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On the Gravity Anomalies at Abu Deleig Sub-Basin and The West of Butana Basement Faulting Zone of the Central African Shear Zone (CASZ), Blue Nile Rift Basin, East of Central Sudan

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Abstract

Following a period of deep erosion, the Sabaloka ring complex and associated volcanic rocks in central Sudan were emplaced in mid-Palaeozoic times including Butana area. The existence of sedimentary basins within this area of central Butana was previously unknown, however a 2-D Gravity modeling ran to uncover the concealed basement-sediments contact through two profiles in addition to evaluate the structural relationships with adjacent basement occurrences. The regional-residual separation made graphically, to separate by referencing the maximum recorded depth to the basement at 37.5 m at Abu Deleig town (after Salvatore, 2001) and then model the residual component in of Bouguer anomaly to obtain the 2D density structural models.A density contrast of -400kg/m3 has been used to model the prismatic configuration of densities distribution. The study area was exposed to several phases of dragging and fraction, which allowed to the settlement of the recent sedimentary cover (i.e., Butana clays and Nubian Sandstone Formation). The Bouguer anomaly map shows a contact with high steep gradients of two closures around Abu Deleig town different in values from -61.5 mGal to -44.6 mGal, surmised to be a major normal fault controls the structure of Abu Deleig sub-basin. The outcome of the present study reveals that the Abu Deleig sub-basin is evidently linked to Blue Nile rift basin. The estimated sedimentary thickness ranges from ≥ 300 meters, probableto contain good quality groundwater aquifers, to 2.4km to the north of Abu Deleig may connects to Shendi basin.

Keywords: 2-D Gravity modeling, Abu Deleig sub-basin, Bouguer anomaly, Central Butana, Central African Shear Zone, Shendi basin.

Introduction

Study area is a transitional area between the Butana basement terrain to the east; and Khartoum and Shendi sedimentary basins to the Wand NW, respectively. The structural setting is complicated and the existence of sedimentary basinal features within this area recently, was unknown. The study area is located in the eastern flank of Khartoum State, bounded by latitudes 15°30′–16°00′N and longitudes 33°30′–34°00′E. (Figure - 1)The Basement Complex is composed of interbedded amphibolitic slates and marbles, quartzites, granitic gneisses and granites, whereas the Nubian Sandstone Formation comprises a basal conglomerate, intra formational conglomerates, mudstones, coarse-grained sandstones and arkosic sandstone. Ahmed [1] mapped and described the petrography and geology of Jebel Qeili ring complex in the Butana area. It is covered by Cenozoic sediments (Butana clays) and sandstone of Cretaceous age, uncomformably overlying the Precambrian basement rocks. Geophysical survey covering most of central Sudan, including Butana area, has been conducted by Sun Oil Company in 1984 [2]. The main objective of this study is to define the geometric configuration of the sedimentary basin and to delineate the boundary between the basement and sedimentary rocks using gravity data. Ordovicion igneous rocks in the study area crop at Wadi Abu Tuleih. This complex was first mapped by Delany [3], but Almond [4] was first to carry out any detailed work. The complex is anorogenic and consists of syenitic and micro-granitic varieties. The complex was probably emplaced about 463 Ma (Middle Ordovicion) [5,6]. Whiteman [7] provided a review about the distribution of the basement and the nomenclature, origin, and composition of Nubian Sandstone Formation. The study aims to investigate the extent of the influence of the fractured contact by the use of gravity methods to delineate the general geological aspects of the sediments overlying the crystalline rocks for exploration of groundwater in the area. Jebel Qeili (Ahmed, 1968, Delany 1955) lies 130km. east of Khartoum and forms an isolated group of hills in the clay plain of the Butana, rising some 150m. above the plain. The riebeckite syenite forming the main hill was recognized many years ago. The area is characterized by undulated topography, which is dominated by the scattered hilly remnants of Nubian Sandstone and the residual of gravels, bounded to the east by the Butana peneplain.The geology and structures of the Pre-Nubian Pan-African (age = 950 to 550 ma) and the basement complex of the Sabaloka inlier west of the study area have been studied by (Dawoud, Almond) [8,9]. Nubian Sandstone Formation of the Nile valleyis divided in the Khartoum basin into five lithological unitsKhairalla (1966).

Geology of the Area

General

The linear exposures in the Gorge of the Nile make it difficult to trace the trend of extensional structures related to the Blue Nile Basin [10]. In the Butana region, several hills occur and make prominent landmarks. The geological column of the study area can be summarized as follow: Superficial deposits of clays, stream's alluvium and wind-blown sands (Quaternary to recent) – Nubian Sandstone Formation of conglomerates, sandstones and mudstone (Cretaceous) – Younger granites; dykes of various composition, Granites, Syenites, Gabbros and Rhyolites being disconformity with Synorogenic granites; Granites,

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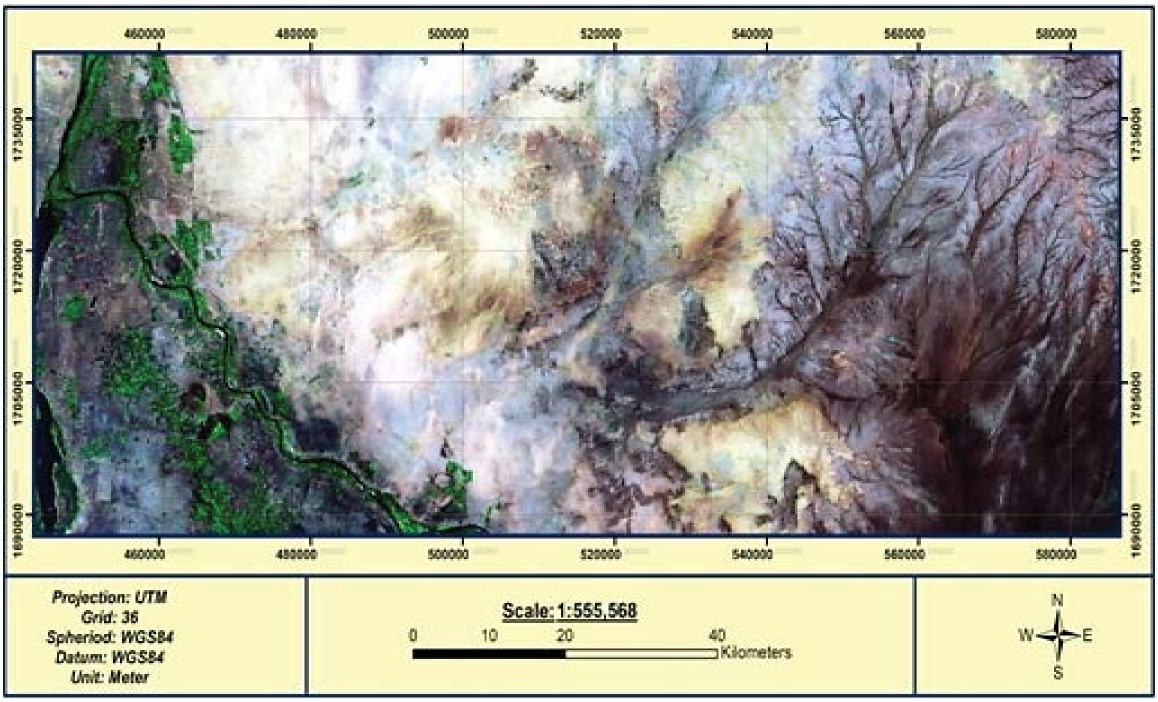

Figure 1: Location of the study area overlain on Landsat ETM color composite.

granodiorites, tonalities and gabbros (Plaezoic to Mesozoic?) – The highly deformed Arc metavolcanics: Metasediments of graphite schists, marbles and quartzites, Ophiolitic complex of serpentinites, talc-carbonate schists, meta-gabbros& pillow lavas, Quartzo-feldspathic gneisses of Biotite-, hornblende-gniesses (Late Proterozoic).

The J. Qeili group results from the intrusion of gabbroic to syenitic derivates of an alkali rich magma through the schist series of the Basement Complex. An outer augite syenite with a chilled quartz-orthoclase margin was intruded by an essexite. The inner syenite oval cuts through the basic phase and was itself disturbed by the emplacement of the central plug of riebeckite quartz-syenite. The centres of the successive intrusions were constantly displaced to the SW. The rock types are definitely disposed in rings but later arcuate dykes, more easily distinguished on the air photographs, contribute especially to the annular appearance of the outer intrusions. Dykes of micro-syenite, sometimes with quartz and riebeckite are abundant in the syenite ovals and chilled margin. Later sodic dykes with varying pyribole content, bostonites, grorudites and felsites may be found in all the intrusions and have frequently a radial orientation, parallel to the joint systems. J. Qeili gravity profile as reported by Sadig and Ahmed, (1989) is marked by a broad negative anomaly on which is superimposed a positive anomaly which coincides with the gabbro intrusion.

Tectonic settings

The Mesozoic-Cenozoic basins through the entire region of Sudan, which were investigated by using aeromagnetic and gravity data, showed several sedimentary structural basins NW of the Central African Shear Zone (Ibrahim, 1993). The area consists of fractured crystalline basement rock which is partially covered by thin layers of superficial aeolian and alluvial deposits. Paleozoic sedimentary rocks within the Blue Nile Basin might be due to uplift during the Paleozoic Era resulting in extensive erosion throughout this area. The Neoproterozoic basement rocks are affected by normal faults which are NNE and ESE-trending normal faults and more common than NE- and NW-trending faults (N. Gani et al. 2009). During the Triassic–Cretaceous time, northern and central Africa was affected by lithospheric extension associated with NE–SWextension [11]. Several metasedimentary sub-parallel belts extend for 10–25km in the form of low to moderately elevated ridges surrounded by Butana clay cover [12]. The early recumbent folding in Sabaloka 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 Butana peneplain lies between two major rift basins; the Nile to the north and the Blue Nile to the south. Blue Nile rift basin terminates sharply in the southeast against the NE-trending Central African Shear Zone, which is considered to be a major dextral strike-slip shear zone [13,14]. Mesozoic sedimentary sections and a few observed NW-trending faults and suggest that the Blue Nile rift Basin is related to Mesozoic rift basins of eastern and central Africa [15]. The Blue Nile Basin is thought to have formed during the Late Jurassic on the basis of K/Ar age (143±6 and 124±5 Ma) of two basaltic layers encountered in the Khartoum Basin of the Blue Nile Rift in Sudan [16].

Nubian Sandstone Formation (Cretaceous)

The term Nubian Sandstone applies to the sandstone occurring in the Nubian Desert of Egypt [17], Libya and Sudan, and early reported by Sandford (1935) [18] for north-western Sudan. The Nubian Sandstone Formation is mainly composed of conglomerates, sandstone, sandy mudstones and mudstones which rest uncomformably on the basement complex. Sedimentological and paleontological studies have contributed greatly to the subdivisions of these rocks. In the Sudan the quasi – horizontal Nubian Sandstone Formation overlies the

Basement Complex rocks with a pronounced angular unconformity. This formation occurs along the NE Periphery of central Butana region [19] and shows deformational characteristics such as; fault breccais, silicified, brecciated dipping about 30° and 80° W.This dip amount is due to possible dragging associated with faults. Lower Sandstone is found uncomformably overlying Neoproterozoic basement rocks and, in turn, is overlain by Early–Late Oligocene volcanic rocks in the NW-flowing segment of the Blue Nile and is considered to be Triassic–Early Jurassic in age [20].

Basaltic Intrusion in Central and NE Sudan

Eruptions of alkali basalt have occurred intermittently in northern Sudan from late Cretaceous until very recent times, but their modes of expression have varied considerably was associated with formation of a NW-trending extensional basin parallel to a newly developing plate margin along the Red Sea depression [21]. The Cretaceous basalts including fine-grained dolerites are generally olivine-bearing alkali basalts. Tertiary basalts cover a vast area in E Sudan, and also extends eastwards into Ethiopian plateau. It overlies unconformably the basement complex of the Precambrian and the Nubian Sandstone Formation of Cretaceous ages. The gravity significance of these volcanics is expected in the shendi basin since it was recorded many times during the drilling operations, and the basin's anomaly is negatively broad but at least one point is higher than the adjacent ones.

Gravity Data Processing

The gravity map of Central Sudan covers an area situated between Latitude 16-18°N and Longitude 32-35°E. The gravity data obtained from the open file of the Ministry of Energy and Mining-Sudan which included 49 Bouguer anomaly points spreading in the area, collected by Sun Oil company (1984) and a recent survey in May 2018 by the University of Khartoum, department of Geology for Soba Valley geophysical investigation project (unpublished report). All gravity stations were tied with the International Gravity Standardization Network (IGSN).The spacing between two adjacent lines ranges from 10-60km, whereas for adjacent stations ranges from 3-5km. The spacing is selected whenever gravity readings are shown to vary rapidly with distance. Two profiles (Figure -2) were selected to conduct 2-D Modeling crossing J. Qeili Basement complex. A density contrast of -400kg/m3 has been implemented (after Qureshi, 1971) [22] to initiate the modeling through open access software GravMod© v.3.2 a program for simple 2-D modeling of Bouguer anomaly data. The residual anomalies have been modeled to obtain 2D density-depth distribution models of basement and sedimentary rocks above it, then interpretation made based on regional structural geology.

Bouguer Anomaly Map

Bouguer anomaly map (Figure- 3) has negative gravity values. With -1.00 mGal interval, it shows many contour closures and steep gradients.It exhibits considerable variations between the Basement complex and sediments above it. The lowest anomaly value is -73.8 mGal at the upper right corner, and the highest value is -28.6 mGal in the lower left cornerin (Figure-2). The Abu Deleig area lies in the upper right corner which's bounded by two contour closures; -48 and -28.6 mGals. This texture reflects a possible structural contact between high density rock of a metavolcanic rock from basement complex, and a relatively low-density rock of Nubian sandstone & Butana clay layers. In addition, the steep gradients in that area it indicates a possible step and deep faults. Generalization of Fig. 2, it seems there's a major controlling structure running N-S. This major controlling fault is within highly basement complex, because the anomaly differences aren't too much in comparison with other adjacent basins. The anomalies range between -28.6 mGal and -40 mGal can be due to high density rock of basalt and granulite facies.

Regional-Residual Fields Separation

The obtained Bouguer anomalies are divided into deep seated and local anomalies based on the basement relief. The anomalies of -45.5

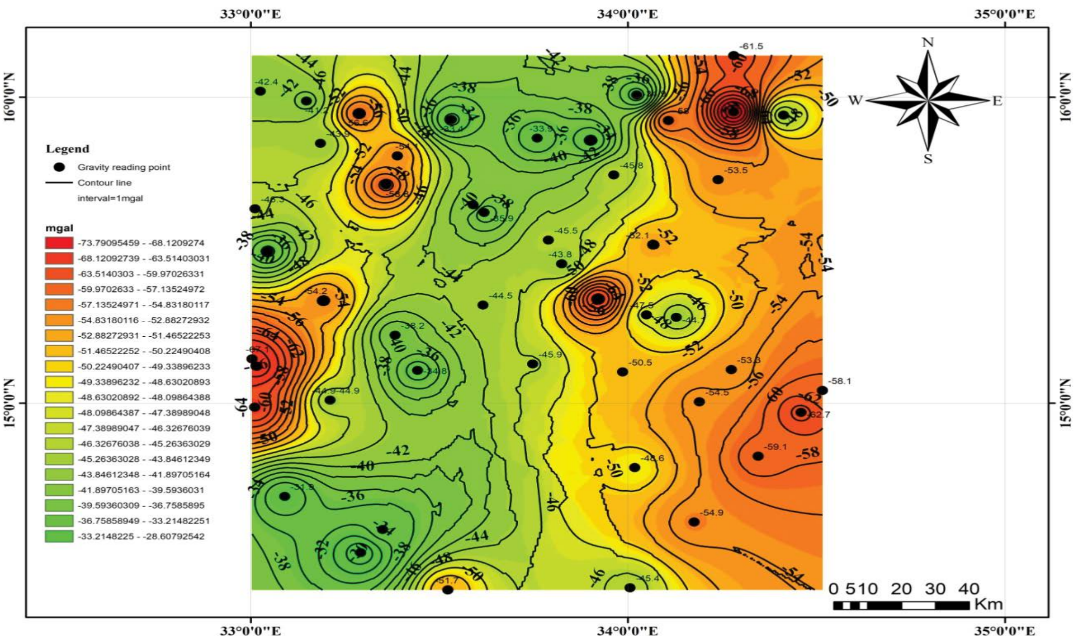

Figure 2: Bouguer Anomaly Map of the study area.

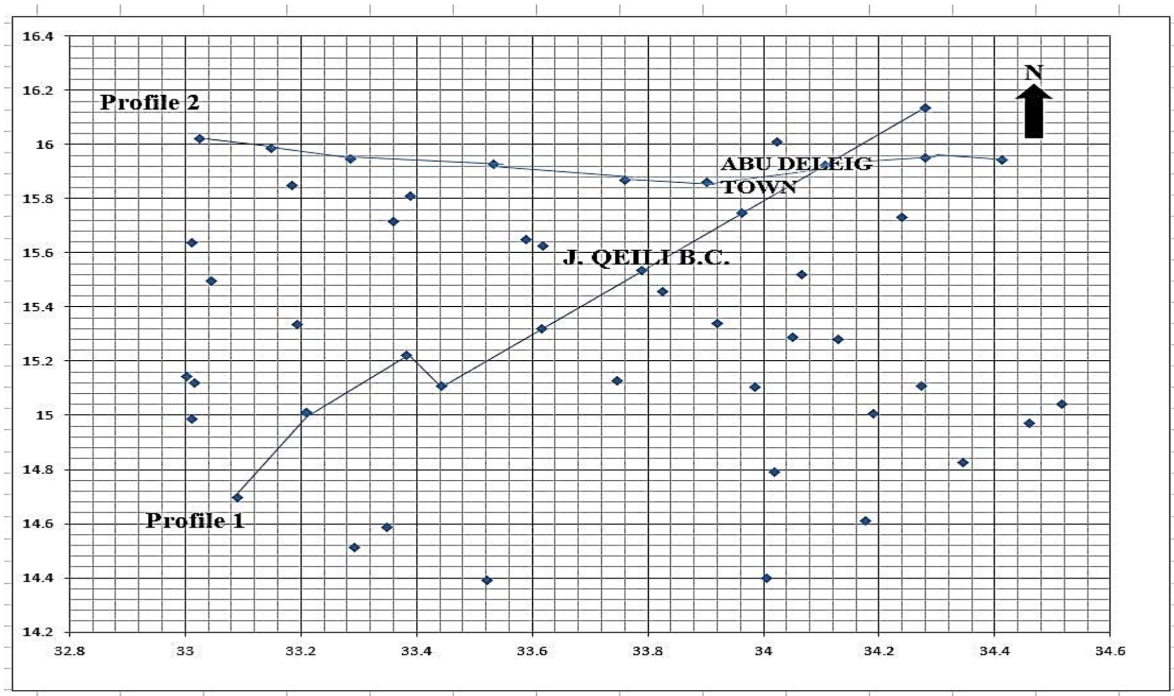

Figure 3: Gravity profiles for 2D modeling in the study area.

mGal was taken at the basement outcrop of J. Qeili (15° 30' N, 33° 45' E) which is considered to be the reference reading to separate regional/residual gravity field, however Gravity data obtained from the open files of the Ministry of Energy and Mining, Sudan were used to construct Bouguer map and to separate, graphically, the residual field from the regional one of the gravity anomaliesby referencing the maximum recorded depth to the basement at 37.5 m (after Salvatore, 2001) and then model the residual componentin of Bouguer anomaly to obtain the 2D density structural models.

2D Modeling Results

The regional Bouguer gravity map of Africa published by the United States Defense Mapping Agency [23] outlines very broad wavelength features in the study area. The average densities of sedimentary cover and Basement complex are considered to be 2.35 gm/cc and 2.75 gm/cc, respectively due to the occurrence of iterative rocks having the same density value. Brown and Girdler (1980) have reported the results of a gravity traverse across northern Africa conducted in 1975 by the British army and air force. The survey started in Dakar, Senegal, and ended in Cairo, Egypt, traversing through northern Sudan, Both the Bouguer anomaly map of Africa and the data reported have provided information concerning the nature of the background gravity field in the Sudan.

Abu Deleig Profile 1

This profile runs from SW to NE directions starting from 33˚.2106 E 15°.0097 N and ends at 34°.2806 E 16°.1355 N. Its length is 28 Km with the highest anomaly of -34.8mGal and the lowest anomaly is -61.5mGal. The thickness of the sediments (red color) at the right side of the profile is more than 1 km while the rest is basement complex (no color) with high density rocks probably the Arc meta volcanics rocks which show faulting. The drilled borehole at Sheikh Ali Abu Deleig village encountered basement rocks at a depth of 37.5 m which lies within -50 mGal contour line (after Salvatore, 2001). The low gravity over the end of this profile may indicate the presence of green schist facies as it has low density similar to the surroundings edimentary formation thus the total thickness of the sub-basin increased dramatically.

Abu Deleig Profile 2

This profile runs from W to E directions starting from33°.0257 E 16°.0194 N and ends at 34°.4124 E 15°.9412 N. Its length is 24 Km with the highest anomaly of -33.4 mGal and the lowest anomaly is -73.8 mGal. The thickness of the sediments (red color) at the middle is about ≥ 1.00 Km and 3.5 Km at the right side while the rest of the profile is dominated by basement complex(no color). In the middle of the profile the anomalies are in the range of -33 mGal which can refer to the granulite facies rocks. The sub-basin has a prism-like shape with its apex at Abu Deleig town. Its length is approximately 40 km, the width ranges from 20 km in the apex to 30 km in the NW. The depth to the basement is 20 m at Abu Deleig and more than 300 m in the northwestern part [24].

The West of Butana Basement Faulting Zone

From Fig.2 Abu Deleig area is a transitional area between the Butana basement terrain to the east; and Khartoum and Shendi sedimentary basins to the West and North West directions, respectively.The tectonic model assumed responsible for generating areas of thinned crust involves lithospheric stretching that results from tensional stresses acting normal to the axes of the rift basins. Such a model provides a mechanism for rift basin formation through isostatic and thermal subsidence [25, 26]. The most negative residual gravity lows are -23.9 and -28.9 mGal for the Khartoum South and Khartoum Basins, respectively (after Jorgensen and Bosworth 1989). The Pan-African granulites of the Sabaloka basement complex (Kroner) [27] occur in an in lier of about 3000 km2 north of Khartoum that is encircled by Nubian Sandstone Sediments of Cretaceous age. The Schists of the green schist facies metamorphism consists of basic volcanic rocks of basaltic to andesitic composition group predominantly developed in the central Butana area. They represent the low-grade metamorphic rocks, an evidence and extension of the ancient subduction zone between Nile craton and Mozambique belt in the area. The Central African Shear Zone (CASZ) is a 4000km in the longest axis, NE-striking wrench fault system, along which motion occurred during the break-up of Gondwanaland, but its location in central Sudan was poorly defined (Ibrahim) [28]. The structural history of the area is complex and difficult to study because of the isolated nature of the outcrops. However, three phases of folding were identified and appear to have affected the basement rocks in Ban Gadeed area north to our study area. No obvious structural differences between the granulites and the enclosing gneisses and migmatites are noted (Dawoud) [29]. Along the Central African Shear Zone (CASZ) a group of basins developed, NW-SE trending, in response to intermittently reactivated pre-cambrian discontinuities [30, 31]. 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 (Browne and Fairhead) [32].

Ibrahim et al. (1996), suggested the existence of approximately ten sedimentary basins in central Sudan, northwest of the CASZ. The second rifting phase occurred during Late Cretaceous/Early Tertiary (Turonian-Paleocene), during which the extension shifted to a NE-SW orientation. During this rifting phase all known Mesozoic basins of Sudan (e.g., Atbara and Shendi basins) were reactivated [33]. The increased depth of burial of the rift structures beneath the post-rift sediments in this region causes an inherent decrease in the resolution of the gravity data, thus the slope breaks which observed in thegravity map (Fig.2) and the model indicates that a series of normal faults occur at west of Abu Deleig area suggesting a beginning of a newly small geometrical graben-like structure (Figure- 4).

Abu Deleig Sub-Basin Geometry

As it known well in eastern Sudan, the Butana area contains sediments that cover the shallow Basement complex. The geological succession here contains: Schist of the green-schist facies metamorphism, basic volcanic rocks of basaltic to andesitic composition, older alluvium deposits of Elat shan Formation cover the area between the Blue Nile and Atbara Riversand unconsolidated sands, clays and gravels as superficial deposits. Fig. 6 shows an estimated geometrical configuration of the Abu Deleig Sub-Basin it displays an increasing thickness of sedimentary rocks in a step manner towards the NW, due to the NE–SW normal faults. The sub-basin has a graben-like shape with its apex at Abu Deleig town, its maximum estimated thickness estimated to be around 300meters. Its length is ~ 45km, the width ranges from 20 km in the apex to 30 km in the NW. The depth to the basement is ~ 40m at Abu Deleig town and more than 300m in the northwestern part, until it reaches Shendi basin to the north which has approximate maximum thickness of ~ 2km depth. The outcome of the present study reveals that the Abu Deleig sub-basin is evidently linked Shendi Basins in the NNW direction, which confirms the results of Elsheikh et al. 2014.

Discussion and Conclusion

There are significant changes in the character of the regional-residual curves when one moves from deeper to shallower sources. The basement rocks are exposed at the surface to the south of Abu Deleig town, whereas the sandstone crops out in the north. The area consists

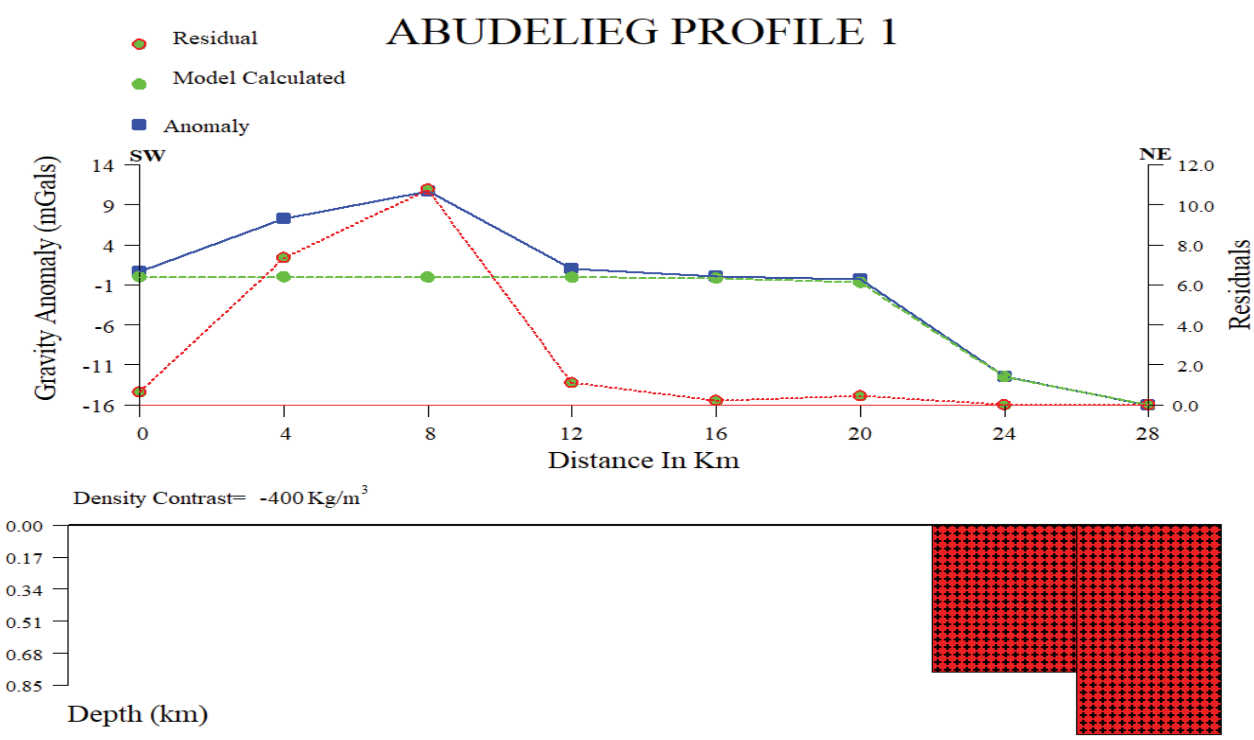

Figure 4: 2-D Density-Depth model of Abu Deleig Profile 1

of fractured crystalline basement rock which is partially covered by thin layers of superficial aeolian and alluvial deposits. Normal faults have been produced from the extensional open fractures in two tectonic phases in the area and can be estimate from Fig. 4 and 5. The sedimentary rocks are supposed to be preserved in the down thrown block of the normal faults. Profile 2 shows a small sub-basin, about 1 km. thickness to the southwest of Abu Deleig village near Awataib valley area similar to some small graben-basin structures discussed by Hussein and Mula [34]. The area north of Abu Deleig town (Fig. 2) shows similar gravity anomaly to sedimentary basin around the area, therefore, this area was expected to represent a shallow sedimentary basin. Browne and Fair head (1983) calculated crustal extension of between 22 and 45 km in the Abu-Gabra Basin of the Southam Sudan Rift using regional gravity models. This suggests that a general decrease in the magnitude of crustal extension occurs from the southwest to the northeast away from the major zone of lithospheric thinning located along the western border of Sudan.

According to Salvatore [35], the low amplitude negative anomaly east to J. Qeili is attributed to the low-density granitic mass, intruded into the relatively denser metamorphic terrain. The Abu Deleig sub-basin has a prism-like shape with its apex at Abu Deleig town. Its length is approximately 40 km, the width ranges from 20 km in the apex to 30 km in the NW. The 2D modeling results of this investigation shows that, the Abu Deleig sub-basin surmised to be linked to Shendi Basin in the northwest. A previous thought was that the Abu Deleig area is mainly built up of impermeable crystalline basement rocks with no possibility of groundwater occurrences.

As in (Figure- 5, 6) the sedimentary covers show considerable variation from few hundreds to up to 3.5 Km, which may indicate a possible fault. As sediment thickness also varies between the Sudanese basins, with up to 15 km of fill in the Muglad basin (Schull) [36] and possibly as little as 1 km in the Blue Nile rift (Jorgensen and Bosworth, 1989). (Figure - 7) describes the Precambrian basement exposures, crustal types, and ophiolites and ophiolitic rocks in the area, however Abu Deleig basement complex presence is surmised to be only be explained by an emplacement of granite-syenite bodies which are characterized by relatively low densities with respect to the regionally extensive basic rocks within the area, also the previous interpretations

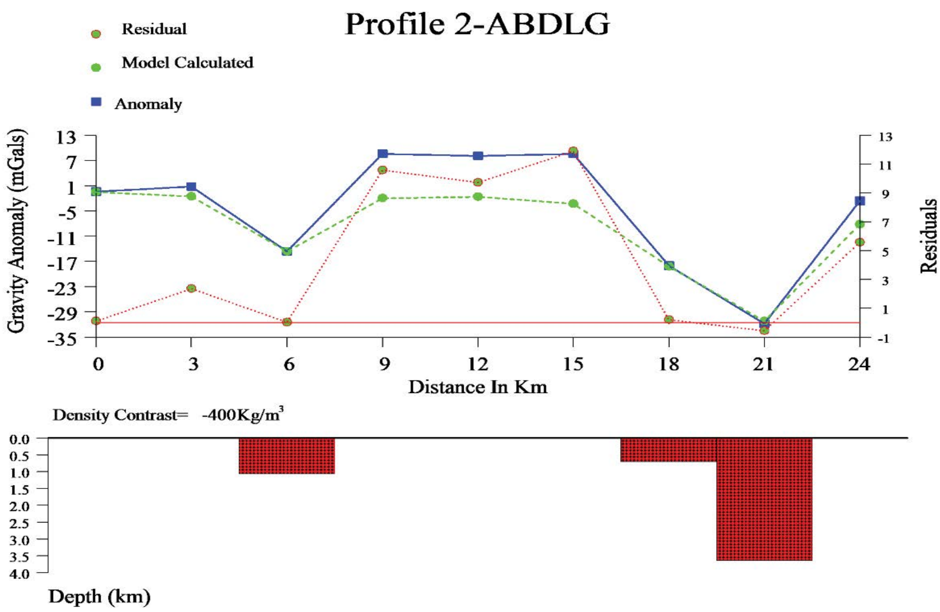

Figure 5: 2-D Density-Depth model of Abu Deleig Profile 2.

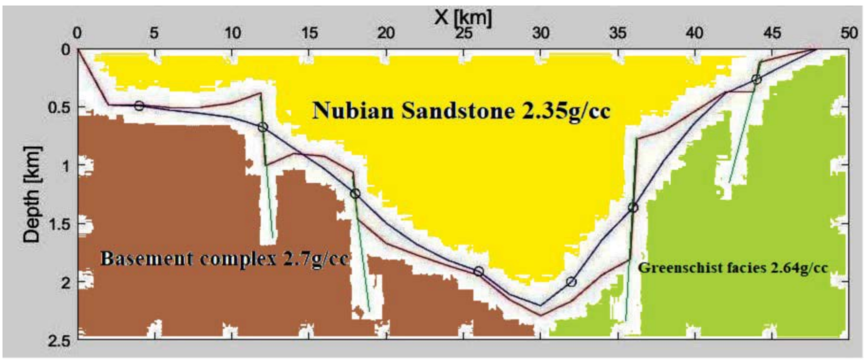

Figure 6: Estimated Geo-gravi-geometrical configuration and sedimentary thickness of the Abu Deleig Sub-Basin and the Adjacent Shendi basin in the middle.

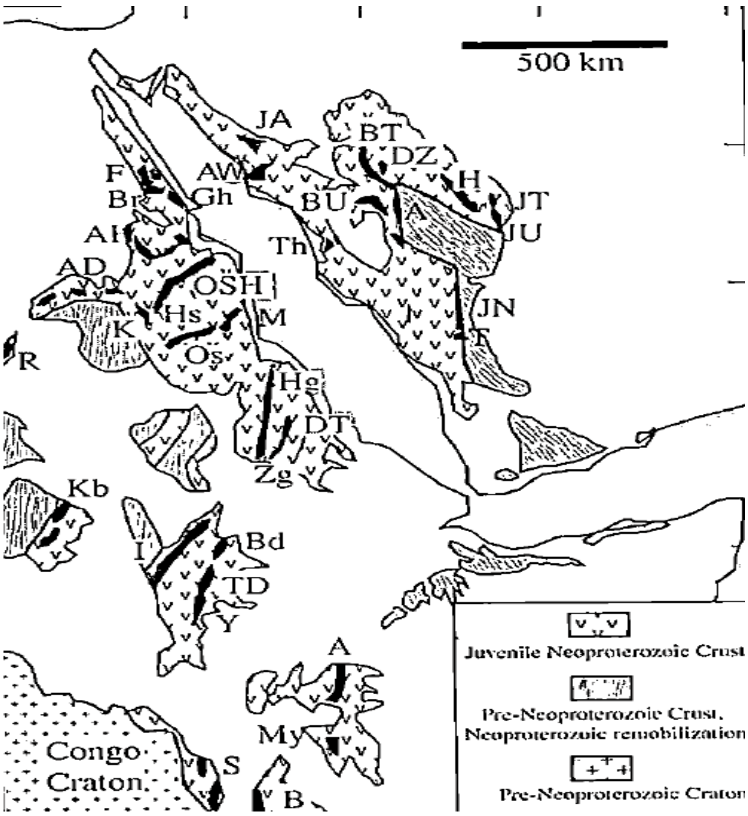

Figure 7: Location of Precambrian basement exposures, crustal types, and ophiolites and ophiolitic rocks

did not satisfy the available geological and geophysical data. More geophysical and structural investigations are required to explain the dimensions of these basement boundaries.

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