Tectonostratigraphic Development of Lacustrine Deposits of Mesozoic-Cenozoic Basins, Muglad Basin, Sudan

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Abstract

Muglad Basin exposed to tectonic and structural regime which can be manifested clearly to characterize the tectonic history of the basin. Accordingly, models for time span, mechanism, deformation, and evolution of the Muglad were proposed. Muglad Basin, is a rift basin developed in Mesozoic-Cenozoic time and was initiated as an extensional basin or graben (half-graben) to the direct south of the Central African Shear Zone (CASZ). The basin opening occurred on a series of half-grabens trending NW-SE in Muglad Basin. The structural style is most convenient to be studied as assemblages of the correlative structures formed under a certain geological conditions, rather than to be studied as structural patterns such as faulting and folding. Structural analysis based on seismic data from Muglad Basin was set. The structural style of continental or nonmarine in Muglad basin, can be categorized into two major styles: thick skinned (basement-involved) and thin skinned (faults restricted to sediments only) categories.
The tecton stratigraphic framework of the rifting of Muglad Basin is a model of three phases was documented for Muglad Basin: pre-rifting phase, syn-rifting phase of three diverse episodes of rifting, and post-rifting sag phase.

Introduction

Lacustrine, nonmarine, and continental basins are terms interchangeably used by authors for those basins developed on continental crust and dominated by continental sedimentary infill. Most of the continental basins were formed in the Mesozoic particularly in the Cretaceous; however, the oldest continental basins were formed in Mid-Late Carboniferous and Permian. Hydrocarbon exploration in lacustrine rift basins has received inadequate conduct until the end of the 1970s. Some major aspects highlighted the significance of rift basins such as the recognition of lacustrine shales as good source rocks and the notable successes of petroleum exploration in rift basins (Begawan and Lambiase, 1995) and sand reservoir including turbidites, deltaic, and fluvial types. Many publications emphasized the economic and scientific interest of lacustrines (e.g., Zhu Xiaomin and Xin Quanlin, 1987a and 1987b; Ponte and Asmus, 1978; Ojeda, 1982; Estrella et. al., 1984 and Hussein, R., 2008).

Muglad Basin is located in the south-central Sudan forms part of a regionally linked intracontinental rift system (Fig. 1) that crossed Central Africa.
The Muglad Basin is the largest of the NW-SE trending rift basins in Sudan which is considered as a main component of West and Central African rift system (WCARS). It extends across at least 120,000 Km2, up to 200 km wide and over 800 km long (Bosworth, 1992) and locally contains up to 13 km of Cretaceous-Tertiary sediments and appears to be terminated against the Central African shear zone (CASZ) which extends for at least 2000 km across Africa from the Atlantic coast in the Gulf of Guinea through Cameroon, Chad, the Central African Republic, and into Sudan (Schull, 1988 and Fairhead, 1988).

This study is to establish and summarize the main features and categories of structures and tectonic development of lacustrine sequences during the geologic evolution of Muglad Basin, and to propose a commonly acceptable opinion on the forming mechanism of the basin.

Apparent role of tectonic on the lacustrine basin and reconstruction of structural style are characterized on the basis of data acquired during oil exploration from Muglad basin since Chevron time up to the recent discoveries.

Regional geology

Muglad Basin is a rift basin developed in Mesozoic-Cenozoic time span. It was initiated as an extensional basin or half-graben in the Late Jurassic/ Early Cretaceous to the direct south of the Central African Shear Zone (CASZ) (Fig 2.). The deep Cretaceous-Tertiary basins of south-central Sudan form part of
a regionally linked intracontinental rift system that crossed Central Africa (Fig. 2). The instigation of intracontinental rifting within West and Central Africa was concomitant with gradual breakup of Gondwana, particularly with separation of South America from Africa, involving their inherent connection. The interior of West and Central Africa exposed to strong and extensive rifting (Guirad and Maurin, 1992; Binks and Fairhead, 1992), which synchronized with the Pacific Plate subduction in the Mid/Late Jurassic-Early Cretaceous (Fig. 3).

**Fig. 1: Location Map of Muglad Basin.**
The first phase of subsidence was quite active and extensive, characterized by early-stage of rifting and late stage of thermal contracted sagging which continued up to the Santonian where a number of basins (particularly those are trending E-W) later uplifted and exposed to erosion.

![Regional Geology and Structure of Muglad Basin Manifesting Early Cretaceous Extension and Strike-slip-dominated Rift Basins in West and Central Africa-Noting two groups of basins with distinct orientations, NE-SW- trending and NE-SW- trending, respectively. CASZ- Central African.](Modified from Genik 1993)

The basin inversion was attributed to the far-field effect of initial collision of the African and Eurasian plates along the Alpine orogenic belt (Fig. 4). The NW-SE trending Tenere and
Muglad rift Basins escaped the inversion, because these basins axes are sub-parallel to compressional stress direction caused by the collision (HcHargue et al 1992).

Fig. 3: Regional Tectonic Setting Illustrating Onset of Opening of Atlantic Ocean on the Western Side and the Indian Ocean in the Eastern Side of Africa during the Late Jurassic to Early Cretaceous. Note: Muglad Rift Basin Initiated as a Result of the Transform Fault which extended into African Continent and leading to Strike-Slip fault of Central African Shear Zone (CASZ) (Modified from Fairhead & Green, 1989).

The second phase of subsidence of the basin initiated as a result of the compressional stress caused by the collision. Then, the direction of movement of the African plate changed relative to Eurasian plate that escorted to crustal-scale horizontal
extension in NE-SW direction in association with wrench-related basin inversion along the CASZ.

The second phase continued until the Middle Eocene, when the most intense collision occurred along the Alpine orogenic belt, resulting in closure of the Tethyan ocean and exerting a very strong influence on basin development in interior of Africa. Most of Mesozoic rift basin came to an end during the Middle Eocene, Except for the NW-SE- trending Tenere and
Sudanese rifts (HcHargue et al 1992).

The third phase of subsidence began in the Late Eocene and occurred in parts of Muglad Rift Basin as transtensional tectonic regime. Rejuvenation of the Central African shear Zone appears to have occurred several times with dextral movement in Late Cretaceous-Early Tertiary times producing narrow subsiding rift basin infilled with Cretaceous-Tertiary sediments (Browne and Fairhead, 1983; Browne et al. 1985).

The existence of Lower Cretaceous sediments within the basins supports the idea that these basins were structurally developing during early Cretaceous times, possibly as response to dextral shear. In western Sudan, the Central African shear zone transforms most of its dextral displacement into the southern Sudan Rift which is a major extensional basin that extends into a southeasterly direction through southern Sudan into Anza rift in the northern Kenya (Bosworth, 1992 and Reeves et al. 1986).

**Structural setting**

The most considerable recent debate is the nature of extensional fault system in the upper crust whether they are dominantly listric (e.g. Gibbs, 1987, 1989) or they are essentially planner (e.g., Jackson, 1989). Gibbs, 1984 used a half-graben model to describe rift-basin geometry. To investigate the nature of extensional fault system it is more convenient and reflective to correlate the structural assemblage
than to investigate the patterns of individual type of structure such as folding or faulting. Harding and Lowell 1979 studied the structural style as assemblages of the correlative structures formed under a certain geological conditions which could be studied collectively in order to attain and predict hydrocarbon traps. The structural style of Muglad basin -which is one of the continental or nonmarine basins- can be categorized into two major styles: thick skinned (basement-involved) and thin skinned (faults restricted to sediments only) categories. The thick skinned (basement-involved) includes: (1) strike-slip or wrench fault assemblage, (2) compressive blocks and thrusts, (3) extensional blocks and (4) warping arches, domes and sags. The thin skinned includes: (1) detached thrust- fold assemblage, (2) detached normal fault assemblage, (3) salt structures, and (4) shale structures. Variety of structural styles prefers allocation in certain plate-tectonic environments and associated with the basin tectonic settings, mechanism of basin formation, and sedimentary sequences. The various geometries of the Sudanese rift-basins are variations on a half-graben idea (D. Craig Mann, 1989).

In this study the structural style of nonmarine basin in Muglad Basin is characterized by extensional and/ or transtensional structural styles resulted from faulting system activities during Early Cretaceous stage and Early Tertiary. Therefore, Muglad Basin is categorized as thick skinned (?) and thin skinned fault
assemblage.

**Thick skinned (basement-involved) category**

Extensional basement-faulted blocks assemblage: In Muglad Basin the extensional sediment-basement-faulted blocks are thick skinned generally asymmetric in configuration and present large scale tilting blocks (shearing) (Fig.5) seismic lines SD77-59 and SD83-28 with steep fault dips that can be classified into two categories: antithetic and synthetic normal faults, and half-grabens which are the basic configurations of several complex rift-faulted basins (Fig. 5).

![Image](image_url)

**Fig. 5:** Seismic section (Line 3-Muglad block) showing several complex rift-basins and their mimic subbasins indicating extensional basement-faulted blocks assemblage. Note: overall basin is composed of at least 6 mimic subbasins.

They may also present some step fault blocks and horsts and grabens combination (Fig. 6). The authentic shape of thick-skin fault is still controversial; however, in Muglad Basin they developed in response to planar or listric (or dogleg) shaped half-graben (Fig.7) originating
within the deep crust or mantle (thick-skinned) creating pull apart.
Thick-skin faults connect to the underlying crustal detachment either on a “flat” or on a “ramp” on the basal detachment are common in Muglad Basin. Fault displacement is transferred between synthetic thick-skin faults by “transfer faults”. Transfer faults have been modeled as near vertical intersecting the main detachment faults at right angle (Lister et al. 1986 and Ebinger et al. 1987).

Fig. 6: Presents Seismic Cross Section Showing Some Step Fault Blocks (Horsts and Grabens Combination).

Nevertheless, in Muglad Basin transfer faults with this geometry (right angle) are rare.
Deformation in extensional basement-faulted blocks assemblage might be contemporaneous and/ or deuterogenic.
The subsiding mechanisms of the basins are ascribed to the block-faulting of the basement despite the type of the basin was post-orogenic, composite block-faults, or intracratonic rift basins.

Thus the majority of the faulting system in Muglad Basins are contemporaneous, i.e. growth faults. However, comparing with the pre-basin faults, they are deuterogenic faults. The rate of continental sedimentation plays a significant role on the erosion of fault scarp depending on the pace of the fault displacement. When the rate of sedimentation is low with rapid fault displacement, fault scarps eroded back.

Also, erosion can occur on the opposite updip side of a basin, when rotation of the block by thick skin faulting creates a new base level for sedimentation in the basin low; the updip edges commonly erodes to fill the newly formed depression. The compensation between basin extensional and subsiding rates controls the dip of contemporaneous faults.
Fig. 7: Seismic section (A) form Muglad Basin and diagrammatic Section (B) showing listric or dogleg shaped half-graben originating within the deep crust or mantle (thick-skinned) conforming to the eroded fault scarp geometry.

When the extensional rate is higher, the dips are gentle but when the subsidence rate is compensated by sedimentation, the dips are steep. In other hand, the composite block-faulted and postorogenic faulted basins have basement faults being relatively steep in dips with planar fault surfaces. The basement blocks of pull-apart basins caused by strike-slippering are theoretically vertical in dips but practically they exhibit small step-wise- basement-faulted blocks with gentle dipping angles. (Fig. 8).

Detached normal faults assemblage: The detached normal
faults assemblage thin skinned are not involved in the basement. Thin-skin detachment faults are antithetic to thick-skin detachment faults (Mann, D. Craig, 1989). They are accommodated in the sedimentary facies on passive margins and thick incompetent rocks inducing gravity slumping which are rare in Muglad Basin due to the gravity differences of the sediments and providing lubricant for detachment.

Fig. 8: Seismic Section Exhibits Small Parallel Stepwise Basement-faulted Blocks with Gentle Dipping Angles.

Thin skinned (basement not involved) category
In Muglad Basin the detached normal faults are characterized by listric plan within sedimentary sequences, steep near the surface and flat at the deep depth. The detached normal faults can be categorized in Muglad basin into the following modes: (i) Common normal faults assemblage, (ii) Antithetic normal faults assemblage, (iii) rollover anticlines or reverse drag anticlines assemblage, and (iv) miscellaneous normal fault
assemblage. (i) common normal faults assemblage are forming as a result of occurrence of the basin under successive extensional subsidence and sedimentation, thus, brittle sand and clay beds might be fractured forming normal faults which flattened out into plastic beds (e.g. salt or shale flowage) and occurred mostly in the flanks of the filled rifts and associated with changes of the thickness and sedimentary facies. (ii) antithetic normal faults assemblage are often observed in intracratonic rift basins. They habitually accommodated in the central areas of the faulted depression, corresponding to the depocenter. The listric faults firmed out into thick mudstones. Sandford (1959) used experiment model which emphasized that the normal faults propagate from outer to center when the cabbage-like graben (Fig.9) is caused by detachment and extension, or they propagate from the center outwards when the graben is caused by upwelling of the basal rocks or structural doming.
Fig. 9: Seismic section (SD82-43) from Muglad Basin Showing Antithetic Normal Faults propagating from the outer to center of the cabbage-like structure. The faults are Dominantly Listric within the Synrift Sequence.

The antithetic normal faults can be established as a result of local compensation of the extensional basal faults in interarc rift basins and in several depressions of the postorogenic basins. (iii) rollover anticlines or reverse drag anticlines assemblage are major structural style of the progressive delta sequences on passive continental margin (Bally et. al 1981, Gibbs 1984); however, they can be seen in the rift infilling sequence of the intracratonic failed rift basins due to reverse drag caused by the slipping and tilting of growth faults. They are occur predominantly in the downthrown blocks of the major boundary growth faults of both the northern and southern depressions of the Kaikang Trough (Fig. 10 - a) with
the axes parallel to the faults. Example is in the western side of the dintersection SD 79-65 and 78-58 b. The rollover anticlines are related to the gravity slumping along the growth fault planes. So long as the sedimentary sequences in basins were reversely dragged, accompanying the growth faults, the induced anticlines can be categorized into this structural style (10- b). The well developed plastic beds in the downthrown block gave rise to growth fault flattened out into the plastic bed and may form some rollover anticline. (iv) the other normal faults assemblage are small normal faults which have no relations to the basement faulted-blocks and couldn’t be referred to the fractured system caused by basin extension. They concentrated in a certain interval, some of them are related to the reservoir rocks and others concentrated in the source rocks. They couldn’t be explained by deuterogenic fractures. Two formation mechanisms could be suggested to explain this kind of faults. One in the reservoir intervals, they are caused by local gravity slumping of the differential compaction due to the irregular distribution of many isolated sandbodies in the deltaic area of a shallow lake basin and they are irregular in both the directions and dip angles but in Muglad basin can form by antithetic bedding plane faults not slumping (Mann, D. Craig 1989, Bally et. al 1981, Gibbs 1984). The other one is that the faults in the source rocks are resulted from minor fractures, which were caused by volume
expansion in the process of oil and gas generation and were displaced slightly under different overlying pressures (10-c).

Fig. 10: (a) Rollover Anticline: Example: West of Intersection of SD 79-65 7 78-58b. (b) Drag Fold Example: Amal -1 Structure. (c) Faulted anticline: Example: South of the Western Fault Step Zone between Seismic Lines SD 79-68 and SD 77-6.

Structural assemblage resulted from deformation of plastic rocks: Structural assemblage of salts, shales and claystones are formed due to the plastic flowage of rocks; however, deformation adjoins some factors such as tectonic settings and sedimentary conditions in order to provoke the formation of this structural style.

Basement flexure-uplift assemblage: It occurs only in intracratonic or stable platform. It is a resultant of vertical
movement of the crust along faults due to the association of faulted blocks in the basement on condition that completely rigidized. This assemblage is not present in Muglad Basin.

Basement thrusts assemblage: It is characterized by thrust faults and associated folds. The thrust faults cut both the basement and the overlying sediments. It is one of the thin skinned structural styles but is often misinterpreted, either as thick-skin basement-involved faults with decreasing displacement downwards, or as basin edge faults, which form the other half of a misinterpreted full graben. On seismic interpretations, reflectors below the detachment falsely appear faulted, but with smaller apparent fault displacements than seen above the detachment. This broken or faulted seismic character below the detachment is artificially produced by complex ray paths and lateral velocity variations across fault boundaries. Another difficulty faces the recognition of detached thrust fold assemblage in Mugald basin is the large variation in the size of detachment. If the study area and seismic lines are too small to see the whole fault system, large detachments can go unrecognized.

Detached thrust folds assemblage: they normally occur in sediments of the down-wrapping basins on cratons and on the sides adjacent orogenies. This structural style deformation happens where the original miogeosynclinal sediments on the continental margin was upthrusted onto the craton due to
terrain collision and the overlying sediments were compressed and deformed, forming complex detached thrust folds which extremely uplifted and induced gravity spreading and gravity sliding while the craton basement reserved comparatively stable due to its rigidity. The major parameters control the grade and convolution of the detached thrust folds are the magnitude of the colliding blocks, the thickness of the sedimentary sequences and the intercalations of competent and incompetent beds of the craton. Strike-slip or wrench fault assemblage: strike-slip deformation has a middle stress. The compressional or extensional field of stress can’t avoid inducing some wrench deformations. An asymmetrical graben structure with a tilted array of planar to listric faults was produced (Fig 11). The faults within the prerift sequence in the graben become sigmoidal as response to the internal deformation in the graben. These faults become listric within the synrift sequence (see fig. 11). The fault nucleation sequence indicates both hanging-wall and footwall nucleation. Many of the faults are nucleated relatively rapidly early in the deformation history and are active throughout the deformation.
Muglad Basin deformed in extensional-wrench. Extensional, pull-apart basins are usually occurred (Crowell, 1973). In addition, seismic line (GN98-020) from Muglad Basin (Fig. 12) the Nayil and Tendi Formations are primarily deposited and cover a thickness of 4 km. as a sedimentary drape strongly controlled by faulting to indicate another intensive phase of rifting.

The resulted sub-basins were superposed upon the Darfur-stage and bored faults were obviously formed by reactivating the previous structures. In addition, many new intra-basin faults were also created.
These newly formed faults, along with reactivated old ones, often make up negative flower structures (see Fig. 12) indicating sinistral movement and which confirms the presence of wrench deformation as one of the most typical criteria of wrench deformation which is characterized by vertical strike-slip faults without apparent vertical displacement. The dextral en echelon faults in horizon and the alternation or combination of the positive and negative flower structures in cross sections verify the presence of wrench faults in the area. Figure 13 summerizes the major structure assemblages of Muglad Basin.
Geometry and nature of the extensional detachment exert a fundamental control on the evolution of extensional basin structures. The horizontal or tilted detachments that generate extension above a restricted area experiencing stretching induce extensional basin geometries at the early stages of rifting. In these early stages rifts form and are bounded by two steep bounding faults, and internal
deformation within the asymmetrical rift is accommodated by an array of planar faults.

- Once the planar faults penetrate the synrift sequence, they become listric growth faults. Simple listric extensional detachments are characterized by rollover anticlines with gometrically necessary crestal-collapse graben structures. Within the crestal-collapse grabens, hanging-wall nucleation of new faults is dominant. At high extension value, the synthetic crestal-collapse graben faults develop into a fan of listric growth faults in the synrift sediments. Superposition of successive crestal-collapse grabens at high extension values produces complex arrays of intersecting faults.

- Ramp/flat listric extensional fault systems are characterized by a rollover anticline and crestal-collapse graben system associated with each steepening-upward segment of the detachment, and a ramp zone consisting of a hanging-wall syncline and a complex deformation zone. The hanging-wall syncline is characteristic of ramp/flat detachment geometries. The ramp/flat evolution of extensional basin structures developed above major detachment surfaces can be generated by horizontal or tilted detachments.

- Assessment for nonmaring deposits of Muglad Basin attained through integrating geophysical data, structural
analysis, and petroleum geology.

- It has been proved that nonmarine petroleum basins have very suitable geological conditions to form oil and gas pools. A series of giant oil and gas fields has been found besides lots of medium to small sized ones. This might enhance understanding of petroleum geological conditions of the Meso-Cenozoic nonmarine petroleum basins, support and enriched the theory of the petroleum formation and occurrence in nonmarine petroleum basins.

- In Muglad Basin, the assessment of petroleum achieved to zones, favorable reservoir–cap combinations and favorable plays and prospects throughout the Muglad Basin. Some remarks are worthy to be stressed. 1. Oil discoveries around the western flank of Unity oil field confirmed the presence of the kitchen in which the organic matters had been cooked and then generated oil and/or gas and latter by expulsion moved to the adjacent areas. The paleostructure was mature enough to trap the oil and later flow it from Tendi Formation to Kaikang-1; 2. In the northern part of the basin near the boarder of Fula subbasin, Abu Gabra Formation is well developed, thus, it is the major Cretaceous source rock in the area of the Unity oil field and; 3. The center of the Muglad Basin was regarded less prospective because the
Abu Gabra Formation is relatively thin due to the gravity study and the structure in the area is young. During the major lake development stage of a half-graben, the block-faulting was strong, the lake was wide and deep, thus, the source rock of large size and reservoir bodies were developed.

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