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The gravity field and gravity data reduction across the continental area of Nigeria

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ABSTRACT

This research presents the variation of the gravity field and associated gravity field components over the continental area of Nigeria to provide data for geoscience research, geodetic and engineering works, aerodynamic studies and deep crustal inferences. Accurate positions and elevations were observed at 58 of the 59 base stations of the Primary Gravity Network of Nigeria (PGNN), whose absolute gravity values had been accurately determined. The absolute gravity values were plotted against their respective positions to reveal the distribution pattern and strength of the gravity field within the study area. Theoretical gravity values at each base station were generated using the Somigliana's equation. The free-air gravity and free-air anomaly gravity values were generated with respect to the World Geodetic System 1984 (WGS84) ellipsoid using GPS-derived elevation data. Then, the perturbing potential, free-air gravity with respect to the geoid, and the indirect effects were evaluated. The average of the indirect effects was used to adjust the WGS84 gravity formula to produce a gravity formula that better approximates the geoid across the continental area of Nigeria, compatible with the heights measured relative to the geoid, which can serve as a reference for establishing a vertical height control. The Bouguer gravity and Bouguer gravity anomalies across Nigeria revealed a “trans-southern gravity high strip” interpreted to be associated with mantle upwelling. Two new major mega-lineaments related to mantle upwelling were mapped. A batholith province trending NW–SE was delineated, occurring from north central Nigeria to the north western region and containing closures of “Bouguer gravity lows” interpreted as batholiths. A separate closure of “Bouguer gravity low” was detected at Azare, north eastern Nigeria, which may be due to the presence of intrusive granitic body. It is recommended that the mantle structure beneath “the trans-southern gravity high strip”, “delineated batholith province” and “isolated gravity closures” around the northeast of Nigeria should be studied from seismic shear wave splitting analysis for better understanding of the deep lithospheric structures and moho relief.

1. Introduction

The Earth's gravity field, which is the vector sum of the gravitational and centrifugal fields, is one of the inherent physical properties of the Earth. Other properties include the geomagnetism, heat flow and spontaneous potential. Though the gravity field is considered passive, it plays a significant role in the stability of bodies. Due to the fact that the Earth is continually rotating and not homogeneous, the strength of the gravity field at the Earth's surface is not uniform but varies from place to place. Knowledge of gravity field variations within a territory is important in various aspects of life and civilisation. Some of these aspects include accurate projection and ranging of objects and missiles, determination of subsurface density distribution, regional geologic mapping and tectonic evolution studies, physical geodesy, earthquake studies, and volcanic eruption monitoring and prediction.

All these listed applications of the knowledge of gravity field variation over a region make gravity data useful for geoscience, aerodynamic and geodetic applications, and their availability becomes highly relevant in the development of the country's

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economic framework [1]. This research presents the gravity field variation and gravity data reduction over the continental area of Nigeria. These include the theoretical gravity with respect to the WGS84 ellipsoid, determined absolute gravity, latitude-corrected absolute gravity, elevation above the WGS84 ellipsoid, free-air gravity with respect to the WGS84 ellipsoid, free-air gravity anomaly with respect to the WGS84 and the perturbing potential with respect to the WGS84 ellipsoid. The study also presents the heights above the geoid (orthometric height), free-air gravity with respect to the geoid, and the difference between the free-air gravity with respect to the WGS84 ellipsoid and the free-air gravity with respect to the geoid, which is also known as the indirect effect. The average of this indirect effect is used to adjust the WGS84 theoretical gravity formula. The adjusted formula gives the theoretical gravity values which are about the same as the expected values on the geoid. It is also compatible with height above the geoid for the computation of gravity anomalies. Free-air gravity anomaly with respect to the geoid is subsequently computed.

The data obtained from the WGS84 datum (ellipsoid) and the geoid across the continental area of Nigeria were compared and interpreted for deductions. It is observed from the analysis of the data that if a height datum chosen for gravity data reduction the corresponding gravity formula was adopted in evaluating the theoretical gravity, the resulting gravity and gravity anomaly field values will be independent of the used datum.

The study area is the whole continental area of Nigeria, which covers from longitude 3°E to 15°E and latitude 4°N to 14°N (Fig. 1). It is bounded by the Benin Republic to the West, Niger Republic to the North, Chad to the Northeast, Cameroon to the East and the Gulf of Guinea to the South. The zone belongs to the West African subregion and is close to the Equatorial African region. It covers an area of 923,768 km^2. The region consists of 13 major geologic provinces, six of which constitute the basement complex terrains (i.e., Southwestern basement complex, Younger metasediments, Older metasediments, Younger granites ring complex, North–central basement, and the Volcanic rock regions of northeastern Nigeria) and the remaining seven (i.e., the Benue trough, Bornu basin, Sokoto basin, Mid-Niger basin, Dahomey basin, the Niger delta, and the Calabar flank) constitute the sedimentary terrains [2–5].

The basement rocks of western and north–central Nigeria are part of the West African Craton, and the age of them ranges from Precambrian to Cambrian [6]. However, they were reworked by the Pan-African thermo-tectonic orogenic event (known as the Pan-African Orogeny) about 600 Ma ago. A region within the north–central basement complex, consisting of predominantly polymetamorphic Migmatite–Gneiss complex, was intruded by Jurassic granites called Younger Granites [7]. Such granitic intrusions are prominent in Jos and Daura, and they are known to extend about 1300 km northward to the Niger republic [6]. Volcanic and intrusive rocks of late Cretaceous to early Tertiary also occur as part of the basement rocks in the eastern half of Nigeria [6]. The Biu basalt is a prominent unit within the volcanic rock region.

It has been proposed that the sedimentary basins have developed from the inland extension of the faults that developed during the opening of the Central Equatorial Atlantic ocean in the process of the separation of South America from Africa [8]. All the sedimentary basins were formed during the Cretaceous except the Niger delta basin that was formed during the Tertiary [9–14].

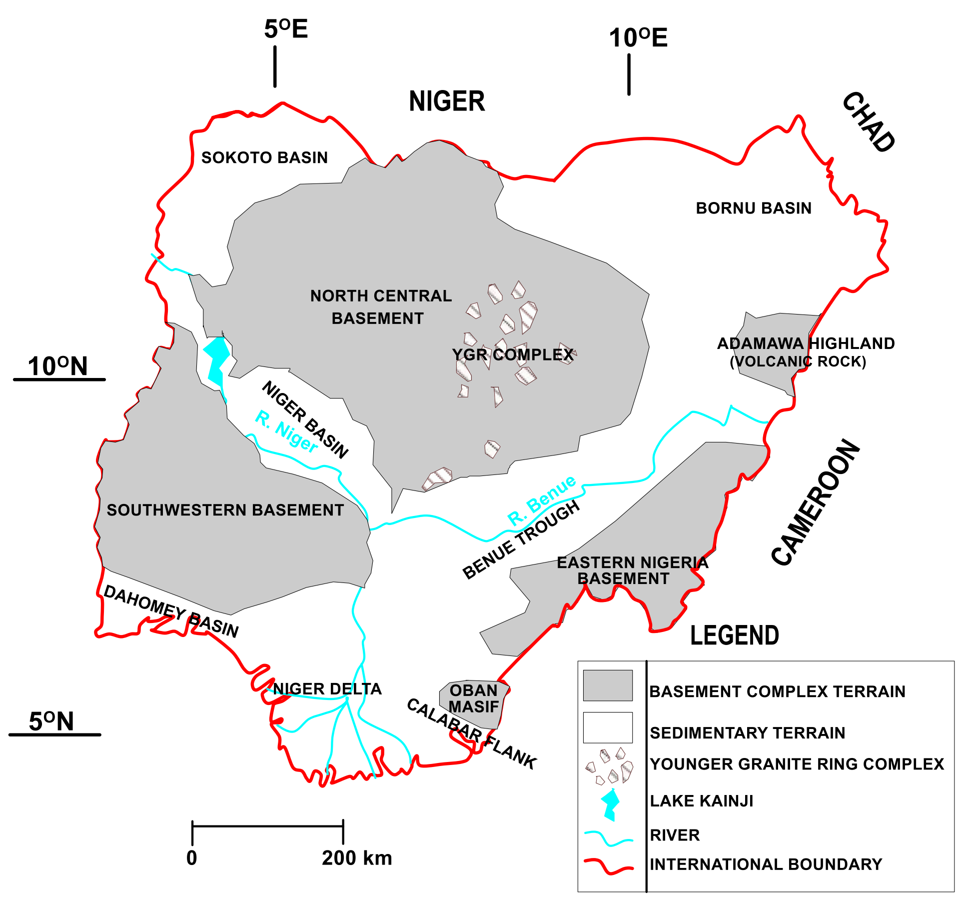

Fig. 1. Geologic map of Nigeria.

2. Method

2.1. The data

The basic datasets used are the evenly distributed absolute gravity data and their corresponding positions and elevations above the WGS84 ellipsoid and geoid. The absolute gravity values are from the comprehensive Primary Gravity Network of Nigeria (PGNN) established by Osazuwa [15], with a total of 59 evenly distributed gravity stations spread across the continental area of Nigeria (Fig. 2). To establish the PGNN (between 1979 and 1983), Osazuwa took precise relative gravity measurements at the 59 stations using LaCoste-Romberg (LCR) gravimeters (models G446, G464 and G468) to determine the relative gravity at each station [16]. Measurements in the gravity network produced 165 links, 111 well-structured triangular loops, and four other loops with sides greater than three. The network covered a gravity field range of 376.948 mGal, which is the largest gravity difference within the continental area of Nigeria. The precision of the PGNN is 0.035 mGal [15]. The network is tied to the IGSN via the IGSN base station in Kano, Nigeria [17]. Standard errors of all stations are shown in appendix. Network adjustment utilized the computer program by Strang van Hees [18]. To establish the gravity network, series of adjustments were carried out on the PGNN, such as using data from the LCR G446 gravimeter, LCR G464 gravimeter and LCR 468 gravimeter for adjustment, using data from the calibration line bases and all the gravimeters during air ties for correction, and using all the gravimeters combined for adjustment. To ensure homogeneity and symmetry in measurements, at least two ties in opposite directions were made along each link.

The positions and elevations at 58 of the 59 stations were recorded using the "Spectra Precision Mobilemapper 20 GIS" differential global positioning system (DGPS). One of the base stations (the station at Daki-Takwas) was not accessible due to security issues. At all 59 stations, the absolute values of the gravity field have been accurately determined and corrected for drift and tidal effects. The network has been properly adjusted for closure errors [15]. With about 10% completeness, 70.6% symmetry and 91.9% homogeneity, the PGNN is one of the largest gravity networks in the world [19,20].

2.2. The latitude correction (g_L) computation

The natural increase of the gravity field towards the geographic poles is considered to constitute a bias to the magnitude of the observed gravity field for stations further north or south during gravity measurements, unless efforts are made to remove the bias. Gravity data free of this latitude-induced bias is called "latitude corrected" gravity data.

However, the issue of latitude correction (g_L) has to be handled carefully when reducing gravity data. For instance, when the data reduction aims to obtain the free-air gravity anomaly (δg_{FA}) or the Bouguer gravity anomaly (δg_B), no latitude correction is required since the computed theoretical gravity (g_o) already contains the latitude effect. Therefore, subtracting g_o from g_{obs} (observed gravity) will automatically make the obtained free-air anomaly or Bouguer anomaly free of latitude effect or bias (Eqs. (3) and (5)).

Since the magnitude of latitude bias contained in the g_o is the same as that in the g_{obs} field, the bias caused by the latitude will be automatically eliminated after subtracting the g_o from the g_{obs}. In other words, the obtained free-air gravity anomaly or Bouguer gravity anomaly data will automatically be free of latitude bias.

However, when computing the free-air gravity (g_{FA}) and Bouguer gravity (g_B), it is still important to apply the latitude correction to remove the bias of the increasing latitude since no theoretical gravity will be subtracted.

2.3. Formulas for theoretical gravity, free-air gravity, free-air gravity anomaly, simple bouguer gravity and simple bouguer gravity anomaly

According to Decker [21] and La Fehr and Nabighian [22], the WGS84 Somigliana's equation is as follows:

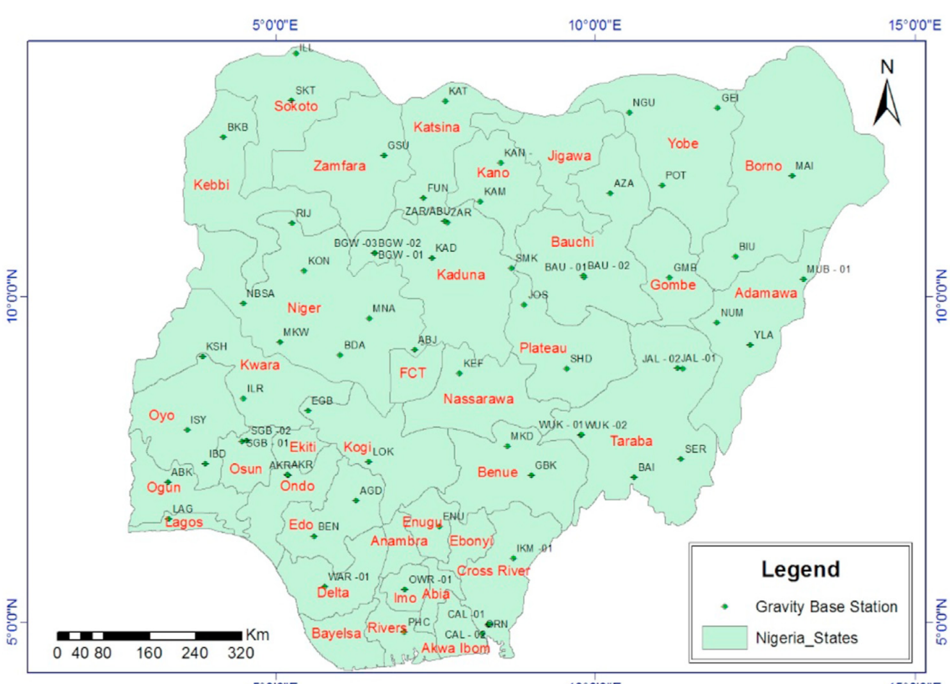

Fig. 2. Location of the gravity base stations.

$$g_o = 978032.53359\left[\frac{1+0.00193185265241\sin^2\theta_g}{\sqrt{1-0.00669437999014\sin^2\theta_g}}\right] \quad (1)$$

Eqs. (2)–(5) are the formulas for computing the free-air gravity, simple Bouguer gravity and gravity anomalies.

$$g_{FA} = (g_{obs} + g_L + \mathrm{FAC}) \quad (2)$$

$$\delta g_{FA} = (g_{obs} + \mathrm{FAC}) - g_o \quad (3)$$

$$g_B = (g_{obs} + g_L + \mathrm{FAC} - \mathrm{BC}) \quad (4)$$

$$\delta g_B = (g_{obs} + \mathrm{FAC} - \mathrm{BC}) - g_o \quad (5)$$

where g_o is theoretical gravity (WGS84), g_{FA} is free-air gravity, δg_{FA} is free-air gravity anomaly, g_{obs} is observed gravity, g_L is latitude correction, FAC is free-air correction, g_B is Bouguer gravity, δg_B is Bouguer gravity anomaly, BC is the Bouguer correction, and θ_g is geographic latitude. The unit of θ_g is degree, while the unit of other quantities is milligal (mGal). It should be noted that the calculated Bouguer gravity and Bouguer gravity anomaly are "simple Bouguer gravity" and "simple Bouguer gravity anomaly", since no topography correction is included. Eqs. (3) and (5) can be found in Telford et al. [23] and La Fehr and Nabighian [22].

2.4. Geoid undulation (N) and height above the geoid (H)

Geoid undulations (N) were computed at each gravity base station using the ELGRAM Software [24]. The software is an ellipsoidal gravity model manipulator that computes geoid undulations using the EGM96 gravity model. The accuracy of gravity anomalies is considered to be better than 0.1 mGal for models that are complete to at least the order of 360 in some places of the earth [24].

Heights above the geoid are computed by subtracting the geoid undulations from elevations above the WGS84 ellipsoid.

$$H = h - N \quad (6)$$

where h is the height of topography above the WGS84 ellipsoid (ellipsoidal height).

2.5. Geodetic and geophysical indirect effects

Gravity indirect effects consist of geodetic indirect effect and geophysical indirect effect. The geodetic indirect effect is the correction applied to the compensated geoid, which is derived from gravity anomalies upward or downward continued to the geoid [25,26]. Though in this research it was computed analytically by directly subtracting the free-air gravity values obtained using the height above the geoid from those obtained using height above the ellipsoid, the same values would have been obtained if the geodetic indirect effect was computed theoretically using Eq. (7).

$$\partial gd_{IE} = (0.3086)*N \quad (7)$$

where ∂gd_{IE} is the geodetic indirect effect, 0.3086 is the free-air gradient constant, and N is the geoid undulation.

On the other hand, geophysical indirect effect is the gravitational effect produced by the difference obtained when different vertical datums are used to specify the theoretical gravity, taking into account the gravity effect of mass between the datums and the topography [25]. It is given as:

$$\partial gp_{IE} = (0.3086 - 2\pi G\sigma)*N = 0.1976N \quad (8)$$

where ∂gp_{IE} is the geophysical indirect effect, 0.3086 is the free-air gradient constant, G is universal gravitation constant, σ is the density of the topographic mass (taken as 2670 kg m^{-3}), and N is the geoid undulation.

3. Results

3.1. Elevations above the WGS84 ellipsoid (h) and height above the geoid (H)

To determine the elevations required to reduce the gravity data, elevation above the WGS84 ellipsoid was measured at each gravity base station and interpolated within the continental area of Nigeria to generate the topographic (ellipsoidal height) map.

The heights above the geoid at base stations were computed according to Eq. (6) and interpolated within the continental area of Nigeria to obtain the map of heights above the geoid. The elevations above the WGS84 ellipsoid and heights above the geoid were presented in Figs. 3 and 4, respectively. The elevation was highest in the north central region and generally decreased southwards. The lowest elevation was observed at Warri base station (2.5 m above the ellipsoid, 16.38 m below the geoid) in the Niger delta region. The geoid undulation (N) used to compute the height above the geoid (H) is presented in Fig. 5.

3.2. Theoretical gravity distribution

Theoretical gravity is the magnitude of the gravity field strength obtained at a specific location if the earth were a perfect and uniform density rotating ellipsoid. If there is no anomalous mass below the ellipsoidal surface, the theoretical gravity value is usually taken as the value of gravity field (on the ellipsoidal surface). The flattening of the ellipsoid at the poles implies that the poles are closer to the earth's centre of gravity than the equator. Also, the earth's centrifugal acceleration is least at the poles but maximum at the equator. Due to the combination of these factors, theoretical gravity values are expected to increase towards the geographic poles. Fig. 6 shows the distribution of the theoretical gravity field across continental Nigeria landmass. As the southernmost base station, the minimum of the theoretical gravity field was obtained at Oron base station, and the maximum was obtained at Illela base station (the northernmost station). The difference between the maximum and minimum theoretical gravity field is 254.7876 mGal.

3.3. Drift corrected absolute gravity field

The determined absolute gravity values at 58 of the 59 gravity base stations were adopted to plot the absolute gravity distribution across Nigerian continent (Fig. 7). It should be noted that at this stage, no correction has been made to the gravity data except for drift correction, although the whole network has been adjusted for closure errors [15]. The maximum gravity value (978221.324 mGal) was observed at Illela base station, while the minimum value (977844.604 mGal) was observed at Jos base station.

3.4. Latitude-corrected absolute gravity values

Fig. 8 shows the distribution of the "latitude-corrected absolute gravity field" across Nigeria. The latitude-corrected absolute gravity value presents the gravity field at each base station without the drift (associated with the creeping of gravimeter spring and tides) and latitude increment bias effects. Thus, if the latitude

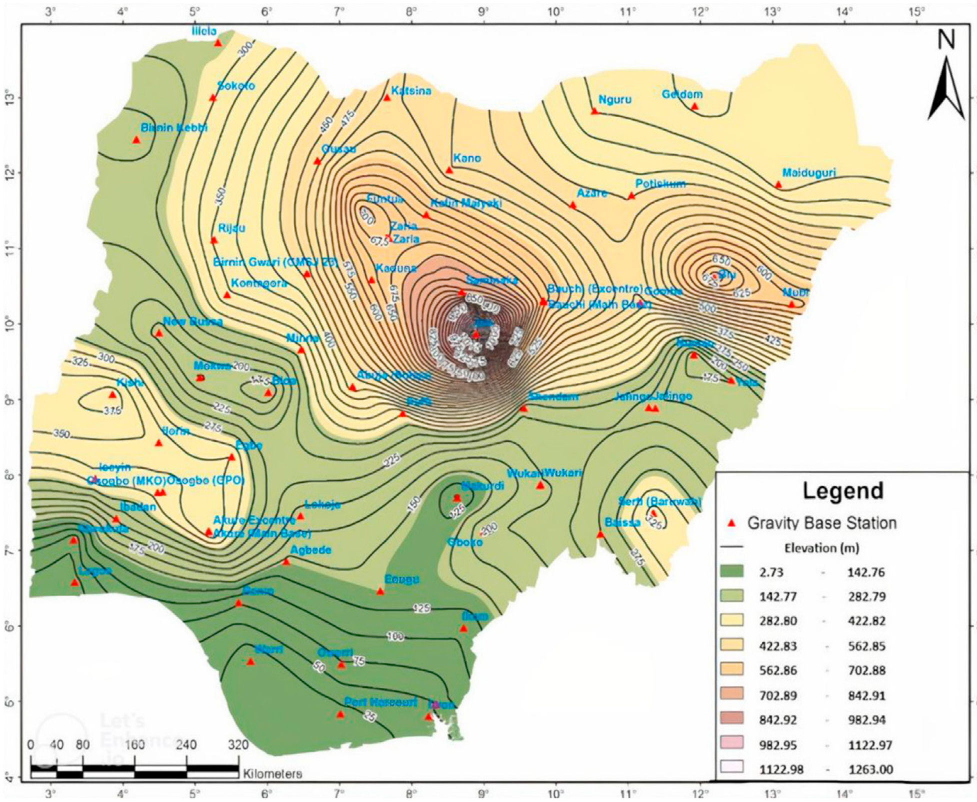

Fig. 3. Elevations above the WGS84 ellipsoid at the base stations.

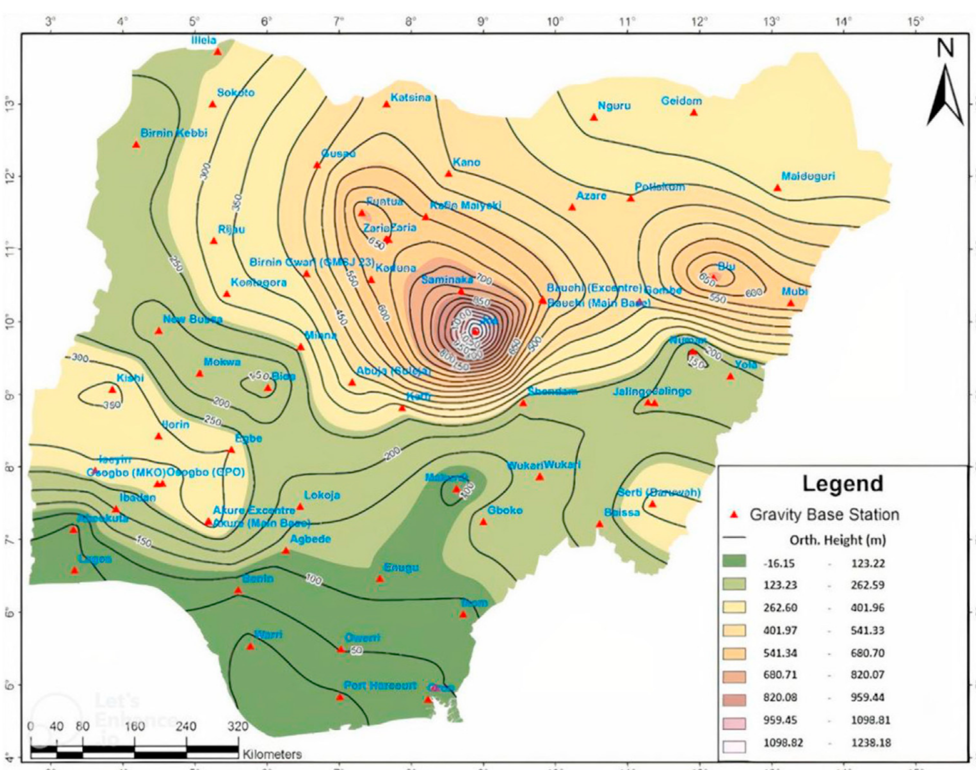

Fig. 4. Heights above the geoid at the base stations (Eq. (6)).

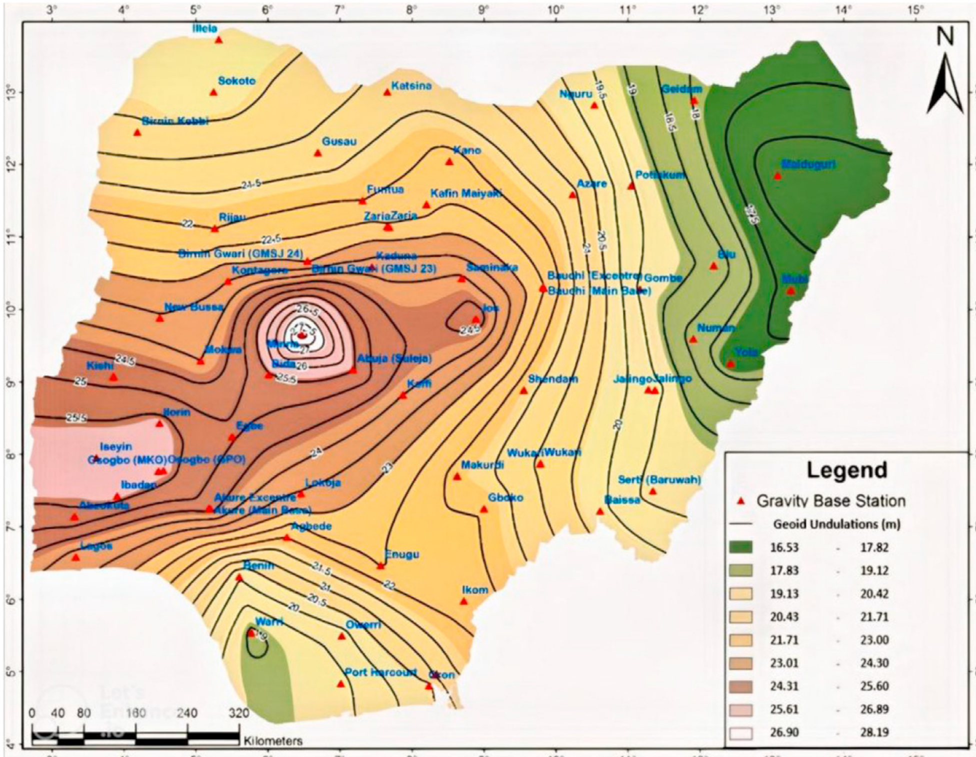

Fig. 5. Geoid Undulation across the Nigerian continent (Eq. (6)).

contribution to the gravity field is not desirable, it should be taken as the PGNN absolute gravity base value for any form of gravity survey (geophysical exploration and geodetic survey), to which further desirable corrections can be applied.

The minimum “latitude-corrected absolute gravity field” values were observed at Jos (977692.922 mGal), Saminaka (977818.406 mGal), Zaria (977837.494 mGal; 977838.567 mGal) and Biu (977844.146 mGal), which were places of high elevation

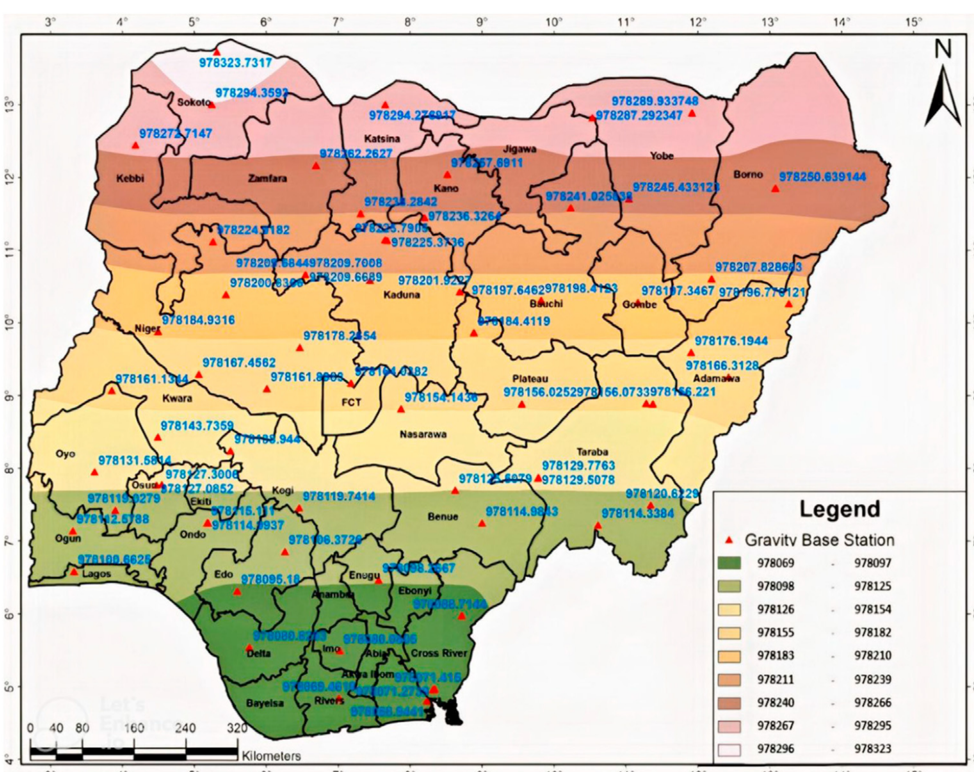

Fig. 6. Theoretical gravity distribution over the Nigerian continent.

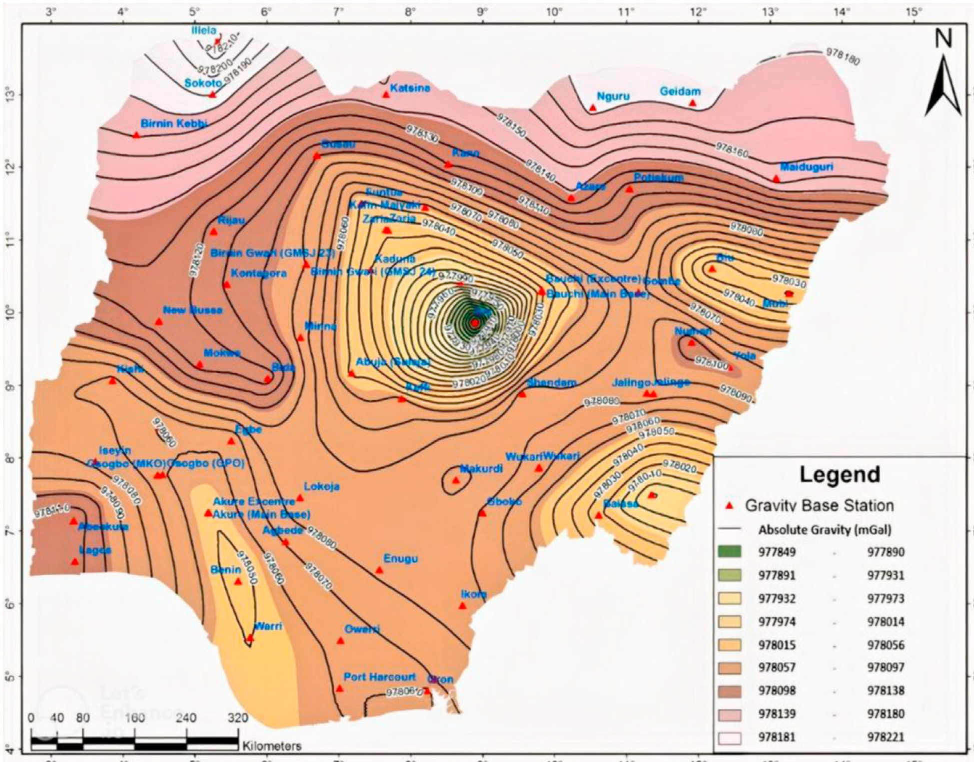

Fig. 7. Absolute gravity field across the Nigerian continent [15].

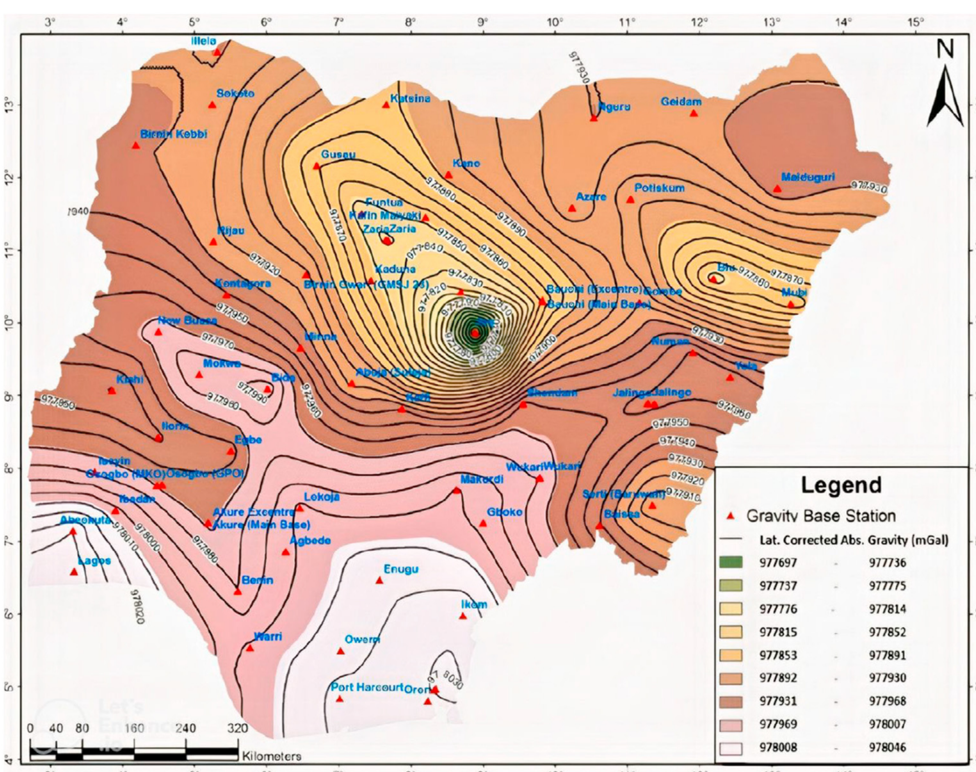

Fig. 8. Latitude-corrected absolute gravity field map of Nigeria.

situated in the basement complex environment. The maximum "latitude corrected absolute gravity field" values were observed at Lagos (978046.381 mGal), Abeokuta (978039.955 mGal), Calabar (978032.567 mGal; 978033.449 mGal), Ikom (978028.606 mGal), Port Harcourt (978024.025 mGal) and Oron (978021.213 mGal), all of which were situated in a sedimentary basin environment except for Abeokuta.

One interesting observation in the "latitude-corrected absolute gravity field" map is its indirect correlation with the topographic maps (maps of elevation above the WGS84 and height above the geoid), so the sedimentary terrains with relatively lower altitudes have higher "latitude-corrected" gravity values, while the basement complex areas with relatively higher altitudes have smaller "latitude-corrected" gravity values (Figs. 3, 4 and 8). The difference between the minimum and maximum observed latitude-corrected absolute gravity values is 353.46 mGal. Fig. 9 shows the value of gravity bias at each base station due to the increase in latitude when we move away from the equator towards the pole (North Pole).

3.5. The free-air gravity field and free-air gravity anomaly on the WGS84 ellipsoid

To evaluate the gravity field values on the WGS84 ellipsoid, the free-air correction was applied to the latitude-corrected absolute gravity field values to obtain the free-air gravity field (Fig. 10). The minimum free-air gravity field values were observed at Warri (978002.443 mGal), Birnin Kebbi (978002.535 mGal), Benin (978003.980 mGal), Serti (978004.455 mGal) and Numan (978009.523 mGal). Maximum values were observed at Jos (978088.547 mGal), Akure (978075.548 mGal, 978077.290 mGal), Iseyin (978075.125 mGal) and Ibadan (978074.129 mGal), all of which were basement complex areas.

The free-air gravity anomaly distribution was similar to the free-air gravity across the continental area of Nigeria (Fig. 11). The minimum free-air anomaly gravities were observed at Warri (−30.2358 mGal), Birnin Kebbi (−30.1671 mGal), Benin (−28.7002 mGal), Serti (−28.2341 mGal) and Numan (−23.165 mGal), while the maximum values were observed at Jos (55.81731 mGal), Akure (44.60687 mGal, 42.86535 mGal), Iseyin (42.44222 mGal) and Ibadan (41.44871 mGal). Free-air gravity anomaly values were negative at 18 of the 59 base stations. In these 18 base stations, 14 stations were situated within sedimentary terrains, and only four stations were in basement complex regions. The negative free-air anomaly implies that there is mass deficiency below the reference ellipsoid.

Figs. 10 and 11 show that both quantities (free-air gravity and free-air anomaly gravity) correlate with the topography of most stations (Figs. 3 and 4), with a few exceptions in places such as Azare, Minna, Gusau, Serti, Enugu and Ikom. This means that most of the stations are still under the influence of the topographic masses above the ellipsoid, though the effect is much more at some stations than others. It may also indicate an isostatic disequilibrium in the regions where the free-air gravity significantly correlates with the topography. The varying degree of the topographic mass effect at different stations can be plausible evidence for crustal heterogeneities, though crustal density heterogeneities can be better discussed with Bouguer gravities.

3.6. Disturbing potential (T) with respect to the WGS84 ellipsoid

The disturbing potential (T), also known as the perturbing potential, is a scalar quantity obtained as the difference between the gravity potential (W) and the theoretical gravity potential (U) at the same point in space, i.e., T (x_i, y_i, z_i) = W (x_i, y_i, z_i) − U (x_i, y_i, z_i),

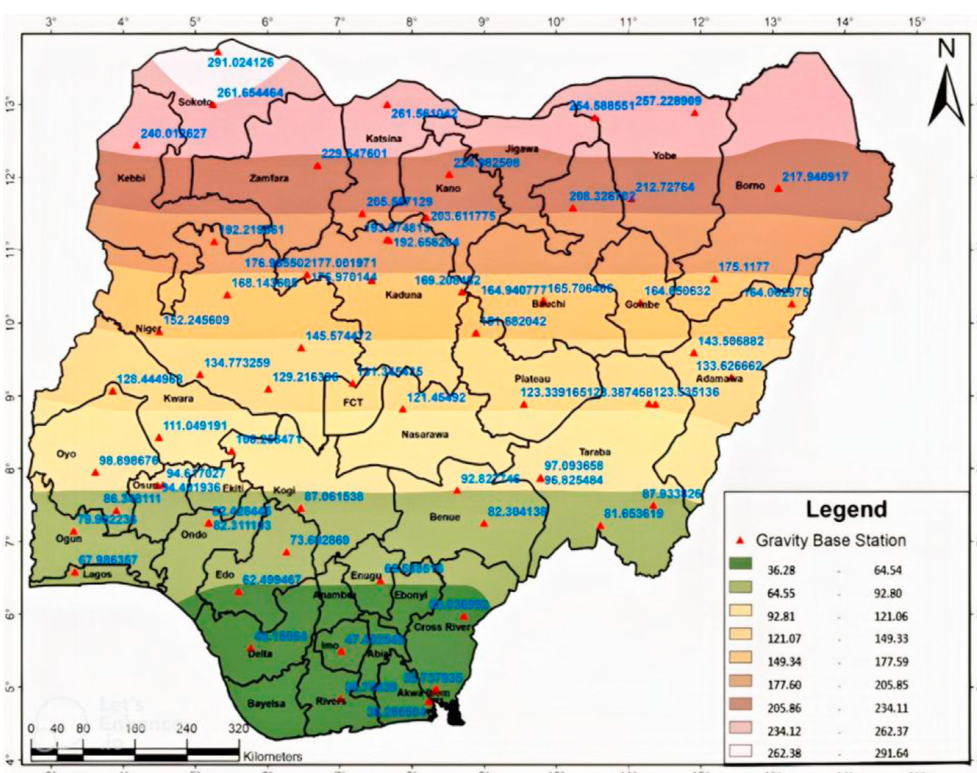

Fig. 9. The magnitude of latitude correction at each base station relative to the equator.

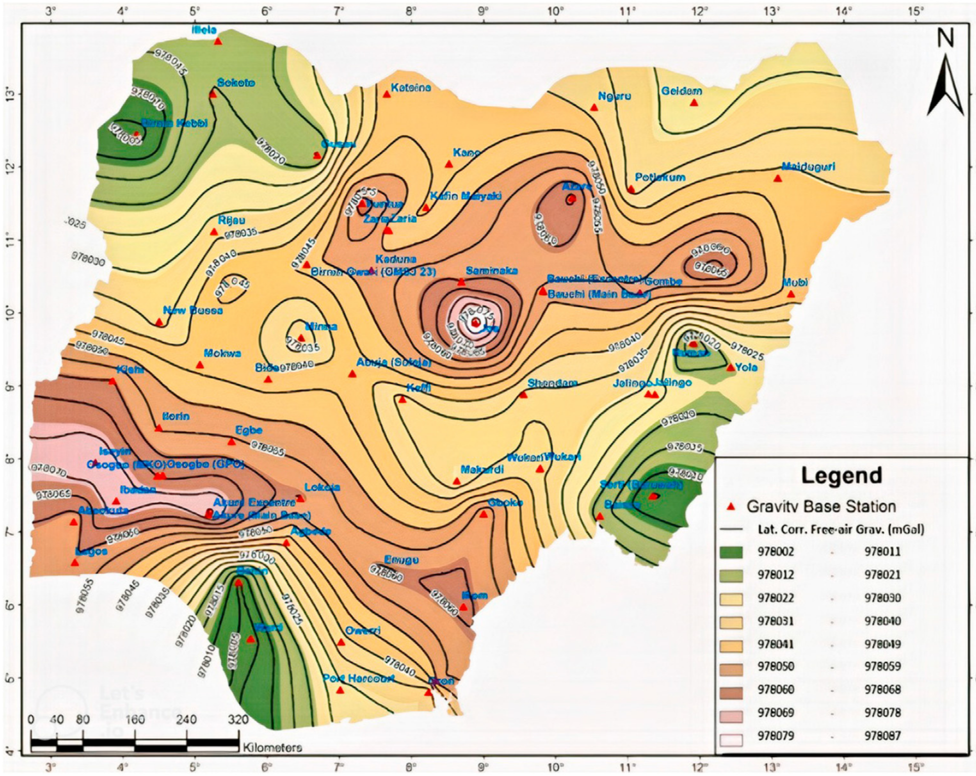

Fig. 10. Free-air gravity field with respect to the WGS84 Ellipsoid.

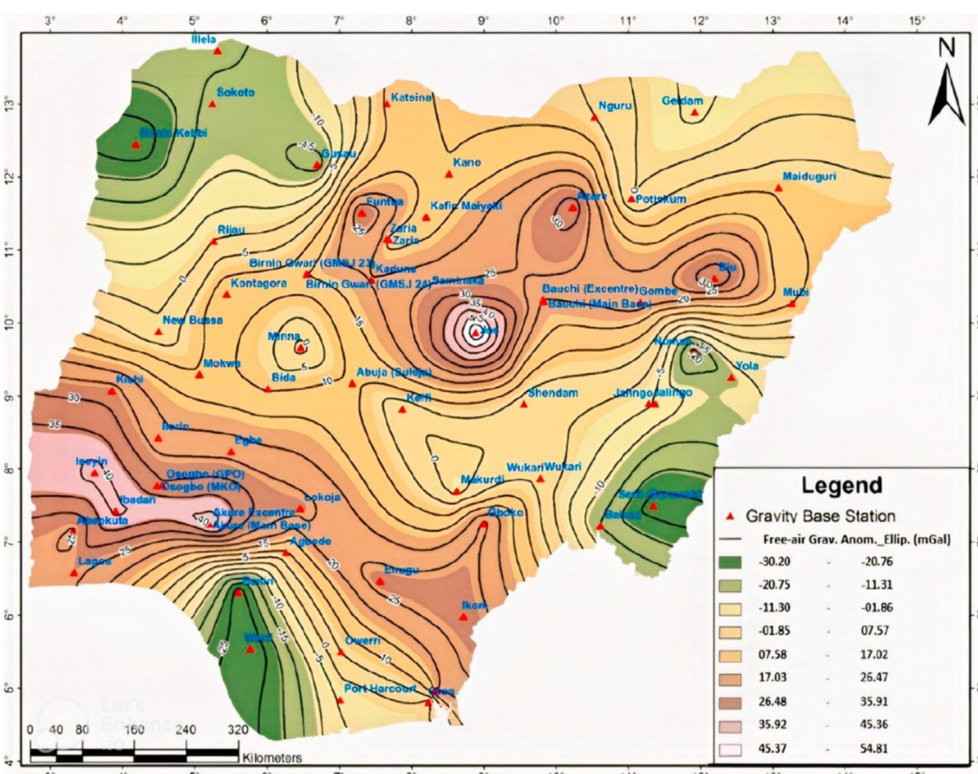

Fig. 11. Free-air gravity anomaly with respect to the WGS84 Ellipsoid.

where x_i, y_i, z_i are the cartesian coordinates of the point (Janák et al., 2010; Torge, W., 2012).

In other words, the perturbing potential (T) is the detected anomalous potential due to the difference between the measured gravity field and the gravity field of the reference ellipsoid (or datum) at the observation point on the top of the topography. It can be obtained from the gravity disturbance (Fig. 11) by integrating (integral calculus) the gravity disturbance at a point over the corresponding elevation. Fig. 12 shows the distribution of the perturbing potential over the Nigeria landmass.

The largest perturbing potential was observed over the younger granite province and environs (Jos: 0.715578 $m^2\ s^{-2}$; Funtua: 0.221956 $m^2\ s^{-2}$; Saminaka: 0.215301 $m^2\ s^{-2}$; Bauchi: 0.134523 $m^2\ s^{-2}$, 0.110654 $m^2\ s^{-2}$), Adamawa highland (Biu: 0.25757752 $m^2\ s^{-2}$) and some parts of the southwestern basement complex (Akure: 0.1588 $m^2\ s^{-2}$, 0.1496 $m^2\ s^{-2}$; Iseyin: 0.134117 $m^2\ s^{-2}$). The minimum values were observed at Serti (−0.09543 $m^2\ s^{-2}$), Gusau (−0.08417 $m^2\ s^{-2}$) and Birnin Kebbi (−0.06969 $m^2\ s^{-2}$).

3.7. Free-air gravity with respect to the geoid

New sets of free-air gravity values were computed at each gravity base station using the height above the geoid rather than the ellipsoidal heights referenced to the WGS84 ellipsoid. These free-air gravity values indicate the magnitude of the absolute gravity field on the geoid (Fig. 13). It should be noted that gravity works carried out in Nigeria used the ellipsoidal heights rather than leveled heights, the Somigliana's equation was used to generate the theoretical gravity, and the anomalies were computed with respect to the WGS84 ellipsoid. Since the ellipsoid lies some meters below the geoid, those anomalies may be overestimated.

For free-air gravities computed with respect to the geoid, peak values were obtained in Younger Granite Province, Adamawa Highland, Southwestern Basement Complex and the region around Oban Massif. The maxmum value was computed as 978080.8708 mGal at Jos and the minimum was 977996.1847 mGal at Birnin Kebbi.

3.8. Computation of indirect effects

3.8.1. Indirect effect due to the height datum difference (geodetic indirect effect)

Within the continental area of Nigeria, the geoid undulation is positive. This makes the observed free-air gravity on the geoid at each station less than the corresponding free-air gravity on the WGS84 ellipsoid since the geoid is above the ellipsoid. The difference between these free-air gravities observed on the WGS84 ellipsoid and the geoid is the indirect effect due to the height datum difference. Fig. 14 shows the computed indirect effect due to the height datum difference at each base station. It ranges from 5.10023 to 8.74948 mGal and has a mean value of 6.804217474 mGal.

3.8.2. Indirect effect due to combined height datum difference and gravity effect of mass (geophysical indirect effect)

Geophysical indirect effect is the gravitational effect produced by the difference between the datum and the topography when using different vertical datums to specify theoretical gravity with consideration of the gravity effect of mass. Within the study area, the indirect geophysical effect ranges from 3.266328 to 5.60196 mGal and has a mean value of 4.355553 mGal (Fig. 15).

3.8.3. Adjusting the theoretical gravity formula to enhance rapid computation of gravity disturbance

Gravity disturbance is the difference between the Earth's gravity and the normal gravity at the same point, while gravity anomaly is the difference between the Earth's gravity on the geoid and the normal gravity on the reference ellipsoid [27–29]. In simple terms,

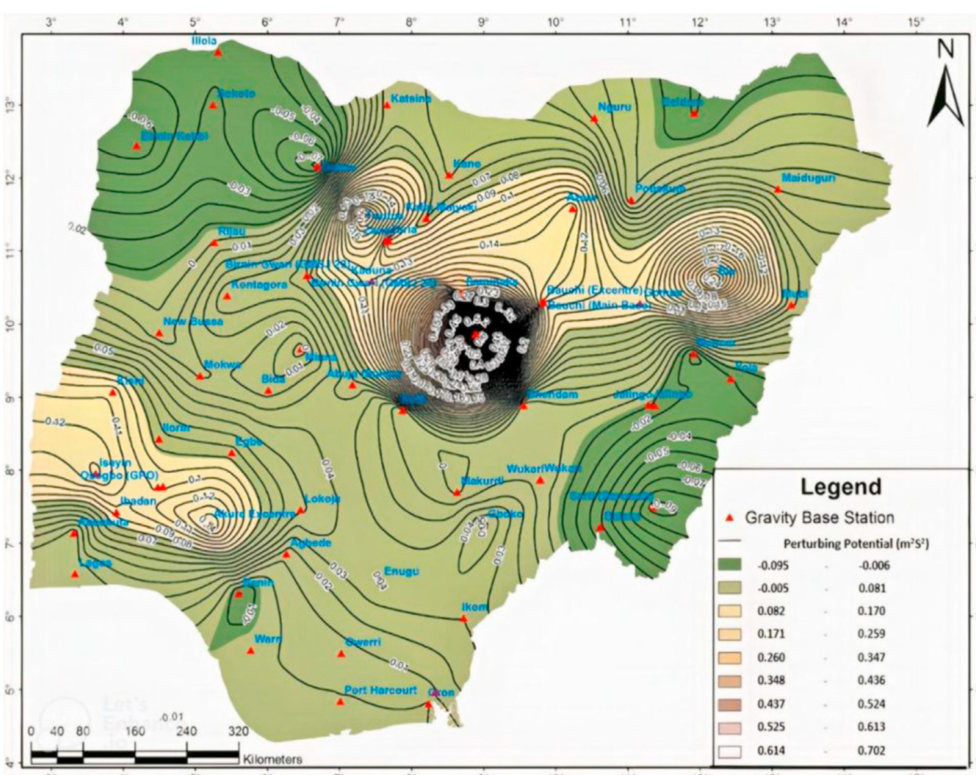

Fig. 12. Distribution of the disturbing potential with respect to the WGS84 ellipsoid.

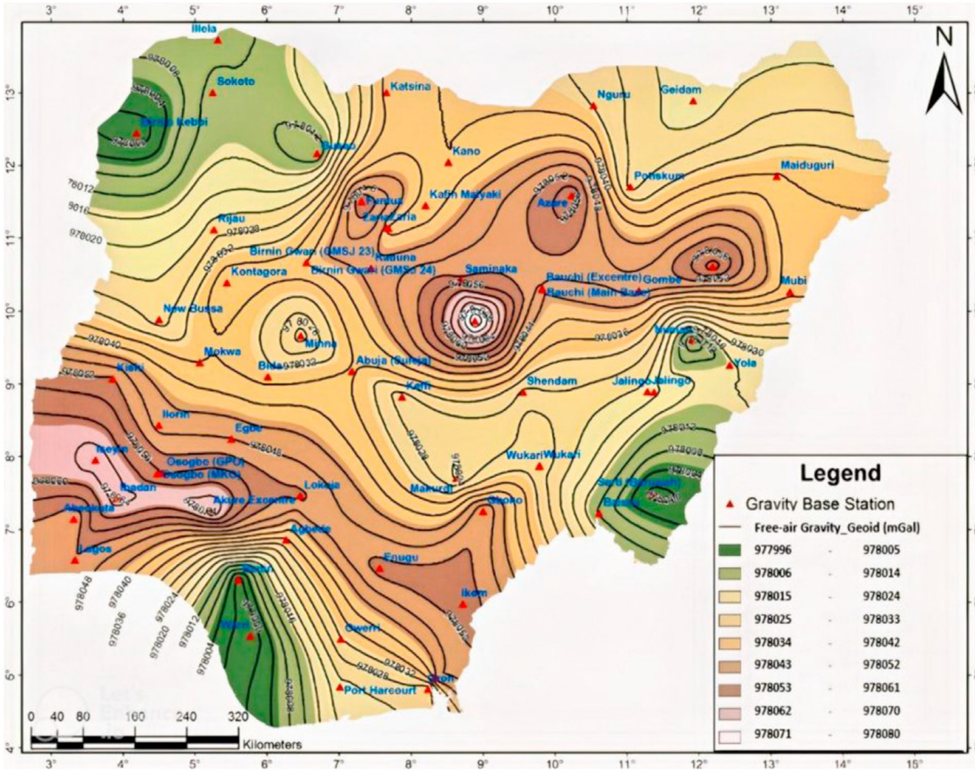

Fig. 13. Free-air gravity on the geoid.

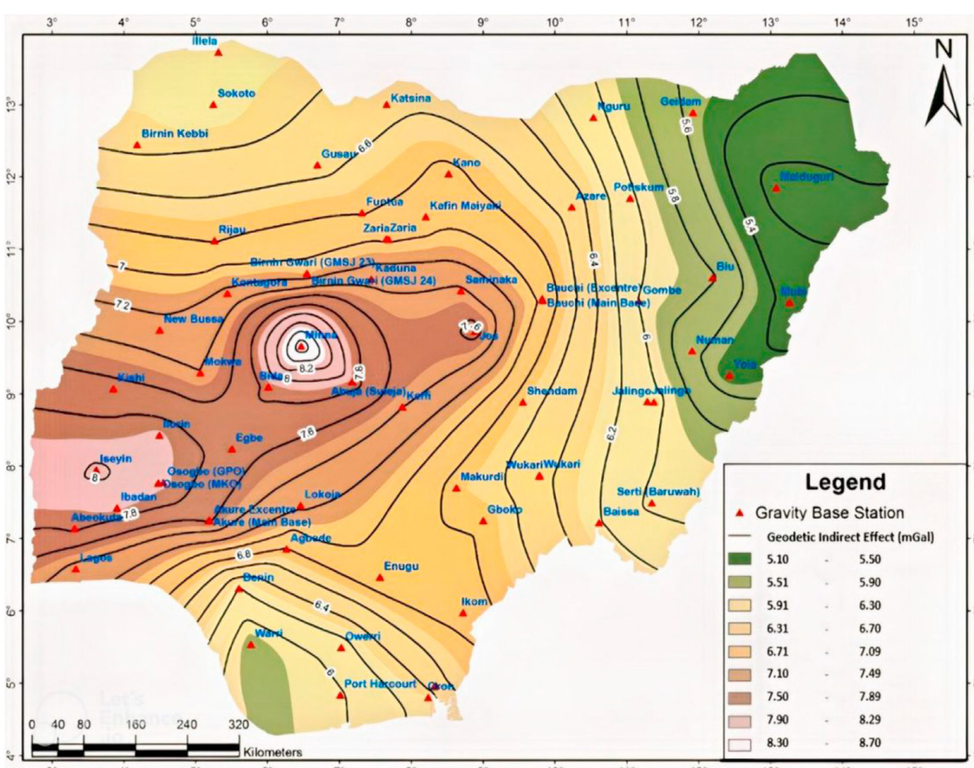

Fig. 14. Map of the geodetic indirect effect.

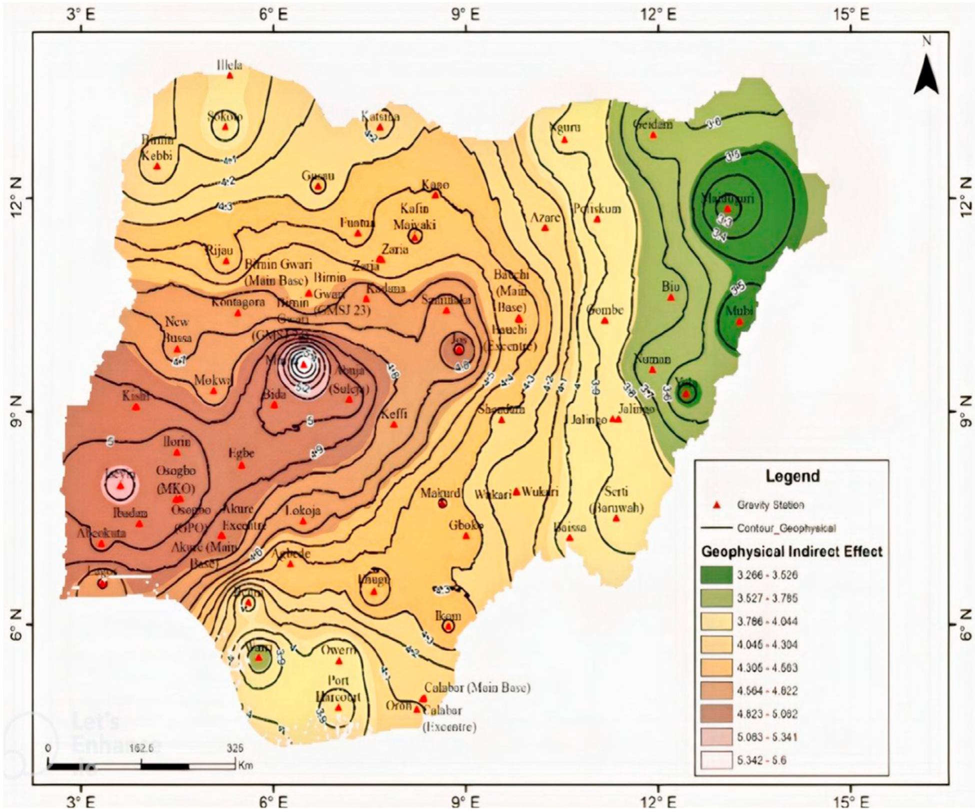

Fig. 15. Map of geophysical indirect effect.

gravity disturbance is obtained by computing gravity data reductions according to the chosen height datum, while the gravity anomaly is calculated by subtracting the gravity on the ellipsoidal surface (i.e., normal gravity) from the gravity on the geoid. The calculation of gravity disturbance is sometimes desirable because it is believed to be devoid of the centrifugal field due to the rotating Earth [27,29]. To enhance rapid computation of gravity disturbance, customised adjustment of the theoretical gravity formula (as a better fit for the Nigerian geoid together with orthometric heights, gravity disturbance of continental Nigeria can be rapidly evaluated without the geoid undulations) was done.

Ranging between 3.266328 and 5.60196 mGal, the variations of the geophysical indirect effect over the continental area of Nigeria were assumed to be negligible when compared with the range of the free-air anomaly at the regional scale framed by the PGNN. This means that it is safe to approximate the indirect effect by a constant value given by the mean of the variations to a reasonable extent.

Therefore, adjusting the theoretical WGS84 gravity formula to better fit the geoid across the Nigerian landmass so that the adjusted WGS84 formula can be correctly used in gravity data correction where only heights above the geoid (orthometric heights) are available, the mean of the geophysical indirect effect (evaluated as 4.355553 mGal) was subtracted from the WGS84 theoretical gravity formula. It should be noted that this method is expected to produce reliable results, although it may produce errors equivalent to the maximum variation of the average geophysical indirect effects (i.e., ±1.246 mGal).

Fig. 15 shows that the variation of the geophysical indirect effect is regional. The amplitudes are small, and the values are entirely positive, which provides confidence for the average approximation method (i.e., subtracting the average of the indirect effect from the WGS84 formula). A similar adjustment can be made to the WGS84 ellipsoid using the geodetic indirect effect computations. Since the geodetic indirect effect ranges from 5.10023 to 8.74948 mGal, the range and the mean of the computed geodetic indirect effect are 3.64925 mGal and 6.804217474 mGal, respectively (Section 3.9.1). To fit a better approximating ellipsoid than the WGS84 ellipsoid, an adjustment has to be made by subtracting the average value of the geodetic indirect effect (6.804217474 mGal) from the WGS84 theoretical gravity formula. The error of the results is expected to be within the range of ±1.945 mGal. Variations of geodetic indirect effect are regional in nature. The amplitudes are small and variations of geodetic indirect effect are entirely positive (Fig. 14).

Eqs. (9) and (10) show the adjusted theoretical gravity formula of the WGS84 is compatible with heights above the geoid for geophysical and geodetic applications, where computation does not go beyond free-air correction.

$$g_{a\_gph} = \left[978032.53359\left(\frac{1+0.00193185265241\sin^2\theta_g}{\sqrt{1-0.00669437999014\sin^2\theta_g}}\right)\right] - 4.355553 \tag{9}$$

$$g_{a\_gdt} = \left[978032.53359\left(\frac{1+0.00193185265241\sin^2\theta_g}{\sqrt{1-0.00669437999014\sin^2\theta_g}}\right)\right] - 6.804217474 \tag{10}$$

where g_{a_gph} is the adjusted WGS84 theoretical gravity for geophysical applications, g_{a_gdt} is the adjusted WGS84 theoretical gravity for geodetic applications, and θ_g is the geographic latitude. The unit of θ_g is degree, while the unit of g_{a_gph}/g_{a_gdt} is in milligal (mGal).

Appendix (Table 1) shows the adjusted WGS84 theoretical gravity values at each base station, which are applicable to the heights above the geoid for geophysical and geodetic applications. It should be noted that Equation (10) gives the value of theoretical gravity at any point on the geoid within Nigeria to a good approximation.

3.9. Free-air gravity anomalies on the geoid

The height above the geoid for free-air correction and the WGS84 theoretical gravity formula (Eq. (10)) corrected by geodetic indirect effect were used to calculate the free air gravity anomaly of all base stations. The results are shown in Fig. 16.

However, even though the free-air gravity anomaly in Fig. 11 was with respect to the WGS84 ellipsoid (i.e., computed using the height above the WGS84 ellipsoid and the WGS84 unmodified theoretical gravity equation), the two values were roughly the same when the free-air gravity anomaly was computed with respect to the geoid (Figs. 11 and 16). The maximum difference between the two values did not exceed ±1.9443 mGal.

Another critical observation from Fig. 16 is the pockets of free-air gravity anomalies centering on Funtua, Jos, Azare and Biu in the north–central and northeastern regions of Nigeria. Though these anomalies occur as local pockets, they seem to be connected regionally through a larger enclosure. The rock types within the coverage of this enclosure are different (the rock types of Funtua and Jos are mostly granite, Azare is underlain by Quaternary sediments of the Chad Formation, while the rock type in Biu is typically basalt). This indicates that the region is not a province of uniform rocks, rather a crustal zone of weakness that has been preferentially exploited by magmatic intrusions before the formation of sedimentary basin in the eastern part. Site dependence seismic spectra attenuation modeling can be used to determine the potential hazard that may be associated with the area as a zone of weakness. Deep lithospheric structure beneath this region can also be studied. Fig. 17 shows the map of the difference between the free-air gravity anomalies with respect to the WGS84 ellipsoid and the newly defined geoid.

3.10. Interpretation of the bouguer gravity anomalies

Figs. 18–21 show Bouguer gravity with respect to WGS84 Ellipsoid, Bouguer gravity with respect to the defined geoid, Bouguer gravity anomalies with respect to WGS84 Ellipsoid, and Bouguer gravity anomalies with respect to the defined geoid, respectively. The density adopted for the Bouguer slab is 2670 kg/m^3.

Generally, the northern part of Nigeria has relatively lower Bouguer gravities and Bouguer gravity anomalies compared to the southern part. This is because the northern region mostly consists of elevated uplands, while the southern region consists of less elevated regions and sedimentary basins. Notable Bouguer gravity anomalies include the "trans-southern gravity high strip" denoted as $TSGH_{STRIP,}$ which is an elongated strip of "gravity-high" traversing the whole of southern Nigeria. The Bouguer gravity values along this strip are mostly positive, ranging from 0 to 20 mGal, and reach peak values at the western and eastern ends. Being parallel and proximal to the coastline, this strip is considered as an expression of the disturbed crustal plates during the break-up of the African and South American plates. This strip is the widest at the southeastern part corresponding to the Anambra Basin and the lower part of the Benue Trough.

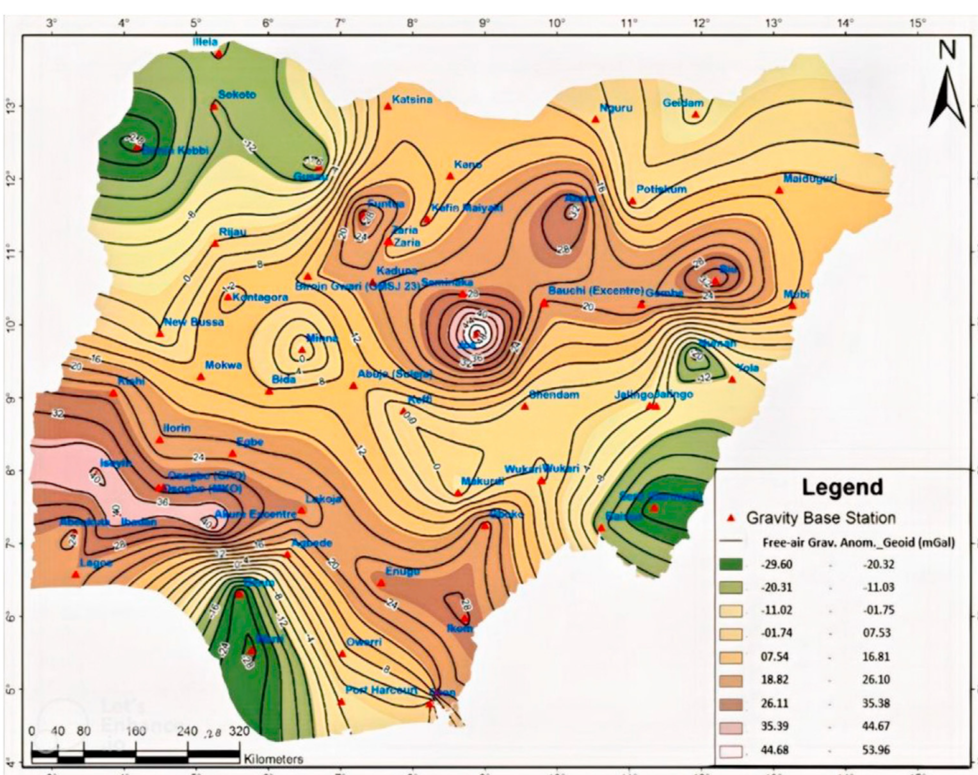

Fig. 16. Free-air gravity anomaly over continental Nigeria geoid.

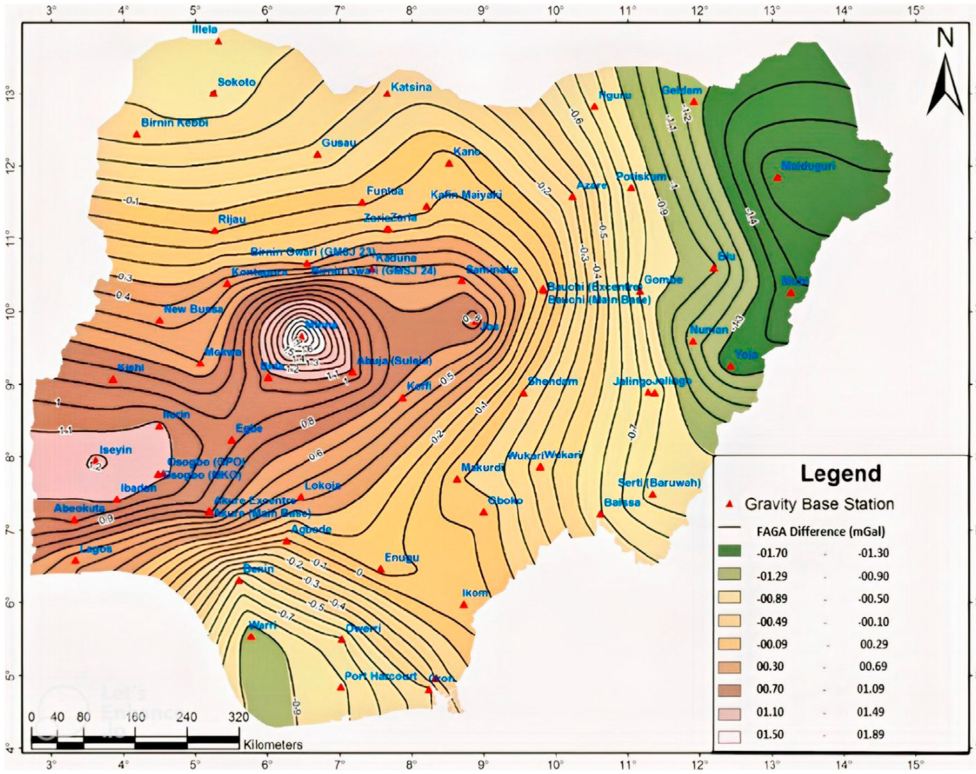

Fig. 17. Difference between free-air gravity anomalies with respect to the WGS84 ellipsoid and free-air gravity anomalies with respect to the geoid.

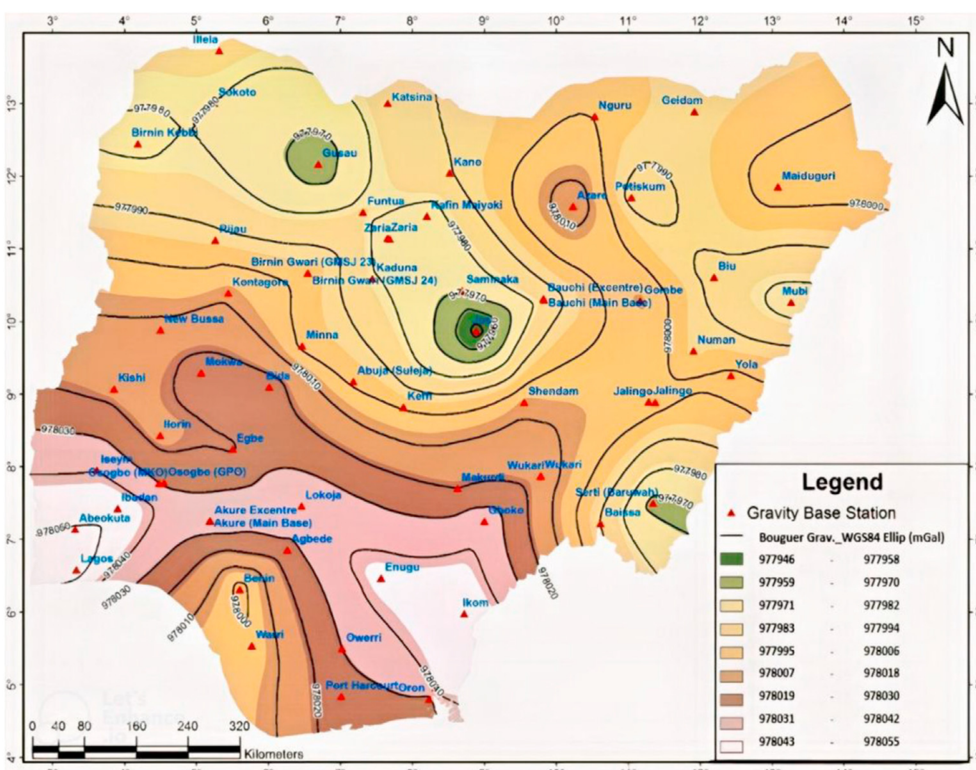

Fig. 18. Bouguer gravity values with respect to the WGS84 ellipsoid.

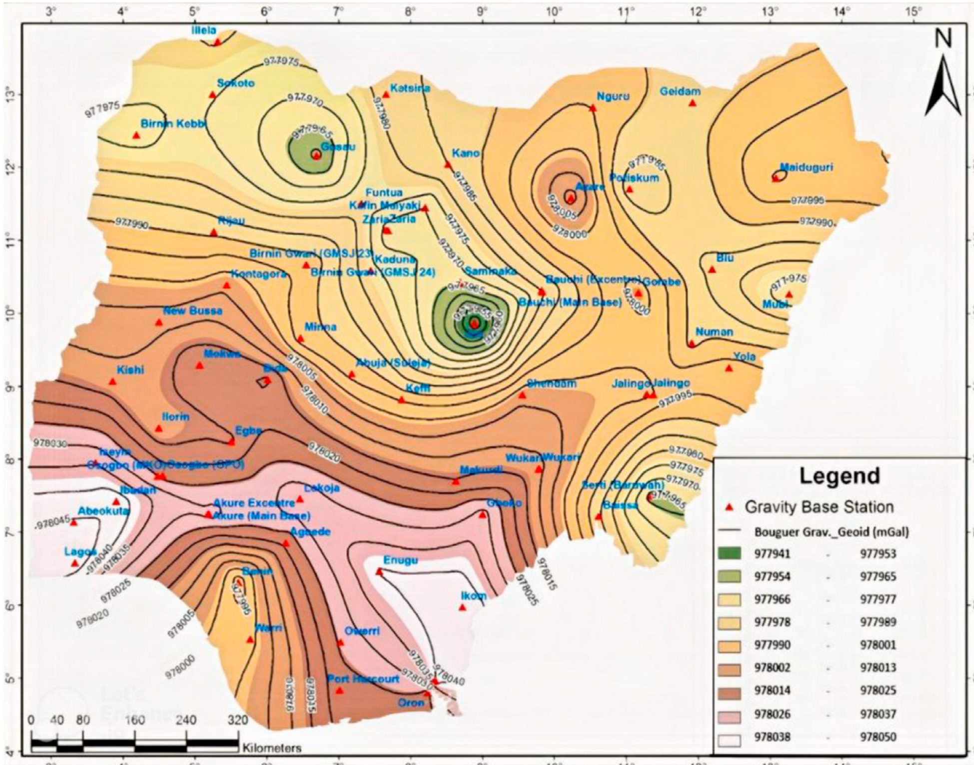

Fig. 19. Bouguer gravity values with respect to the geoid.

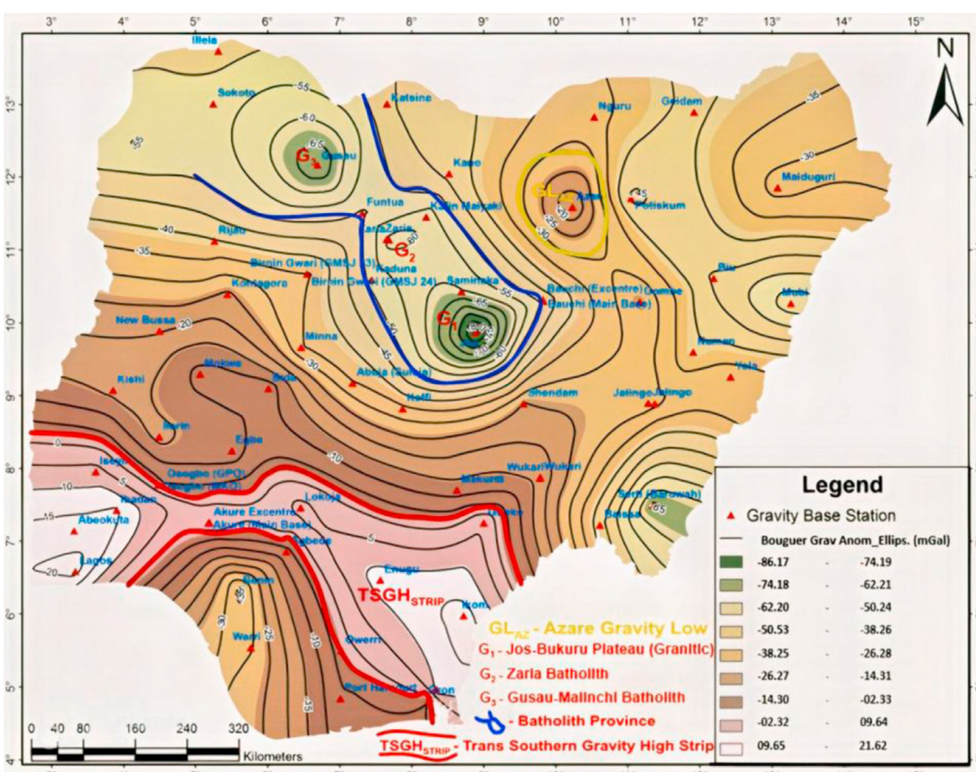

Fig. 20. Bouguer gravity anomaly values with respect to the WGS84 ellipsoid.

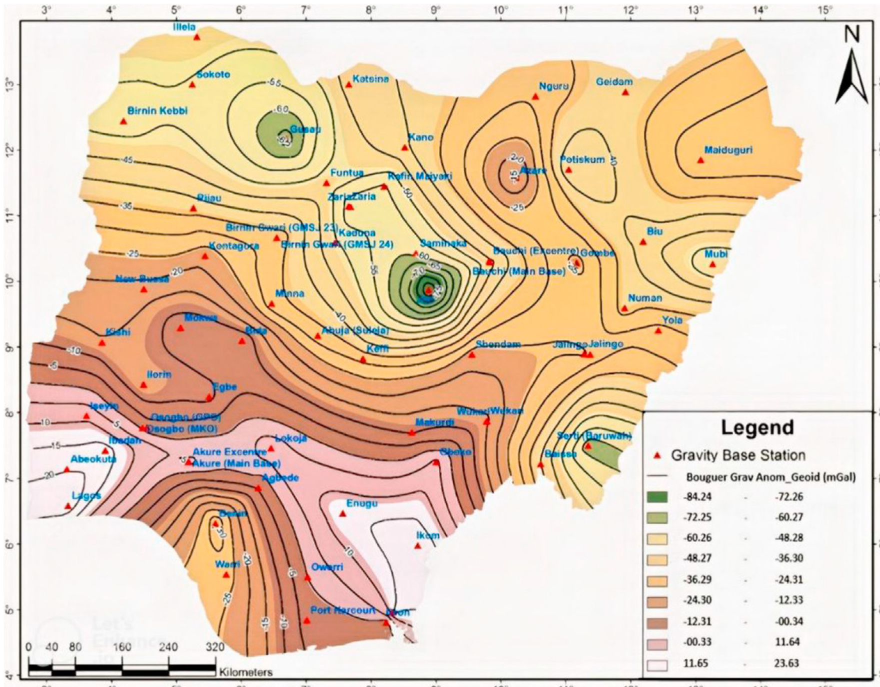

Fig. 21. Bouguer gravity anomaly values with respect to the geoid.

Though the strip has conspicuous margins on the north and south sides, it has no obvious displacement along the strike. Aside from the Ifewara-Zungeru fault with a length of about 250 km, the margins of the “trans-southern gravity high strip” having lengths of about 640 km (southern margin) and 890 km (northern margin) may be other mega lineaments within the continental area of Nigeria. The parallel arrangement of contour lines of intermediate gravity range having the same outline as the strip for a considerable length of distance (up to 132 km) away from the top of the strip indicates that the margins of the strip are not sharp but tapered.

The high axial gravity within the Benue Trough, which was mapped by Cratchley and Jones [30] and Osazuwa et al. [31], was also noticed within the Benue Trough region and has expressions as the easternmost bulge (around Gboko, Makurdi, Wukari and Shendam) on the northern margin of the “trans-southern gravity high strip” (depicted as a red line on Fig. 20). After connecting the “trans-southern gravity high strip” with the separation of African and South American plates, it will be more plausible to explain the bulge in terms of moho relief rather than a sort of volcanic activity under the Benue Trough.

On the Bouguer gravity anomaly map, it is also obvious that a NW−SE trending batholith province extends from the north−central to northwest Nigeria. The Bouguer gravity anomalies values within this province are negative, ranging from −50 to −88.3 mGal. The province includes the Jos-Bukuru granitic plateau designated as “G_1”, Zaria batholith designated as “G_2”, and the Gusau-Malinchi Batholith designated as “G_3”. Another obvious anomaly is the Azare “Gravity-Low” defined as “GL_{AZ}” around the northeastern section of Nigeria. Bouguer gravity anomalies approach −30 mGal within this closure. The “trans-southern gravity high strip” is associated with the mantle-upwelling, which is a precursor to the opening of the central equatorial Atlantic ocean around the gulf of guinea. The values of Bouguer gravities and Bouguer gravity anomalies are presented in appendix.

4. Conclusion

This research presents the gravity field distribution and gravity data reduction across the continental area of Nigeria. The data were processed with respect to the WGS84 ellipsoid and the geoid so that the indirect effects can be easily computed.

The WGS84 gravity formula is adjusted using the average of the indirect effects across the base stations of the PGNN, so that it can yield a better gravity field approximation across continental Nigeria, which is compatible with the geoid heights. The gravity reductions should be computed strictly according to the chosen height datum. Under this condition, the obtained gravity and gravity anomaly field values will be independent of the datum used, otherwise the final gravity anomaly may be overestimated (reference ellipsoid) or underestimated (reference geoid).

Adopting the WGS84 datum for data reduction means that the used height is the ellipsoidal height and the theoretical gravity must be computed from the WGS84 equation. Alternatively, one can adopt the newly defined Nigerian geoid datum so that the used height will be the height above the geoid (Fig. 4) and the theoretical gravity must be computed from the modified gravity equation (equation (9)). The obtained gravity anomalies using these two different approaches are about the same in value. This suggests that the approximation in Equation (9) is reasonably valid outside the error defined by the indirect effect range.

However, it should be noted that using the height above the geoid with the WGS84 equation or using the ellipsoidal height with the modified gravity equation is an aberration because of datum mismatch. The corresponding height for the WGS84 datum is the ellipsoidal height, while the corresponding height for the newly defined Nigerian geoid is the height above the geoid.

Bouguer gravities and Bouguer gravity anomalies across continental Nigeria revealed a “trans-southern gravity high strip” associated with mantle upwelling. A batholith province containing low Bouguer gravity anomaly closures was also delineated. An independent closure of low Bouguer gravity was also detected at Azare, which may also be due to the presence of intrusive granites.

It is recommended to study the mantle structure beneath "the trans-southern gravity high strip", "delineated batholith province" and "isolated gravity closures" around the northeastern part of Nigeria through seismic shear wave splitting analysis.

Author Statement

Oluwatimilehin B. BALOGUN: Methodology, Funding acquisition, Software, Data curation, Writing – original draft Preparation, Reviewing. **Isaac B. Osazuwa**: Conceptualisation, Supervision, Funding acquisition, Writing – review & editing. The authors appreciate Drs. Akinola S. Akinwumiju and Adesuji A. Komolafe for helping to generate the maps.

Conflicts of interest

The authors declare that there is no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geog.2022.09.003.

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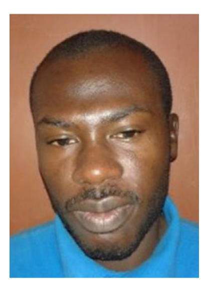

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