Regional tectonic controls on basement architecture and oil accumulation within the Muglad basin, Sudan

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SUMMARY

The Muglad basin, Sudan, is a good example of polyphase rifting with at least three major phases of basin development. Each phase has resulted in the generation of source rock, reservoir and seal geology with structural traps often closely linked to basement highs. In this contribution we investigate the tectonic processes that have contributed to basin development at both macro and micro scales.

The macro perspective investigates the basin's evolution as part of an Africa wide rift system and how it is intimately linked to global plate tectonics and to changes in plate interactions. These changes in plate interactions have caused significant modifications in the orientation and magnitude of the African stress field which in turn has controlled the development of the rift system. On the micro basin scale, the methods used to investigate structure include the compilation of structural maps for different time periods of the individual rift basins into regional structural maps, the role and importance of stratigraphic unconformities within basins and geophysical mapping of the basement morphology of the Muglad basin using an integrated interpretation approach.

INTRODUCTION

The Mesozoic plate tectonic link between the opening of the Atlantic Ocean and the development of the West and Central African Rift system (WCARS) via the Benue Trough and shear zones cutting Cameroon is not a new idea, nor is the polyphase development of the WCARS. What is new is the improved resolution and definition of the datasets used to establish the linkage. We now have for the Atlantic Ocean, the best available satellite derived free air gravity dataset (Fairhead et al 2009; Figure 1) which has improved the spatial resolution down to ~6.5 km (half wavelength). The gravity data principally images the response of the bathymetry and near sub-seafloor structures, mainly resulting from seafloor spreading processes at the mid Atlantic ridge. Thus the enhanced resolution gravity data are able to improve the plate model to define its opening history. The message that comes repeatedly from the gravity field of the oceanic sector is that the opening process at the mid-oceanic ridge clearly responds to changes in relative plate motions resulting from local and far field changes in plate interactions e.g. Africa-Europe and India-Asia plate collisions. This is recorded by both subtle and distinctive changes in the fracture zone (flowline) directions with a estimated response time of about 10 Ma. We show how such changes in plate motions, seen within the oceanic domain are replicated within the rift basins of the WCARS in the form of changes in structural style that relate closely to rift orientation and ultimately to the stratigraphic record within the basins in the form of unconformities. We further show for the Muglad rift basin that by mapping the structure and depth to basement, based on the interpretation of the gravity data, constrained by magnetic, seismic and well data, that the fracture pattern within the rift has a distinct rhomb style that has developed from repeated periods of extension and shear tectonics. This has resulted in the current basement architecture which contains elongate basement highs as deduced from the inversion of the gravity data. Such basinal studies thus help to high grade target areas within the basin for future exploration

RELATIVE PLATE MOTIONS

The free air gravity image of the oceans has been derived from satellite altimetry data and principally images the gravity response of the sea floor density interface and provides important insights into the plate tectonic fabric of the ocean floor

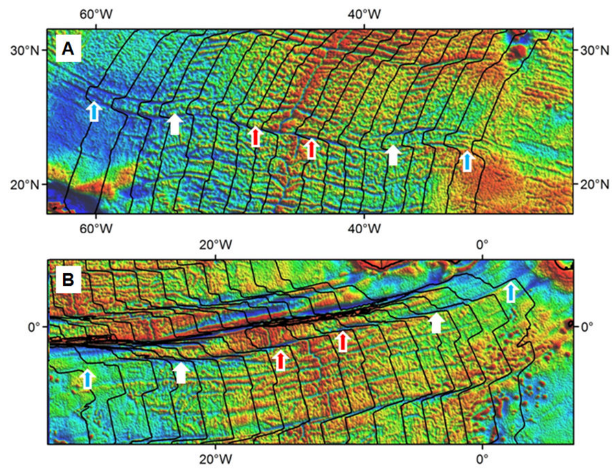

Figure 1. Free air gravity maps for A: The Central Atlantic and B: Equatorial and northern South Atlantic based on the satellite solution after Fairhead et al (2009). The images clearly show well defined fracture zones and their subtle changes in relative plate motions. Superimposed are the isochrons at 10Ma intervals and arrows (red 16Ma, white 55Ma and blue 89Ma) of the mid-age of the unconformities shown in Figure 3.

Figure 1 shows the gravity field of the Central Atlantic and the northern South Atlantic. It images the fractures zones emanating from the mid Atlantic ridge which allow the relative flowline directions of plate motion to be identified. These fracture zones systematically change direction in a temporal and spatial manner and thus record changes in relative plate motions. Superimposed on the images are magnetic isochrons at 10 Ma intervals, excluding the 0 Ma the mid ocean ridge. This allows the age of the ocean crust to be determined. The gravity images reveal that the flow lines are more distinct (greater curvature) in the Central Atlantic and less so in the northern South Atlantic. This is considered to be due, in part, to the transformation of the differential plate motions on either side of the Equatorial fracture zone being taken up by crustal deformation within Africa as the WCARS.

WEST & CENTRAL AFRICAN RIFT SYSTEM

The plate tectonic link between the oceanic fracture zones and the WCARS occurs at the Niger delta. Here at the SW end of the Benue Trough the gravity and magnetic data (see Figure 2) clearly show the ocean fracture zones beneath the Niger Delta and continue into the Benue Trough. The overall tectonic model for the WCARS is a complex set of interconnecting shear, wrench and extensional basins extending from Nigeria and Cameroon, on the Atlantic coast, eastwards via Chad and Central African Republic into Sudan through Kenya to the Indian Ocean and north from Lake Chad as the Tenere rift and extending into southernmost Algeria (Figure 3).

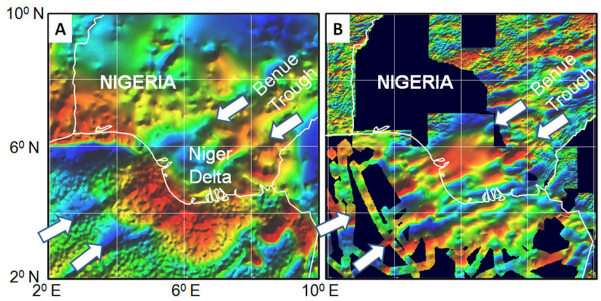

Figure 2. A: The free air (offshore) and Bouguer (onshore) gravity field of the Niger Delta region showing that the oceanic fracture zones can be identified beneath the delta and enter the Benue Trough. B: The Total magnetic intensity (TMI) field response of the fracture zones supports the gravity interpretation that oceanic crust exists beneath a major portion of the delta.

Each rift section of WCARS exhibits the classic features of the McKenzie sedimentary rift basin model (McKenzie, 1978). Under tension, the upper crust will undergo brittle failure resulting in rifting while the lower crust/upper mantle will deform by ductile stretching resulting in an overall isostatic subsidence of the ground surface and elevation of the Moho beneath the rift basin. When the crustal tension is reduced or removed, the tectonically driven subsidence changes to a sag phase of subsidence resulting from the passive response of a cooling and thermal contracting upper mantle beneath the rift. Such a model is consistent with the regional positive gravity response seen over all segments of the WCARS (Fairhead and Green 1989, Figure 3). The most recent sag phase is clearly seen on seismic reflection data for the basins in NE Nigeria (Avbovbo, et al.,1986) and for Sudan see Figure 3.

Since the WCARS cuts Africa from the Atlantic to the Indian Oceans, the rift system acts as an effective west-east stress barrier to stress propagation originating from the collision of the Africa - Europe plates. As with the adage "*A chain is as strong as its weakest link*", then the WCARS is Africa's 'weakest link' such that stresses originating from the Africa - Europe plate collision will be accommodated within the WCARS by crustal deformation (compression, shear and/or extension). However, the geometry i.e. orientation of the rift basins (Figure 3), and the motion of North Africa (with anticlockwise rotation) will control how each rift basin responds, at any given time, to the stress field. For example a compression event observed for one rift basin, perpendicular

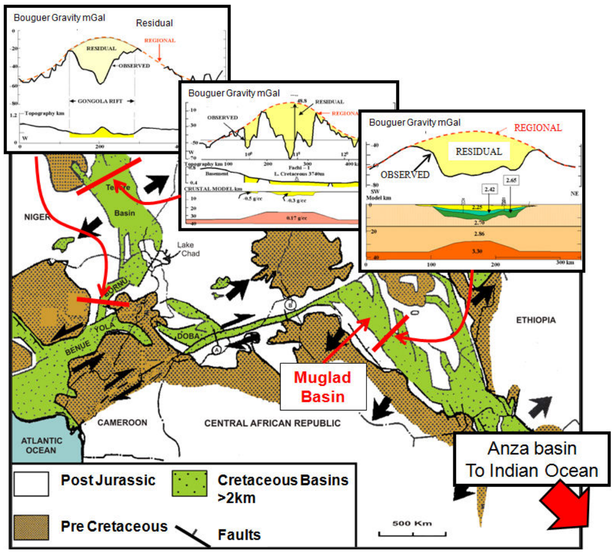

Figure 3. The spatial geometry of the West Central African Rift system (WCARS) showing the strong regional positive gravity response over the rifts (due to the shallow Moho) from selected profiles across three segments of the rift system.

to the principal horizontal stress direction e.g. Santonian event in the Benue Trough, will be seen as either a shear movement if a rift strikes parallel to the stress direction or an extensional event, e.g. Sudan rifts, as a result of the anticlockwise rotation of North Africa. All these structural styles, at any given time, will be linked to the same stress field but the orientation of the rifts within the stress field significantly alters the resulting structures. Since the stress field has changed with time, a distinct set of stratigraphic unconformities have developed and are recorded by seismic reflection imaging and from well data. The unconformities represent hiatuses in basin development that can be correlated between basins within the WCARS (Guiraud et al., 1992).

The regional uplift, resulting from the Tertiary development of the Cameroon volcanic line, has resulted in many of the Mesozoic rift basins, in the region of the uplift, being partly exposed, thus allowing them to be investigated in great detail by Rene Guiraud over a thirty year period. His structural mapping of the Benue Trough and southern Chad rift basins shows for the Barremian (~120Ma), the Aptian-Albian (~101Ma) and the late Santonian (~84Ma) that the orientation of the stress system changed dramatically. For this early period within the Muglad basin there are three unconformities shown in Figure 4. The correlation of these and the other two unconformities between the basins of the WCARS have already been identified and reported by Guiraud et al., (1992) representing regional changes in the stress field. For the Muglad basin. Guiraud and Bosworth (1997) have also reported the early shear events along the axis of the rift.

THE MUGLAD BASIN, SUDAN

The unconformities identified within the Muglad basin of Sudan (Figures 4) clearly indicate at least three major extensional rifting events have occurred (McHargue et al., 1992). Using the new stratigraphy chart for the Muglad basin, we have superimposed the mid-point of the timing of these last three unconformities onto the fracture zone geometry of the Central and northern South Atlantic sections of the oceanic crust using the magnetic isochrons as a time reference.

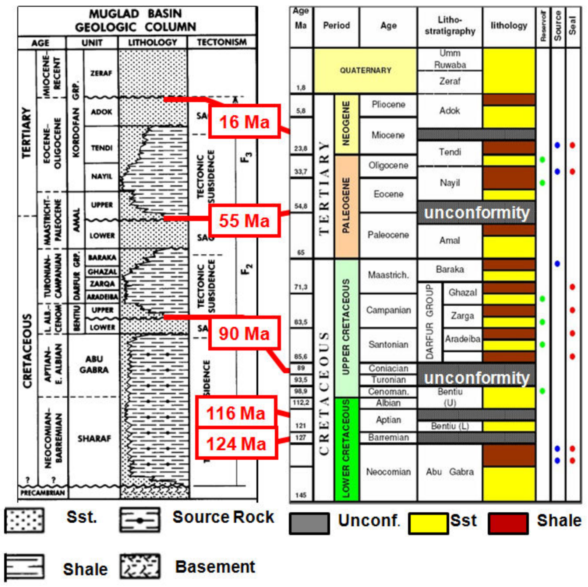

Figure 4. Stratigraphy Charts for the Muglad basin, Sudan Left: after Mc Hargue et al., 1992 and Right: more recent GNPOC version showing the major and minor unconformities with mid-age in red.

There is a good temporal correlation of the timing of the three youngest unconformities at 16Ma, 55Ma, and 89Ma with the inflection points in the curvature of the fracture zones (Figure 1). The stratigraphy chart, indicates the duration of these unconformities are between 7 and 10 Ma which is similar to the period of time that fracture zone take to change direction (Figure 1).

STRUCTURAL STYLE OF THE MUGLAD BASIN

To undertake a detailed structure and basement mapping of the Muglad basin requires a good quality compilation of all the available gravity and aeromagnetic datasets. These datasets are the only datasets that completely cover the basin (Figure 5) and through their inversion we have the ability to map the deep seated structures and morphology of the rift basement surface.

To map the structural faulting of the basin we used the total horizontal derivative of the Bouguer anomaly (Figure 6) such that faults and contacts appear as local maxima. Tracking these maxima enabled us to delineate most of the major structures. Since the study area straddles the magnetic equator, we could not use the magnetic data in any direct way to map these structures due to magnetic anisotropy effects.

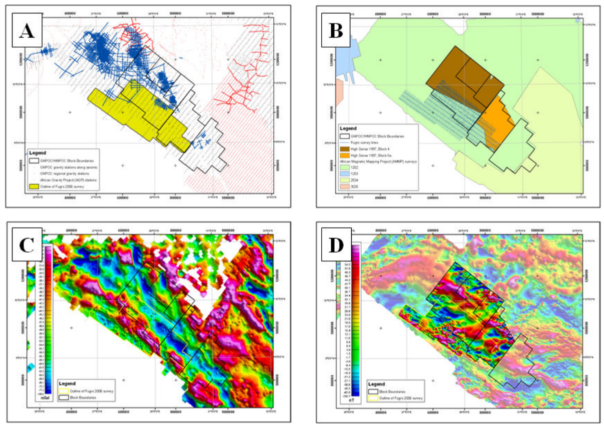

Figure 5. The compilation of available (A) gravity and (B) aeromagnetic datasets and the resulting (C) Bouguer anomaly and (D) TMI maps.

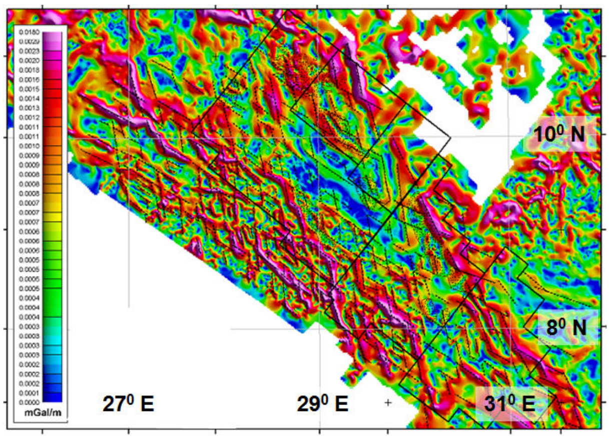

Figure 6. The horizontal derivative of the Bouguer gravity showing the strong rhomb style of faulting with fault trends N to NNW and NW

The faults mapped in Figure 6 show a distinct rhomb geometry, consisting of two distinct oblique fracture directions N to NNW and NW. Such geometry supports a multiple phase tectonic reactivation of the basin with significant components of wrench/shear and extension.

To obtain a robust 3D basement depth map suitable for identifying potential exploration targets, the density-depth function of the basin was first determined using a series of carefully selected 2D profiles (Figure 7) that coincided with wells and interpreted seismic lines.

The 2D gravity and magnetic profile interpretations were constrained by 14 well density and interval velocity datasets, by numerous seismic sections that were used to define both the internal structure of the basin along the profiles and depths derived from the TWT and average processing velocities. In addition magnetic derived basement depth estimates based on the Euler, SPI and Tilt-Depth methods were used. The modelling (see example of Profile 2, Figure 8) was also used to define the Moho' uplift in the region.

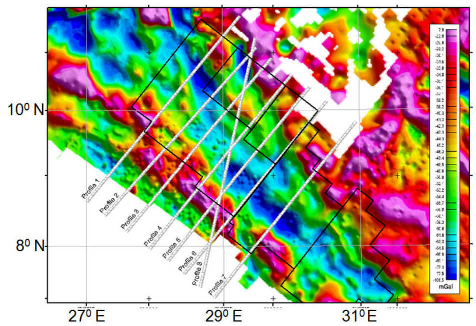

Figure 7. Bouguer anomaly map of the Muglad basin showing the 8 profiles used for 2D interpretations.

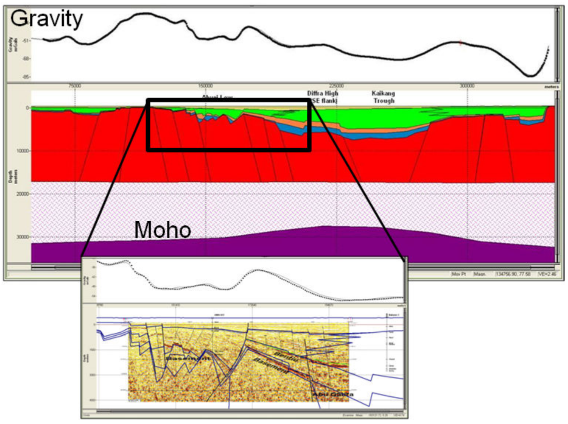

Figure 8. Profile 2 showing crustal and upper crustal 2D model with location of seismic section and 3 wells (not shown) to constrain the interpretation.

The derived density depth function was then used within the 3D inversion model program of Cordell & Henderson (1968), suitably modified to handle a set of smoothly varying density-depth functions to determine basement depth. The gravity field used had been corrected for the smooth regional positive gravity field resulting from the elevated Moho' (see Figure 8). The correlation between the gravity response and the basement surface is excellent, as previously proprietary exploration studies have determined.

CONCLUSIONS

Although there are uncertainties in the age of oceanic crust and basinal unconformities, this study has shown at a macro tectonic scale the importance of unconformities as a tectonic correlation tool. These unconformities are common to all basins in the WCARS, mark changes in the African stress field and can be directly linked to changes in the relative opening of the ocean floor. The Muglad basin has undergone a polyphase development which has resulted in three major phases of extension with intervening periods (unconformities) when uplift, erosion, non-deposition have taken place. Evidence from other rift basins within the WCARS infers that the Muglad basin has also undergone periods of shear deformation. Thus the WCARS can be shown to be intimately connected to regional plate tectonic processes which are recorded in the stratigraphy and fault geometries of the basins. How the sequence of plate tectonics events links with the stratigraphy and changes in plate motions is complex and is still poorly understood and is a research area that is worthy of further investigation.

The polyphase development of the Muglad basin and the strong rhomb fault geometry of the basement is clearly delineate by the gravity data. Such geometries are conducive to the reworking of basement faults resulting in block and/or linear uplift. Such uplifts have deformed the sedimentary layers above generated a significant number of oil traps above these basement highs.

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REFERENCES

Avbovbo, A. A. Ayoola, E. O. and Osahon, G. A.[1986] Depositional and structural styles in Chad basin of north eastern Nigeria. Amer. Ass. Pet. Geol. Bull. 70 (12):1787-1798.

Cordell, L. and Henderson, R.G. [1968] Iterative three dimensional solution of gravity anomaly data using a digital computer. Geophysics, 33, 596-601.

Fairhead, J.D. and 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 Sciences, Vol. 8, Nos. 2/3/4, pp. 231-249.

Fairhead, J.D., Williams, S.E., Fletcher, K.M.U., Green, C.M. and Vincent, K. [2009] Trident – A New Satellite Gravity Model for the Oceans EAGE Amsterdam, Extended Abstract 6039, 71st EAGE Conference & Exhibition — Amsterdam, The Netherlands, 8 - 11 June 2009

Guiraud, R., Binks, R.M., Fairhead, J.D. & Wilson, M. [1992] Chronology and geodynamic setting of Cretaceous-Cenozoic rifting in West and Central Africa, Tectonophysics, 213, p. 227-234.

Guiraud R. & Bosworth W. [1997] – Senonian basin inversion and rejuvenation of rifting in Africa and Arabia. Synthesis and implications to plate-scale tectonics. Tectonophysics, 282, p, 39-82.

McHargue, T.R., Heidrick, T.L. & Livingstone, J. [1992] Tectonostratigraphic development of the Interior Sudan Rifts, Central African. In: P.A. Ziegler (ed.), Geodynamics of Rifting, Vol. II. Case History Studies on Rifts: North and South America and Africa. Tectonophysics, 213 p. 187-202.

McKenzie, D.P., [1978] Some remarks on the development of sedimentary basins. Earth Planet. Sci. Lett., 40: