

The geometric configuration of the newly discovered Abu Deleig sedimentary sub-basin, Central Sudan, using remote sensing, structural analysis, and geophysical survey

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Received: 8 October 2012 / Accepted: 3 February 2013 / Published online: 19 February 2013
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Abstract Abu Deleig area is a transitional area between the Butana basement terrain to the east; and the Khartoum and Shendi sedimentary basins to the west and northwest directions, respectively. The existence of sedimentary basins within this region of Sudan was previously unknown. Landsat images have been used for delineation of lineaments and drainage system, followed by a structural analysis and geophysical investigations including gravity and resistivity methods. The interpretation of the remotely sensed data revealed that the drainage pattern is structurally controlled. The structural analysis defined the trends of the shear and tensional fractures. The structural analysis revealed that Wadi Al Hawad is the southern continuation of the Keraf Shear Zone. The related minor fractures in a NE–SW direction exhibit normal faults governing the geometry of the Abu Deleig sub-basin. The geophysical investigations confirmed the findings of structural analysis and portrayed the subsurface geometry of the sub-basin. The newly discovered sub-basin has a prism-like shape with its apex occurring at Abu Deleig town and extends to 40 km in NW direction. The depth to the basement increases from 20 m at Abu Deleig in step form to more than 300 m, where it is linked with the Shendi Basin in the northwestern part. The results of this study, however, did not confirm any link of Abu Deleig sub-basin with Atbara Basin to the NE or Khartoum Basin to the west as have been previously suggested.

Keywords Remote sensing · Structural analysis · Geophysics · Sedimentary basins · Butana · Sudan

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Introduction

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 droughts in the latest decades in Northern and Central Sudan have focused attention on the scarce water resources, where groundwater resources in sedimentary basins represent the only realistic resources in such areas (Edmunds et al. 1987). The application of remote sensing combined with structural analysis and geophysical surveys prove to be a powerful tool in studying structurally complicated terrains (Elsheikh et al. 2009). The geological and structural setting of Abu Deleig area is complicated and the existence of sedimentary basins within this area was unknown. This study endeavors to link Wad El Hawad structural phenomenon to the related regional structures in NE Sudan and to investigate the possibility of the development of small sedimentary basins in the area that may help solving water scarcity problem.

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.(Fig. 1). Physiographically, 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.

Several geological works have been performed in and around the study area that have defined the general geologic framework (Ahmed 1968). Delany (1953) compiled a geological map of the Eastern province which shows the lithological units with special emphasis on the classification of the basement rocks. Khairalla (1966) studied the Nubian Sandstone Formation of the Nile Valley between 14°N and 17°40′N. He divided the Nubian Sandstone Formation in Khartoum basin into five lithological units. Ahmed (1968)

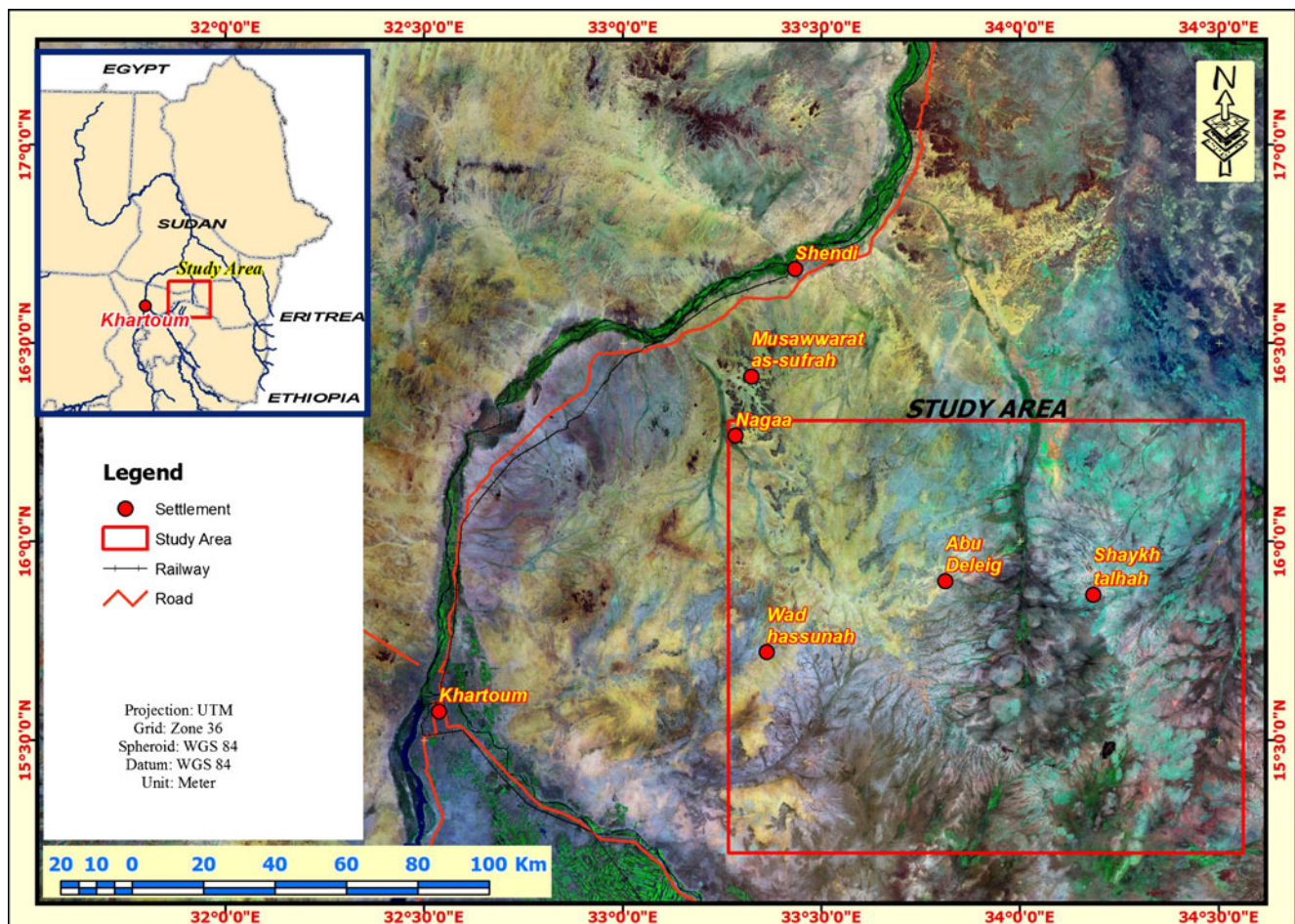


Fig. 1 Location map of the study area overlain on Landsat ETM color composite

mapped and described the petrography and geology of Jebel Qeili ring complex in the Butana area. Dawoud (1970) and Almond (1980) discussed the geology and structures of the Pre-Nubian Pan-African (950–550 m.a.) Basement Complex of the Sabaloka west of the study area. Whiteman (1971) provided a review about the distribution of the basement and the nomenclature, origin, and composition of Nubian Sandstone Formation. Saeed (1976) discussed the geology and hydrogeology of Khartoum province. Vail (1987) compiled a geologic map of the different parts of Sudan in which the Khartoum–Butana rock sequences were defined. Geophysical survey covering most of central Sudan, including Butana area, has been conducted by Sun Oil Company in 1984 (Ibrahim 1993). The British Geological Survey (Edmunds et al. 1987) investigated the source of aquifers recharge in the lower Atbara River including the study area; they conclude some link of the sedimentary basins in the area with Shandi Basin using geochemical investigations. In addition to other unpublished reports including the geophysical investigations in Abu Deleig area for groundwater exploration, El Jah (2008) studied the geological aspects of the area with emphasis

on El Tuwal ophiolite in southern Butana. All the above-mentioned researchers never point out to the existence of a sedimentary basin in Butana area.

The main objective of this study is to define the geometry of the sedimentary basin and to delineate the boundary between the basement and sedimentary rocks using gravity and resistivity data. Additionally, to determine the role of the regional structures that control the existence and configuration of the sedimentary basins which are the main source of groundwater and to verify its relation to the adjacent sedimentary basins.

Data

The following data types were used in the current study:

A mosaic of Landsat ETM+ 7 imageries, (1) path 172, row 49 acquired on 13th Nov. 1999 and (2) path 172, row 49 acquired on 24th Dec. 2000. The satellite imageries have been downloaded from Global Land Cover Facility (GLCF) of Maryland University, USA. The remote sensing data was digitally processed and enhanced for visual interpretation.

Gravity data obtained from the open files of the Ministry of Energy and Mining, Sudan were used to construct Bouguer map and to compute the residual component of the gravity anomaly. Resistivity measurements were acquired in the current study using vertical electrical sounding method (VES).

Methodology

The obtained Landsat imageries are geometrically corrected and co-registered on a UTM projection, zone grid 36N with WGS_1984 spheroid. Sub-scenes of both the multispectral and panchromatic bands have been mosaicked according to the routine techniques to obtain regional scenes covering the whole area. The multispectral bands were fused with the panchromatic band via IHS transformation to obtain spectrally and spatially enhanced image. The remotely sensed data was interpreted for the geological and geomorphological features delineations. Structural analysis based on stress–strain was applied to the delineated lineaments map. The expected expression of the rock mass movement due to the faults generation was resolved. The geophysical investigations were carried out to confirm the interpreted

remotely sensed data and the results from the structural analysis. The gravity data obtained from the open file of the Ministry of Energy and Mining—Sudan which included 48 Bouguer anomaly points spreading in the study area. Regional/residual gravity anomaly separation was computed during the course of the present study. A vertical electrical sounding survey was conducted using ABEM SAS 1000 Terrameter for resistivity measurements. Thirty-six soundings were carried out across the detected main regional structures using a Schlumberger array where the central point of the array remains fixed. The measured apparent resistivity values were inverted in computer software, that uses least squares approach, for the determination of true subsurface resistivity and depth to basement.

Results and discussions

Image enhancement and interpretation

The obtained image permits the visual interpretation of the geological features. Landsat ETM image showed the nature of the geological features and enabled the delineation of regional structures (Fig. 1). The area consists of fractured

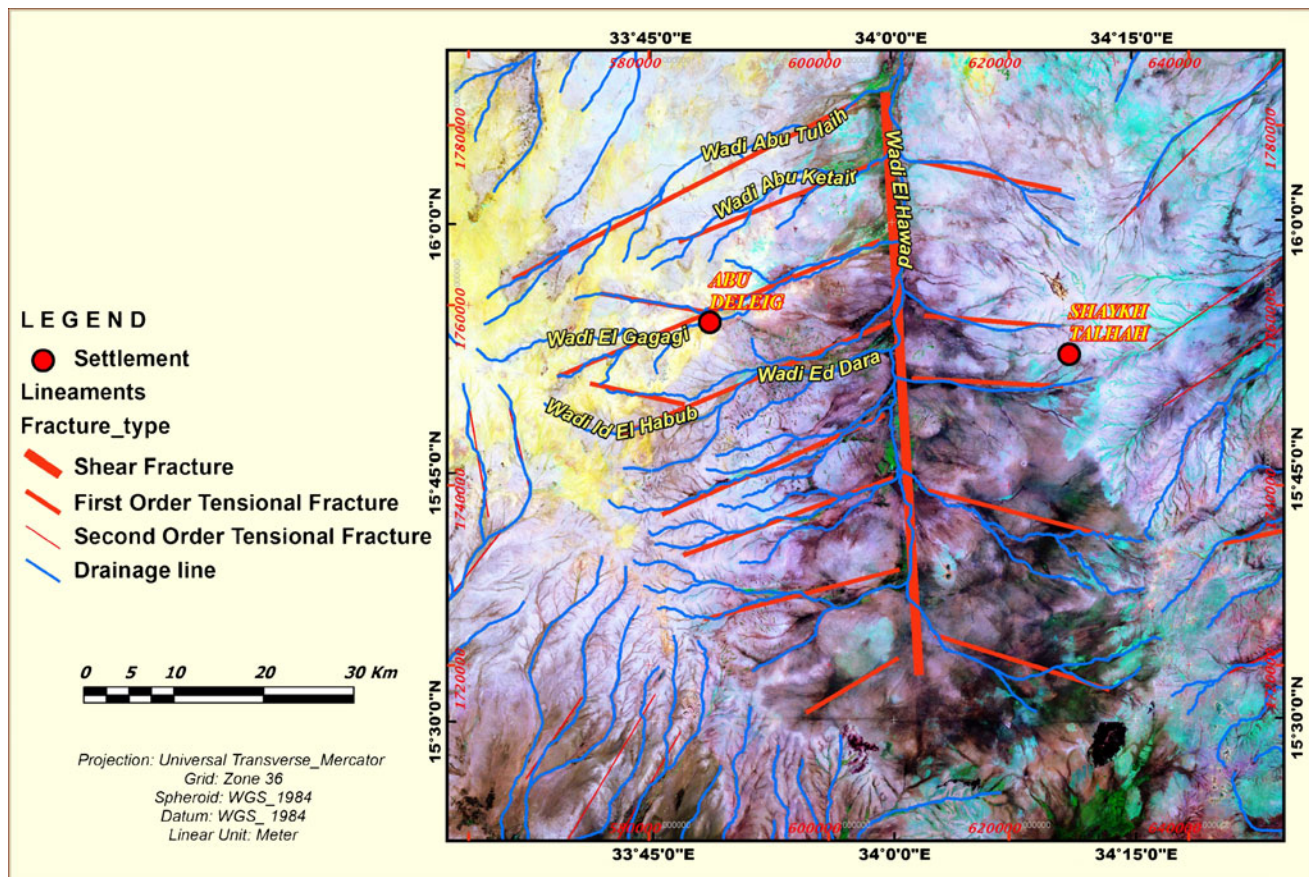


Fig. 2 Showing the drainage pattern in the study area reflects the influence of both the lithological and structural character of the underlying rocks

crystalline basement rock which is partially covered by thin layers of superficial aeolian and alluvial deposits.

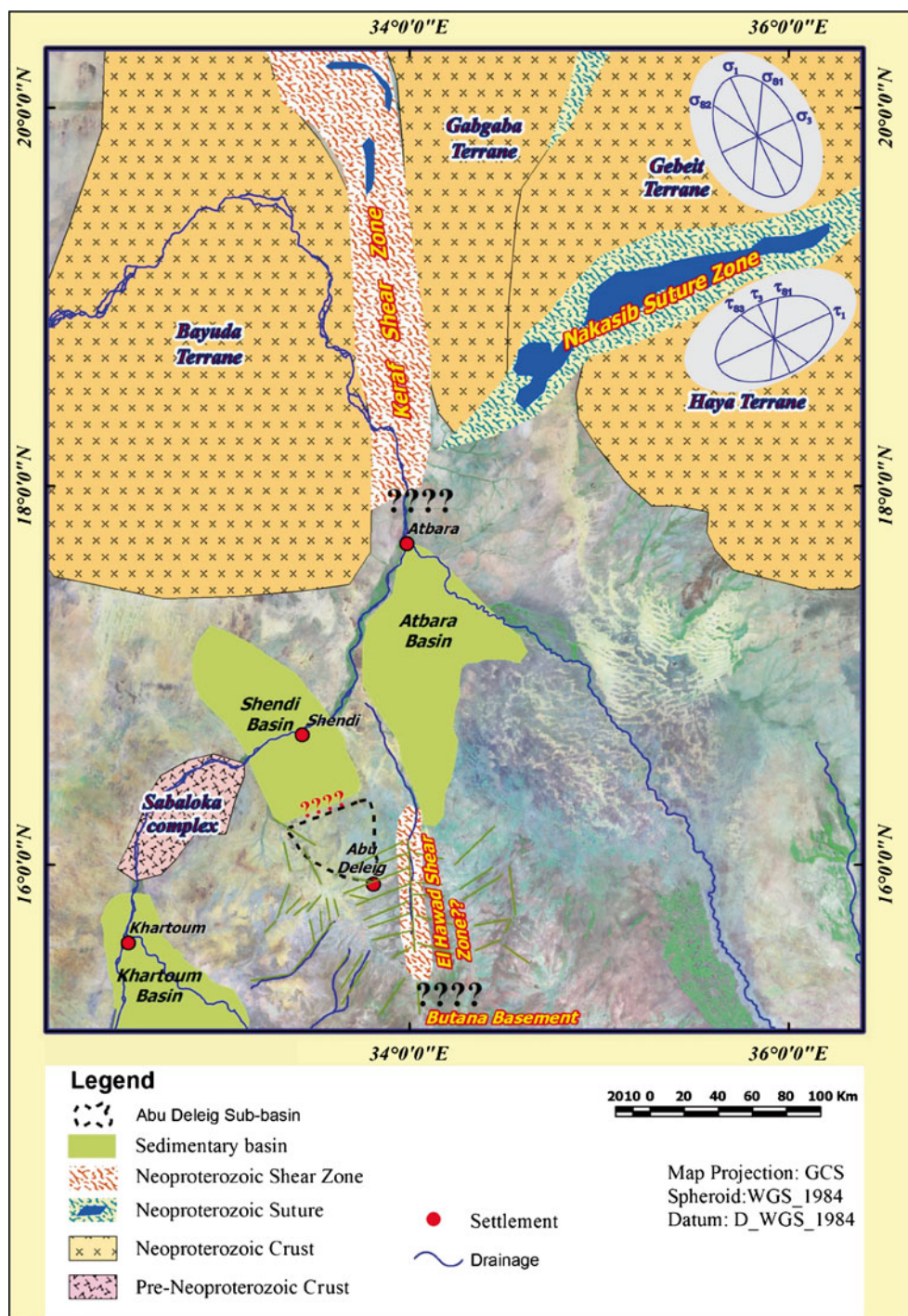
Figure 2 was digitized to delineate the main drainage systems and major lineaments from the fused image. It is obvious that the major drainage in the area is a modified parallel system and controlled by the major and sub-major lineaments that trend N–S and NE–SW. The first-order N–S lineament trend (Fig. 2) controls the main drainage of wadi El Howad, while the second- and third-order lineaments control

its tributaries and other minor wadis in the study area.

Structural analysis

The structural analysis of the lineaments is an important facet that helps in acquiring a basic understanding of the basins geometry. Stress is a pair of equal and opposite forces acting on unit area of a body and the strain is the geometrical expression of the amount of deformation caused by stress

Fig. 3 A simplified tectonic map of Central Sudan showing the main sedimentary basins around the study area overlain on a Landsat image



(Park 1997). Stress–strain ellipsoids used in this study for the structural analysis to represent the distributions of the main principal stress and strain axes (Twiss and Moores 1992). In the stress ellipsoid the principal maximum stress axis (δ_1) and the least principal stress axis (δ_3) are perpendicular to each other and the main intermediate principal shear stress axis (δs_1 and δs_2) deviate from (δ_1) by 30° – 45° clockwise and anticlockwise. Whereas in the strain ellipsoid, the maximum strain axis (τ_1) is parallel to the (δ_3) and the least principle strain axis (τ_3) is parallel to the (δ_1) in the stress ellipsoid and the intermediate strain axes (τs_1 and τs_2) are parallel to (δs_1 and δs_2) (Twiss and Moores 1992). The force distribution was deduced from the trend of the regional extension of the Nakasib Suture Zone (NSZ) to the northeast and the Keraf Shear Zone (KSZ) to the north of the study area (Fig. 3), which belong to the Pan-African Orogeny (950–500 Ma) (Schandelmeier et al. 1993; Stern 1994; Kröner et al. 1987).

The NSZ (trends N 60–70 E) separates the Haya Terrain from the Gebelit Terrain (Fig. 3). This suture trends parallel to the least stress axis (δ_3) and the greatest strain axis (τ_1) in the stress and strain ellipsoids, respectively. The force

direction was detected from the configuration of the Pan-African Orogeny in the region in which the force is perpendicular to the NSZ (150° – 160°). The KSZ (\approx N–S) is parallel to the shear axis (δs_1) in the stress ellipsoid (Fig. 3).

From Fig. 3, it is apparent that Wadi EL Hawad is parallel to the KSZ. Both of them are coincident with the longitude 34 E and are separated by the Mesozoic Atbara basin. There are many field criteria prove that Wadi El Hawad represents the southern continuation of the KSZ. These include the dextral sense of movements and occurrence of gold mineralization within the highly sheared rocks south of the study area along Wadi El Hawad. A number of minor wadis, such as Wadi El Gagagy, Abu Ketair and Abu Tulaih bisect Wadi El Hawad at 30° – 45° (Fig. 2). These wadis are controlled by the tensional fractures that may be generated due to the reactivation of the shear zone.

Normal faults have been produced from the extensional open fractures in two tectonic phases. The first phase involves the generation of open fractures related to the shear zone. The reactivation of the shear zone produces normal faults coincident with the open fractures in the second phase. These normal faults resulted in the formation of

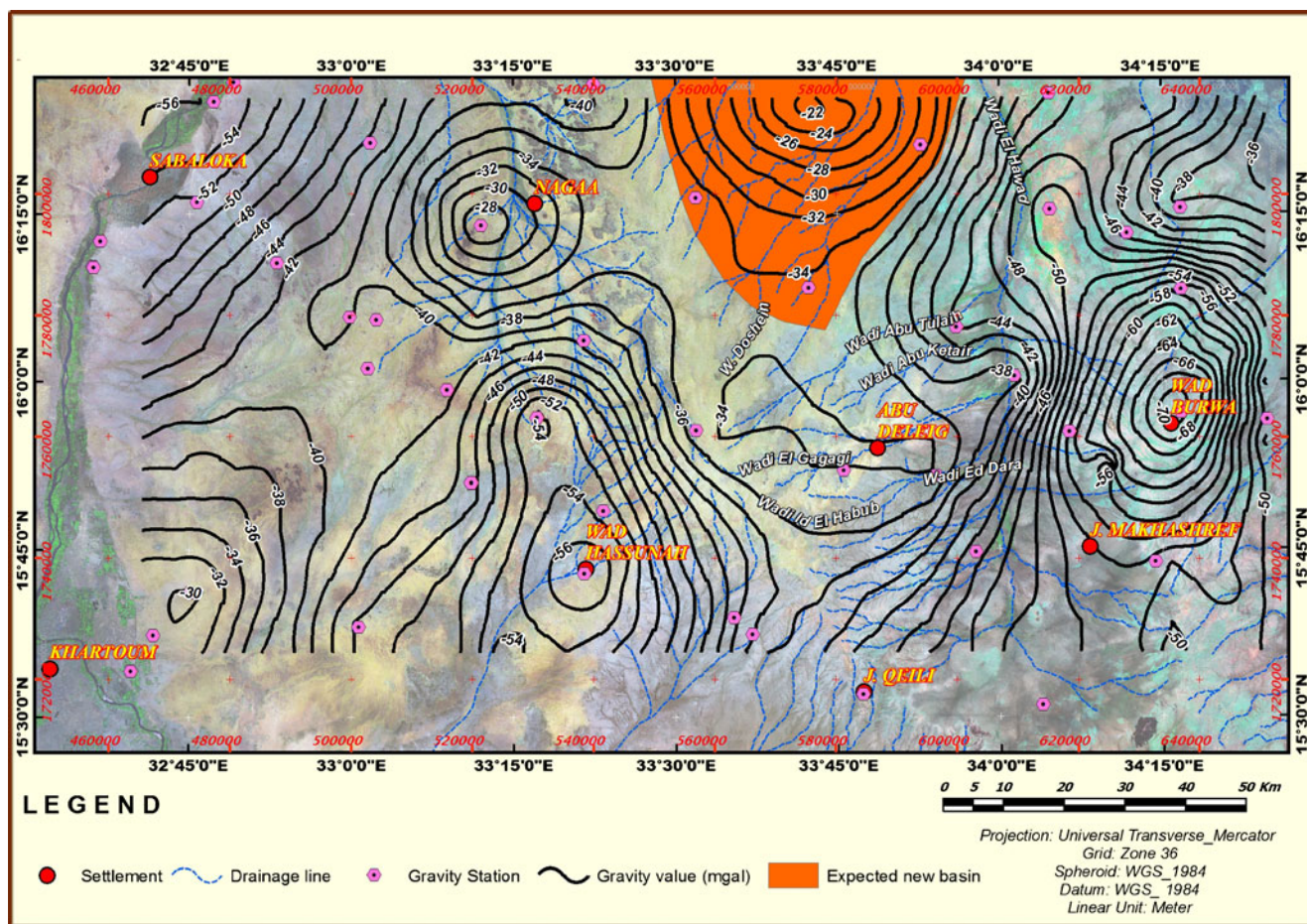
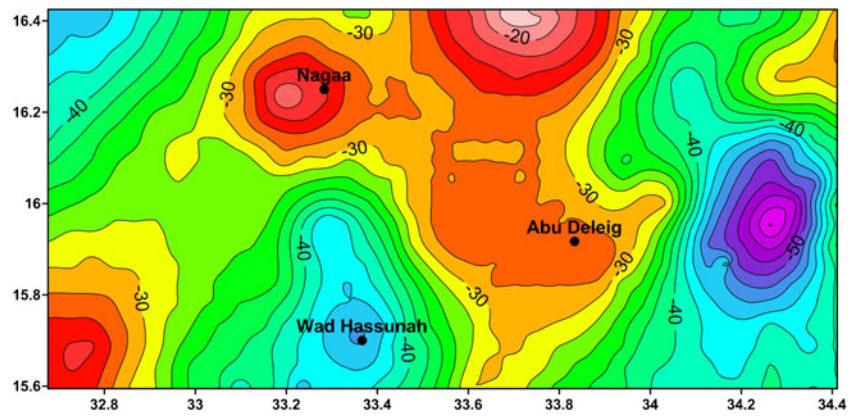


Fig. 4 Bouguer anomaly map of the study area

Fig. 5 Residual Bouguer anomaly map of the study area



graben and horst structures or the development of step faults. The basement rocks are exposed at the surface to the south of Abu Deleig town, whereas the sandstone crops out in the north. The sedimentary rocks are supposed to be preserved in the down thrown block of the normal faults. The resistivity survey was planned according to this finding.

Geophysical analysis

A Bouguer gravity anomaly map of the study area was constructed by gridding and contouring the Bouguer gravity anomaly values (Fig. 4). In this map, the eastern part of the study area is characterized by high amplitude negative Bouguer anomaly located around the Wad Burwa village,

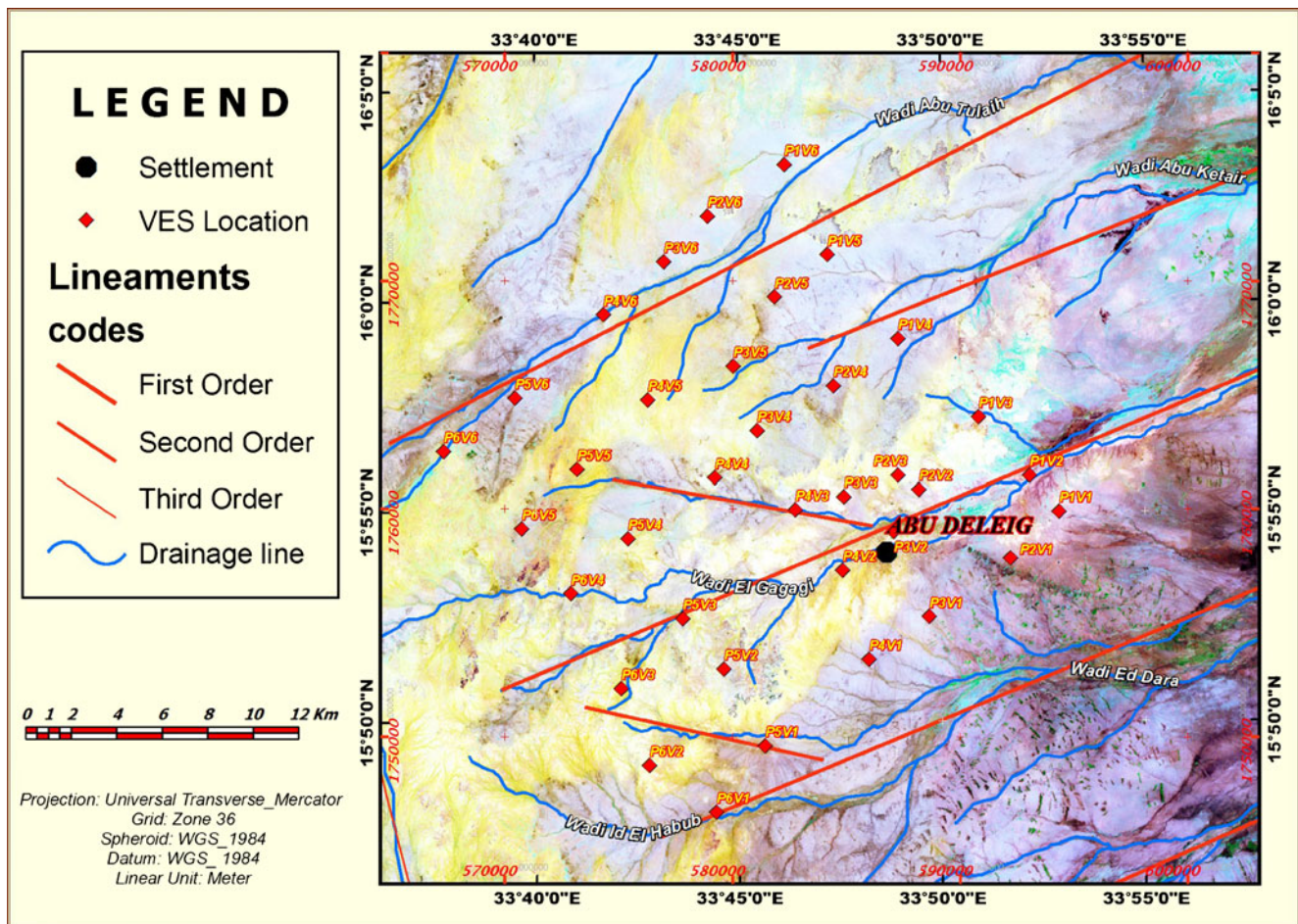
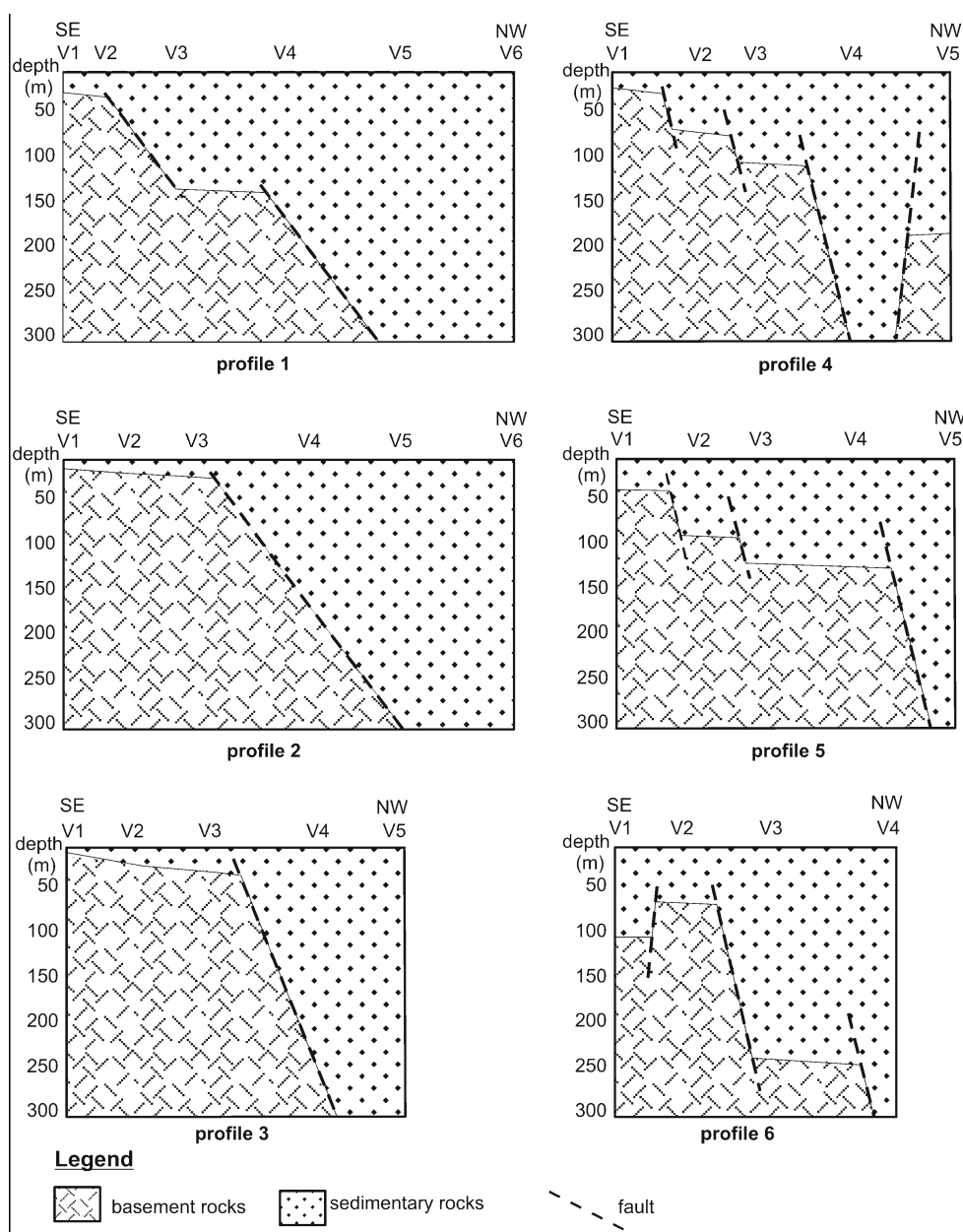


Fig. 6 Location map of the vertical electrical soundings overlain on the Landsat ETM image

with a peak value of -70 mGal. According to Salvador (2001), the low amplitude negative anomaly in the Wad Burwa area and the anomalies east of J. Qeili are attributed to the low density granitic mass, intruded into the relatively denser metamorphic terrain. The field check in the present study confirmed the existence of granitic outcrops as J. Makhshref near this low anomaly. The Sabaloka Igneous Complex to the northwest of the area is characterized by high amplitude negative gravity anomaly. Wad Hassunah which is the northern termination of Khartoum Basin reveals relatively high amplitude negative anomaly and represent a shallow part of the basin. On the other hand, Shendi Basin at Nagaa displays low amplitude negative anomaly. Khartoum Basin east of the Nile shows the same gravity anomaly as

Shendi Basin at Nagaa. Comparatively, the area north of Abu Deleig shows similar gravity anomaly to sedimentary basin around the area, therefore, this area was expected to represent a shallow sedimentary basin. In order to test the above hypothesis, a regional residual gravity separation was conducted using the averaging separation method (Serkerov 1999). A contour map generated from the results of the computation of the residual gravity is presented in Fig. (5). The map shows high amplitude negative anomaly near Wad Burwa which represents low density granitic mass. The medium amplitude negative anomaly in the northwestern part of the study area represents the shallow basement of the Sabaloka. Likewise, the shallow basement in Wad Hassunuh is represented by medium amplitude negative anomaly. The detected low

Fig. 7 Geological profiles obtained through interpretation of VESs



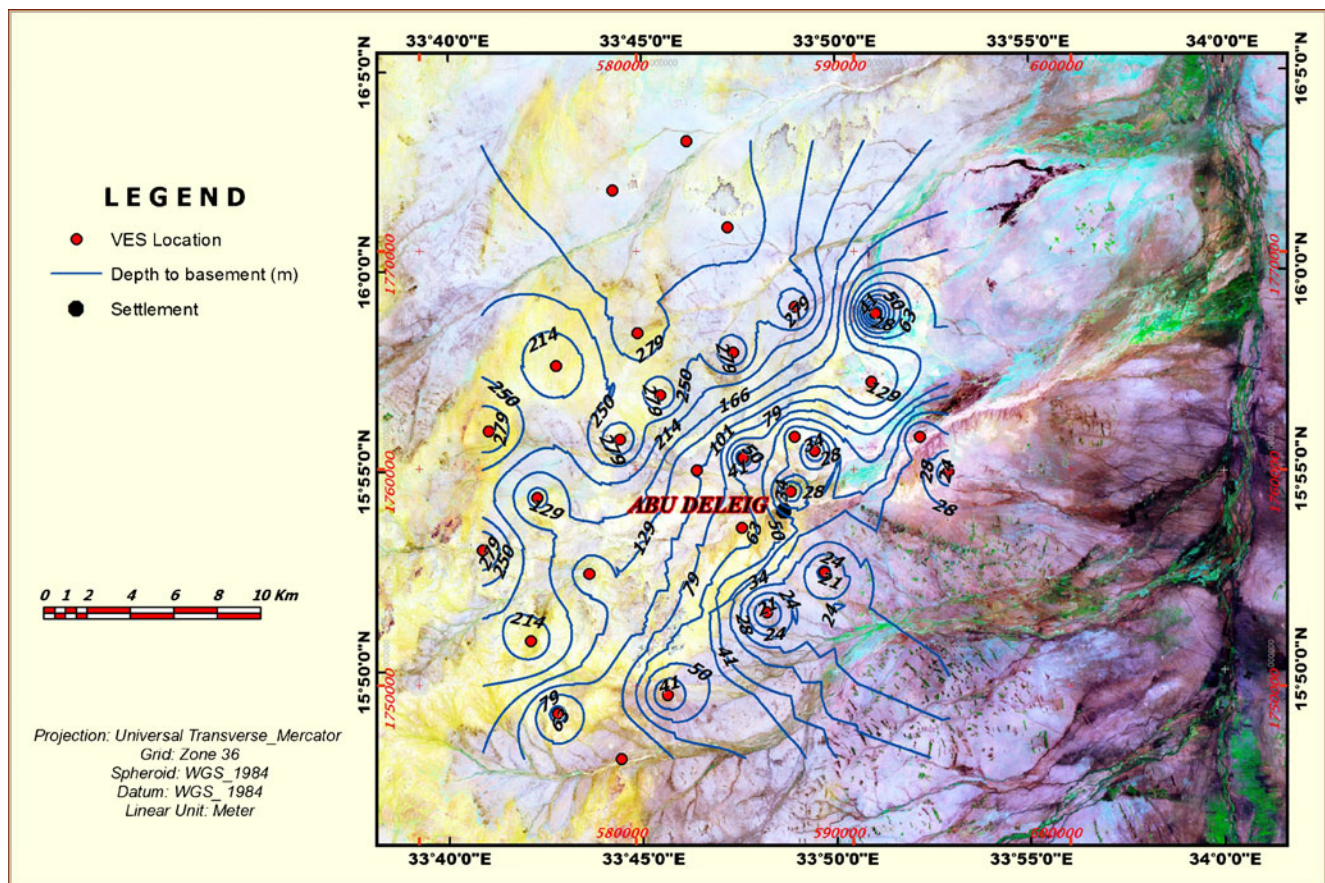


Fig. 8 Depth to basement map obtained from electrical resistivity data

amplitude negative anomaly north of Abu Deleig resembles that of the known Khartoum and Nagaa sedimentary basins. Gravity results indicate four main sets of linear trends NE, NW, and EW trending fault. The main trend of the negative anomalies is directed NE, related to Precambrian basement faults which were reactivated during the opening of the Red Sea. Equally, the residual gravity map confirmed the results obtained from the Bouguer anomaly map.

Accordingly, the resistivity survey was planned to confirm the existence of the assumed Abu Deleig sub-basin.

Thirty-six vertical electrical sounding surveys were conducted along six profiles crossing the minor structures (Fig. 6). Additional scattered VESs were used from the previous surveys in the investigated area.

The resistivity data were analyzed and interpreted using IPI2win to define the true resistivity and thickness of sediments in addition to the depth to the basement in the expected sub-basin. The results were calibrated with the data of the drilled boreholes in the area. Accordingly, six 2D geological sections were constructed to show the geometry of the sedimentary rocks in the basin (Fig. 7). These sections show 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 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 (Fig. 8).

The outcome of the present study reveals that the Abu Deleig sub-basin is evidently linked to Shendi Basin in the NW direction. This finding is concordant with the results of the research conducted by the British Geological Survey to estimate the aquifer recharge in lower Atbara River Basin using geochemical isotopes (Edmunds et al. 1987). However, there is no confirmation of a link with Atbara Basin to the NE or with Khartoum Basin to the west as believed before (Ibrahim 1993).

Conclusions

The digital image processing of the remotely sensed data helped in the delineation of lineaments and drainage system in the study area. The drainage pattern seems to be structurally controlled. Structural analysis of the lineaments defined the trends of the shear and tensional fractures. Wadi Al Hawad represents the southern extension of the well-known Keraf Shear Zone. The related minor fractures in

NE–SW direction exhibit normal faults governing the geometry of the Abu Deleig sub-basin. The geophysical investigations authenticated the findings of structural analysis and portrayed the subsurface geometry of the sub-basin. The newly discovered sub-basin has a prism-like shape with apex at Abu Deleig town and extends to 40 km in NW direction. The depth to the basement increases from 20 m at Abu Deleig in step form to more than 300 m, where it links to Shendi Basin in the northwestern part. Nevertheless, there is no confirmation of a link of Abu Deleig sub-basin with Atbara Basin to the NE or Khartoum Basin to the west.

A previous thought was that the Abu Deleig area is mainly built up of impermeable crystalline basement rocks with no possibility of groundwater occurrences. The discovery of this new sedimentary basin raises the hope to have potential groundwater resources to solve the chronic problem in water supply for the most vulnerable area in Khartoum Estate. Similar potential structures for groundwater occurrence could be found in the Butana arid region.

Acknowledgments The Faculty of Petroleum and Minerals, Al Neelain University is highly acknowledged for financing the field work. Thanks are due to the Ministry of Energy and Mining of Sudan for providing the gravity data. Global Land Cover Facilities of Maryland University is much appreciated for making remote sensing data available. The local community of Abu Deleig area is appreciated for the generous hosting and facilitating the field work.

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