GLOBAL JOURNAL OF GEOLOGICAL SCIENCES VOL. 3, NO. 1, 2005: 61-69
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GRAVITY ANOMALIES OVER THE GONGOLA ARM, UPPER BENUE TROUGH, NIGERIA.

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(Received 1 June 2004; Revision accepted 8 October, 2004)

ABSTRACT

A regional gravity survey of the Gongola Arm of the Benue trough was carried out with the aim of determining structures of interest. The results of the gravity interpretation showed that the area of study is characterised by negative Bouguer anomalies that trend in the NE-SW direction and range in value from -75 to -15 mGal with an average of -42 mGal. A first order polynomial was used to approximate the regional anomalies in the area. The residual gravity anomaly map shows anomalies that range in value from -32 to +20 mGal. 2.5-D modelling of the residual gravity anomalies suggests that the area has a horst and graben structure, with the grabens being as large as 60 km in width and filled with sediments that are up to 4.5 km thick. Results also suggest the existence of high-density rocks of basic composition at depth. The general indication of the structure of the Gongola arm of the Benue trough is that it is a half graben (width ca 60 km) bounded by normal faults.

INTRODUCTION

The Gongola arm of the Upper Benue trough is part of the NE-SW trending 250 km wide and 1000 km long Benue rift structure (Fig. 1). The development of the Benue rift has been closely associated with the separation of Africa from South America and the opening of South Atlantic Ocean.

The Benue rift can be compared with some well known rift systems such as the East African, the Rhine Graben, the Baikal rift and the Rio Grande rift. These rift systems are all associated with volcanism and regional uplift. Mareschal (1983) indicated the basic geophysical characteristics of a rift as having a thin crust, a low velocity and density upper mantle and higher than normal heat flow.

Geophysical studies in the Benue trough have shown that the crust trough is indeed thinned (Cratchley and Jones, 1965; Adighije, 1981; Ajayi and Ajakaiye, 1981; Osazuwa *et al.*, 1981; Cracthley *et al.*, 1984; Elf, 1985; Stuart *et al.*, 1985; Saugy, 1987; Fairhead and Okereke 1987, 1990; Benkhelil et al., 1988). A low velocity and density upper mantle is inferred from gravity (Fairhead and Okereke 1987). There is also the presence of warm springs within the trough, thus suggesting enhanced heat flow.

There are also gross similarities between the Benue trough (depicted as a failed arm or aulocogen structure) and the East African Rift (Red Sea - Gulf of Aden - Afar triple junction). These similarities include the patterns of the gravity field of the Benue trough (a central high flanked onoth sides lows) and the central Red Sea, the contemporaneous magmatism and lead-zinc mineralisation, which are attributable to a triple junction.

The Gongola arm of the Benue rift system remains the part of the system that has not been completely covered bv previous gravity studies. The present study is a detailed gravity survey of the area carried out between 1993-1995 covering an area 49000 km^2 between latitudes' 9° 45' N and 11° 00' N and longitudes 9° 45'E and 13° 00' E. Gravity data were collected at 3 km intervals along all major and accessible roads in the area, resulting in 1150 gravity stations. Results of interpretation of the gravity field in the Gongola arm of the Benue trough is presented in this paper.

Geological background

The regional geological features of the Gongola area (Fig. 2) include a Precambrian crystalline basement made of granitoids and gneisses on which rest the Upper Cretaceous to Quaternary Sedimentary and Volcanic rocks (Carter et al., 1963; Benkhelil and Robineau, 1983; Benkhelil, 1988, 1989; Maurin et al. 1985; Coulon et al., 1996). The Cretaceous sedimentary rocks include the continental Bima Sandstone; a major sandstone unit succeeded by transitional beds, which pass upwards into a Turonian to Senonian marine sequence. Continental conditions are believed to have been re-established in the Maestrichtian that resulted in the deposition of the Gombe Sandstone (Maurin et al., 1985, Benkhelil, 1989). A period of folding then followed after which another continental sequence, the Tertiary Kerri-Kerri Formation was deposited. This formation unconformably overlies the continental Maestrichtian (Adegoke *et al.*, 1986) along the western margin of the study area.

The Bima Sandstone occurs at the base of the sedimentary succession and is exposed in the cores of great anticlines and directly overlying the crystalline basement floor (Maurin et al., 1985). The thickness of the formation ranges from about 100 m to at least 3500 m. The Yolde Formation, a sequence of sandstone and shale mark the transition from continental to marine sedimentation. This formation is diachronous and shows lateral variations in thickness, but is believed to be up to 380 m thick (Benkhelil, 1989). The Pindiga Formation is a sequence of marine shales, which include a number of limestone beds towards the base. At Gombe, boreholes have penetrated about 190 m of Pindiga Formation (Wardrop, 1989). The Gombe sandstone is a sequence of estuarine and deltaic sandstone, siltstones shales and ironstones. It is the top member of a folded and partly eroded sedimentary sequence and it is not possible to determine its original thickness. The Tertiary Kerri-Kerri Formation consists of a sequence of flat-lying grits, sandstones and clays. This Palaeocene formation rests unconformably upon folded Cretaceous rocks (Adegoke *et al.*, 1986).

The Biu Plateau extends for over 1250 km^2 of which the western margin (ca 250 km^2) lies in the study area (Fig. 2). It is capped by Neogene sheets of olivine-basalts, prominent well-preserved volcanic vents with well-defined craters. The vents are composed of basaltic agglomerate, ash, lava, and tuffs. Small flows resting on the Plateau have been issued from these craters.

The structure of the Upper Benue Trough is much more complex than lower and middle parts of the trough and is characterised by cover tectonics (Benkhelil, 1988). The Upper Benue can be subdivided into several smaller units; the Kaltungo Inlier, formed by a horst of basement rock, the Pindiga-Gombe basin (Benkhelil, 1988), the Gombe ridge separating small deep basins and the Palaeocene flat-lying

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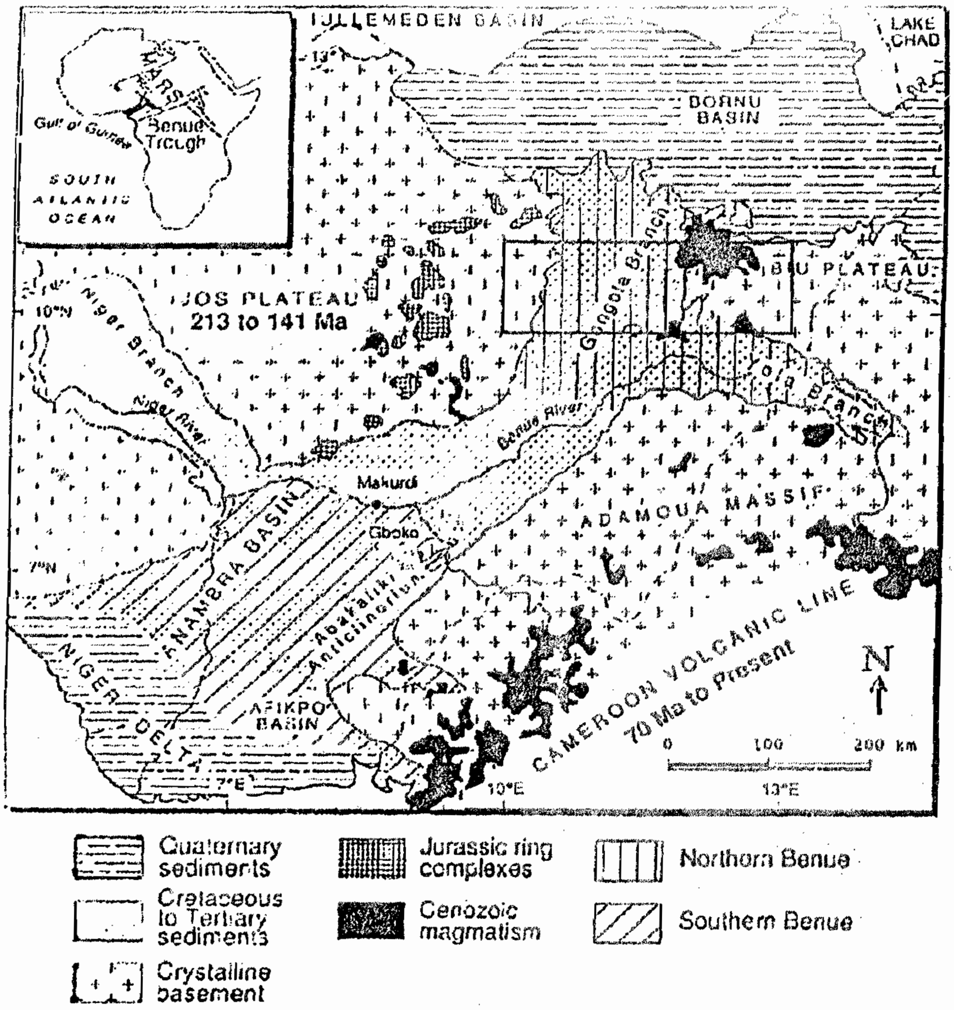

Fig 1 Location Map of the area of study (Adapted from Coulon *et al.*, 1996). Solid rectangle indicates area of study.

Table 1: Density Values of rocks in the Gongola Arm of the Upper Benue Trough

Rock type	number of samples	range (10^{-3} kg m^{-3})	dry	wet	mean	SD
Biu basalt	10	2.58-2.78	2.77	2.79	2.78	±0.012
Kerri-Kerri Fm	15	2.30-2.5	2.38	2.39	2.40	±0.035
Gombe Fm	20	2.25-2.90	2.37	2.43	2.40	±0.100
Pindiga Fm	15	2.30-2.85	2.47	2.57	2.52	±0.025
Bima and Yolde Fm	40	2.40-2.80	2.46	2.48	2.47	±0.053
Older granite	20	2.40-2.76	2.59	2.60	2.62	±0.0112
Migmatite - Gneiss	30	2.65-2.77	2.69	2.70	2.70	±0.0710

Kerri-Kerri basin. The Gongola and Yola arms are digitations of the Upper Benue Trough and present a similar tectonic style.

Folding in the northeastern part of the Benue is Post-Maestritchtian (Maurin et al., 1985; Benkhelil, 1988). A notable display of this folding occurs in sediments of the area of study where they are folded once gently and uniformly (Benkhelil, 1988). Tensional faulting is present in the sediments flanking the basement (Maurin et al., 1985) and within the crystalline rocks. The faults strike approximately at right angles to the basement boundary, and radially around the crystalline rocks. These faults probably represent adjustment to folding stresses (Adegoke *et al.*, 1986).

GRAVITY DATA COLLECTION AND REDUCTION.

The gravity survey was carried out between 1993 and 1995 using a Lacoste-Romberg gravimeter. 1150 gravity stations were established at 3 km spacing on all available roads and tracks (Fig. 3) Two Wallace and Tiernan altimeters were used to determine the station elevations. Base stations were established using the ABABCBCD... 'looping' technique.

The heights obtained with the altimeters were tied to benchmark values and they agreed with the benchmark values within 1 m.

Repeated observation of gravity at data stations indicates an observational accuracy of 0.03 mGal. Errors in the Bouguer anomalies are not greater than ±0.25 mGal, with the largest contribution coming from errors in station elevations.

The regional base-network was tied to 3 bases earlier established by Osazuwa (1985) at Bauchi, Gombe and Biu. All reductions normally applied to raw gravity data were carried out in order to obtain the Bouguer anomalies shown in Figure 3 The method of polynomial fitting (Zeng, 1989 and Beltrao *et. al.*, 1991) was used to derive the regional anomaly using data uniformly sampled over the Bouguer anomalies. A first

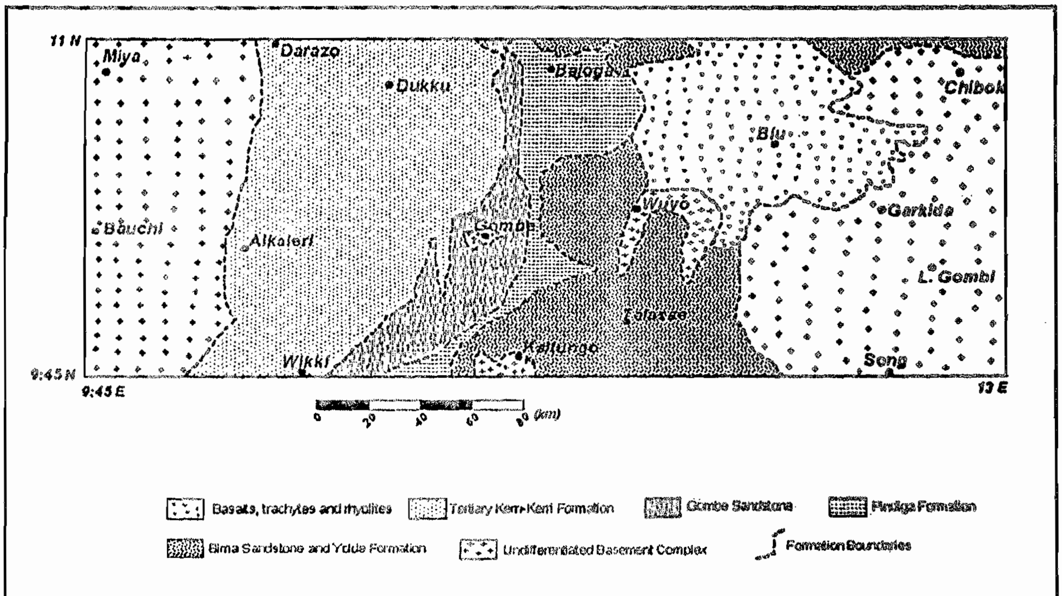

Fig. 2

Fig.2 Geological Map of the Gongola Arm of the Upper Benue Trough, N.E Nigeria (after Geological Surveys of Nigeria 1994).

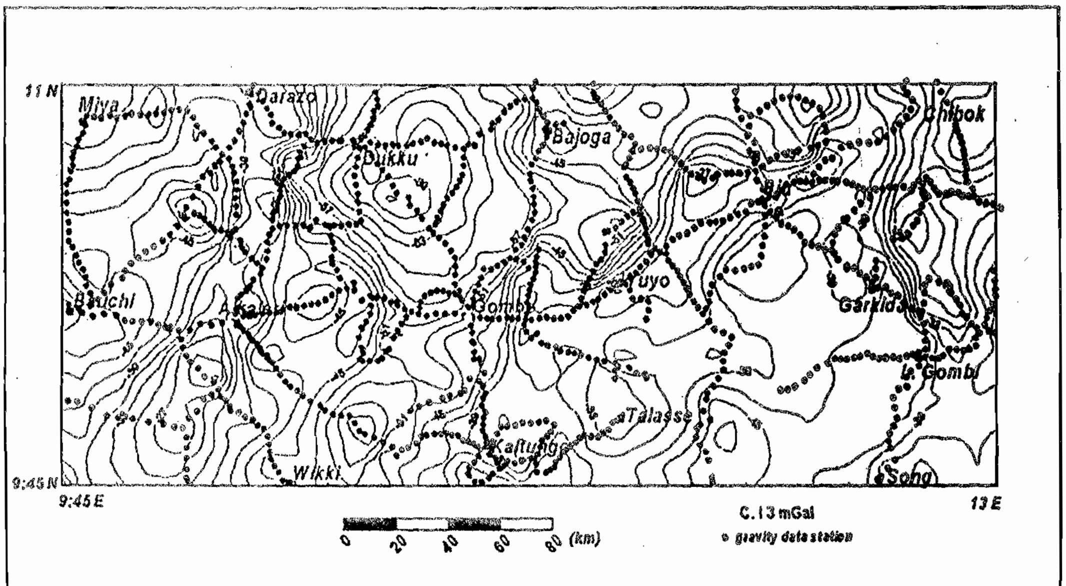

Fig 3

Fig.3 Bouguer Anomaly of The Gongola Arm of the Upper Benue Trough, Northeastern Nigeria

order surface was found to be an adequate representation of the regional anomaly. The residual anomalies superimposed on the geological map are shown in Fig. 4.

A total of 150 representative rock samples were collected for laboratory determination of densities. Table 1 summarizes representative rock densities collected during the study, while Table 2 gives the values obtained by previous workers (Cratchley and Jones, 1965; Ajayi, 1979 and Adighije, 1981) at a regional scale.

An inversion program package INVERT (Smilde, 1998) was used to interpret prominent anomalies in the study area

INTERPRETATION METHOD

Inversion of the gravity anomalies is used as a tool. *A priori* information is always needed. Quantitative interpretation and inversion, first of all, requires forward routines for computing gravity effects at observation points for assumed geometrical and density models. The program used has many options, but here only 2-d models are considered (at right angles to strike) and the forward calculation of the gravity effects was done by the Talwani et al. (1959) method. Limited background knowledge does not warrant the more complicated 3-d approach. The observation points are assumed at the topographic surface. The general inversion problem is non-linear. The traditional "trial and error" procedure tis inadequate for exploring the model space.

The procedure is non-linear iterative inversion where the geometrical aspects of the modelling are stepwise linearized

Table 2: Generalised rock densities obtained in the BenueTrough

Rock Type	Cratchley & Jones, 1965;	Ajayi, 1979;	Adighije, 1981
Basement:	2.65	2.64 ±0.034	2.70± .07
Shale (Albian)	2.65	2.65± 0.04	2.62
Sandstone (Bima)	2.45 - 2.5	2.48± 0.05	-
Sandstone (Turonian-Senonian)	2.40 - 2.5	2.45 ± 0.05	2.40± 0.161
Shale (Turonian-Senonian)	2.50 - 2.55	2.53± .02	2.60
Sandstone (Tertiary)	1.90 - 1.94	2.30± 0.09	
Basic intrusions	2.75 - 3.00	2.64 - 2.90	

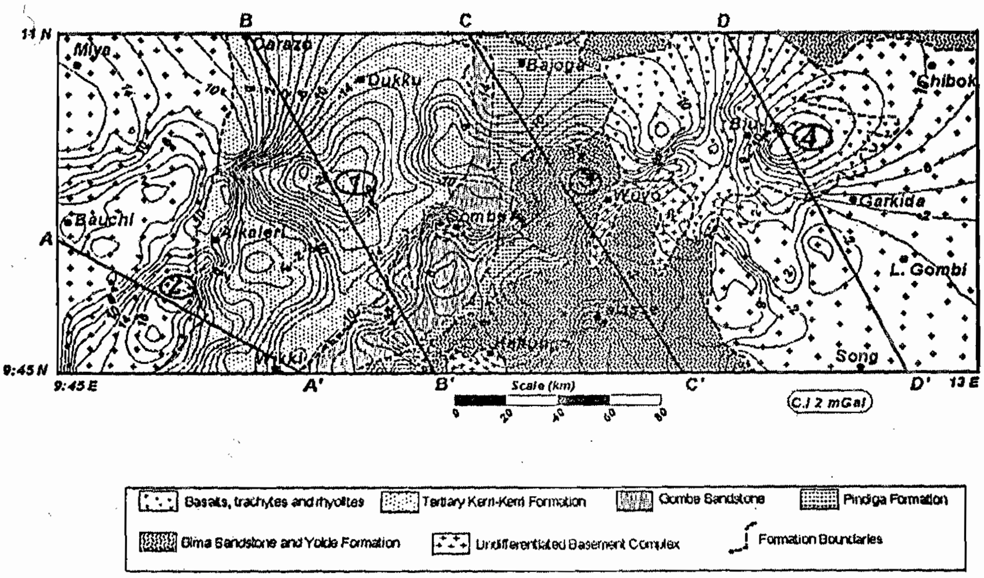

Fig. 4

Fig.4 The Residual Bouguer anomaly map superimposed on the Geological map of the area of study. Indicated also are the locations of interpreted profiles A-D across anomalies 1-4

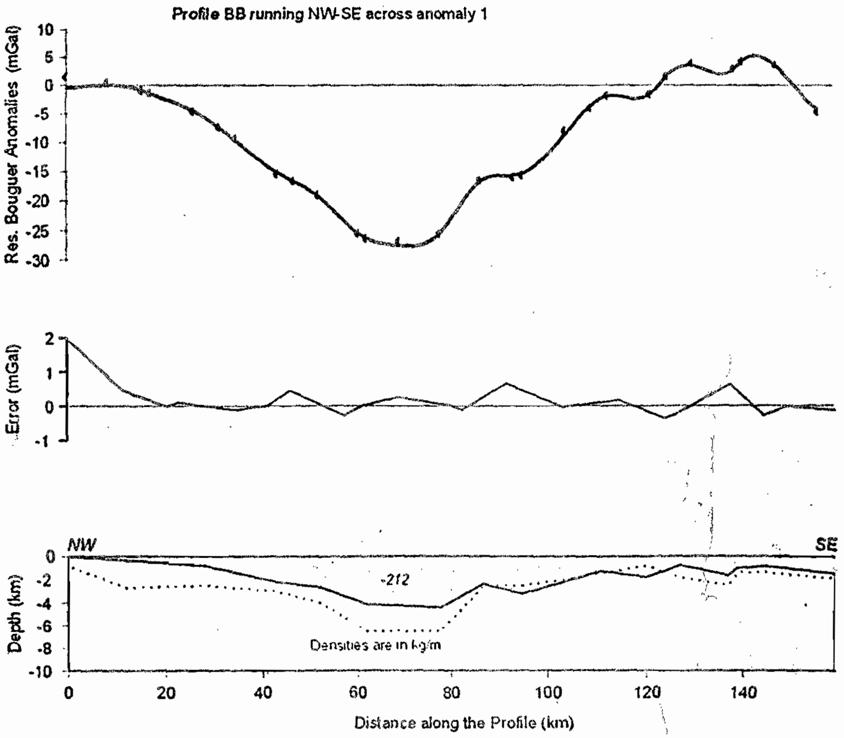

Fig.5 Simple 2.5D Interpretation of the Residual Bouguer anomalies along Profile BB'(fig. 4) in terms of a thick sedimentary cover. Density contrast between the basement and the sediments is -212 kg/m^3

and the solution is obtained by iteration; the program package INVERT is used written by Smilde (1998). In a starting model both the *a priori* geometrical and density assumptions (parameters, e.g. coordinates) are specified and, equally important, the error limits of the parameters. In the Bayesian approach the model parameters and their uncertainties are treated equivalently to the data or observations. The *a priori* information comes from geophysical and geological data, sometimes simply guesses on the basis of comparison and experience. INVERT allows changing, and experimenting with, relative weighting of the gravity observations and the model parameters.

In INVERT the linearization is done by numerically differentiating the field effects (at all observation points) with respect to all model parameters, i.e. by computing the effects at the initial values and closely neighbouring values of the parameters. The linearized equations are the basis of the normal equations to be solved for the parameter adjustments. Then new residuals are computed and new parameter adjustments are computed the same way. The program allows to assume any norm, usually norm 2 (least-squares), but often a final iteration with norm 1, minimizing the sum of the absolute values of the residuals, will render the most stable results. By this procedure gravity and initial parameter values are fitted within their error limits for densities, depths and locations. Good judgement of the user is needed to decide

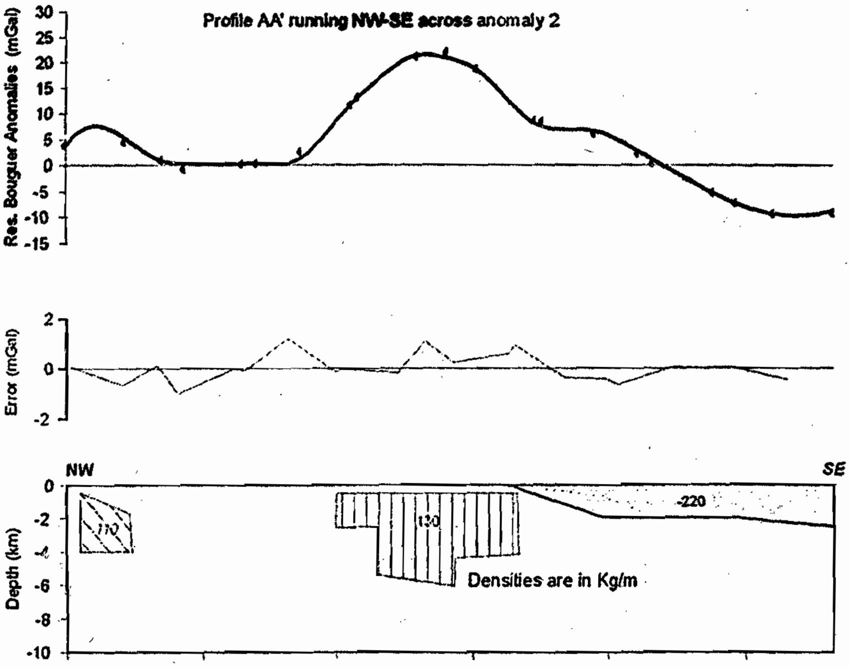

Fig.6 Simple 2.5D Interpretation of Residual Bouguer anomalies along profile AA'(fig. 4) in terms of a marginal intrusion with a density contrast of +130 kg/m^3. Density contrast between basement and the sediments is -220 kg/m^3. The presence of this intrusive at a depth of about 0.5 km was required for the anomalies to fit.

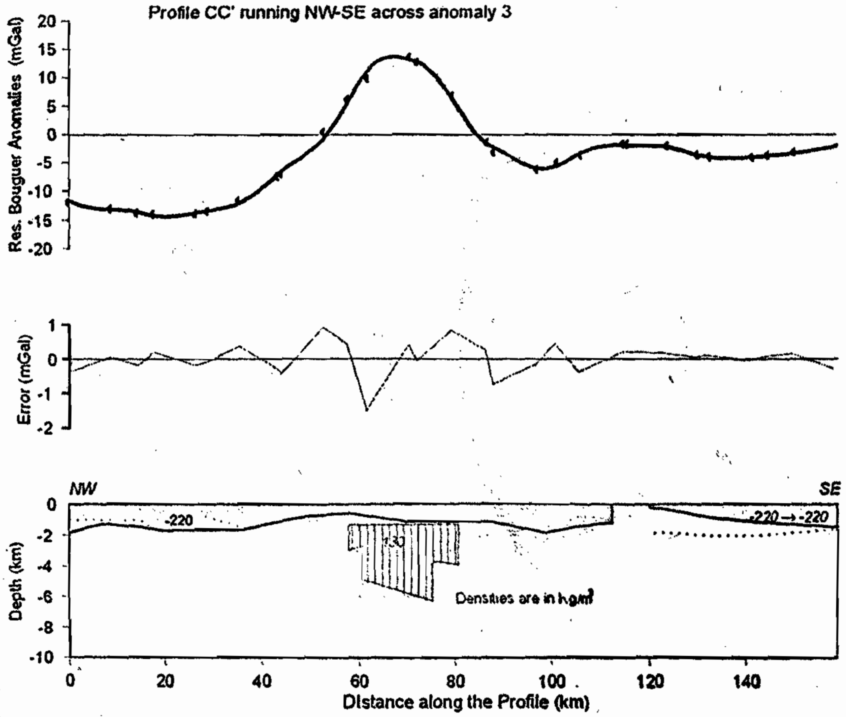

Fig.7 Simple 2.5D Interpretation of Residual Bouguer anomalies along profile CC' (Fig. 4) in cover. Density contrast between the basement and the sediment is -220 kg/m^3. Th intrusive at depth of density contrast of +130kg/m^3 was required for the anomalies to fit

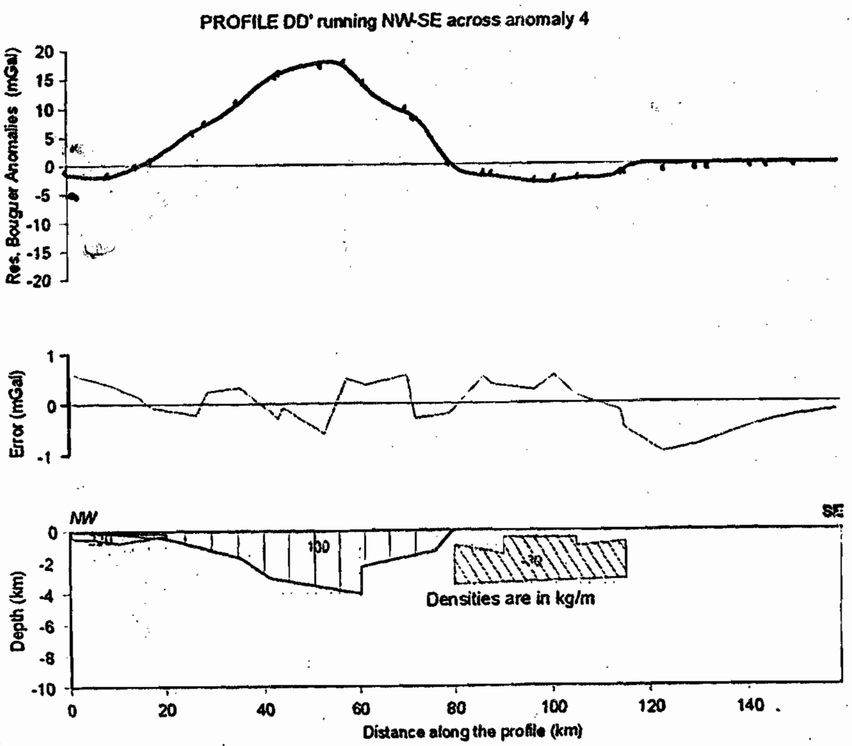

Fig.8 Simple 2.5D Interpretation of Residual Bouguer along profile DD' (Fig. 4). A dense body of density contrast +130 kg/m^3 with the basement was required for the anomalies to fit. The presence of an intrusive granite body at depth with density contrast of –30 kg/m^3 with the basement was inferred in the model.

whether a result is acceptable.

RESULTS

Residual Anomalies and Surface Geology

Figure 4 represents a superposition of the residual anomaly map on the geological map. This was used to carry out qualitative interpretations of the major anomalies in relation to the surface geology. Four profiles (1-4) across major anomalies were selected for two-dimensional modeling and interpretation and the results are used to support the qualitative interpretation. The anomalies are due to density contrasts between the rift sedimentary rocks (Cretaceous and Tertiary) and the underlying basement or intrabasinal mafic intrusions.

Anomaly 1

This anomaly is characterised by negative Bouguer values of up to -75 mGal (Fig. 3). The anomaly is centred between Alkaleri, Dukku and Gombe (Fig. 4), entirely located over the Neogene and Cretaceous sedimentary rocks.

Figure 5 is the result of 2-D modelling along profile BB'. The profile runs NW-SE over the sedimentary sequence and covers a distance of about 160 km (Fig. 4). The observed and computed anomalies together with the vertical cross-section for the interpreted model of the profile are shown in Figure 5. A density of 2670 kg m-3, which is the average value determined for the basement rocks (Table 1), was used for the modelling, while a statistically determined average of 2450 kg m-3 was used for the sediments. The model suggests that the Cretaceous sediments attain a maximum thickness of 4.5 km towards the centre of the profile (Fig. 5). The computed anomalies are seen to fit the observed anomalies within ±2 mGal (Fig. 5). The deduction that could be made from the model is that block faulting led to the development of a graben filled by sediments.

Anomaly 2

The gravity anomaly 2 is a positive gravity anomaly lying SE of Bauchi and SW of Alkaleri (Fig. 4). This anomaly trends in a NE-SW direction, about 100 km long and 25 km wide. It stretches from beyond Alkaleri to the southwestern end of the map at the western margin of the basin. Here the Tertiary Kerri-Kerri Formation is in contact with outcrops of the basement complex and the thickness of the sediments is believed to be very small (> 2 km). This anomaly coincides with the axial positive anomaly of Fairhead and Okereke (1987). Previously, these authors were unable to properly identify this positive anomaly because of lack of data. The anomaly suggests the existence of high-density igneous mafic rocks at depth along the margin of the trough. Suh *et al.* (2000) identified highly tectonised zones along the basement sediment contact intruded by mafic rocks. Volcanic rocks at Bashar in the middle Benue trough and Biu in the east (Fig. 2) could be the volcanic expression of the igneous bodies.

The 2.5 dimensional modelling along profile AA' (Fig. 6) that cuts across anomaly 2 suggests the existence of a about 25km wide high density body (2800 kg m^{-3}) with a width of about 25 km at a depth of ca 0.5 km beneath the surface. The modelling suggests a ca 2km thick sediments infill in the eastern margin of the profile.

Anomaly 3

Anomaly 3 (Fig. 4) is positive gravity anomaly of up to 14 mGal and is possibly due to very shallow basement rocks and a thin sedimentary cover. Alternatively this could mark mafic intrusions below and/or within the sediments. The 2-D modelling along the NW-SE trending profile CC' (Fig. 7), suggest that the positive anomaly on this profile is due to the existence of mafic intrusives. A density of about 2800 kg m^{-3} was assumed for the intrusive. The model (Fig. 7) reveals that the bodies occur between 1 and 6 km. The Cretaceous sediments of density 2450 kg m^{-3} along this profile have a maximum thickness of ca 1.8 km.

Anomaly 4

Anomaly 4 occurs around Biu and is a positive anomaly with a maximum value of +18 mGals (Fig. 4). It is caused by mafic intrusive bodies inferred to be the roots of the Biu basalts. Figure 8 is the 2.5 dimensional modelling for profile DD' which extends for a distance of about 160 km. The source of the large positive anomaly is modelled using a ca 20 km wide mafic body, which spreads out, at a distance of about 80 km, An older granite suite (of density 2637 kg m^{-3}) was modelled to be part of the basement rocks at depths between 0.5 and 3 km along the profile. This probably accounts for the low gravity between 100 and 118km along the profile. The model suggests that the basaltic flow at the north-western end of the profile is a thin layer overlying the Cretaceous sediments that are up to 0.9 km thick.

Crustal Structure of the area

The crust and upper mantle under the Gongola arm of the Upper Benue Trough and adjacent areas were modelled along profile QQ' using the gravity field over the area.

Figure 9a shows a plot of the Bouguer anomalies along profile QQ'. The observed Bouguer anomalies along this profile were resolved by matching marginal gradients and extending them smoothly, as carried out by Ajayi (1987) for the gravity data within the Benue Trough, into the following three components :

1. a very long wavelength (λ=350 km) negative anomaly,and assumed to be due to asthenospheric rise under the trough (Fig 9a).

2. an intermediate (λ=250 km) positive anomaly, also centred over the trough which is considered to be due to crustal thinning (Moho uplift) under the area of study (Fig. 9b) and

3. a short wavelength (λ=180 km) negative anomaly due to the Cretaceous and Tertiary sediments filling the trough.

Figure 9c is a plot of the topography along this profile (QQ'). The topography along this profile is plotted in order to be able to determine whether or not the area is isostatically compensated.

Figures 9a and c shows that aninverse relationship exist between the Bouguer anomalies and topography in the area of study suggesting that the area is isostatically compensated.

Two-dimensional modelling was carried out for Profile QQ' to determine the crustal structure in the area. An average crustal thickness of 34 km was obtained in the project area and this value corresponds to that obtained by Fairhead and Okereke (1987) for the Yola arm of the Benue trough just to the south-east of the present project area.

Figure 10 shows the interpreted gravity model for Profile QQ'. A density contrast of +0.17g cm^{-3} between the base of the crust and upper mantle was used. The model for the dense mantle body has outward sloping flanks which are steeper on the western margin than the eastern one. This assymetry probably reflects, to some extent, the nature of the upper mantle beneath the Biu Plateau (Fig. 2) to the northeast. The width of the uplifted Moho (crustal thinning) is about 50 km giving a Moho rise of 5.5 km from 34 km. It is evident from Figure 10 that the Moho uplift broadens at the base extending over about 200 km.

DISCUSSION AND CONCLUSIONS

Gravity anomalies have been used to investigate the framework of the Gongola Arm of the Benue rift system.

The results of the interpretations of gravity anomalies

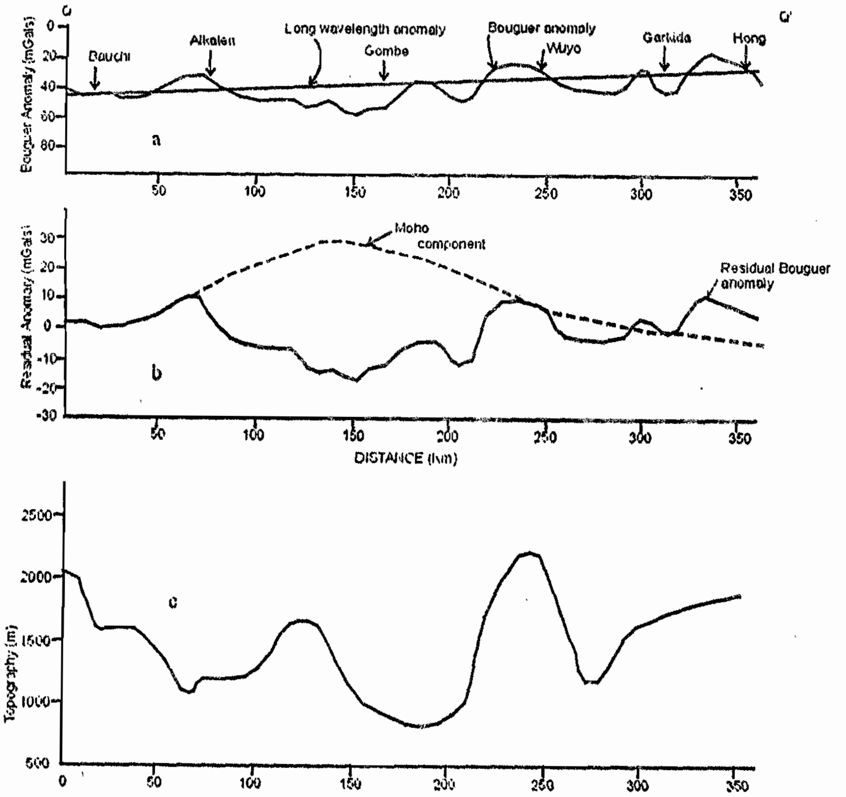

Fig. 9 Plot of Bouguer Gravity and Topography along profile QQ' across the Gongola Arm of the Benue Trough

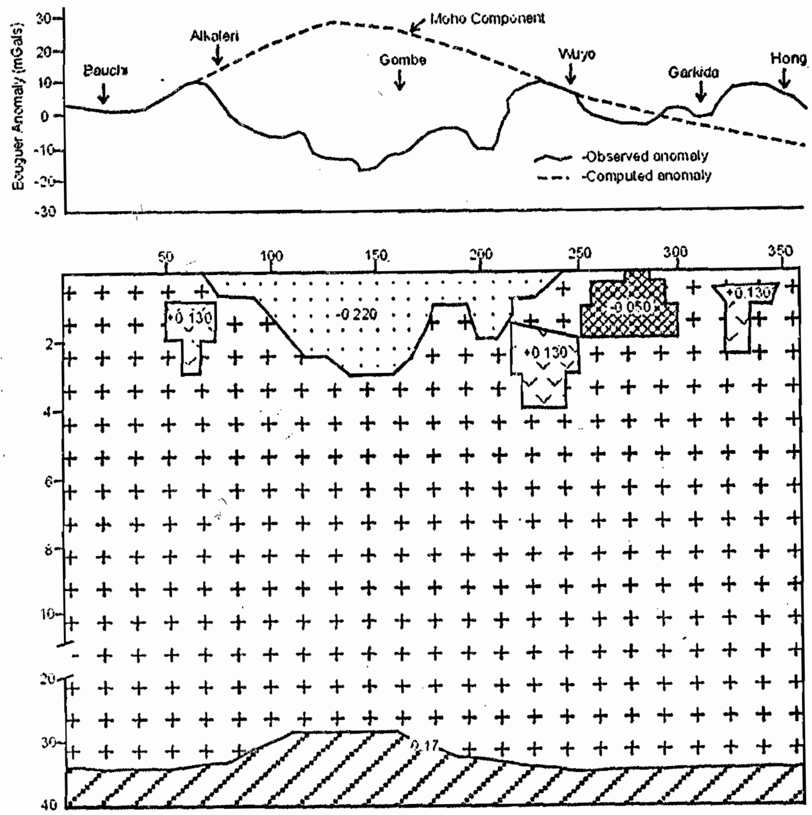

Fig. 10 Simple 2-D Crustal Model of the Area of Study along profile QQ'

⬚ Sediments ▩ Older granite ☐ Basic intrusives ▨ Upper mantle

suggest the existence of intra basement intrusives of high densities in the trough at depths between about 0.5 and 2 km. The existence of intrusive in suggests the existence of deeply penetrating fractures within the area. Basic intrusives have been inferred from results of geophysical studies conducted in different parts of the world over major rift systems such as the Rhine Graben and the Baikal rift (Zorin *et al.*, 1975; Zorin, 1971, 1981, Logatchev, 1993).

The prominent negative residual anomaly 1 between Dukku, Gombe and Alkaleri (Figs. 4& 5) shows a graben filled with sediments has been interpreted as a basement depression, which has been filled with sediments. This graben is hereby called the Dukku sub-basin or Dukku Graben. The results of the interpretation suggest that the graben is filled with sediments of thickness about 4.5 km and is about 60 km wide. For the sediments to have attained a thickness of about 4.5 km, within such a short distance from the basement, suggests that block faulting most likely took place in the area. The existence of block faulting has been suggested in the area Adegoke *et al.* (1986), and Enu (pers. communication, 1995).

Field evidence also suggests that block faulting took place in the area. This evidence includes the sheared and fractured Kaltungo inlier (Maurin *et. al.*, 1985), the highly sheared/fractured basement outcrop (inlier) around Gombe, and the sheared/fractured basement outcrop around Wuyo (Fig. 2) also in the area of study. These inliers could have been brought up to the surface by fault movements; and they are most likely to be the upthrown blocks of the fault movements, while the down-thrown blocks must have formed grabens such as the one seen in this area.

The results of the study in the area suggest that the area of study is essentially made up of graben and horst structure, with associated basic intrusion at depth. The width of ca 60 km is similar to more mature continental rifts such the Baikal rift, and thus suggesting that the width of these rift was acquired early in the evolution of of the rift. The differential block faulting observed in the area is believed to be a result of mantle upwelling and regional tension that were concentrated near deep crustal faults, and emplacement of basic intrusions in close association to these faults. Buried basic intrusives exist at depths ranging from 0.5-2 km, suggesting the existence of deep fissures in the crust beneath the area of study, which might have originated during rifting and parts of which became the foci of intrusives into the crust.

ACKNOWLEDGEMENTS

The authors will like to thank Dr Herbert Wallner of the Geophysics Group of the Mainz Universität; the DAAD Academic Exchange programme for financing the stay of the first author at the Universitaet of Mainz, which enabled the successful completion of this work and the Abubakar Tafawa Balewa University Bauchi, Nigeria authorities are gratefully acknowledged for providing funds for the fieldwork.

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