Research Article **Open Access**

Gravity-Based Structural Modelling of Awataib Area, River Nile, State, Central Sudan

Hussein AH[1]* and El-Mula AAG[2]

[1]Faculty of Minerals and Petroleum, International University of Africa, Khartoum, Sudan
[2]Department of Geology, Faculty of Science, University of Khartoum, Khartoum, Sudan

Abstract

In this paper the authors are discussing the structural setting of Awataib valley area through Gravity-based variation measurements, which have been obtained by Simple Bouguer Anomaly formula that uses the relative difference in the vertical component of the earth gravitational field between Base station and other observational points. The study objective at using Regional gravity survey is to reveal the subsurface structural geology of Awataib valley and adjacent areas. Land Sat image aided by collected field data were used in this study. Surfer software version 8.02 used to produce contoured-base map of gravity data set. Grav Modeler Program in the Geological Research Authority of Sudan (G. R. A. S.) has been just used to perform 2-D Density-Depth modeling. Free-hand graphical technique has been used to perform geological sections from derived gravity models. The NW-SE lineament has been considered as fault coincides with valley of Awataib, thus faults map has been suggested from the calibration of Bouguer anomaly steep gradients and field observations. Some of the geology faults are considered to be a rejuvenation of pre-Nubian fractures; so far, this study suggests an extension of Umm Marahik strike slip fault with general trend of NE-SW ending at Awataib valley. The depth of sediments less than 450 meters and the average effective thickness is about 275 meters which's making up basinal features that probably considered as water-bearing formations ready to be drilled.

Keywords: Regional gravity; Bouguer anomaly; Density-depth models; Awataib valley; Tectonic setting

Introduction

Gravity survey involves measurement of the differentiation in the gravitational field of the earth's surface, caused by local variations in the density of subsurface overburden rocks, in a wide area varies from 1, 3 to 5 km for each observation point, and here the interval was 1 km for each observation points [1]. The goal of gravity surveying is to locate and describe subsurface structures from the gravity effects caused by their anomalous densities [2]. An absolute gravity is the gravity acceleration at a point on the earth's surface. Since the gravimeter only measures the relative differences in gravity, the measurements need to be tied into places of Known gravity.

The main purpose of recent study is to determine the structural setting of Awataib valley and surrounded area (e.g. Sabaloka and El Ban Gadeed) moreover to link Awataib tectonically with the event of Central African Shear Zone (CASZ). The study area (Figure 1) is suited north of Khartoum state between lat. 16.35-16.9°N and Long. 33.05-33.35°E and bounded by Sabaloka village from south and Shendi city from north. The area belongs to the desert-semi desert climatic regime.
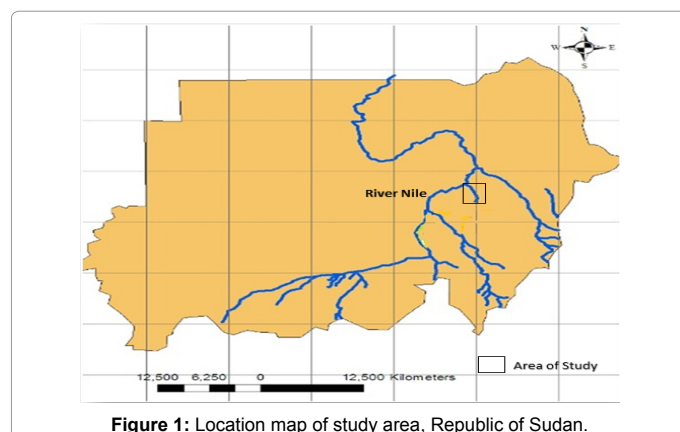

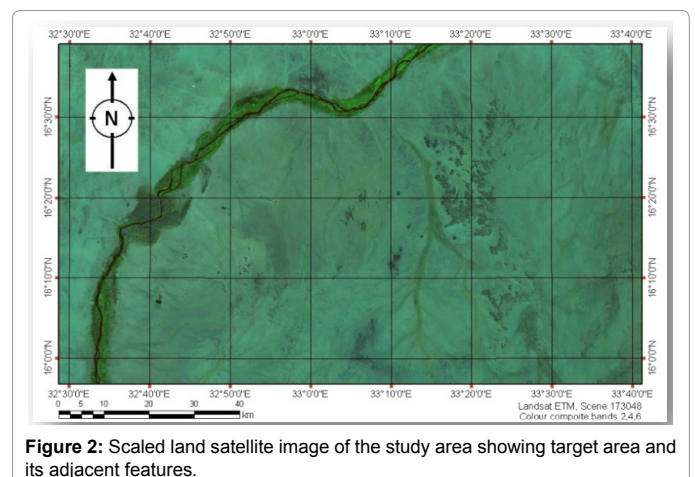**Figure 1:** Location map of study area, Republic of Sudan.

Figure 2: Scaled land satellite image of the study area showing target area and its adjacent features.

The main hydrological features in the study area are the River Nile and River Atbara beside the other seasonal valleys such as Awataib (Figure 2). The Geology of the study area is represented by different rock units ranging from Pre-Cambrian, Cretaceous and Cenozoic to Quaternary. Chronologically the units of the study area from young to old are: superficial deposits, Umm Ruwaba Formation, Cenozoic Volcanoes, Hudi chert Formation, Cretaceous Nubian Sandstone

*Corresponding author: Hussein AH, Faculty of Minerals and Petroleum, International University of Africa, Khartoum, Sudan, Tel: 249906778918; E-mail: hmhmd125@gmail.com, gadelmula@yahoo.com

Formation and Precambrian Basement Complex Rocks [3]. The rocks of granulite affinity are scattered all over the Sabaloka basement inlier and considered they are the source of the high gravity anomaly in the Sabaloka inlier as recorded by Sadig [4].

In Figure 3, significant changes are observed in the behavior of the Basement Complex rock depths and its distribution is grading from shallow zones at the west, to a deeper ones at the east in the map. Noted contour closures interpreted usually, either deeper or shallower Basement depth levels. Looking at the map bellow; there is a characteristic structural texture extends from west to east, generally, and the Basement depth levels are ascending from 10 meters, as minimum, and descending to 140 meters, as maximum. In reality this coincides with the Basement outcrops in Sabaloka area, at the west, and Shendi-Atbara sedimentary basin at the east, and this dipping in Basement from previous studies of due to the regional metamorphism of the granulite facies and other Basement rocks that took place by tectonics of CASZ [4-6].

Geological and Tectonic Settings

The granulites represent the oldest rocks of the Basement complex in Sudan. The granulites found in Sabaloka Basement inlier are made up of an association of meta-igneous and meta-sedimentary gneisses. The density contrast between this granulite and the other Basement complex rocks is -0.35 and many granulite occurrences in Ban Gadeed particularly the calc-silicate type are interlayered with migmatites and so in many outcrops they do not have depth [4]. A large inlier of Basement complex rocks surrounded by Cretaceous sediments north of Khartoum comprises a grey gneiss assemblage intruded by late-tectonic adamellitic batholiths and a shallow-level granitic ring complex [7]. According to Dawoud and Schulz-Dobrik these granulites were formed deep in a thickened crust at depth of 27 km, and information on how these granulites exposed to the surface from those deep levels to [8]. Apart from uplift due to isostatic adjustment, thrusting might have played a role in this uplift. The Pressure/Temperature (PT) calculation based on coexisting mineral pairs of the granulites indicates that the granulites are formed at depth of more than 25 km. Using statistical analysis of the relationship between Bouguer gravity anomaly, topography and depth to the Mohr, the crustal thickness of the Sabaloka Inlier is found to be 41 km [4]. The early recumbent folding in Sabaloka

Figure 3: Depth to basement complex contour map from boreholes data of the study area.

area implying that the crustal shortening which was associated with the Pan- African orogeny and accretion of island arcs to the east in the Red Sea Hills resulted in thickening of the crust at Sabaloka and thus facilitated granulites metamorphism. The granulites were uplifted to their present level by tectonic processes rather than by erosion only. Structural and gravity data, which show a remarkable correlation, indicate thrusting as the major cause of uplift for the granulites [5]. The Mesozoic-Cenozoic basins through the entire region of Sudan, by using aeromagnetic and gravity data, showed several sedimentary structural basins NW of the Central African Shear Zone (CASZ), [9]. The term Nubian Sandstone had been introduced to distinguish between Paleozoic and Mesozoic Sandstone in Nubian Desert. Omer proposed a fluviatile origin to the sandstones of Khartoum region and assigned to these sediments a Cretaceous age by dating fossil wood [10]. This undifferentiated Cretaceous sandstone, siltstones and mudstones have been studied south of Ed Damer, but are thought to be unfossiliferous. The paleocurrent directions are dominated by NNE and N directions, suggesting mainly SSW source areas and the depositional environment of Shendi Formation is consisting of fluvial and lacustrine deposits. The sequences are topped by laminated to massive mudstone facies, sometimes occur as mud drapes [11]. This unit was deposited by currents flowing generally in northerly direction. The term Markhiyat Sandstone uses in Khartoum region for the sedimentary rocks near Omdurman city [12]. The later subdivisions by Bireir and Awad, on classifying Omdurman Formation into two members, Upper Member (Markhiyat Member) and Lower Member (Umm Badda Member) are adopted to avoid the confusion associated with the Nubian Sandstone Formation nomenclature [13,14]. During the late Proterozoic the Central African Shear Zone (CASZ) was initiated. It can be traced from Cameroon trough of Central Africa, Chad to North Kurodfan in Central Sudan, and probably further into the Red Sea in NE Sudan representing one of the major shear zones of lithosphere weakness in Africa, [15]. Therefore, the Central Sudan lies in the eastern part of the Central African Rift System (CARS) which extends from Benue Trough in Nigeria to the Atbara Rift in Sudan [16].

Gravity data and analysis

The present study is based mainly on regional gravity survey by using LaCoste and Romberg Model-D No.108 Land gravimeter (r), (calibration constant=1.0863 mGal/dd.) for 79 gravity observation points (with average drift of 0.00038 dd/min) along three conducted profiles around the Awataib valley.

Corrections are made to obtain Simple Bouguer Anomaly $\left(\Delta g_{B.A}\right)$ formula (Equation 1), which is the algebraic summation of observed gravity $\left(\Delta g_{obs.}\right)$, the elevation correction from geoid surface $\left(\Delta g_{Elev.}\right)$ and the theoretical or normal gravity $\left(g_{\ddot{o}}\right)$.

$$\Delta g_{B.A} = g_{obs.} + g_{Elev.} - g_{\varphi} \tag{1}$$

The Tide $\left(\Delta g_{tide}\right)$ and Terrain $\left(\Delta g_{ter}\right)$ effects on the gravimeter readings, have been ignored due the reconnaissance survey, so far the final product is Bouguer Anomaly map (Figure 2) characterized with steep gradients and contour closures g_{obs} is obtained from drift calculations and summed to pendulum readings of tow base stations at Sabaloka and Musawarat. Combined elevation correction $\left(\Delta g_{Elev.}\right)$ was done using the average crustal density of 2.7 gm/cc for the surface rocks which gives a correction factor of 0.1967 mGal/meter, in addition $\left(g_{\varphi}\right)$ formula of 1967 has been used.
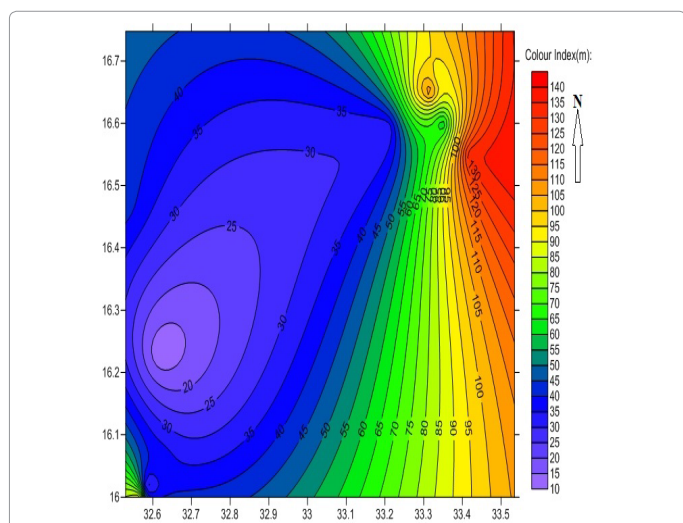
Borehole name	Longitude (Dec. deg.)	Latitude (Dec. deg.)	Depth to Basement Rocks (meters)
bh1	33˚.3389	16˚.6736	89.9
bh2	33˚.4167	16˚.55	133.5
bh3	33˚.35	16˚.6	60
bh4	33˚.2083	16˚.5917	30.2
bh7	33˚.5347	16˚.7472	135.7
bh9	32˚.6167	16˚.23	12.7
bh21	33˚.2927	16˚.393	77

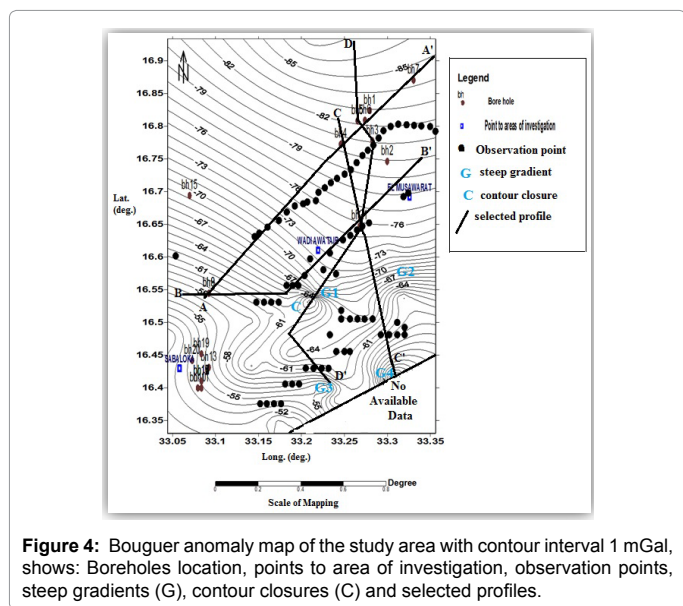**Table 1:** Boreholes used in regional-residual field's separation.

Figure 4: Bouguer anomaly map of the study area with contour interval 1 mGal, shows: Boreholes location, points to area of investigation, observation points, steep gradients (G), contour closures (C) and selected profiles.

Limitation of gravity methods

Relatively time intensive for a trained interpreter in the field and lab. Needs to be "calibrated" at one or more control points using complementary well data or other geophysics (e.g. seismic refraction/reflection).

Analysis of Bouguer Anomaly Map

Analysis of data include mainly, the digital contouring of reduced reading, which was performed using Surfer software version 8.02 ©, the 2-D Density-Depth models was performed using GravModeler Program and the geological models were estimated by paint-free-hand technique, which demands a clear displacement in the Density-Depth models to delineate faults [17].

Bouguer anomaly map

The Bouguer anomalies (Figure 3) are predominantly negative and vary between -52 mGal and -85 mGal. The trends of these anomalies follow the structural grain of the terrain and exhibit considerable variations between the Basement Complex and Sediments above it. The most pronounced anomaly in the region is a broad gravity low of -70 mGal centered over the beginning of Shendi-Atbara basin covering Awataib valley (-64 mGal) and the Basement Complex bodies in the south-central part of the stud region at C1 which is a high gravity, suited between latitudes 16.5-16.55°N and longitudes 33.18-33.22°E, its shape is semi-spheroid the highest value reaches -59 mGal and the lowest value is about -62 mGal with amplitude of +3 mGal. This due to the low-density rocks such as sediment. Steep gradients (G1, G2, G3,

and G4) are concentrated mainly in the lower half of the map. It is as follows:

(G1) Located at the middle part of the map extends from East to the middle coincides with Awataib valley between lat. 16.55-16.60°N and Long. 33.175-33.35°E, its length is about 11.5 Km with amplitude of +9 mGal and value of 0.783 mGal/km. It suggested being due to fault in Awataib valley.

(G2) Located at south-eastern part of the map below (G1) between lat. 16.4-16.55°N and long. 33.24 -33.35°N, its length is about 11.5 km, also, with amplitude of +6 mGal and value of 0.521 mGal/km. it suggested this gradient is due to fault south of Musawarat, may be the same as (G1).

(G3) Located in southern part of the map and generally at Ban Gadeed village between lat. 16.38-16.45°N and long. 33.10-33.25°E, its length is about 9.2 km with amplitude of +9 mGal and value of 0.978 mGal. This gradient may coincide with a fault in Ban Gadeed discussed earlier by D C. Almond and F. Ahmed [18].

(G4) Located in south-eastern part of the map (east of G2) between lat. 16.37-16.43°N and long. 33.27-33.35°E, its length is about 3.8 km with amplitude of +6 mGal and value of 1.579 mGal/km. Another distinctive and much weird feature is the reversible steep gradients between Lat. 16.45-16.5°N and Long. 33.15-33.2°E and its surmised as a rotational strike slip movement extend from Sabaloka.

Regional-residual anomalies' separation

The Bouguer anomaly is composed of two components, one is the regional and the other is a residual. The regional anomalies are the effect of the large-scale, broad, and deep-seated structures, while the residual anomalies are the effect of small, confined and shallow structures such as basins and ore bodies. Because a Bouguer map shows horizontal differences in the acceleration of gravity, only horizontal changes in density produce anomalies [1]. As the source of an anomaly deepens, the anomaly becomes more spread out and its amplitude decreases. The smoothness of anomalies is generally roughly proportional to the depth of the lateral density changes. Residualizing attempts to remove the regional to emphasize the residual [19] in areas where borehole data are available, having depth to basement and densities of both Sedimentary and Basement rocks (Table 1), the regional anomaly value at the borehole is computed using the following equation:

$$\Delta g_{B.A} = \Delta g_{Res.} = 2\pi\gamma\Delta\tilde{n}h \qquad (2)$$

Where (h) is the depth to the Basement rocks in the boreholes that crossed by the profile (Table 1) and $(\Delta\rho)$ is density contrast between Basement and Sedimentary rocks which equals to -0.4 g/cc. Once the regional is determined and contoured, it may be subtracted from the observed map either graphically or numerically to obtain residual anomaly map. Graphically the residual field will be:

$$\Delta g_{Res.} = \Delta g_{Reg.} - g_{B.A} \qquad (3)$$

In order to ascertain the depth and extent of various sub-surface masses causing the gravity anomalies, four profiles were conducted along Bouguer anomaly map (Figure 4) to delineate 2D-density-depth models.

Gravity Modeling

The subsurface density structure investigated along four gravity

profiles AA' to DD' (Figures 5.1a, 5.2a, 5.3a and 5.4a) cutting across steep gradients, contour closures and lineament features to estimate geo-gravity sections (Figures 5.1b, 5.2b, 5.3b and 5.4b) for the structural revealing of Awataib area tectonic setting.

Constrains on subsurface densities and its structure

The occurrence of Basement complex crystalline rocks and the Sedimentary Formations of Nubian Sandstone produced anomalous effects, which represented in regional-residual fields (Figures 5.1a -5.4a),

of buried bodies that vary in thicknesses as densities. Table 2 represents some densities of rocks that were observed in the field. Any way the average densities of Sedimentary rocks and the Basement complex considered to be 2.35 g/cc and 2.75 g/cc respectively due to the occurrence of several iterative rocks and reconnaissance of basinal feature purposes.

Gravity derived subsurface models

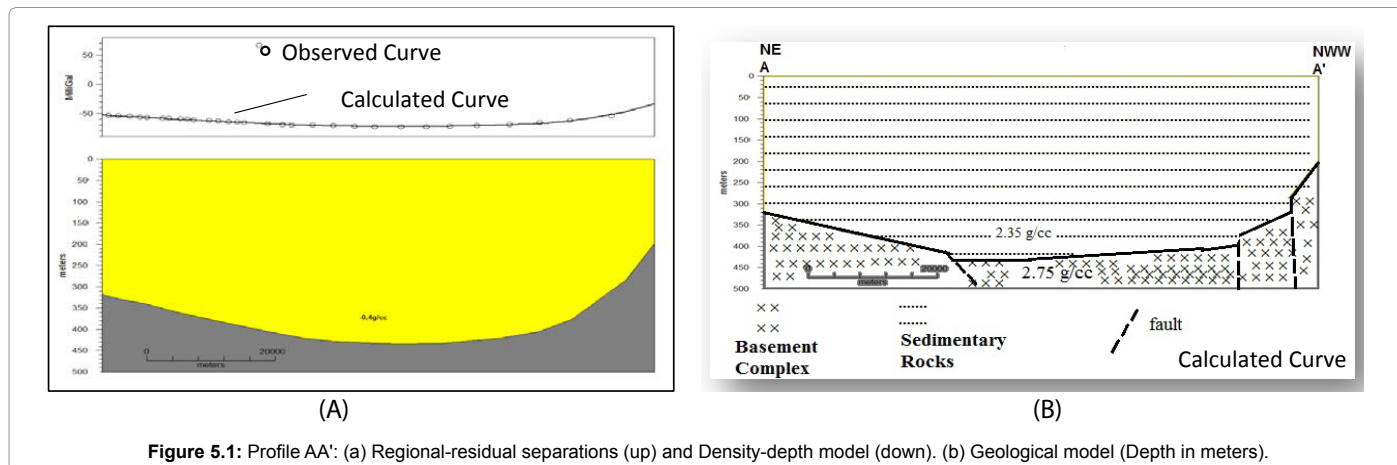Tow-dimensional gravity models along the four profiles (AA'-DD')

Figure 5.1: Profile AA': (a) Regional-residual separations (up) and Density-depth model (down). (b) Geological model (Depth in meters).
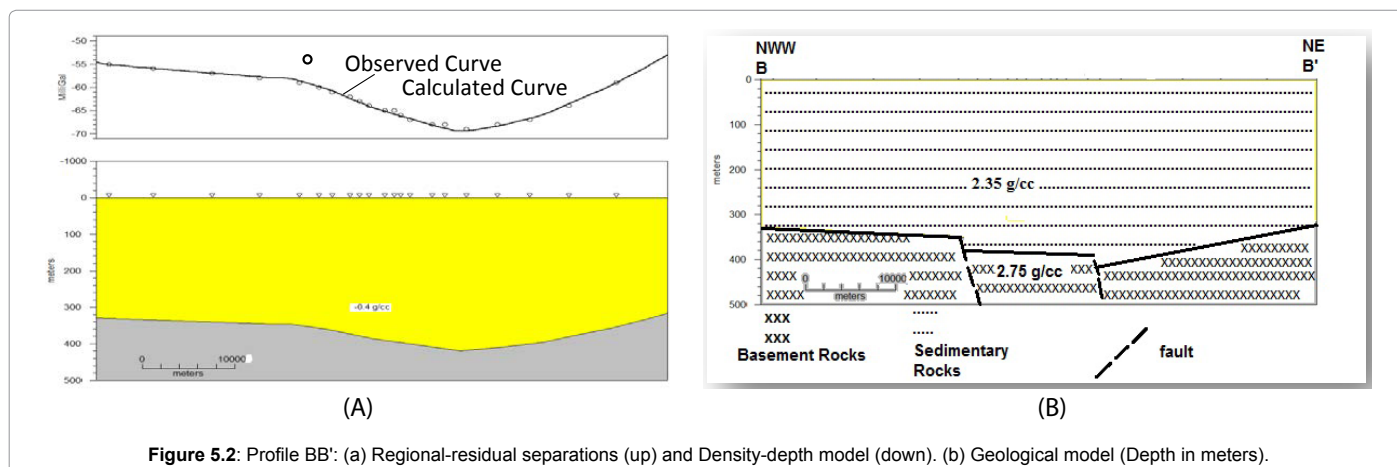

Figure 5.2: Profile BB': (a) Regional-residual separations (up) and Density-depth model (down). (b) Geological model (Depth in meters).
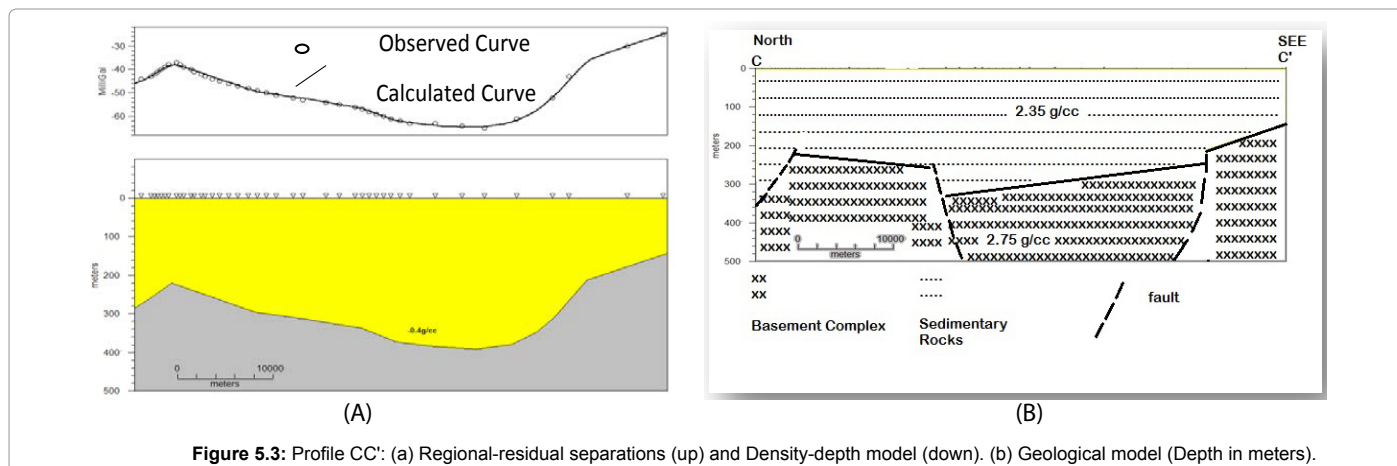

Figure 5.3: Profile CC': (a) Regional-residual separations (up) and Density-depth model (down). (b) Geological model (Depth in meters).
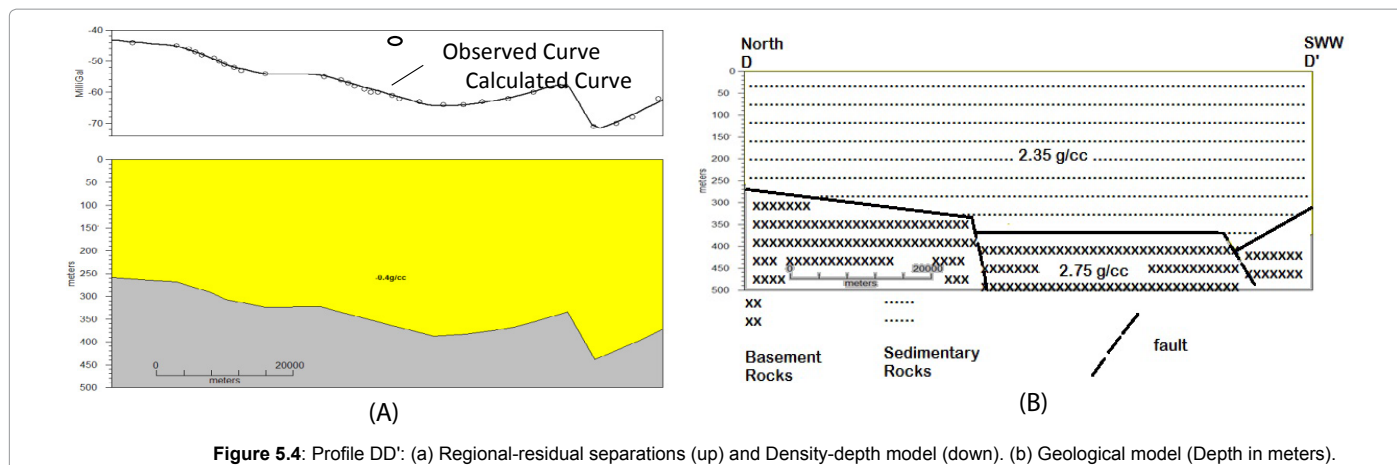
Figure 5.4: Profile DD': (a) Regional-residual separations (up) and Density-depth model (down). (b) Geological model (Depth in meters).

Rock type	Range (g/cc)	Average (g/cc)
Gneiss	2.59 – 3.00	2.65
Sedimentary rocks (av.)	-	2.35
Basalt	2.70 – 3.30	2.99
Basement Complex rocks (av.)	-	2.75
Acid igneous	2.30 – 3.11	2.61

Table 2: Density values of major rock types in the study area [5,19].

cutting a cross major structural features of the study area presented in Figures 5.1-5.4 and notable aspects of each of these modeled profiles have been discussed below.

Profile A-A': The profile AA' (Figure 5.1) begins from contour -58 (Long.16.85°N, Lat. 33.325°E) at NE crossing Awataib valley (Long. 16.54°N, Lat. 33.09°E) with length of 105 km. the model consists of one anomalous body (Nubian Sandstone) from the background (Basement) with gravity difference (effective density) of -0.4 g/cc with average thickness of maximum value about 430 meter at the middle of the profile and minimum value about 200 meter at the end of the profile and the structures have been estimated to be two faults, which bounding the grabben structure with decreasing of thickness towards the ends of the profile.

Profile B-B': Profile BB' (Figure 5.2) begins from contour -58 (Long.16.85°N, Lat. 33.325°E) at NWW crossing Awataib valley (Long. 16.54°N, Lat. 33.09°E) with length of 120 km. The model consists of one anomalous body (Nubian sandstone) from the background (Basement) with gravity difference (effective density) of -0.4 g/cc and average thickness of maximum value about 420 meter at the middle of the profile and minimum value about 325 meter at both ends of the profile and the structures have been estimated to be two faults which forming grabben structure with decreasing of thickness towards the end of the profile.

Profile C-C': Profile CC' (Figure 5.3) begins from B.H4 at N which the Basement level is 30 meter, at (Long.16.7°N, Lat. 33.25°E) crossing Awataib valley and ends at S (Long. 16.35°N, Lat. 33.32°E) with length of 130.2 km. The model consists of one anomalous body (Nubian Sandstone) from the background (Basement) with gravity difference (effective density) of -0.4 g/cc and average thickness of maximum value of 390 meter at the middle of the profile and minimum value of 145 meter at the end and the structures have been estimated to be two faults which forming grabben structure with decreasing of thickness of sediments thickness towards the end of the profile.

Profile D-D': Profile DD' (Figure 5.4) begins from B.H1 at contour -82 mGal (Long.16.78°N, Lat. 33. 25°E) at N, crossing Awataib valley and ends at S (Long. 16.825°N, Lat. 33.725°E) with length of 214.5 km. the model consists of one anomalous body (Nubian sandstone) from the background (Basement) with gravity difference (effective density) of -0.4 g/cc and average thickness of maximum value of 460 meter at the end of the profile and minimum value of 210 meter at the beginning of the profile and the structures have been estimated to be faults which forming grabben shape with decreasing to the end of the profile. The high relief in this density-depth section considered due erosion conditions rather than tectonics.

Discussion

The structural setting of Awataib valley is estimated by the regional Bouguer formula. This allows the buried unconformity surface in the region to be evaluated and contribute to the determination of variations in the crustal density across the major tectonic boundaries between Basement Complex and Sediments. There are significant changes in the character of the regional-residual curves when one moves from deeper to shallower sources. Interpretation of the profiles has shown that the structures responsible for the relatively high and low anomalies in the area are less dense than the standard upper mantle. Bouguer anomaly map, strongly, is surmising that the weird reversible steep gradient is due to rotational strike slip movement with NE-SW, crossed by another faulted-steep gradient with NW-SE at Awataib and continuing beyond the valley with the same trend NE-SW above Awataib valley. The last steep gradient is trending nearly W-E direction, fairly occurred at El-ban Gadeed village and probably related to a fault that have been discussed earlier by Almond and Ahmed [18].

Figure 5.1.b showed three estimated displacements that forming basinal grabben structure model. At the beginning of this profile a week steep gradient appears in Bouguer anomaly map coinciding with the trend of Awataib valley (Figure 2), but it ends at lat. 33.3°N long. 16.85°E and lies in Shendi-Atbara basin [19,20] suggested that Shendi-Atbara sub-basin was formed as isolated half-grabben structure during upper most Jurassic to lower most Cretaceous time.

Figure 5.2.b contains two fault models that seem to be produced with the same stress. At the beginning of the profile the first fault actually corresponds to the same week steep gradient in profile AA'. Figure 5.3.b shows a very characteristic feature at the beginning of the profile seems to be a horst structure, that formed by two opposite displacements in sense of ascending Basement, also it is crossing
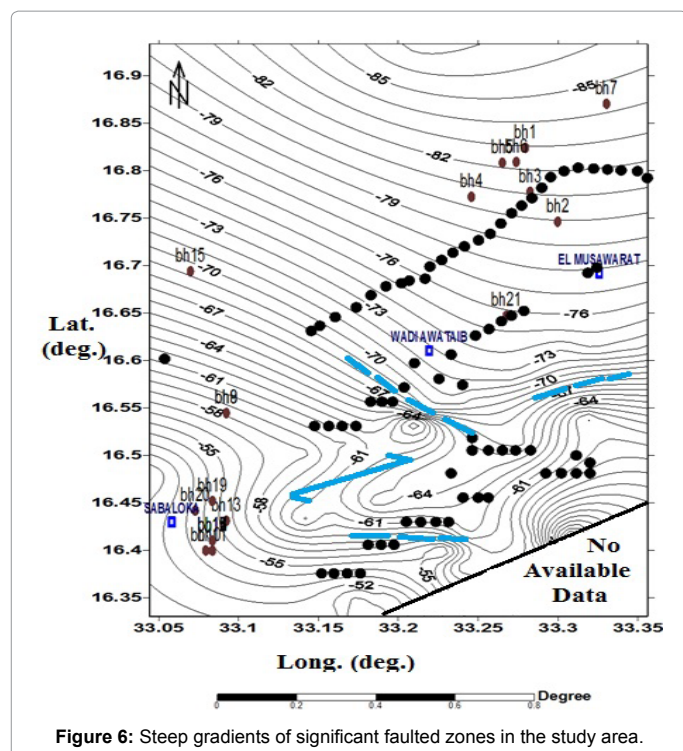
Figure 6: Steep gradients of significant faulted zones in the study area.

the eastern part of Awataib valley. The end of this profile consists of considerable steep gradient in Bouguer anomaly map coincides with eastern part of Awataib. Along the Central African Shear Zone a series of NW-SE trending transitional basins developed in response to intermittently reactivated pre-Cambrian discontinuities [21].

In Figure 3, in the middle south-eastern part of Bouguer anomaly map another weird and distinctive feature alike reverse directional steep gradients crossed partly by profile DD' (Figure 5.4). This profile (Figure 5.4b) shows two displacement models, the first in the middle and nearly coincides with the middle part of Awataib valley, the second is at the final part of the profile and is suggesting another fault zone backs us to Sabaloka area which already had been characterized by a strongly strike slip movement, but here, this movement somehow seems to be extended to cover the region between Sabaloka inlier and Awataib valley, moreover the trend of CASZ can be traced along the displacement zone with general trend of NE-SW. This new suggested faulting zone featured with directional lineaments of felsite dykes mostly with NW-SE may take place during very recent igneous activity. On the basis of geological and geophysical investigations, [22] confirmed the existence of several deep (>2 km) grabben and half-grabben structures. These structures are located southeast the Central African Fault Zone (CAFZ) [23]. The occurrence of obsidian bodies in close association with the felsite dykes put doubts about their age, and aged from K-Ar the obsidian 69 ± 2 Ma [18], but it is clear that at least some felsites predate the Nubian Sandstone Formation as they are seen overlain by Nubian Sandstone Formation in Sabaloka. The dominant dyke's trend is those in NNE, ENE, and NE, which are coinciding with some regional trends. Those trends are parallel to that one of the Central African Shear Zone (CASZ). In the study area, this direction has been shown by silicified elongated ridges of Nubian sandstone indicating faulting direction and then this raises the question of the beginning of new basin at Awataib valley (NW-SE general trend) [24].

The highs steep gradients at El Ban Gadeed and Naga are interpreted

as being associated with scattered meta–basic patches which probably have a much greater volume at depth than can be surmised from the surface outcrops as recorded by a gravity and magnetic survey of the Sabaloka area [4], which lies in our region of study. Some features that are delineated from geo-electrical resistivity data and steep gradient zones of gravity map, which are referred as faults, coincide with some valleys such as Awataib and affecting the Mesozoic sedimentary rocks that fill the above mentioned basinal features, but it is well known that these faults were formed during the first and second rifting phase. Thus, it is suggested that these faults were reactivated during the third rifting phase during Late Eocene/Miocene [6].

The Ban Gadeed- Naqa (adjacent to Awataib valley) modeled high anomaly as a western-dipping slab of dense, granulite facies rocks, which has been thrusted up westwards along a fault-plane dipping about 15°[8]. In fact, Awataib valley is being surmised as an up lifted Basement with high weathering conditions could took place after tectonic movements that showed in some miles SW away, in shape of several lineaments of felsite dykes which shows; silicified elongated ridges of Sandstone, slicking sides along the dykes and breccia blocks.

Conclusion

So far, all gravity models are containing considerable displacements coincide with some field observations that are characterizing the faulting zones. The detailed analysis of Bouguer anomaly map and the gravity derived models along the four profiles bring out two layer structures, which are: Basement Complex Crystalline Rocks and the Cretaceous Nubian Sandstone with density contrast of -0.4 g/cc. Steep gradients in Bouguer anomaly map (Figure 6) indicates four sets of faulted zones have general trends of NW-SE, SW-NE, and W-E as mentioned. The Density-Depth models produced geological sections that revealed small Grabben and Horst structures which are characterizing the Bouguer map and forming tow basinal feature that have been guessed, adjacently to the north-eastern and south-western directions of Awataib valley, have thickness about 275 meters suggesting good water-bearing Formations and boreholes could be drilled for, but at the south from the valley no basin or sub-basin estimated. At Awataib valley the high gravity has been considered due to the presence of Basement Complex that has been faulted and displaced.

The low gravity zone above it has been considered the beginning of Shendi-Atbara basin from the supposed fault boundary at Awataib valley. The displacement at Sabaloka through strike slip fault (Umm Marahik fault) is being extended as rotational strike slip movement into the suggested Awataib fault plane in sense of sub-basinal feature.

References

1. Ibrahim AM (2014) Gravity methods.

2. Lowrie W (2007) Fundamentals of geophysics.

3. Whiteman AJ (1971) The geology of the Sudan Republic. Clarendon Press, London pp: 290.

4. Sadig AA (1969) A gravity and magnetic survey of the Sabaloka area (Sudan) with details on the ring complex.

5. Dawoud AS, Sadig AA (1988) Structural and gravity evidence for an uplifted Pan-African Granulite Terrain in the Sabaloka Inlier, Sudan. J African Earth Sciences 7: 789-794.

6. Adam AO (2011) Geological and structural investigation based on regional gravity and vertical electrical sounding data of the East Nile Rift Basin – Sudan.

7. Almond DC (1980) Precambrian events at Sabaloka, near Khartoum, and their significance in the chronology of the basement complex of North-East Africa. Precamb Res 13: 43-62.

8. Dawoud AS, Schulz-Dobrik B (1993) PT conditions of Pan-African granulite facies metamorphism in Sabaloka inlier, North of Khartoum, Sudan.

9. Ibrahim AE (1993) Interpretation of gravity and magnetic data from the Central African Rift System, Sudan.

10. Omer MK (1983) The geology of the Nubian sandstone formation in Sudan: Stratigraphy, sedimentation dynamics and diagenesis, Sudan.

11. Abdullatif OM (1995) Lacustrine deposits in the upper cretaceous shendi formation, Central Sudan. Department of geology, University of Khartoum, Sudan. Abstracts of papers. The First International Limno-Geological Congress Copenhagen, Denmark.

12. Kheiralla MK (1966) A study of the Nubian sandstone formation of the Nile Valley between 12°N and 17°42'N with reference to the groundwater geology.

13. Bireir F (1993) Sedimentological investigation around the state of Khartoum and on the northern Central part of Gezira formation. Central Sudan.

14. Awad MZ (1994) Stratigraphic, palynological and palaeoecological studies in the east-central Sudan (Khartoum and Kosti Basins), Late Jurassic to Mid-Tertiary.

15. Schandelmeier H (1987) The proterozoic of Southern Egypt and Northern Sudan and its relationship to the Mozambique Belt.

16. Browne SE, Fairhead JD (1983) Gravity study of the central African rift system, a model of continental disruption, The Ngaoundere and Abu Gabra Rifts. Tectonophysics 94: 187-203.

17. Talwani M, Lamar WJ, Mark L (1959) Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone. J Geophys Res 64: 49-59.

18. Almond DC, Ahmed F (1993) Field guide to the geology of the Sabaloka Inlier, Central Sudan.

19. Telford WR, Geldart LP, Sheriff RE (1990) Applied geophysics: Cambridge University Press, Cambridge, New York.

20. Bussert R, Brasse H, Radic T, Reynolds O (1990) Sedimentation and structural style of a rift-structure in Northern Sudan: The Humar Basin 1: 89-108.

21. Jorgensen GJ, Bosworth W (1989) Gravity modeling in the Central African Rift System, Sudan: Rift geometries and tectonic significance. J African Earth Sci 8: 283-306.

22. Wycisk P, Jas C, Reynolds O (1990) Intracratonal sequence development and structural control of phanerozoic strata in Sudan. Berline Geowiss Abh 120: 45-86.

23. Schandelmeier H, Pudlo D (1990) The Central African Fault System (CAFZ) in Sudan – A possible continental transform fault: Berliner Geowiss Abh A120: 31-44.

24. Ali AS (2001) Geology and structure of the north-eastern periphery of Khartoum Basin –Sudan, using remote, sensing technique and gravity method.