IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 5, Issue 5 Ver. I (Sep. – Oct. 2017), PP 19-25
www.iosrjournals.org

Geology of the Muglad Rift Basin of Interior Sudan

Hassan A. Ahmed and Maduka Bertram Ozumba
Pan African University (PAU) Life and Earth Sciences Institute University of Ibadan, Nigeria

Abstract: *The Muglad rift basin of interior Sudan is an integral part of the West and Central African Rift System (WCARS). It has undergone a polyphase development which has resulted in three major phases of extension with intervening periods when uplift and erosion or non-deposition have taken place. The depositional environment is nonmarine ranging from fluvial to lacustrine. The basin has probably undergone periods of transtensional deformation indicated by the rhomb fault geometry. Changes in plate motions have been recorded in great detail by the stratigraphy and fault geometries within the basin and the contiguous basins.*

The rift basin has commercial reserve of petroleum, with both Cretaceous and Tertiary petroleum systems active. The major exploration risk is the lateral seal and locally the effect of the tectonic rejuvenation as well as tectonic inversion. In some oilfields, the volcanic rocks constitute a major challenge to seismic imaging and interpretation.

Date of Submission: 23-09-2017 Date of acceptance: 06-10-2017

I. Introduction

This paper attempts to summarize the geology of the Muglad Basin from literature and the works of oil exploration companies in order to present the latest views on the subject. Rift basins of interior Sudan represent one of the major rift systems of the world. The deep Cretaceous – Tertiary basins form part of a regionally linked intracontinental rift system that crosses Central Africa (Fig. 1). The Muglad Basin is the largest of these NW – SE-oriented rift basins. The Muglad rift basin is up to 200 km wide and over 800 km long (i.e. *ca*. 160,000 km^2 in area) and locally contains up to 13 km thick Cretaceous-Tertiary nonmarine sediments (El Hassan *et al*., 2017). The smaller Melut, Ruat, White Nile, Khartoum, Atbara and Blue Nile rifts are evident on regional gravity maps and parallel the NW – SE Muglad trend (Fig. 1). To the northwest, these rift basins appear to terminate against the Central African Shear Zone (CASZ), which extends from Cameroon through Chad to Sudan according to Fairhead (1988). However, some crustal extension may have occurred to the north of the CASZ in the vicinity of the Blue Nile Basin. The southeastern limit of the Sudan extensional system is poorly known. However, the Muglad and Melut Basins may coalesce southeastward and link up with the Anza Rift in Kenya.

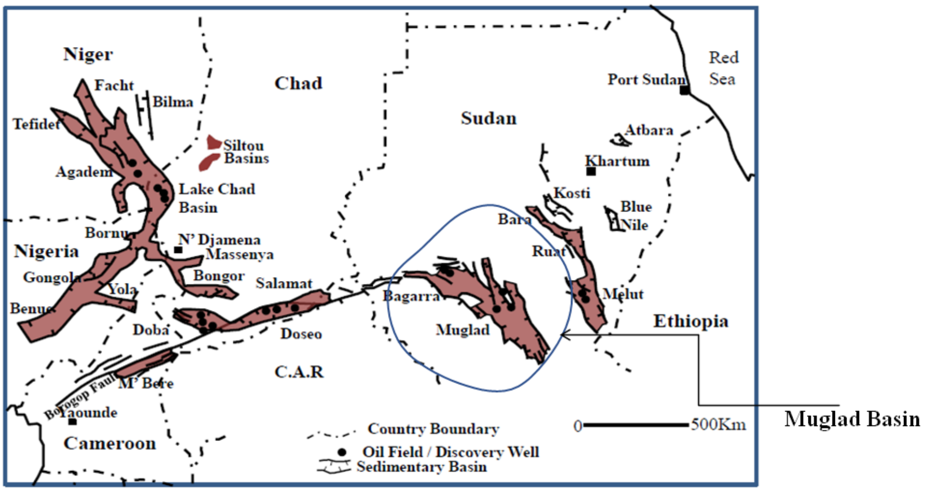


Fig. 1. Map showing the location of the Muglad Basin of Sudan as a part of the Central African Rift System (after Omatsola, 1987)

Various aspects of the Muglad Rift Basin, as part of the WCARS, have been studied over the past 35 years. Schull (1988) and El Hassan *et al*. (2017) proposed three rifting episodes giving three cycles of sediment deposition, with each cycle generating coarsening upward sedimentary sequences. McHargue *et al*. (1992) recognized three major episodes of rifting, concomitant subsidence and nonmarine sedimentation. Mann (1989) presented a model to interrelate thick-skin and thin-skin faults in the structural development of a half-graben basin in Sudan. Ibrahim *et al*. (1996) used potential field studies to investigate the lithospheric extension northwest of the Central African Shear Zone in Sudan. Mohamed *et al*. (1999, 2000) modeled the source rock section for hydrocarbon generation in the Abu Gabra Formation. Mohamed *et al*. (2001) studied the structural development and crustal stretching in the Muglad Basin. Dou *et al*. (2006) studied the control of the regional Aradeiba seal on the hydrocarbon accumulations. Dou *et al*. (2013) studied the petroleum geology of the Fula sub-basin (northeastern part of the Muglad Basin). Fairhead *et al*. (2013) investigated the role that plate tectonics, inferred stress changes and stratigraphic unconformities played in the evolution of the WCARS and the Atlantic continental margins. Dong *et al*. (2015) carried out tectono-sequence stratigraphic analysis of the Lower Cretaceous Abu Gabra Formation in the Fula sub-basin.

II. Tectonic Evolution

From these referenced studies, the Muglad Basin has been shown to be one of a series of Cretaceous - Cenozoic failed rifts extending from Benue Trough in Nigeria up to Sudan (Giedt, 1990). Fairhead (1988) interpreted the right-lateral movement on the CARS to have translated to the northeast – southwest extension, beginning in Barremian – Neocomian time and resulting in basins with an overall northwest – southeast trend, *i.e.* nearly perpendicular to the shear zone filled with about 13 km thick of nonmarine sediment. Schull (1988) and Giedt (1990) agreed that rifting continued into the Cenozoic, with seismic data indicating that approximately 35 km of the tectonic extension took place in the Muglad Basin.

III. Stratigraphic Frame and Depositional History

The Muglad Basin is filled with a Cretaceous - Cenozoic nonmarine sedimentary succession which is over 13,720 m thick in the deepest parts of the Kaikang Trough depocenter (Schull, 1988). McHargue *et al*. (1992) concluded that three major episodes of extensional tectonism are recognized: - Early Cretaceous (140 - 95 Ma), Late Cretaceous (95 - 65 Ma), and Paleogene (65 -30 Ma). Each episode started as a rifting phase and ended with a sag phase (Fig. 2). The stratigraphic succession of each rift-related depositional cycle begins near the rift margins with basal sand, followed upwards by a shale-dominated interval, reflecting the deepening of the basin. Shale-dominated sediments accumulated during periods of active rifting when subsidence was maximum. Sand-dominated sediments accumulated when rates of subsidence were relatively low, especially during the thermal sag phases. Syn-rift deposits of the first cycle (Abu Gabra Formation), is dominated by extensive lacustrine shales. Schull (1988) concluded that the lake water depth was apparently sufficient for the accumulation and preservation of organic-rich kerogenous shales that are the main source rocks for the oils found in this basin. Giedt (1990) supported the notion that the syn-rift deposits of the second episode (Aradeiba, Zarqa, and Ghazal Formations) and the third episode (Nayil and Tendi Formations) consist mainly of lacustrine as well as fluvial overbank shales.

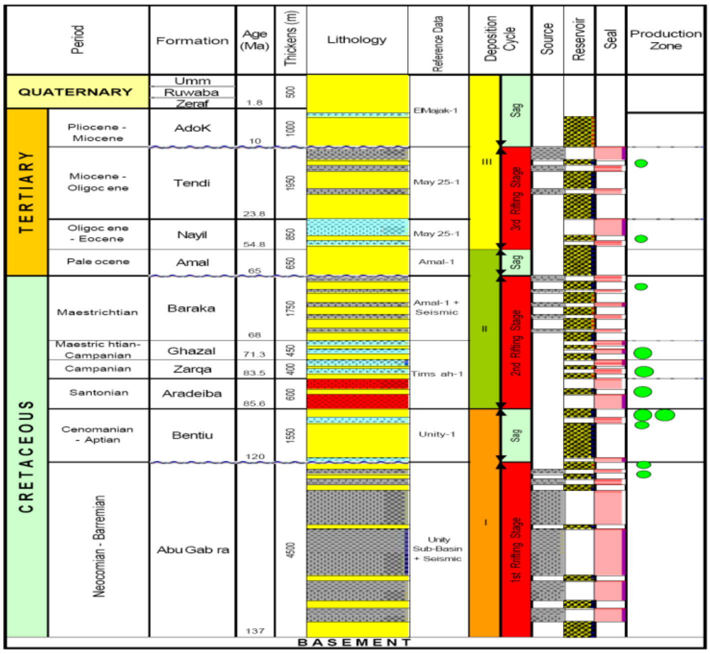


Fig. 2. General stratigraphic column - Muglad Basin, Sudan, showing three geological cycles – Neocomian to Barremian, Aptian to Maastrichtian, and Paleocene to Pliocene - Miocene, or Quaternary and Petroleum Systems (after Awad, 1999).

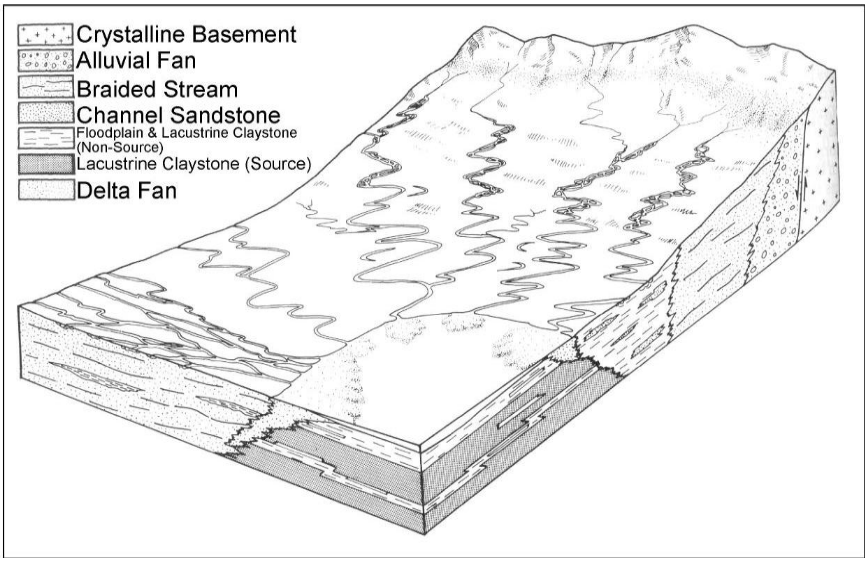


Fig. 3. Generalized depositional model depicting the environments operative during the filling of the southern Sudan Rift basin (after Schull, 1988).

Stratigraphic charts (Fig. 2) showing unconformities for the Muglad rift basin, are based on work by Chevron and GNPOC. These charts illustrate the difficulties of identifying unconformities and relating them to particular stages. What these charts do identify, however, are at least three major extensional rift basin events with each event having both a tectonic subsidence and a sag phase according to McHargue *et al*. (1992). Other stratigraphic charts (not shown) by Exxon, such as those by Genik (1993) and Guiraud (1993), do show that whilst the unconformities seen in Sudan are widespread within the WCARS basins, their precise timing remains uncertain. Fairhead *et al*. (2013) attempted the construction of the unified Tectonic correlation chart (Fig. 4) in order to correlate the unconformity events within the WCARS basins and bring order to ~~its~~ their tectonic evolution.

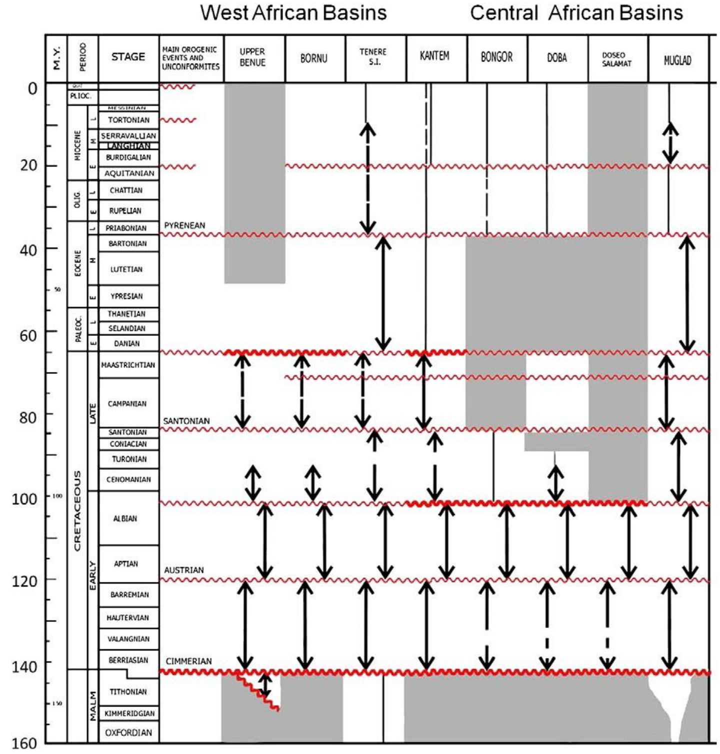


Fig. 4. Tectonic correlation chart of the Late Jurassic to Recent for WCARS and neighbouring basins constructed by R. Guiraud for GETECH (2002). Time scale in Ma after Gradstein and Ogg (1996). Unconformities are shown as red horizontal wavy lines with thicker red lines indicating major folding events. Double-headed arrows show rifting events. Grey areas indicate erosion or very reduced sedimentation.

IV. Structural Frame

Constructing a detailed structure and a basement map of the Muglad Basin requires the assembly of all available gravity and aeromagnetic data sets. These are the only data sets that completely cover the basin and that could be used to map the deep-seated structures and the morphology of the rift basement surface. To map the fault pattern of the basin. Fairhead *et al*. (2012) used the total horizontal derivative of the Bouguer anomaly (Fig. 5) such that faults and contacts appear as local maxima (red). Tracking these maxima enabled them to delineate most of the major structures. Since the study area straddles the magnetic equator, they did not use the magnetic data in any direct way to map these structures due to magnetic anisotropy effects, *i.e.* N–S trending structures are poorly imaged. The fault pattern mapped by Fairhead *et al*. (2013) (Fig. 4) shows distinct rhomb geometry, consisting of two distinct oblique fracture directions N to NNW and NW. Such geometry has probably resulted from the polyphase development with each phase having differing amounts of transtension according to Wu *et al*. (2009). The extensional nature of the basin has been clearly demonstrated by the broad-scale gravity response and by the known stratigraphy. The strike-slip component is more difficult to identify, but can be inferred from the development of the WCARS as a whole.

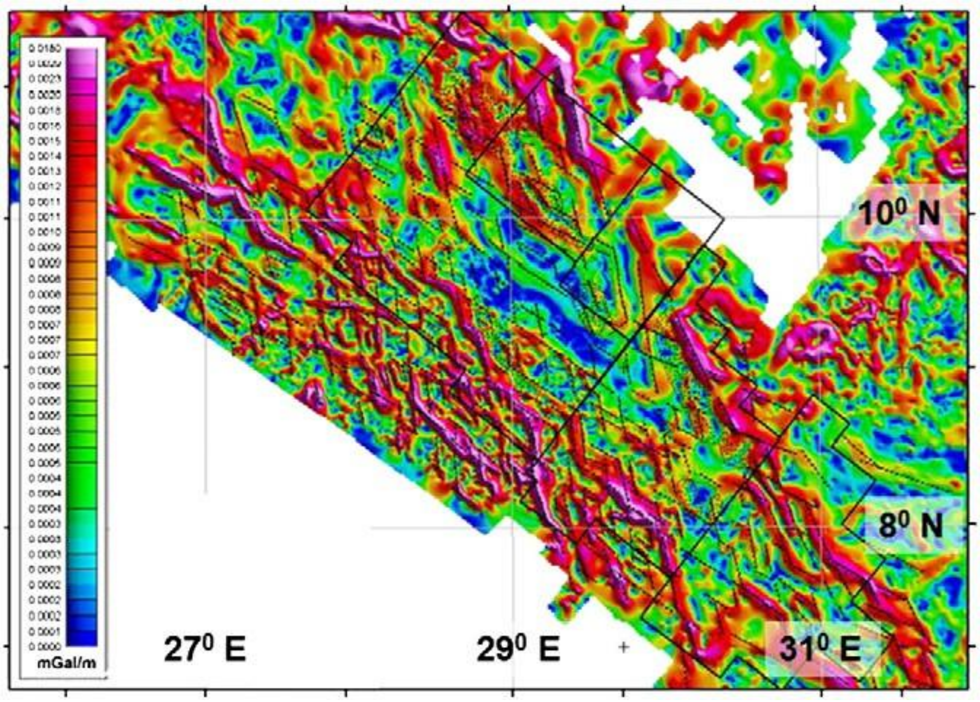


Fig. 5. The horizontal derivative of the Bouguer gravity showing the strong ‘rhomb’ geometry of fault pattern with fault trends N to NNW and NW (after Fairhead *et al*., 2013).

V. Petroleum Systems and Hydrocarbon Potential

Sudanese interior rift basins have been proven to be rich in hydrocarbon resources and the exploration and drilling activities provided tremendous amount data that assisted in understanding the tectonic regime within the region (El Hassan *et al*., 2017).

Exploration results have proved working hydrocarbon systems in both Tertiary and Cretaceous sections. The main hydrocarbon play is the Cretaceous petroleum system which has a perfect assemblage of source, reservoir, and top seal. The source is the Lower Cretaceous lacustrine shale of “Abu Gabra” Formation. The reservoir is the braided-stream sandstones of “Bentiu” Formation, and the top seal is the fluvial shale of Aradeiba Formation (Fig. 3). More than 70% of traps are tilted fault blocks with high dependency on the lateral seal across the bounding fault. Therefore, the above perfect association of source, reservoir, and top seal is counter-acted by a higher risk in the lateral seal. Bentiu Formation contains a massive thick sand (over 1500 m in some parts) of good quality reservoirs with localized shale interbeds 20 – 60 m thick.

VI. Hydrocarbon Exploration

The Muglad Rift Basin contains hydrocarbon accumulations of various sizes, the largest of which are the Heglig and Unity fields in Sudan and South Sudan respectively (El Hassan *et al*., 2017). The basin accounts for the bulk of Sudan's known oil reserves. Systematic hydrocarbon exploration in the interior basins of Sudan was carried out by Chevron Overseas Petroleum from 1975 to the 1990s, and significant hydrocarbon discoveries were made. The country currently produces about 280,000 BOPD. Blocks 2, and 4 (Fig. 6) lie in the central part of this basin. Greater Nile Petroleum Operating Company (GNPOC) operates these blocks for a consortium of China National Petroleum Company (CNPC) (40%), Petronas Carigali Overseas Bhd (PCOSB) (30%), ONGC Videsh Limited (OVL) (25%), and Sudanese Petroleum Corporation (SUDAPET) (5%).

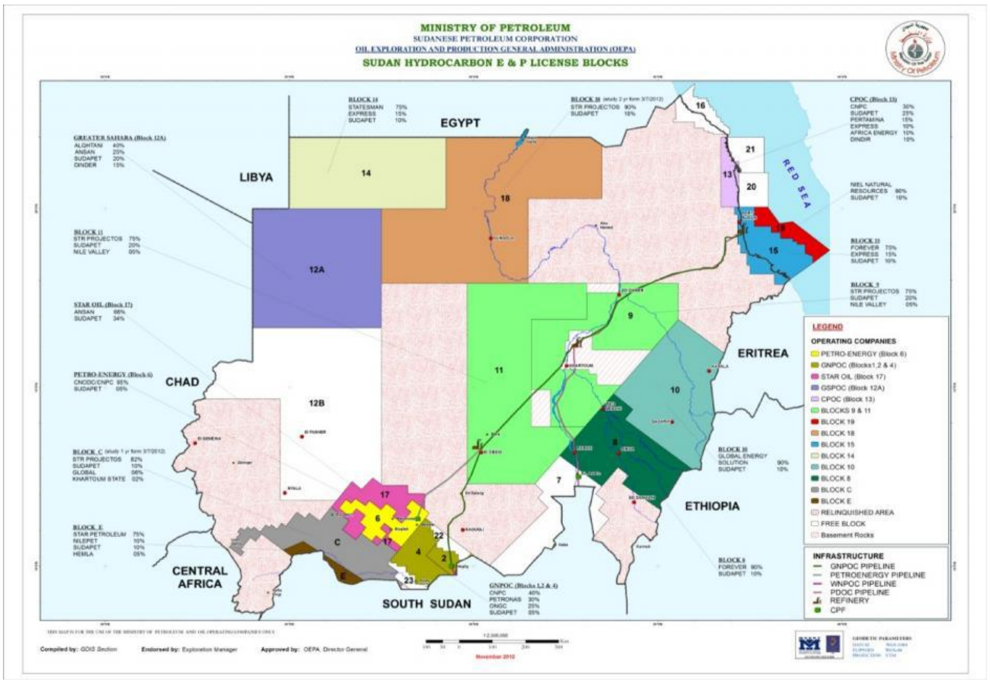


Fig. 6. Sudan hydrocarbon E & P license Blocks (after OEPA, 2012). Map showing the location of blocks 2 and 4.

VII. Hydrocarbon Traps, Trapping Configurations and Sealing Styles

The Muglad rift basin remains an active exploration and development focus. Tilted fault blocks, horst blocks, anticlinal drapes, and hanging-wall rollovers along normal faults have been proven as hydrocarbon traps (Fig. 7).

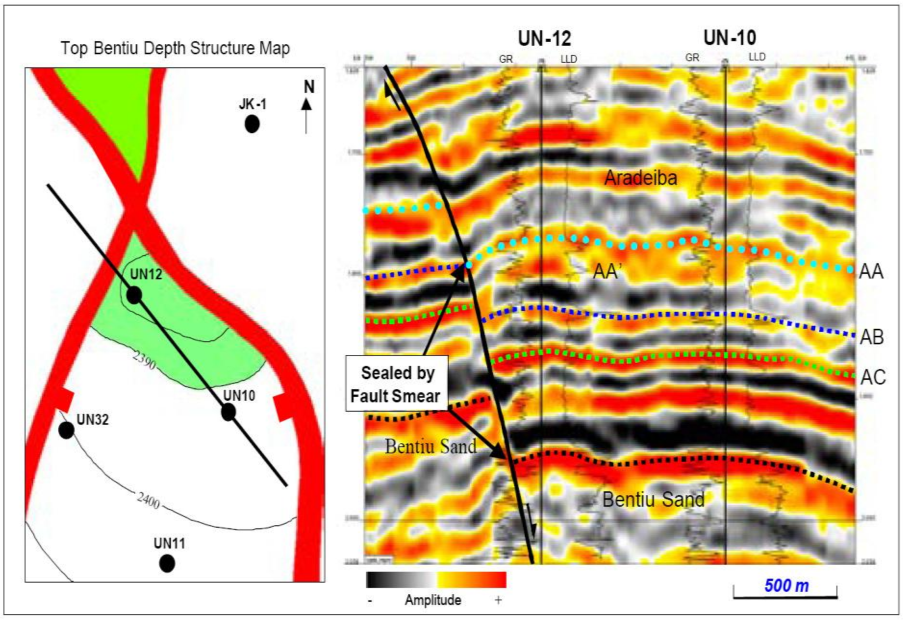
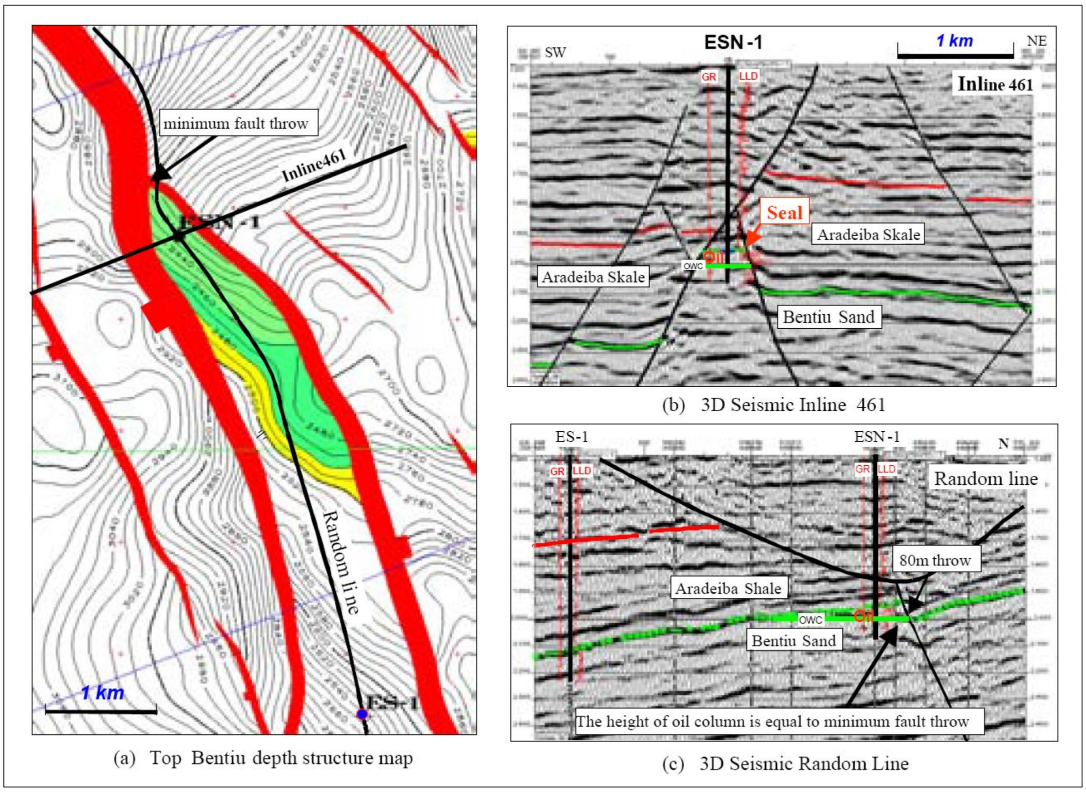


Fig. 7. Example of oil discovery in a hanging-wall fault block. AA, AB, and AC sands are production zones with more than 50-m oil columns. AB and AC sands juxtaposed against Aradeiba intraformational shale across the fault provide good lateral seal; AA and Bentiu sands are juxtaposed against AB sand and Bentiu massive sand respectively, but shale fault smear provides a good lateral seal, resulting in a small oil column in Bentiu reservoir. (after Idris *et al.*, 2005).

Lateral seal depends on the thickness and the lithology of the Aradeiba shale and the magnitude of fault throw. The Aradeiba Formation is highly variable in thickness and in sand/shale ratio. Thickest Aradeiba Formation penetration to date is in excess of 1000 m in the central part of the basin, decreasing to less than 20 m along the basin edges. Most of the perfect lateral seals are due to direct juxtaposition of the Bentiu Sandstone reservoirs against the Aradeiba Shale. Examples of this situation are illustrated in (Fig. 8). In some cases, clay smear and shale gouge ratio play an important role in lateral seal integrity (Fig. 7). The shale gouge ratio seems to depend on shale thickness and the amount of displacement along the fault plane. Shale gouge will, of course, also



(a) Top Bentiu depth structure map

(b) 3D Seismic Inline 461

(c) 3D Seismic Random Line

Fig. 8. An excellent fault-seal example. (a) Oil column is controlled by the fault throw in the northern part. (b) The thick (approximately 400 m) massive Aradeiba Shale provides a good top and lateral seals for the Bentiu reservoir. (c) 3D random section illustrates that the oil column is nearly equal to minimum fault throw (80 m) at which point sand is juxtaposed (after Idris *et al*., 2005). depend on clay mineralogy, but this aspect has not been fully investigated in the basin (Idris *et al*., 2005).

VIII. Summary

The Muglad Basin of Sudan is an integral part of the WCARS. Its geology has been better understood based on published studies and reports of oil and gas companies. The fault pattern shows distinct rhomb geometry consisting of two oblique fracture systems trending north and northwest, though to be due to polyphase development with varying amounts of transtension. Basin fill was in three phases and consisted of both sand-dominated and shale-dominated facies accumulated during low rates of basin subsidence. Lacustrine shales deposited in deep lacustrine settings favoured the accumulation and preservation of organic-rich shales that generated hydrocarbons. The basin thus has commercial reserves of petroleum, with both Cretaceous and Tertiary petroleum systems active. The major exploration risks include lateral sealing, the effect of the tectonic rejuvenation and tectonic inversion as well as the presence of volcanics which tend to adversely affect seismic imaging.

References

[1] Awad, M. Z., 1999. General stratigraphic column - Muglad Rift Basin of Interior Sudan.

[2] Dong, W., Xiaomin, Z., Yongdi, S., Yutong, L., Zhi, L., Yuanyuan, Z., 2015. Tectonosequence stratigraphic analysis of the lower cretaceous Abu Gabra Formation in the Fula sub-basin, Muglad Basin, southern Sudan. Mar. Petroleum Geol. 67, 286e306.

[3] Dou, L., Cheng, D., Li, Z., Zhang, Z., Wang, J., 2013. Petroleum geology of the Fula sub-basin, Muglad Basin, Sudan. *J. Petroleum Geol*. 36, 43e60.

[4] El Hassan, W.M, Farwa, A.G., Awad, M. Z., 2017. Inversion tectonics in Central Africa Rift System: Evidence from the Heglig Field. Marine and Petroleum Geology 80 (2017) 293-306.

[5] 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, 181e191.

[6] Fairhead, J.D., Mazur, S., Green, C.M., Masterton, S., Yousif, M.E., 2012. Regional plate tectonic controls on the evolution of the West and Central African rift system, with a focus on the Muglad Rift Basin, Sudan. SAPEG. Journal Sudanese Association of Petroleum Geoscientists (3), 14–29 (Feb 2012).

[7] Fairhead, J.D., Green, C.M., Masterton, S.M., Guiraud, R., 2013. The role that plate tectonics, inferred stress changes and stratigraphic unconformities have on the evolution of the West and Central African Rift System and the Atlantic continental margins. *Tectonophysics* 594, 118e127.

[8] Genik, G.J., 1993. Petroleum Geology of cretaceous–tertiary rift basins in Niger, Chad, and Central African Republic. American Association of Petroleum Geologists Bulletin 77, 1405–1434.

[9] Giedt, N.R., 1990. Unity field. In: Beaumont, E.A., Foster, N.H. (Eds.), Structural Traps III. Treatise of Petroleum Geology, Atlas of Oil and Gas Fields. AAPG, pp. 177e197.

[10] GETECH, 2002. Central African basins study. Unpublished report pp. 253.

[11] Gradstein, F.M., Ogg, J., 1996. A Phanerozoic time scale. *Episodes* 19, 3–4 (and table).

[12] Guiraud, R., 1993. Late Jurassic rifting - Early Cretaceous rifting and Late Cretaceous transpressional inversion in the upper Benue Basin (NE Nigeria). *Bulletin des Centres de Recherches Exploration - Production Elf-Aquitaine* 17, 371–383.

[13] Ibrahim, A.E., Ebinger, C.J., Fairhead, J.D., 1996. Lithospheric extension northwest of the Central African Shear Zone in Sudan from potential field studies. *Tectonophysics* 255, 79e97.

[14] Idris, K. M., and Yongdi, S., 2005. Lateral Seal – A Major Exploration Risk in the Faulted Traps of the Cretaceous Petroleum System - Central Muglad Basin, Sudan. AAPG International Conference & Exhibition, Cancun, Mexico, October 24-27, 2004.

[15] Mann, D.C., 1989. Thick-skin and thin-skin detachment faults in continental Sudanese rift basins. *J. Afr. Earth Sci*. 8, 307e322.

[16] McHargue, T.R., Heidrick, T.L., Livingston, J.E., 1992. Tectonostratigraphic development of the interior Sudan rifts, central Africa. *Tectonophysics* 213, 187e202.

[17] Mohamed, A.Y., Pearsons, M.J., Ashcroft, W.A., Iliffe, W.A., Whiteman, A.J., 1999. Modelling petroleum generation in the southern Muglad Rift Basin, Sudan. *AAPG* 83, 1943 – 1964.

[18] Mohamed, A.Y., Iliffe, J.E., Ashcroft, W.A., Whiteman, A.J., 2000. Burial history and maturation history of the Heglig filed area, Muglad Basin, Sudan. J. Petroleum 23, 107- 128.

[19] Mohamed, A.Y., Ashcroft, W.A., Whiteman, A.J., 2001. Structural development and crustal stretching in the Muglad Basin, southern Sudan. J. Afr. Earth Sci. 32, 179-191.

[20] OIL Exploration and Production Authority (OEPA), Ministry of Petroleum. Sudan hydrocarbon E & P license Blocks. 2012

[21] Schull, T.J., 1988. Rift basins of interior Sudan: petroleum exploration and discovery. AAPG 72, 1128e1142.

[22] Wu, J.E., Mcclay, K., Whitehouse, P., Dooley, T., 2009. 4D analogue modelling of transtensional pull-apart basins. *Marine and Petroleum Geology*, 26(8), pp. 1608–1623.

Hassan A. Ahmed Geology of the Muglad Rift Basin of Interior Sudan. IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG) , vol. 5, no. 5, 2017, pp. 19-25.