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Geophysical Analysis of Gravitational Attractions of Metasedimentary and Metavolcanic Rocks in Northwest Nigeria.

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Abstract

Relative gravity measurements were carried out on the metasedimentary and metavolcanic rocks area of Northwestern Nigeria. The observed gravity values were reduced to the datum of the mean sea level using a uniform crustal density of 2.67 g/cm^3 to produce the Bouguer gravity anomaly values. A two and half dimensional modeling of the gravitational effects of assumed mass distributions was carried out on the resultant residual anomalies and various estimated thicknesses and depths of the schist and granite bodies in the area were computed. Depths estimates obtained are comparable with results obtained in similar environment in other parts of the world.

1.0 Introduction

Gravity is useful as a prospecting tool because the density of rocks varies laterally, which in turn causes the gravitational attraction of the earth to vary laterally. LaCoste and Romberg gravity meters, and similar instruments, provide great precision in the observation of gravity at the earth's surface because they are designed to measure directly small differences in the strength of gravity.

To calculate the gravity anomaly of an irregular 3D mass body with spatially variable density contrast, the mass body usually is approximated as a collection of vertical 3D rectangular prisms in juxtaposition. The gravity anomaly from the whole mass body is an algebraic sum of the contributions of all vertical prisms at appropriate depths and distances from the observation point. This procedure is widely used in gravity-anomaly forward modeling and inversion [1], [2]and [3].

2.0 The Study AreaAnd Previous Geophysical Work

Nigeria lies within the vast Pan-African (650 $\pm$ 200 Ma) mobile belt which separates the West African and Congo cratons[4] and [5]. There are ten major schist belts within the northwestern Nigerian basement complex. These include BirninGwari, Kazaure, Maru, Malumfashi, Kushaka, Maru, Toto, Ushama, Wonaka and Zuru belts[6].

The present study area occurs in the northwestern part of Nigeria (Figure 1), bounded by latitudes 11^{o}00'N to 13^{o}00'N and longitudes 6^{o}00'E to 8^{o}00'E and covers an area of approximately 57,600 km^2. It is underlain by rocks of the basement complex. The area is of interest because it covers the schist belts of NW Nigeria which is of economic importance. McCurry [7],produced a generalised geological map of parts of northwestern Nigeria, and recognisedquartzites, schists, metavolcanics and "older granites" as the major rock units in the area.

Geophysical investigations in Nigeria have been largely confined to sedimentary formations with proven natural resource potentials. Limited number of geophysical surveys has been carried out within the area of study. The first comprehensive geophysical work in the area was the aeromagnetic mapping carried out all over the country for the Geological Survey of Nigeria in 1974. Osazuwa[8], established a primary gravity network for Nigeria of which exist base stations in the study area to which all measurements were tied to absolute values.

During the 1964 – 1967 period, a United Nations project involving the use of aeromagnetic, aero electromagnetic, electrical and ground magnetic methods, in search of minerals, was carried out and it covered the area of study. Adeniyi[9], carried out regional gravity and magnetic survey which covered latitudes 9^{o}00' and 9^{o}48' N and longitudes 6^{o}00' and 6^{o}36'E. Gandu et al [10], carried out a gravity study of the Precambrian rocks between latitudes 11^{o}30' and 12^{o}15' N and longitudes 7^{o}30' and 8^{o}15'E which is within the schist belts of NW Nigeria. The study estimated the thickness of the Malumfashi schist as between 4 to 5 km and proposed sharp contacts between the granites and the schists.

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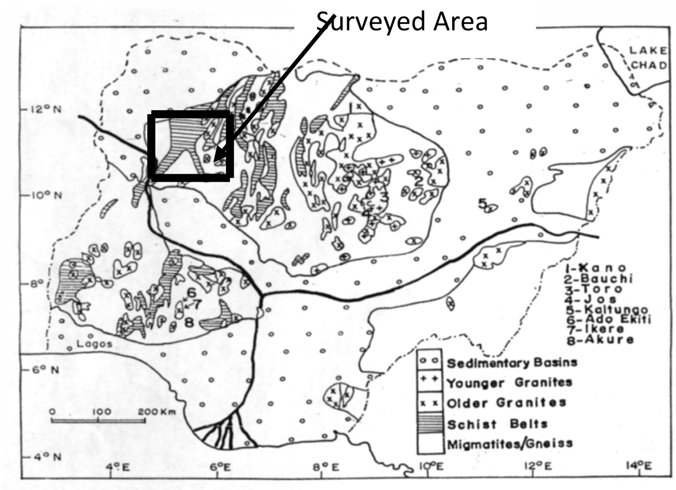

Figure 1: Outline Geological Map of Nigeria showing Area of Survey

The study showed lack of high positive Bouguer anomalies over the schists in the area which confirms the geological evidence of the schists having evolved in an ensialic environment. Udensi*et al*[11], carried out a three dimensional interpretation of the Bouguer anomalies over the Minna Batholiths between latitudes 9^{o}25' and 10^{o}5' N and longitudes6^o and 7^o E. The modeling suggests that the contacts of the granite suite with the flanking BirninGwari and Kushaka formations are steep and that the maximum thickness of these formations are 11km and 6 km, respectively. Umego[12],carried out gravity and aeromagnetic investigation of the Sokoto basin lying west of the study area. Three prominent linear belts with concentration of short wavelength anomalies were delineated.

These belts are interpreted to be zones of probable crustal weakness and believed to be part of the continent – wide conjugate system of strike – slip fractures which have been interpreted to be of significant tectonic origin. These belts could also be loci of economic mineralization. Aku et al [13], carried out gravity investigation of the Older Granite plutons between longitudes 6^o 15' and 7^o 00'and latitudes 12^o 00' and 12^o 40'. A 3 –D modeling of the residual anomaly shows that the isolated outcrops in the area coalesce at depth into one big pluton still being unroofed at the present time.

3.0 Aims and Objectives Of The Study

The work was carried out in order to investigate the lithologies and structures present in northwestern part of Nigeria, and the relationships between the various rocks in the area and the gneissic complex. This study is significant because it is the first attempt to carry out a geophysical survey over a large schist area of NW Nigeria.

This research, which is an open field data collection, followed by analysis and interpretation, is hoped to contribute to the rapid enhancement of general geophysical studies and in particular, gravimetric, in Nigeria.

The goals of this work are of national and academic interest; national because it will contribute to research issues of national economic importance and academic oriented because it focuses on developing techniques and methodologies for advancing geophysical research in Nigeria.

4.0 Three Dimensional Vector Gravity Potential

Gravity g, is given by the expression

$$g = G\iiint_v \rho\nabla\left(\frac{1}{r}\right)dv + \frac{1}{2}\omega^2\nabla\left(x^2+y^2\right) \qquad (1)$$

where G is universal gravitational constant, ρ is the density of the earth material, is the gradient vector, ω is angular velocity of the earth's rotation, r is the distance of the attracted body from the earth's centre, and x and y are respective projections of r on the x- and y- axes of the plane parallel or co-planar to the equatorial plane. For clarity, equation (1) can be rewritten vectorially as

$$g = g' + f \qquad (2)$$

The two components of gravity are therefore g′, which represents the force with which a non-rotational hypothetical earth attracts every unit mass situated at its surface or beyond; and f, the centrifugal force exerted by the earth, as a result of its rotation on every unit mass situated on the surface of the real earth[14]. The first term of the equation above is called gravitational field (which is obtained from the Newtonian force of attraction).

Consider the geometry of the rectangular prism in Figure 2.

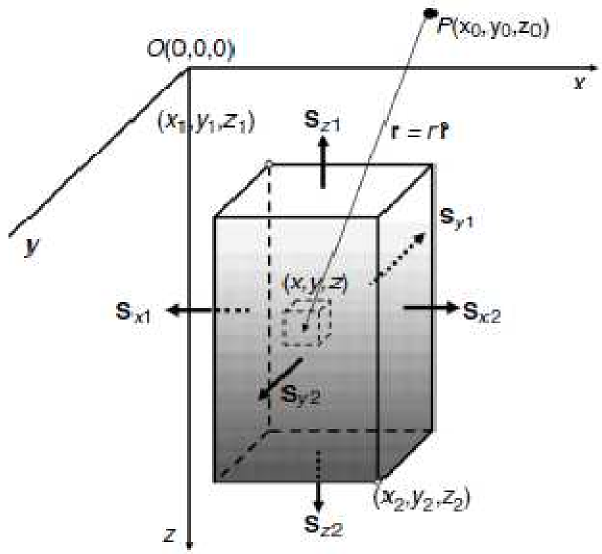

Figure 2: Drawing demonstrating the gravity anomaly at an observation point $P(x_0,y_0,z_0)$ resulting from a mass element at source point P(x,y,z) .

The prism is bounded by six planar surfaces: S_{x1}, S_{x2}; S_{y1}, S_{y2}; and S_{z1}, S_{z2}. The direction of each surface normally outward from the prism.

Therefore $S_{x1} = - S_{x1}\hat{\imath}$, $S_{x2} = Sx_2\hat{\imath}$;$S_{y1} = - S_{y1}\hat{\jmath}$, $S_{y2} = S_{y2}\hat{\jmath}$; and$S_{z1} = - S_{z1}\,\mathbf{k}\hat{}$, $S_{z2} = S_{z2}\mathbf{k}\hat{}$,

where $\hat{\imath}$, $\hat{\jmath}$, $\mathbf{k}\hat{}$ are unit vectors along the x-, y- , and z- axes respectively. An infinitesimal mass dm = ΔρdV between a 3D mass and its background is at point (x,y,z), where Δρ is the density contrast and dV = dxdydz is the infinitesimal volume. The observation point is at point $P(x_0,y_0,z_0)$. From Newton's law, the magnitude of attraction on unit mass a point arising from the infinitesimal mass at distance r_0 is given by

$$dF = G\frac{dm}{r_0^2}\hat{\mathbf{r}} = G\frac{\Delta\rho dV}{r_0^2}\hat{\mathbf{r}} \qquad (3)$$

where$G$ is Newton's gravitational constant, r_0 is the distance between the observation point and the mass source dm = ΔρdV , and $\mathbf{r}\hat{}$ is the unit vector in the direction from the observation point to the mass source. The displacement vector from the observation point to the mass source is

$\mathbf{r} = r_0\mathbf{r}\hat{} = (x - x_0)\mathbf{i}\hat{} + (y - y_0)\mathbf{j}\hat{} + (z - z_0)\mathbf{k}\hat{}$. The vertical component of the gravity anomaly observed at point $P(x_0,y_0,z_0)$ is

$$\Delta g_z(x_0, y_0, z_0) = G\int\frac{\Delta\rho dV}{r_0^2}\widehat{k}\ \cdot \widehat{r} = G\int\frac{(z - z_0)\Delta\rho}{{r_{0(x,y,z)}}^3}dydxdz \qquad (4)$$

with

$$r_{0(x,y,z)} = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}$$

The nonuniqueness of the 3D vector gravity potential and theuniqueness in the calculated gravity anomaly make it possible to selecta form of the 3D vector gravity potential as simple as possible toconvert the 3D volume integral to 2D areal integrals.The 2Dareal integral can be converted to 1D line integral through defining a2D vector gravity potential [2] and [15].

5.0 Data Collection

Several observational field procedures exist: the leapfrog sequence, A-B-A-B-C-B-C; etc. The ladder sequence, A-B-C-D-E-D-C-B-A; double closed loop sequence, A-B-C-D-E-A-E-AD-C-B-A; etc.Woolard and Rose [16], in their elaborate drift analysis have shown that there is no advantage of any of the observational methods over the other in terms of reliability of result.

The single nested loop observational sequence was adopted in this survey with the aim of having effective control over the drift of the gravimeter. The loop tie was established by taking a reading at base station at the beginning of survey and another at the same station at the end of the survey.

A network of 7 base stations was established so that corrections could be made for the drifts of the instruments. A total of 948 secondary stations at 2 - 3 km interval along the survey routes were occupied using the single-base method of gravity measurement. Altimeter and GPS readings were taken simultaneously with gravity readings at any given station to determine station locations and elevations. Dry and wet bulb temperature readings were also taken alongside the altimeter readings using the psychrometer for air temperature and relative humidity corrections. This correction is required when using Single Base or Leapfrog methods of altimetry. A base station was always visited at the beginning and at the end of each time range where linear drifts were estimated to hold for both gravity meter and altimeters for each day's work. The gravity data were tied to the first order gravity network base stations located at Gusau, Funtua , Dakin Takwas and Katsina[8] and station elevations were calculated relative to the Standard Bench Mark (SBM) at Anka junction with absolute height of 399.52 m.

5.1 Data Processing

Gravity data processing or reduction constitutes applying any or all of the Bouguer, elevation, free-air, isostatic, latitude, and terrain corrections to the gravity measurements.

The following corrections were carried out

5.2 Tidal Correction

The tidal correction is the factor applied to the station gravity that compensates for the gravitational attraction of the Sun and Moon. The tidal corrections, which are usually added to the observed gravity values can be expressed as

$$TC = P + N\cos\varphi\,(\cos\varphi + \sin\varphi) + S\cos\varphi\,(\cos\varphi - \sin\varphi) \qquad (5)$$

where P is the correction required at the pole and is usually neglected in gravity surveys, φ is the latitude. N and S are corrections at latitudes 45^o N and 45^o S respectively and are usually given on a daily basis at hourly intervals to an accuracy of 5 mGals in tables published yearly by the European Association of Exploration Geophysicists.

5.3 Drift Correction

The readings of all gravity meters drift with time, due to very slow creep in the springs although temperature and pressure changes have been shown to also contribute to it [17]. The difference in gravity o

bservations (after removing known effects such as tides) can

be used to estimate the meter drift.

Assuming a linear drift for each complete loop, the drift rate, μ was computed using the

formula: $$\mu = \frac{(\overline{g_2} - \overline{g_1}) - (g_{02} - g_{01})}{t_2 - t_1} \qquad (6)$$

where $\overline{g_2}$ *and* $\overline{g_1}$ are the absolute gravity values of the terminating stations of the loop, g_{01} and g_{02} are the observed gravity values corresponding to g_1 and g_2 at time t_1 and t_2 respectively.

The required drift correction δ_d to an observed gravity value at any detailed station d at time t_d within the loop is given by

$$\delta_d = \mu\left(t_d - t_1\right) \qquad (7)$$

5.4 Latitude Correction

The United States National Imagery and Mapping Agency published the most recent version of the formula in 1998[18]. According to this new formula, the theoretical gravity g_ϕ obtained from the gravity field of the World Geodetic System (WGS 84) reference ellipsoid is

$$g_\phi = 978032.53359\frac{\left(1 + 0.00193185265241\sin^2\phi\right)}{\sqrt{1 - 0.00669437999014\sin^2\phi}} \text{ mGal} \qquad (8)$$

where ϕ is the geodetic latitude. When using this formula, a small atmospheric gravity correction is necessary because the WGS-84 earth's gravitational constant includes the mass of the atmosphere.

5.5 Elevation Correction

Since the gravity value at a station varies with height of the station, it is necessary to correct all observations to a datum which is usually but not always sea-level (i.e, the surface of the reference ellipsoid). This correction consists of two parts, the Free-air and Bouguer corrections.

5.5.1 Free Air Correction

The free-air gradient accounts for only part of the change in gravity with height [i.e. difference in station elevation (h) above the datum plane (Geoid)]. Observed gravity at elevation h is reduced to its sea-level equivalent on the assumption that topographic masses are displaced vertically down to sea level. The free air correction (FAC) is given by

$$FAC = 0.30877h \qquad (9)$$

where h is station's elevation in meters. As gravity decreases with height this correction has to be added to the observations to correct to sea level.

5.5.2Bouguer Correction

Between any elevated station and the datum plane (usually the sea level) there is a slab of material with thickness equal to the station height (h), exerting a gravitational attraction at the surface which can be considered to be additional to that due to the mass of the earth below the reference ellipsoid. The correction for this factor, called Bouguer correction (BC) is given by

$BC = 2\pi G\rho h$ (10)

where $G = 6.67 \times 10^{-11} mkg^{-1}s^{-2}$ is the universal gravitational constant and $\rho = 2.67 \times 10^{3}\ kgm^{-3}$ is an assumed average crustal density for the slab.

5.6 Gravity Anomalies

After the observed gravity values have been corrected, two basic gravity anomalies, Free-air (FA) and Bouguer (BA) are obtained and these are given by the following expressions

$BA = (g_{ob} + FAC - BC) - g_{\varphi}$ (11)

and

$FA = (g_{ob} + FAC) - g_{\varphi}$ (12)

where g_{ob} is observed gravity.

The gravity correction process really boils down to

Bouguer Anomaly = Observed Gravity – Earth Model (13)

The Bouguer anomaly is therefore that part of the difference between observed gravity (after Bouguer, Free-air and terrain corrections have been carried out) and the theoretical gravity at any point on the earth which is due purely to lateral variations in the density beneath the surface. When only free-air correction is applied to the observed gravity the difference gives the Free-air anomaly.

The method of least squares polynomial surface fitting was used in this survey to estimate the regional effects. This is a purely analytical method in which matching of the regional trend by a polynomial surface of a low order exposes the residual features as random errors. The treatment is based on statistical theory.Subtracting the regional trend from the observed Bouguer anomaly gives the residual anomaly map. The residual anomaly map obtained by subtracting the regional field from the Bouguer anomaly field is shown in Figure 3. It has both negative and positive contour closures corresponding to granites and schists respectively. The residual map was superposed on the simplified geologic map of the area to ascertain any correlation between gravity and geology of the area.

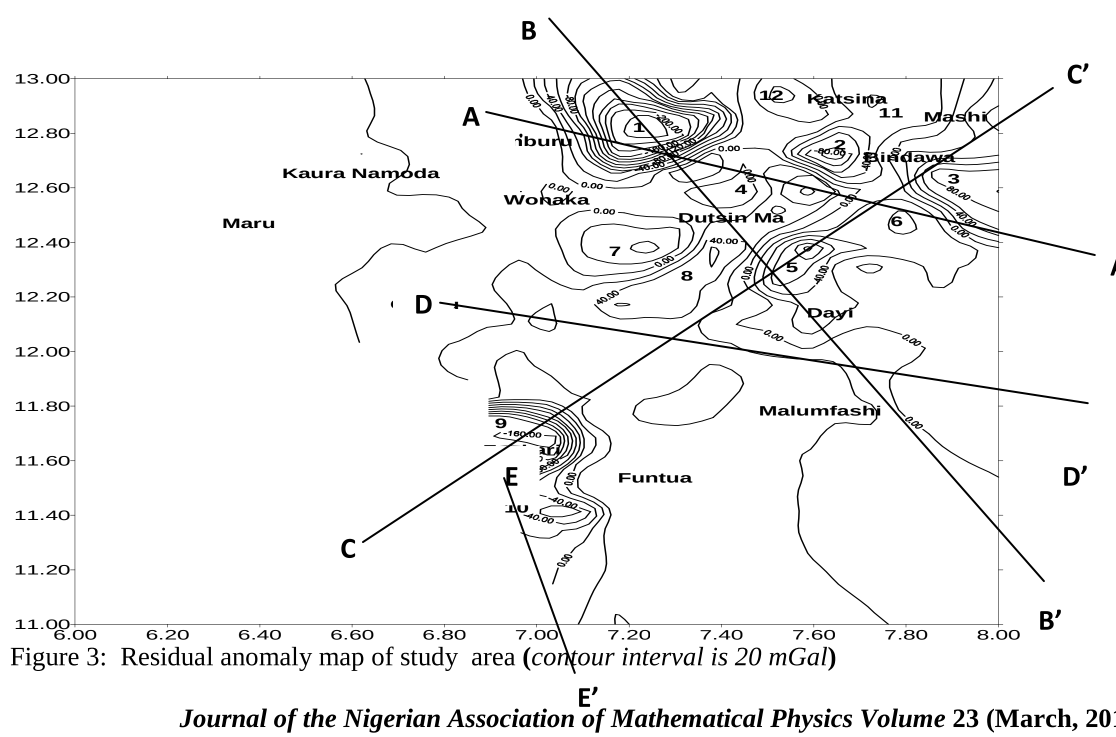

Figure 3: Residual anomaly map of study area **(***contour interval is 20 mGal***)**

In Table 1 is the residual profiles identification, their directions, approximate lengths and the numbered bodies along each.

Table 1: Profiles I.Ds, their directions, approximate lengths and numbered bodies along them

Profile Name	**Profile Direction**	**Profile Length (km)**	**Numbered Bodies Along Profile**
Profile AA′	NNW-SSE	100	1, 2 and 3
Profile BB′	NW-SE	103	1, 4, 8 and 5
Profile CC′	SSW-NNE	88	7, 4 and 2
Profile DD′	NE-SE	116	7, 5
Profile EE′	NN-SS	88	9 and 10

6.0 Modeling and Interpretation

Ten major contour closures depicting the residual anomalies are numbered 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11 and shown in Figure 3. For quantitative interpretation, straight line model profiles AA′, BB′, CC′, DD′ and EE′ were chosen, each on the criteria that

(i) it crossed the major residual anomalies as well as many contour closures of interest in the area

(ii) it has observed data points throughout or almost throughout the length of the profile.

(iii) it intersects anomalies perpendicular to their strikes.

Five residual profiles, AA′, BB′, CC′, DD′ and EE′ (Figure3) were quantitatively modeled and interpreted for the major granitic bodies and the surrounding schists.

Forward modelling involves creating a hypothetical geologic model and calculating the geophysical response to that earth model. A program that enables intuitive, interactive manipulation of the geologic model and real-time calculation of the gravity response was used. The methods used to calculate the gravity response are based on methods of Talwani et al [2] and Talwani and Heirtzler[3] and make use of the algorithms described in Won and Bevis[19].Two and the half dimensional calculations are based on Rasmussen and Pedersen [20]. Plausible models with computed anomalies which fit the observed residuals reasonably well for each of the profiles are shown in Figures 4.1, 4.2, 4.3, 4.4 and 4.5

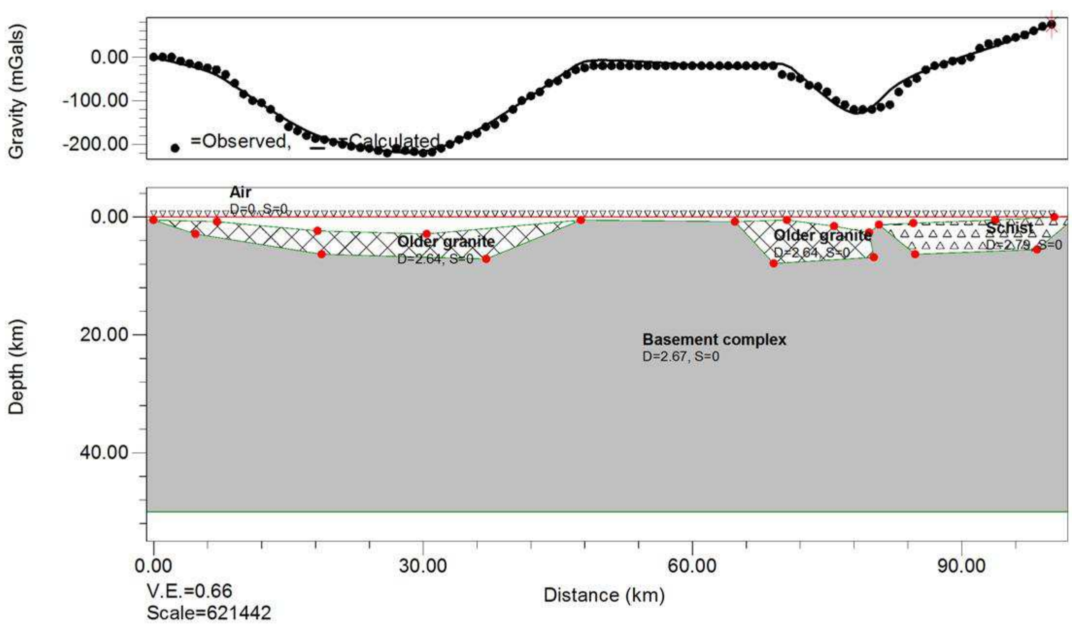

Figure 4.1: Two and half dimensional model of resdual anomaly along profile AA’

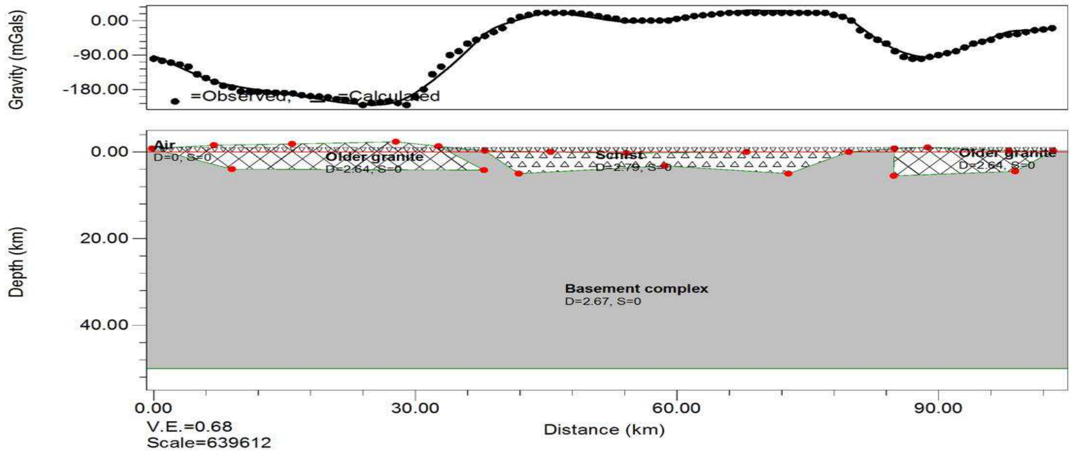

Figure 4.2: Two and half dimensional model of resdual anomaly along profile BB'

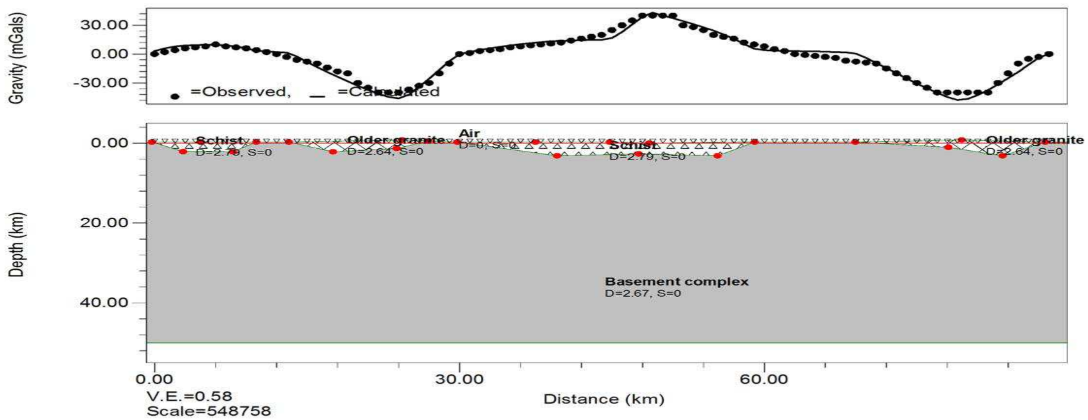

Figure 4.3: Two and half dimensional model of resdual anomaly along profile CC'

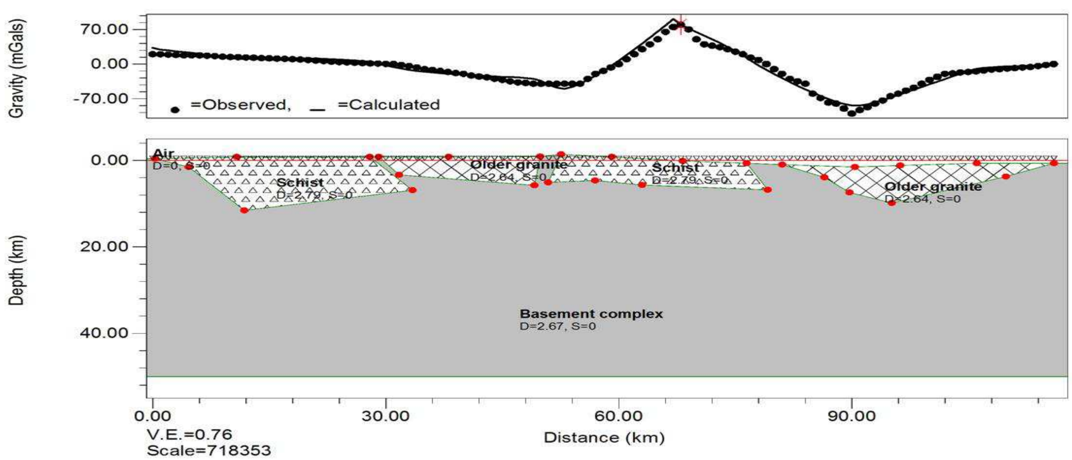

Figure 4.4: Two and half dimensional model of resdual anomaly along profile DD'

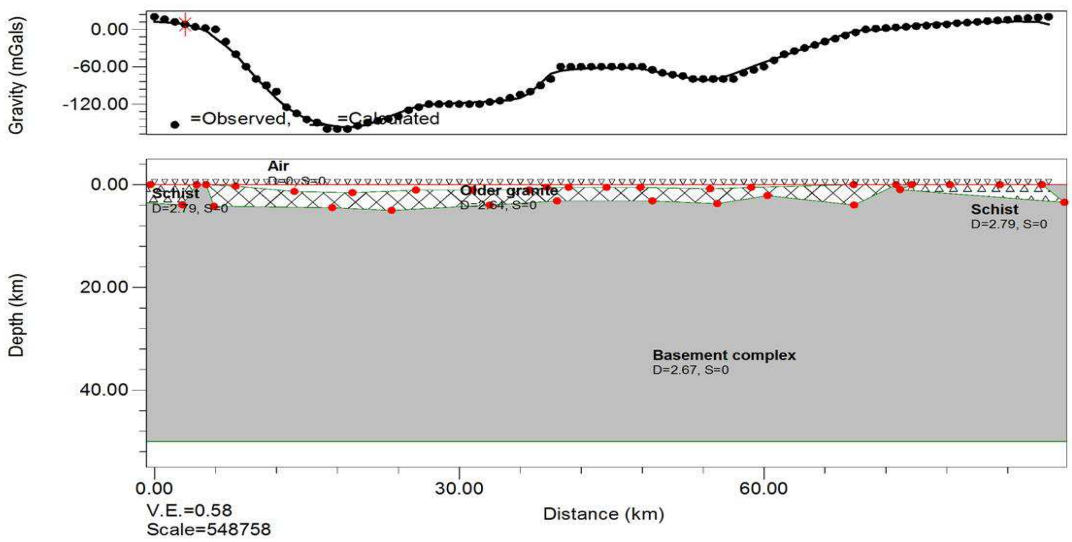

Figure 4.5: Two and half dimensional model of resdual anomaly along profile EE'

6.1 Depths Estimation From Earth's Surface

Tables 2.1 – 2.5 give the summary of rock types and their estimated depths from the surface of the earth along the profiles. The lateral extents can easily be estimated from the models. In tables 2.3 and 2.5, the schist bodies without identification numbers extend beyond area data coverage and so not much can be say about them.

Table 2.1: Anomaly I.Ds, rock type and estimated depths along profile AA′

Anomaly I.D No	1	2	3
Rock Type	Older Granite	Older Granite	Schist
Depth (km)	5	5	4

Table 2.2: Anomaly I.Ds, rock type and estimated depths along profile BB′

I.D No	1	4	5
Rock Type	Older Granite	Schist	Older Granite
Depth (km)	7	5	5

Table2. 3: Anomaly I.Ds, rock type and estimated depths along profile CC′

I.D No	-	7	4	2
Rock Type	Schist	Older Granite	Schist	Older Granite
Depth (km)	-	3	4	4

Table 2.4: Anomaly I.Ds, rock type and estimated depths along profile DD′

I.D No	7	4&8	5
Rock Type	Older Granite	Schist	Older Granite
Depth (km)	6	6	4

Table 2.5: Anomaly I.Ds, rock type and estimated depths along profile EE′

I.D No	-	9 & 10	-
Rock Type	Schist	Older Granite	Schist
Depth (km)	-	6	-

7.0 Discussion and Conclusion

The nonuniqueness of the 3D vector gravity potential and theuniqueness in the calculated gravity anomaly make it possible to selecta form of the 3D vector gravity potential as simple as possible toconvert the 3D volume integral to 2D area integrals. This vector-gravity-potential and line-integral method was applied togravity data collected to produce possible plausible models.In producing the models, it was assumed that the granites outcrop at their roof zones, hence the presence of root plugs in the modeled granite bodies. The models suggest that the magma might have risen through weak zones of the country for about the various lengths before spreading to their present widths possibly due to changes in temperature, pressure and other conditions near the surfaces**.** In general, the models show that the bodies have steeply dipping contacts with one another and the host rock. The high dips and sharp contacts of the granites with other surrounding rocks suggest that magmatic stoping might be the most likely probable mode of emplacement of the granites which must have later been drawn out and localized through the weak zones in the host gneiss .

Depths estimates obtained are comparable with results obtained in similar environment in other parts of the world. For example, Bott[21], showed that the Bodmin Moore granite, southwest England has a maximum thickness of 12 km. Brisbin and Green [22], showed that the Aulneau batholith, Canada has a depth of 6 km over the area it covers while in two regions, two plugs extend to depths of between 7 and 12 km. Previous geophysical study have been carried out in some parts of, near or adjacent the present area. Ojo and Ajakaiye[23],carried out a regional gravity survey with the middle Niger Basin (Nupe Basin), which extended to the southeastern part of the study area.

The main conclusions are:

(1) the study area in northwestern Nigeria is characterized by large negative Bouguer anomalies ranging from -34 mGal in the southeastern part to -220 mGal in the northeastern part. A regional gradient of 0.243 mGal/km in northeastern could be said to be due to a thinning of the crust in that direction.

(2) the positive and negative anomalies correlate with schists with high density of 2.78 x 10^3 kg/m^3 and granites with low density of 2.64 x 10^3 kg/m^3 respectively.

(3) the sharp contacts between the granites and the schists show that such contacts are possibly faulted. Also, sharp contact relations between the granites and the host gneiss support the suggestion of magmatic stoping as mode of their emplacement.

(4) the lack of high positive Bouguer anomalies over the schists in the area confirms the geological evidence for the Nigerian schist belts with Algoma type banded iron formations having evolved in an ensialic environment and are Eburnean in age.

(5) Gravity investigation seems so far the only geophysical method that has given reliable and consistent information on the sub-surface extent of the plutons in Northwestern Nigeria.

8.0 Recommendation

It is recommended that, there is need for the Federal Survey Department to update the available road maps and the Geological Survey of Nigeria to update geological maps of the basement complex in order to enhance accuracy in correlation of geophysical and geological studies in the country. Comprehensive geophysical surveys covering northwestern Nigeria and the entire Nigerian basement complex generally should be carried out. Magnetic, V.L.F and Seismic refraction methods of survey will greatly complement the aims and objectives of this gravity research in this very important economic region. Emphasis should be given to delineation of the Older Granite bodies, the schists and fault zones which are possible entrapments of economic minerals normally associated with schists occurrence. Intensive and accurate density and susceptibility studies of rocks in the schists area is also recommended for successful various geophysical interpretations. Most of geophysical work carried out so far concentrated over the schist belts associated with the Kalagai-Zungeru-Ifewara (KZI) fault. It is recommended that comprehensive geophysical work should be carried out over the schist belts associated with the Anka-Yauri-Iseyin (AYI) fault. This will enhance understanding of the evolutionary models of the Nigerian schist belts classify as ensialic for those associated with KZI fault and ensimatic for those associated with the AYI fault.

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