STRUCTURE AND EVOLUTION OF THE BENUE TROUGH

BY

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INTRODUCTION

Rifted structures represent one of the most important geological features in the world. They are to be found over oceans as well as within the continents. Rifts represent sites of continental breakups or failed breakups and are often associated with the accumulation of hydrocarbon and such minerals as coal, phosphates, barite, copper, lead, zinc, collumbite, uranium and sulfides

•The African continent is characterized by two major rift systems. These are the East African Rift System of Tertiary to Recent age and the West and Central African Rift System of Cretaceous to Early Tertiary age.

•The NE trending Benue Trough with an approximate length of 800km is the main component of the West and Central African Rift System which is linked to the East African Rift System via the Abu Gabra Rift.

•The Benue Trough has for long been recognized as one of the main structures associated with the breakup of Gondwana, the separation of Africa from South America and the opening of the South Atlantic Ocean (Figure 1).

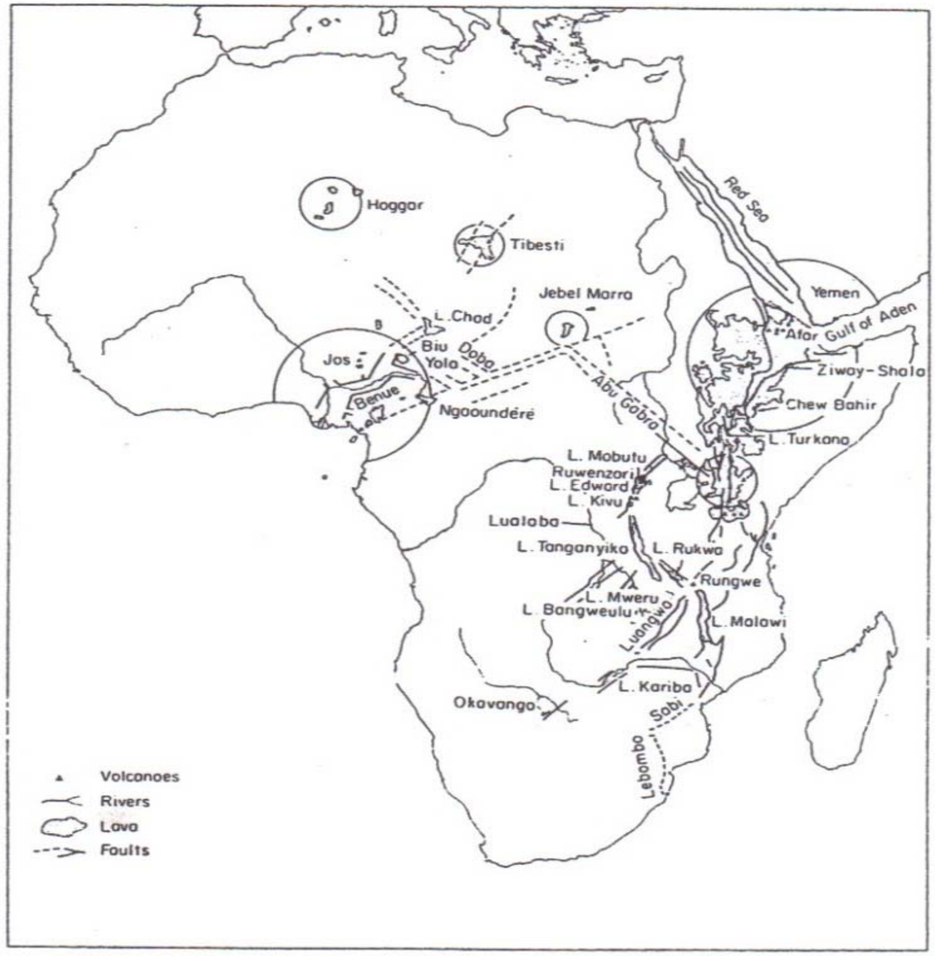


Figure 1: Extent of rifting in Africa (After Grove, 1986).

•At about the middle of its 800 km length, the Benue Trough is divided into the Cross River and the Anambra/Niger River Basins by the N-S trending Okaba/Nsukka/Enugu-Okigwe Escarpment. In the north, the Benue Trough splits into two to give the Gongola and Yola Rifts. The Gongola Rift continues subsurface under the Chad where it splits into two.

•One arm continues as the Niger Rift while the other arm continues as a buried rift which extends towards the Central African Shear Zone as the Bousa Rift. The Niger Rift in turn continues up North as a system of three rifts (Tenere rifts) which includes the Tefidet graben. The Yola Rift on the other hand can be traced to the Central African Shear Zone via the slightly displaced Doba Rift and Garousa Basin. Also linked to this shear zone are theNgaoundere and Bake-Birao Rifts as well as the Darfur Uplift and Abu Gabra Rift. (*Figure 2)*

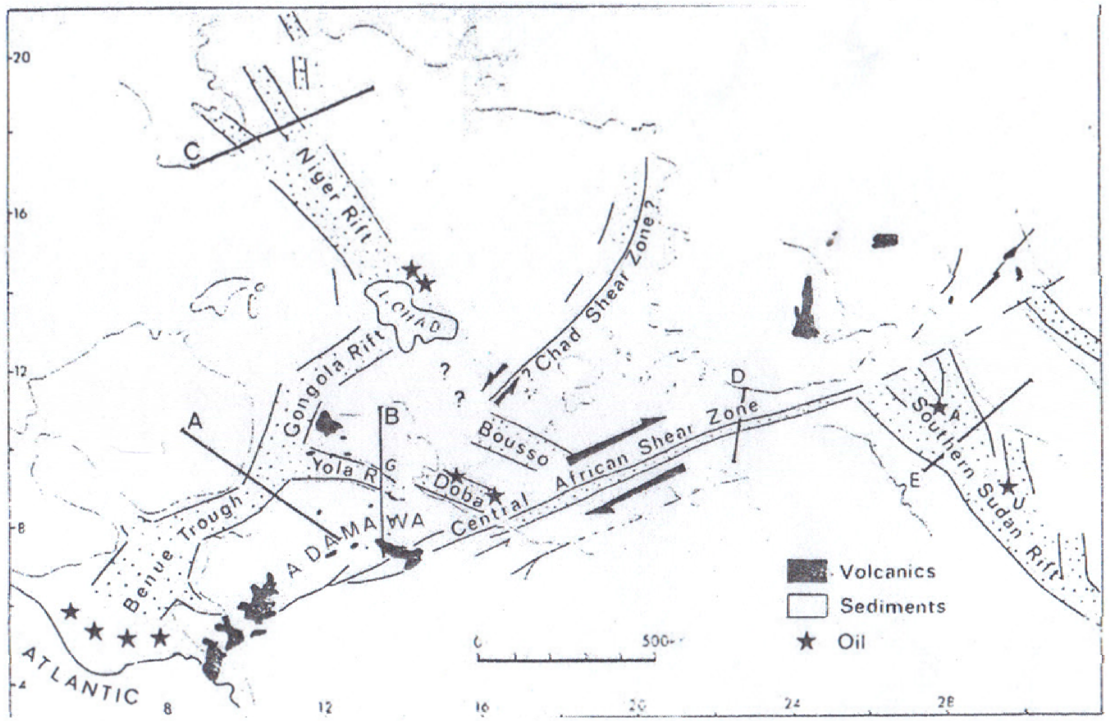
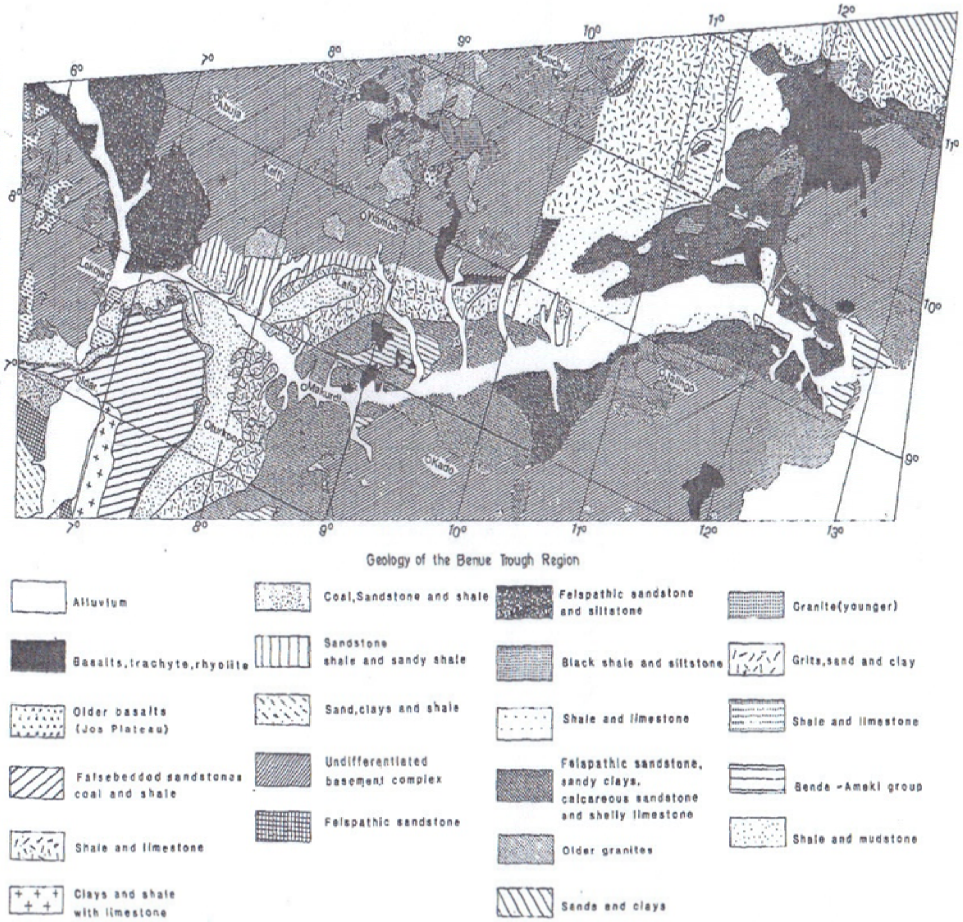


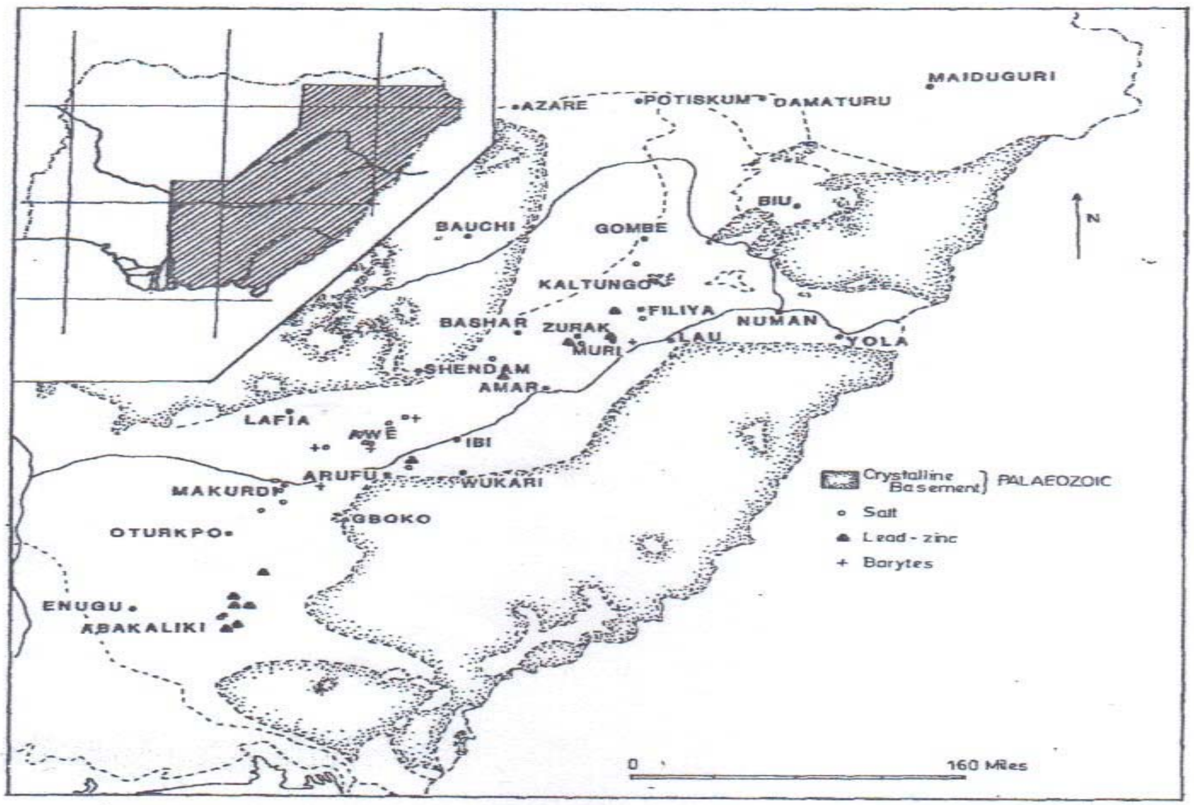
Figure 2: Sketch map showing the distribution of the main rifts making up the West and Central African Rift System.

Figure 3 is the Geological Map of the Benue Trough. The Trough has a largely coherent depositional history along its entire length.

- The geology of the Benue Trough in general and component inland basin
(e.g. Anambra Basin) has been well documented (Ofoegbu, 1985; Ofodile, 1976). The Benue Trough is rich in Hydrocarbon and mineral deposits (Fig. 3b).

Fig 3a Geology of the Benue Trough Region.





THE BENUE TROUGH AND ITS LEAD-ZINC FIELD.(AFTER CRATCHLEY AND JONES 1965)

Fig 3b The Benue Trough and its Lead-Zinc Mineralization. (After Cratchley and Jones, 1965).

Relationship of the West African Rift System to the East African Rift System

Significant differences exist between the two Rift Systems:

Volcanism

•A major difference between the West and Central African Rift System and the East African Rift System lies in the extent to volcanism and sedimentation that characterize them. While the East African Rift System is characterised by domal uplift, extensive volcanism and only minor sedimentation, the rifts that make up the West and Central African Rift system experienced extensive subsidence and sedimentation and a limited degree of volcanism.

- The absence of extensive volcanism in the Benue Trough can now be explained. Fitton (1980; 1983) and Fitton and James (1986) have shown that the Cameroon volcanic line (Fig. 3a) is a feature complimentary to the Benue Trough but without rift faulting even though its volcanic rocks have rift valley affinities. Its shape and size closely resembles that of the Benue Trough and it can be superimposed on the Benue Trough by rotation of 70 about a pole located in Sudan

•The presence of the Cameroon volcanic line to a great extent now explains the lack of extensive volcanism in most of what is the Benue Trough. Magma which was meant for the trough is thought to have come to the surface as the Cameroon line in Tertiary to recent times due to a displacement of the African lithosphere relative to the underlying asthenosphere between 80 and 65 Ma (Fig. 4).

•The rocks of the Cameroon volcanic line shows similar affinities with similar rocks found in the Lower benue Trough at Abakaliki, Uturu and Ezillo(Pearce and Cann, 1973; Okeke *et al.*, 1988; Butler and Woronow, 1986, Amajor *et al.*, 1990; Amajor and Ofoegbu, 1988a; Amajor and Ofoegbu, 1988b). This supports the above thesis.

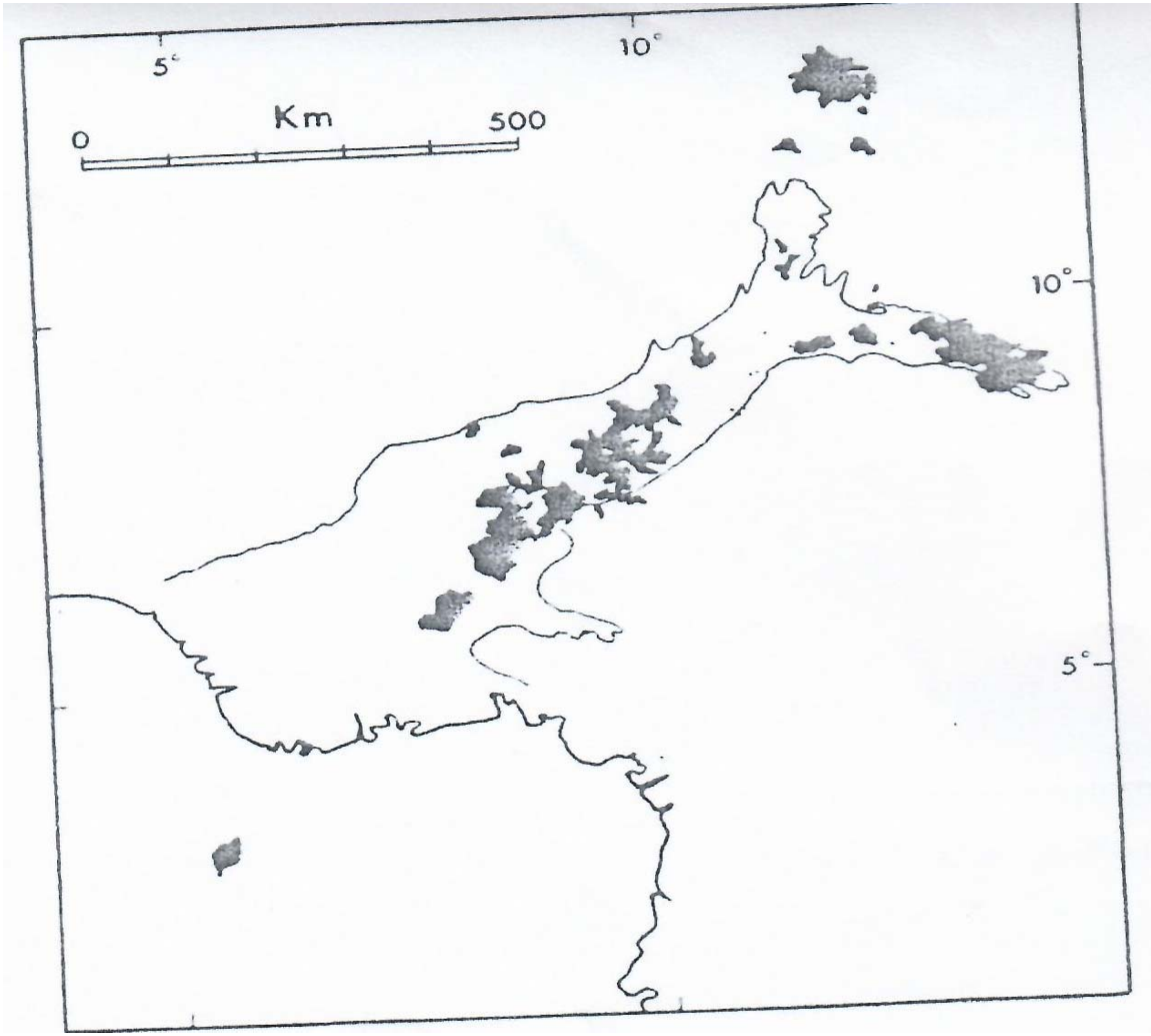


Figure 4a; the location of the Cameroon volcanic line relative to the Benue Trough (After Fitton, 1980)

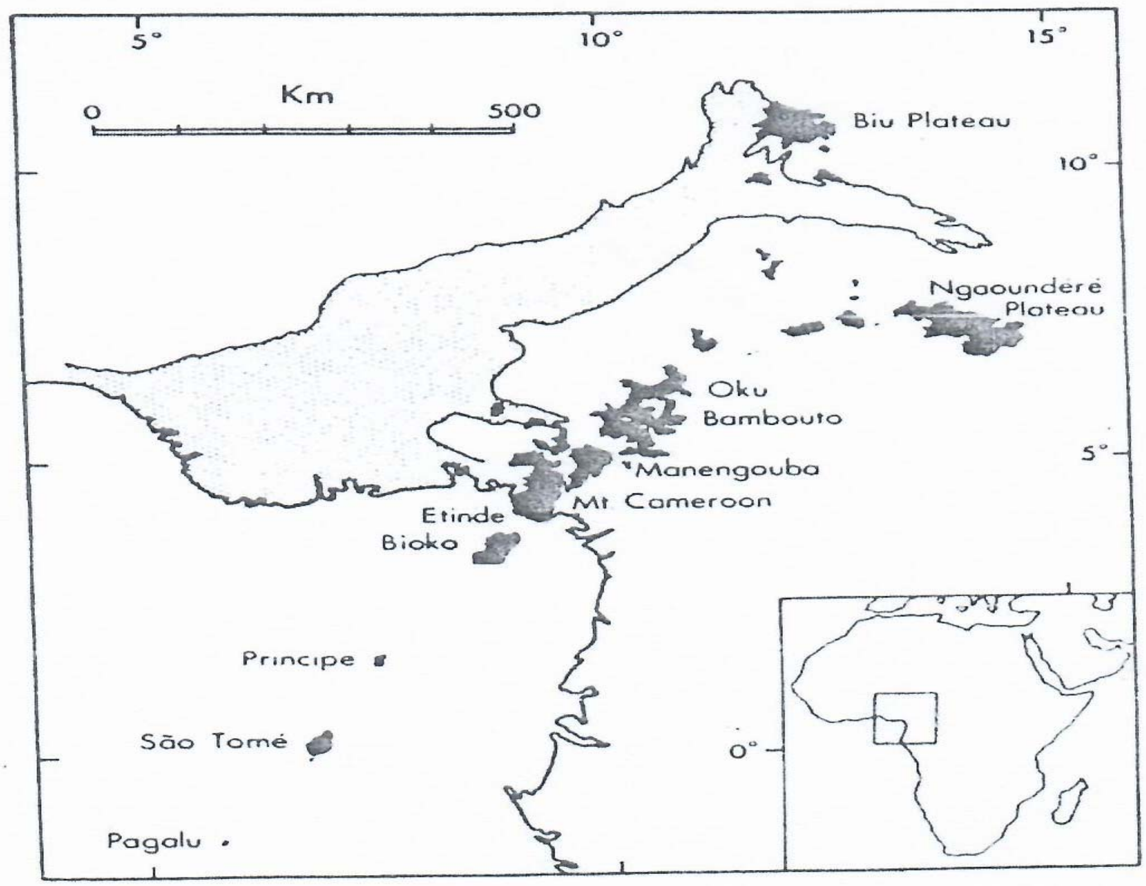


Figure 4b: the Cameroon line superimposed on the Benue Trough by rotating the former clockwise relative to the latter by 70 about a pole at 12.20 N, 30.20 E (after Fitton, 1980; Ofoegbu, 1991).

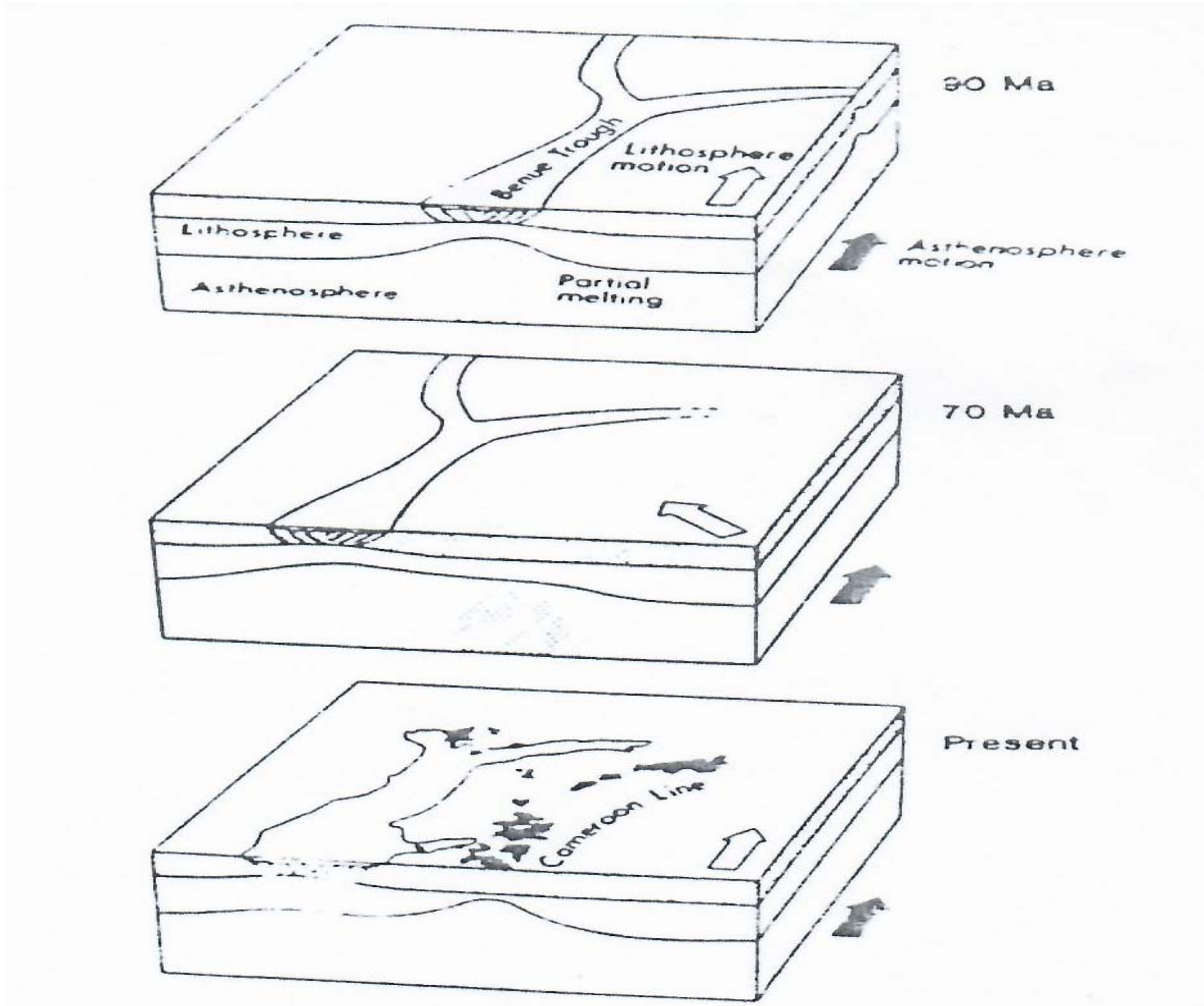


Figure 4c: Schematic diagram showing the evolution of the Cameroon line. (Ofoegbu,1991).

Crustal Extension

•Another significant difference between the West and Central African Rift System and East African Rift System is the extent of crustal thinning and extension that has taken place across the grabens that make up the systems. The amount of crustal extension which has taken place across the different grabens in the West and Central African Rift System has been independently estimated by different authors from the analysis of gravity data over these grabens (Birmingham *et al.*, 1983; Browne and Fairhead, 1983; Fairhead and Okereke, 1987; Okereke and Ofoegbu, 1989; Ofoegbu and Onuoha, 1989; Onuoha and Ofoegbu, 1989).

•The amount of crustal extension across the Ngoundere Rift has beeb found to range from 6-13km while that across the Abu Gabra Rift has put at 22-48 km for different parts of the rift (Browne and Fairhead, 1983). Fairhead and Okereke (1987) put the amount of crustal extension across the Garoua Rift at 55 + 5 km and across the Middle Benue and Gongola Rift at 95 ±10 and 65 ± 5 respectively (Fig. 6).

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•Independent estimates using the energy budget approach of Bott (1976, 1981) and Cordell (1982) by Onuoha and Ofoegbu (1989) put the amount extension across the Middle Benue, the Gongola and Yola Rifts at 130,118 and 78km respectively assuming density contrasts of -0.21×10^3, 0.27×10^3, and -0.07×10^3, kg/m^3 for the sedimentary fill, intrusive and the asthenospheric uplift respectively. Crustal extension across the East African Rift System is smaller than that across the West and Central African Rift System by as much as a factor of four.

- Estimates by various authors put the amount of extension for the East African rifts at between 10 and 35 km (Searle, 1970; Fairhead, 1976,1980; Baker and Wohlenberg, 1971; Wendlandt and Morgan, 1982; Brown and Girdler, 1980). The widths of the Rifts in West and Central Africa (150 km for Abu Gabra; 150 km for Benue Trough; 200 km for Garoua) are also more that those associated with graben structures in East Africa.

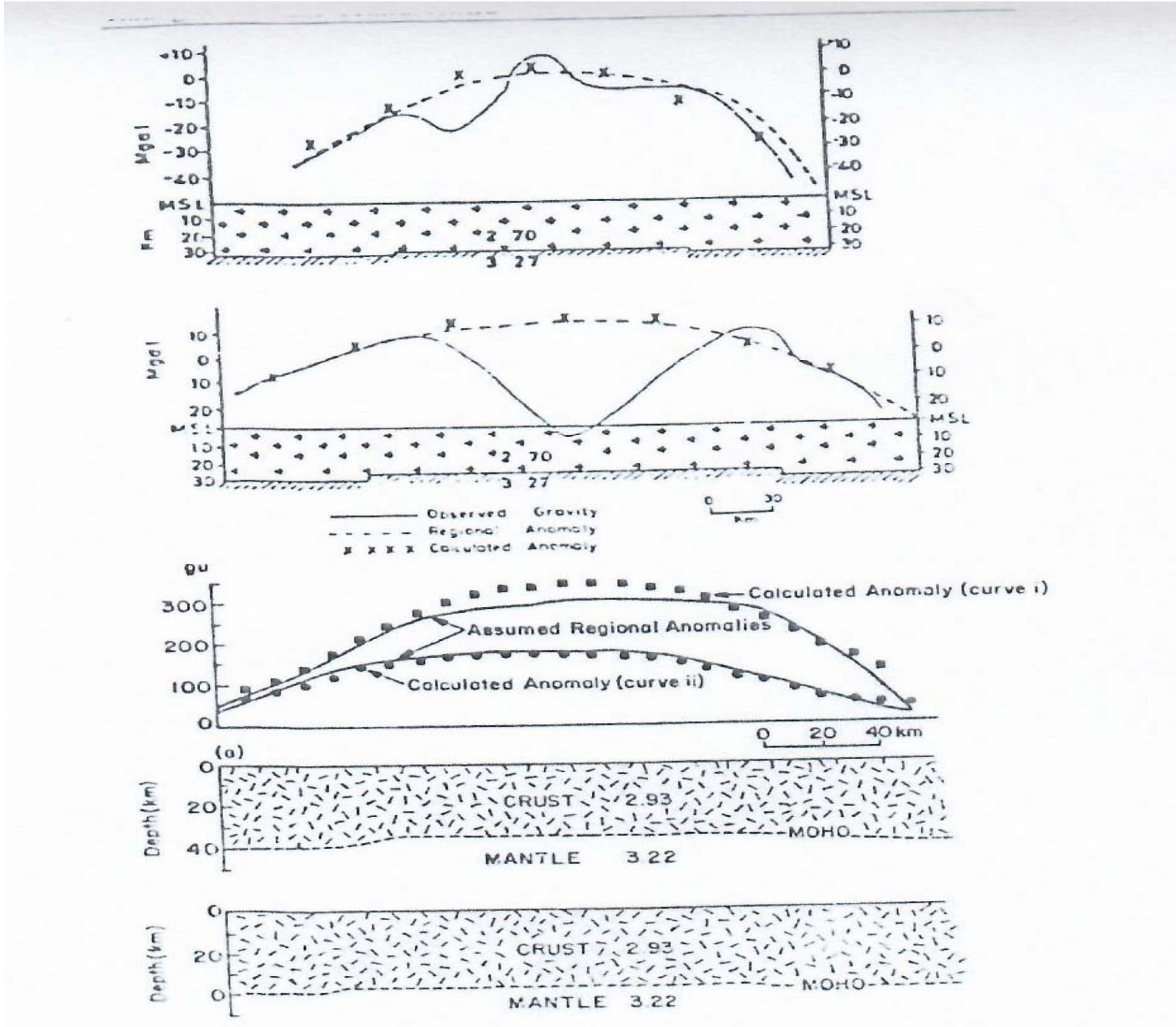


Figure 6a, b: Crustal model for a selection of rifts in the West Central African rift System: (a) Middle Benue Trough (b) Yola Rift. (Okereke and Ofoegbu, 1991).

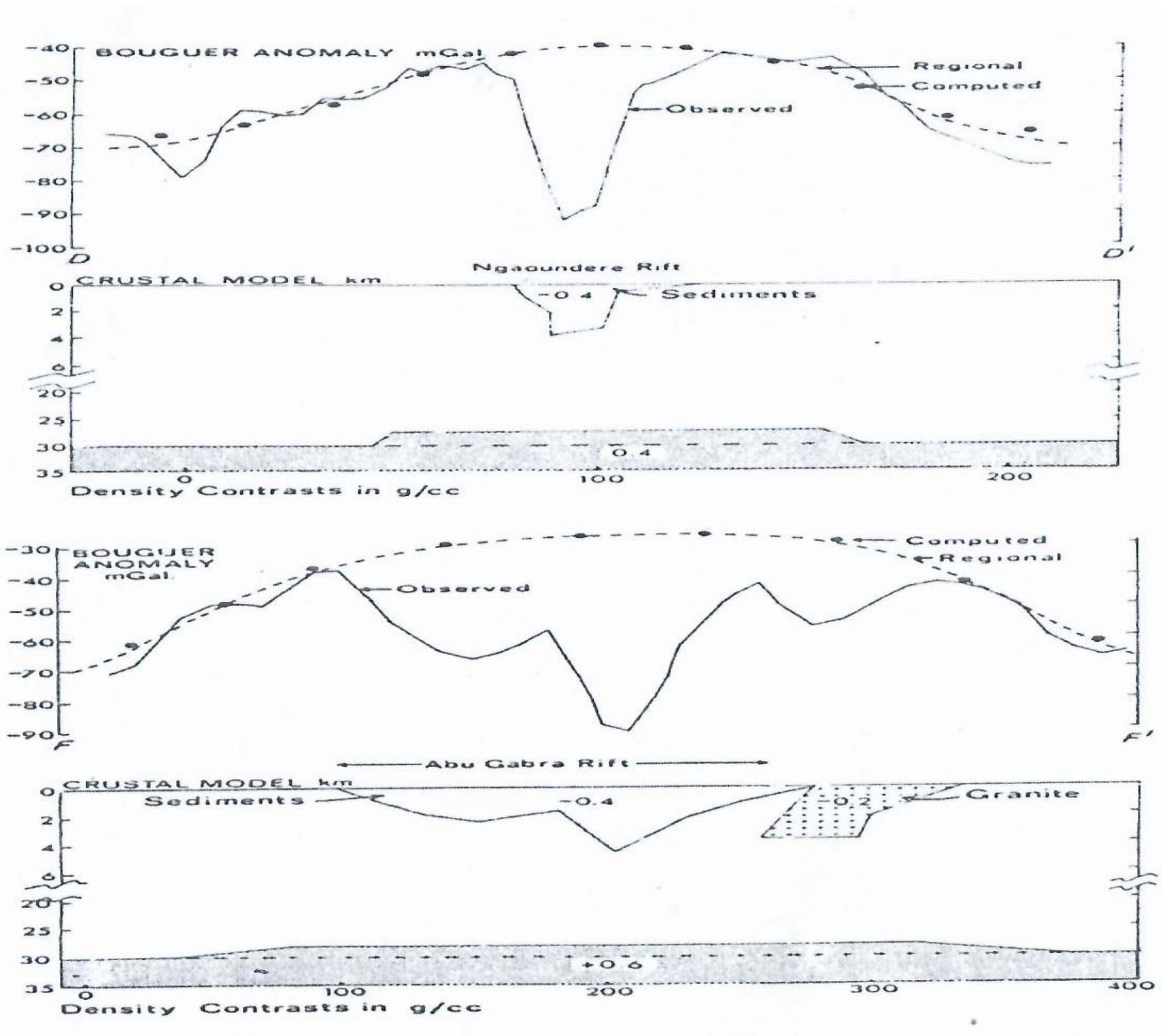


Figure 6c, d: Crustal models for a selection of rifts in the west and Central Africa Rift System: (c) Ngaoundere Rift (d) Abu Gabra Rift. (Ofoegbu and Onuoha, 1991).

Review of Geophysical Studies over the Benue Trough

•Published Geophysical Studies over the Benue Trough have in the main been gravity, magnetic and to some extent refraction seismic and basin analysis (Adighije, 1979,, 1981a,1981b; Ajayi and Ajakaiye, 1981; Cratchley and Jones, 1965; Ofoegbu, 1984a,b; Ofoegbu and Onuoha, 1991, Onuoha and Ofoegbu, 1988; Ofoegbu, 1985,1986, 1991 and others). Most of these studies have centered on estimating the depth to the basement and other structural features (Figures 7-12).

•More recently, the depth to the bedrock underneath the Benue Trough and lineaments pattern over the Trough have been mapped through the analysis of high resolution aeromagnetic anomalies and seismic refraction studies (Ibiene *et al*., 2019; Mbachi *et al*., 2018; Mgbemere *et al*., 2018; Obaje and Ofoegbu, 2017, Nur et al., 2002, Ofoegbu and Mohan, 1990, Abass and Mallam, 2013; Adetona et al, 2013).

•Power Spectrum Analysis of aeromagnetic anomalies over the Benue Trough (Ofoegbu, 1985) indicated a variable Currier Isotherm (18km – 27km) which is indicative of lateral and vertical variations in the composition of the crust and depth to the magnetized lower crust (Figure 12). This is of crucial relevance to the structure and evolution of the Benue Trough.

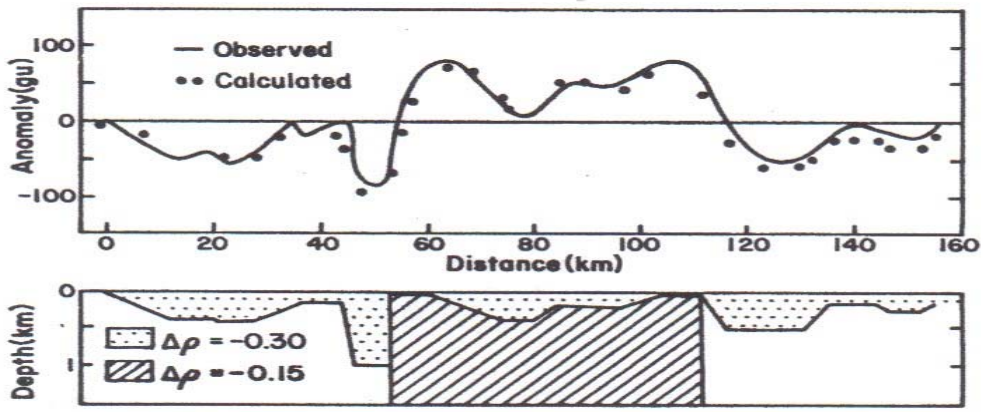


Figure Interpretation of a Gravity Profile Across the Yola Arm of the Benue Trough.

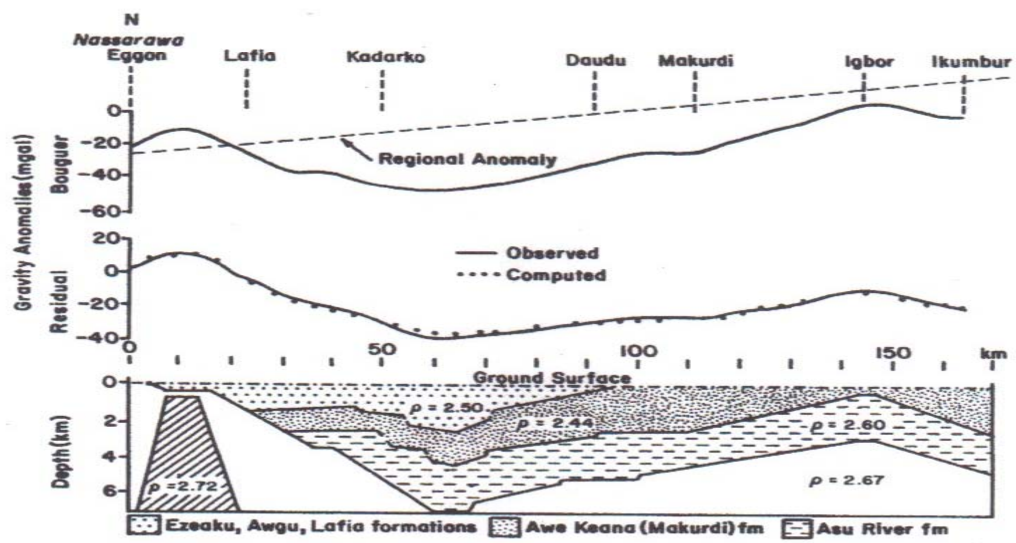
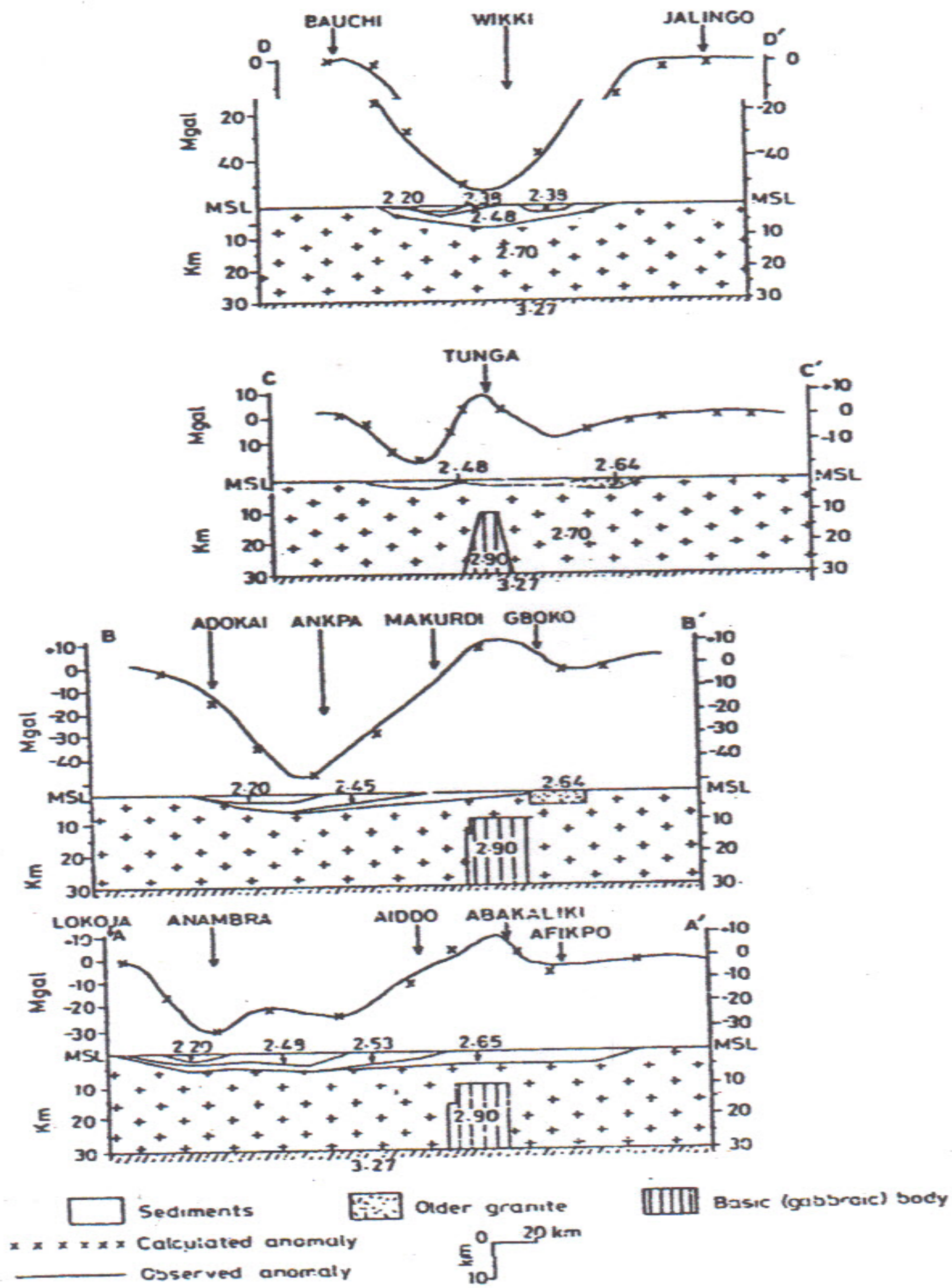


Figure Interpretation of a Gravity Profile Across the Middle Benue Trough


BAUCHI
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ADOKAI
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Sediments
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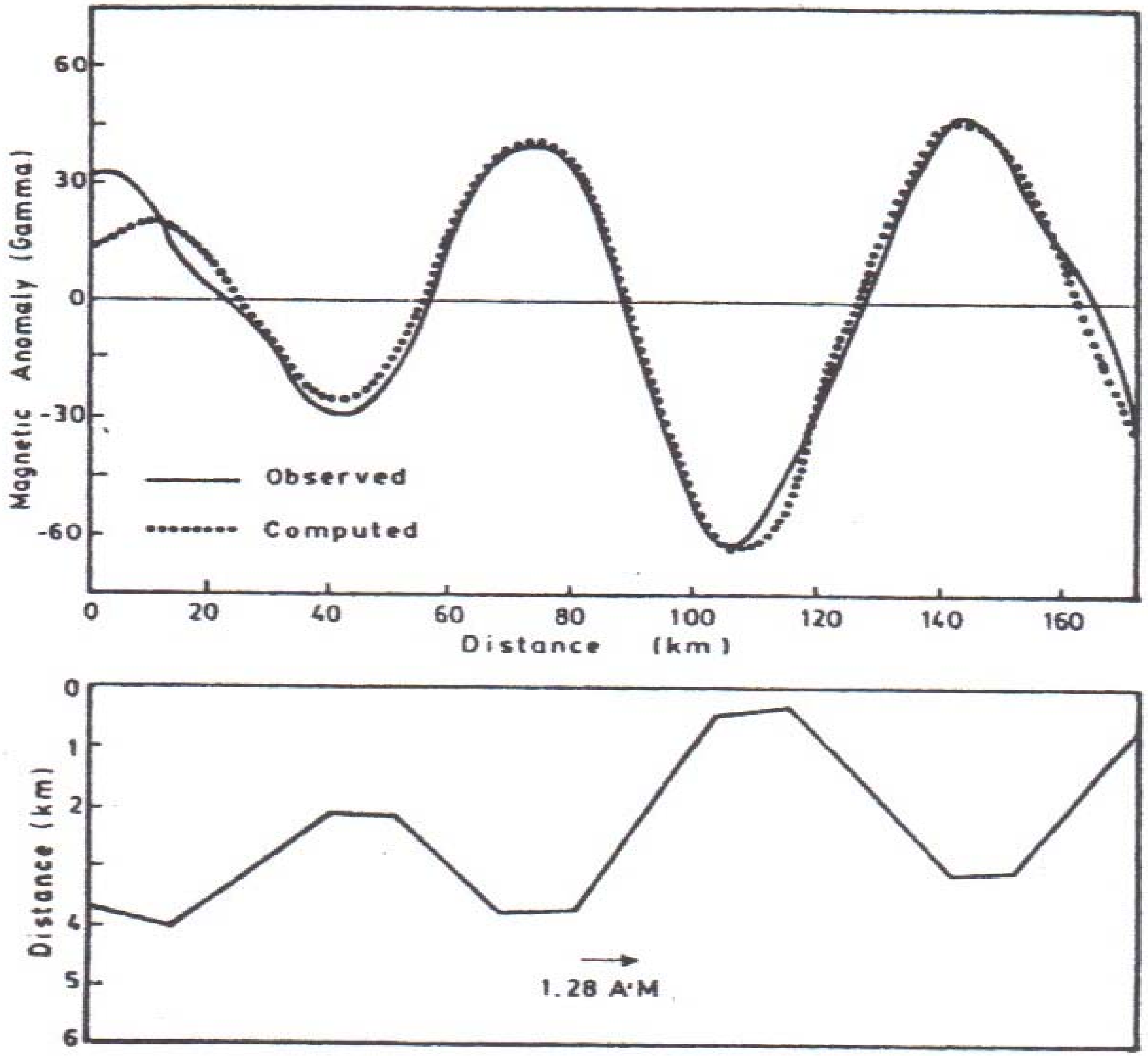

Figure 9 : Basement Depth Estimate in the Middle Benue Trough.

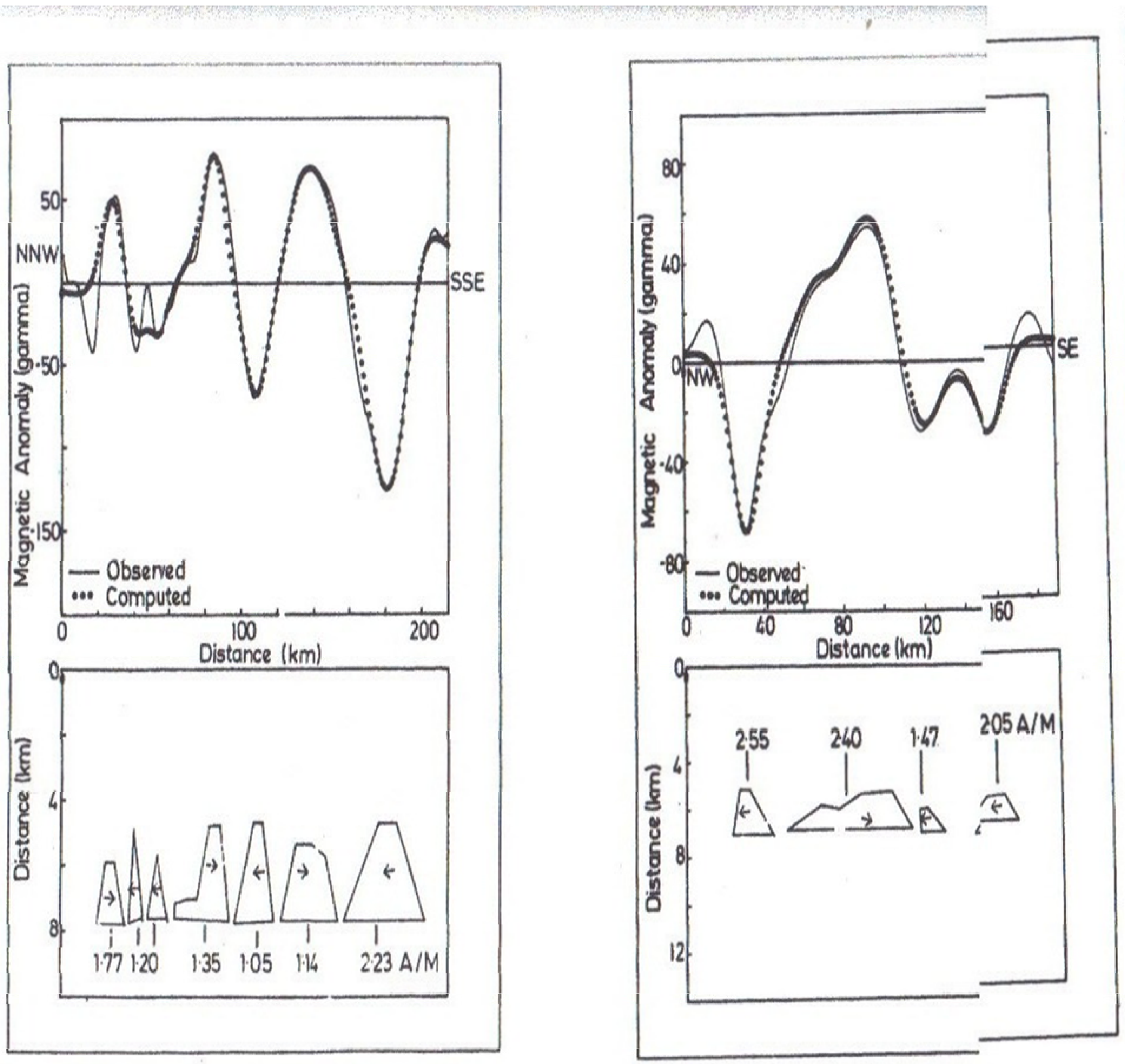

Figure 10: Interpretation of an Aeromagnetic Profile Across (a) Lower Benue Trough (b) Middle Benue Trough.

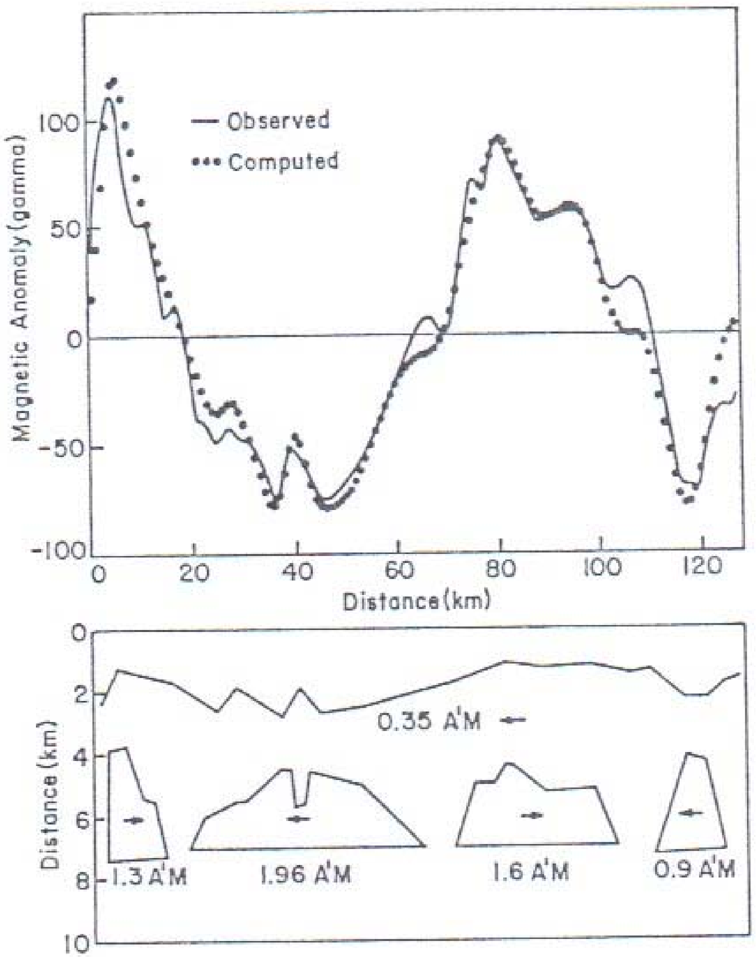

Figure 11: Interpretation of an Aeromagnetic Profile Across the Benue Trough (After Ofoegbu, 1988)

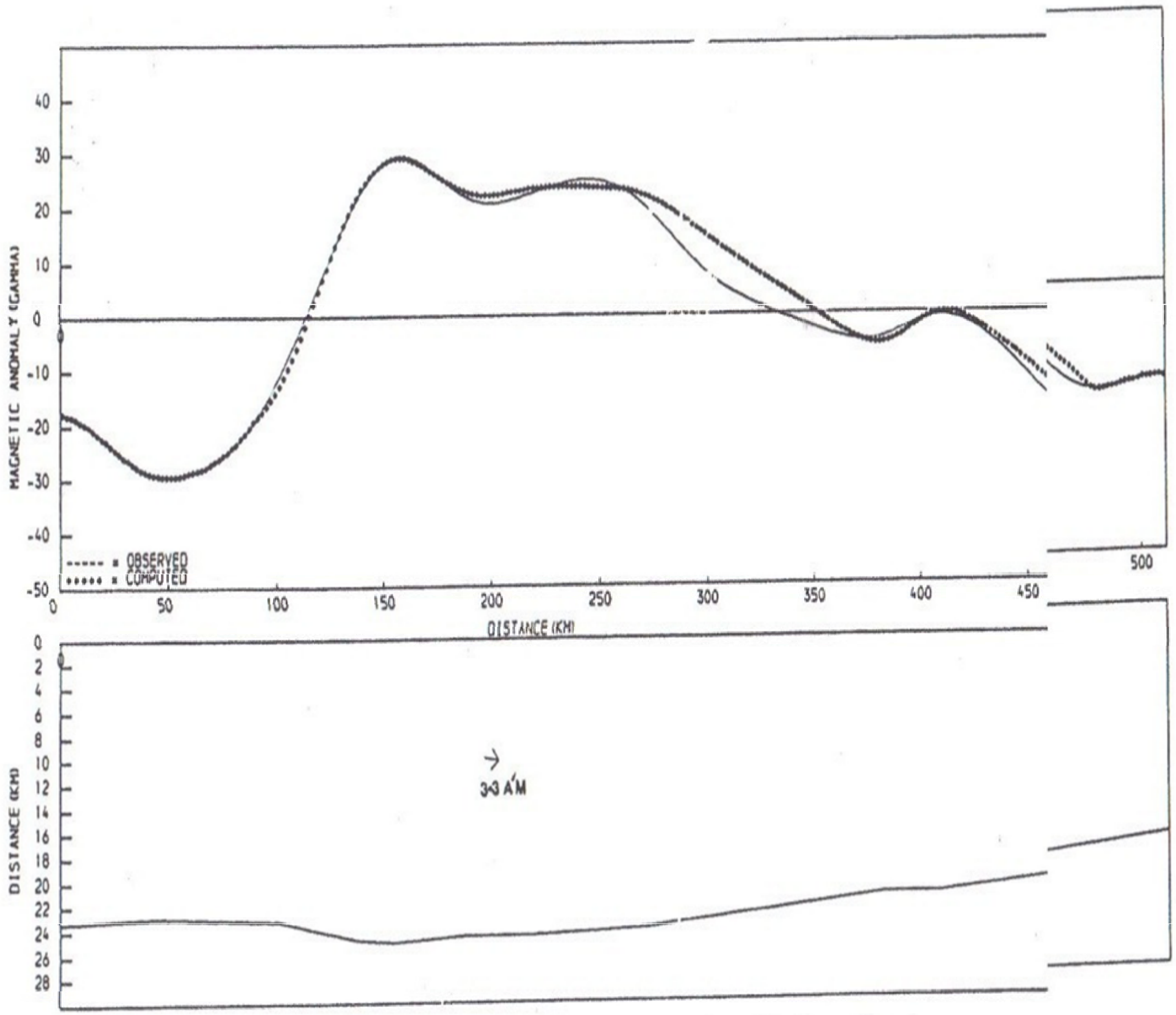

Figure 12: Estimate of the Curie Isotherm Across Part of the Benue Trough.

Evolution of the Benue Trough

•Several ideas have in the past been advanced to explain the origin and evolution of the Benue Trough. These include the early theories of King (1950), Farrington (1952), Lees (1952) and Cratchley and Jones (1965). Others which were based on the modern concepts of plate tectonics include the theories of Wright (1968), Grant (1971), Burke *et al*., *(*1971, 1972), Olade (1975, 1978), Benkhelil (1982), Freeth (1978a,b), Nwachukwu (1972), Fitton (1980, 1983), Agagu and Adighije (1983), Cratchlcy *et al*., (1984), Fairhead and Okereke (1987), Onuoha and Ofoegbu (1988) and Ajakaiye *et al*. *(*1986)).

•Some of these ideas are however complimentary to one another. Wright (1981) and Ofoegbu (1984c) have given detailed and critical reviews of the different ideas on the origin and evolution of the Benue Trough.

•The present author had in an earlier paper (Ofoegbu, 1984c) put forward a model to account for the tectonic evolution of the Benue Trough. According to his model, the tectonic evolution of the Benue Trough involved the rise of a mantle plume due to upwelling, thinning to some degree and the development of initial lines of weakness marginal to the plume, emplacement of intrusive igneous materials in the crust, more extensive stretching and thinning and consequently rifting.

•This sequence of events according to the author was repeated in a cyclic manner with accompanying intercyclic deformation taking place. In the present paper, this model (Ofoegbu, 1984c) is further discussed in the light of previous and recently available geological, geochemical and geophysical information

•It is now generally accepted that an R-R-R (rift-rift-rift) triple junction existed at the site of the present Niger Delta in Early Cretaceous times with arms as, the Gulf of Guinea (R), the South Atlantic (R), and the Abakaliki-Benue arm (R) (Burke *et al.*, 1971; Whiteman, 1982; Ofoegbu, 1984c; Onuoha and Ofoegbu, 1988).

• The Gulf of Guinea arm is believed to have later evolved into a rather complex long ridge-ridge transform, the South Atlantic arm into a shorter ridge-ridge transform while the Abakaliki-Benue arm opened slightly and then closed (Onuoha and Ofoegbu, 1988).

• The initial formation of the R-R-R triple junction at the location of the modern day Niger Delta was a consequence of a cycle of events which led to the separation of Africa from South America, opening of the South Atlantic and the tectonic evolution of the Benue Trough

•In the light of available geological, geochemical and geophysical information on the Benue Trough and current views of riftogenesis, the sequence of events that led to the development of the Benue Trough is summarized as follows:

•Rise of a mantle plume under the modern day Niger Delta giving rise to updoming and an uplifted lithosphere in a state oftentional stress. Tension giva rise to brittle fractures within the plate and the development of initial lines of weakness;

•Continued updomoing and uplift of the lithosphere gave rise to the development of more pronounced zones of weakness and possibly a slight amount of wedge subsidence;

- Associated extension at the base and the weakness of the uplifted lithosphere allowed the rise of less dense materials of asthenospheric origin, and the emplacement of igneous bodies along the previously established zones of weakness.

- This gave rise to a more extensive stretching and thinning of the crust followed by the breakup of the crust and block faulting and the deposition of sediments. 0-33

•This sequence of events was repeated a number of times in cycle with intercyclic deformation taking place to give rise to the folding of sediments in the trough. The first mantle plume activity and associated events loading up to the evolution of the Benue Trough is believed to have taken place during Aptian to Albian times (110 Ma B.P) and was associated with the eruption of the alkaline Abakaliki and Uturu lavas and the desposition of sediments of the Asu River Group.

• Reduction in tension prior to the initiation renewed mantle plume activity gave rise to the Cenomanian deformation which manifests itself as folds in the Albanian sediments of the Asu River Group (Nwachukwu, !972; Ofoegbu, 1984c; Ofoegbu, 1985a) as well as the deposition of the Odukpani Formation on the Calabar Flank.

- The next phase in the evolution of the Benue Trough involved the renewal of mantle plume activity be it on a reduced scale in Turonian times. This cycle of events which lasted from Turonian to the start of the Santonian was associated with the deposition of the Ezeaku Shales on the Asu River Group and the emplacement of the lavas found at Ezillo (Okeke *et al.*, 1988).

- The reduction of tension which followed this cycle gave rise to the deformation of older sediments and deposition of younger ones. The sequence of events from this point onwards is discussed in Ofoegbu (1984c) and this included an eastward shift in the centre of tectonic activity and continuation of minor crustal movements, sedimentation and continued subsidence under the weight of sediments deposited.

- The final separation of Africa from South America took place at about 80 Ma and this contributed to the major change in the stress pattern within Africa.

•Ideas on the mechanism of graben formation and continental rifting are based mostly on the wedge subsidence hypothesis originally put forward by Venning Meinesz (1950) and modified by Bott (1976).

•From an Analysis of the energy budget of the process of wedge subsidence, Bott (1976) has shown that the tensile stress needed to cause a subsidence with sediment infill of 5km or more must be a continually renewable one, persisting throughout the process of rifting.

• He estimated that a basin subsidence of about 5km with sediment fill would need tensile stress of the order of 1 to 2 kbar.

•Upwelling of mantle material with excess mantle pressure is capable of inducing thermo-mechanical stresses on the lithospheric plate. Bhattacharji& Koide (1978) studied the resulting stress contours and elastic displacement vectors and showed that an area of relative subsidence would generally occur in the center of the domal uplift.

•An elongate rift valley bounded by marginal inward dipping faults could later evolve from this. However, tensile stresses associated with lithospheric arching can only probably account for graben subsidence not exceeding 200 m (Bott, 1981) and can, therefore, only play a minor contributory role in the formation of rift valleys with several kilometers of sediment such as the Benue Trough.

•However, there are additional stresses that may be associated with uplifted regions arising from the additional surface load of the updomed topography and the upthrust of the underlying isostatic compensation in a purely elastic lithosphere (Bott, 1981; Artyushkov, 1973). These stresses cannot, however, account for a rift valley of more than 2km sediment infill unless the lower part of the crustal lithosphere deforms by creep (Bott&Kusznir, 1979).

•The heating and thinning of continental lithosphere by thermal conduction from below would entail an unrealistically long time scale for sufficient uplift, this time scale can be reduced if the lithosphere is net-veined by rising magma which leads to a replacement of loose blocks by asthenospheric material from below.

•Furthermore, the tensile stress associated with rift valley formation, favors the emplacement of dyke-like bodies which could lead to a further stretching of the brittle upper crust, significant extension of the underlying part of the lithosphere by ductile necking and consequently, rifting and depending on the amount of magma present and time available, such a structure might develop into a split continent.

•Bhattacharji& Koide (1978) have shown that an excess magma pressure of the order of 1 kbr or more can originate due to vertical dyke-like intrusions from the upper mantle into the crust. It can therefore be assumed that the stresses generated and imparted to the lithospheric plate by asthenosphericupwell, doming and protrusion of dyke-like bodies could be sufficient to lead to the formation of rift structures with sediment infill as large as is found over the Benue Trough.

•Several ideas have been suggested to explain the evolution of the Benue Trough. Of these, those of Burke et al. (1971, 1972) and Olade (1975) have remained the most quoted and these deserve spbnecial mention.

•While accepting the basic idea of an RRR triple junction underlying the present day Niger Delta, several authors (Wright, 1976, 1981; Nwachukwu, 1972; Olade, 1975) believe there are flaws in the model as put forward by Burke et al. (1971, 1972) and the model has therefore, been extensively criticized.

•Furthermore, based on a detailed analysis and description of regions of low and high magnetic anomalies, Ofoegbu (1982 a, b) has shown that

(a) the belts of magnetic highs and low are not continuous but exist as elongated anomalies,

(b) the belts of magnetic highs and lows have trends sun-parallel to the trend of the trough and

(b) the belts of magnetic highs and lows have trends sun-parallel to the trend of the trough and

(c) the character of low wavelength anomalies found over the sedimentary basin differs significantly from those over the basement and these suggest that the Benue Trough is not underlain by an oceanic crust and the extensional hypothesis of Burke et al. (1971, 1972) does not adequately explain the tectonic evolution of the `Benue Trough

- The model put forward by Olade (1975) to account for the evolution of the Benue Trough appears to me the most acceptable of all ideas so far put forward to explain the origin of the Benue Trough. It cannot however completely explain the evolution of the Benue Trough as the model now stands and needs modification.

- Upwelling of mantle material with its accompanying excess mantle pressure is capable of inducing thermo-mechanical stresses on the lithosphere and may lead to basin subsidence.

•However, as already stated, the stresses arising from domal uplift alone cannot account for graben subsidence exceeding 200m (Bott, 1981) and can therefore only play a contributory role in the formation of rift structures having sediment thickness of several kilometers as is found in the Benue Trough.

•The Evolution of the Benue Trough must therefore in addition to updoming involve other stress generating means suchas the protrusion of dyke-like bodies as suggested by Ofoegbu (1984).

CONCLUSION

In the present paper, an attempt has been made to present a wholistic picture of the Benue Trough, its place as part of a complicated web of rifted structures transversing Sub-Saharan Africa, its structure and evolution based on plate tectonics and principles of riftogenesis.