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# Tectono-Gravity Probing and Observations on the Rising Mantle Wedge in Central, NE and N Sudan Areas

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## Abstract

In the present study, two regions of the NE, N areas of Sudan have been investigated through gravity probing. A recognized number of anomalies have been observed, interpreted in the light of the plate tectonics theory models and the related structural deformation of the Wilson cycle in the western part of the Nubian-Arabian Shield. These gravity data have been acquired by many foreign and geological institutions contoured to prepare two gravity maps of the whole country, and N Sudan regions. The derived models uncover a new region with mantle up-welling and mantle wedge along the Red Sea offshore and central NE Sudan as a possible extension of S of Keraf Shear Zone, respectively, while the others have shown crustal thickening decorated by ophiolitic shear zones. High anomalies indicate a higher density-rock appraised to exist from the 3D gravity model and buried within the vicinity of Atbara and Shandi cities and are being referred to as buried ophiolitic sinusoids, low-grade metamorphic rocks of greenschist facies with tectonic mélange of a subduction zone. Their possible source according to the anomalies is surmised to be the Serpentinized - Mantle wedge of the Neoproterozoic subduction zone formed beneath the southern extension of Keraf Shear Zone, which is buried under the recent thinner and lighter geological cover in the Shendi-Atbra vicinity. A crustal thickening texture with various undulations in the Mohos' interface has been observed from the gravity map that occurs in the lithospheric length between Nile valley and the Red Sea offshore.

**Keywords:** Keraf Suture; Gravity methods; NE Sudan Geology; Nile craton; Mozambique belt; Serpentinized-Mantle wedge.

## Introduction

The Red Sea is characterized by positive gravity anomalies along its center, whereas the East African Rift Valleys have negative anomalies [1], also he concluded that the gravity maximum appears to be associated with a deep trough (about 30 to 40 miles wide)alongside the Red Sea but the anomalies on each side being small. The Precambrian geology in NE Africa comprises two distinct crustal domains: the Nile craton and the Arabian-Nubian Shield [2 - 4]. (Figure - 1). The supercontinent of Greater Gondwana formed by collision between East and West Gondwana at about 650–600 Ma after consumption of the Neoproterozoic 'Mozambique Ocean' [2]. This resulted in the formation of the~ 5000 km long East African Orogen, which comprises the Arabian-Nubian Shield in the north and the Mozambique Belt to the south [2]. The Nile craton is dominated by heterogeneous gneisses and supra-crustal metasediments of pre-Neoproterozoic ages and ensialic geochemical affinities [3,4]. The Nile craton has been pervasively remobilized during the Neoproterozoic Pan African Orogeny [2-4]. The location, nature and deformation history of the boundary between the Arabian-Nubian Shield and the Nile Craton are controversial topics [5]. The identification of the Nile craton came mainly from the geo-chronological and isotopic composition of the gneisses. U/Pb zircon ages, Nd model ages, Pb, Sr and Nd isotopic composition point to the fact that the gneisses west of the Nile are mostly older than 900 Ma and have an old crustal history [6, 2]. Shuttle Imaging Radar data enabled tracing structures in the Keraf Shear Zone for~ 550 km from the Sudanese/Egyptian border south to the vicinity of Atbara, where the structure is lost beneath Phanerozoic sediments [7,8]. The older granitoids group is characteristic of the basement complex of Sabaloka inlier and defines a phaseof granites very closely related to the high-gradegneisses and metasediments [9]. In the Sabaloka in lier three types of older granitoids can be distinguished.

In mid-seventies, the campaign for hydrocarbon exploration in the Sudan was intensified. The gravity survey conducted by geophysical Companies in 1984 for the above-mentioned purpose revealed numerous high and low gravity anomalies distributed in various parts of Sudan. Fig. 1 displays the map of Sudan, as the objective of the recent work is to cover the whole country with gravity anomalies and then delineate the tectono-gravity textures by 2D gravity-modeling theory and a unified crustal layer and mantle assumptions. The ophiolite model for the crust of the deep oceans must be approached with some caution, however, because most major ophiolite complexes may represent either fore-arc limbs of island arcs (Gealey, 1980), marginal basin material (Harper, 1980) or former oceanic crust adjacent to fracture zones (Karson and Dewey, 1978). Reconstructed stratigraphy of the oceanic crust shows basic volcanics at the top with associated metalliferous sediments which grade downward into sheeted dolerite dykes and then into a cumulate section whose base is usually a metamorphic peridotite (Coleman, 1977).

The oceanic crust stratigraphy provides a framework for systematic prospecting of on-land ophiolites. For example, the massive sulphide deposits and their associated gold-rich gossans which form presently at hydrothermal vents on the modem seafloor are restricted to the mafic volcanic units (pillow lavas) and chromite deposits are confined to the ultramafic units of the suite. Massive sulphide deposits have been found associated with active hot springs in a variety of geotectonic settings on the modern seafloor, including mid-ocean ridges, axis and off-axis seamounts, back-arc spreading centres and sedimented intera-

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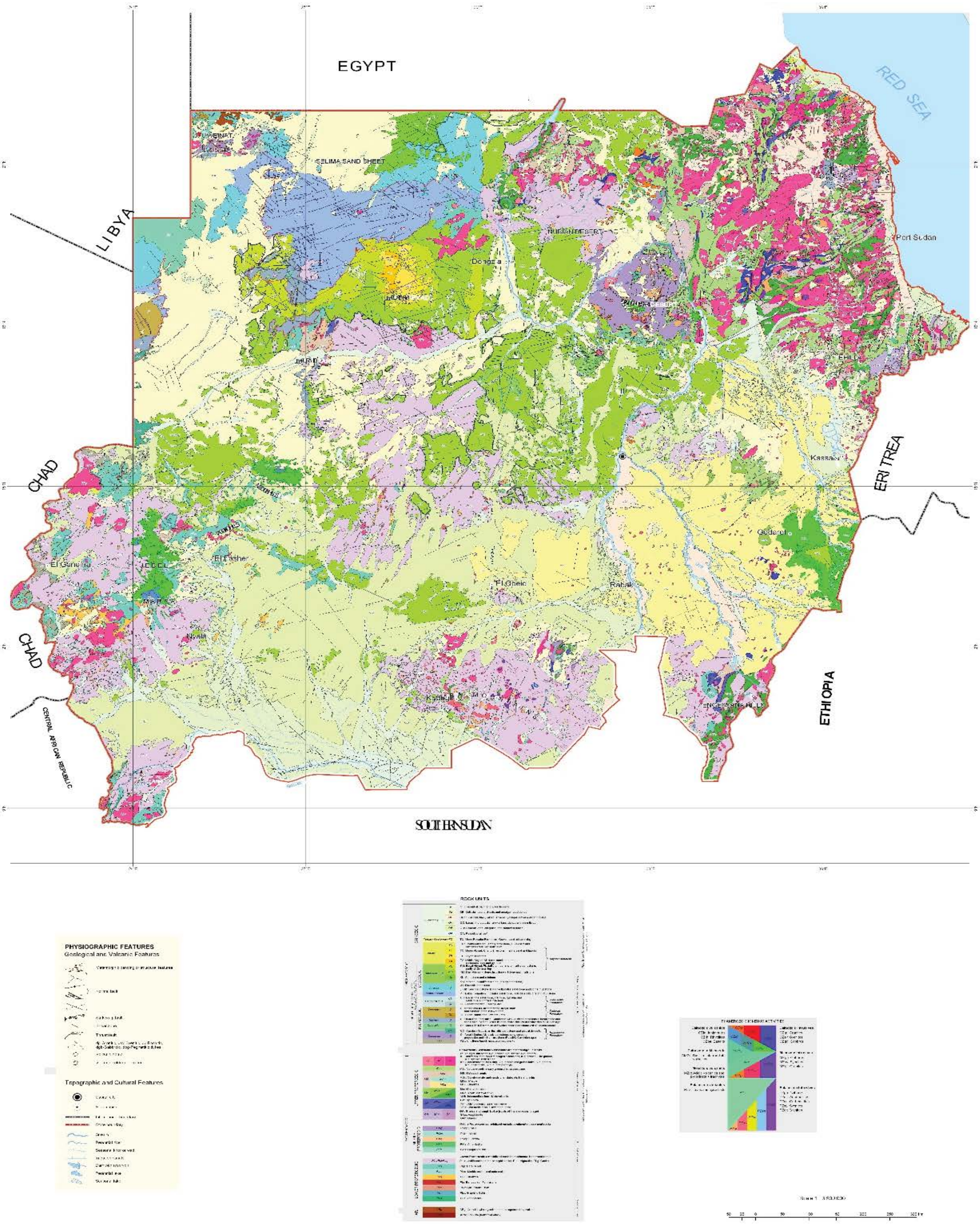


**Figure 1:** Geological map of Republic of Sudan.

cratonic rifts (Bonds, 1988; Hannington et al., 1991). Active vents are found along rift zones at divergent plate margins where heat is provided by the intrusion of magma to a few kilometers of the seafloor. Seawater-rock interactions at temperatures up to 400° C leach base and precious metals from the permeable volcanic rocks in quantities large enough to produce ore-forming fluides (Seyfried et al., 1988). The nature of oceanic crust and underlying mantle material was little known until the realization that ophiolitic mafic-ultramafic complexes within some younger orogenic belts exhibited thicknesses, seismic and petrologic features that closely matched those known from oceanic areas (Coleman, 1977).

## Motivation of the Present Work

Regarding the usage of calibrated geophysical surveys to investigate crust-mantle and rift basins in Sudan, many publications have indicated the presence of mantle upwelling in central and northern Sudan, however the gravity grid in (Figure -2) contains abnormal gravity observations in the vicinity of Shendi-Atbra reported in (Table 1). These Bouguer anomalies have risen the surmising of possible new mantle upwelling zone since this area is bounded by Nakasib Suture Zone (NSZ), which is a part of the Arabian-Nubian Shield (ANS), from the east, Keraf Shear Zone (KSZ) from north, Bayuda

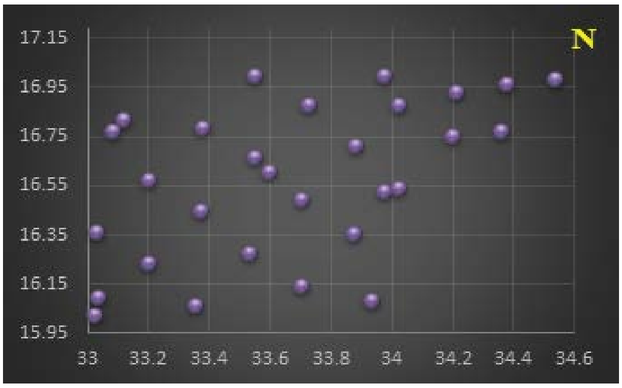


**Figure 2:** Shendi-Atbra vicinity gravity anomaly grid (as in Table 1) prepared for 3D gravity modelling.

**Table 1:** Shendi-Atbra vicinity gravity anomalies grid.

| **Longitude** ° N. | **Latitude** ° E. | **Bouguer Anomaly (mgal)** |
|---|---|---|
| 33.11971 | 16.81331 | -54.81 |
| 33.02941 | 16.35698 | -43.90 |
| 33.20359 | 16.56981 | -45.42 |
| 33.37851 | 16.78179 | -45.80 |
| 33.55301 | 16.99409 | -29.52 |
| 33.02577 | 16.01942 | -42.40 |
| 33.20031 | 16.23341 | -24.30 |
| 33.37432 | 16.44462 | -42.01 |
| 33.55481 | 16.66299 | -27.70 |
| 33.72991 | 16.87571 | -25.00 |
| 33.97632 | 16.99349 | -45.30 |
| 33.35861 | 16.06121 | -41.31 |
| 33.53232 | 16.27402 | -35.50 |
| 33.70601 | 16.48631 | -14.32 |
| 33.88542 | 16.70680 | -27.09 |
| 33.70621 | 16.14012 | -34.61 |
| 33.87992 | 16.35301 | -31.10 |
| 33.93598 | 16.08013 | -45.00 |
| 33.60191 | 16.60141 | -18.01 |
| 33.08199 | 16.76850 | -54.17 |
| 33.03892 | 16.09269 | -44.79 |
| 33.97680 | 16.52322 | -28.71 |
| 34.02631 | 16.87499 | -52.20 |
| 34.21349 | 16.9286 | -60.62 |
| 34.02768 | 16.53711 | -33.87 |
| 34.20409 | 16.74912 | -46.63 |
| 34.38149 | 16.96150 | -69.96 |
| 34.36151 | 16.76916 | -38.84 |
| 34.53701 | 16.97960 | -65.12 |

terrane from west, the thrusted high-grade metamorphic orogenic-granulite facies, Sabaloka inlier, to the south and it lies on the along the Neoproterozoic structural line formed by the subduction of Nile craton and Mozambique belt.

## Tectonic and Structural Settings

The seismicity of the Red Sea, Gulf of Aden and the East African Rift shows that three plates meet at the south end of the Red Sea. The Red Sea and the East African Rift Valley were the first major features to be recognized as having been produced by extension of the Earth's crust(McKenzie et al. 1970). In contrast to the Gulf of Aden, the structure and evolution of the Red Sea are much more controversial. Though noticed that the coast lines on each side fitted together, it seemed unlikely for several reasons that the whole of the Red Sea was underlain by oceanic crust. The Arabian-Nubian Shield collided against the Nile craton along a N-S trending boundaryextending from south Kenya to south Egypt (Stern, 1994; Abdelsalam and Dawoud, 1991; Vail, 1988) (Figure- 3).

During the collisional processes, the eastern foreland of the Nile craton was remobilized and most of the cratonic signatures were overprinted by the juvenile Pan African features. The evolution of the Arabian-Nubian Shield and the remobilization of the eastern foreland of the Nile craton is termed the East African Orogen [2]. In N Sudan and south Egypt, the Nile craton-Arabian Nubian Shield boundary is represented by the Keraf Shear Zone (Stern, 1994; Abdelsalam and Dawoud, 1991; Vail, 1988).

The northeastern part of the Saharan Metacraton is dominated by medium to high-grade gneisses and migmatites, disrupted by belts of low-grade volcano-sedimentary sequences representing arc assemblages and highly dismembered ophiolites, and intruded by A-type granitoids (Abdelsalam et al., 2002). In 1971 Qureshi investigated, via gravity methods, and described a crustal thinning and thickening at the axial trough and the coast of the red sea zone, respectively. He derived by a gravity modeling computer program [10] a homogenous andsmoothness to the depths of the Moho in the continental part, but a gentle 12º dip from coast to the axial trough is existed, which resembles the same models of the east Americans' bay.

The Keraf Shear Zone (KSZ) of NE Sudan formed in Neoproterozoic time when juvenile crust of the Arabian–Nubian (Bailo et al. 2003). Fig. 2 represents the examined area in the lights of geological and geo-chronological studies along the vicinity of Keraf Shear Zone (KSZ) and associated structural styles in summary as fellow: The KSZ was first identified and named by Almond and Ahmed (1987) [11]. Keraf Shear Zone is a transitional domain between the ensialic Nile craton and the ensimatic Nubian Shield (modified after Abdelsalam and Stern 1996. Abdelrahman [12] identified ophiolitic fragments in the Keraf area. The western and the southern extensions of the Nile Craton are not precisely defined yet, therefore many names apart from 'Nile Craton' are [13-15]. Pre-Keraf structures are best preserved in the Nubian and Bayuda Deserts to the west of the Keraf shear zone [5]. This region is dominated by medium- to high-grade gneisses of Paleoproterozoic and Mesoproterozoic age and associated meta-sedimentary and meta-volcanic covers. The evolution of the Atmur-Delgo Suture and its structural relationship with the KS are outlined by Schandelmeier and Abdelsalam [6,7]. This suture separates the Halfa terrane in the north from the Bayuda terrane to the south and is defined by ophiolitic remnants that extend in a WSW direction for at least 100 km [6]. Ophiolitic remnants occur as S-verging nappes dominated by ophiolitic mélanges (Schandelmeier ). These nappes structurally overly carbonate rich turbidites to the south (Stern; Schandelmeier).

The cyclical opening and closing of ocean basins caused by movement of the Earth's plates is known as Wilson Cycle. The Arabian-Nubian Shield of NE Africa is an example of a late Proterozoic orogenic belt that was formed by Phanerozoic-type plate tectonic processes [16]. The basic and the felsic rocks, of the Red Sea Hills (Figure - 4), belong to the Hawaiian alkali-basalt type with extreme alkalinity and contain unique rare earth, and trace elements geochemistry when compared to other African orogenic granites [17]. The strong geophysical anomalies

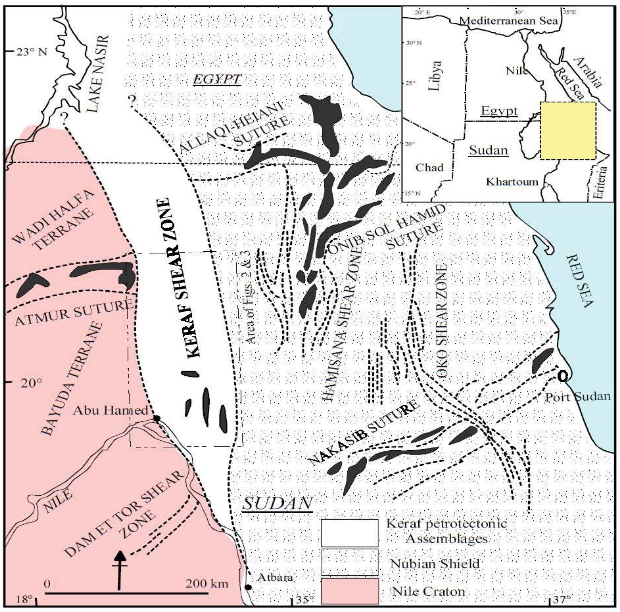


**Figure 3:** Simplified tectonic map of NE Sudan and Central Northern Sudan. The dominant features are the NE-SW trendingophiolite-decorated sutures offset dislocated by younger N-Strending shear zones (modified after Abdelsalam and Stern 1996, Schandelmeier et al. 1994).

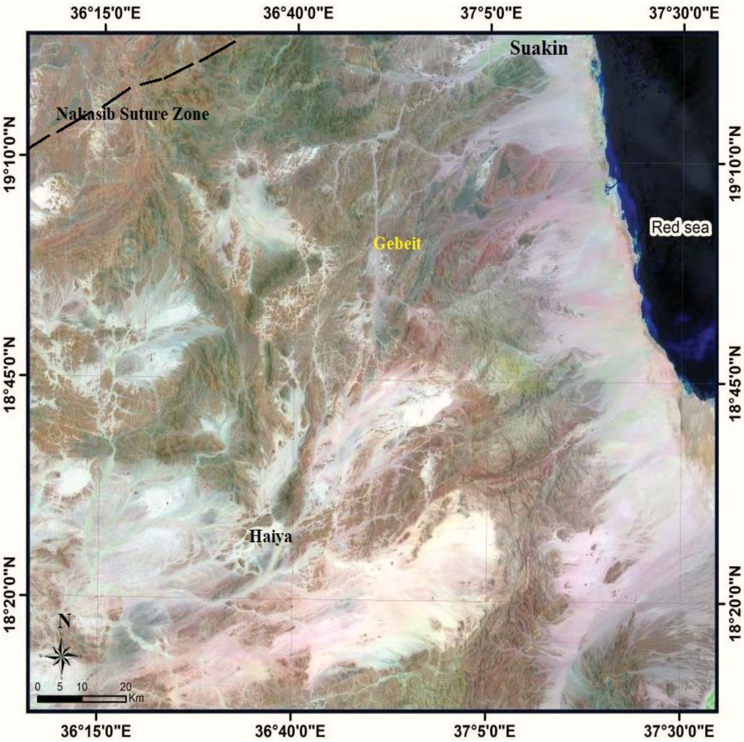


**Figure 4:** NE-Sudan Landsatview.

over the Nakasib Suture Zone (NSZ) are in keeping with interpretation of this zone as a reworked oceanic suture and the regional gravity profile is similar to those measured elsewhere on the flanks of the Red Sea and reflects thinning of the lithospheric units as the Red Sea axis is approached [18]. Suturing in Arabian-Nubian Shield involved the closure of a relatively long-lived oceanic basin and makes the Bi'rUmq-Nakasib shear zone the oldest accretionary structure known among the juvenile Neoproterozoic rocks of the northern East African Orogen [19].

One of the most robust tectonic models for SSZ ophiolite formation is that of Stem and Bloomer [20], which builds on earlier work by Hawkins [21] and others. This model proposes that ophiolites generally form during subduction zone initiation, when old, relatively dense, oceanic lithosphere crust begins to sink into the as the no sphere (Figure - 5). Lithosphere in the upper plate adjacent to the sinking lithosphere must extend rapidly into the gap left as the dense lithosphere sinks. The crustal formation is fed by melts from the hot as the no sphere that must flow upward into the region above the sinking plate margin, and from the as the no sphere displaced by the sinking plate itself (Stem and Bloomer). Melting of the hot as the no sphere that flows into the gap created by the sinking plate margin is enhanced by massive fluid flux from the sinking lithosphere. This combination of rapid decompression melting with fluid enhanced lowering of the solidus leads to extensive melting of the shallow as the no spheric wedge, creating refractory lavas such as boninites and high-Magnesium and e sites rocks and leaving an even more refractory residue of harzburgite tectonic (Stern and Bloomer). A similar progression could also form during major reorganizations of plate boundaries. Shervais searched this model in some detail, and showed that the sequence of magmatic events in all SSZ ophiolites is consistent with the progressive stages of this model, and this sequence may lead to the emplacement of an ophiolite or to its burial as the basement of a superjacent island arc complex.

## Gravity Data and Processing

The recent study is based mainly on regional and semi-detailed gravity surveys by using different gravimetric instruments implemented since the 70th of the past century by I. R. Qureshi &Abdel Hafiz G. Mula from the University of Khartoum, Dept. of Geology, CHE18SUDCHE, AGI07SUDDMA, STROSUDLEE and GRA01SUDROB companies for prospecting of the mineralogical deposits and hydrocarbon accumulations that are covering all the Republic of Sudan with more than 80,000 gravity observation points, however part of the gravity stations have been collected recently during an excursion to Soba valley in 2018 by GRAS and U. of K., Department of Geology technical team to evaluate the sedimento-hydrogeological situation there. The accuracy of the Bouguer Anomaly varies due to using different types of gravimetric instruments and the long duration of data collection. All gravity stations were tied with the International Gravity Standardization Network (IGSN). It is concluded that the absolute values of gravity may be in a constant error of about ±3 mgal and relative values in errors less than ±0.3 mgal (after Qureshi).Most of the secondary base stations here derived from U. of K., Dept. of Geology and Dept. of Physics-base stations. No detailed geological information is available along the profiles. The Bouguer anomaly extracted from these surveys (Figure - 6 & Figure - 7) are showing the contour lines of all Sudan and focusing on the northern and eastern parts which is the most characterized area in the country due to its complicated structural and tectonic styles dominated by the Neoproterozoic Pan African Orogeny and the later subdivision of the supercontinent of Greater Gondwana. Surfer ® version 13.5.583 used here to create contour maps from two gravity data set of all Sudan and N&NE Sudan spreadsheet files. The Bouguer anomalies are interpreted using GRAVMOD v3.2Mark W. Hounlow 1997-2011© with the aid of geologic information in the area to produce geological sections of subsurface of the area. GRAVMOD

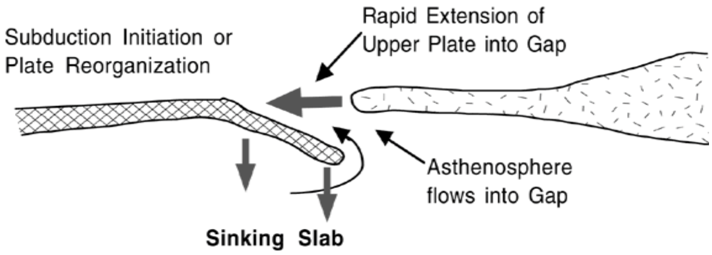


**Figure 5:** Schematic model for ophiolite formation by rapid extension in the upper plate of a nascent subduction zone, in response to sinking of the lower plate lithosphere (after Stem and Bloomer, 1992and Eljah, 2008). MORB-source asthenosphere flows into the wedge beneath the extending lithosphere and is fluxed with fluids from the sinking slab. Melting occurs in response to decompression of the lithosphere and the aqueous flux from the slab.

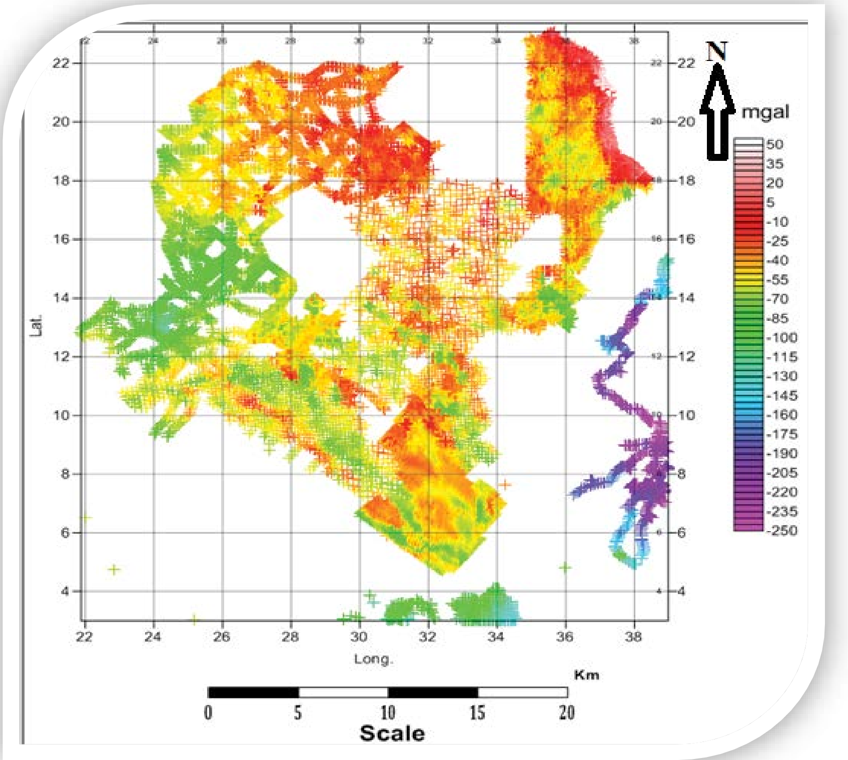


**Figure 6:** Post gravity-map of Sudan.

program performs 2D modeling of gravity data. It operates on a PC running on Windows XP or above versions. It is based on the line integral approach of the classical Talwani's [22] method. According to the qualitative interpretation the models are constructed in terms of densities and depths (depth-density models).

## Analysis and Qualitative Interpretation

The gravity anomaly maps show very high zones, at the red sea offshore that indicates upper-mantle undulation of -5mgal anomaly. Another anomaly observed, in yellow, inside the continent between latitudes 16°-18° N. and longitudes 33°-35° E. which may indicate no-crustal masses with approximately density higher than its perimeters which in fact is not predicted within this area since its dominated by the subduction zone traces and sedimentary basins. But a mantle source could possibly be the reason and explained in the light of the plate tectonic theory as the source can be non-crustal one, the other parts of the gravity maps showing an average crustal anomaly which can represent volcano sedimentary hills and small sub-basins. On the other hand, in these anomalies aren't obvious and are showing moderate crustal-gravity anomaly to the west of the country as no regional change deforms the Meta Sahar craton plate. In fig.4, the orogenic belts and the shear zones characterize the whole area and reflected on the relatively low bouguer anomalies, however there are some small sinusoids of relatively high anomalies of unknown sources within the continent, specifically in the Shendi-Atbra vicinity. The first sinusoid is between latitude 16.4863°N. longitude 33.70612° E., the second one is between latitude 16.6014° N. longitude 33.6019° E. Those sinusoids are bounded by confirmed sub-basins in the Shendi-Atbra vicinity. These gravity anomalies, taken together with those observed by other workers and corrected for shallow density variations, show the existence of a regional anomaly with a maximum at about +140 mgal over the Red Sea axis and a minimum at about -82 mgal over the Red Sea Hills (Qureshi).

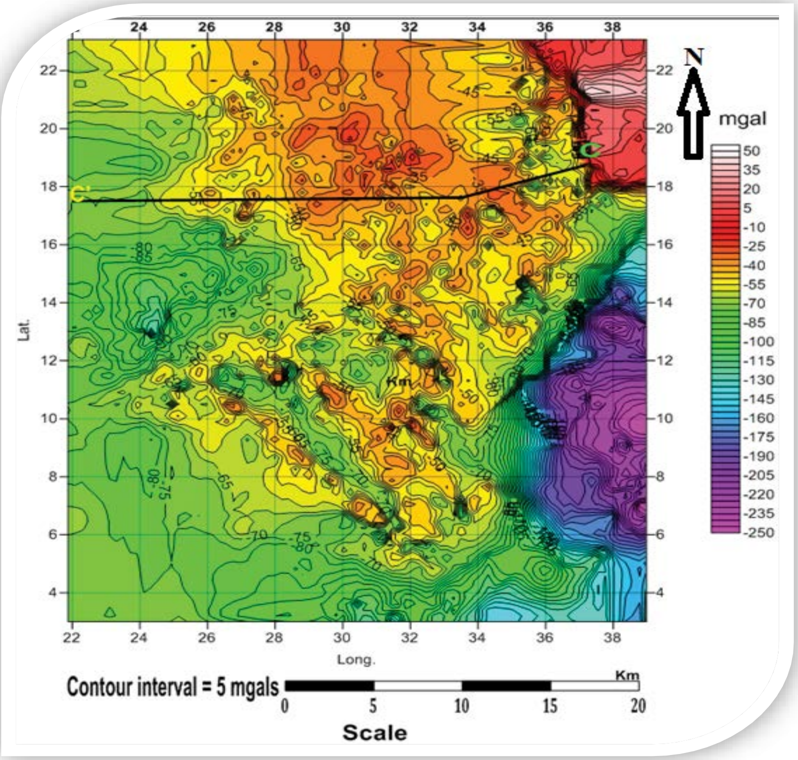


**Figure 7:** Gravity-contour map of the Republic of Sudan, showing profile C-C'.

## Regional-Residual Fields Separation

The residual field sought is the gravity field which would be measured if the effects of near surface deviations from crustal homogeneity, produced by rift basins and other high order features, were removed from the observed gravity. The remaining field is the regional anomaly which represents the deep-seated structures beneath the lighter sedimentary and recent covers. Once extracted, this field can be modelled in terms of crustal-mantle boundaries. The regional gravity field can be evaluated and constrained using several sources of information. Mathematical approaches to anomaly separation that can be applied to the Bouguer gravity data include polynomial fitting, upward continuation, and spectral analysis combined with band pass filtering, gives approximate values of this field. Deviations from crustal homogeneity can be partially accounted for by attributing the gravitational effects of high frequency variations in crustal density to the residual gravity field. Low order change, such as gradual density increases with depth, can be accounted for by equating their effects to the background gravity field which is removed from the regional field prior to modeling.

In our study the gravity effect of the sediments reaches -38 mgal in the region of Dungunab Bayas reported by Qureshi. Seismic modeling in the Khartoum basin indicated that a residual field of approximately -29 mgal is required to account for the basin fill (Jorgensen and Bosworth, 1989).The n according to the above-mentioned information our regional anomaly can be modeled smoothly, after subtracting these values from adjacent observation points, by a density contrast of -431kg/m3 between the average mantle (since this part of the mantle had been mixed with the lower subducted crust materials, though the density is slightly decreased from the average mantle density of the order 3.3gm/cc and it has been adjusted after several modeling trials) and an average crustal layer (2.75gm/cc).Where rock samples were not available average density values were adopted on the basis of lithology. It's assumed that since the existence of regional anomaly with a maximum at about +140 mgal over the Red Sea axis (Qureshi, 1971) the true mantle gravity signature would be less than that inside the content especially at the lower crust-mantle wedge resulting in the approximated above-mentioned density contrast of -431kg/m3.

## Derived 2D Modelled Anomalies

A mass distribution which remains constant perpendicular to a diameter, within the walls of avertical cylinder, is defined as a bounded two-dimensional mass distribution. Assumption of such a distribution may be more realistic than the assumption of an unbounded two dimensional distribution in many situations (Qureshi, 1976). Two-dimensional gravity models along the three profiles cutting across the major structural features of the N and NE Sudan are presented in Figs. (7,8,9) and salient aspects of each of these modelled profiles have been discussed below. The 2D models A-A', B-B', C-C' (Figure - 8,9,10) represent the processed and the modelled gravity data based on the assumption that the relative effects of basins are neglectable in all models, thus the whole Bouguer anomalies have been simulated in the light of a unified crustal layer and mantle beneath. Also, the undulations at the bottom of the prismatic 2D models, in red, represent the estimated Moho's interface depth and therefore an interpretation can be given as follow:

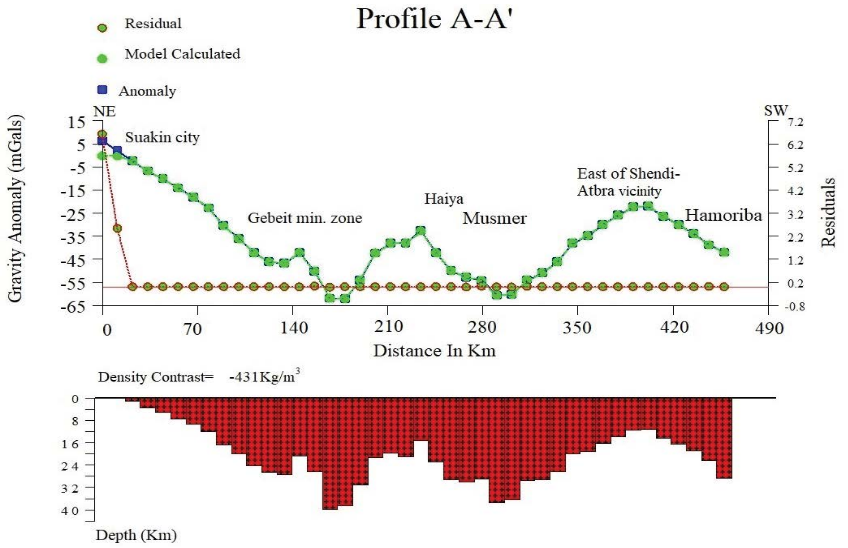


**Figure 8:** Gravity Anomaly and 2D density-depth crustal-mantle model along Profile *A-A'*.

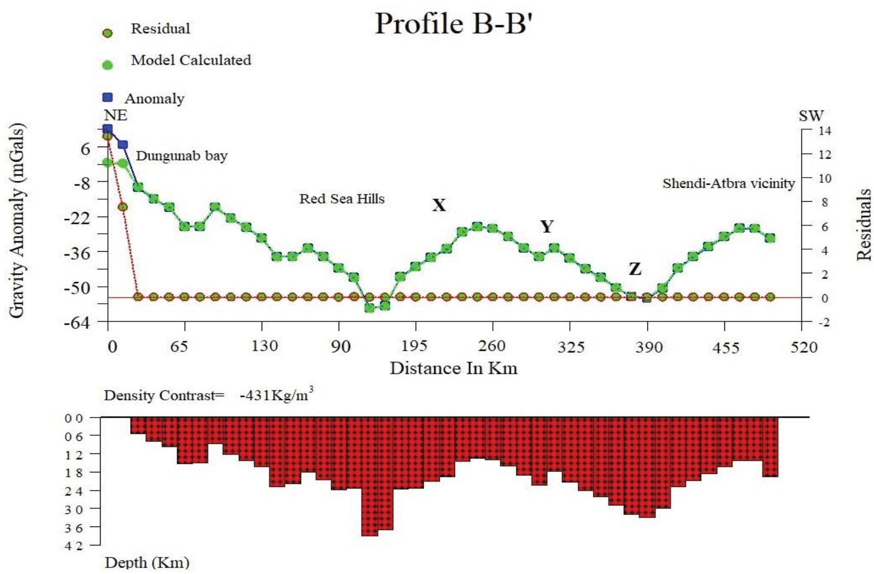


**Figure 9:** Gravity Anomaly and 2D density-depth crustal-mantle model along Profile *B-B'*.

## Model A-A'

The length of this profile is ~ 490 km from Suakin bay to the east of Shendi city. The highest anomaly is +5.15 mgal and the minimum is -62.1 mgal. The Moho interface appears close to the axis of the Red Sea at Suakin which is due to a new oceanic crust creation, but the crustal thickening increases at the Red Sea Hills area in Gebeit, and again it is the location of the Nakasib Suture zone that caused by the closing of Haiya and Gebeit terranes [23,24]. At Haiya there is a slight Mohos' uprising to a depth of 15 km. The East of Shendi-Atbra vicinity shows a maximum crustal thickness of 12 km which indicates an unpredicted mass presence and likely to be mantle fragments or uprising delimits the crust and juxtaposes it as proposed from the plate tectonic theory models within the continent. The ending of the profile shows a regular crustal thickening as predicted.

## Model B-B'

The length of this profile is ~ 520 km from Dungunab bay, north of Port Sudan city and near SE of Egyptian borders, to the east of Shendi-Atbra vicinity. The highest anomaly is +13 mgal and the minimum is -62.1 mgal. At Dungunab bay the mantle appears to be upwelling due to the adjunction to the axis of the Red Sea axis which is because of the oceanic crust creation. Inside the content at the Red Sea Hills, the crust sinks deep inside the upper mantle, around 40 km, due to orogeny, while it increases dramatically at the unknown localities X and Y, but at Z the crustal thickening rises up again reaching a depth of around 32 km. In the Shendi-Atbra vicinity the Moho interface shows the same features as in profile A-A' reaching the Moho interface at a depth of around 14 km.

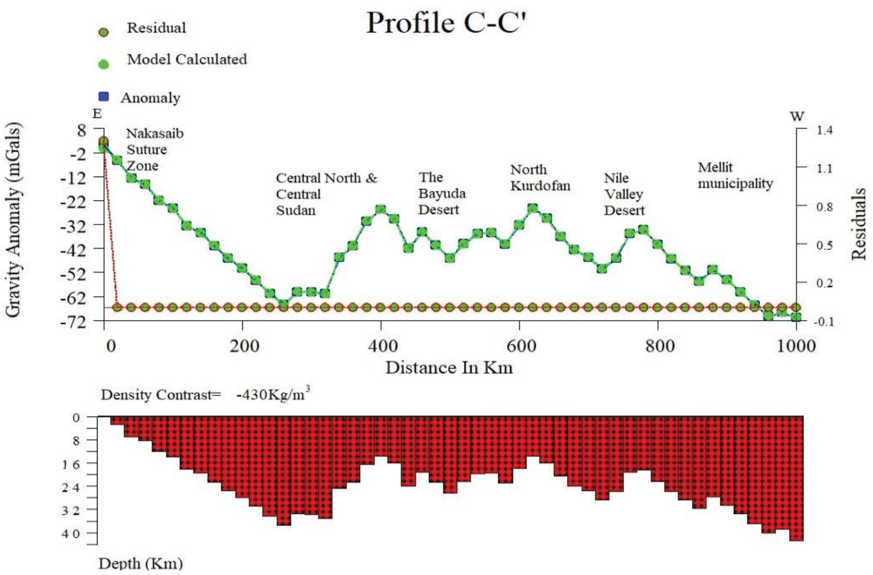


**Figure 10:** Gravity Anomaly and 2D density-depth crustal-mantle model along Profile *C-C'*.

## Model C-C'

The length of this profile is ~ 1000 km starting from Nakasib Suture Zone, between Gebeit and Haiya terranes to the west of Sudan until Mellit municipality. The highest anomaly is +1.09 mgal and the minimum is -70.68 mgal. At Nakasib suture the enclosing of terranes formed an orogenic crustal thickening that reaches about 35 km in-depth, however, the area is decorated by ophiolite sinusoids. Central North, Central Sudan, Northern part of Kurdofan state and Mellit municipality has some undulations in Mohos' interface, and these ones reflected in the presence of small old basement groups and series, however, the story is different for the Bayuda desert since it contains the igneous and medium-highly grade metamorphosed rock affinities and that interprets the sudden changes in the depth to the Mohos' interface between 18 km, 24 km and 26 km.

## 3D Gravity Modeling of the Shendi-Atbra Vicinity

In this study we applied 3D gravity modeling and inversion ina complex geological setting involving several crustal rocks and mantle wedge embedded in suture and shear zones, representing a challenging and quite realistic scenario commonly found in the N and NE Sudan displays the gravity anomalies grid picked from the to calibrate the 2D models.

A computer program written and developed at the University of Khartoum, Department of Geology (Mula and Abdalla, 2020; personal comment), have been used to simulate the 3D gravity models (Figure - 11). The gravity anomaly grid generated by the 3D model shows that, despite the apparent differences in the central part of the grid corresponding to the gravity minimum, the amplitudes are similar to the gravity anomaly in (Figure - 12) of the picked grid. The RMS of the Bouguer anomaly for the 3D model is 1.5e-09(mgal) indicates that the inverted gravity anomaly successfully resembles the anomaly. Based on this last fact we find our inversion results very encouraging and gave the interpretations on the possible source of these abnormal gravity anomalies. The inverted 3D density model successfully retrieves the mantle up-rising body ensemble in central NE Sudan, but it shows ambiguous high-density occurrences at the middle with small thickness, this anomalous gravity body has higher density withing the continent thus, it's more likely to agree with the 2Dinterpretations of the previous findings.

## Possible Source of Shendi-Atbra vicinity anomalies

The region between Gebel Uweinat in the west of Sudan and the Arabian-Nubian Shield in the east is part of the eastern foreland of a Pre-Pan-African tectonic domain in NE Africa (Schandelmeier et al., 1988). The predominantly high-grade gneisses and migmatites, with interfolded supracrustal meta sediments, typical of this region, belong to an older sialic continental plate named Archaean-Middle Proterozoic (Harms 1984; Bernau 1987) which is referred to as the Nile Craton (Rocci, 1965), the Sudan Shield (Vail, 1976), the East Sahara Craton according to Kroner (1979) or the East Saharan Craton according to Schandelmeier et al., (1988). The late Proterozoic crust in Saudi Arabia, Egypt, and Sudan was formed by the growth of several intra-oceanic island arcs, by later growth of Andean-type magmatic arcs, and by coalescence (or cratonization) of these to form large continental masses (Greenwood 1976). The evolutionary sequence can be divided into the Early, Middle, and Late Pan-African, in the periods 1200-1000 Ma, 1000-600 Ma, and 600-500 Ma, respectively. The juvenile Arabian terranes are bordered by thick undeformed Palaeozoic cover in the Arabian Peninsula [25,26], the margins to the Nubian Shield are less precise (Vail, Ries , Almond and Ahmed, Krone). Similarly, the extent and orientation of the Sudanese ophiolitic suture zones are still debatable [27]. The relatively high Bouguer anomalies that have been observed in the study area are of the order; -24.30, -26.70, -25.90, -14.30, -18.00 mgal. Thus, the Shendi-Atbra vicinity can be considered as an extension of the subduction zone between Nile craton and Mozambique belt, and in addition, it inherited the tectonic products after several metamorphism and partial melting phases. Then KSZ came later and expose these structures. The surmising here is pointing at that the mantle layer beneath this vicinity was (is?) highly active which can be extrapolated after these interpretations in the light of KSZ generation alongside the course of the River Nile in central and northern Sudan.

Amphibolite facies meta sediments which overlie the grey gneiss to the north and northeast of the Sabaloka inlier probably equate with

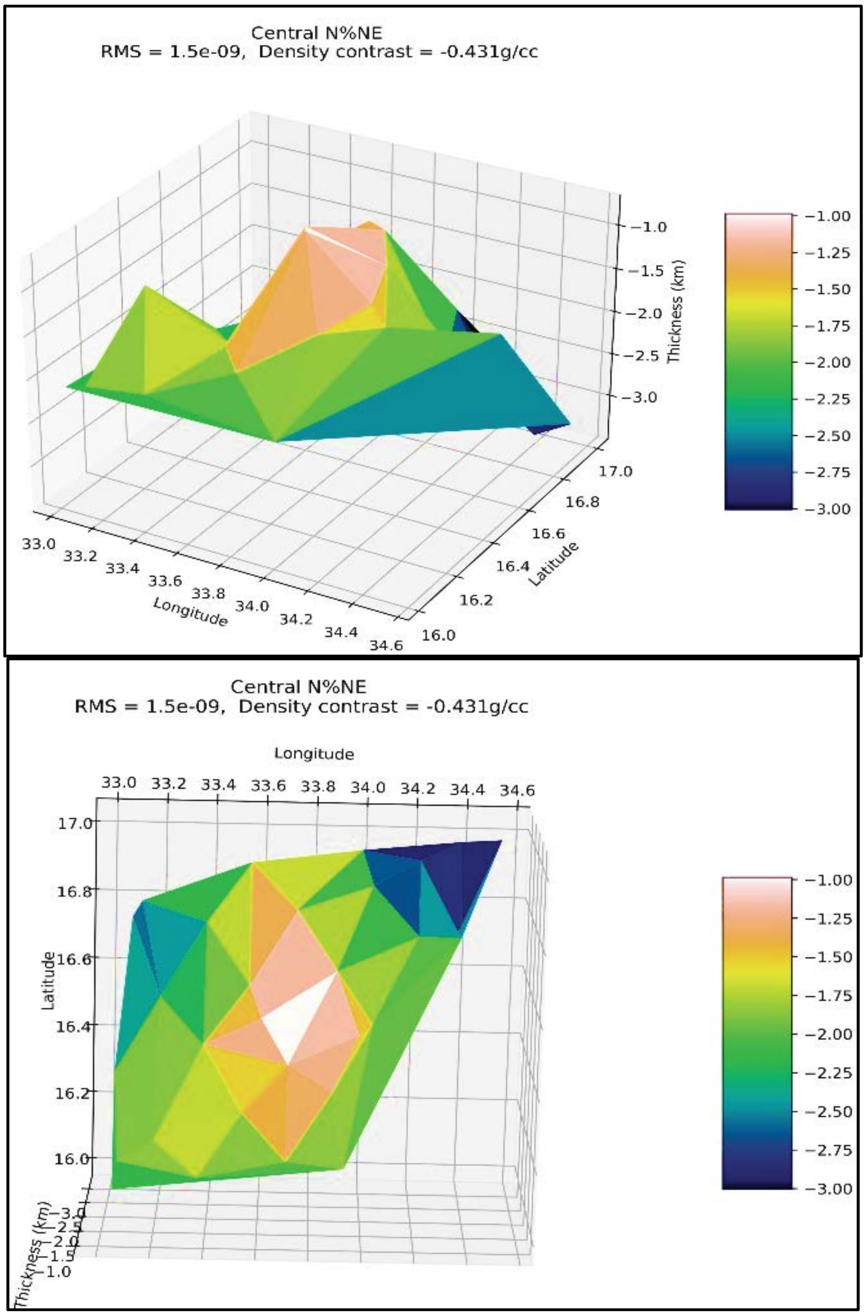


**Figure 11:** 3D inverted model generated from the 3D gravity anomaly inversionas looked from Above (left-side figure)and NW direction(right-side figure).

the Early and Middle Proterozoic cover sequences which in the east African sector of the Mozambique belt are strongly interfolded with thoroughly reworked Archaean basement. The adamellite batholiths are in places strongly discordant to their country rocks and may be coeval with the 'batholithic granites' of the Red Sea Hills, emplaced in late Proterozoic times, during the last stages of deformation in the Red Sea belt. The adamellite batholiths are in places strongly discordant to their country rocks and may be coeval with the 'batholithic granites' of the Red Sea Hills, emplaced in late Proterozoic times, during the last stages of deformation in the Red Sea belt. The whole area was later affected by reheating and limited tectonism during the Pan-African event (550±100Ma) with consequent resetting ofK-Ar apparent ages (after Almond, 1979).

In fact, the central and northern Sudan is at the junction of the Nile craton and Mozambique belt and decorated by the Keraf Shear Zone (KSZ). The KSZ (Fig. 1) is a N-S trending fault-bounded and wedge-shaped structural belt in northern Sudan and southern Egypt. The area affected by the shearing is confined by the co-ordinates 18°` -22°30` N. and 34°00`-35°00`E. The width of the sheared area ranges from ~100 km in the north, where the KSZ truncates the Allagi suture, to 30 km in the south, at the junction of the KSZ with the Dam et Tor shear zone (Fig. 1). In terms of crust-mantle boundaries this vicinity lies exactly at the southern adjunct of Keraf Shear Zone (KSZ), whereas the southern part is characterized by N- and NNW-trending, sinistral, strike-slip faults. The differences in structural styles along KSZ's strike

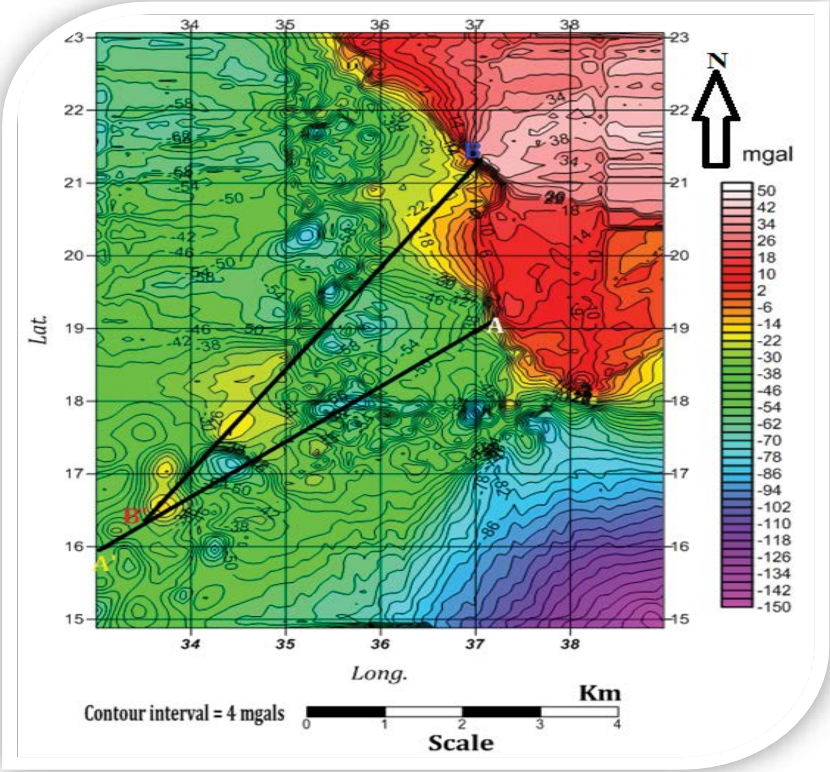


**Figure 12:** Gravity map of central N and NE Sudan showing profile A-A' and B-B'.

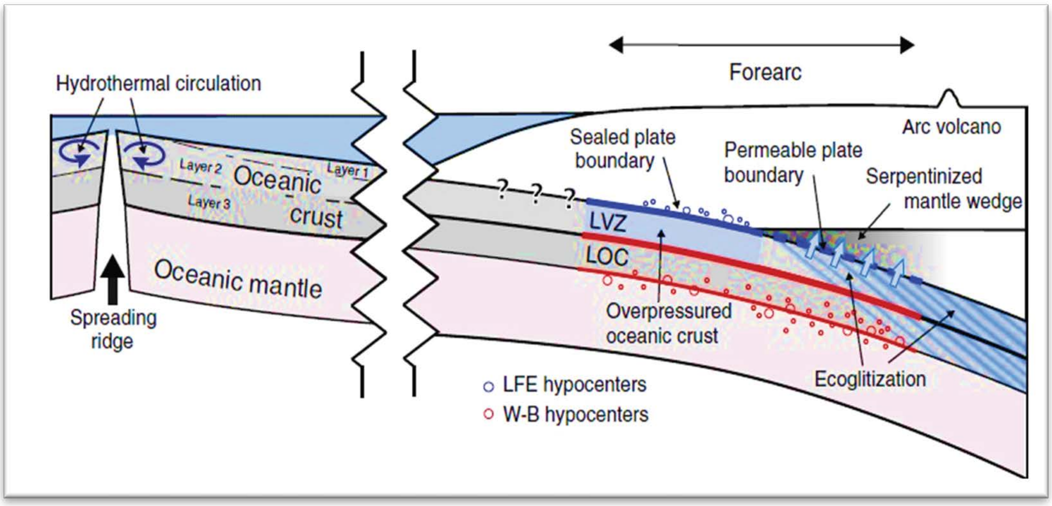


**Figure 6:** Schematic model illustrating hydrologic evolution of oceanic crust in Cascadia from left to right (after Audet etal.,2009 and Hansen et al. 2012). Upon initiation of subduction, metamorphic dehydration reactions (± compaction) commences to produce free fluids at near-lithostatic pressures within Layer 2 (± Layer 1).

is due to formation of the Keraf Suture by sinistral transpression, which accompanied early NW-SE oblique collision between East and West Gondwana at ~ 650–600 Ma and terminal collision at ~ 580 Ma. (Abdelsalam 1997) and covers the serpentinized mantle wedge of the Neoproterozoic subduction zone, which is likely to be responsible for these abnormal high Bouguer anomalies. (Figure - 13) represents the earth's components and conditions during subduction and new oceanic crust opening and explains the idea of how this Serpentized mantle wedge rises up due to bouncy force. Ecolgitization commences near 45 km depth and is accompanied by a ~ 10% volume change that compromises the plate boundary sea-land initiates serpentinization of the mantle wedge. If this interpretation is correct, then it suggests a thrusting scenario of the mantle wedge and had compressed again by suturing finally resulting in discretized sinusoids buried under the recent cover.

## Crustal Thickening & Thinning

In the Bayuda desert the meta sedimentary rocks were thought to have witnessed an amphibolite facies grade of metamorphism prior to the late Proterozoic Pan African event and it was assumed that they overlie an older, probably Archaean, basement of gneisses, migmatites and related older granitoids correlated with those metavolcanics were thought to overlie or were thrust onto the older units (Dawoud, 1980, Almond 1983).The continent of Africa has experienced a long and complex history of rifting since the Proterozoic. The Mesozoic saw the fragmentation of Gondwana, with major phases of rifting in Africa resulting in the development of the West and Central African rift system during Jurassic-Cretaceous times (Fig. l; Schull, 1988; Bosworth, 1992). Parts of Central and East Africa have experienced at least two more episodes of rifting in Eocene-Recent times (e.g., Ebinger and Ibrahim, 1994).Except in NW Sudan where Palaeozoics and stones overlie basement rocks, the sedimentary section overlying basement in central Sudan is of Early Cretaceous to Recent age (Robertson Research International and Geological Research Authority of Sudan, 1989). However, commonly marine sedimentary rocks are the oldest rocks drilled in the Bara and Khartoum basins (Wycisk, 1990). Intercalated upper most Jurassic basalts and clastics floor the Khartoum basin (Wycisk, 1990). North west and NE-trending faults are interpreted from analyses of aeromagnetic and gravity data calibrated with geological data [28].

Granulite facies rocks of Pan-African age are exposed within retrogressed gneisses and migmatites of amphibolite facies in the Sabaloka inlier north of Khartoum and represent deep-seated metamorphism in athickened crust, while in the Red Sea Hills to the east and in the Bayuda to the north the volcano-sedimentary sequence of green schist facies metamorphism and associated granitoids of Island arc affinity represent the low and medium grade metamorphism, respectively.The three sets of metamorphic rocks represent an orogenic belt in which its contact line or subduction surface is located where thedeep-seated metamorphic rocks are. The gravity high and low over the area have been interpreted by a thickening and thinning of the underlying crustal layer in accord with the Airy concept of isostasy. The isostatic response from 10 to 15 km of crustal thinning is sufficient to account for the low elevations between the heterogeneity suggests broad uplift throughout eastern Africa. A possible explanation is that multiple episodes of rifting thinned the crust across the region, and that isostatic adjustments from the thinning resulted in lower elevations, however whether or not the crust has been thinned across the entire region remains unknown.

All models suggest a rapid thinning of the continental crust beneath the coastal plain and inside the continent at the described vicinity. The Red Sea Hills, Nakasib Suture Zone (NSZ), Bayuad terrane and Nile valley areas are considered to exhibita crustal thickening due to or ogeny, since its crustal depth converges to 30km.Girdler(1969) posited an alternative to separation in the northern part of the Red Sea as feasibility of the crustal thinning and McKenzie et al., (1970) proposed crustal thinning beneath the Gulf of Suez. Girdler et al. (1969) infer an attenuation of the lithosphere in East Africa and described this as an early stage of break-up of the African plate. Modeling results give Sn velocities of 4.1–4.3 km/s and average crustal thickness of 25 ± 5 km, some 10 to15 km thinner than the crust beneath the East African and Ethiopian Plateaus (after Benoit, 2006).

Since the shoulders of the Red Sea have several geological and geophysical features in common with the continental rifts (Girdler, 1964) the inference is forced that in the first stage the Red Sea evolved as a rift through a stretching of the upper crustal layer concomitant with important tension faulting at the margins. This stage was probably initiated in the late Oligocene-early Miocene times and culminated in the late Miocene with the formation of the main trough [29]. A stretching of the upper crust does however imply addition of new material underneath or sub-crustal spreading. But it results in a reduced relative displacement of the margins in contrast to separation. Modeling results give Sn velocities of 4.1- 4.3 km.s-1and average crustal thickness of 25 ±5km, some 10 to15km thinner than the crust beneath the East African and Ethiopian Plateaus (Benoit et al. 2006).

## Conclusion

Dawoud and Sadig (1988), based on structural and gravity evidences suggested that the granulite in Sabaloka inlier were thrusted, as this is the major cause of uplifting,to their present level by tectonic processes rather than by erosion only. The correlation is likely to be acceptable, only for thrusting of the mantle wedge at alongside the southern periphery of KSZ, since it adjacent to the Shendi-Atbra vicinity of abnormal gravity readings thence, we suggest; this mantle up welling is produced during subduction rather than as new hotspot which is dubious to produce volcanic activity. It is suggested that the concepts embraced by the terms 'Pan-African event', 'Red Sea belt cycle' and 'Mozambique belt cycle' are best kept distinct from each other since their affects appear to differ in spatial and temporal distribution (Almond 1979).However detailed deep seismic reflection and closely-spaced regional gravity surveys should be carried to model and interpret then to address the crust-mantle boundaries along the strike of south of KSZ. In addition, the mechanism of subduction and thrusting needs more attention though, the recent plate tectonics models do not provide enough modeling flexibility since its necessary in the realization of accurate geometrical model of the subduction zone. But active Remote Sensing and Orbital Imaging Radar (OIR) techniques can possibly unveil the buried mantle wedge in the Shendi-Atbra vicinity more precisely.

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