TREND SURFACE ANALYSIS AND INTERPRETATION OF GRAVITY DATA FROM THE MIDDLE NIGER BASIN, NIGERIA

BY

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DEDICATION

I dedicate this work to my parents and in memory of

D.L. Barkah (5th July, 1990).

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any other University or Institution. Information derived from published and unpublished works of others has been properly acknowledged in the text.

Likkason Othniel Kamfani 18/7/91

CERTIFICATION

This thesis entitled: Trend surface analysis and interpretation of gravity data from the Middle Niger Basin, Nigeria, by Othniel K. Likkason meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, and is approved for its contributions to knowledge and literary presentation.

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ABSTRACT

A set of Bouguer gravity values from the Middle Niger (Nupe) Basin is fitted with polynomial surfaces of various degrees and these and the associated residuals are contoured. On the basis of close correlation of residuals from the fourth degree surface with geologic structures of the area, and the fact that the fourth degree corresponds with the point which is closest to the discontinuity on the plot of variances against degrees of polynomial surfaces, giving the optimum degree that fits the data (Zeng, 1989), it is concluded that this surface best represents the regional field of this area. A prominent long wavelength anomaly on this surface is interpreted to be an upper mantle plume 2-4km above an average Moho depth of 35km. The associated residuals from this surface show prominent positive anomalies of the order of 15mGals. A 3-dimensional computer interpretation attributes these anomalies to shallow sources as well as a high density metamorphic basement of schist or amphibolite composition. Basic and ultrabasic rocks are considered possible sources of the prominent residual Bouguer anomalies. The negative anomalies are attributed to Older Granite suites that predominate the area and to the thick Cretaceous sediments where such are considered significant.

The contour patterns at the boundaries of the basin do not indicate faulting. This does not, however, rule out faulting at the contacts of the basin in view of the available evidence of major and minor faults indicated from Landsat imageries, drilling

logs and aeromagnetic analyses. Thus the effects of faults are taught to have been obliterated by the gravity effects of the shallow structural features.

The general indication is that the Niger Valley may be a rifted structure and the region where the prominent Bouguer residual anomaly occurs is thought to be a magmatic focus.

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CHAPTER 1

INTRODUCTION

1.1 General

The area treated in this thesis is located in the central region of Western Nigeria (Fig.1.1). It lies between latitude 7°30'N and 11°30'N and between longitude 3°40'E and 8°00'E.

The rock types located within the area are of the Precambrian (>500Ma) to probably Palaeozoic Basement Complex in which some portion are overlain by the sandstones of the Nupe Basin. The sandstones of the Nupe Basin are Cretaceous rocks which show occasional gentle folding. The basal sediments are believed to be of alluvial fan origin and comprise rounded to subrounded coarse conglomerates and cross-stratified sandstones locally scattered (Adeleye, 1976). These basal sediments are overlain by lithology comprising mainly sandstones, claystones, fine conglomerates, siltstones and in some places by ironstones of marine affinity. The Basement Complex rocks are presumably derived from ancient sedimentary series that covered the area which were subjected to several periods of regional metamorphism altering them to gneisses, migmatites and metasediments.

Younger metasediments believed to be Upper Proterozoic (1000-600Ma) in age (McCurry, 1976), were deposited on this granitised basement and folded along with it during the Pan African Orogeny (650-450Ma). The basic, intermediate and acid plutonic rocks known as the Older Granites intruded the basement rocks and the Younger supracrustal cover during the Lower Palaeozoic epeirogenic uplift following the Pan African Orogeny.

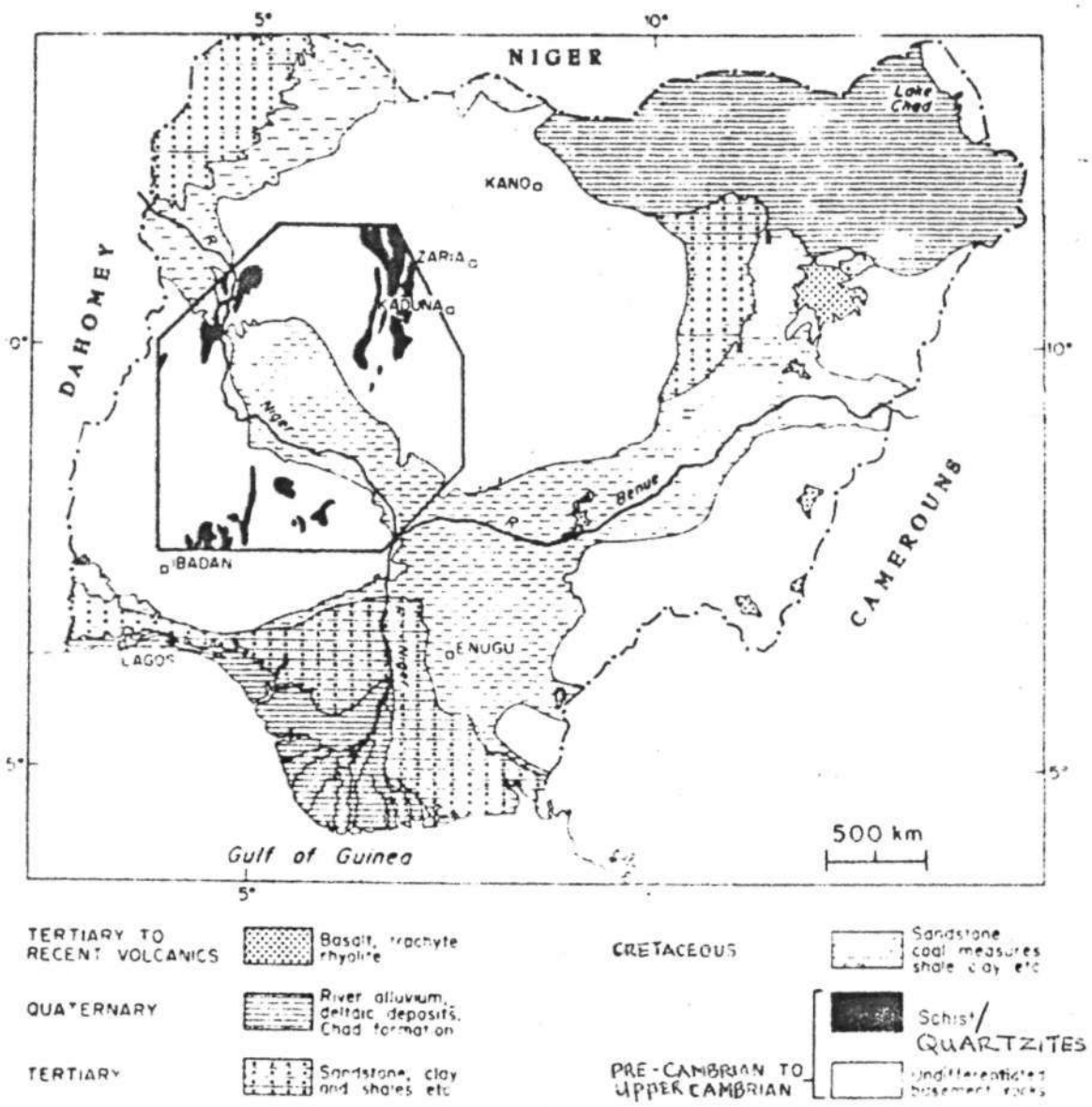


Fig.1.1 Simplified geological map of Nigeria showing the survey area (After Ojo and Ajakaiye, 1976)

1.2 Scope of Work

The present survey is a follow-up to the preliminary interpretation of gravity measurements in the Middle Niger Basin area by Ojo and Ajakaiye (1976). The profile interpretation of the gravity data structurally established the geometry of the sedimentary strata of the Middle Niger Basin area in addition to the provision of the base network for the area.

The field work undertaken in the course of this work was undertaken to fill a gap in the original data set of Ojo and Ajakaiye (1976) made possible by a new road in the area. A gravity profile was run from Tegina to Mokwa- Kontagora-Tegina junction (a distance of 103km) at station intervals of 2-4km. Fig. 1.2 shows the original gravity traverses including the present one.

The overall gravity data have been fitted with polynomial surfaces of various degrees. The fitted surfaces and their residuals were manually contoured because of lack of a suitable contouring package. On the basis of close correlation of residuals from the fourth degree surface fit with the surface geological structures and for the fact that fourth degree corresponds with the point which is closest to the discontinuity on the plot of variances of polynomial surfaces, it was concluded that the fourth degree surface best represents the effects of deep-seated structures in the area. The residuals from this surface were used for the structural determination of the gravitating bodies by three-dimensional modelling techniques.

The results obtained from all the above will be discussed especially as they relate to the origin of the Middle Niger Basin.

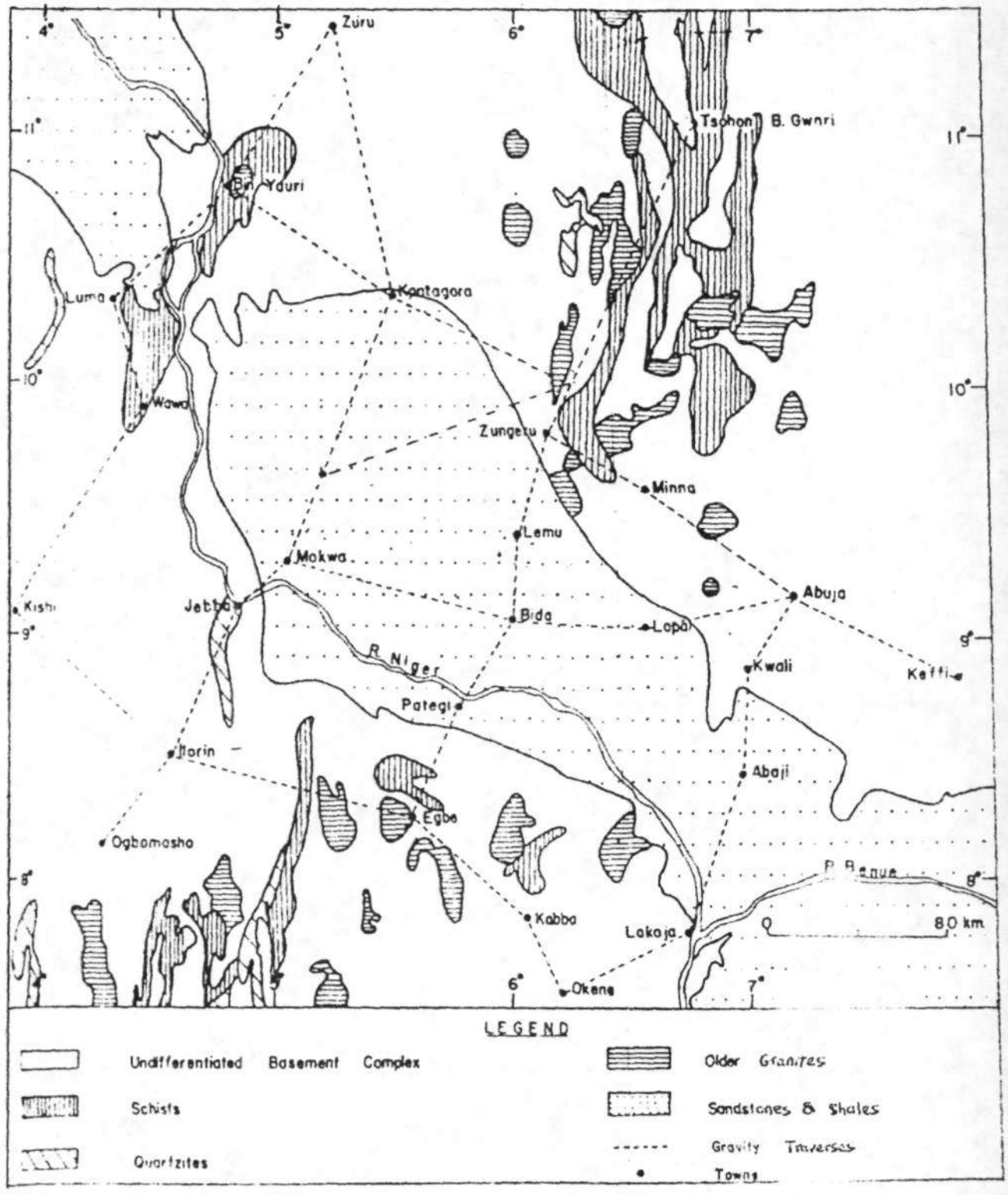


Fig.1.2 Geological sketch map of the survey area showing gravity traverses (After Ojo and Ajakaiye, 1976)

CHAPTER 2

THE GEOLOGY

2.1 Introduction

The Middle Niger Basin, also called variously the Nupe Basin, Bida Basin or Niger Embayment is situated in the western portion of central Nigeria. It lies between latitudes 7°30'N and 11°30'N and longitudes 3°40'E and 8°00'E. It covers an area of approximately 180,000km^2 (Fig.1.1). The greater part of this basin is filled with Upper Cretaceous sediments of Campanian-Maastrichtian marine to fluviatile depositional strata. The strata are believed to be more than 300m thick (Adeleye, 1976). These overlie the Precambrian to probably Palaeozoic Basement Complex.

2.2 General

Tectonic activities affected the Precambrian rocks of the Middle Niger Basin and are believed to have had severe geomorphological consequences in the pre-Cretaceous age. Some minor movements also took place in the Tertiary (Russ, 1957).

The effect of these geomorphological consequences is the gentle sloping of the country south-west ward (Russ, 1957). The slope represents a peneplain underlain by Precambrian rocks of various composition. The surface exposures are mostly isolated or grouped inselbergs of Older Granites with some low ranges of smooth schists. The south-west portion however consists of mesas. The Nupe Sandstones form part of this portion.

2.3 Physiography

The physiographic units of the Middle Niger Basin consist of three recognisable features (Fig.2.1). The Niger and its flood plains and tributaries make one feature. The tributaries are rivers Gurara, Chanchaga, Kaduna and a few small streams that drain the Northern Nigerian Basement Complex. The Niger itself runs ESE in the southern marginal areas of the basin and its flood plain is broad and could be up to 20km (Adeleye, 1976). A discontinuous belt of mesas forms another feature. These scattered flat-topped hills are seen in the Nupe sandstones with occasional outliers of these sediments found far from the main outcrop (Russ, 1957). It runs 16km east of Mokwa through an area south of Bida to Baro, Lokoja and south-west Dekina (Fig.2.1). The mesas cover about 10% of the basin (Adeleye, 1976). Intermediate break of slope are sometimes present along mesa walls: indicative of occurrences of relatively resistant beds. Continued weathering and erosion reduce mesas to isolated, steep-sided pillar-like hills (Blyth and deFreitas, 1984).

The plains that make the third feature take up about 70% of the basin (Adeleye, 1976). The plains are flat-lying to gently - rolling and these are sometimes broken by residual hills which are either conical or flat-topped as seen along Mokwa-Bida and Bida-Zungeru roads.

2.4 Lithological Units

2.4.1 General

Igneous and metamorphic rocks cover almost half the surface area of Nigeria. They occur mainly in three regions of

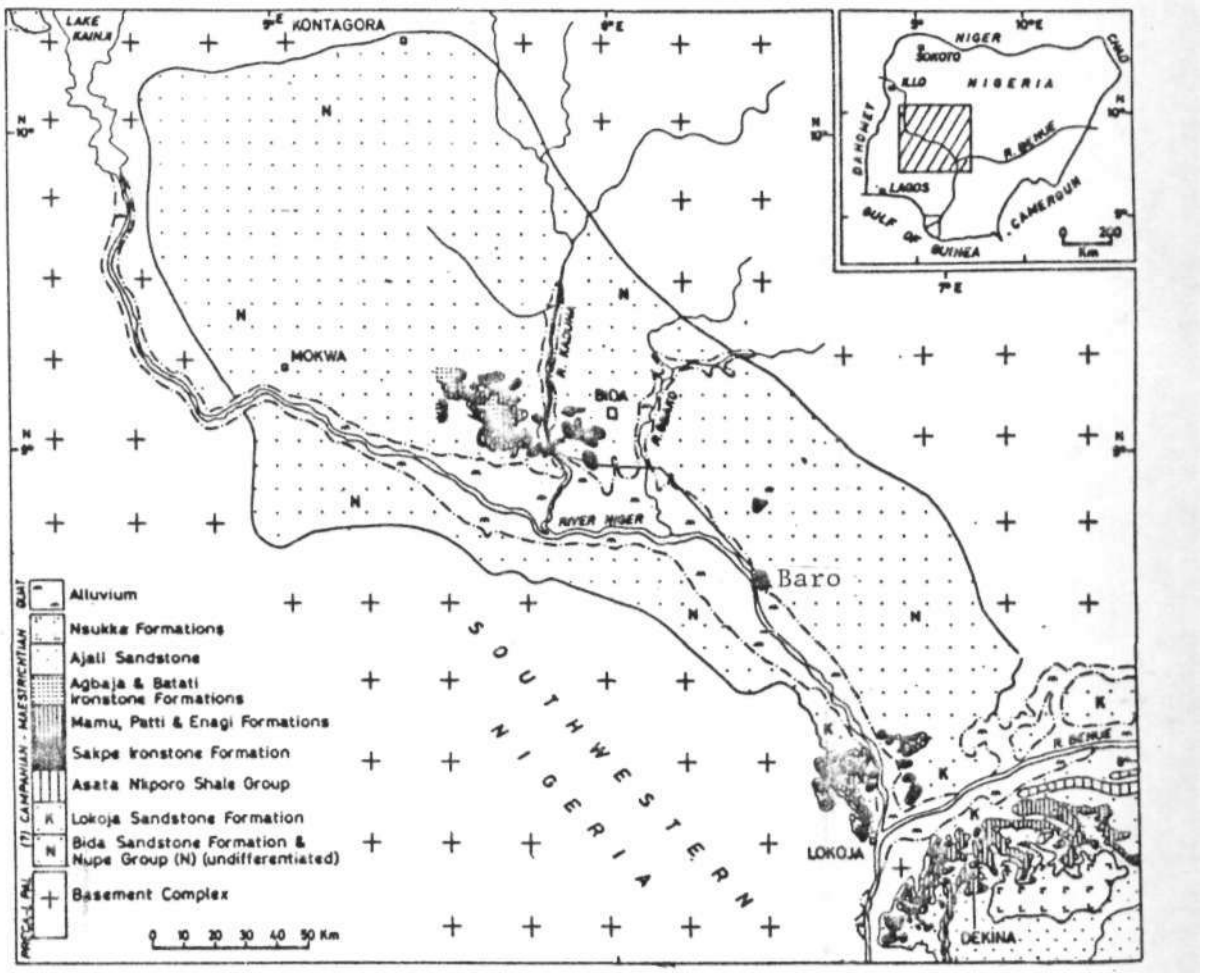


Fig.2.1 Lithological Units of the Middle Niger Basin
(After Adeleye, 1976)

the country: central North, South-west and extreme East (Fig.1.1). The other half is occupied by sedimentary rocks. The Nupe Basin occupies the western portion of central Nigeria.

The structural expositions of the area as reported by Jones (Adeleye, 1976) is a gently down-warped trough whose buried Basement Complex has a high relief with sedimentary formations of more than 300m thick. The epeirogenesis responsible for the basin genesis seems closely connected with crustal movements of the Santonian orogeny of South-eastern Nigeria and the nearby Benue Valley (Adeleye, 1976). The earlier periods of sedimentation and intrusion in the Precambrian represent a complex vast period of history in the area (Russ, 1957). These earlier sediments and some minor intrusion must have been subjected to several periods of metamorphism.

2.4.2 Igneous and Metamorphic Rocks

About 80% of these rocks form the Basement Complex and the remaining 20% as Younger intrusives and volcanic lavas. A large part of the Basement Complex rocks are of Precambrian age while the rest are of Cambrian age (Oyawoye, 1964). The Older Granites are batholithic masses of plutonic granites and granodiorites and form the larger part of the Basement Complex. The Younger Granites are high level intrusive-granites and occur in most part of Jos Plateau province.

Presumably, some ancient sedimentary rocks or series covered a great portion of the country. These could have been subjected to one or more periods of regional metamorphism which altered them to schists and finally to granulites, quartzites and calc silicates (Russ, 1957). These small bounds of granulites and calc

silicates commonly found in the Basement Complex today, are relict of these once extensive metasediments after they have been transformed to migmatites, gneisses and granites (Oyawoye, 1964).

Three distinct groups of rocks are recognisable from the igneous and metamorphic rocks in Nigeria. These are:

(i) Older Metasediments and Younger Metasediments.

(ii) The gneisses, Migmatites and Older Granites.

(iii) The Younger Granites and Volcanics.

The last group is not treated since they are not prominent in the Middle Niger Basin although their significance would be mentioned in due course.

The Older Metasediments

These are the oldest rocks in the Basement Complex. They consist of granites, calc silicates, arkosic quartzites and high grade schists, granulites and marble. They are scantly represented as lenticular relicts in the regional gneisses and have a wide spread occurrence.

Younger Metasediments

These include phyllites, schists, quartzites, slates, gneisses, conglomerate and volcanics. Different varieties of these metasediments occur scantly over the Basement Complex of Nigeria.

The Gneisses

The principal types of gneisses that occur in the Basement Complex are the biotite gneiss and the banded gneiss. Biotite gneisses are widespread and are usually fine-grained and strongly foliated (Oyawoye, 1964).

The Migmatites

The types of migmatites common in the Basement Complex are lit-par-lit gneiss and the agmatitic gneiss. Lit-par-lit gneiss is the gneiss produced due to intrusion of granitic material into older beds. Agmatitic gneiss is the gneiss produced due to the intruding granitic material forming a network of veins throughout the country rock.

The Older Granites

These are complex of gneissose granites, coarse porphyroblastic granites, granodiorites, charnockites, syenites, migmatites, pyroxene diorite and gabbro. They occur as batholiths in many parts of the Nigerian Basement Complex and are of Eburnean Orogeny (2,200Ma) through Pan-African in age (650-450Ma).

The Pegmatites

These are commonly found in the gneisses and are believed to have the same origin with the Older Granites. They are widespread in the Basement Complex and usually composed of microcline and quartz. They vary in widths from a few centimetres to about a metre.

2.4.3 The Nupe Basin

This trough is filled with Upper Cretaceous sediments and is mainly occupied by the Nupe sandstones. The original rock of the area could have been subjected to considerable erosion before the Upper Cretaceous beds were laid down. The sandstones consist of unfossiliferous shallow water sandstones and pebble beds. It is probable that these sandstones could have covered a larger area (continuous to the Sokoto Basin) than now (Russ, 1957). Tertiary earth movements could have impacted low dips to this formation leading to erosion over wider areas. The youngest rocks of the area are laterites and alluvial, terrace and terrestrial deposits of Tertiary and Recent age (Russ, 1957).

The general stratigraphy and sedimentation processes consist of the lithologies overlying the Precambrian Basement Complex. The sequence is divided into a number of formations and lithologies characteristic of the age group. The Precambrian to probably Palaeozoic rocks are the oldest rocks and form the Basement Complex (Adeleye, 1976).

During the Upper Cretaceous times, depositional cycle started with overlying of the Nupe Group (undifferentiated sandstones) in the Santonian (82-76Ma). Adeleye (1976) gave the remaining sedimentary succession as follows. Sandstone formations of Bida and Lokoja followed in succession up to the end of Santonian. During this period, there were no severe crustal movements to alter the geometry of the layers at the end of each depositional cycle. Thus these formations overlie conformably on one another.

At the beginning of the Maastrichtian (68-65Ma), the Aghaja (around Niger/Benue Confluence) and Batati (around Bida) Formations were deposited conformably over the Mamu Formation. The Agbaja and Batati Formations comprise ironstones of the Minette-type of iron ores (Adeleye, 1976). These ironstones have identical properties to the iron ores of Minette-type of Europe and America, which contain 1.3-0.8% phosphorus, small percentage of alumina, sulphur and silica (Adeleye, 1976). The depositional sequence is followed by Ajali Sandstones and the coal seams and sandstones making the Nsukka Formation.

The Quarternary deposits are the recent alluvium, laterites, terrace and terrestrial gravels and sands (Russ, 1957).

The sedimentary facies of the area and the description of the major formational lithologies have been given by Adeleye (1976). The beds are believed to be more than 300m thick.

2.5 Economic Geology

2.5.1 Gold Production

The Middle Niger Basin, being made up of marine to fluviatile strata overlying the Basement Complex had intensive mining activities in the 1930's. The Quarternary to Recent alluvial deposits found in the area became principal sources of nuggets.

The combined production capacity of North Western Nigeria (The Middle Niger Basin inclusive) was put at 236,000 ounces (about 6690kg) for a ten-year period, from 1933-42 (Russ, 1957). By the year 1954-55, production was almost negligible because being alluvial mining, the deposits discovered were soon exhausted (Russ, 1957). The gold in the Nigerian Precambrian is widely disseminated and usually does not justify working on anything but a small scale (Russ, 1957). Thus the gold winnings of the Middle Niger Basin were through alluvial, eluvial and vein mining; the chief areas being around Minna and Kazai-Beni, 60km East of Minna.

Traces of gold were also found in the Nupe sandstone. Blocks of silicified auriferous conglomerate are found in the soil along the banks of the Kaduna River at Guwa (Russ, 1957). Between Kontagora and Jebba, pebble beds occur in the Nupe sandstones at several horizons and some contain gold, as found in Momaji. Most conglomerates occur at the base of the Nupe sandstones, some in the outliers and others insitu (Russ, 1957). Thus gold mining that took place in the Middle Niger Basin were exploited from four main types of deposits: alluvial, eluvial, conglomerate and lodes or vein. Alluvial and eluvial gold

winnings were greater compared to the lode deposits and small amount coming from conglomerate deposits. The gold qualities coming from these sources are different. Gold won from lodes deposit tend to be uneconomic to work unless the gold has been released through weathering at surface and concentrated in the eluvium. Gold won from conglomerates might represent an ancient alluvial deposits formed long after the emplacement of the auriferous quartz veins in the schists (Russ, 1957). It could also occur that gold was deposited from solution which ascended along planes of weakness in the shatter belt.

2.5.2 Ironstones

With the exhaustion of the precious minerals, like gold, in the Middle Niger Basin, attention was directed at the ironstones that exist in appreciable quantity in the area.

Most of the ironstones found in the area are oolitic and pisolitic and occur in abundance around the Bida and the Niger/Benue confluence areas. The oolitic ironstones of the Lokoja (Agbaja Ironstone Formation) compare favourably with the Minette-type ores of Europe and North America (Adeleye, 1976). Most plateaux around Lokoja are capped by the ironstones of more than 10m thick and cover about 240sq.km (Adeleye, 1976). The iron content of the ore is put at 45-50% from the estimate of the content from drill samples around the area. The same source of estimate gave 7,000 million tons of the ore around Lokoja alone (Adeleye, 1976). Sample ores assayed in the area gave an average of 50% iron and thickness of 10m.

The Lower Ironstones of Bida (Adeleye, 1976) have a maximum thickness of 5m and have oolitic facies which are sandy. In most places around Bida, ironstones occur below the argillaceous Enagi siltstone Formation which renders open cast mining difficult (Adeleye, 1976). The Upper Ironstones also occur in Bida and have the same aerial coverage as that of Lokoja. Like the Lower Ironstones, ore samples have not been assayed. These ironstones have thickness that lie between 10-5m and more sandy in the oolitic facies than the Lower Ironstones. It is believed that the over-burden of the Upper Ironstones is a low grade ore of forms of laterite, similar to that of Agbaja Ironstones Formation (Adeleye, 1976).

There is a need therefore, to take full advantage of the existing deposits of ironstones and the adjacent deposits of calcitic marble around Okene-Auchi areas. These two deposits make two-thirds the requirements for the principal raw materials needed for smelting of iron. Haematitic ironstone somewhat similar to the Precambrian banded ironstones have also been reported around Okene and Osokosoko areas (Adeleye, 1976).

2.5.3 Other Minerals

Apart from huge deposits of ironstones in the area, other minerals also occur, and as far as is known, these are unprofitable to exploit. Minerals like galena, pyrites, chalcocite, arsenopyrite,

malachite and azurite have been identified in Minna and Izom (24km west of Abuja). These minerals are not always found together and are always associated with gold (Russ, 1957).

Minerals not associated with gold, like diamond have been reported in Kabba province in 1936 (Russ, 1957). Kyanite schists were found in Kazai-Beni area around Minna. Kyanite is well known for its use as refractory. Whitish, sandy, kaolinitic claystones have been reported in various localities in the Basin. Hazel (1950) reported that tops of prominent plateaux around Lokoja have up to 6m band of pure kaolin with about a metre of black shale parting (Adeleye, 1976). The claystones could be useful in ceramic industry in addition to its use as fire-clay.

CHAPTER 3

FIELD PROCEDURE AND DATA REDUCTION

3.1 General

The field work undertaken in the course of the project was very minimal because the bulk of the data had already been collected (Ojo and Ajakaiye, 1976). The survey was carried out along the new Tegina-Mokwa road, covering a distance of 103km to a point where it joined Kontagora-Mokwa road. The additional data would fill in a gap in the originally collected data which was not possible as a result of non-availability of the road along this profile at the time of the original survey.

3.2 Previous Geophysical Work

A United Nations Project involving the use of aeromagnetic, aero-electromagnetic, electrical and magnetic methods was carried out during the period 1964-1967. The project was aimed at exploration for mineral resources, especially the base metals (Ojo and Ajakaiye, 1976). The result showed that no important primary deposits of precious or base metals were to be found in the area.

A gravity survey was carried out in the early seventies in which a gravity base network for the area was established (Ojo and Ajakaiye, 1976). The data were collected along some profiles including some beyond the margins of the basin. A total of 870 gravity stations were established along these profiles at 1-4km intervals. Interpretation of the data was done along these

profiles; the aim of which was to establish the maximum thickness of the Upper Cretaceous sediments and their epeirogenesis. Another primary aim was the establishment of a gravity base network for the area.

Rock samples collected during the survey showed a density of $2.70 \pm 0.052 \times 10^3 kg\,m^{-3}$ for the basement complex rocks and $2.51 \pm 0.348 \times 10^3 kg.\,m^{-3}$ for the Upper Cretaceous sediments.

The area, according to the profile interpretation was characterised by both negative and positive Bouguer anomalies with a range of 70mGals . Negative residual anomalies obtained from visual smoothening and centred on the basin were explained by the presence of thick Cretaceous sedimentary rocks. From the 2-D modelling, it was estimated that the maximum possible thickness of the sediments is generally of the order of 1km and was nowhere considered to exceed 2km. Positive residual anomalies occuring in some part of the basin were attributed to high density metamorphic basement, and to masses which are probably of schist composition. The basin was thought to be an area of local subsidence.

Other studies in the area include a memorandum on resistivity surveys in the Ihima District, near Okene reporting one of the results in the search for groundwater (Cole, 1958). The survey showed that the bedrock was too shallow for water yields in the weathered material to be very good. A 3-D interpretation of Bouguer anomalies over the Minna Batholith (Udensi, 1984) and the geophysical investigation of the Bida Basin (Adeniyi, 1984)

are other studies undertaken in the area. A recent study (Kehinde and Loehnert, 1989) in the Bida Basin was directed at determining the flow parameters of the area. About 150 lithological logs of boreholes drilled to a maximum of 200m covering the area, showed that the sediments were fluviatile and consist of intercalation of sands, silts, gravels and loosely compacted and friable sandstones, siltstones, shales, conglomerates and in places ironstones.

3.3 Instrumentation and Fieldwork

The instruments used are the Lacoste-Romberg gravimeter (Model G.446), two Wallace and Tiernan altimeters (Model FA.181) and a psychrometer.

Before the fieldtrip, the gravimeter and four altimeters (A,B,C,D) were observed for 21 hours in the Geophysics Equipment store. The drift curves (including tidal effects for the gravimeter) are as shown in Fig.3.3.1 and Fig. 3.3.2.

The striking feature of the two figures is their cyclic nature. The instruments are sensitive enough to record the changes in acceleration due to gravity caused by the movement of the sun and the moon. These tidal variations are cyclic and their effects on field measurements become significantly great if field measurements are spread over a long period of time. The usual recourse is to correct for this earth tide if tidal tables for corrections are available for that range of latitude. Lack of tidal tables, however, couldnot permit corrections for earth tide for the present survey and so the survey was restricted to the linear portions of the curves.

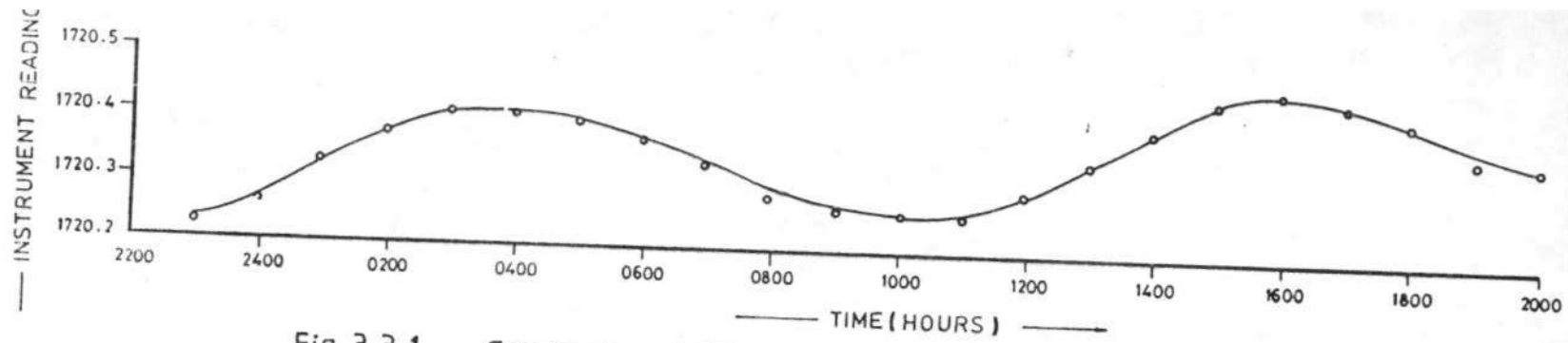


Fig. 3.3.1 Gravimeter drift curve (including tidal effects).

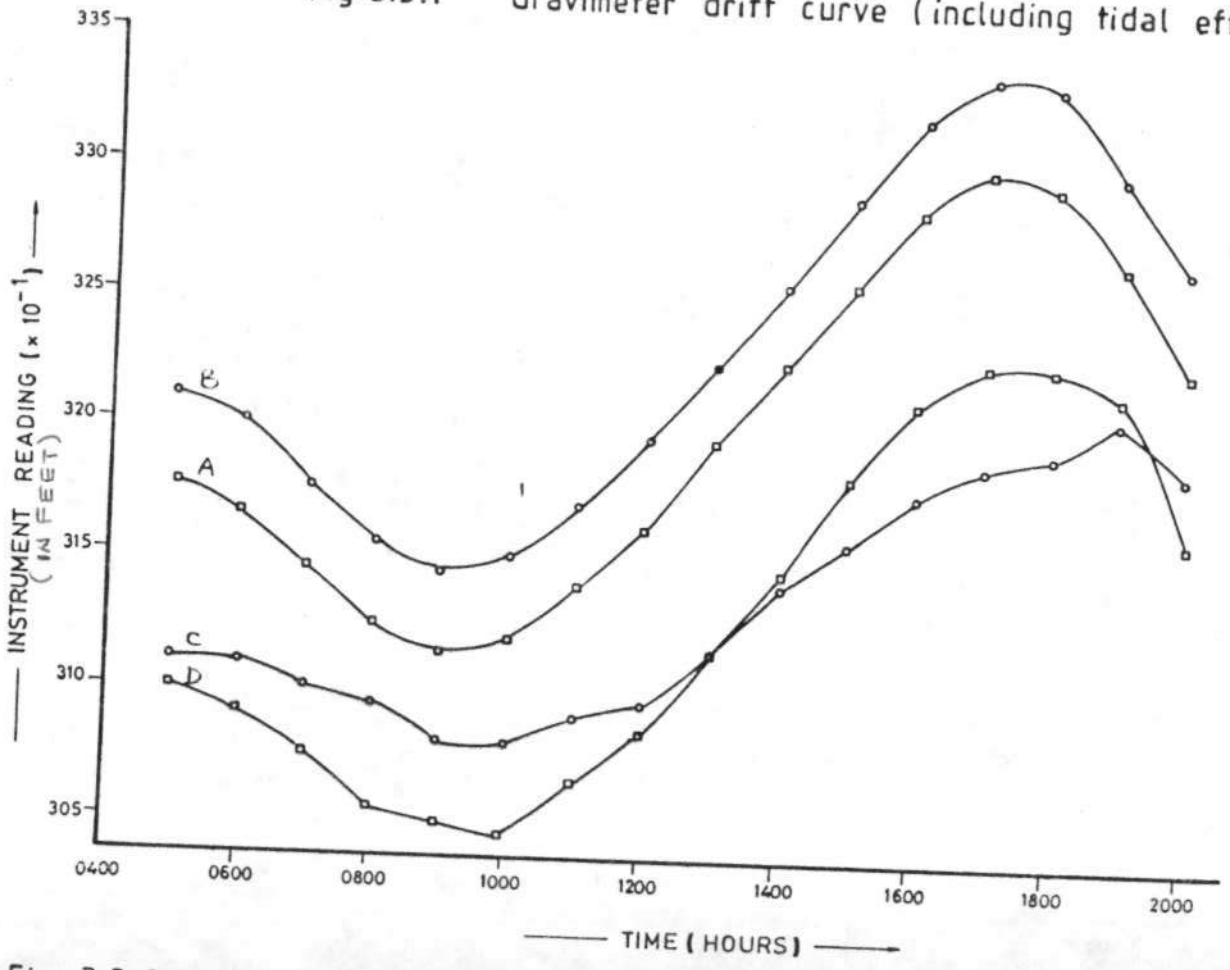


Fig. 3.3.2 Drift curves for the four Altimeters.

Figure 3.3.1 shows that the gravimeter displayed a linear drift between 2400-0230 hours with a drift rate of 0.054mgal/hr and between 0530-0800 hours with a drift rate of -0.044mgal/hr. The maximum range within these time intervals is 0.16mgal. Linear drifts were also observed between the hours of 1100-1500 with a drift rate of 0.052mgal/hr and between the hours of 1730-1900 with a drift rate of -0.050mgal/hr. The maximum range within these hours is 0.22mgal.

For the altimeters observed, the pattern of drift curves for altimeters A and B were similar and uniform throughout the 21-hour observation (Fig.3.3.2). They were therefore chosen for the survey. Altimeter C shows erratic behaviour beyond 1500 hours. The two chosen altimeters showed that their drift characteristics are similar to that of the Lacoste - Romberg gravimeter (Fig.3.3.1). Thus measurements during the survey were carried out at the same time for gravimeter and the altimeters using the single loop observational technique. A base station was established at Tegina via a state survey bench mark (BM.MN.CS. 68T) at Minna, used by Ojo (1974). The base station was used to tie measurements along the surveyed profile.

3.4 Data Reduction

Variations in gravity as recorded by the gravimeter as it moves over the ground surface generally include several effects unrelated to geology. Effects due to the oblateness of the earth, changes in elevation, isostatic compensation, drift of instruments, tidal effects and to various other causes are responsible for some of the variations observed. Thus the concern is to remove from the

data as carefully as possible, all these extraneous disturbances. Only after these are accomplished can geophysical interpretation be seriously attempted.

3.4.1 Drift/Tidal Correction

The survey was carried out in the linear region of the drift characteristics and the tidal correction was incorporated into the instrument drift correction. Linear drift is assumed for this correction. The drift correction for the station S, δ_s, is given by

$$\delta_s = \frac{(R_B - R_A) - (g_B - g_A)}{t_B - t_A} \cdot (t_S - t_A) \quad \ldots\ldots\ldots\ldots (3.4.1a)$$

where R_B and R_A, g_B and g_A and t_B and t_A are respectively the instrument readings (in mgals), gravity values (in mgals) and times of readings at base stations B and A; t_s being time for readings at station S.

The drift correction is subtracted from the station readings. The observed gravity at station S is g_S given by

$$\left.\begin{aligned} g_S &= g_A + (R_S - R_A) - \delta_s \\ \text{or} \qquad & \\ g_S &= g_B + (R_S - R_B) - \delta_s \end{aligned}\right) \quad \ldots\ldots\ldots\ldots (3.4.1b)$$

R_S is the reading for station S. The formulae (3.4.1a) and (3.4.1b) also apply to altimetric drift correction appropriate to units of measurements used.

3.4.2 Latitude Correction

The normal gravity values (theoretical gravity values) at the reference ellipsoid is given by the Geodetic Reference System (GRS 67) Formula (1967) as

$$g_{\phi} = 978031.846(1 + 0.0052788\,95 \sin^2\phi + 0.000023462 \sin^4\phi \ldots\ldots\ldots (3.4.2)$$

This gives the normal gravity g_{ϕ} in mgals at latitude ϕ. This takes care of latitude effect. The formula is used to compute the normal gravity at all the stations once their latitudes are specified. The gravity anomaly is the difference between the observed gravity and this theoretical gravity for all the stations.

3.4.3 Free-air Correction

Gravity stations that either lie above (or below) the reference ellipsoid (the mean sea level) will have their gravity values reduced (or increased). Therefore some corrections have to be made to bring all the stations to this datum level.

The free-air correction g_{FA}, in mgals is given by

$$g_{FA} = \pm \frac{dg}{dz} h$$

$$= \pm 0.308596h \qquad \ldots\ldots\ldots\ldots (3.4.3),$$

h being in metres and dg/dz is the vertical gravity gradient which is 0.308596mgal/m at the mean sea level.

3.4.4 Bouguer Correction

The earth material between the point of observation and this datum level (mean sea level) also contributes to the observed gravity. If this is assumed to be an infinite slab, then the Bouguer correction g_{BE} in mgals is given by

$$g_{BE} = \mp 2\pi G \rho_c h \qquad \ldots\ldots\ldots\ldots\ldots (3.4.4)$$

where G is the Universal constant of gravitation, ρ_c is the assumed crustal density and h is the height or elevation of the station with respect to the mean sea level. The gravitational attraction of such a slab on a unit mass is $0.04186\,\rho_c$ mgals per metre.

3.4.5 Bouguer and Free-air anomalies

If the drift corrected observed gravity value for a station S, is g_s, then the free-air anomaly FA in mgals is given by

$$FA = g_s - g_\phi \pm 0.308596h \quad \text{.....(3.4.5a)}$$

The Bouguer anomaly, BA in mgals, is given by

$$BA = g_s - g_\phi \pm 0.308596h \mp 0.04186\,\rho_{ch} \quad \text{....(3.4.5b)}$$

3.4.6 Errors in Bouguer Anomalies

In analysing the accuracy of gravity anomalies Δg, it is necessary to appraise the accuracy of the method used in computing them. Terms neglected in simplified formulae and erroneous values of constants may cause systematic errors in the computed anomalies Δg. A systematic error is created in Bouguer anomalies, for example, by neglecting the correction for irregularities in the terrain or by omitting Bullard's term. Other sources of systematic error include non-linear drift of the instrument, instrument and operator precision and errors in calibration factor of the gravimeter.

It is also necessary to assess the effect of random and systematic errors of the parameters of the formulae, the values of which are determined separately for each point of gravity.

These include the observed value of gravity, g, the geographic latitude $\emptyset$ and the elevation of the point of gravity h. Also to be considered are the variable parameters of the model of topographic, or compensating masses, for example, the mean elevation of the terrain in the individual sectors into which the neighbourhood around the point of gravity has been divided for computing the terrain correction.

The overall mean square error $M_{\Delta g}$ of the gravity anomaly Δg is defined by

$$M^2_{\Delta g} = m^2_{\Delta g} + c^2_{\Delta g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4.6a)$$

where $m_{\Delta g}$ is the mean square random error and $c_{\Delta g}$ is the mean square systematic error. The latter error is very difficult to discern.

The law of propagation of errors applies to the mean square of the random error in practical gravimetry (Miloš et al, 1973). Thus

$$m^2_{\Delta g} = m_g^2 + (\partial \Delta g / \partial \emptyset)^2 m^2_{\emptyset} + (\partial \Delta g / \partial h)^2 m^2_h + m^2_T + \ldots . (3.4.6b)$$

where m_g, $m_{\emptyset}$ and m_h are mean square random errors in determining the gravity g, the geographic latitude $\emptyset$ and the elevation h of the point of gravity respectively; m_T is the mean square error of the terrain correction. Thus equation (3.4.6b) serves the purpose of computing the mean square error of the Bouguer anomaly.

The value m_g is determined by checking the gravity measurements. At the l gravity checkpoints, n independent

measurements of the gravity g were made. The mean value of g and of the deviation d is determined at each control point for the individual observation with respect to the former. Thus

$$m_g^2 = \sum d^2/(n-1) \qquad \ldots\ldots\ldots\ldots (3.4.6c)$$

Since the latitude ϕ is usually taken from map, the error m_ϕ depends on the graphical accuracy with which the point of gravity is plotted. A graphical accuracy of ±0.5mm on a map with scale of 1:100000 represents an error m_ϕ of ±50m (Milos et al, 1973) and error in Bouguer anomaly of 0.08mgal for $\phi = 45°$.

The derivative $(\partial \Delta g/\partial \phi) \approx (\partial g_\phi/\partial \phi)$. Thus the International Gravity Formula can be used to compute this derivative. Similarly the derivative $(\partial \Delta g/\partial h)$ can be computed from equation (3.4.5b). The errors in elevation measurements m_h especially with altimeters can be up to 3m (Ojo, 1974). This gives $(\partial \Delta g/\partial h) m_h$ = 0.6mgal in the Bouguer anomaly. The mean square error m_T in the terrain correction depends on the accuracy of the elevation in the individual sectors. In mountaneous regions, the error amounts to several tenths of a milligal. Although terrain corrections were carried out for the original data set where elevation variations justified them, they were not carried out for the additional data collected for this study. Computation of terrain correction, ΔT, is tedious and numerical techniques normally employed make use of high speed computers. Graphical techniques require reasonably accurate topographic maps which were not available for the area. In areas of low-to-moderate

relief, these corrections rarely exceed a very few gravity units (Grant and West, 1965). Terrain correction computed for a station surrounded by hills as high as 300m (Ojo, 1974) showed a value of 0.2mGal.

Under normal atmospheric and instrument conditions, errors in Bouguer anomaly coming from repeated measurements of gravity at a point are usually negligible. Thus the errors in Bouguer anomaly are coming from inaccurate determination of the latitude and station elevations. A graphical accuracy of ±0.5mm on map has a maximum error in Bouguer anomaly of 0.08mGal. The elevation error in Bouguer anomaly for error in altimetric levelling of 3m is 0.6mGal. Thus errors in Bouguer anomaly coming from these sources nowhere exceed 0.7mGal.

CHAPTER 4

ROCK DENSITY MEASUREMENTS

4.1 Introduction

Some of the corrections applied to gravity measurements require a knowledge of rock densities. These include the terrain and Bouguer corrections in which a knowledge of near-surface rock densities is important. Also, the picture that emerges after Bouguer gravity values are obtained is usually a reflection of lateral variation in rock densities in the upper crust. A knowledge of rock densities is therefore very relevant in the interpretation of gravity anomalies in a survey area. This is because the accuracy of interpretation of gravity anomalies depends greatly on the assumed density contrasts of the rocks, which are usually small. The density difference between the various rock types in a study area must be known in order to appropriately restrict density contrasts used in model computations.

Various authors have published tables of rock densities (Dobrin, 1976; Milos̆ et al, 1973; Telford et al, 1976; Smithson, S.B. 1971) affording a general survey of rock densities. Densities from these tables cannot be assumed to be the representative densities of any particular area of study, because rocks of the same lithologic units may vary in densities depending on the local geological conditions that prevailed over the area. The usual recourse is to collect fresh samples of rocks from outcrops and determine their densities in the laboratory. Most exposed rock surfaces are however weathered to some extent so that

a more appropriate method would have been to determine rock densities in-situ. However, there is no satisfactory way to measure densities of rocks in-situ (Grant and West, 1965).

4.2 Measurement Technique

Portions of rocks exposed on the earth's surface are usually 'dry' compared to the 'wet' portions underneath. Since most rock samples collected in the course of a gravity survey are fresh samples from outcrops, the representative properties of the rocks should be the average between the 'dry' and 'wet' properties.

The laboratory techniques of density measurements involve the determination of 'dry' and 'wet' rock densities. The 'dry' density of a rock sample is determined by method of relative density measurements for a solid of irregular shape. The rock sample is weighed in air and then completely immersed in water and its weight also determined. If W_1 is the weight of a rock sample in air and W_2 its weight when completely submerged in water, then with the provisional assumption of water density to be 1000kg m^{-3},

$$\text{density of rock (in kg m}^{-3}) = \frac{W_1}{W_1 - W_2} \times 1000$$

The rock samples are then submerged in water for at least 24 hours. At the end of the period, they are removed, dried of excess surface water and weighed as described above. These will give the 'wet' densities. The mean density for a particular rock type and the standard deviation from the mean are determined for each rock type. The standard deviation is given by,

$$\text{Standard deviation} = \pm \sqrt{\frac{\sum_{i=1}^{n} (X_i - \text{mean})^2}{n}}$$

where n is the number of rock samples and X_i the sample rock densities.

In the course of the present work, only few rock samples were collected along the profile on which the gravity measurements were carried out. Thus only 20 fresh rock samples from outcrops were collected with the hope that previous values of rock densities (Ojo 1974) determined for the Middle Niger Basin area would mostly be taken into consideration. 15 of the rock samples were of the Basement Complex while 5 belonged to the sedimentary formations. A digital balance was used for the weighing of the rocks. It has an accuracy of $\pm 0.1 \times 10^{-3}$kg. Table 1 shows the summary of the density of rock types collected during this survey.

TABLE 1 The density of Rock Types

ROCK TYPES	NO. OF SAMPLES	RANGE $\times 10^3$kg m^{-3}	MEAN DENSITY $\times 10^3$kg m^{-3}	STANDARD DEVIATION $\times 10^3$kg m^{-3}
Biotite granite Granite gneiss Migmatites Schists	15	2.56-2.84	2.70	±0.092
Ferruginous Sandstones and Ferruginous Ironstone	5	1.87-2.63	2.35	±0.327

4.3 Review of densities from previous work

Fresh samples of Basement as well as sedimentary rocks were collected when the original gravity measurements were carried out by Ojo in 1972-3. 201 rock samples altogether were collected in which 143 were of the Basement Complex, 36 of the ferruginous

sandstones and siltstones and 22 of the ironstones. The densities of these rock samples were determined together with their mean densities and standard deviations. Table 2 and Table 3 show the densities of the lithologic units of the Basement Complex and sedimentary rocks respectively.

TABLE 2 Densities of lithologic units of the Basement Complex rocks (After Ojo, 1974)

GROUP NAME	ROCK TYPE	NO. OF SAMPLES	RANGE $x10^3$ kg m^{-3}	MEAN DENSITY $x10^3 kg\ m^{-3}$	STANDARD DEVIATION $x10^3 kg\ m^{-3}$
BASEMENT COMPLEX (Pre-Cambrian)	Biotite granite	32	2.60-2.71	2.65	±0.024
	Granite gneiss	14	2.56-2.75	2.68	±0.046
	Migmatite	45	2.62-2.85	2.72	±0.047
	Granodiorite	32	2.62-2.69	2.66	±0.019
	Quartz diorite	4	2.64-2.71	2.76	±0.009
	Mica Schist	12	2.72-2.79	2.76	±0.021
	Metamorphosed rhyolite	4	2.62-2.67	2.66	±0.018

TABLE 3 Densities of lithologic units of the sedimentary rocks (After Ojo, 1974)

GROUP NAME	ROCK TYPE	NO. OF SAMPLES	RANGE $x10^3 kg\,m^{-3}$	MEAN DENSITY $x10^3 kg\,m^{-3}$	STANDARD DEVIATION $x10^3 kg\,m^{-3}$
SEDIMENTARY	Ferruginous sandstone	20	1.95-2.24	2.09	±0.100
ROCKS OF NUPE BASIN	Ferruginous sandstone with high % iron	12	2.50-2.79	2.64	±0.069
	Ferruginous siltstone	4	2.12-2.41	2.27	-
	Ironstone	22	2.50-3.04	2.86	±0.136

4.4 Summary of Rock Densities

A summary of the densities for the Basement and sedimentary rocks as obtained from previous work is given in Table 4. It shows that the average density of the basement rocks is 2,700kg m^{-3} which is in agreement with Table 1. This will be accepted to be the mean density of the basement rocks. It exceeds the usually assumed density of 2670kg m^{-3} for the granitic crust used in Bouguer density. A mean density of 2510kg m^{-3} was calculated for the sedimentary strata (Ojo, 1974). This was not thought to be representative of the typical Nupe sandstone at depth because most samples obtained for the sedimentary strata were ferruginous sandstone which appears to cover the area extensively (Ojo and Ajakaiye, 1976). A density of 2400kg m^{-3} was instead adopted to represent the density of the sedimentary strata.

The ironstones of the Middle Niger Basin are not dominant over the area and are of shallow marine to freshwater origin and have thickness of 5-10m (Adeleye, 1976). Thus the representative density of the sediments cannot be that of ironstone. Ferruginous sandstone and ironstone which appear to cover the area give an approximate density of 2400kg m^{-3}, Table 1 notwithstanding. This density is assumed to be the density of the Cretaceous sediments of the Nupe Basin. Whatever the case, this density is tentatively taken to be consistent with the density range of the sediments in the region.

TABLE 4 Summary of the density of Rock Types (After Ojo, 1974)

ROCK TYPES	NO. OF SAMPLES	RANGE $x10^3$kg m^{-3}	MEAN DENSITY $x10^3$kg m^{-3}	STANDARD DEVIATION $x10^3$kg m^{-3}
Biotite granite Granite gneiss Migmatites Granodiorite Quartz diorite Schists and rhyolite	143	2.56-2.85	2.70	±0.052
Ferruginous Sandstone Ferruginous Siltstone Ironstone	58	1.95-3.04	2.51	±0.348

CHAPTER 5

REGIONAL-RESIDUAL SEPARATION

5.1 Introduction

Interesting anomalies on gravity map are most often masked by deep-seated structures. Separation of these anomalies (often referred to as the noise) from the regional background or regional trend constitutes one of the greatest problems of geophysics in the realm of filtering. These noises or residual anomalies often provide a direct evidence for reservoir-type structures or mineral ore bodies and hence, for structural interpretation, these effects have to be separated from the regional background.

There are several techniques of removing the regional trend. One approach is entirely graphical and another is analytical. The graphical and smoothing techniques, apart from being highly flexible since they allow the interpreter to incorporate personal judgement of rightness about the forms of residual anomalies, do not have legitimate bearing on solution of some problems. If the regional trend is very strong the residual anomalies will be very difficult to discern. The same problem is encountered over very rugged terrain and surface materials of considerable inhomogeneity (Grant and West, 1965).

The analytical approach is purely numerical. The second derivative technique resolves directly the harmonic equation to which gravity fields are subjected to. Since the technique is a measure of curvature of the fields, enhancement of near-surface structures is often the object of interest. The main problem

with this technique is its apparent lack of interpretational basis to which the fields are to be subjected to. This is due to imperfection in the data with each differentiation: an inherent problem of numerical differentiation. Thus the chief functions of second derivative method is to indicate the presence of anomalies under difficult circumstances (Grant and West, 1965).

Another widely used technique for regional-residual separation is polynomial fitting. It has many applications in geology and related fields especially in stratigraphic studies. This technique is reviewed in the next section.

5.2 Basis of Polynomial Fit

The fitting of polynomials to observed gravity data is used to compute the mathematical surface giving the closest fit to the data that can be obtained within a specified degree of details. This surface is considered to approximate the effect of deep-seated or regional structures if it is of low degree. The function that generates this surface is called the trend function for that specified degree and the consequent analysis of this surface constitutes the trend surface analysis. This is a small segment of the larger statistical field of regression analysis. The polynomial fitting therefore is based on statistical theory. The analytical methods and, in particular, this technique assumes the residuals to be random errors whose sum is zero (Telford et al, 1976). The fitting surface which represents the regional, is a surface which will have both positive and negative flanks from the observed data points with the residuals balanced between positive and negative areas (Nettleton, 1973).

Analytical methods of regional-residual separation become very useful if the total labour involved, complexity of the gravity map, density and distribution of the stations and the quality of the data are significant. With large quantities of data and complex regional field, analytical methods have an advantage over other empirical techniques (Telford et al., 1976). The rather involved mathematical procedure of surface fitting has become feasible with the advent of high-capacity electronic computers. Higher degree fits emphasize smaller and sharper residuals in details than low degree fits (Nettleton, 1973). Polynomial fit is similar in its results to second derivative maps because of negative as well as positive flanks of residual anomalies (Nettleton, 1973). For this reason, the residual anomalies from surface fitting techniques cannot generally be said to represent the local geological effects for any degree of surface. Therefore, not all results for surface fits can be used directly for quantitative geological interpretation by calculating the gravity effects to compare with the observed anomaly. The system is however very effective in picking out local anomalies (Nettleton, 1973). By appropriate choice of the order of residual, it is possible to isolate or emphasize anomalies of almost any magnitude desired within limits of the definition by the spacing of the original data. For any quantitative evaluation of particular anomalies by calculation from geological interpretations or assumptions to be carried out, the original Bouguer gravity map must be referred to.

5.3 Concept of Polynomial Fit

The objective of most trend surface analyses is to obtain a polynomial of sufficiently high order to give a surface of 'best fit' to the map data. The polynomial fit will be restricted to surfaces or 2-dimensional trend-surface analyses. The analyses are accomplished by fitting a trend function to a set of data values. Trend functions are described by equations. For surfaces of degree n, the trend function F is (Simpson, 1954).

$$F(x,y) = \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j \quad \text{.....(5.1)}$$

where a_{ij} are coefficients to be determined by adjustment using the least-squares method; x,y are co-ordinates of the point at which the function is evaluated. In gravity measurements, the x and y co-ordinates of a point represent the longitudes and the latitudes respectively.

When measurements are taken on a regular grid, the co-ordinates x and y in the latter series are replaced by orthogonal polynomials F(x) and F(y) (Milos$^{\check{}}$ et al, 1973). Non-orthogonal polynomial analyses are used to estimate trends when observations on a map cannot be taken directly on a grid pattern (Krumbein, 1959). Thus F(x,y) is the estimated regional field at a point x,y for polynomials of any degree. If G(x,y) is the observed Bouguer gravity value at that point, then the residual anomaly, R(x,y) will be

$$R(x,y) = G(x,y) - \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j \quad \text{.....(5.2)}$$

R represents the random components plus some small scale fluctuations (Krumbein, 1959). A problem in fitting trends involves selection of the terms that are to be included in the trend, after which all remaining terms are combined in the residual. It can be seen from (5.2) that once the coefficients a_{ij} are known, the regional values and hence the residual or deviation values will be completely evaluated. Since coefficients depend on the co-ordinates which are accurately known and fixed in time, they remain constant for any degree of fit (Harbaugh and Merriam, 1968). The least squares criterion to be satisfied by equation (5.2) becomes that of determining the position of the surface so that the sum of the squared deviations R is a minimum. Thus,

$$\sum_{k} R^2(x,y) = \sum_{k} (G(x,y) - \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j)^2 \quad \ldots\ldots(5.3)$$

is a minimum. For computation of the coefficients, see appendix I.

5.4 Goodness of Fit

It is important to compute measures that express the goodness of fit of the trend function to the data and then to determine whether the trend functions are statistically significant. One of such measures is the deviation of variable, Z, from its mean which is an index of the total variation within the entire data set. The total corrected sum of squares of deviations from the mean, Stl is

$$Stl = \sum (Z_{obs} - \bar{Z}_{obs})^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(5.4a)$$

Equation (5.4a) can be written as

$$S_{t1} = \sum Z_{obs}^2 - \frac{(\sum Z_{obs})^2}{N} \quad \text{.....(5.4b)}$$

where Z_{obs} = observed value of variable Z at data points.

$\bar{Z}_{obs}$ = arith metical mean of the observed value of Z

N = Number of data points

S_{t1} consists of two sources of variation, namely, that part contributed by the trend function, S_{tr} and that part due to deviations from the trend function, S_d (Harbaugh and Merriam, 1968). Thus,

$$S_{t1} = S_{tr} + S_d \quad \text{.....(5.5a),}$$

with

$$S_{tr} = \sum (Z_{tr} - \bar{Z}_{obs})^2 \quad \text{.....(5.5b)}$$

$$S_d = \sum (Z_{obs} - Z_{tr})^2 \quad \text{.....(5.5c),}$$

where Z_{tr} is the trend function evaluated at the point of observation. The sum of squares due to deviations is a reflection of the failure of the trend values to coincide with observed values (Harbaugh and Merriam, 1968).

The goodness of the fit is conveniently expressed as that part of total sums of squares accounted for by the trend function as a percentage. This has an advantage of easy comparison of trend function fitted to different sets of data. Thus the percentage reduction in total corrected sum of squares accounted for by the fitted surface or simply, the percent of total sum of squares, S_u (Harbaugh and Merriam, 1968) is:

$$S_u = \left(1 - \frac{S_d}{S_{t1}}\right) \times 100 \qquad \text{.....(5.6a), or}$$

$$S_u = \left[1 - \frac{\sum (Z_{obs} - Z_{tr})^2}{\sum (Z_{obs} - \bar{Z}_{obs})^2}\right] \times 100 \qquad \text{.....(5.6b)}$$

A fit of 100% is uncommon. A perfect fit will be realisable if the number of terms in the trend function equals the number of data points (Harbaugh and Merriam, 1968). A small value of S_u (say below 15%) depicts deviations or residuals which are geologically significant (Harbaugh and Merriam, 1968). Higher values of S_u are signal that most variation present in the data is not represented by the trend function (Harbaugh and Merriam, 1968).

5.5 Variance and Surfaces

Let a data set be represented theoretically by a function

$$f(x_i,y_i),\ i = 1,2,.....,L.$$

Let a polynomial surface

$F_d(x_i,y_i)$, $i = 1,2,....,L$ be fitted to this data set. L is the number of data points according to the principle of minimum variance σ_d, and d the polynomial degree,

$$\sigma_d = \frac{1}{L} \sum_{i=1}^{L} [f(x_i,y_i) - F_d(x_i,y_i)]^2.$$

Zeng (1989) showed that the variance σ_d decreases with increasing d and that the point of discontinuity on the curve of σ_d versus d gives the desired degree n of polynomial $F_d(x_i,y_i)$ that approximates $f(x_i,y_i)$. Ideally for $d < n$, σ_d decreases with increasing d and $\sigma_d = 0$ when $d \geq n$.

Fitting a set of data with polynomials $F_d(x,y)$ to gravity anomaly $\Delta g(x,y)$ yields a graph of σ_d against d. From the point of discontinuity of the gradient on this graph, the optimum degree n can be estimated.

The Bouguer gravity anomalies Δg_B can be regarded as the superimposition of anomalies from sources at varying depths. Thus,

$$\Delta g_B = \Delta g_1 + \Delta g_2 + \ldots + \Delta g_k,$$

where subscript represents the contribution from a specific depth. Thus Δg_1 is due to deepest disturbing mass, Δg_2, the next deepest and Δg_k the shallowest one: each source having a different frequency of anomaly (Zeng, 1989). Clearly the first degree polynomial accounts for the deepest anomaly and progressive degree polynomials include the effects of the next deepest and the following ones.

5.6 Spacing of Data Points/Structural Analysis with Trend Surfaces

Data spacing is very critical in trend surface analysis. Under normal circumstances, data points are supposed to be evenly distributed geographically over a region of interest, but not necessarily on a grid. One spectacular aspect of equable distribution is that when the least-squares criterion is satisfied, closely spaced points exert undue influence on configuration of the trend surface as compared to widely spaced points (Harbaugh and Merriam, 1968).

Fortunately, most geophysical data points are equably distributed, thus providing greater potentials for analysis of equably distributed data-points. In most cases, irregularly spaced data have an advantage over regular or gridded data points in the realm of geological applications. If, for instance, there is regular periodicity in the surface being analysed, as in the case of folds of shorter wavelength superimposed on folds of longer length, the grid points may coincide with crests or troughs and thus introducing an unwanted bias in the data. Geophysically, irregularly spaced data provide an impetus for survey over a wide area where gridding becomes impracticable.

Any pattern of contoured surfaces might be difficult to ascribe any meaningful features if the features sought are partly masked by large-scale or regional effects. Separation of the regional components from this pattern leaves the residual components which bring details that have escaped notice. A regional component, being represented by polynomials of different degrees, provides regional surfaces that yield residuals of varied amplitudes. Thus a plane surface or first degree fitting provides the simplest regional surface and yields largest residual values while progressively higher degrees permit extraction of residuals of progressively smaller magnitude.

The selection of which degree represents the most appropriate degree of trend surface depends on the geologic objectives. If the objective is to discern complex relationships, a trend function of relatively high degree may be necessary. If

the objective is to discern general trends in complex data, low degree trend surface may be desirable (Harbaugh and Merriam, 1968). If the structures to be analysed are complex, then it would be irrelevant to fit a plane surface to the data because the residual that will emerge will reflect the main structural trends. It is equally unreasonable too to fit higher degree polynomials to data where the geologic structure is relatively simple considered regionally. This is because increased fit of the trend surface due to higher degrees might not be statistically significant.

CHAPTER 6

QUALITATIVE ANALYSIS

6.1 General

The first step in gravity interpretation is the preparation of a Bouguer map (where the survey area is isostatically compensated) or the isostatic map. Free-air anomalies are not suitable if the principal aim of such a map is to derive geological information. Free-air anomalies contain the vertical component of the gravitation effect of topographic masses which obscure to a large extent, the effect of anomalous masses.

The Bouguer map contains gravitational effects of distant topographic masses and of all compensating masses. If the area of survey is small, contributions coming from these sources are often constant. Thus the variation in the Bouguer gravity values are due to anomalous geological masses at small depths below the earth's surface in the survey area. These anomalous geological masses are of great interest and form the basis of gravitational interpretation. The approximately constant field due to distant topographic and compensating masses are removed to bring out the remaining information of interest.

6.2 Description of the Bouguer Anomaly Map

The Bouguer map of the Middle Niger Basin area is shown in Fig.6.1. The anomaly map is characterised by

(a) A prominent positive anomaly A at the southeast corner of the area generally trending north-northwest to south-southeast with a maximum contour value of 10mGals. This anomaly extends southeastward in the adjoining area not covered by this survey.

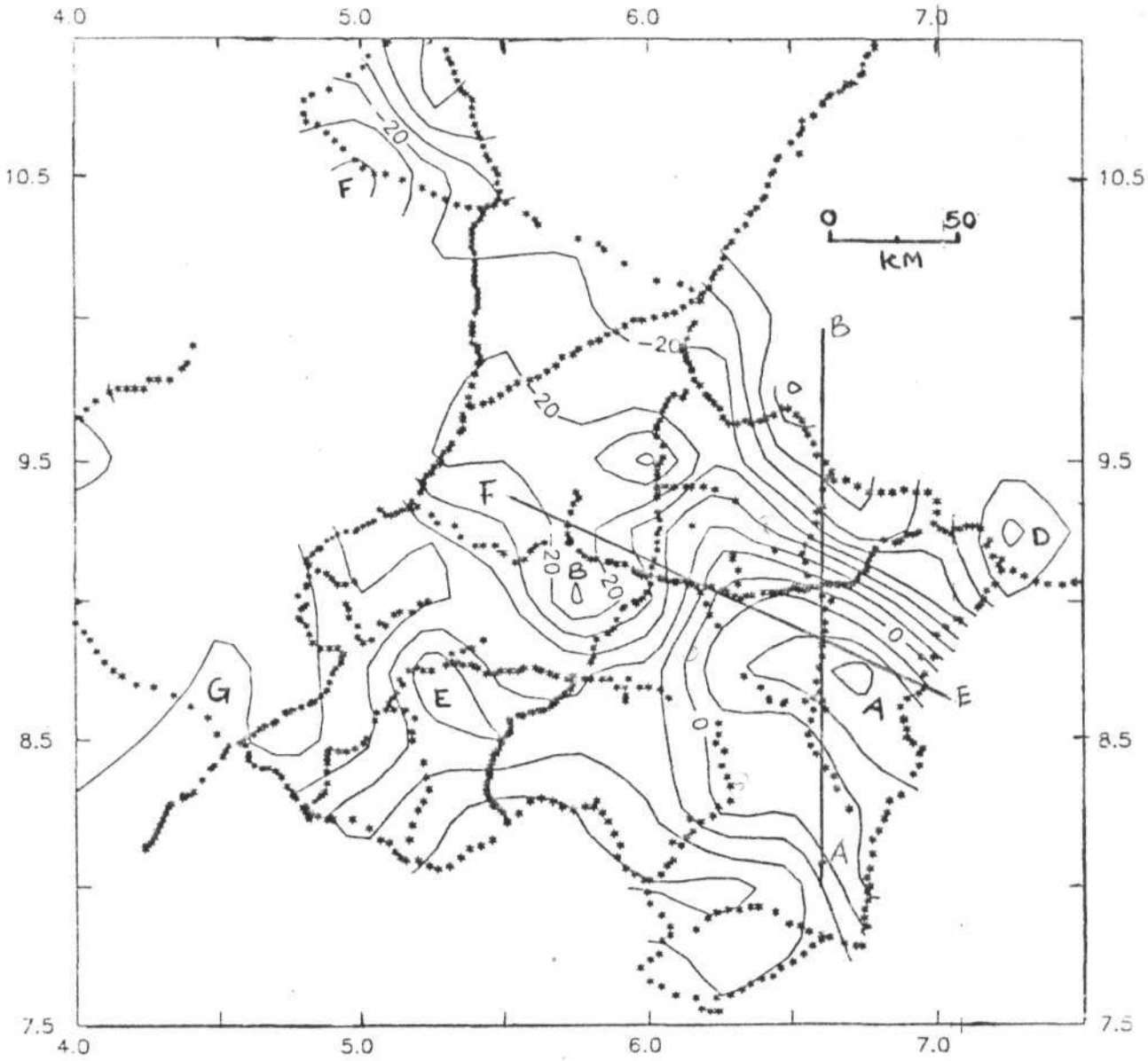


Fig.6.1 Bouguer Gravity anomaly map of the Middle Niger Basin

(contour interval= 4 mGals)

(b) Anomaly A is flanked to the northwest by a negative anomaly B with maximum contour value of -25mgals, to the north-east by negative anomalies C and D which have maximum contour values of -30mgals and to the west by an elongate anomaly E whose values increase to zero.

(c) Anomalies F and G are in zones with insufficient data and thus represent pictures yet to emerge properly.

Anomaly A is not connected with any other anomaly of comparable magnitude. Its contour values decrease northwestward with a gentle gradient of 0.5mgal/km towards anomaly B. It is thus an elongate anomaly trending northwest by southeast. Anomaly B is negative and elongated southward.

6.3 Polynomial Surfaces and General Interpretation

6.3.1 Introduction

It is not possible to ascertain the nature of variations in basement depth and the associated variations in stratigraphic thickness from surface geology. Gravity investigations, however, can detect these variations provided the changes in thicknesses are considerable and density contrast exists between the sediments and basement rocks. The usual assumption in gravity interpretation is that regional changes in Bouguer gravity values are related to changes in the thickness of the earth's crust, and that where there are anomalous gravity values, there is an anomalous value of crustal thickness. If the anomalous regional Bouguer values are positive, it is assumed that the crust, is too thin, and if the anomalous Bouguer gravity values are negative it is assumed that the crust is too thick.

Local anomalies on the other hand are usually attributed to near-surface mass distribution. Negative values are identified with sedimentary basins, granite outcrop areas and grabens (Woollard, 1969). Positive anomalies are often identified with uplifts, horsts and mafic rocks.

6.3.2 Bouguer Anomalies and Crustal Thickness

The interpretation of regional anomalous gravity values in terms of anomalous crustal thickness is based on the constancy of the mean density of the crust and of the mantle. If the densities do not remain constant, the relationship usually assumed will not hold.

Available data from seismic studies show that there is a fairly uniform density contrast between the crust and the underlying mantle for some areas (Woollard, 1969). For such areas, one can use the Bouguer anomaly values to predict the depth of the Moho discontinuity with reliable accuracy. In areas where prediction of Moho discontinuity is not reliable, the Bouguer anomalies might not be caused by lack of isostatic equilibrium, but by rather significant changes in the density contrast between the crust and mantle.

Woollard and Strange (1962) gave the formula for the depth of Moho, Hm in kilometres for the whole surface of the earth as

$$Hm = 40.5 - 32.5 \tanh \left(\frac{\Delta g + 75}{275}\right) \qquad \text{.....(6.3.2)}$$

where Δg is the Bouguer anomaly in milligals. Crustal thickness determined by means of this relationship usually differ to some extent from those determined by seismic investigation. These differences are due to possible errors in seismic determination, significant changes in crustal structure associated with major geological structures and inhomogeneity in the mantle (Demenitskaya and Belyaevsky, 1969). Crustal thickness given by this relation is called 'normal crust' (Demenitskaya and Belyaevsky, 1969).

6.3.3 First Degree Polynomial Surface

The first degree surface for the study area (Fig.6.2) is a plane dipping NNW at a rate of 0.083mgal/km. The first degree surface does not follow the generalised trend of the Bouguer map of the area (Fig.6.1). However, an examination of the 1°x1° means data set provided by the United States Defense Mapping Agency (DMAAC) (1973) for the study area (Fig.6.2.1) shows a trend similar to that in Fig.6.2.

The decrease in regional Bouguer values to the north shows that the lithosphere thins in the same direction since first degree fit emphasizes deepest disturbing sources (Zeng, 1989). There is a remarkable correlation of this northward decreasing gravity values with the 'smoothed' profile constructed from the DMAAC Bouguer gravity anomalies map of Africa in which the Bouguer values decrease northwards (a portion of which is Fig.6.2.1).

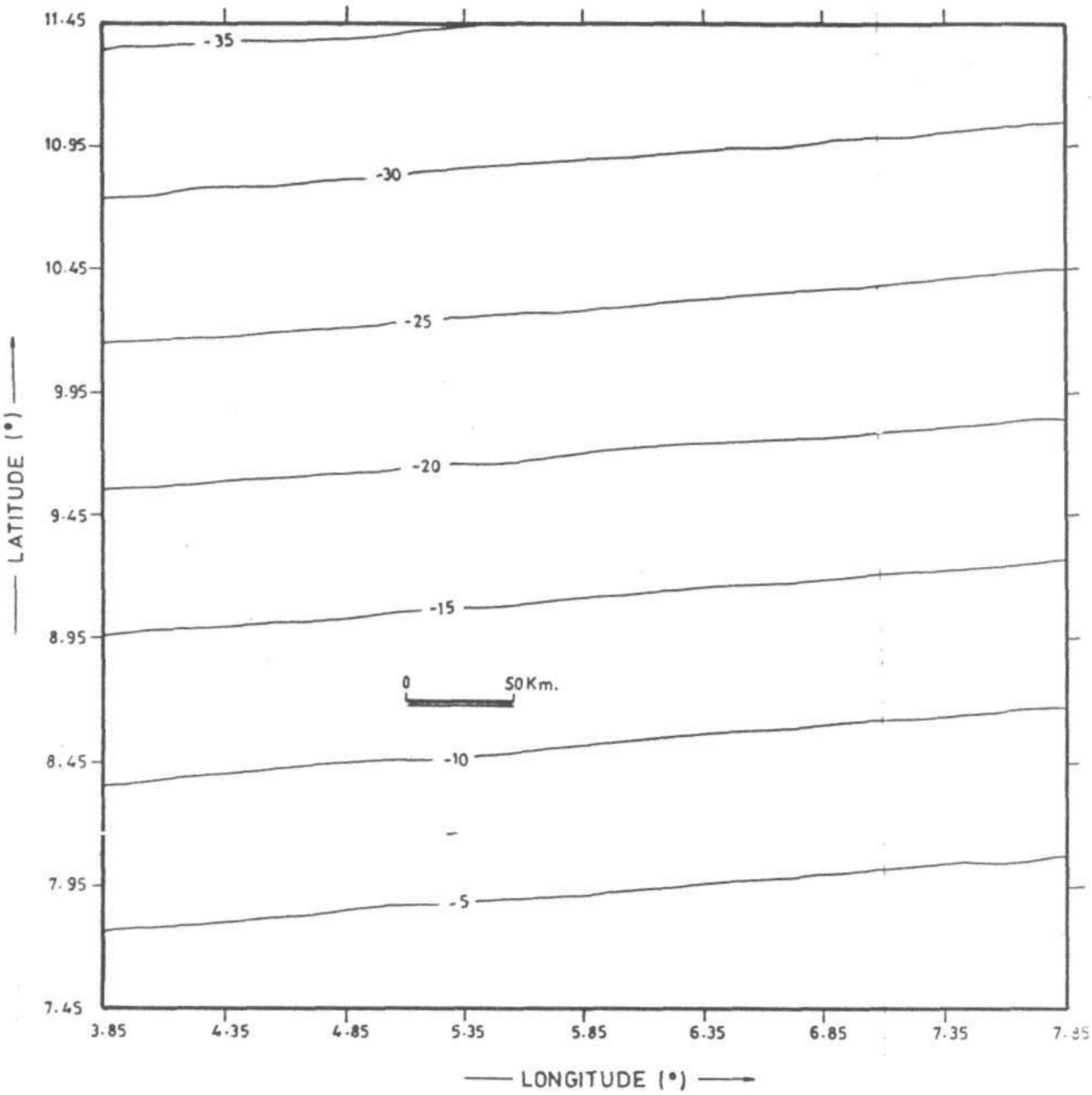


Fig. 6.2 First Degree Regional Bouguer map of the Middle Niger Basin. (values in MGALs).

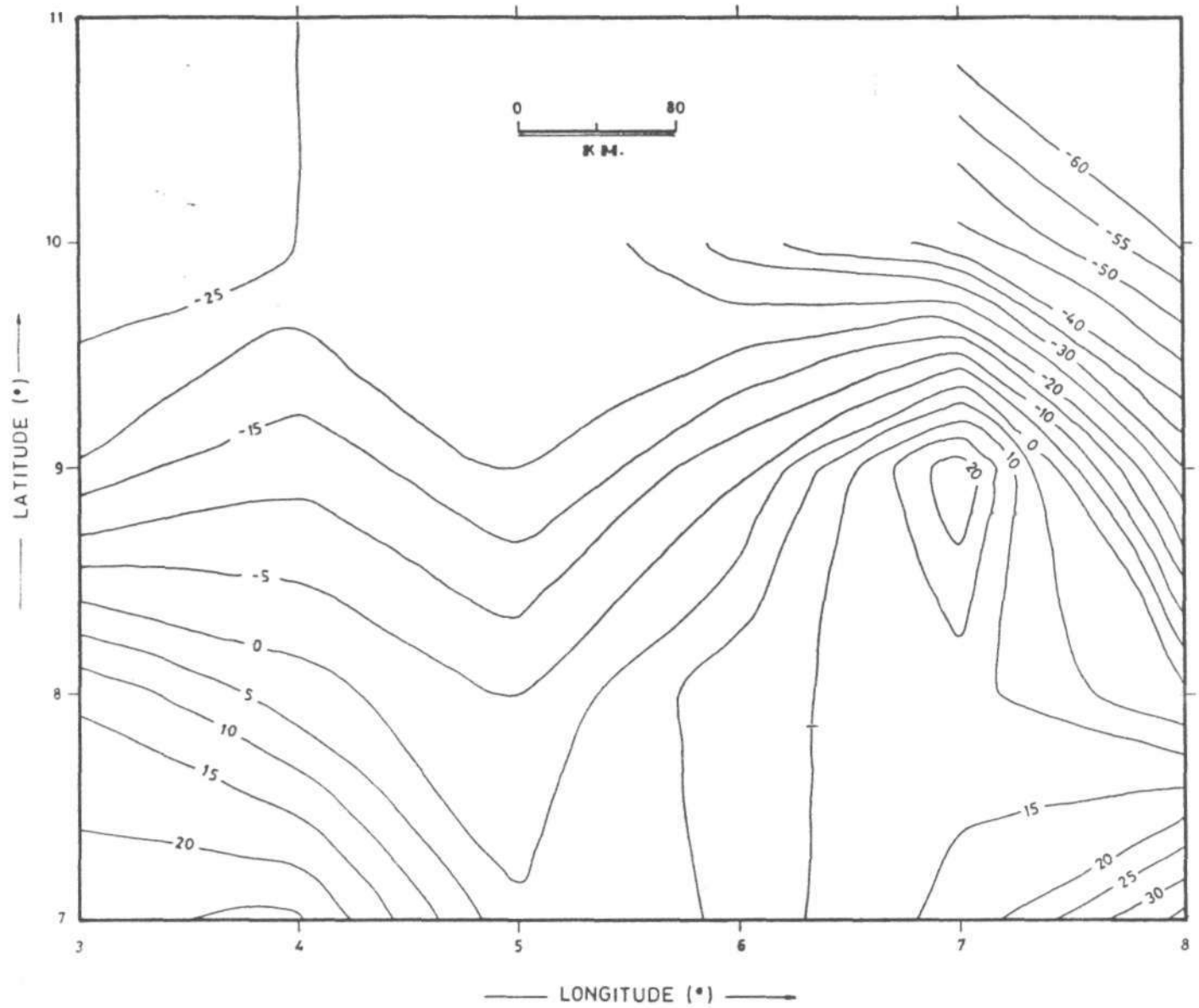


Fig. 6.2.1 1° × 1° Bouguer anomaly means of the Middle Niger area (values in MGALs) (After DMAAC, 1973).

6.3.4 Second Degree Polynomial Surface

The second degree (Fig.6.3) is an anticlinal surface plunging in the NW direction, and reaching values of -90 and -35mgals in the northeast and southwest respectively.

Brown and Girdler (1980) in their interpretation of African gravity, assumed a 100km-thick lithosphere corresponding to a modal Bouguer anomaly of -48mgals and a 36.2km-crust-only lithosphere, corresponding to -170mgals. Some features of the second degree surface can be explained based on these assumptions. The zone of decreasing gravity values (-0.33mgal/km) along the northeastern flank of the northwest dipping nose on the second degree surface generally coincide with the great negative Bouguer anomaly following the thinning of the lithosphere occuring in the northeast of Africa (Brown and Girdler, 1980). This direction of greatest thinning coincide with the distribution of rift volcanism (Brown and Girdler, 1980).

6.3.5 Third Degree Polynomial Surface

The third degree surface (Fig.6.4) is similar to that of second degree surface in its trend. The trend of decreasing gravity values along the northeast flank of the dipping nose is due to the thinning of the lithosphere in that direction. The northwestly decreasing Bouguer gravity values may generally coincide with intrusive granites syntectoniques of Benin Republic. The large positive long wavelength anomaly extending from the SE to the centre of the survey area is responsible for the intense distortion of the Bouguer anomaly field. The large positive anomaly source could be a diapiric penetration of upper mantle materials into the crust.

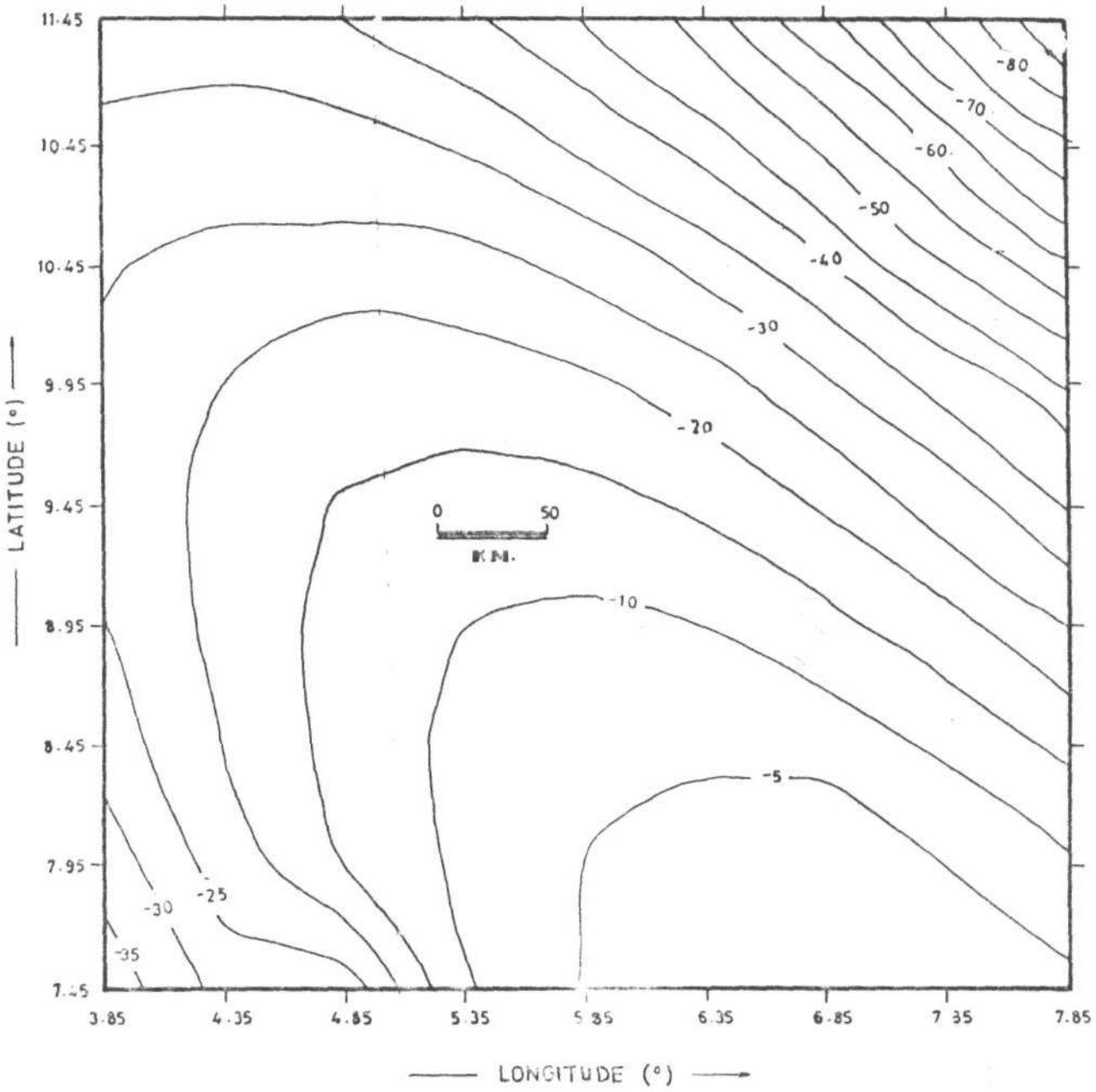


Fig. 6.3 Second Degree Regional Bouguer map of the Middle Niger basin (values in MGALs).

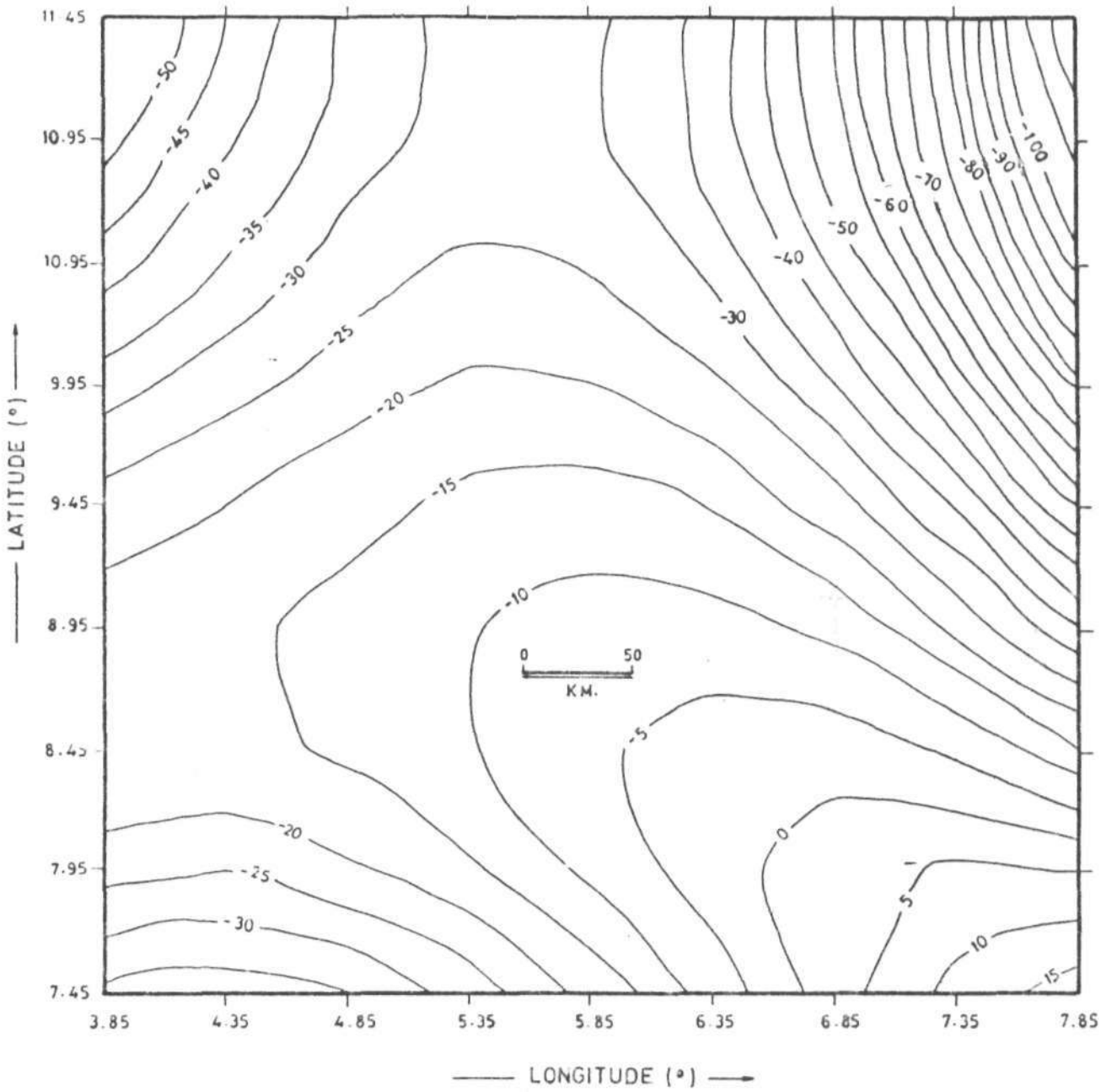


Fig. 6.4 Third Degree Regional Bouguer map of the Middle Niger Basin (values in MGALs).

6.3.6 Fourth Degree Polynomial Surface

A long wavelength anomaly shows prominently in the central southeast portion of the survey area (Fig.6.5) trending northwestwards. It has a maximum contour value of 5mgals. The semi-major axis is approximately 250km and its semi-minor axis about half this value. The deep-seated anomaly is likely to be an upper mantle uprise into the crust.

The great negative Bouguer anomalies that flank this anomaly both to the northwest and east/northeast coincide generally with the great granites syntectoniques of Benin Republic and the thinning of the lithosphere northeasterly respectively.

6.3.7 Fifth and Higher Degree Surfaces

The fifth and sixth degree surfaces are shown in Fig.6.6 and Fig. 6.7 respectively.

Apart from lack of fit of data with higher degrees than five, the general trend of the polynomial fields for such degrees-cum-orders are inept. In particular, the sixth degree fit shows a decrease in percent fit and close examination of the original Bouguer map for the area shows that such a fit does not have any bearing with the solution of the problem sought. Higher degree fits than six were considered unnecessary since the legitimate objective is not to indefinitely fit surfaces to the Bouguer data, but to ascertain reasonably the unique surface that gives close correlation of the residuals to any known surface geological feature of the area.

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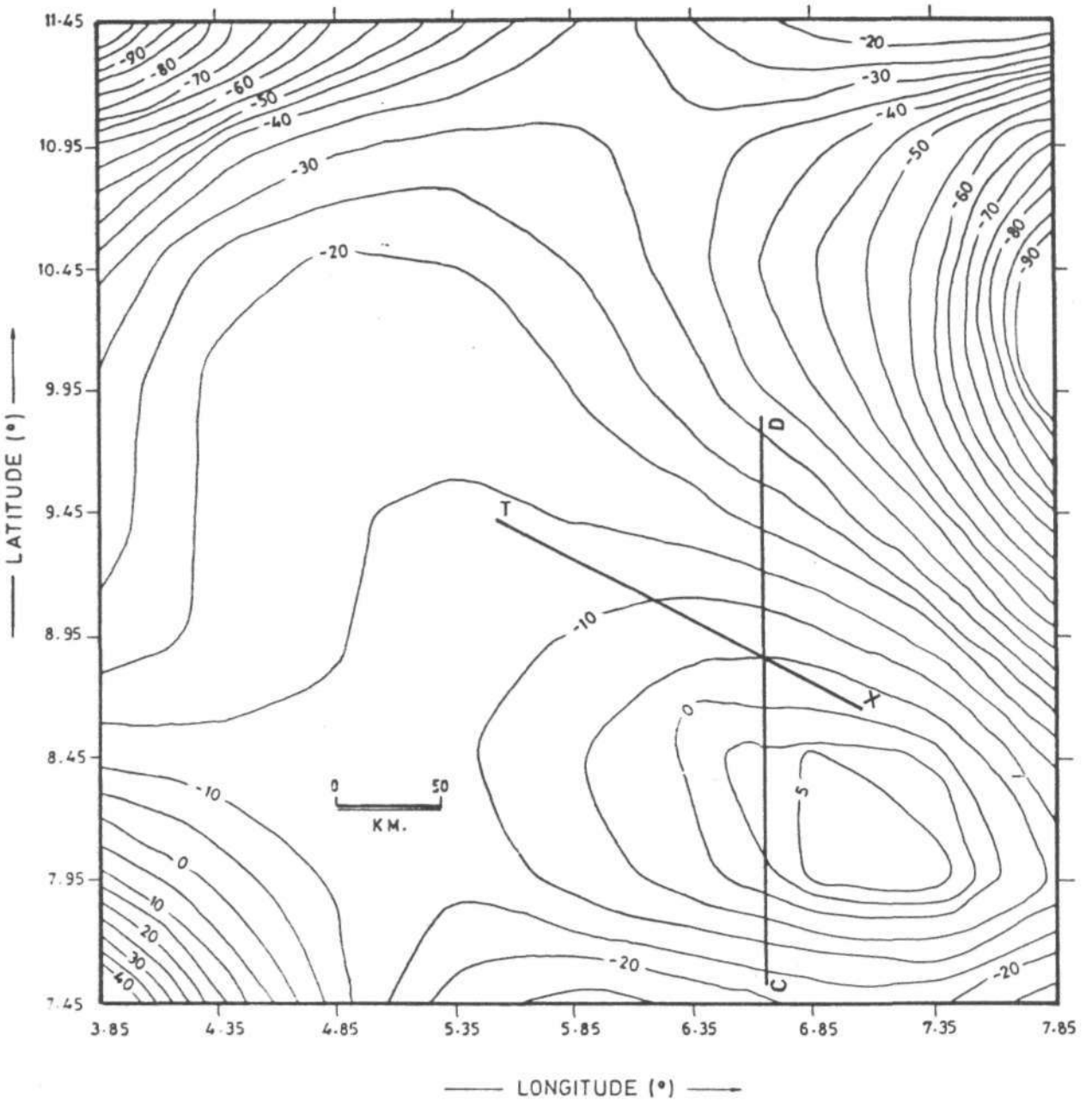


Fig. 6.5 Fourth Degree Regional Bouguer map of the Middle Niger Basin (values in MGALs).

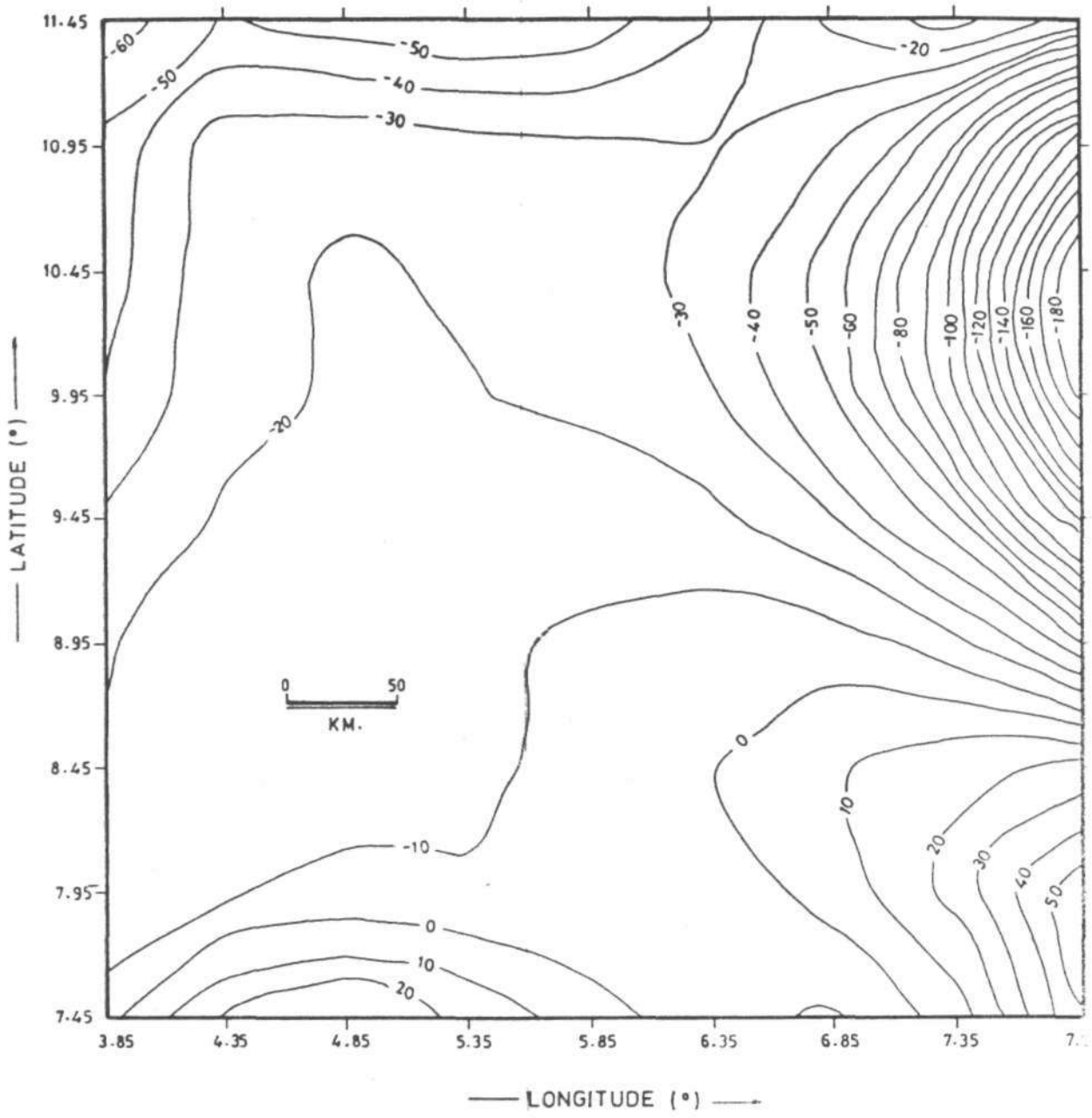


Fig. 6.6 Fifth Degree Regional Bouguer map of the Middle Niger Basin. (values in MGALs).

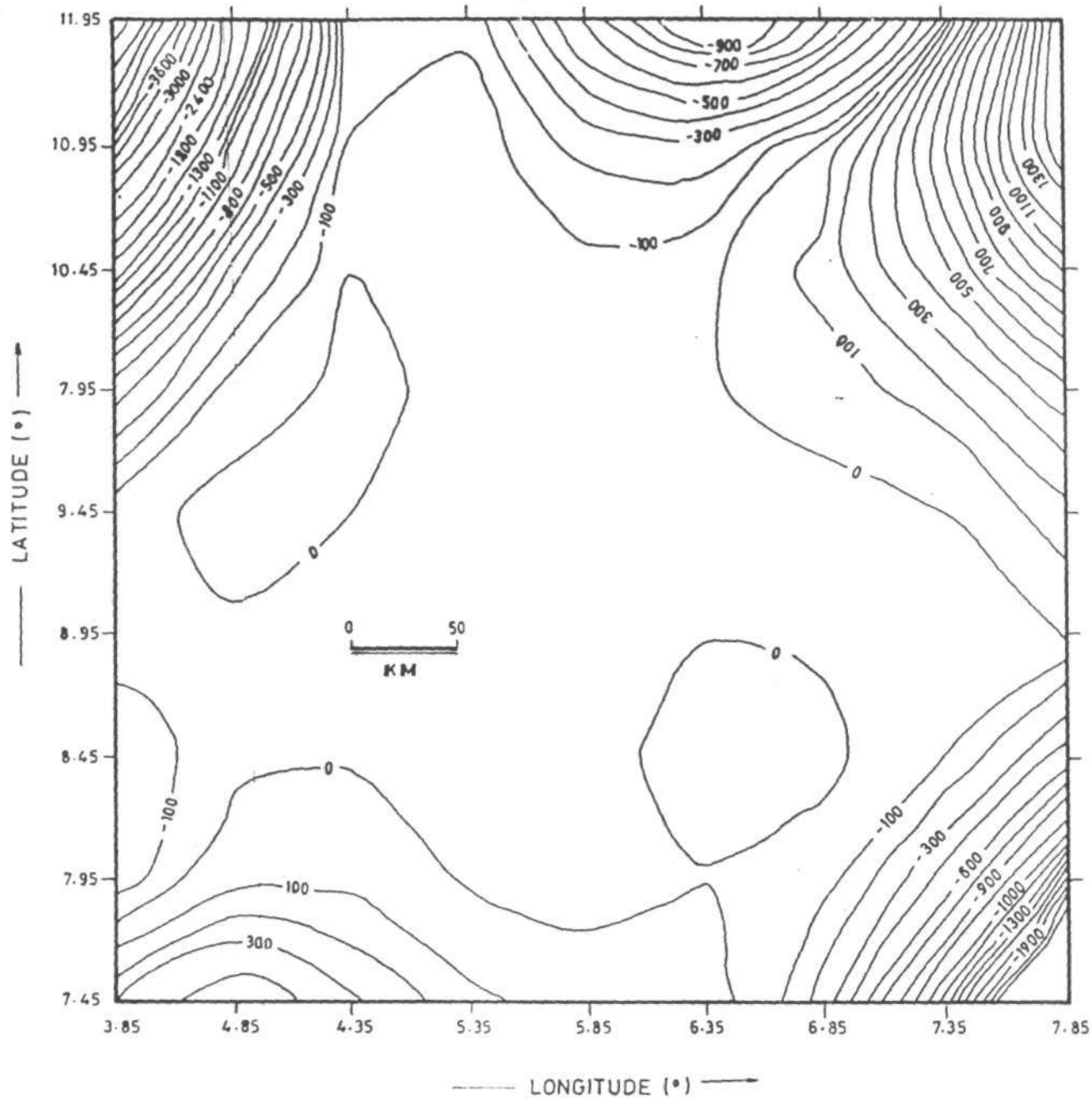


Fig. 6.7 Sixth Degree Regional Bouguer map of the Middle Niger basin (values in MGALs).

6.4 Reasonable Surface

The surface fit technique does not necessarily give a plausible geological representation of the subsurface. With increasing degree of the fits, local features are greatly enhanced in the remaining Bouguer map: a result very much in agreement with second derivative or grid residual type calculation.

A reasonable surface fit to the data set would be a surface that can be explained by the geological structures of the area. It is often difficult to establish a reasonable surface from the regional Bouguer field, because surfaces fitted usually contain, to a greater extent, gravitational effects due to distant masses. If the configuration of the distant topographic masses is not known, their constant gravitational effects are difficult to discern.

The only solution to this problem is to resort to two things. The first is a close comparison of the original Bouguer anomaly map with the surfaces fitted to ascertain which surface or surfaces best approximate the long wavelength features on the Bouguer anomaly map. The second thing is to examine the residual fields from these surface fits and correlate these with any known geological structures that are mappable in the area. The latter is less subtle than the former.

Examination of the polynomial surface maps suggests that the first and sixth-degree fits are not in consonance with the original Bouguer map. A first degree fit is often a poor fit to the data, especially if the original Bouguer map have numerous convolutions. The goodness of fit is 37% and the regional trend does not agree with the generalized NNW-SSE - trend of the Bouguer map. Similarly, the sixth degree regional does not seem to have

any significance partly because of its drop in the percentage goodness of fit (62%) compared with that of the fifth degree (72%) and partly because of the large magnitudes of the field values which flank the central portion of the mapped area. These large negative values exceed the largest known negative anomaly of -240mgals in Africa associated with the Ethiopian rift zone (Brown and Girdler, 1980).

The second, third, fourth and fifth degree fits tend to follow the generalized long-wavelength trend of the area and also show an increase in their percentage goodness of fit: 52%, 57%, 67% and 72% respectively.

The fourth degree surface, nevertheless has been chosen to represent the regional field of the area because close examination of the residual fields associated with it reveals that the fourth degree residual correlates well with available geological structures than any other surface (Fig.6.8). Such superficial geological structures include narrow strip of massive undifferentiated metasediments and some negative Bouguer fields that predominate over Older Granite suites that flank the Nupe sandstones.

Additional attempt was also made to justify the choice of the fourth degree polynomial surface in representing the regional field of the survey area. The set of the gravity data was fitted with polynomials of increasing degree up to twelve. A graph of variance σ_n against the degree n is plotted and shown in Fig.6.9. The optimum degree of fitting polynomial surface corresponds to the point of discontinuity of the graph of σ_n versus n. This gives the desired degree of polynomial that approximates the gravity

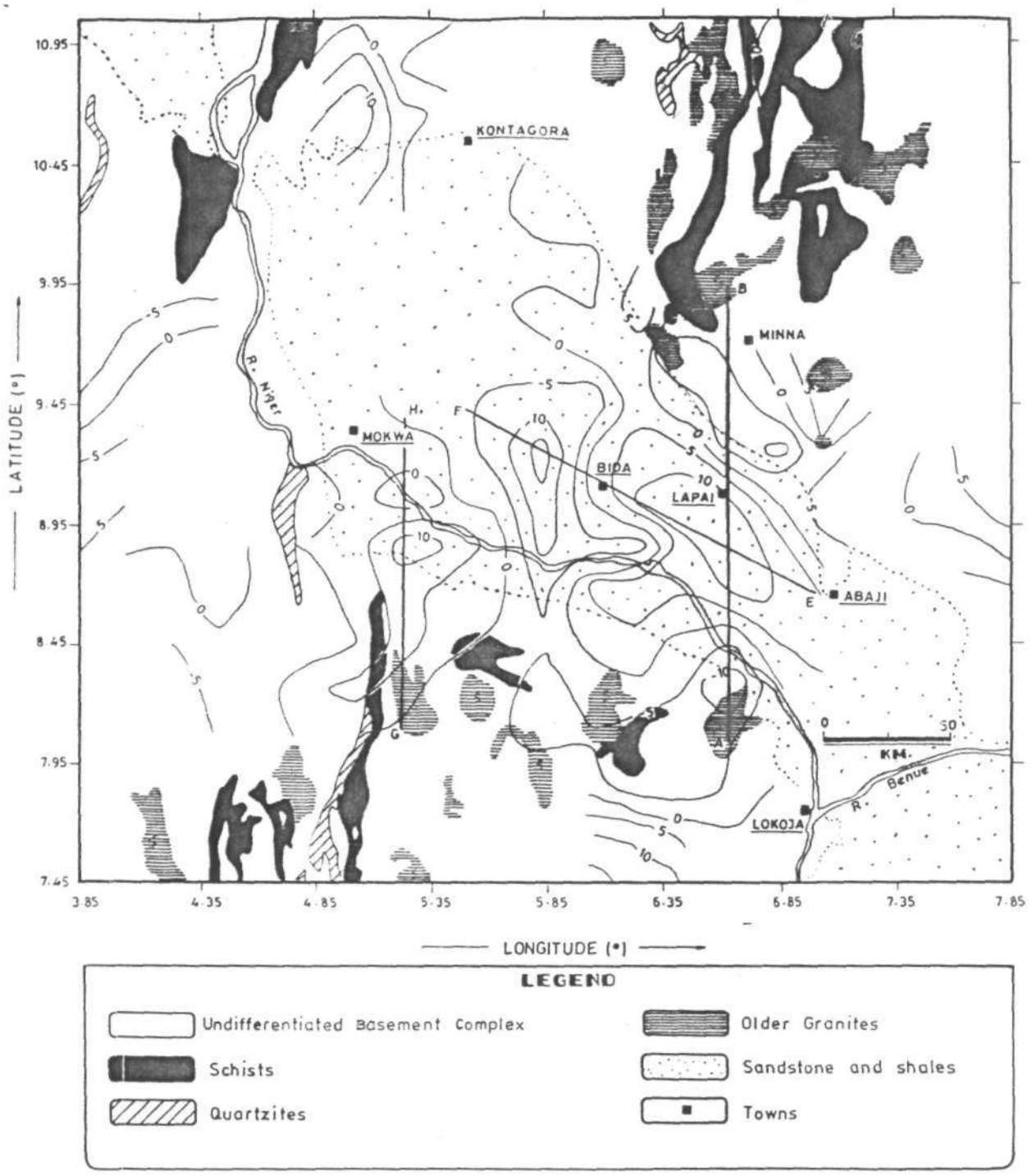


Fig. 6.8 Fourth Degree Residual Bouguer map superposed on the Geology of the Middle Niger basin (values in MGALs).

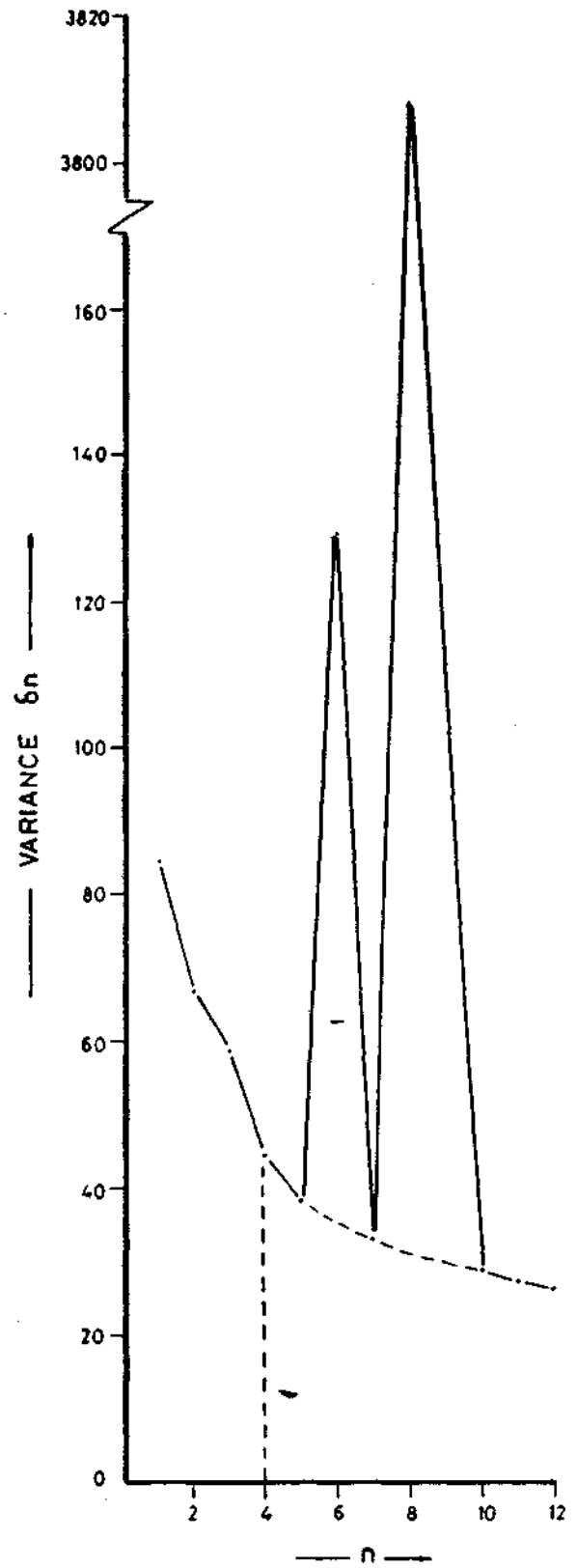


Fig. 6.9 Variance δn against polynomial degree n for the gravity anomaly.

set. Th ough an examination of Fig. 6.9 shows that the fifth degree corresponds to the point of discontinuity, it is considered unreasonable because that is the point the curve starts behaving erratically. The fourth degree is thought to approximate this point and is chosen instead. Furthermore, Figs 6.10a, 6.10b show two profiles from the Bouguer anomaly map on which corresponding profiles from the regional field (fourth degree surface) are drawn. The Figures show that the regional fields seem to be consistent with the regional trend that could be obtained if visual smoothing were to be adopted as the method of regional-residual separation on these Bouguer profiles. This lends support to the choice of the fourth degree polynomial surface as the surface that best represents the regional background of the area.

6.5 Interpretation of the Regional Anomaly

It has been shown in the previous section that the fourth degree surface best represents the regional field of the Middle Niger Basin area. If this assumption is valid, there is therefore a need to explain this regional field in terms of the deep structures in the area. Similar long-wavelength and positive anomalies in other basin environment (e.g the Benue Trough) have generally been found to be caused by a thinning of the crust. This can be also assumed to be true for the Middle Niger Basin.

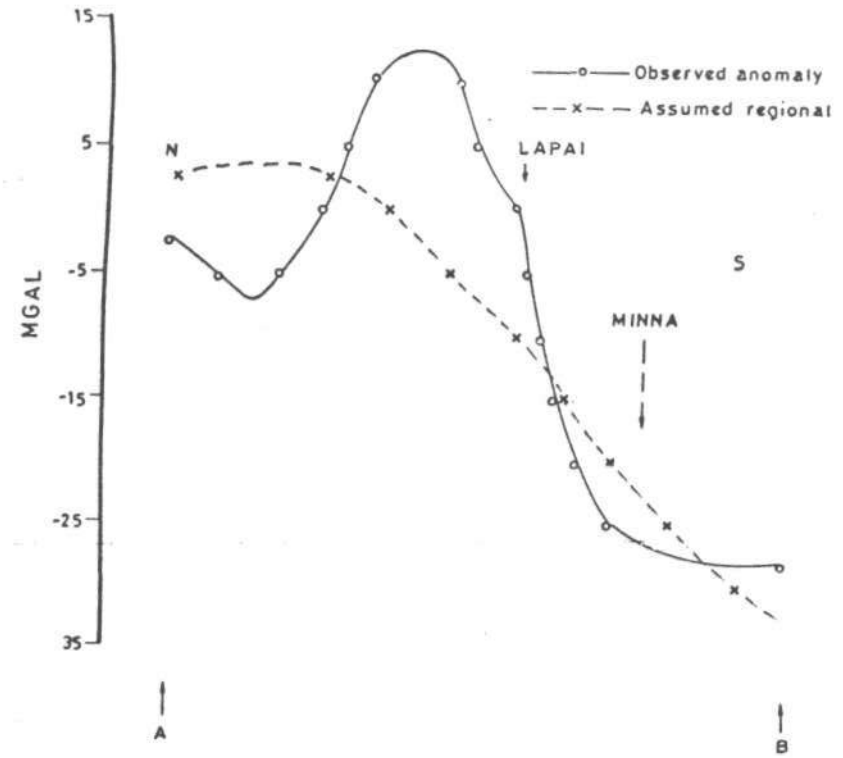


Fig.6.10a

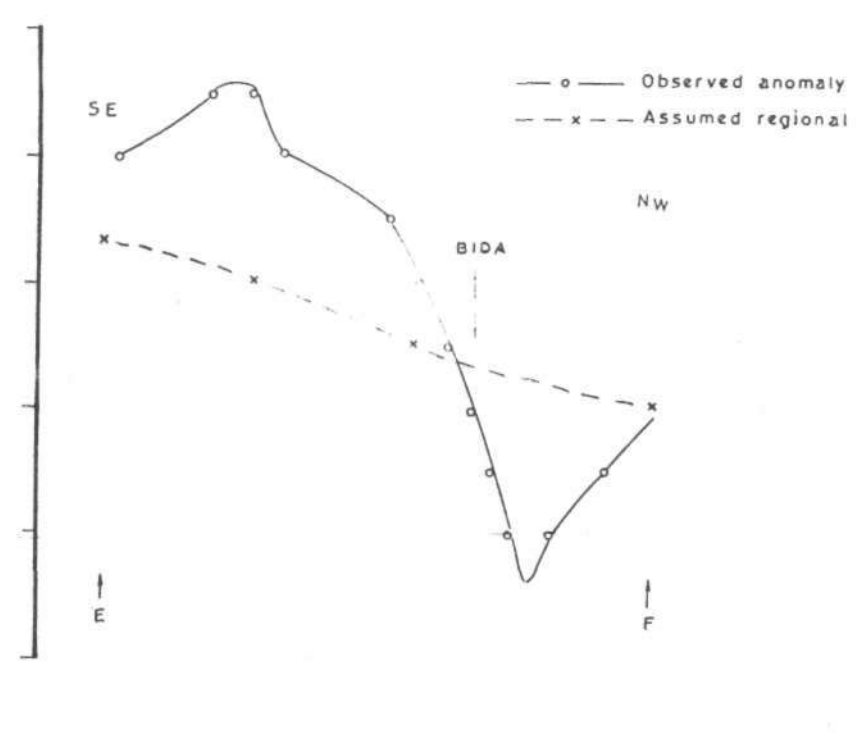


Fig.6.10b

Plots of fourth degree regional gravity field of two profiles on the Bouguer anomaly map

On the basis of this, the Moho map constructed by making use of equation (6.3.2) is shown in Fig.6.11. A north-south profile, CD, over this surface and cutting the oval-shaped positive anomaly gives a Moho topography shown in Fig.6.12. This gives an average Moho of 35km and wavelength of approximately 370km across this profile.

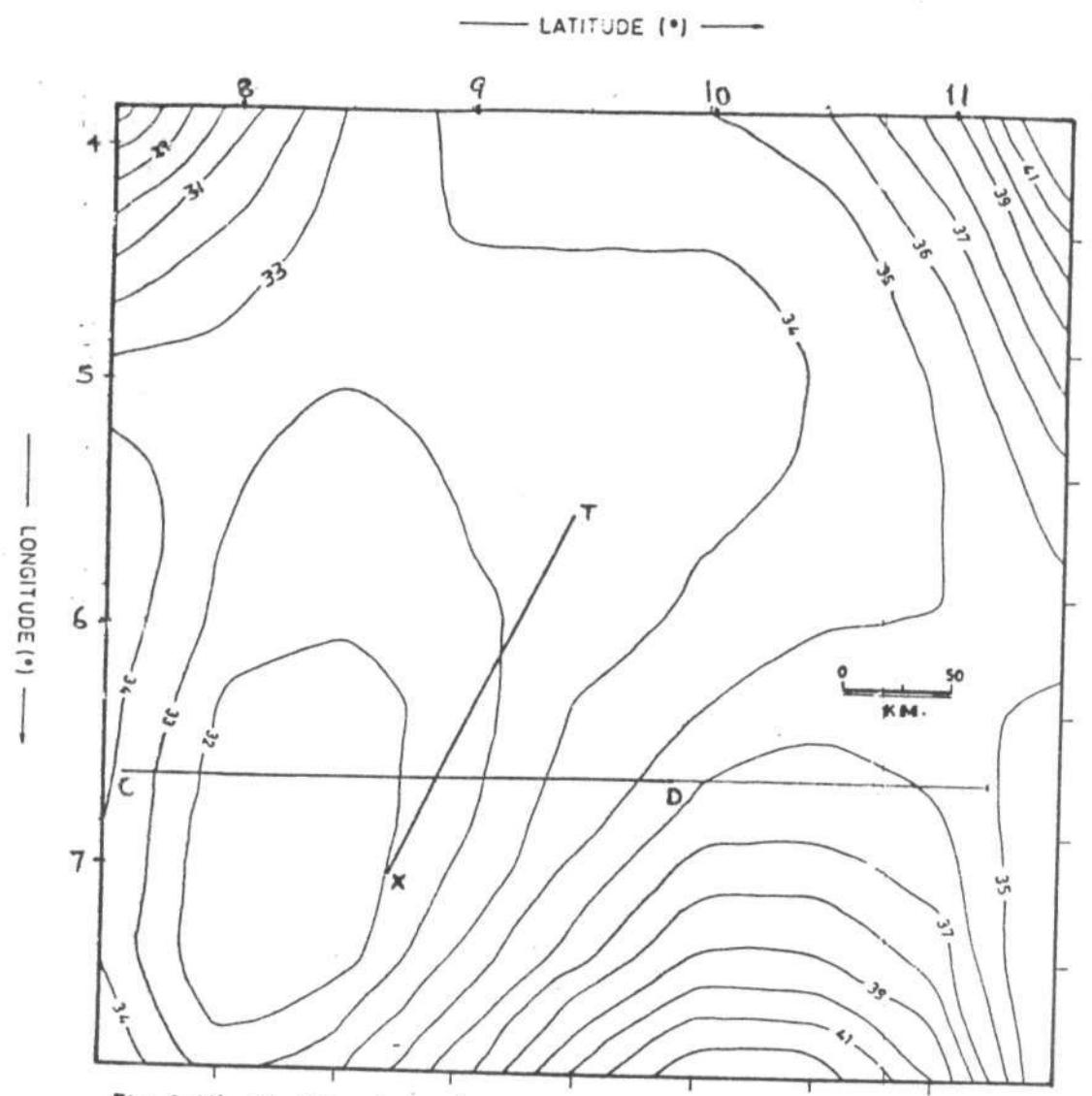


Fig. 6.11 The Deduced MOHO map of the Middle Niger basin (values in Kilometres).

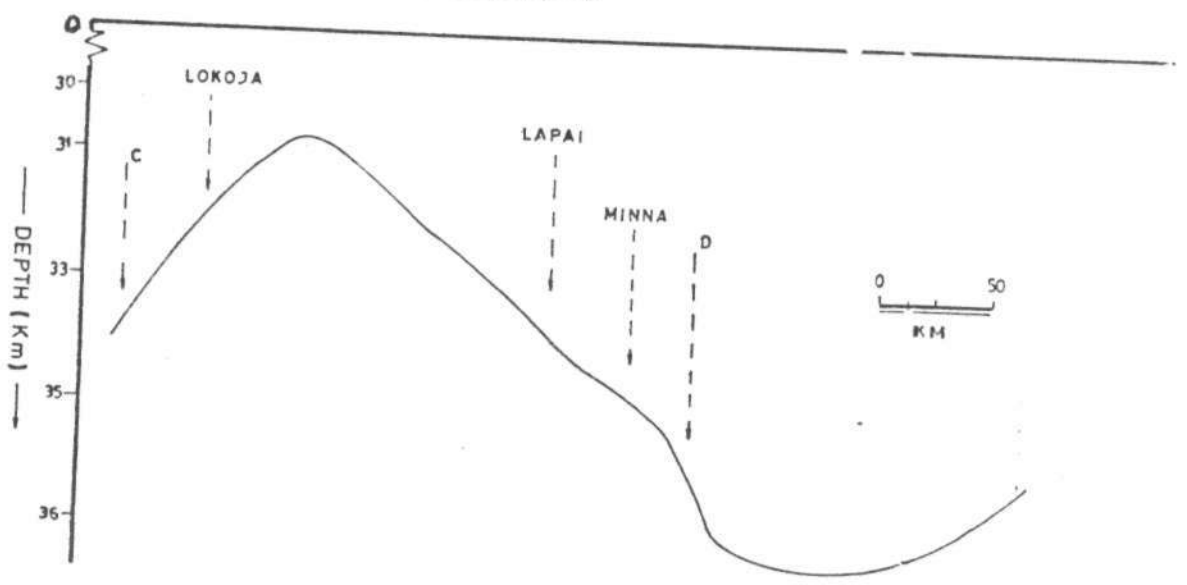


Fig. 6.12 The MOHO on profile CD

CHAPTER 7

QUANTITATIVE ANALYSIS

7.1 Introduction

Quantitative interpretation of gravity fields means finding out the position, size and shape of a gravitating mass through analysis of its potential field. Field values arising from deep-seated and distant topographic masses are usually constant and removed from the total field values. The remaining field values are ascribed to shallower geological structures. These structures are often of interest and the ultimate aim of quantitative interpretation is to determine the dimensions of these geological bodies. Apparently, this is solving the inverse problem of potential field theory.

A complete solution of inverse problem is impossible in both practice and theory (Grant and West; 1965). The usual approach is to seek approximate solutions through ascribing geological bodies to mathematically definable shapes and computing their gravitational effects to match the observed effects. The ambiguity inherent in inverse potential field problems often renders these approximate solutions unreliable if some observable parameters of the bodies are not available. These limitations of the gravity method in defining subsurface structure follow from standard potential theory; they have been well-illustrated in a much-quoted paper by Skeels (1947).

Before proceeding to describe the quantitative interpretation of the residual anomalies, it may be pertinent to briefly look at the tectonics of the region because of their relevance to the numerical modelling.

7.2 Tectonics

The Precambrian rocks of the Middle Niger Basin is part of the Nigerian Basement Complex. These underlying rocks comprise gneisses, migmatites and metasediments of Precambrian age (McCurry, 1976). The Precambrian rocks have been thought to have their origin from ancient sedimentary rocks and constitute the Older Metasediments. They have been intruded by a series of granitic rocks of Late Precambrian to Lower Palaeozoic age (McCurry, 1976). The Older Metasediments and the intruded granites, through at least two tectono-metamorphic cycles, have been converted to migmatites and granite-gneiss (McCurry, 1976). The granitized basement was overlain by Younger Metasediments or Schists series which are believed to be Upper Proterozoic in age. Both the Younger supracrustal cover and the basement rocks were folded together to produce mainly overturned, tight isoclinal, non-cylindrical major folds with approximately N-S axial trend with lithological boundaries, fold axial planes and foliation trends parallel (McCurry, 1976; Rahaman, 1976). This happened during the Pan African Orogeny culminating into intrusive series of basic, intermediate and acidic plutonics known as the Older Granites (McCurry, 1976). In areas where there are suites of volcanic rocks, the same are believed to have intruded into the Older Granite bodies during Lower Palaeozoic epeirogenic uplift following Pan African Orogeny. The Older Granites are believed to have a magmatic origin (Rahaman, 1976).

The two phases of tight isoclinal folding that have been recognised in the Younger Metasediments/Schists and basement gneisses are deformational episodes accompanied by progressive regional metamorphism and separated and followed by phases of static metamorphism (McCurry, 1976). The two deformations were under constant pressure and temperature. At the end of the last deformation, the intrusion of a suite of syn-to late-tectonic granites accompanied migmatisation and granitization of the basement gneisses. The last stage of the orogeny was marked by cooling, uplift and fracturing and the intrusion of high level volcanic rocks.

The Upper Cretaceous sediments of the Nupe Sandstones overlie this Basement Complex.

7.3 Epeirogenesis of Nupe Basin and Adjacent Benue Trough

The Basin is believed to be a gently down-warped trough filled with the oldest marine sediments of Nigeria. The basin genesis is closely connected with crustal movements of the Santonian Orogeny of southeastern Nigeria and the nearby Benue Valley. Stresses responsible for the generation of the latter are believed to be responsible for that of the adjacent Nupe Basin.

The origin of the Benue Trough has been a source of speculative discussion since the middle of the 20th century. King (1950) suggested the trough to have evolved as a result of stresses which accompanied the continental separation of Africa and South America. The rifted depression concept is supported by geophysical investigation by Cratchley and Jones (1965) and by Ajakaiye and Burke (1973). Because of lack of geological

evidence of rift faulting along margins of the trough, the concept was considered inadequate (Wright, 1976). The plate tectonic models of Burke et al(1970)and Grant(1971) all potray the Benue Trough as originating as a triple junction similar to that of the Red sea - Gulf of Aden-Afar triple junction (Wright, 1976). The RRR (ridge-ridge-ridge) triple junction of Burke et al(1970)accounts satisfactorily for the present arrangement of transform fracture zones in the Gulf of Guinea region, but fails in its postulate of generation of strip of new oceanic crust (200km spread) beneath the Benue Trough from Albian to Santonian ages. There are no evidence of these mantle plumes (Wright, 1976). The deficiencies of the models of Burke et al (1970) have been pointed out by Nwachukwu (1972).

The model by Wright (1976) accepts the Benue Trough to be part of the RRR triple junction in which the three arms developed at different times. The Southern arm (Congo Craton) developed first in the Lower Cretaceous time followed by the Benue arm (Guyana Craton) in Albian time. The last to develop is the West African Craton at the Late Lower Turanian. He had earlier envisaged the trough to have evolved due to tensional fracture system formed by differential stresses set up in the African Plate as it was wedged apart from South America. Accordingly, with the final separation, the plate was no longer subject to distortional stresses. This made the crust to re-adjust with the tensional regime responsible for initiation of the Benue Trough being replaced by slight compressional one, closing the trough slightly and folding the sediments within it (Wright, 1968).

The model envisages limited spreading of the crust beneath the Benue arm which (affecting southwestern portion of the trough) ceased with the development of the sector of West African Craton. The causal relationship is not known. The Maestrichtian transgression that spread right up the Benue Trough and for the first time up the Middle Niger Valley is evidence of further subsidence (Wright, 1976). Whether the subsidence is as a result of renewed tension across the trough, is not known.

The Middle Niger Basin came into existence only after the first major (Santonian) folding in the main trough (Wright, 1976). Thus the Niger embayment became significant with the development of Northwest arm (West African Craton) of the RRR triple junction. Geophysical investigations gave the maximum thickness of the Cretaceous sediments in the Benue Trough to be 5.5km, while that of the Middle Niger to be between 1-2km (Ojo and Ajakaiye, 1976). The shallow crustal sag was probably produced by a small amount of crustal extension parallel to the line of the Benue Trough (Wright, 1976). Wright (1976) asserts that the regional stress pattern in later Cretaceous times was quite complex. It would therefore be logical to suppose that the Niger arm is another triple junction, attributable to a mantle plume of Maestrichtian age and also devoid of magmatism.

7.4 Interpretation

7.4.1 General

It has now been accepted that there has been at least two orogenic cycles in the Nigerian Basement: one in which the gneisses were emplaced and the other leading to the emplacement of the

schists and the Older Granites (Ajibade, 1976). The schists were infoled remnants of a sedimentary succession which formerly covered the area (Russ, 1957).

The Middle Niger Basin lies nearly perpendicular to the N-S trending schist belts of Northwestern Nigeria. The stresses responsible for the genesis of the Middle Niger Basin must have altered the structural trends of the Older Granites and Younger Metasediments that underlie the Basin.

The fourth degree Bouguer residual map superposed on the geology map of the Middle Niger Basin is shown in Fig.6.8. This residual map is used for depicting the geological structures of the area.

7.4.2 Synopsis

A large positive anomaly with its centre 20km south of Lapai and trending Northwest - Southeast shows up clearly in the residual map. This anomaly is flanked to the North, South and Northwest by negative anomalies and a positive southwardly-elongated anomaly 140km to the West.

The interpretation of these anomalies and in particular the positive anomalies are based on new evidence in support of the origin of the Middle Niger Basin. Earlier gravity work by Ojo and Ajakaiye (1976) attributed the positive anomalies to be due mainly to extremely shallow basin floor underlain by predominantly intermediate rocks of schist or amphibolite type. Although there is considerable ironstone of marine affinity over the area, their thickness was not considered sufficient to give

rise to this large scale anomaly over the basin (Ojo and Ajakaiye, 1976). They also considered the possibility that basic igneous intrusive occuring predominantly within the shallow basement could be responsible for the large anomaly, but ruled out this because of lack of geologic evidence.

Three possibilities are considered to be the major sources of the large positive anomaly that characterises the central portion of the Middle Niger Basin. The basin cuts across a zone of approximately north-south trending metasedimentary belts. Gold winnings from auriferous Precambrian rocks, in particular schists, over the basin suggests that schists must be concealed beneath the Cretaceous strata (Russ, 1957). Thus extremely shallow basin floor underlain by high density metamorphic rocks could be a possible source of the large positive anomaly. High density metamorphic rocks underlain by basic rocks could be another possible source of the large positive anomaly. The large positive anomaly could also be attributed to predominantly basic rocks at depth though there is no surface evidence of these rocks.

The other positive anomaly occurs at the extreme nose NW of the basin over high density metamorphic rocks (Fig.6.8) but lack of sufficient data in the vicinity does not warrant any meaningful interpretation.

Negative anomalies occur over the Older Granite suites and those that occur beneath the Cretaceous sediments have contributions coming from the thick sediments.

7.5 Method of Interpretation

The three-dimensional (3-D) method of Talwani and Ewing (1960) was used to interpret the anomalies on the residual map. The method uses a computer programme that calculates the gravity effect of the assumed body at a field point. The 3-D method represents an arbitrary 3-dimensional body by depth contours: each contour being approximated by an n-sided polygonal lamina . The gravity effects of these polygonal laminae making up the body are summed up at the point. A detailed explanation of the 3-D method used is given in appendix II. Three profiles, AB, EF and GH representing vertical cross-sections through the assumed bodies were chosen to highlight the goodness of fit of the calculated and observed anomaly.

7.5.1 Profile AB

This profile which represents the eastern section of the basin runs north-south and passes near Lapai and Minna. Fig.7.1a shows a basement density of 2700kg m^{-3} overlain by a high density basement of schist composition of density 2780kg m^{-3}. Alternative models are shown in Fig.7.1b and Fig.7.1c in which basic intrusives of density 2850kg m^{-3} are incorporated to give rise to the large positive anomaly. Figs.7.1a and 7.1b give the depth of the source of the positive anomaly to between 6.0 and 7.0km underlying Cretaceous sediments of density 2400kg m^{-3} and depth 0.8km. The predominantly basic igneous intrusion shown in Fig.7.1c as the source of the positive anomaly is buried between 3.80km to 10.0km beneath the Cretaceous sediments of density 2400kg m^{-3} and maximum depth 1.2km.

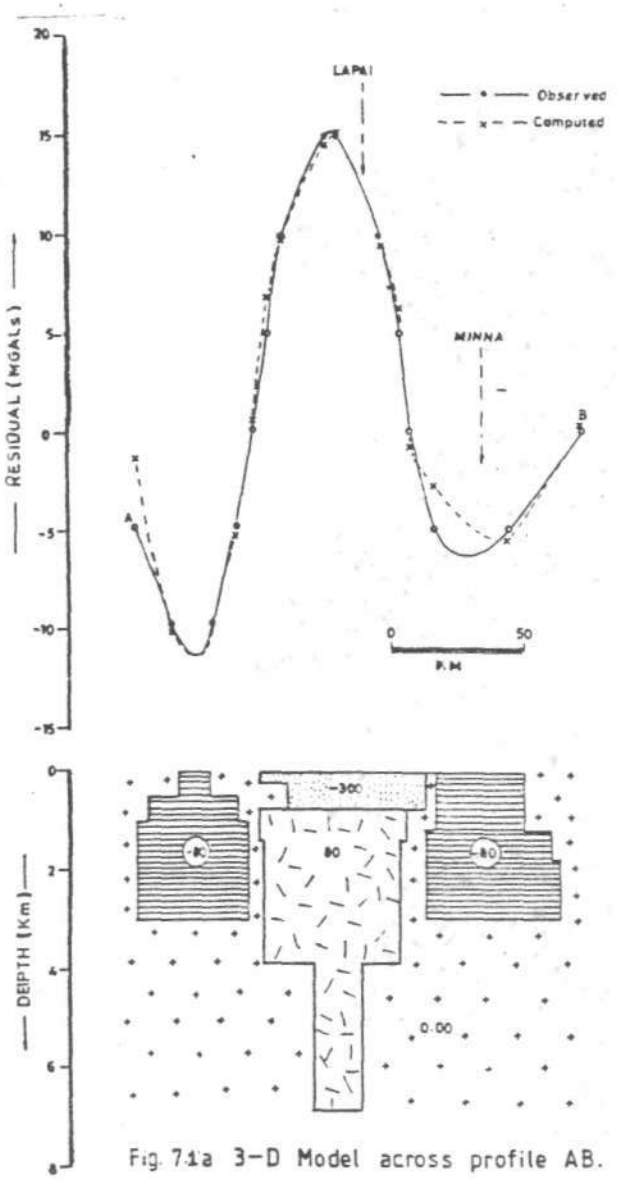


Fig. 7.1a 3-D Model across profile AB.

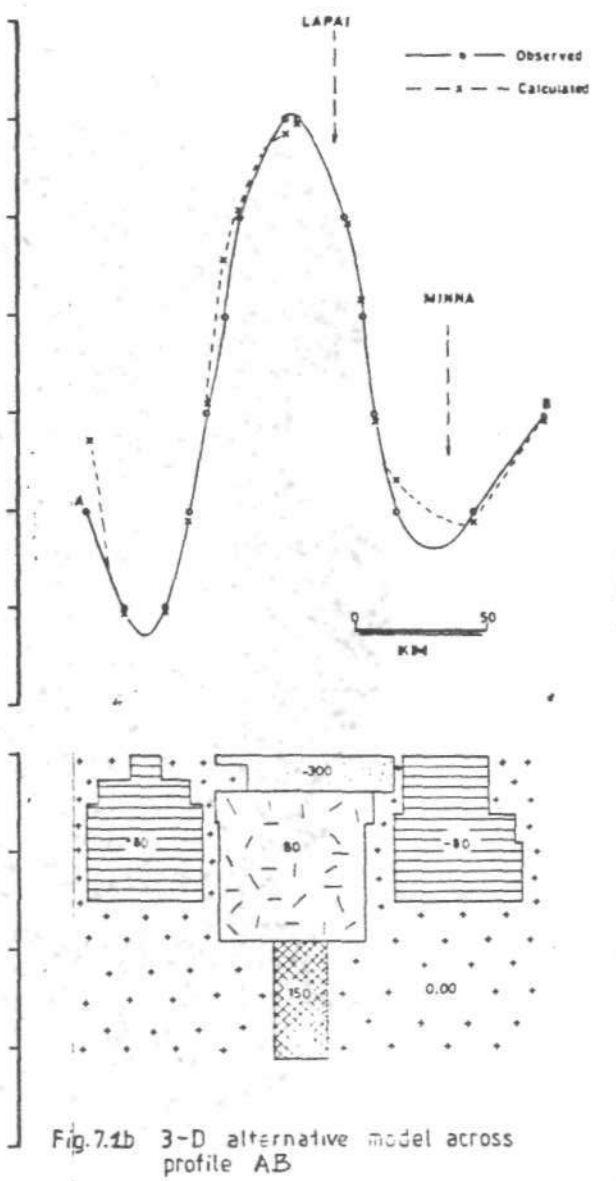


Fig. 7.1b 3-D alternative model across profile AB

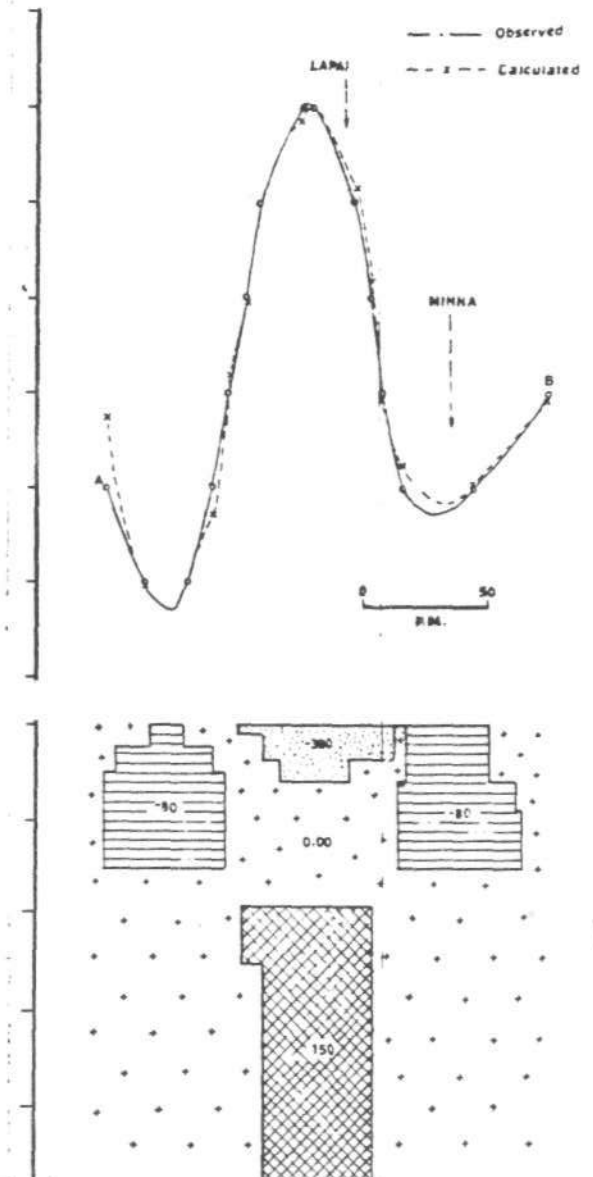


Fig. 7.1c 3-D alternative model across profile AB

The thickness of the sediments is consistent with the one obtained from earlier gravity work in which the thickness of the Cretaceous sediments was of the order of 1.0km and nowhere exceeded 2.0km (Ojo and Ajakaiye, 1976). The Older Granite suites with densities of 2620kg m^{-3} intruded the basement rocks.

7.5.2 Profile EF

This profile runs parallel to the length of the basin (Northwest-Southeast) cutting across the large positive anomaly and profile AB. It cuts through a negative twist northwest of Bida. Figs.7.2a, 7.2b and 7.2c show the possible models accounting for especially the large positive anomaly. Thus the sources of the large positive anomaly are attributed to metamorphic basement of high density (2780kg m^{-3}) folded into a Basement Complex of density 2700kg m^{-3}, high density metamorphic basement underlain by basic rocks and entirely to predominantly basic rocks of intermediate composition. Like profile AB, the Cretaceous sediments have thickness that lie between zero and 1.2km with density of 2400kg m^{-3} while the Older Granite suites that predominate the area have densities of 2620kg m^{-3}.

7.5.3 Profile GH

This profile runs north-south covering part of the Western side of the basin. Most part of the profile runs outside the Nupe sandstones to the south. The other end of the profile terminates near Mokwa to the north-east. The elongated positive anomaly is attributed to the long strip of schist/quartzites that run southwardly.

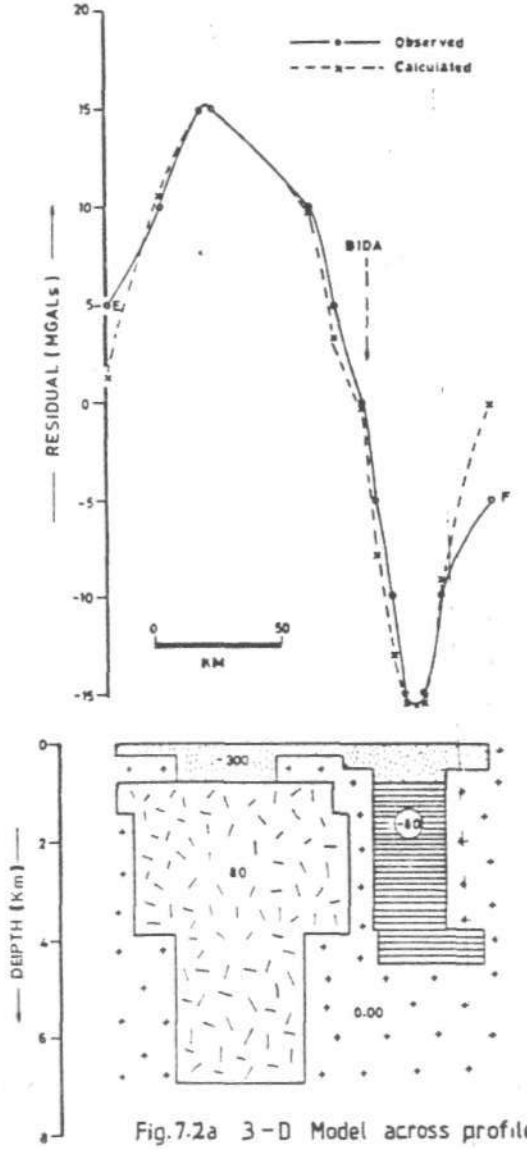


Fig. 7.2a 3-D Model across profile EF.

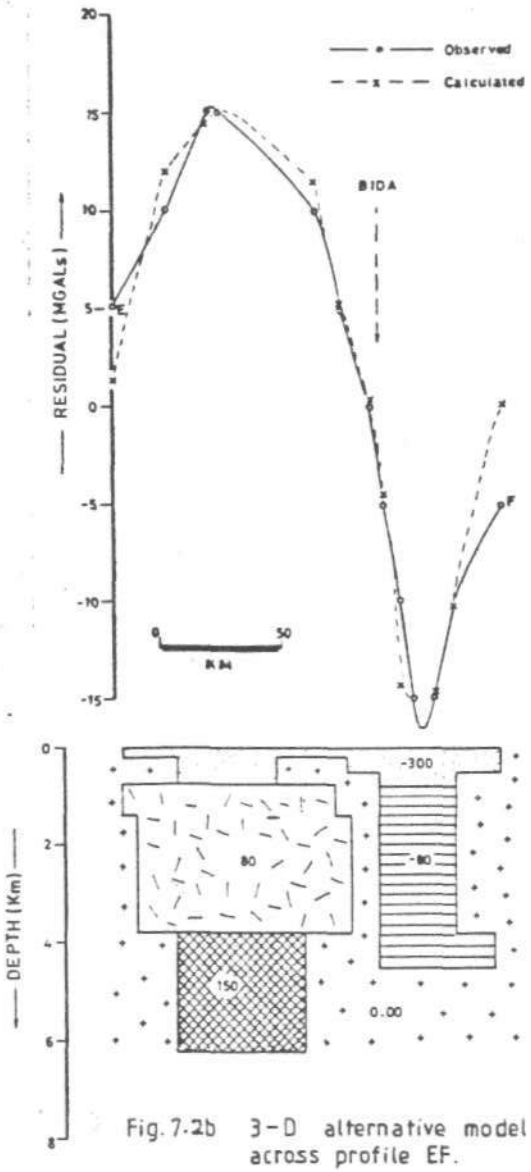


Fig. 7.2b 3-D alternative model across profile EF.

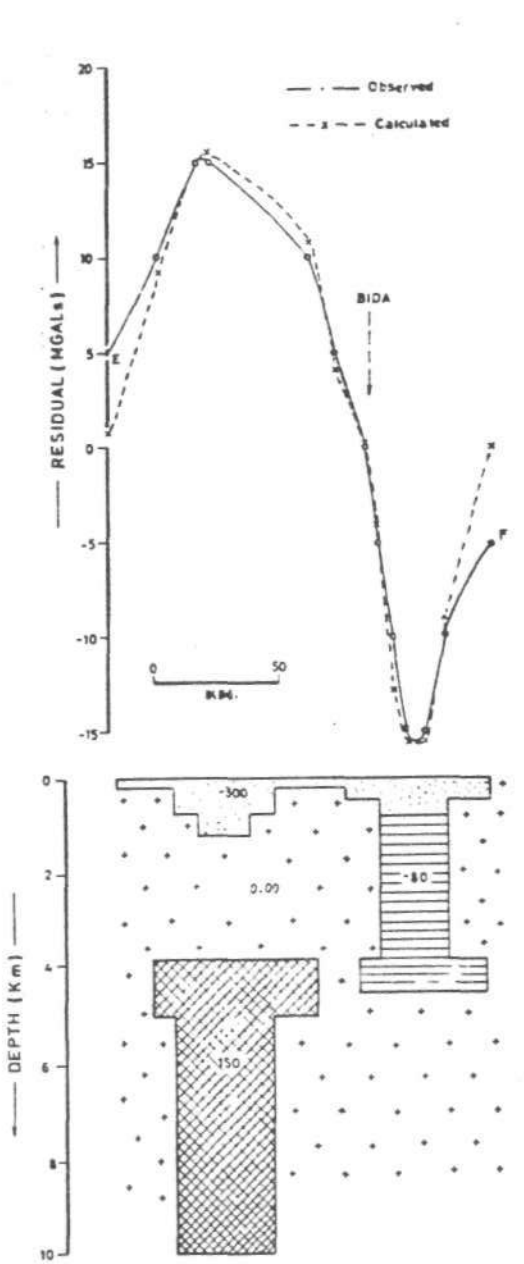


Fig. 7.2c 3-D alternative model across profile EF.

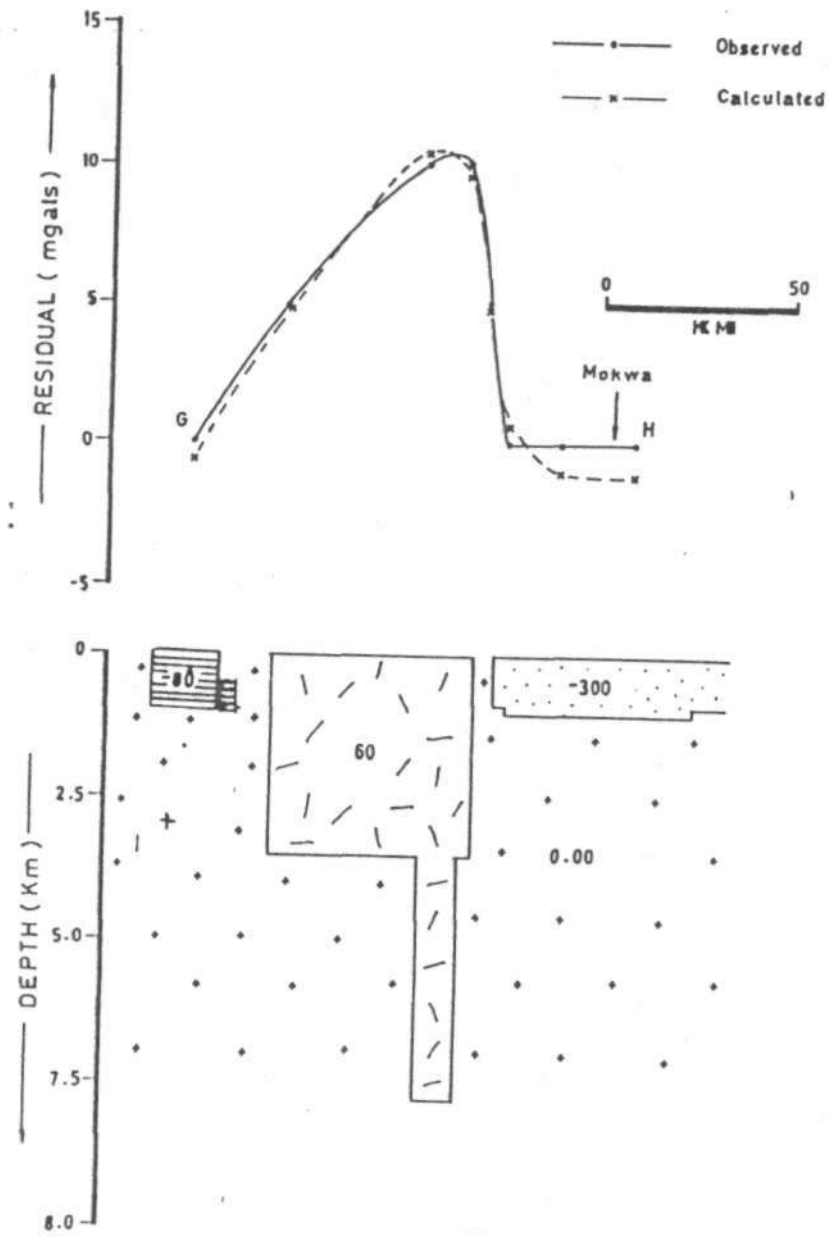


Fig. 7.3 .3—D Model across profile GH.

The model shown in Fig.7.3 shows the long strip metasediments of density 2760kg m^{-3} folded into a basement of density 2700kg m^{-3}. This source of the positive anomaly is interpreted to have a maximum length of 90km and a width of 40km. The depth is shown to be 7.5km.

7.5.4 Crustal Structure of the Middle Niger Basin

The interpretations of the regional and residual fields give rise to the crustal structure of the area. Two of the profiles AB and EF, on which gravity models were carried out in the previous sections are hereby reconstructed with the interpretation of the regional structure and one of the models on the residual fields. Figs.7.4 and 7.5 show the crustal structure of the Middle Niger Basin over these profiles.

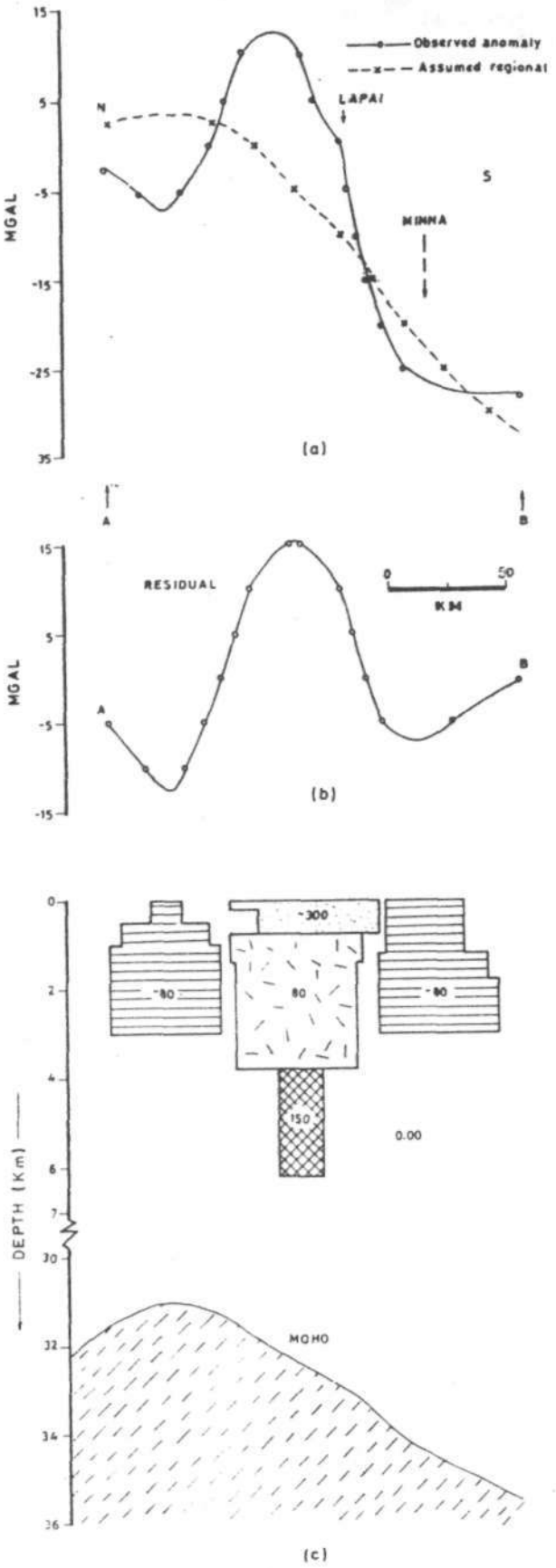


Fig. 7.4 Crustal structure of the Middle Niger basin on profile AB.

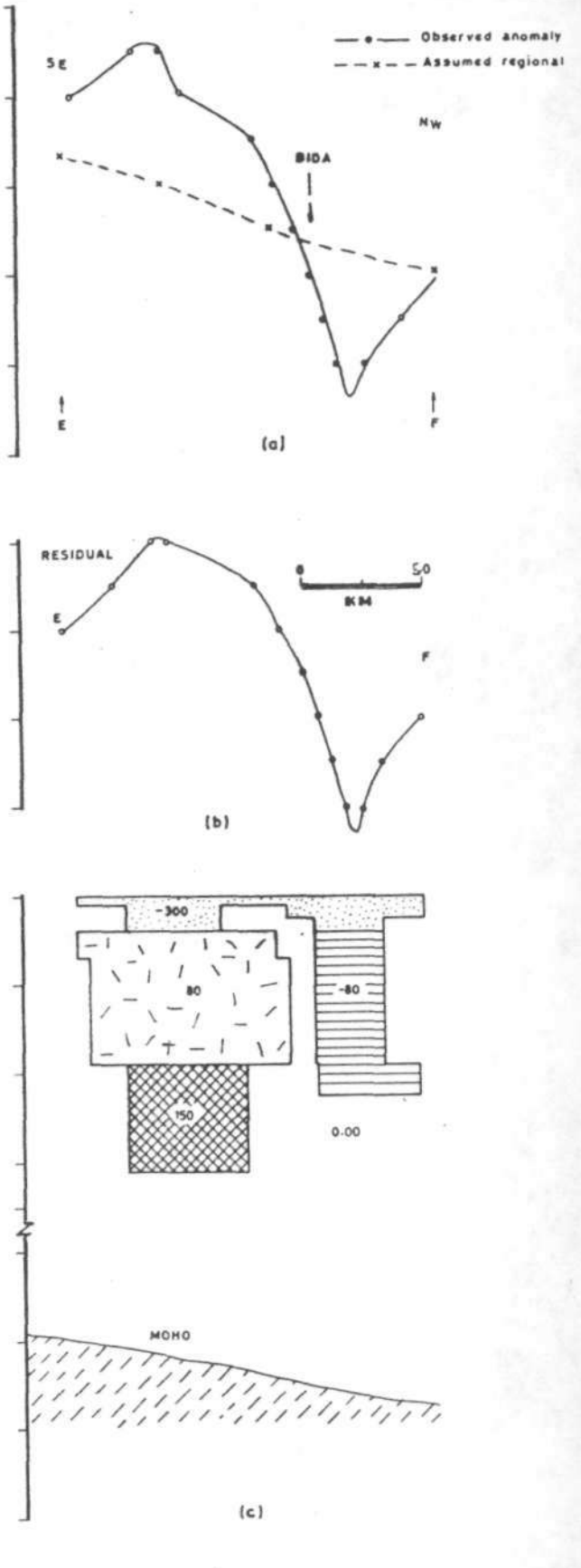


Fig. 7.5 Crustal structure of the Middle Niger basin on profile EF.

CHAPTER 8

DISCUSSION/CONCLUSION

8.1 Discussion

The Middle Niger Basin has an axial positive Bouguer anomaly extending to Bida from the southeast of the basin (Fig.6.8). The positive anomaly is flanked to north, south and northwest by negative anomalies. These negative anomalies are attributed to Older Granite suites and/or the thick Cretaceous sediments.

An interpretation of magnetic anomalies in the Middle Niger Basin (Ojo, 1990) suggested that the axial positive Bouguer residual anomaly of the basin which is characterized by a magnetic low is caused by predominantly basic rocks at depth. The presence of high magnetic susceptibilities as suggested by the aeromagnetic interpretation of the area is the first indication of basic rocks and volcanic activity (Ojo, 1990). The Nigerian schists are not known to have high magnetic susceptibilities to give the kind of magnetic anomaly consistent with that observed over the region (Ojo, personal communication). The above thus leads to the suggestion that the area might represent on old rift zone where diapiric intrusion of mantle rock rose to the lower and upper crust causing thermal expansion of the lithosphere. Subsidence and sedimentation probably then followed emplacement of the mafic rocks. This model appears to be supported by the present gravity interpretation. The alternative suggestion for subsidence attributed to diapiric penetration

of hot mantle rock followed by downward deflection of the lithosphere due to heavy cooled body was considered to be one of fine details which could not be resolved by presently available data.

The geophysical investigations of the adjacent Benue Valley by Cratchley and Jones (1965) and Ajakaiye and Burke (1972) also showed that the Trough has an axial positive Bouguer anomaly flanked on either side by elongate negative anomalies. The positive anomalies of the Benue Valley were ascribed to a central zone in which the oldest Cretaceons rocks (of Albian) are close to the surface and contain igneous material of intermediate to basic composition. There is also a close association between the lead-zinc mineralisation belt and the zone of positive Bouguer anomaly (Grant, 1971; Wright, 1976).

In addition, interpretation of aeromagnetic anomalies over parts of the Benue Trough by Ajakaiye et al. (1986), Ofoegbu and Mohan (1990) generally indicates the existence of major NE-SW lineaments representing major fault zones which separate the area into two major segments. Some minor faults are also reported to be aligned parallel and close to the edges of the Middle Niger Basin (Ofoegbu and Mohan, 1990). A regional gravity study over the Benue Trough indicates the presence of prominent positive residual Bouguer anomaly near Abakaliki and was interpreted to be a massive diapiric body (Adighije, 1981) and supported by Ofoegbu (1987) through the analysis of aeromagnetic anomalies in the Benue Trough.

Burke and Dewey (1971) reported 'andesitic and basaltic' volcanics of Santonian age in the southwestern portion of the Benue Trough and this portion seems to lie on a major Niger lineament (Ofoegbu, 1987). The area around Abakaliki represents one zone of magmatism and mineralization over which a complicated system of lineaments, faults, fractures has been mapped (Ofoegbu and Odigi, 1989). Similar magmatic foci are known to exist at Awi and Gombe, both in the Benue Trough and one mineralised granitoid area in the Basement Complex bordering the ring complexes of Jos Province. All these are centres of mineralisation.

The interpretation of the prominent positive residual Bouguer anomaly of the Middle Niger Basin takes into account the available evidence on the origin of the basin. The models shown in Figs. 7.1a, 7.2a, 7,1b, 7,2b, 7.1c, 7.2c are cross-sections of possible geological structures accounting for the gravity anomalies in the area. A predominantly high density metamorphic basement of schist or amphibolite composition (Figs. 7.1a and 7.2a) cannot be the only gravitating source of the positive anomaly because it will not account for the magnetic anomalies (Ojo, 1990). The alternative models shown in Figs. 7.1b and 7.2b incorporate basic intrusives lying between 3.8 - 6.2 km beneath the high density metamorphic basement. This basic intrusive has a width of 18 km (Fig. 7.1b) and a length of 50 km (Fig. 7.2b). The thickness of the basic intrusive of roughly

2 km is in agreement with the results obtained from aeromagnetic interpretation (Ojo, 1990). Figs. 7.1c and 7.2c show basic intrusive which extends to a depth of 10 km from 3.8 km well below the Cretaceous sediments giving an approximate width of 45 km. The thickness of this intrusive would give twice the amplitude of the observed aeromagnetic anomaly if the susceptibilities of the high density schists approximate that of the granitised basement. For this reason, this latter model is less favoured.

8.2 On the Origin of the Middle Niger Basin

There is a close relationship between the Middle Niger Basin and the Benue Valley. The evolution of the Benue Valley, according to several workers (King, 1950, Burke et al., 1970; Wright, 1976; 1981) is related to that of the South Atlantic Ocean. It has been suggested that the Gulf of Guinea, the Benue Valley and the South Atlantic developed between two RRR triple junctions, one situated under the present Niger Delta and the other, as reported by McConnel (1969), is situated north of Takatu rift structures of Guyana. Thus the Benue Valley is confirmed as a rifted structure believed to have developed during the break-up of Gondwanaland and was subsequently filled with sediments ranging from Albian to Recent.

The Middle Niger Valley on the other hand was earlier thought to be an area of local subsidence from gravity measurements (Ojo and Ajakaiye, 1976). However, new evidence from the interpretation of gravity and magnetic anomalies whose distribution and pattern appears common to both the Niger and Benue Valleys; and the study of Landsat imageries

and analysis of drilled rock samples from the area(Kogbe et al., 1983) suggest rifting as a possible origin of the Middle Niger Basin. The course of the river Niger which is the major drainage system in the region as revealed by Landsat imageries is structurally controlled by sets of parallel faults which fringe the Valley sides. Foundation drilling logs by Julius Berger construction engineers also confirmed the existence of major faults on both sides of the River Niger Valley (Kogbe et al., 1983).

Examination of the residual anomaly map (Fig. 6.8) does not indicate distortion of contour lines along the margins of the basin. The effects of faults (Kogbe et al., 1983) along the margins of the basin could have been obliterated by the gravity effects of shallower features. What could be responsible for the existence of the faults? The presence of the 'domed structure' (Fig. 6.11) indicates a rise in the upper mantle which seems to follow the basin trend and supports the suggestion that the Niger arm is another triple junction attributable to a mantle plume of Maastrichtian age (Wright, 1976). Plate movements are periods of lithospheric motion alternating with stationary episodes which can last for tens of millions of years (Wright et al., 1985). It has been proposed that during these stationary episodes, thermal plumes in the upper mantle can focus sufficient heat on the overlying lithosphere and crust to cause doming and igneous

activity. The younger Granites decrease in age from north to south in Nigeria (Wright, 1973). This led to the proposition that the African Plate was moving northwards over a mantle plume during Jurassic, but sufficiently slowly for magmas of different complexes to be generated in turn. Earlier manifestations of the same plume have been correlated with Younger Granites of Air and Southern Niger which resulted from plume activity during stationary episodes 340 - 290 Ma and 430 - 380 Ma ago respectively (Wright et al., 1985). After Jurassic, the African Plate moved further north, and it is further proposed that about 100 Ma, the plume lay beneath the triple junction now occupied by the Niger Delta and thus was a major factor in opening the South Atlantic and forming the Benue Trough (Wright, 1968; Wright et al., 1985).

Complicated lineaments over the Niger and Benue Valleys which bear close similarities (Ofoegbu and Mohan, 1990) as well as the presence of several magmatic foci which concide with positive Bouguer residual anomalies lead to the conclusion that the source of the positive Bouguer residual in the Middle Niger Basin may be a magmatic focus which lies well below the Cretaceous sediments. Thus the Middle Niger Valley may be a rifted structure trending in a NW-SE direction and linking up with the Benue Rift Valley around Lokoja (Kogbe et al., 1983).

8.3 Conclusions

The fourth degree polynomial surface of the gravity field (Fig.6.5) represents the surface that best describes the regional gravity background of the Middle Niger Basin area. The prominent long wavelength positive anomaly on this surface is interpreted in terms of a rise in Moho discontinuity (Fig. 6.11) i.e. a diapiric rise in mantle material into the lower part of the earth's crust.

The positive residual Bouguer anomaly which occurs at the southeastern portion of the Nupe Basin (Fig. 6.8) was explained in terms of three possible gravitating sources:

I. As predominantly high density metamorphic basement rocks of schist or amphibolite composition below Cretaceous sediments of thickness 800m (Fig. 7.1a, 7.2a). This possibility is considered because of the fact that the Cretaceous sediments of the Niger Valley cut across a zone of north-south metasedimentary belts.

II. A combination of high density metamorphic basement of schist or amphibolite composition and basic intrusive overlain by Cretaceous sediments of thickness 750m (Figs. 7.1b, 7.2b). The inclusion of the basic intrusives is supported by aeromagnetic interpretation over the region.

III. As basic intrusives well below Cretaceous sediments (of thickness 1.2km) extending from a depth of 3.8km to a depth of 10km (Figs. 7.1c, 7.2c).

Of these 3 models, the models in II and III seem to be supported by aeromagnetic interpretations. The depth of the basic intrusive obtained for the model in II is however more consistent with that obtained from interpretation of a magnetic low over the same body by Ojo (1990), especially when the relative magnetic susceptibilities of the metasediments and the granitised basement is zero. Furthermore, gold winnings from auriferous schists over the basin suggest that schists lie right beneath the sediments (Russ, 1957). Thus these sources are the most likely combination for the gravitating source.

The general indication is that a diapiric basic intrusion lies well below the Cretaceous sediments. The mechanism by which the dense material was forced upward through the crust with subsequent subsidence and sedimentation remains a complicated issue which could be related to a general global phenomenon embodied in the rift hypothesis. The point here is that gravity measurements over the basic or ultrabasic rocks in this area provide information on the concealed parts of the masses, and any theory of intrusion must explain the form which is found. If the area is of great mass excess locally, with the basic material representing an uncompensated load on the crust, then the area might be assumed to be sinking on this account in geologic times. There is no evidence, however, to support this, though the possibility of this cannot be ruled out.

There is generally a need to carry out deep seismic sounding to determine the depth to the Moho and possibly establish a velocity contrast at some depth below the Cretaceous sediments where the suspected basic materials lie.

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APPENDIX I

The method of estimating coefficients of a polynomial trend function by least-squares is basically the same for any variant of the general linear model regardless of the degree and number of variables involved.

If G(x,y) is the polynomial surface to be fitted to a set of gravity measurement g(x,y) at point (x,y), then the deviation, or residual R(x,y) at this point is

$$R(x,y) = g(x,y) - G(x,y) \quad \text{.....(I1)}$$

The residual can be made as small as possible by adjustment of equation (I1). For polynomial fit of degree n, then the surface

$$G(x,y) = \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j \quad \text{.....(I2),}$$

where a_{ij} are coefficients to be determined for the polynomials. The least squares criterion demands that the sum of squares of the residuals over a pattern P be made minimum. Thus

$$\sum_{p} R^2(x,y) = \sum g(x,y) - \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j \quad \text{....(I3),}$$

be made minimum. If,

$$I(a_{ij}\text{'s}) = \sum_{p} R^2(x,y) \quad \text{.....(I4),}$$

then from (I3)

$$I(a_{ij}\text{'s}) = \sum_{p} \left[\sum_{i=o}^{n} \sum_{j=o}^{n-i} \sum_{k=o}^{n} \sum_{l=o}^{n-k} a_{ij} a_{lk} x^{k+i} y^{l+j} \right]$$

$$- 2 \sum_{p} g(x,y) \sum_{i=o}^{n} \sum_{j=o}^{n-i} a_{ij} x^i y^j + \sum_{p} g^2(x,y) \quad \text{....(I5)}$$

To minimise the residual function, we differentiate partially I with respect to the coefficients a_{ij} and equate these to zeros. Thus,

$$\frac{\partial I}{\partial a_{ij}} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (I6)$$

And

$$2 \sum_{k=o}^{n} \sum_{l=o}^{n-k} a_{lk} \sum_{p} x^{k+i}\, y^{l+j} - 2 \sum g\, x^{i} y^{j} = 0$$

or

$$\sum_{k=o}^{n} \sum_{l=o}^{n-k} a_{lk} \sum_{p} x^{k+i}\, y^{l+j} = \sum_{p} g x^{i} y^{j} \qquad \ldots\ldots\ldots (I7)$$

where $j = o, 1, 2, 3, \ldots\ldots, (n-i)$

$i = o, 1, 2, 3, \ldots\ldots, n$

Equation (I7) yields normal equations expressed in a standard matrix notation as

$$\left[\sum_{p} x^{k+i}\, y^{l+j}\right] \cdot \left[a_{kl}\right] = \left[\sum_{p} g x^{i} y^{j}\right] \qquad \ldots\ldots\ldots (I8)$$

To solve equations (I8) for a_{kl}, we premultiply the RHS and LHS of (I8) by the inverse matrix $\left[\sum_{p} x^{k+i}\, y^{l+j}\right]^{-1}$ to yield

$$\left[a_{kl}\right] = \left[\sum_{p} x^{k+i}\, y^{l+j}\right]^{-1} \cdot \left[\sum_{p} g x^{i}\, y^{j}\right] \qquad \ldots\ldots\ldots (I9)$$

It can be seen from (I9) that computation of the coefficients a_{kl} can be carried out with the use of available data points once their co-ordinates are known. The inverse matrix does not depend on gravity values and may be found for any polynomial order once the pattern P is specified. Simultaneous computation of the coefficients using (I9) introduces some inherent, truncation and roundoff errors (Dorn and McCracken 1972).

Inherent errors refer to errors in the data while truncation and roundoff errors refer to errors that are introduced by numerical procedures themselves. In computation of the inverse matrix in (I9), truncation error is minimized because of the finite series on which the operation is performed.

For rectangular pattern where gravity values are taken on regular grids, axes can be chosen so that the rectangle is symmetrical about them and ordinates and abscissae taken to be integers. This reduces the number of elements in the equation and consequently, some coefficients drop out. Orthogonal polynomial analysis has been treated by Oldham and Sutherland (1955).

Non-orthogonal polynomial analysis is used for treatment of data set that are not arranged on a regular grid. The only criterion is that data be equably distributed over the region of interest. The equation (I9) becomes increasingly tedious to solve with high degrees of polynomials. However, the advent of high capacity electronic computers have made such computation feasible and faster for any degree.

A computer program adapted for Cyber 932-11 NOS/VE computing machine for A.B.U. Zaria is available. The program is designed to compute the coefficients of surfaces of any degree desired. Errors associated with simultaneous computation of coefficients are also incorporated into the FORTRAN program. The program was designed by Dan Dyrelius in Sweden.

APPENDIX II

THREE-DIMENSIONAL GRAVITY COMPUTATION

The analysis that is presented here assumes a 3-dimensional body of arbitrary shape. This body is represented by depth contours and each depth contour represented by an n-sided horizontal polygonal lamina approximating the depth contour. Fig.II-1 shows the 3-dimensional body represented by contours.

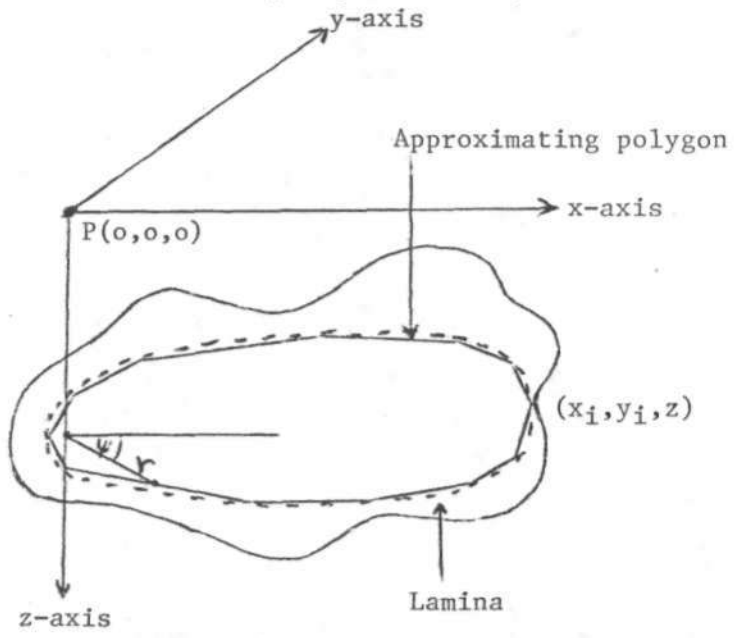


FIG. II-1. Three-dimensional body represented by depth contour

The contribution by the lamina to the gravity anomaly is Δg given by

$$\Delta g = G\Delta\rho \left[\int d\psi - \int z/(r^2+z^2)^{\frac{1}{2}} \cdot d\psi \right] \quad .....(II-1)$$

where r, ψ and z are cylindrical co-ordinates of a point on the contour and G and $\Delta\rho$ the gravitation constant and density contrast respectively. For numerical computation, the actual contour may

be replaced by a polygon of which the vertices are (x_i, y_i).

Then the gravity effect due to the polygon is

$$\Delta g = G\Delta\rho \sum_{i=o}^{n} \left[\text{Warccos} \left\{ \left(\frac{x_i}{r_i}\right)\left(\frac{x_{i+1}}{r_{i+1}}\right) + \left(\frac{y_i}{r_i}\right)\left(\frac{y_{i+1}}{r_{i+1}}\right) \right\} \right.$$

$$\left. - \arcsin \frac{Zq_iS}{(P_i^2+Z^2)^{\frac{1}{2}}} + \arcsin \frac{Zf_iS}{(P_i^2+Z^2)^{\frac{1}{2}}} \right] \quad \text{.....(II-2)}$$

Where

$S = +1$ for $P_i > 0$

$= -1$ for $P_i < 0$

$W = +1$ for $m_i > 0$

$= -1$ for $m_i < 0$

$$P_i = \frac{y_i - y_{i+1}}{r_{i,i+1}} \cdot X_i - \frac{(x_i - x_{i+1})}{r_{i,i+1}} \cdot y_i$$

$$q_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \cdot \frac{x_i}{r_i} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \cdot \frac{y_i}{r_i}$$

$$f_i = \frac{x_i - x_{i+1}}{r_{i,i+1}} \cdot \frac{x_{i+1}}{r_{i+1}} + \frac{y_i - y_{i+1}}{r_{i,i+1}} \cdot \frac{y_{i+1}}{r_{i+1}}$$

$$m_i = \left(\frac{y_i}{r_i}\right)\left(\frac{x_{i+1}}{r_{i+1}}\right) - \left(\frac{y_{i+1}}{r_{i+1}}\right)\left(\frac{x_i}{r_i}\right)$$

$$r_{i,i+1} = + \left[(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2\right]^{\frac{1}{2}}$$

$$r_i = + (x_i^2 + y_i^2)^{\frac{1}{2}}$$

$$r_{i+1} = + (x_{i+1}^2 + y_{i+1}^2)^{\frac{1}{2}}$$

The expression for the attraction of the lamina is now in digital form involving only the co-ordinates of the vertices of the polygon. The attraction of the complete 3-D body may be obtained by numerical integration over Z of the contribution of all laminae. Thus

$$\Delta g_{total} = \int_a^b \Delta g dz \quad \ldots\ldots\ldots\ldots\ldots\ldots (II-3)$$

where dz is the intervals between contours and a and b being the depths of the 3-D body at bottom and top respectively. If Δgo, Δg_1 and Δg_2 are values of Δg corresponding respectively to contours at heights Zo, Z_1 and Z_2, then the gravity anomaly caused by the portion of the body lying between horizontal planes at depths Zo and Z_2 given by choosing successive sets of three points is

$$\int_{Zo}^{Z_2} \Delta g dz = \frac{1}{6}\left[\Delta g_o \frac{Z_o-Z_2}{Z_o-Z_1}(3Z_1-Z_2-2Z_o)\right.$$

$$\left. + \Delta g_1 \frac{(Z_o-Z_2)^2}{(Z_1-Z_2)(Z_1-Z_o)} + \Delta g_2 \frac{Z_o-Z_2}{Z_2-Z_1}(3Z_1-Z_o-2Z_2)\right] \ldots (II-4)$$

In application of the method, the body whose attraction is desired is first represented by horizontal contours at equal intervals of Z, drawn on squared paper. Sufficient points (x_i,y_i) are then chosen on these contours to represent them to the desired degree of precision, and the co-ordinates as read off the diagram are inserted in the machine programme for the evaluation of equation (II-2). Note that, just as in the case of 2-D the

co-ordinates of the first point are read twice. The computer is programmed to determine also the integration over Z so that the complete attraction of the 3-D body is obtained. The value of the anomaly at other points is obtained by shifting the origin, adding the desired increments to the values of x_i and y_i.

The concept above was developed and put in a digital form by Talwani and Ewing (1960). The computer programme was used to compute models as described in this work.