts was matched on well logs. The isopach maps and seismic facies maps of each sequence were also plotted. And then, the seismic facies were shifted to sedimentary facies and five depositional system distribution maps of each sequence were obtained. Ultimately, the controlling factors of each depositional system were analyzed.

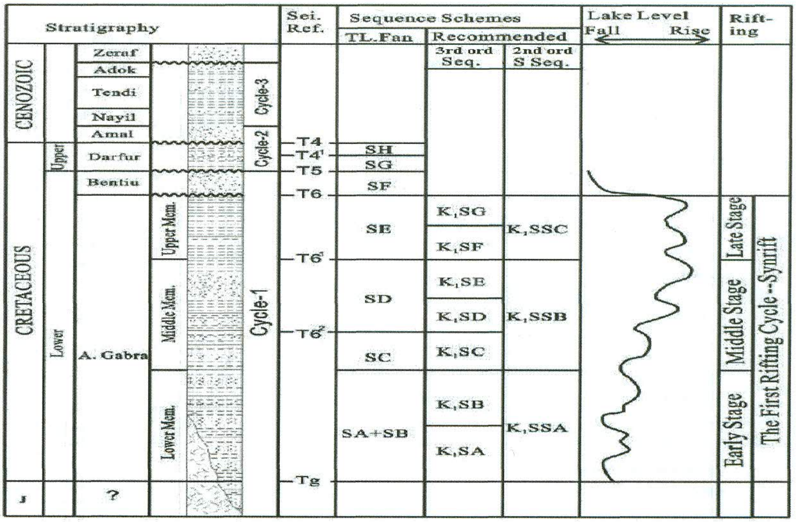


Table 1 -- Well log and seismic sequence stratigraphic scheme of Fula Subbasin, Muglad Basin

DATA AND METHODOLOGY:

1. Data of Investigation

Data set from 25 boreholes including seismic profile data and well log data were used in the investigation of sequence stratigraphy and depositional systems of Fula Subbasin. The 25 boreholes exposed the Abu Gabra Formation. Most of the wells reached upper or middle Abu Gabra Formation. The only one well that revealed the entire Abu Gabra Formation was Well T-1 in the northeastern fault zone. This made it difficult to subdivide the sequences and to analyze the sedimentary facies of middle and lower Abu Gabra. In addition, most of the wells were drilled in the central fault zone with complex structure and minor strata thickness, which resulted the lack of certain sequences or systems tracts. This also brought some inconveniences to borehole sequence subdivision (Fig.1). We selected wire line logging data of gamma ray log (GR), acoustic log (DT), resistivity log (RD, RS, and RMSL), and spontaneous potential log (SP) as the basis of sequence stratigraphy investigation. There were no coring data in the studied area, which are the vital data for sedimentary facies analyze. In this work, we collated all the cuttings logging data including lithology, mineral composition of rocks, grain size, sorting, roundness, compaction, color of sediments, etc, which are the major parameters for sedimentary facies interpretation. There are plenty of seismic data in Fula Subbasin. The density of seismic lines reaches 2×2.5km or 1×2km in some areas. Most of these lines were recorded and processed during 1970s, and were of poor quality at large. One of the crucial reasons was the immaturity of early seismic geophysical method, the others were severe subaerial conditions and complicated subsurface geological structure. CNPC executed 348km^2 of 3D seismic exploration on the central fault zone and 1200km of 2D seismic lines on northeastern fault zone, southern sub-depression, and northern sub-depression. These data are relatively good quality although they are extensional limited. In this study, all the previous and new seismic data were integrated to achieve seismic facies and to predict depositional systems.

2. Methodology

Contraposed the data complexion and geological character mentioned above, we first started up with seismic profiles and identified sequence stratigraphic boundaries of different orders according to the onlaps, trunca- tions, toplaps and downlaps of seismic reflection events. Then we identified the sequence boundaries, first flooding surfaces and maximum flooding surfaces according to lithologic association and the stacking patterns of parasequence sets on the well log sections. Finally, the sequence stratigr- aphic boundaries on the seismic profiles and on the well logs were function- ally combined via synthetic seismogram. By means of repeatedly correla- tion, the well logs delimination and seismic horizons were adjusted time and again to guarantee the consistence of well log sequences and seismic seque- nces.

After the sequence stratigraphic scheme was drawn out, the seismic facies of each sequence in a seismic section was determined for plotting the seismic facies distribution ichnography. The sedimentary facies of each system tract and sequence were identified on well log sections. The log facies and seismic facies were also functionally combined via synthetic seismogram. In this way, each seismic facies was assigned corresponding sedimentary facies meaning, and the seismic facies was converted to sedimentary facies. Consequently, the objectives of depositional systems prediction of Fula Subbasin were fulfilled.

Sequence Stratigraphic Frameworks

The recognition of sequence boundaries and flooding surfaces on seismic and well log sections is the foundation of sequence stratigraphic analyzes (Dominic Emery and Keith Myers, 1996). On studying a seismic section, we often find truncations and toplaps below sequence boundaries and onlaps and downlaps above sequence boundaries (Charles E. Payton, 1977). The absence of facies on well log sections is a key evidence of sequence boundary. On the well logs association, the sequence boundaries are presented by the abrupt change from progradation to retrogradation. Flooding surfaces are downlap surfaces on seismic profile and transition surfaces of retrogradation to progradation on well logs. Here, eight sequence boundaries were recognized in Abu Gabra Formation of Fula Subbasin, which were respectively named KSB1, KSB2, ... KSB8 from bottom to top. These boundaries divided Abu Gabra Formation into three second-order sequences and seven third order sequences. The seven sequences were named K_1SA, K_1SB, ...K_1SG, and the three secondary sequences were named K_1SSA, K_1SSB and K_1SSC as shown in Table 1.

1. Lithostratigraphic Correlation

A lithostratigraphic correlation was carried through before determin- ation of sequence stratigraphic scheme. One purpose of the correlation was to nail down the boundary lines of upper, middle, and lower Abu Gabra Formation. The other was to discover their lithologic variations among all wells. Such correlation was carried out upon well log data. The well log responding characters of each member's boundaries were specified through the correlation. This might also lay a foundation for sequence stratigraphic correlation since the lithostratigraphic boundaries were simultaneity seque- nce boundaries. The lithostratigraphic study only correlated the top and bottom boundaries of upper Abu Gabra because most wells in Fula Subbasin didn't reach lower Abu Gabra Formation.

The boundary between Abu Gabra Formation and above Bentiu Forma- tion, namely top end of Abu Gabra, was characteristically obvious on most well logs. A section of mudstone of 50m more or less with thin siltstone interlayers was deposited on the top of Abu Gabra Formation. The top boun- dary of Abu Gabra Formation was located at the top end of this mudstone section (Fig.2). Based on the borehole data, this mudstone section was stably distributed on the central fault zone. The mudstone section thickened up to 80m on the Well FW-1 in southern sub-depression, and pinched out at the slope area of basin margin. The wire line log response of this mudstone section was even more obvious. Affected by the above sandstone of Bentiu Formation and thin siltstone interlayers in the mudstone section, the electric logs such as gamma ray and resistivity were all funnel trends (Fig.2).

The mudstone section at the top of Abu Gabra Formation is shown in Fig. 2. It is obvious that the thickness of monolayers and whole section accreted from A-1 to FW-1 direction. The layer thickness and grain size of interbeded sand decreased at the same direction. On every well in Fig. 2, The RD and RS response of the bottom of the mudstone was a distinctive high value sharp. The same peaks were found on GR and DT logs. The well log values decreased upwards and appeared funnel trends. It was easy to recog- nize the top of Abu Gabra Formation depending on this character. Using the same method, the boundary between upper and middle Abu Gabra Formation was correlated. This boundary was also easy to recognize on well logs, which was at the top of a wide spread mudstone section. Trough repeatedly correlation on the well logs and seismic profiles the boundary of upper/ middle Abu Gabra Formation was adjusted. Such works made the well log stratification easier to correlate in horizontal direction and more accordant with seismic sequence stratigraphy.

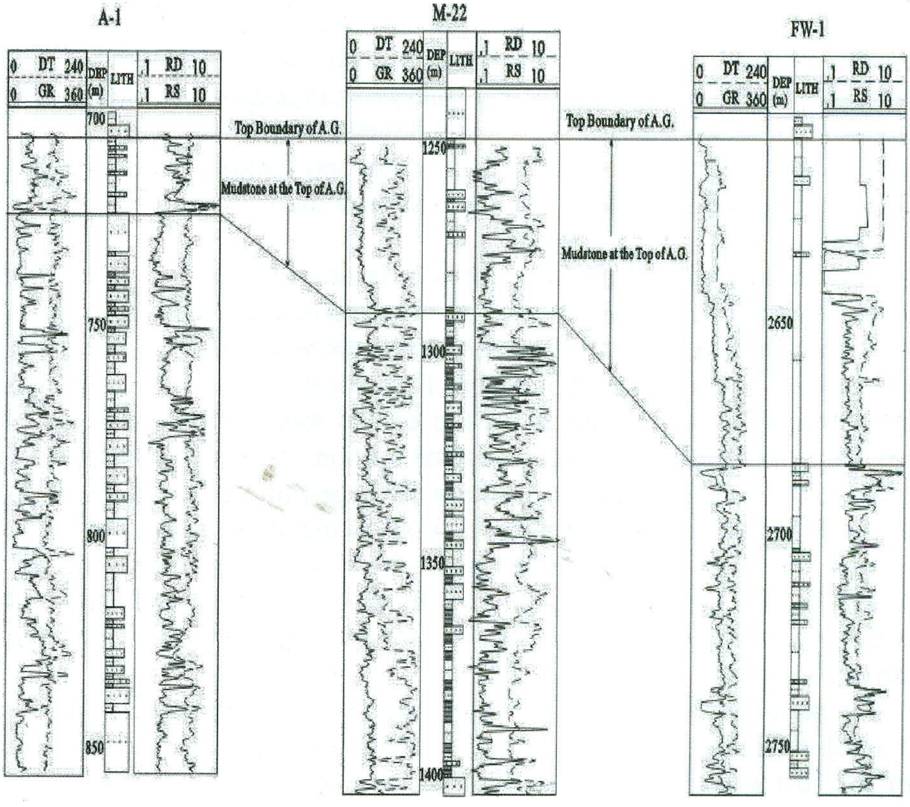


Fig. 2 - The well log character of mudstone section at the top of Abu Gabra Formation, in Fula Subbasin

2. Identification of Sequence Stratigraphic Surfaces

Like the lithostratigraphic correlation of well logs, the recognition of sequence stratigraphic surfaces needs not only well logs data but also seismic data. Sequence boundaries are generated by a fall in relative sea level or lake level. In fact, they are difficult to recognize in a core or well log data set since the downward shift in coastal onlap is rarely evident. Direct evidence for exposure, erosion, and forced regression must be sought instead (D. W. J. 1998; Dominic Emery, 1996). A facies dislocation, that is a surface where rocks of shallower facies rested directly on rocks of signifi- cantly deeper facies, was found in Well FC-3 (Fig.3). As shown in Fig. 3, first, KSB6 was a distinctive surface where lithology and electrical property changed abruptly. An abrupt upward decrease in GR readings and increase in SP readings is obvious in (Fig.3). And this is regionally recognizable. Secondly, the stacking patterns beneath KSB6 were progradation para-sequence sets and retrogradation above KSB6. Lastly, the braided delta front deposits above KSB6 directly overlapped on the under deep-water lacustrine deposits, which showed a distinctive facies change. The above evidences showed that there were good basis to nail KSB6 as a sequence boundary on the well logs. This surface had similar character on all wells in Fula Subba- sin, and it was accordance with the dividing line of Upper and Middle Abu Gabra Formation.

It is easier to identify the unconformity and the accordance conformity on seismic profiles than on well logs. The truncations, onlaps, and toplaps represent the unconformities were obvious especially on the seismic of proximal Fula Subbasin. The top and bottom boundary of Abu Gabra is an unconformity, which respectively corresponds to syn-rift and post rift unconformity. On seismic profiles proximal Fula Subbasin the onlaps above KSB8 and the truncations beneath it were obvious as shown in Fig. 4-a. The difference of the seismic facies beneath and above the sequence boundaries is also obvious. On the seismic profile SD84-234 as shown in (Fig. 4-a), KSB8 is a continuous strong event. The seismic facies beneath KSB8 is moderate amplitude, continuous, parallel, sill like reflections, and low amplitude, semicontinuous to discontinuous, subparallel, sill like reflections above KSB8. The sedimentary meaning of such seismic facies is that the shallow to deep lacustrine deposits of Abu Gabra Formation under KSB8 is overlaid by the above fluvial facies sediments of Bentiu Formation. The seismic facies can be used as a basis to identify sequence boundaries and to subdivide sequences. The division of sequence K_1SA and K_1SB on seismic profiles especially in depressions mostly depends on this distinction. Two seismic facies units were recognized on the seismic profiles of Lower Abu Gabra Formation. Each unit represented a sequence. The upper one is high ampli- tude, continuous reflection and the lower is moderate to low amplitude, semicontinuous to discontinuous reflection (Fig. 4-b).

3. Identification of First Flooding Surfaces

The first flooding surface and maximum flooding surfaces are also key surfaces in sequence stratigraphic analyzing besides sequence boundary. The former is boundary between the lowstand systems tract and transgr- essive systems tract. The later is the demarcation line of transgressive syste- ms tract and highstand systems tract. These surfaces were not recognised on seismic profiles due to the low quality of seismic data. The identification of flooding surfaces and the division of systems tract was carried out on well logs.

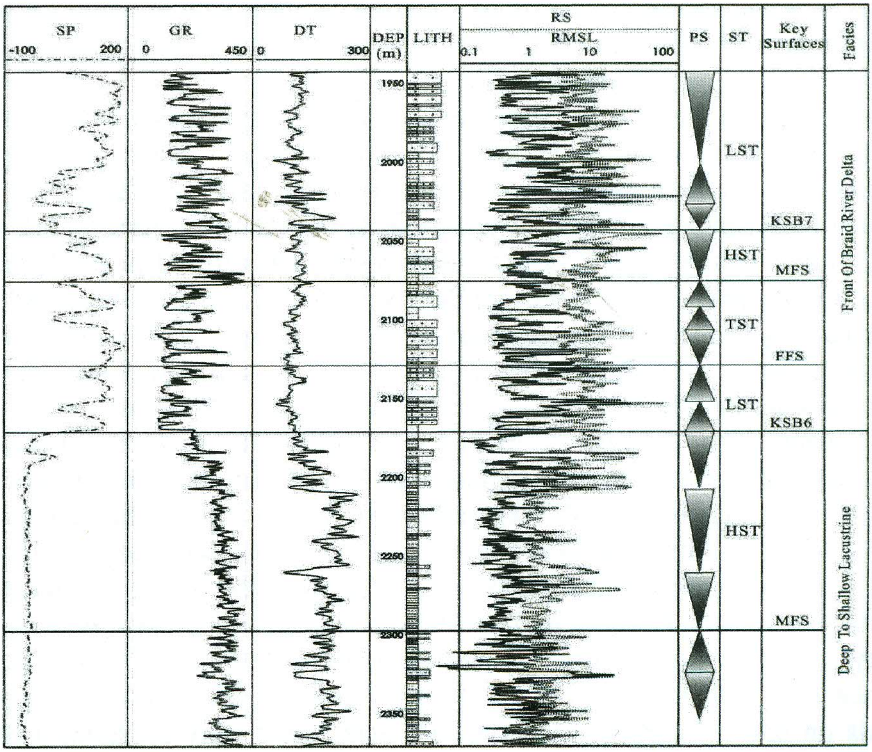


Fig. 3 - The identification of key sequence surfaces in Well FC-3 of Fula Subbasin, Muglad Basin

The first flooding surface represents the first extensive lake level rise. This often takes place when the progradation of lowstand systems tract reaches it's maximum. Consequently this surface usually coincides with the maximum progradation surface. However, at shallow to deep lacustrine locations, or due to the variation of sediment supply, the lowstand systems tract could be composed of several retrogradation parasequence and the lacustrine transgressive surface could locate between a retrogradation unit and an overlying progradation unit as shown in (Fig.3). On the other hand the lacustrine transgression will lead to the extension of the lake which result the shoreline of transgressive systems tract extend the shoreline of lowstand systems tract. Thus the lowstand systems tract sediments rested directly on the erosion or bypass area of lowstand systems tract, and the first flooding surface inside the Subbasin will coincide with the sequence boundary in proximal locations.

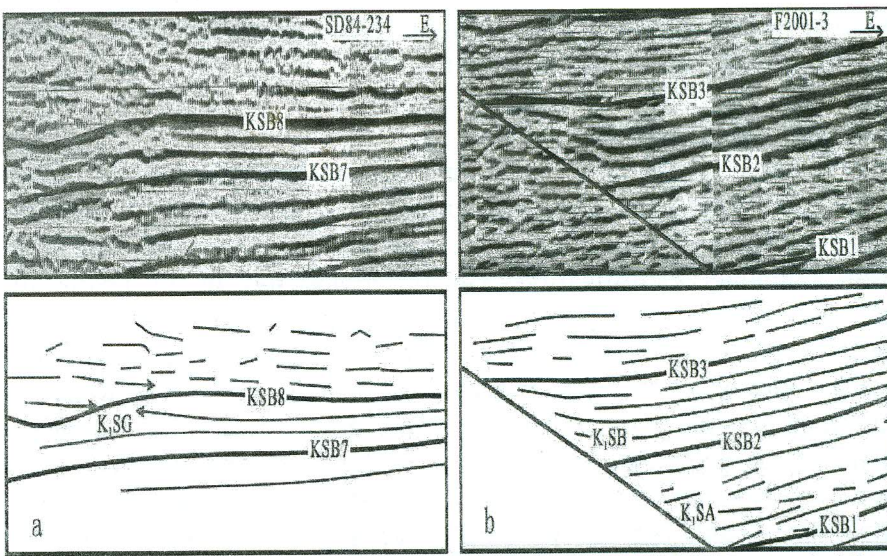


Fig. 4 - The seismic character of sequence boundaries of Fula Subbasin, Muglad Basin

The maximum flooding surface was identified according to the stacking patterns of parasequence sets on well logs. It could be recognized in proximal locations as the surface between a retrograding unit and an overlying prograding unit. Where these were dirtying-up and cleaning-up units respectively, the maximum flooding surface would be a gamma ray maximum. A clear maximum flooding surface was marked on (Fig.5). As shown in (Fig.5), it was obvious that the transgressive systems tract of K_1SF sequence on Well M-21was stacked by 5 retrograding parasequence sets and the highstand systems tract was composed of 3 prograding units. The maxi- mum flooding surface lay above the retrograding interval and below the prograding interval. A distinctive variation of lithological and electrical property could be seen thereabout the maximum flooding surface in (Fig.5). The sediments of transgressive systems tract below the surface were mainly composed of dark grey or grey mudstone with fine to medium grain sandwi- ching. Compared with above highstand systems tract, the former had less numbers of sandwiching and thicker sand layer. Proportionally the sand bodies of transgressive systems tract had a bell trend or boxcar trend whereas the sand beds of highstand systems tract have a sawtooth response. Most of the maximum flooding surfaces have the similar characters on well logs of Fula Subbasin.

4. Sequence Stratigraphic Scheme

The seismic sequence scheme was coincide with the results of well log sequence analysing, since the seismic data was considered in wireline logs sequence stratigraphic analysis and the well log data was combined in seismic sequence boundary identification. The differences lay in the resol- ution of seismic and well log data set. The parasequence sets and systems tracts of a sequence were divided on well logs. However the inner archit- ecture of the third order sequences was not analysed on seismic profiles restricted by the resolution of seismic reflections. The two kinds data sets were combined by synthetic seismogram. We calibrated 10 wells with seis-mic profile through synthetic seismogram and conducted depth time conver- sion to all the wells revealed Abu Gabra Formation in Fula Subbasin in this work. Through such calibration and correlation the sequence stratigraphic surfaces of Abu Gabra Formation were identified both on seismic profiles and well logs. The amalgamation of seismic and well logs sequence stratig- raphic scheme was realized as shown in Table 1.

MAJOR SWDIMENTARY FACIES TYPES:

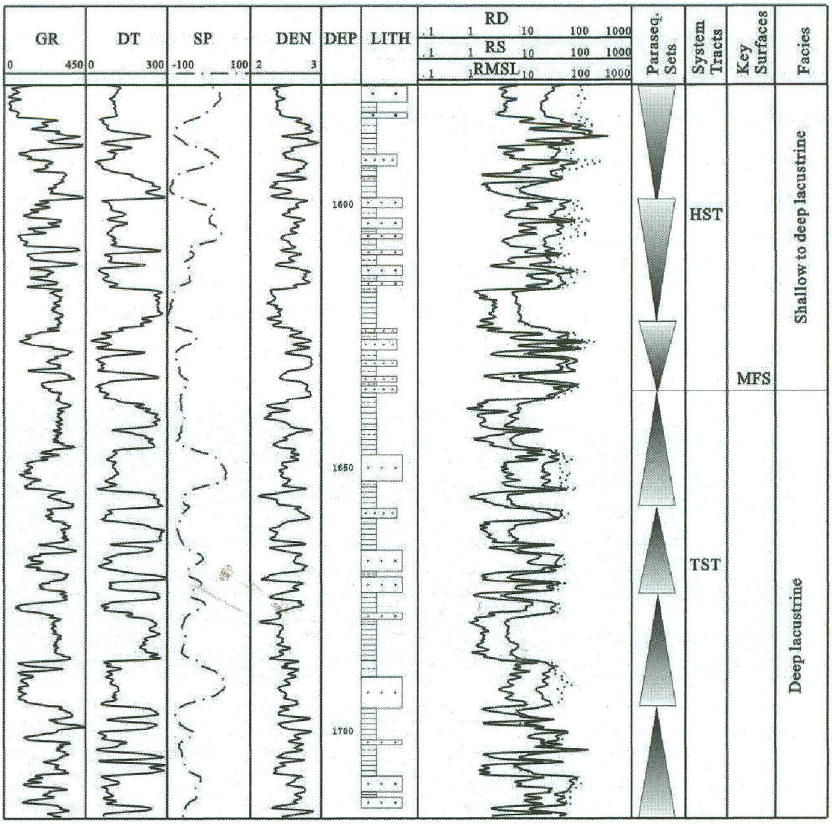


Fig. 5 - The maximum flooding surface of Well M-21 in Fula Subbasin, Muglad Basin

According to the analyzing of well log and seismic data, six types of sedimentary facies were recognized in Fula Subbasin: fluvial facies, fan delta facies, braided delta facies, delta facies, nearshore subaqueous fan facies, and lacustrine facies.

1. Fluvial Facies

The fluvial facies were mainly present in the lower two sequences (K_1SA and K_1SB) of Abu Gabra Formation. It was the result of basin infill at the early stage of syn-rifting. The lake strandline extended to the border of Fula Subbasin and the fluvial facies retrograded out of the study area. The recognition of fluvial facies and their distribution was based on seismic data since the fluvial sediments were not revealed in boreholes. The chaotic and subparallel seismic facies of the lower two sequences were interpreted as alluvial or fluvial facies as shown in (Fig. 6).

2. Fan Delta Facies

The fan delta facies that only presented at the northeastern fault zone were recognized by the well log data of Well A-1 and the seismic profiles of this area. The paleogeographic and paleotectonic pattern were also considered in determining the facies.

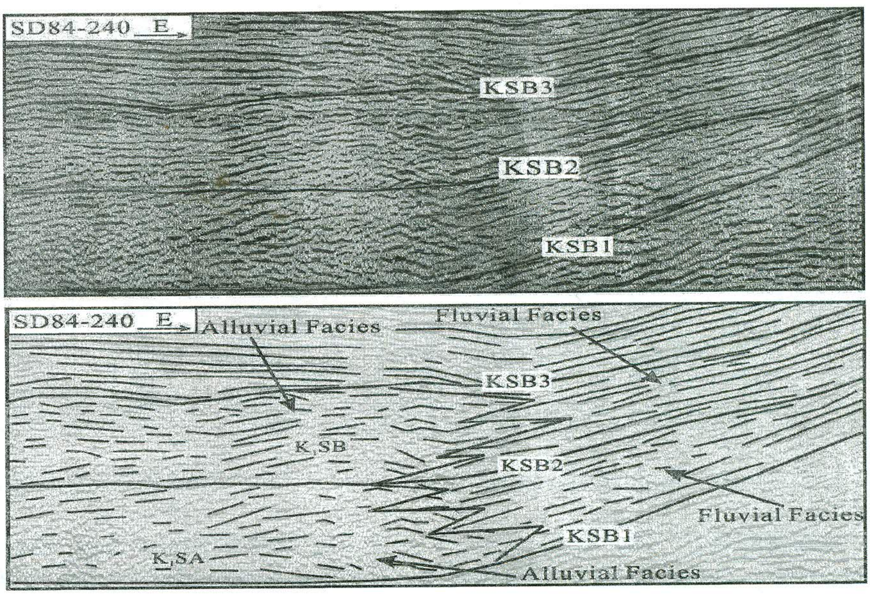


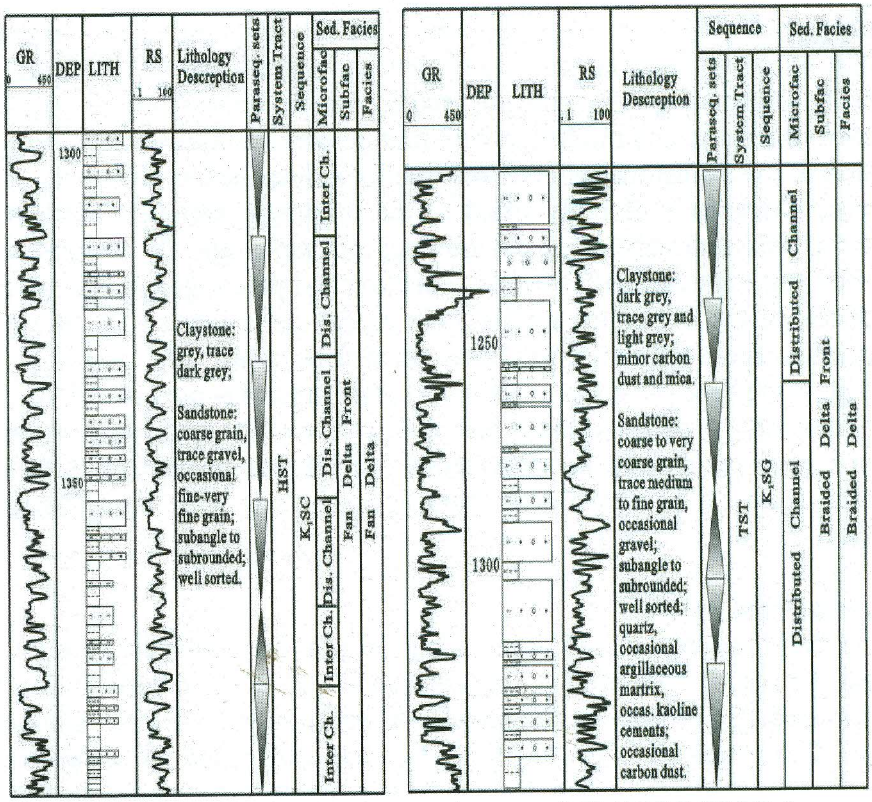
Fig. 6 - The seismic reflection character of alluvial-fluvial facies on profile SD84-240 in Fula Subbasin, Muglad Basin

Fig. 7-a shows the depositional character of highstand systems tract of sequence K_1SC in Well A-1, which was composed of six parasequence sets with total thickness approximate 100m. Five of these six parasequence sets were

prograding unit and the other one was retrograding unit. The colour of mudstone is mainly grey or dark grey which emphasising that it could be a subaqueous deposition. Seen from the lithologic association, it was composed of interbeded sandstone and mudstone with nonuniform thickness. The sorting and roundness of the sandstone reflect a relative long distance transfor- mation. The log curves character preferably fitted to the lithologic variation although the cyclicity of this sediments was not obvious on well logs. By integrating the above well log character with seismic reflection and paleo- geographic structure we ascertained the sediments as the front of fan delta facies. The lower two parasequence sets with relatively fine sandstone grain size and low sand percentage were recognized as inter-distributary microfa- cies of the fan delta front. The middle 3 parasequences sets that were mainly composed of pebbled sandstone were recognized as subaqueous distributary channel microfacies of fan delta front. The uppermost parasequence set was inter-distributary sediments.

3. Braided Delta Facies

The braided delta facies were recognized at the southeast area of Fula Subbasin. They mainly distributed in sequences K_1SC~K_1SG in vertical direction. The sediments of Well F-5 were typical braided river delta facies as shown in (Fig.7-b). The sequence K_1SG of Well F-5 was composed of conglomerate, sandstone and mudstone. The former two components accou- nted for 62 percentages and the latter for 38 percentages. The sandstone was coarse to very coarse grain size with pebbles in it. The mineral composition was mainly quartz, which was subangular to subround and well sorted. The colour of mudstone was mainly dark grey, minor grey and light grey. Carbon dusts were common in the sandstone and mudstone. Compared with the fan delta front sediments of Well A-1, the depositional cyclicity of Well F-5 was more obvious. The log response of the sediments was sawtoothed boxcar trends. According to above lithologic and wireline data from Well F-5 and adjacent wells this section was recognized as coarse grain subaqueous distributary channel microfacies of braided delta front.



a. Sequence K_1SC of Well A-1 in Fula Subbasin b. Sequence K_1SG of Well F-5 in Fula Subbasin

Fig. 7 - The well logs character of fan delta and braided delta in Fula Subbasin, Muglad Basin

(Fig. 8-a) showed the well log character of the transgressive systems tract and highstand systems tract of sequence K_1SC in Well M-23, which was dissimilar with the braid delta sediments of Well F-5. In lithological character: the grain size, thickness, and percentage content of the sandy delta front sediments in Well M-23 were all minor than Well F-5, and the occurrence of sandstone and mudstone in Well M-23 was uniform interbeded other than the thin band of mudstone in Well F-5. In electrical character: the motifs of the logs in Well M-23 were bell trend, funnel trend, sawtooth trend and boxcar trend rather than the motifs of sawtoothed boxcar trends in Well F-5.

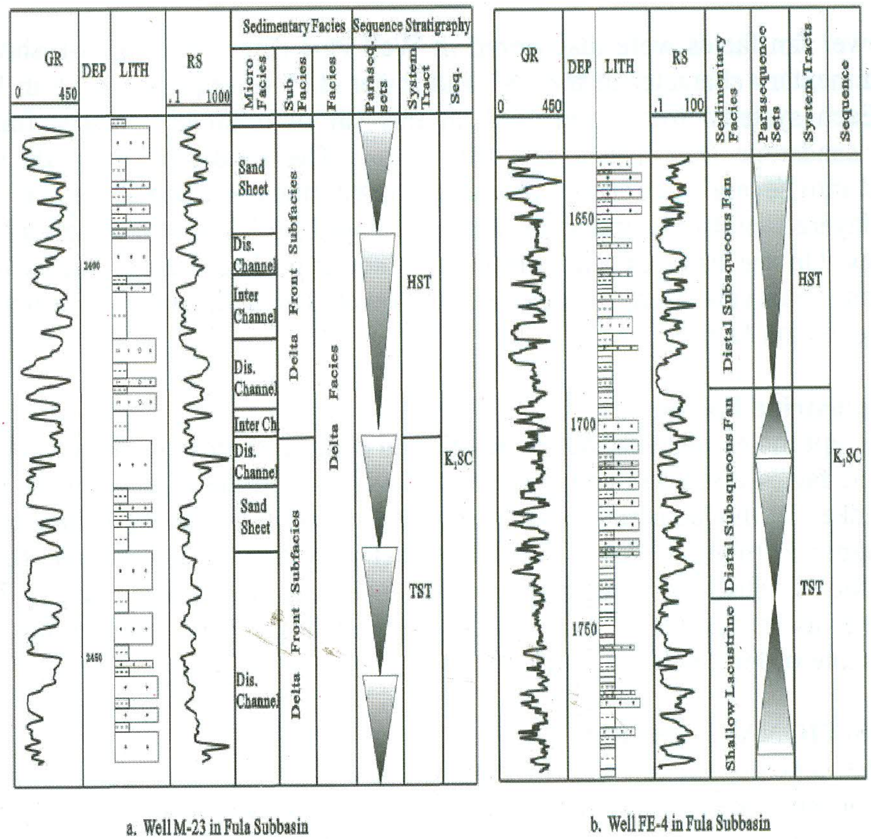


Fig.8 - The well log character of delta facies and nearshore subaqueous fan facies of Fula Subbasin, Muglad Basin

5. Nearshore-Subaqueous Fan Facies

The nearshore subaqueous fan facies were recognized at the actic region aside the throw walls of boundary faults in Fula Subbasin (Fig. 9). They developed at a wide range in sequences K1SC, K1SD and K1SE which were formed during the extensive lacustrine transgression stage of Fula Subbasin. This type of facies was mainly developed aside the throw wall of western border faults for its high activity, great fault displacement, and steep paleogeographic slope gradient. In addition, the nearshore subaqueous fan facies were also recognized at eastern border fault where the fault displacement is greater.

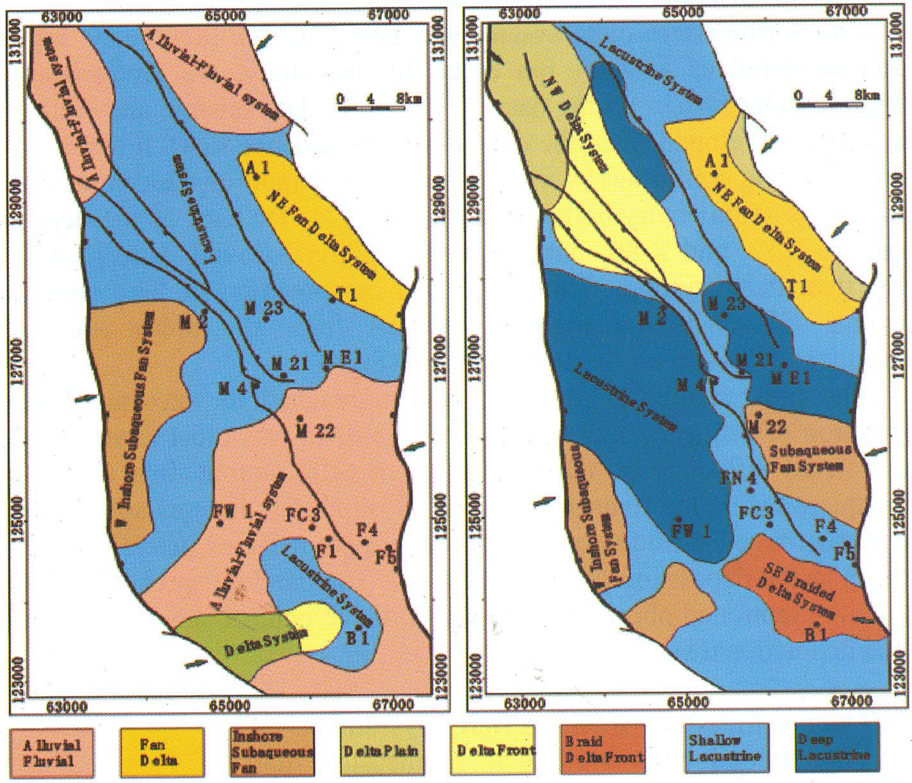
The lower fan facies were discovered in Well FE-4 (Fig. 8-b). Fig. 8-b showed the sedimentary character of the TST and lower HST of sequence K1SE in Well FE-4. Each systems tract comprised an interval of relatively thicker fine to coarse sandstone (1700-1730m and 1640-1650m). The sandstone intervals were divided into several sections by thin intercalated mudstone and shale bed. And heavy layered mudstone and shale were developed both above and beneath the intervals. On the basis of such lithologic association and seismic facies these sandstone intervals were recognized as lower fan sediments of nearshore subaqueous fan facies.

6. Lacustrine Facies

Except the extensively developed fluvial sediments in sequences K_1SA and K_1SB, the facies discussed above were all developed in the lake or on the edge of the lake. So the lacustrine facies were well developed in every sequences of Abu Gabra Formation. We divided this facies system into three sub facies: shore facies, shallow lacustrine facies, and deep lacustrine facies. They extended as banding or ring shape controlled by the morphology and architecture of Fula Subbasin (Fig. 9).

DEPOSITIONAL SYSTEM:

The depositional systems of Abu Gabra Formation were determined by comprehensive analysis of well log data, seismic data, and other regional geologic data. By studying the sedimentary general plane of every sequence we could find that the depositional systems and sedimentary facies of different sequences had many characteristic so inherited and distinctive characteristic of varied. Because the activities of the faults controlling the forming of sub depressions were of great variance in space the sedimentary facies and depositional systems of different sub depressions were of great variance in the same era (Gian Battista Vai, 2003). Five depositional systems were recognized in Fula Subbasin: the northeastern fan delta system, the northwestern delta system, the southeastern braid delta system, the western nearshore subaqueous fan system,and alluvial-fluvial system. The following texts will discuss the depositional systems developed at different tectonic units as shown in (Fig. 9).



a. Depositional System of Sequence K_1SB b. Depositional System of Sequence K_1SE

Fig. 9 - The depositional systems of Abu Gabra Formation in Fula Subbasin, Muglad Basin

1. The Northeastern Fan Delta System

The fan delta system developed at northeastern fault zone in Fula Subbasin was confirmed on both seismic profiles and well logs (Fig. 7). This system created in sequence K_1SA at the early stage of syn-rifting period and existed to sequence K_1SG at the late stage of syn-rifting period. The spread and strike of faults controlled the depositional body which trends northwestern as a band. The banding lithosomic body trended the same direction of faults in the northeast faults zone. And the southwestern boundary of the system didn't exit across the southwestern end of the faults zone as shown in (Fig. 9).

2. The Northwestern Delta System

The northwestern delta system was best regarded previously, however; it was considered as a small fan delta. In this study, we recognize it as an extensive delta system on the basis of the up to date seismic and well log data, which was developed since the deposition of sequence K_1SC. It trends NW-SE as spread banding controlled by the northern trough fault of the central fault zone. In fact, this sedimentary body came into being as far back as the deposition of sequence K_1SA and K_1SB, but it was just alluvial-fluvial depositional system other than delta system. Along with the outspreading of lake shoreline, the previous alluvial-fluvial system retreated from the study area and the subsequent delta system began to develop (Fig. 9).

The progradation of the delta system reached its maximum during the deposition of sequence K_1SC and K_1SD. The delta was most extensively spread and had an influence on the Well M-23 or M-21 at that time (Fig. 8-a). The subsequent lacustrine transgression and erosion of sediments source area made the system receded unceasingly. The deltaic plain facies petered out the study area up to the deposition of sequence K_1SG. The banding spreading character of the delta mentioned above was the result of the control action of central faults to the depositional systems.

3. The Southeastern Braided Delta System

The braided delta system at southeastern part of Fula Subbasin was another important lithosomic body. The existence and extension of this system were affirmed on well log data and the depositional system maps as shown in (Fig. 7-b and Fig. 9). It developed and expanded at the beginning of sequence K_1SE. Because the braided delta developed during the inundation phase of the second order sequence when the lake basin reached its maxim- um extension, only the front of the braided delta was recognized in Fula Subbasin. The relationship of the braided delta to the northwestern delta was worth of note. When the former advanced into the center of the Subbasin, the latter retreated to the border. And the reverse was true. As mentioned above in section 5.2, the northwestern delta system developed from sequence K_1SC to K_1SG. This was a process of unceasingly recession. On the other hand, the development of the southeastern braided delta system was a process of expansion from sequence

K_1SE to K_1SG. The above diversification reflected the differentia of the tectonic activities at different areas and different phases. At the early and middle stage of the syn-rifting period, the tectonic fluctuating rejuvenated and rifting was more active at northwest part of Fula Subbasin and inactive at southeast. At the late stage of the syn-rifting period the regime was reversed. The changeover time was approxim- ately at a certain moment during the deposition of sequence K_1SE or K_1SF.

4. The Western Nearshore Subaqueous Fan System

An expansive lake developed in the northern part of the sub-depressions since the deposition of sequence K_1SB. And a series of nearshore subaqueous fans was developed at throw walls of the western boundary faults. They spread as banding or lobe shapes along the faults and were recognized mainly depending on the internal reflection configurations and external reflection appearance that due to the absence of well data. As shown in the sedimentary facies maps (Fig.9), the nearshore subaqueous fan systems were of greater dimensions in sequence K_1SB, K_1SC, and K_1SD. They extended through the entire western boundary fault zone from south to north and evolved into three fans in sequence K_1SD from one in sequence K_1SB. The dimensions of the fans became smaller and smaller and the location of the fans migrated southward in the process of time. This evolution law was consistent with the northwestern delta system discussed in section 5.2. In fact, this consistency was inevitable since all the depositional systems in the Subbasin were controlled by same tectonic settings and faulting activities.

5. The Alluvial-Fluvial Systems in Early Stage

The alluvial-fluvial system was recognized in sequences K_1SA and K_1SB which was deposited in the early period of the syn-rift stage. A small lake developed in the northern sub-depression and a fan delta system was recognized in the northeastern part of the lake during the deposition of sequence K_1SA. In addition, a small lacus was likely to develop in the southern sub-depression in sequence K_1SA. The other extensive areas were overlay by alluvial-fluvial systems. The extension and revolution of this system was recognized on seismic data because there was no well revealed the lower two sequence in Fula

Subbasin. On the seismic profiles, the alluvial-fluvial system presented as chaotic or filled internal reflection configurations and sphenoid or sill like external reflection appearance. The horizontal distribution of this system was similar with other systems. Its distribution range migrated southward in the process of time. This character was accordance to the pattern that lacustrine systems were first developed in the northern sub-depression. With the transgression of the lacustrine, the dimension of the alluvial-fluvial system became smaller in sequence K_1SB than in sequence K_1SA.

CONCLUSIONS

The Abu Gabra Formation of lower Cretaceous in Fula Subbasin Could be divided into three second order sequences and seven third order sequences according to the update well log and seismic data. The sedimentary facies revealed in well logs and interpreted on seismic profiles included fluvial facies, fan data facies, data facies, nearshore subaqueous fan facies and lacustrine facies. The seismic facies were analysed in seque- nce units. The sedimentary meanings of the seismic facies were interpreted based on the tectonic settings and the matching of seismic facies with well log facies. Subsequently six sedimentary facies distribution maps of seven sequences were drawn out. Five depositional systems were formed by the sedimentary facies developed in the sequences. They were the northeastern fan delta system, the northwestern delta system, the southeastern braid delta system, the western nearshore subaqueous fan system, and the early stage alluvial-fluvial system.

REFERENCES

1. **Abdalla Y. Mohamed, Michael J. Pearson, William A. Ashcroft, (2002).**Petroleum maturation modelling, Abu Gabra Sharaf area, Muglad Basin, Sudan, Journal of African Earth Sciences, **35(2):** 331-344.
2. **Abdalla Y. Mohamed, W.A. Ashcroft, A.J. Whiteman, (2001).**Structural development and crustal stretching in the Muglad Basin, southern Sudan, Journal of African Earth Sciences, **32(2):** 179-191.
3. **Abdullatif, O. M., (1989).** Channel-fill and sheet-flood facies sequences in the ephemeral terminal River Gash, Kassala, Sudan, Sedimentary Geology, **63(1):** 171~184.

4. **Ahmed, Y.M., (1996).** Organic matter characterization and environmental control on organic facies and lithofacies of early Cretaceous Lake Assalam, NW Muglad Basin, Sudan. Ph.D. Thesis, University of Tokyo, 110-112.
5. **Atalay Ayele, (2002).** Active compressional tectonics in central Africa and implications for plate tectonic models: evidence from fault mechanism studies of the 1998 earthquakes in the Congo Basin, Journal of African Earth Sciences, **35(1):** 45-50.
6. **Beauchamp, J. Omer, M. K., Periaux, J., (1990).** Province and dispersal pattern of the Cretaceous clastics in northeast Africa: Climate and structural setting. Journal of African Earth Science, **172(3):** 243-253.
7. **Bermingham, P. M., Fairhead, J. D. and Stuart, G. W., (1983).** Gravity study of the Central African Rift system: A model of continental disruption, The Darfur domal uplift and associated Cainozoic volcanism, Tectonophy- sics, **, 94 (2):** 205-222.
8. **Bosworth, W., (1992)** .Mesozoic and early Tertiary rift tectonics in east Africa, Tectonophysics**, (1), 209**, 115-137.
9. **Browne, S. E., Fairhead, J. D., (1983).** Gravity study of the central African rift system: a model of continental disruption, 1, The Ngaoundere and Abu Gabra rifts, Tectonophysics, **94(2):** 187-203.
10. **Browne, S. E., Fairhead, J. D., Mohamed, (1985).** Gravity study of the White Nile rift, Sudan, and its regional tectonic setting, Tectonophysics, **113 (1):** 123-137.
11. **Browne, S. E., Fairhead, J. D., (1983).** Gravity study of the central African rift system: a model of continental disruption, 1, The Ngaoundere and Abu Gabra rifts, Tectonophysics, **94 (2):** 187-203.
12. **Charles E. Payton, (1977).** Seismic stratigraphy, applications to hydrocarbon exploration, Tulsa, The American Association of Petroleum Geologists, 65-67.
13. **Dominic Emery, Keith Myers, (1996).** Sequence Stratigraphy, Oxford, Blackwell Science, 64-67.
14. **D. W. J. Bosence, (1998).** Stratigraphic and sedimentological models of rift basins, in: Sedimentation and Tectonics in Rift Basins, London: Chapman Hall, 9-25.

15. **Fairhead,** J. D., **Green,** C. M., (1989). Controls on rifting in Africa and the regional tectonic model for the Nigeria and east Niger rift basins, Journal of African Earth Science, **8(2):** 231-249.

16. **Gian Battista Vai,** (2003). Development of the palaeogeography of Pangaea from Late Carboniferous to Early Permian, Palaeogeography, Palaeoclimatology, Palaeoecology, **196(1-2):** 125-155.

17. **Kaska,** H. V., (1989). A spore and pollen zonation of Early Cretaceous to Tertiary non-marine sediments of central Sudan, Palynology, **13(1):** 79-90.

18. **McHarque,** T. R., **Heidrick,** T. L., **Livingston,** J. E., (1992). Tectonostratigraphic development of the interior Sudan rifts, central Africa. In: geodynamics of Rifting, Volume II, Case history studies on rifts: north and south America and Africa (Ed. by Ziegler, P.A.). Tectonophysics, **213(2):** 187-202.

19. **Mohamed,** A. Y., **Pearson,** M. J., **Ashcroft,** W. A., **et al.,** (1999). Modelling petrol- eum generation in the southern Muglad Basin, Sudan, American Association of Petroleum Geologists Bulletin, **83(6):** 1943-1964.

20. **Schull,** T. J., (1988)2 Rift basins of interior Sudan: Petroleum exploration and discovery, American Association of Petroleum Geologists Bulletin, **72(5):** 1128~1142.

21. T. **Pletsch,** J. **Erbacher,** A.E.L., **Holbourn,** (2001). Cretaceous separation of Africa and South America: the view from the West Africa margin (ODP Leg 159), Journal of South America Earth Sciences, **14(2):** 147-174.