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Application of Aero Gravimetry for Litho Structural and Depth Characterization of Greater Dutse, Jigawa State, Nigeria

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Abstract

Airborne gravimetry, like other satellite and aerial-based geophysical survey techniques, has an edged advantage over ground-based survey because of its fast and effective data acquisition process irrespective of the accessibility of the study area. This work is an appraisal of the capability of airborne gravimetry in delineating topographic features and mapping basement depths. Airborne gravity dataset of Dutse, Jigawa State, Nigeria was acquired from the National Aeronautics and Space Administration (NASA)'s Gravity Recovery and Climate Experiment (GRACE) website and processed using the analytic signal (AS) for edge detection and resolution of physical features of the subsurface topography. The vertical component of the analytic signals (VAS) was used in association with the AS to spatially estimate the basement depths of the area. The resulting AS map provides images of different geologic features on the bases of their degree of density contrast. This enables the identification of basement rocks and sediment deposits within the subsurface of the study area. The basement depths range from zero (outcrops) to a maximum of 14.1 km. The work demonstrates the capabilities of the readily available airborne gravity data as a reconnaissance survey tool for topographic and natural resource mappings.

Keywords: Airborne Gravimetry, GRACE, Analytic Signal, Dutse, Gravity method, basement complex.

INTRODUCTION

Gravity method of geophysical prospecting is one of the most effective non-destructive and non-invasive techniques of mapping the properties of the earth subsurface for diverse economic and environmental applications. The technique is based on the relationship between the variations in the local acceleration due to gravity with the density of the subsurface earth materials. It is used widely for large-scale crustal studies such as mapping

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variations in subsurface rocks densities (Sultan et al., 2009; El-Bohoty et al., 2012; Mandal et al., 2013; Biswas et al., 2014). It is also used for mapping basement topography and study of the structure and mapping of the sedimentary basin (Okpoli and Akingboye, 2019), investigation of regional groundwater exploration in crystalline rock (Murty and Raghavan, 2002). Gravity technique is also used as a reconnaissance tool in petroleum exploration, where large scale sedimentary basins typically have a lower density than the basement rocks (Zeng et al., 2002). The anomaly, in such cases, will show up as gravity low.

Gravity surveying is one of the few potential field methods that are considered as a natural source because no external agent or energy source is required in conducting the measurement. The procedure simply involves measurement of the gradient of the earth's gravitational potential energy. Hence, the technique requires high precision equipment and laborious exercises to tackle the challenges of the extreme weakness of the variation in the potential field due to the insignificant difference in density contrast between the earth materials. Measurements are practically done on land (ground-based), sea (marine), and airborne. The ground-based survey can be conducted on the land surface by moving gravimeter from one station to another with additional labour of periodic reoccupation of survey-based station to correct error due to the effects of instrument drift and the earth tides (Holon and Oldow, 2007). The ground-based survey is very convenient in the high-resolution mapping of a specific area of interest. Its laborious demands, however, limit its applicability significantly to a small area of coverage and limited access point stations.

Airborne gravity survey is very convenient for a large scale regional mapping as it enables data acquisition at the speed of a remote satellite over a large region of interest. It is found to be very effective especially in areas that are practically inaccessible due to either terrain difficulty or presence of permanent structures. Successful application of the airborne gravimetry was recorded in regional crustal studies (Li et al., 2013), litho-structural and depth characterization (Okpoli and Akingboye, 2019), determination of the geodetic datum of global terrestrial reference frames, requisite information for precise knowledge of the Earth's gravity field structure which applies to GPS based surveying, lithospheric modeling, sea-level change research, modeling of water flow for hydro-engineering, (Meijde et al., 2015) and lots more.

Airborne gravimetry or aero gravity method is a satellite-based system of measuring spatial changes in the earth's gravity values for the surface. There are various satellite missions and programs for the measurement of the earth's gravity. Prominent among them is the National Aeronautics and Space Administration (NASA)'s mission known as Gravity Recovery and Climate Experiment (GRACE) launched in 2002. The mission consists of two twin satellites at the same orbit separated 220 km apart at an altitude of 460 km above the earth's surface. (NASA, 2018). Earth's gravity is measured based on the variation in separation between the two satellites in response to the variation in the gravitational attraction of the leading satellite relative to the trailing satellite as they cross over a point of varying attraction at different times. As the leading satellite passes over an area of greater g value, it gets pulled down due to the increase in gravitational attraction. This displaces the relative positions of the two satellites. The displacement created, though very minute, is accurately measured with a microwave electromagnetic distance measuring system and calibrated in a gravity unit based on the working principle of normal gravimeter. GRACE gravity data for different parts of the world are freely available for download on request from the official web site (https://earth.esa.int/web/guest/pi-community/apply-for-data;jsessionid=90A1F62170CB707C98BC0E5976E8C0DD.jvm2).

In this work, aero gravity dataset of Dutse, the Jigawa state capital, and its environs were acquired and used to map the basement topography, structural geometry and estimate the basement depth of the area. The work is aimed at investigating the topographic features of the region which is associated with a contact zone between two major litho petrophysical components that make up the geology of the study area. The work is a cost-effective approach to gravimetric survey of the area where the laborious requirement of moving gravimeter from one point to another is virtually eliminated. Hence it provides effective alternative to subsurface structural mapping on a regional scale. Adequate data acquisition with regular spatial sampling, hitherto constrained by the inaccessibility of some stations, are sufficiently achieved with aerogravimetric approach. Also, large scale regional gravimetric mapping which will not have been possible using ground based method, is developed, leading to subsurface structural mapping that can serve as a veritable tool for detail geophysical investigations. The study therefore demonstrates the potential application of aero gravity data in subsurface mapping and petrophysical investigation.

MATERIALS AND METHODS

The study intersected a rectangular area of 270 km^2 including Dutse, in the Jigawa State of Nigeria, and its surroundings (Figure 1). The lower left and upper right corners in this area are located at 11°38′0.27″ N, 9°15′56.34″ E and 11°48′4.43″ N, 9°24′0.23″ E, respectively; with an average altitude of about 434 m above mean sea level. The area is underlain by the Precambrian basement complex of north-central Nigeria (Obaje, 2009) characterized by diverse landforms, including a few elevated landscape features of igneous rocks surrounded by a relatively flat landscape.

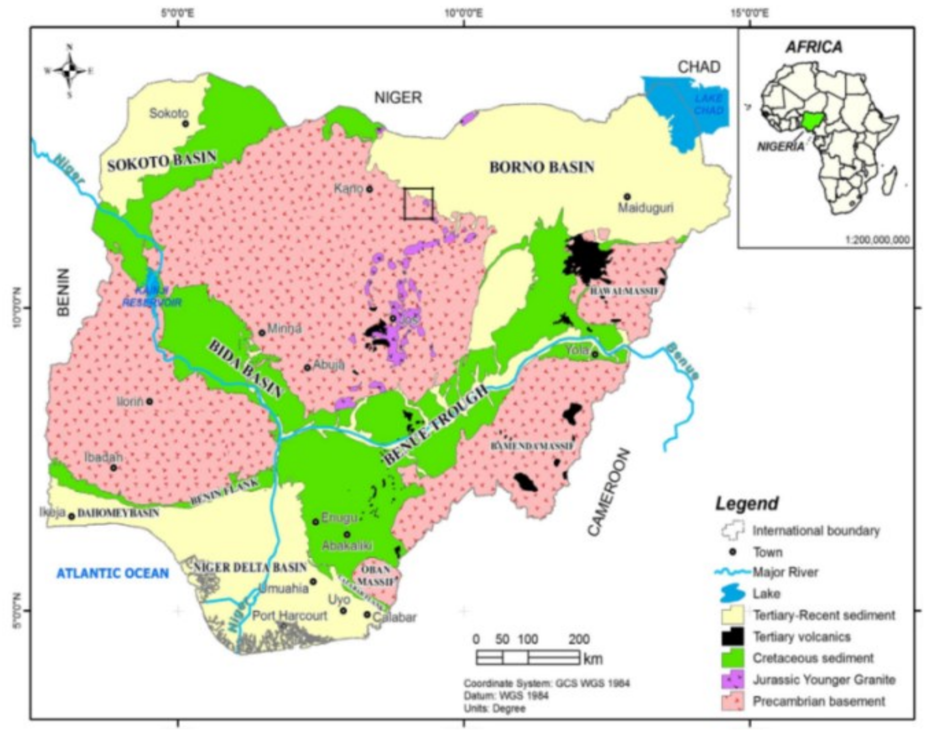

Figure 1. Geologic map of Nigeria showing the study area in rectangle

The predominant rock types in the area are coarse porphyritic biotite granite and older Pan-African granitoids. Other minor members of the group are younger granite of Jurassic age, porphyritic granitoid, and medium to coarse-grained hornblende-biotite granite belonging to the Pan-African older granitoid (Phillips, 2002). The study area is very close to the geologic contact between the Precambrian basement complex and the Chad basin. As shown in Figure 1, the area enclosed a contact zone between the southwestern end of the Quaternary Chad basin and the North-eastern end of the Cretaceous basement complex of northern Nigeria. Thus, the area is made up of both crystalline and sedimentary rocks. The Quaternary Chad formation mainly consists of clays, siltstone, and lenses of gravels at different depths with a maximum depth of 165 m (Offidile, 2002). The basement complex unit within the study area is generally made up of Migmatite Gneiss complex (Obaje, 2009), granite, granite porphyry, medium to coarse-grained hornblende biotite granite and coarse porphyritic biotite granite (Hamid et al., 2016). It is however occasionally intruded by the Mesozoic ring complex of Younger granite (Obaje, 2009).

Data acquisition and processing

Gravity survey is mainly used to locate and describe subsurface structures from the observed gravity effects caused by their anomalous densities. In this work, the aero-gravity dataset was acquired from the official website of GRACE through a third party vendor, European Space Agency (ESA) (https://earth.esa.int/web/guest/data-access/browse-data-products/-/article/grace-level-2-data-product-gx-og-_2-gsm). The acquired dataset covering the study area was downloaded in csv format. It consists of columns of latitude (in degree decimal), longitude (in degree decimal), altitude (in metre), and relative gravity (in mgal). The data was acquired along a regular grid with a line spacing of 1.813km along with both x and y directions. The dataset is available at different levels of processing. In this work, a processing level is selected which ensures the removal of non-geologic effects so that the resulting gravity values are only due to the effect of variation in local densities of the geologic formation. Figure 2 is the contour plot of the spatial variation of the acquired gravity data within the study area. An analytic signal is an effective enhancement technique applicable to potential field data (gravity and magnetic) routinely for mapping geologic contacts, faults, and dikes (Emujakporue et al., 2017). It has the potentiality of delineating the edges of the boundaries of the anomaly source and can, therefore, resolve source geometry. The magnitude of the analytic signal $|AS|$ is defined as the square root

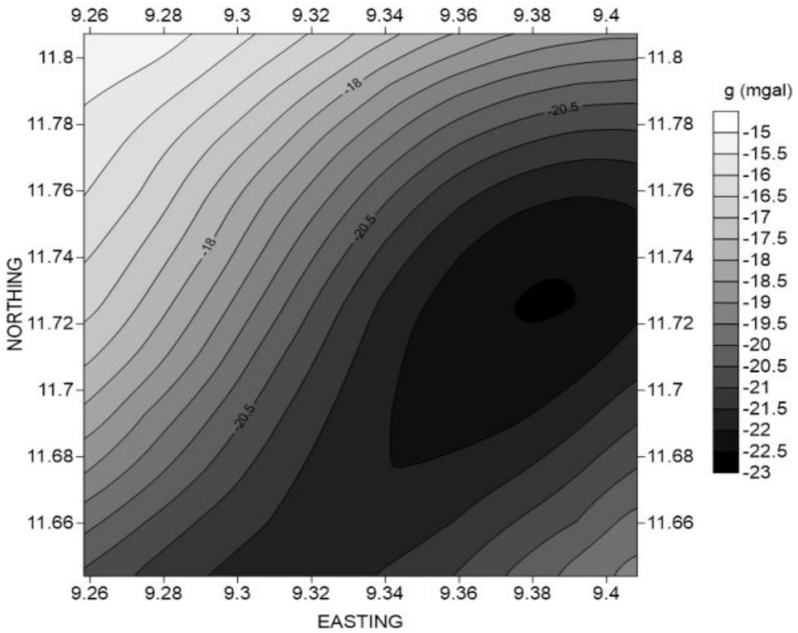

Figure 2. Gravity contour map of the study area

of the sum of squares of the derivatives of the potential field data in the x, y, and z directions. That is

$$|AS| = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2 + \left(\frac{\partial g}{\partial z}\right)^2} \tag{1}$$

The vertical gradient $\partial T/\partial z$ of the gravity values are the measure of the ratio of the difference in the magnitude of the gravity vector recorded at a point on two different vertical positions to the spatial separation between the two points. It is obtained based on the fact that the gravitational field vector g is derivable from the gradient of gravitational potential U as

$$g = -\nabla U \tag{2}$$

which obeys Laplace equation (Ibe and Iduma, 2018)

$$\nabla^2 U = \nabla \cdot \nabla U = -\left(\frac{\partial g}{\partial x} + \frac{\partial g}{\partial y} + \frac{\partial g}{\partial z}\right) = 0 \tag{3}$$

and thus

$$\frac{\partial g}{\partial z} = -\left(\frac{\partial g}{\partial x} + \frac{\partial g}{\partial y}\right) \tag{4}$$

Thus the amplitude of the AS was computed based on the combination of the three orthogonal gradients of the gravity values. The plot of the amplitude of AS over a geologic contact is a Gaussian-shaped symmetric function with maximum occurring directly over the top of the contact and width directly related to the depth of the contact (Debeglia and Corpel, 1997). The amplitude of the analytic signal is expressed by the vector addition of the vertical and horizontal components of the derivative of the gravity values.

The magnitude of AS is used to estimate the shape, horizontal extent, and depth of the gravity causative body. Because the amplitude of AS is maximum over the source of the causative body, near-vertical subsurface contacts or faults with significant density contrast can easily be detected by mapping the maxima which are located directly over the edges of the contact. The technique is used by many authors to estimate parameters of 2D gravity and magnetic anomaly source. For instance, Bastani and Pedersen (2001) used AS of the total magnetic field anomaly along a profile to estimate the dip, depth, width, and strike of dikes.

We used the amplitude of the AS to compute the depth d from the surface to the top of the observed anomaly sources based on the ratio of AS to the vertical derivative of AS, VAS given by Al-Badani and Y. M. Al-Wathaf (2018) as

$$d = \frac{|AS|}{|VAS|} * N \tag{5}$$

where

$$|VAS| = \sqrt{\left(\frac{\partial}{\partial x}\left(\frac{\partial g}{\partial z}\right)\right)^2 + \left(\frac{\partial}{\partial y}\left(\frac{\partial g}{\partial z}\right)\right)^2 + \left(\frac{\partial^2 g}{\partial z^2}\right)^2} \tag{6}$$

and N is a numerical parameter related to the geometry of the source known as its structural index. Values of N for different sources' geometry are given as (Al-Badani and Y. M. Al-Wathaf, 2018)

Contacts	1
Thin dike	2
Pipe/kimberlite	3
Sphere	4

RESULTS AND DISCUSSION

The amplitude of the analytic signal of the gravity data was computed from the three orthogonal derivatives of the field using equation (1). Figure 3 is a plot of the amplitude of the analytic signal obtained. The analytic signal is a pattern recognition algorithm that tends to image the shape of the anomaly source in potential field data. It is the measure of the magnitude of the rate at which the gravitational field vector changes spatially in all directions within the x-y-z vector space. It is therefore very sensitive to the edge of transition between high and low-density bodies. Thus the large value of the magnitude of AS is an indication of significant contrast in gravity values which also signifies inhomogeneity of the subsurface composition.

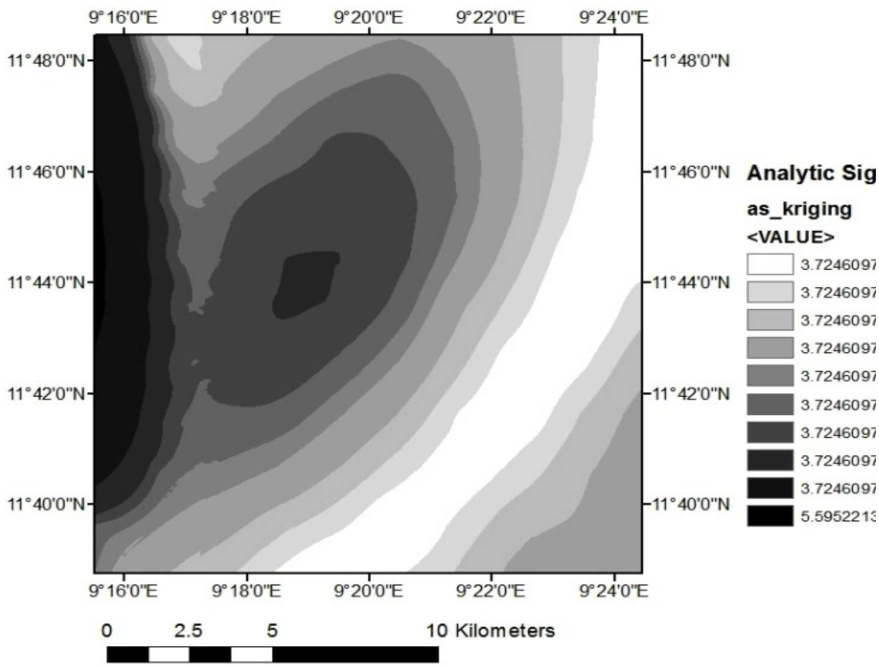

Figure 3. Analytic Signal (AS) of the gravity data. Location of intruded Dutse granite is shown in white colour

The plot of the amplitude of the analytic signal shown in Figure 3 revealed the geometric form of the anomaly sources where high AS values recorded within the centre and the extreme western portion of the study area occurs within the inhomogeneous clay and siltstone deposit of the Chad basin in association with the fractured basement of gravels and sandstones. Basement rocks, on the other hand, coincide with the regions of low AS value due to their relatively clearer definition. In this case, low AS values recorded with NE-SW trends are interpreted as an intrusion of granitic fresh basement rocks. Thus the high gravity anomaly of oblate shape observed in Figure 2 can be attributed to the presence of this denser intrusion of the fresh basement.

Based on the geometric form of the observed sources given in Figure 3, it is assumed that the sources are predominantly made of geologic contacts. They are therefore approximated by a contact (*N=1*). Equation (5) was therefore used to compute the depth of the sources from the surface. A 3-D surface plot of the depth (Figure 4) indicates a high degree of topographic depth variability ranging from zero (outcrop) to about 14.1 km depth.

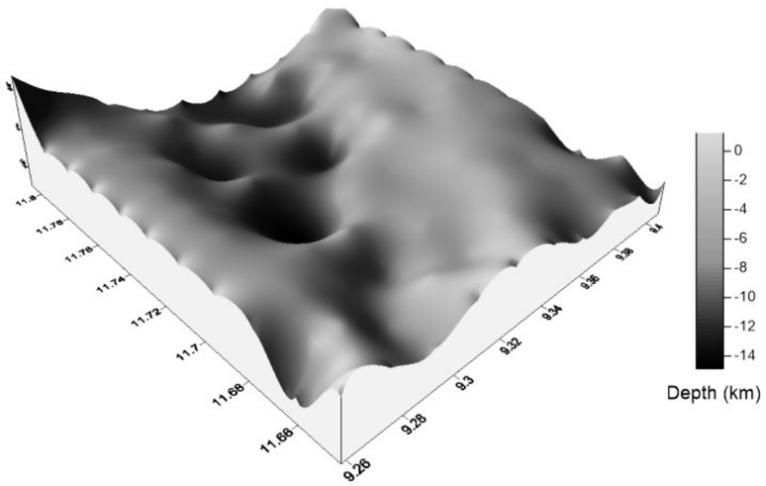

Figure 4. 3-D surface map of the basement depth

Outcrops of the fractured basement rocks are visible along the western end of the study area. Fresh basement rocks appeared at a shallower depth within the NE-SW-trend intrusion. The depression of the basement along the centre of the area which extends to the northern end is a further confirmation of the occurrence of high sediment and fractured basement deposits identified in Figure 3. Comparative analysis of Figure 4 with the geologic map of the area indicates that the basement depression recorded in the northern part of the area coincide with the southern end of the quaternary Chad formation while the surrounded basement elevation roughly coincide with the cretaceous basement complex.

Based on the fact that strong gravity anomalies are associated with fresh basement, Figure 4 indicates large variability in the basement topography of the subsurface of the area. The north and central portion of the area are characterized by basement depression intruded occasionally by dike-like features which are likely volcanic intrusions (Szentes, 2009). The eastern portion of the area is dominated by shallow sources representing near-surface geologic features which slope deeply and unconformably toward the south. This characteristically implies significant variation in the thickness of overlain sediments and fractured basement within the formation. This finding is in line with results obtained by Chifu et al. (2019) where application of electrical resistivity in mapping groundwater potential of a portion of the study area indicates the existence of isolated deep depressions within the basement which appears to be filled by water bearing sediments and was thought to be favorable structures for groundwater accumulation. These bedrock depressions overlaying conformable depression in the crystalline basement could serve as a settling basin for inflow of water. Study on static water level characteristics of the area by Hamidu et al. (2017) shows that boreholes located within the quaternary sediment of the Chad formation generally have deeper static water level than those within the crystalline basement. Basement depressions structures within the region are therefore considered favourable structures for groundwater accumulation.

CONCLUSION

This work is an appraisal of the application of aero gravity data in mapping basement terrain and topographic structure of the subsurface. The satellite-based airborne gravity dataset was acquired and used to image the subsurface structures based on the analytic signal technique. The vertical component of the analytic signal was also computed and used together with the magnitude of the AS to estimate basement depth within the area. Groundwater accumulation zones were identified as the region of crystalline basement depression which vertically coincides with the region of thicker accumulation of sediments and fractured basement. The work, therefore, demonstrates the potential application of satellite-based aero gravity data, which is freely available, as a reconnaissance survey tool for topographic mapping and investigation of groundwater potential of a formation.

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