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Research paper

Crustal architecture, geodynamics and structural evolution of en nuhud basin area, kordofan region, Sudan

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Abstract

Borehole data, geophysical investigations and remote-sensing prospection were used to demonstrate structural setting of the study area. Up to lifting, erosion subsidence and sedimentation activities intervene in the completion of the present geological setting. Different fault systems of NNW-SSE and E-W trends that coincide with the regional structural trends control the formation of En Nuhud Basin. Strike-slipping along the NNW-SSE system manifests at the southeastern part of the basin. An age of Precamberian for the formation of these structures is proposed. Later in the Cainozoic, the area was subjected to tensional forces, and hence a pull-apart basin is formed as a half graben with stepping depth in the south. The thickness of the sedimentary sequence generally ranges between few meters at the boundaries and about 1000 meters at the southern part of the basin. The study area seems to be tectonically active during the subsequent time. Sync-tectonic deposition is clearly shown in the relatively thick Superficial Deposits above the subsided zones. Elevation of the study area above the surroundings indicates an inversion stage for the basin, and presence of far-field effects is suitable in this case.

Keywords: *En Nuhud Basin; Kordofan; Subsidence; Syn-Tectonic Deposition; Inversion Stage.*

1. Introduction

The study area is situated in west-central Sudan and extends within Kordofan Region covering an area of about 20,466 km. It is bounded by longitudes 28° 15' and 30° 00', and latitudes 12° 22' and 13° 28' (Fig. 1).

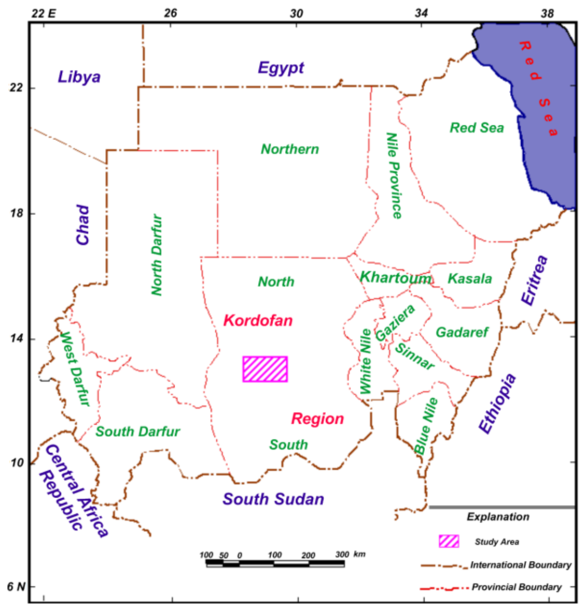


Fig. 1: Location Map of the Study Area.

Many studies were conducted including the area under this study such as: Rodis et al, (1964), Karkanis B.G. (1966), Strojexpt in the period (1971-1976), Ginaya (2001) and (Ginaya, 2011). These studies take care of geology, geomorphology, hydrogeological conditions controlling groundwater occurrence, groundwater flow and groundwater quality, but they didn't pay attention to the tectonics and structural setting in the area.

2. Objectives of the study

The main objectives of this study are to investigate the structural setting and characteristics of En Nuhud Basin, and to deduce the geodynamics and structural evolution of the study area.

3. Materials and methods

Data used in this study is compiled from many institutions and agencies and practitioners; in addition to the fieldwork of this study. The data collected comprises boreholes reports, geophysical measurements, geological observations, and different types of maps. Complexes of geophysical methods (gravimetric, piezoelectric, magnetic and well-logging) integrated with borehole data were used to examine the subsurface structures in the area. The obtained data and information were processed and interpreted to construct maps, profiles and sections, and then a comprehensive picture for the study area is deduced. Deduction, correlation and integration represent the main pillars to the data interpretation. Because of lack or inadequate control data in some parts of the study area, ambiguity occurs and many models of interpretation were possible, hence the best and more logical interpretation is adopted. Sometimes interpretation is made by correlation with the adjacent areas or comparisons to similar conditions or areas around the world. Models were prepared without the assistance of the computer software.

4. Geology

4.1. Rock units

Four geological units underlie the area, those are: Basement Complex, Nubian Sandstone Formation, Laterites, and Pleistocene and recent deposits (Strojexport, 1976), (Fig. 2).

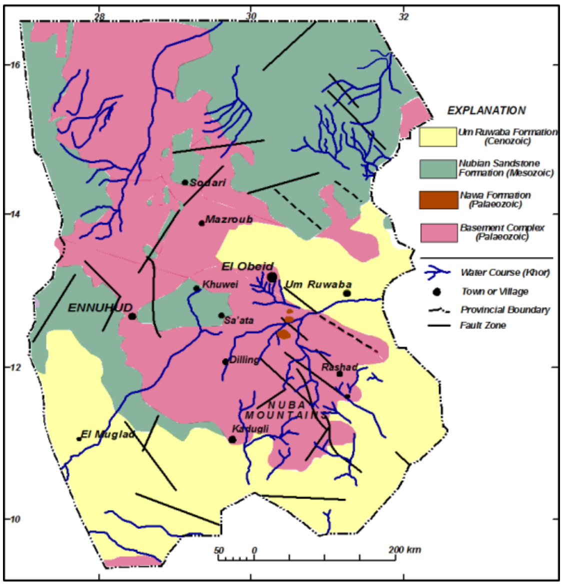


Fig. 2: The Main Rock Units in Kordofan Region (Modified after G.M.R.D, Khartoum, Sudan 1981).

Basement Complex is of Precambrian age, and includes metamorphosed and folded schists and gneises as well as sky-orogenics or late orogenics granitic emplacements and basic and ultra basic bodies (Vail, 1978); in Kordofan, it is composed predominantly of granite, nice and schist with quartzite and crystalline limestone (Rodis et al, 1964); they crop out at many places, and some have been evidenced in drilled holes (Strojexport, 1976).

The origin and age of the Nubian Sandstone Formation in Sudan have been controversial but most geologists believe that it was laid down in subaqueous environment (Whiteman, 1971). Deposition in continental and\or near-shore environment was advocated by Rodis et al (1964). For the age, Whiteman (1971) allocate Early Cretaceous in the base of fossil evidence; Harms et al (1990) categorized it as Upper Jurassic/ Cretaceous.

Strojexport, 1976 classified the Nubian Sandstone in the study area into: pelite-aleurite facies (grains size less than 0.05mm) and psammite –psephite facies (grains size more than 0.05mm). The Cretaceous Sandstone Formation varies considerably in thickness as regionally described. Borehole data and geophysics in En Nuhud outlier show maximum thickness of about 1000- 1200 m.

The laterite consists of a highly ferruginous layer of ironstones usually of few meters thick. Erosional remnants of laterites are recorded north-east En Nuhud, and at the center of the study area (Whiteman, 1971). Geologists proposed ages extended from late Cretaceous to Early Tertiary (Whiteman, 1971). Rodi's etal (1964) proposed the age of Early to Middle Tertiary time for laterites in Kordofan province.

Pleistocene and Recent deposits include Qoz sands (gently-rolling sheets and fixed dunes), clay plains, hill wash deposits and alluvial deposits, (Grabham, 1935). Edmond (1942) proposed the Qoz sands are a product of weathering of the Nubian Sandstone. Most geologists proposed the origin of clay deposits as alluvial deposits; Grabham (1935) postulated an aeolian origin.

4.2. Tectonics and structures

4.2.1. Tectonic history

Most of the Sudan is placed within the so-called the Saharan Metacraton, (Fig. 3). This Craton was remobilize during the Neoproterozoic in the form of deformation, metamorphism, emplacement of igneous bodies, and probably rifting and oceanic basin development. Relics of un-affected or only weakly remobilize old lithosphere are present. Geochronological and isotopic data indicate that this region constitutes Pre-Neoproterozoic continental crust over-printed by Neoproterozoic tectonic events as well as containing Neoproterozoic juvenile material (Abdelsalam et al, 2002).

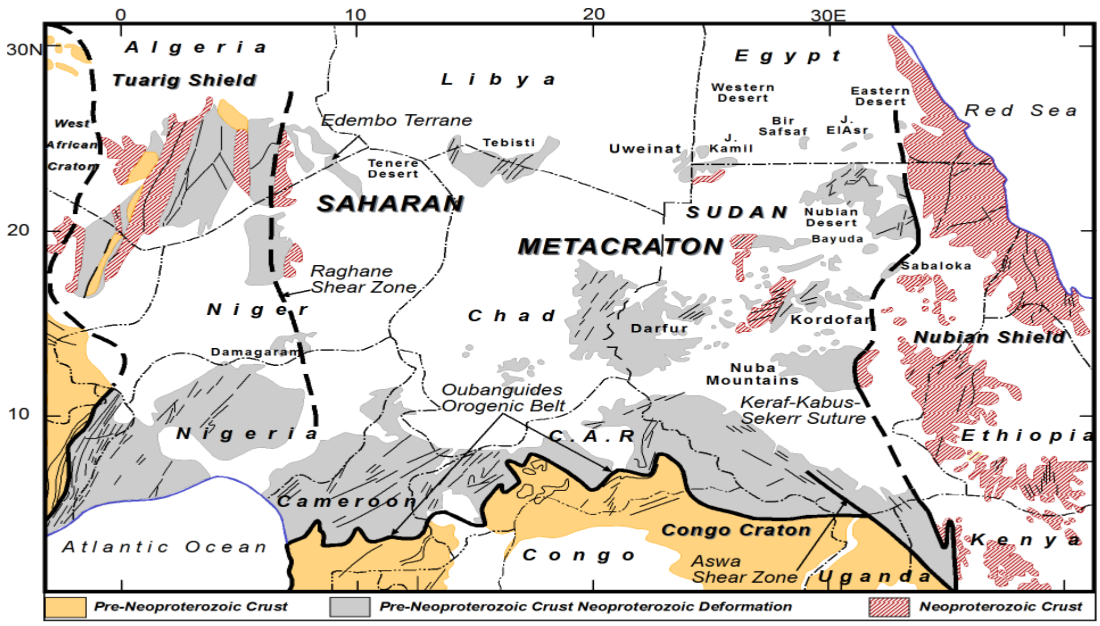


Fig. 3: The Saharan Metacraton (Modified after Abdelsalam Et Al, 2002,).

4.2.2. Regional structures

Two structural trends dominate the Saharan Metacraton, an early ENE-WSW (Zalingei Folded Zone), and younger N-S. The (Zalingei Folded Zone) has been reported many places in Sudan such as Bayuda Desert, the Nubian Desert, Kordofan and Darfur (Abdelsalam et al, 2002); (Whiteman, 1971) obtains 630- 620 Ma U/Pb zircon ages from granitoids deformed by these structures. The N-S trending structures constitute N-trending upright fold deformation by N to NW-trending strike-slip faults, when both are more or less parallel to Keraf Suture. The final deformation along the Keraf Suture is also defined by N-trending upright folds and NNW- trending sinistral strike-slip faults. Ar/Ar ages obtained indicate an age of 560 Ma for the end of this deformation (Abdelsalam et al, 2002). Other N-trending structures in the Saharan Metacraton are in the form of folds and thrust belts, such as those of Jebel Rahib in Kordofan, and normal shear zones such as those in the Nubian Desert.

Schandelmeier et al (1991) revealed the existence of four major deformational episodes in the Basement of the Um Badir and Sodari areas of Northern Kordofan Region as D_1, D_2, D_3 and D_4. D_1 deformational episodes are attributed to a late Proterozoic ductile shearing along subhorizontal planes which produced isoclinal folds in Um Badir belt with axes NW-SE to WNW-ESE. Sub-horizontal foliation and fold, with axes of NW-SE to WNW-ESE and Sub-ordinately NNE-SSW trends. D_2 deformational episode represent a phase of intense NNE-SSW ductile shearing in the Um Badir Belt refolded earlier structures and it is of late Pan-African age. The features of D_2 comprise ductile shear zones, mineral stretching lineation and tight to open folds. D_3 that known as Um Badir Shear Zone (UBSZ) developed during the intensive Late Pan-African crustal shortening and consists of a system of sub-parallel brittle shear zones which cross-cut all the previously described ductile fabrics of the Um Badir belt (Fig. 4), with master faults generally trend around N51°. D_4, the Sodari Shear Zone (SSZ) deformational episode is a late Carboniferous to Triassic brittle shearing reactivation event in the Um Badir and J. Nehud areas (dextral) and in Sodari area (Sinistral) (Fig. 4). It is a large wrench fault zone with master fault striking approximately N35° direction.

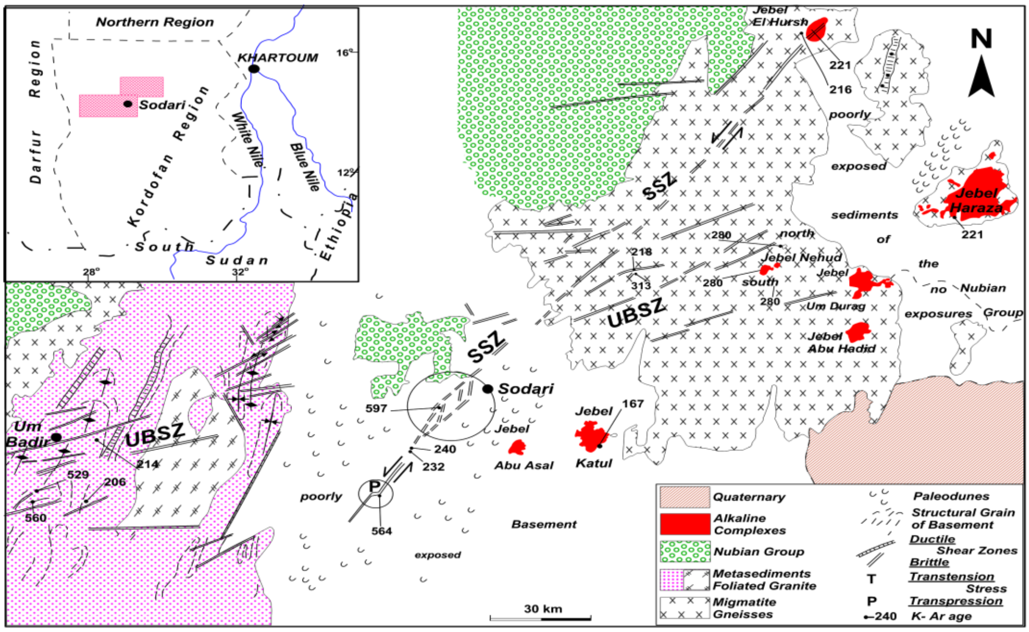


Fig. 4: Major Structures of the UBSZ and SSZ (Modified after Schandelmeier and Richter, 1991)

4.2.3. Rift structures and rifting phases

The movement of the African plate during the Cainozoic created rift structures which formed by successive block faulting along paleo-trends; the biggest of these rift structures is the Sudanese Rift System- SRS (Salama, 1997), (Fig. 5).

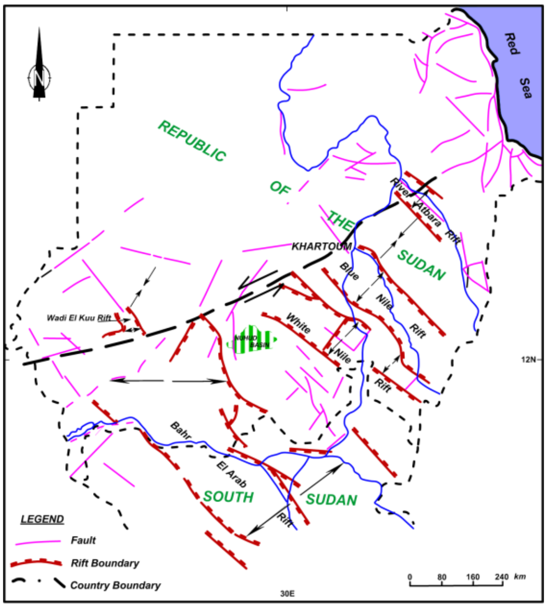


Fig. 5: The Sudanese Rift System (Modified after Salama, 1997).

Girdler and Daracot (1972) suggested that separation of Arabian from the African plate along the Red Sea with its rotation pole in North Africa, created northeasterly tensional stress fields and northwesterly structures in Sudan. In contrast, in the southern part of the continent rotation about poles in southeast Africa caused northeasterly structural patterns.

The basic theory for the formation of the SRS is that anticlockwise rotation of Africa during the latest 70 million years Girdler (1968) led to the opening of the southern SRS and the clockwise rotation which started in the latest 10 million years created the northern SRS. The two systems are separated by the Darfur Dome (Salama, 1997). Based on the length, depth and width of the SRS, it is clear that the forces which caused the rift are more prominent in the western side and seems to fade away towards the east. This indicates that the stress in the SRS increases from east to west (Salama, 1997).

5. Results and discussion

5.1. Crustal architecture of el nuhud basin

First-layer geology methods are failed in exploring the geometrical setting and the stratigraphy of the study area, due to that the deep structures are not manifested at the surface, where the recent deposits veil the subsurface. Hence second-layer geology is used to portray the structural attitude of the subsurface horizons. The crustal architecture of El Nuhud Basin is achieved by structural interpretation based on some limited rock outcrops around the area, surface topography, borehole data, geophysical measurements and other geological observations. Integration of these tools and data sources enabled geological correlation, and hence determines the geometry of the deeper beds structure.

Bouguer gravity contours (Fig. 6) show many anomalies (highs and lows).

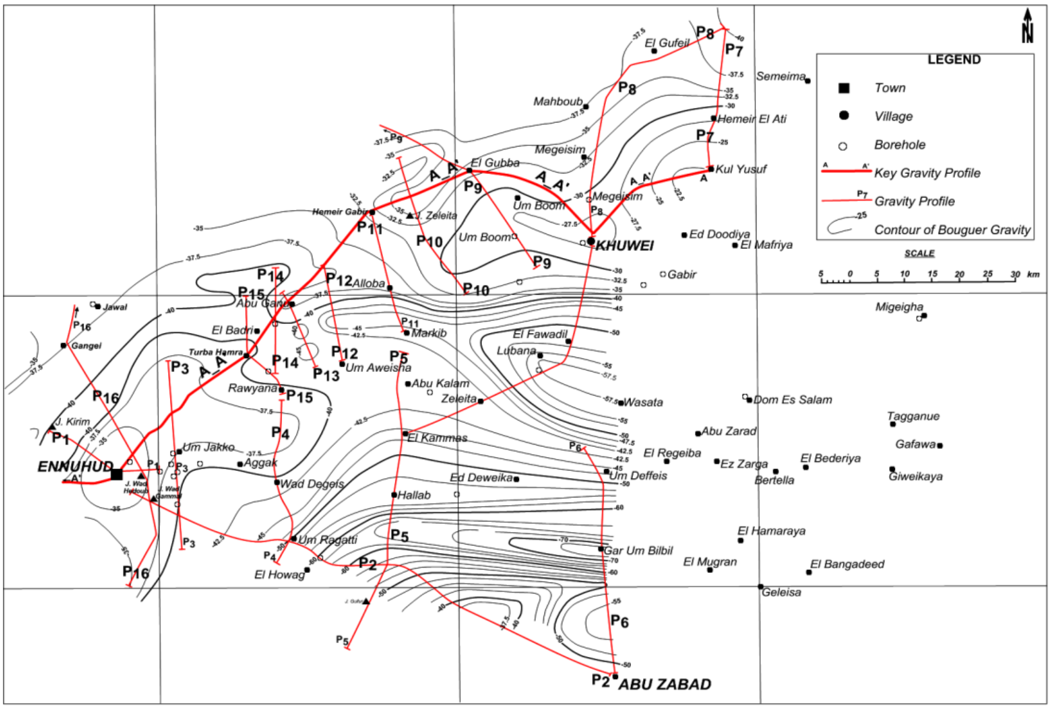


Fig. 6: Bouguer Contours (Based on Strojexport 1975, Plate 13, Area B, En Nuhud-El Khuwei).

These anomalies are interpreted as due to variation in density and or the thicknesses of the sedimentary sequence; i.e. they reflect to more extent the morphology of the Basement Complex as elevations and depressions (Fig. 7).

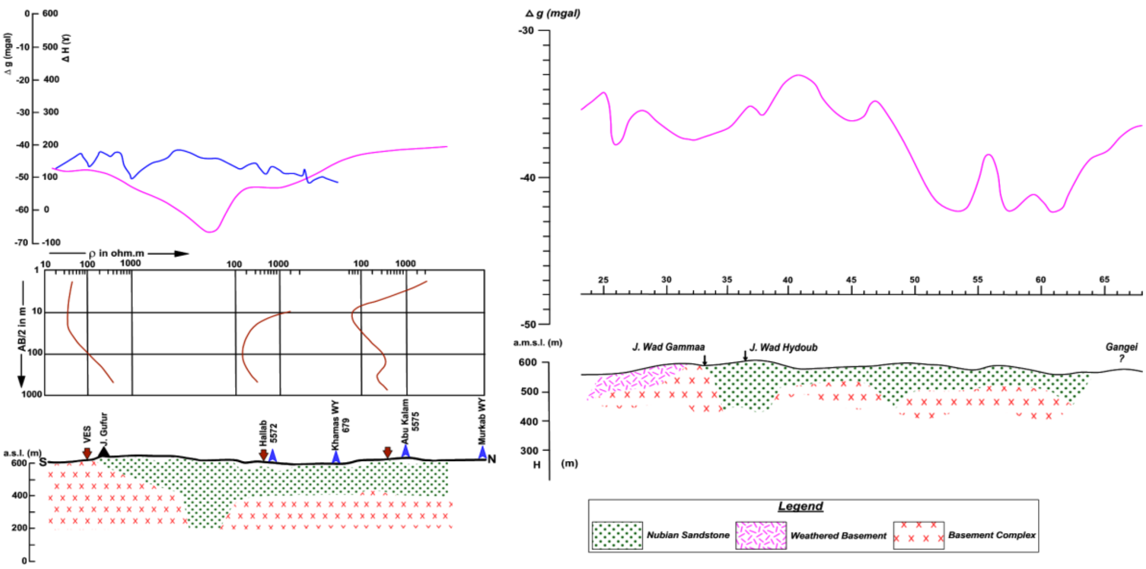


Fig. 7: The Morphology of the Basement Complex.

The most prominent depressions can be named as: El Fawadil graben, Murkab graben, Um Lubana graben, Hydoub graben, Hallab graben and the deepest one, the Gar Um Bilbil graben at the southern part of the basin (Fig. 6).

The constructed structural map (Fig. 8) indicates that En Nuhud basin is a fault-bounded depression produced by intensive faulting. It is tightly controlled by two sets of faults trending NNW-SSE and E-W, which intersected by an angle of about 60^o. NE or ENE set of fractures is seemed to be of a limited effect on the general architecture of the basin. The structural map (Fig. 8) highly supports the results of gravity, especially in concern to the main structural units where additional details are ensured. One is the presence of some sub-basins within the main structural grabens. Gar Um Bilbil graben is seemed to be right-handed displaced northwards and two structural units are formrd as El Mayaa and Gafawa grabens. Also the contours of equal depth to the Basement at the southern boundary of the basin indicate steep fault surfaces and large throws of the rock masses.

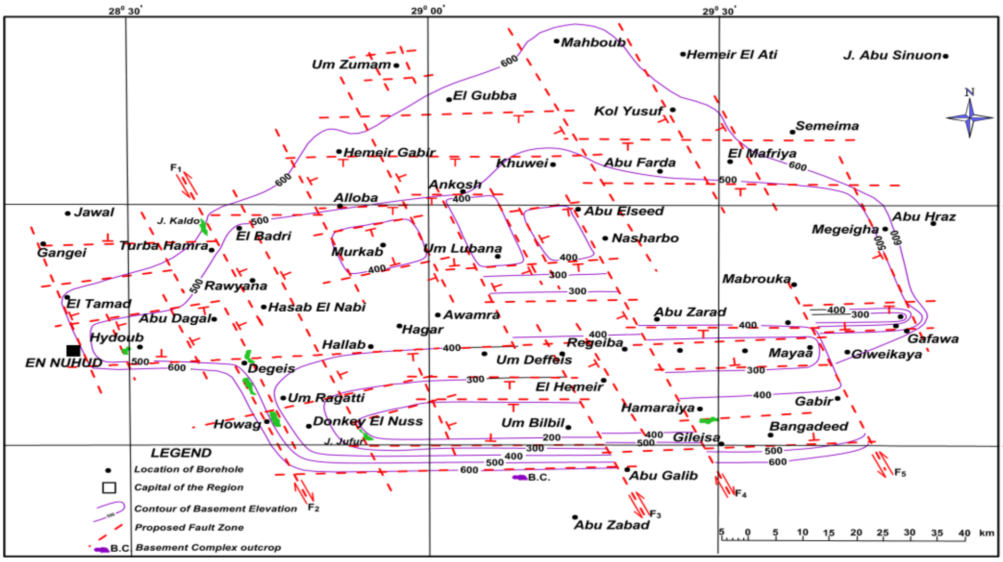


Fig. 8: The Morphology of the Basement Complex and the Dominant Structures.

Strike-slip displacements are clearly marked along the NNW-SSE fractures at the southern and western ends of the basin. Accordingly some large blocks were displaced, such as the situation along the fractures F_3 (sinistral), F_4 (dextral) and F_5 (Sinistral). The situation around the fractures F_1 (sinistral) and F_2 (dextral) is questioned, where displacements of which are all in the left side towards each other. The preponderant and more logic interpretation for this case is made by correlation with the adjacent areas; that is stated as crumpling and/or thrusting of the sedimentary sequence have been taken place, under the influence of the compression stresses that acting NW-SE or N-S, and hence shortening of the formation, where thrusting is proposed to be active along highly inclined fractures, Billings (1972). The geological conditions around these structures show high complexity and discrepancy on the which support the above concept.

Based on the statement that "the surface topography is a rather direct expression of the subsurface structure, especially in regions of recent tectonic activity", Billings (1972), the surface topography (Fig. 9) is correlated to the Basement topography. The result is that the surface topography, to some extent, confirm this postulate, and it is noted that the low elevations is consistent to that of the Basement Complex. The low elevated area around El Hemeir at the southeastern part is the prominent example and can be considered as the deepest area within the basin. Geological cross sections constructed on the basis of the integration of borehole and geophysical data give detailed dissection for the basin geometry and stratigraphy.

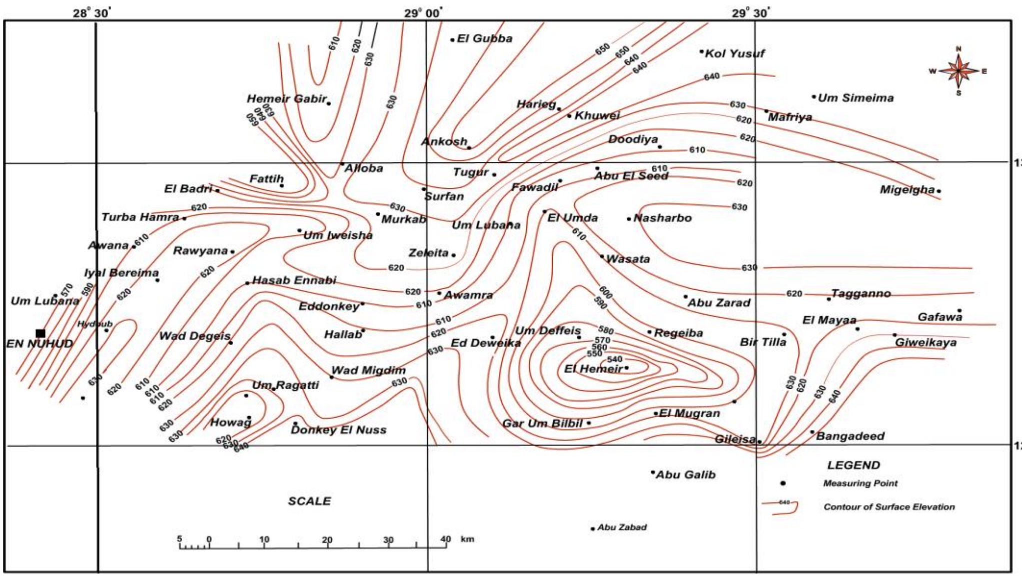


Fig. 9: Ground Surface Topography Contours.

A quick notice on these sections is the strong breaking and ripping of rock structure in the area, due to fracturing and faulting, ductile deformation is not evidenced. Vertical displacements along fractures are usually confirmed by discontinuity and variations in depth of strata by the sides of the fracture; brecciation sometimes occurs. Strike-slip along these fractures usually manifests as approximately full-scale or a complex contrast in lithology by the sides of the fracture (Fig. 10). Displacements along fractures are most probably expected to be of a complex manner.

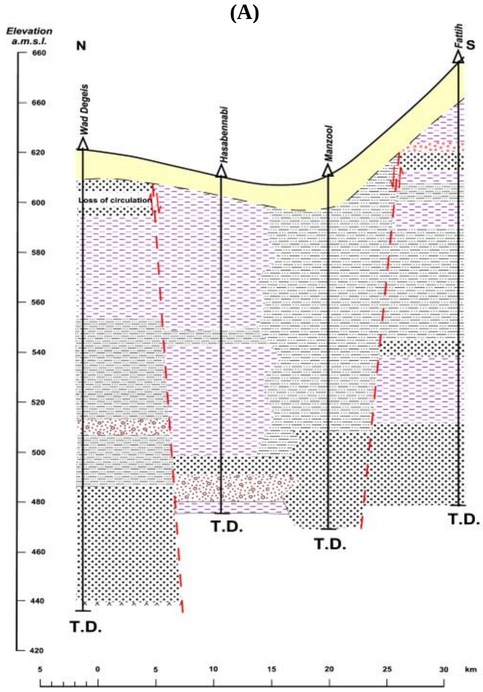
At the surface of the ground, fault zones usually express themselves by many ways: Some subsidence on the ground surface; many times thickening of the Superficial Deposits occurs; loss of circulation of drilling fluids can be an evidence for fracturing around the bore site (Fig. 11 and Fig. 12).

Subsidence and thickening of the Superficial Deposits can be considered as strong evidence for active faults, where simultaneous subsidence and sedimentation can take place for a time.

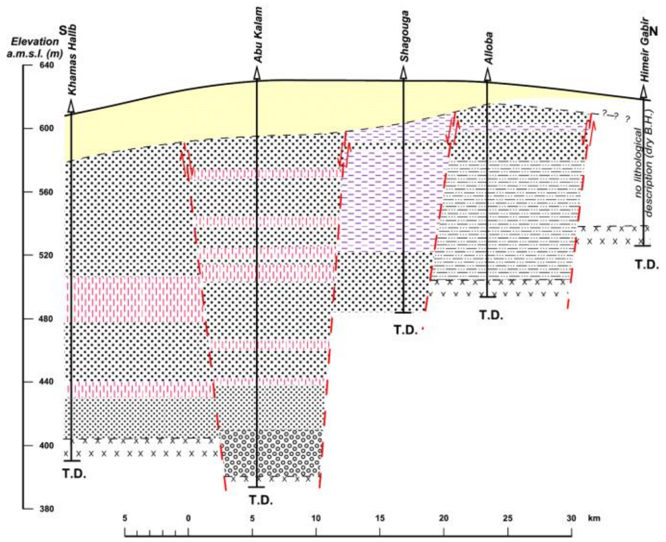
Strike-slip displacement along fractures assigned previously on (Fig. 8) as F3, F4 and F5 can be confirmed by many evidences, such as:

- The displacement of the contour lines, in the surface topography map (Fig. 9) and in the sand ratio map (Fig. 13), coincide with the proposed direction of the displacement along these fractures (towards the north); sand ratio contour map is constructed upon the basis of the estimated thickness of coarse material (> 2mm) as a percent of the total thickness of sediments in borehole lithologic logs.
- Deviation of contours of equal elevation of Basement Complex in the same direction (Fig. 8).
- The Geological boundaries of the basin are clearly defined in the micro-drainage map where high accumulation of drainage line at the borders of the basin traced the rift edges as a water divide line (Fig. 14). As well the landsat image prepared for the geological features also illustrates the basin boundaries and it is manifested as a distinct geological unit (Fig. 15). On the other hand the digital elevation map with drainage shows that the study area is clearly elevated above the surroundings where the area is drained outwards (Fig. 16). The more elevated zones are at the northern and north-eastern parts of the basin; these areas are compared to elevated Basement blocks where drilling failure is recorded at those parts.

(A)



(B)



(C)

(D)

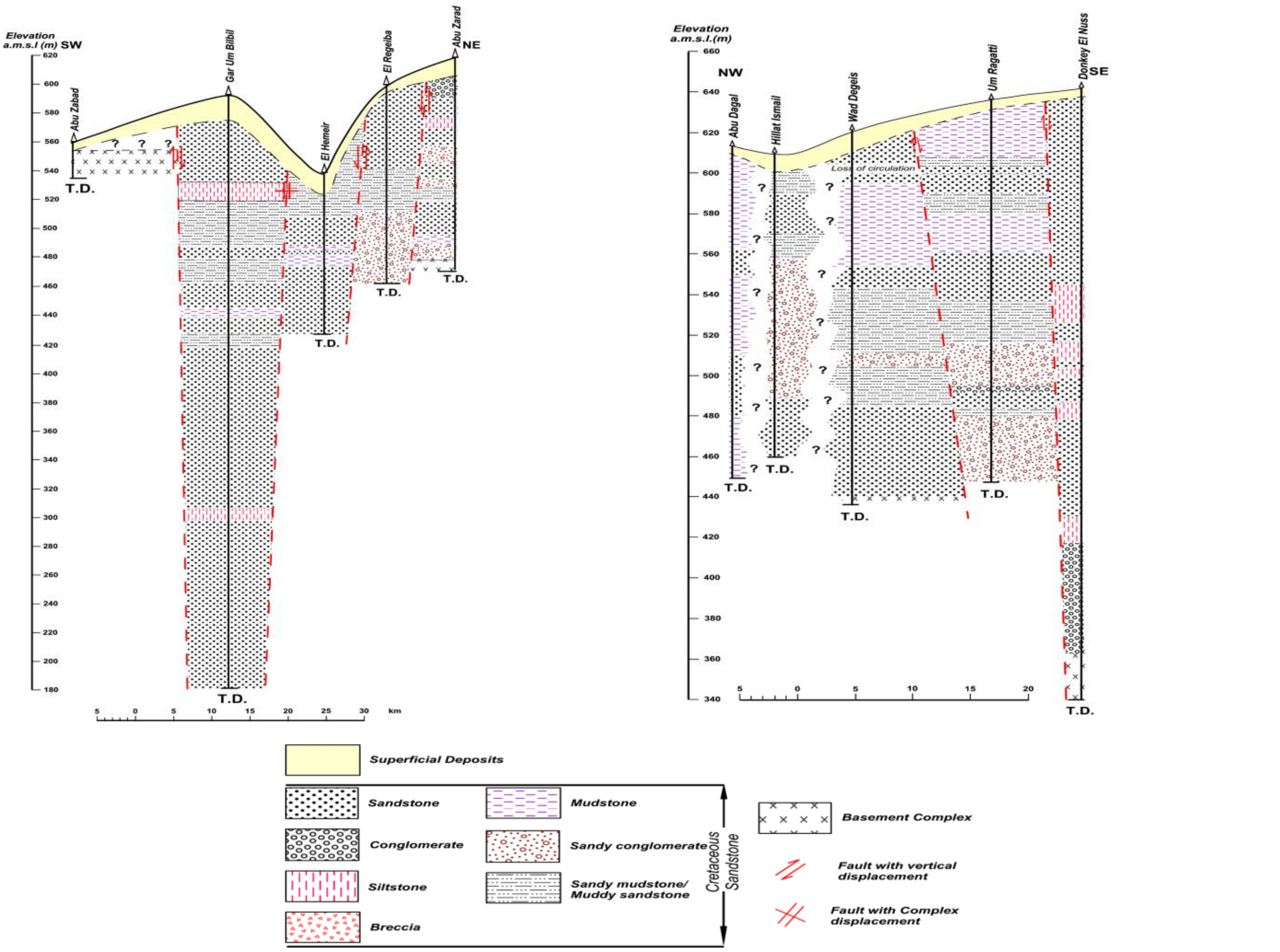
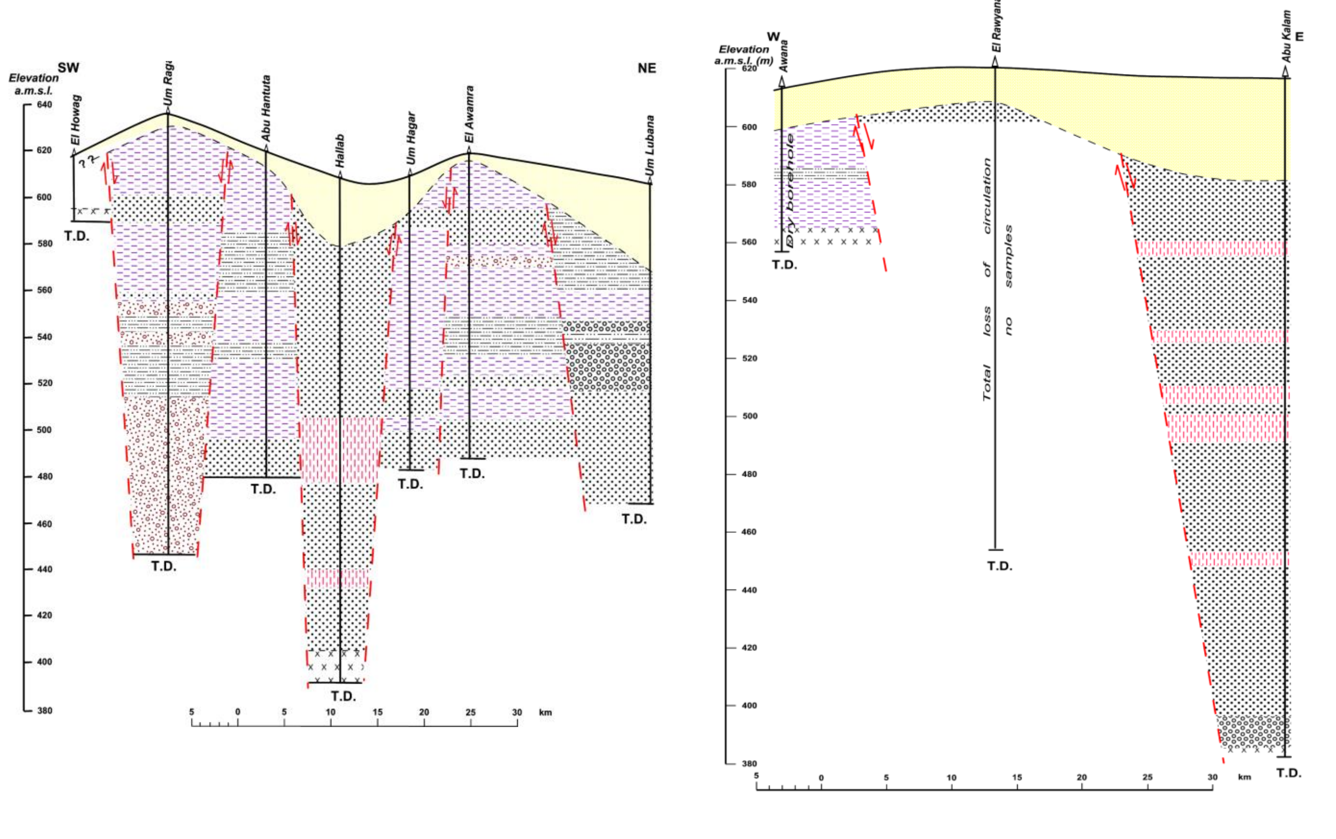


Fig. 10: Cases For Displacements Along Different Types Of Faults.

(A) **(B)**



(C) (D)

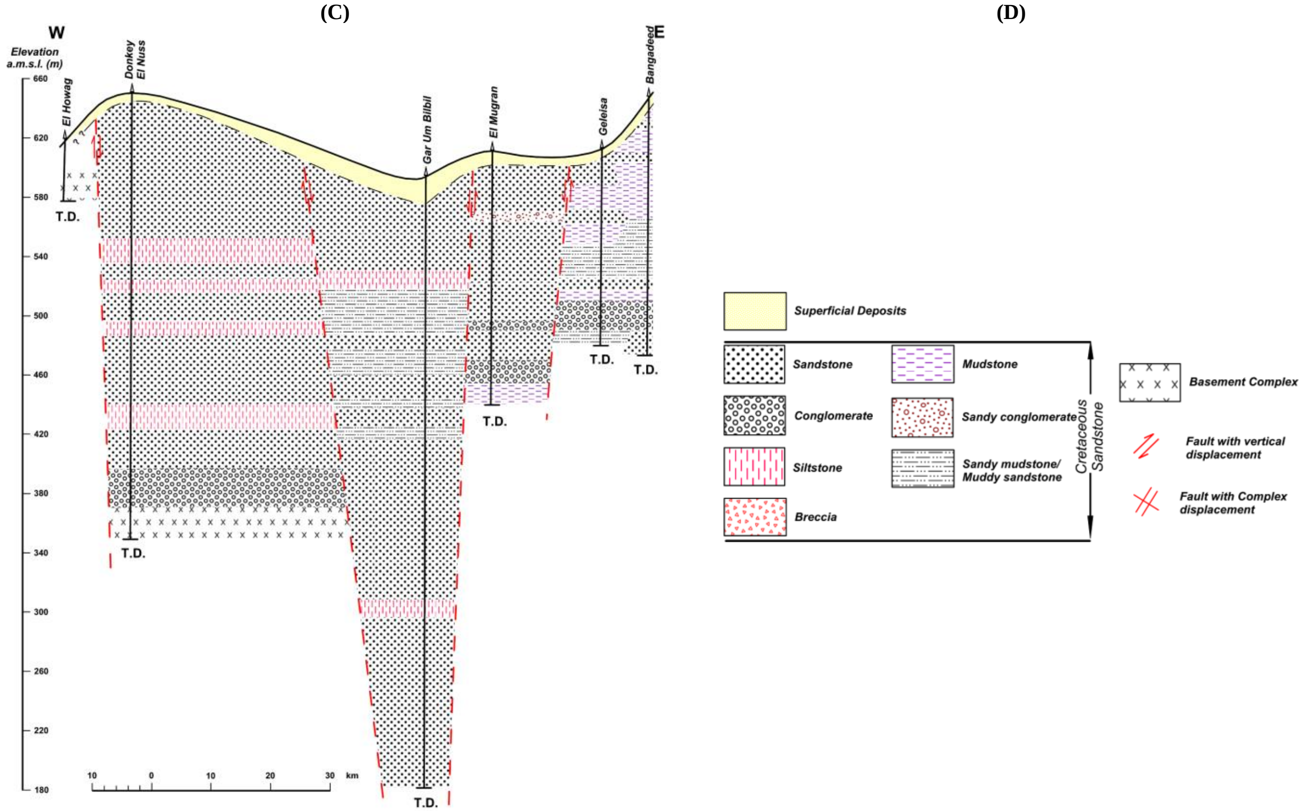
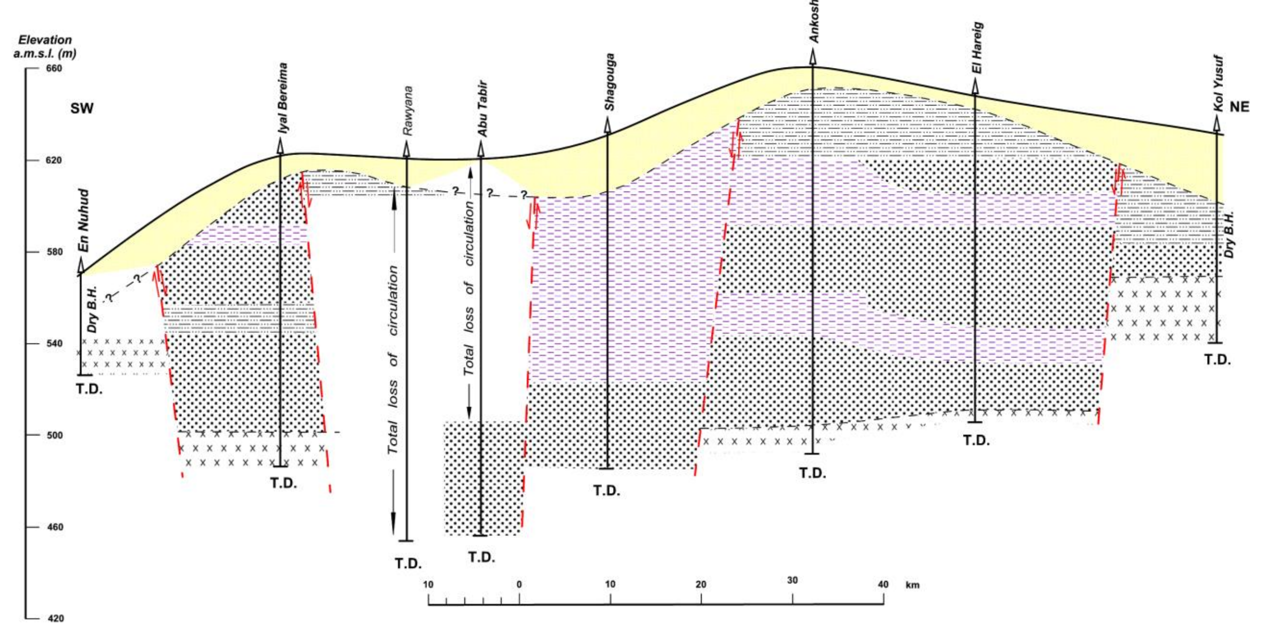


Fig. 11: Subsidence, Thickening of the Superficial Deposits and Loss of Drilling Fluids.

(A)



(c) (B)

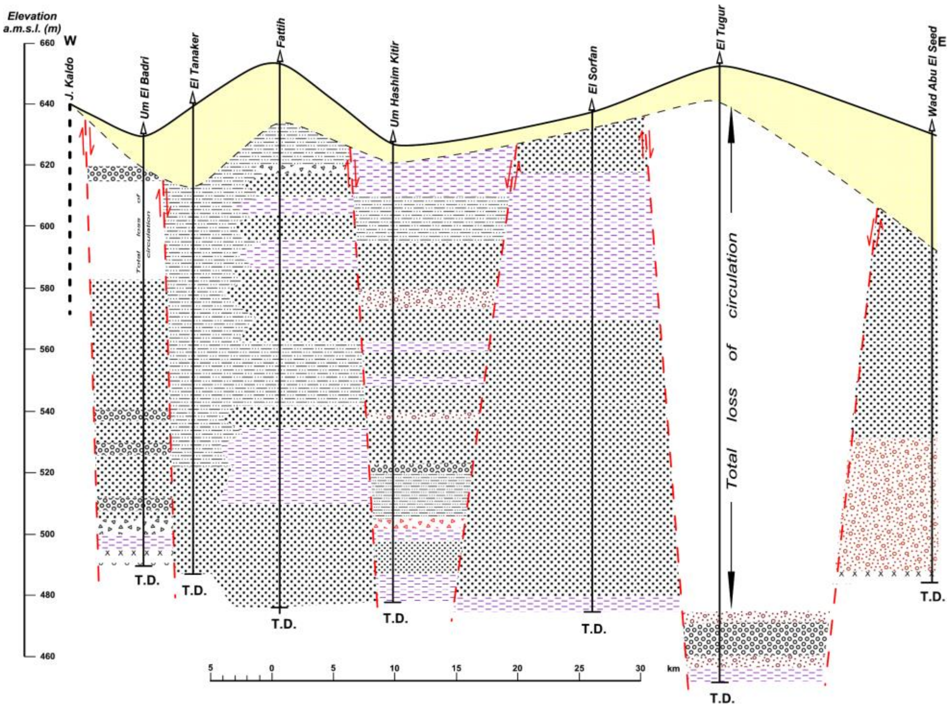


Fig. 12: Cases for Subsidence, Thickening of the Superficial Deposits and Loss of Drilling Fluids.

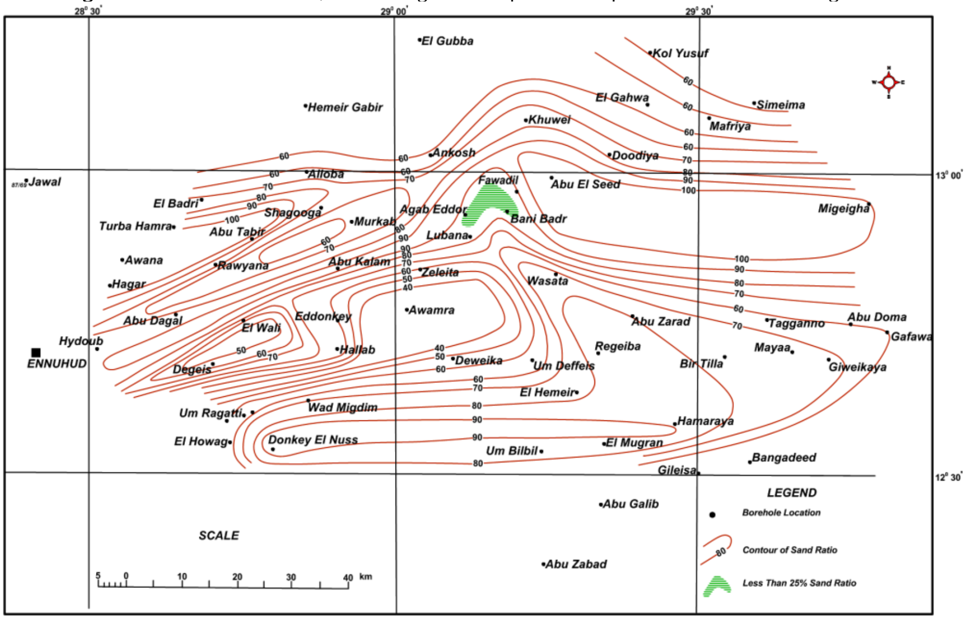


Fig. 13: Sand Ratio in the Study Area.

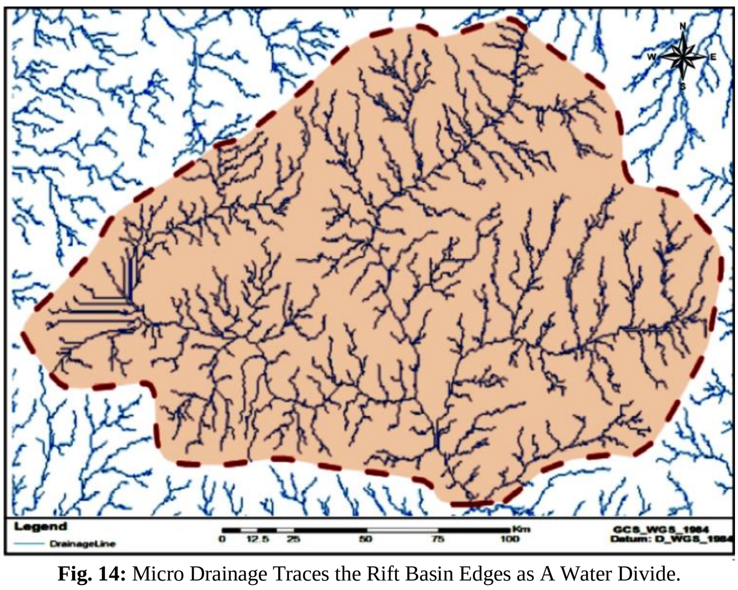


Fig. 14: Micro Drainage Traces the Rift Basin Edges as A Water Divide.

5.2. History and structural evolution of en nuhud basin

Based on the structural setting, tectonic characteristics of the basin, and the regional and global tectonic events, a conception on the tectonic history and structural evolution of the basin is stated. The statement considered the time, mechanism and the order of the different events that produced the present geological feature; En Nuhud Basin. These are proposed as follows:

As it is illustrated in (Fig. 8), the dominant trends of the brittle structures are NNW-SSE and E-W. Two assumptions are stated for the evolution of the basin; one is explained on the basis of different time formation for these sets of fractures, the second is based on synchronizing formation of the two sets of fractures,.

The first explanation, the different time or separately formation of these fractures can agree formally with many local and regional tectonic events. Fleck et al. (1980) proposes a model in which the new create crust of proto-Arabia eventually collide with the proto-Africa continent to the west.

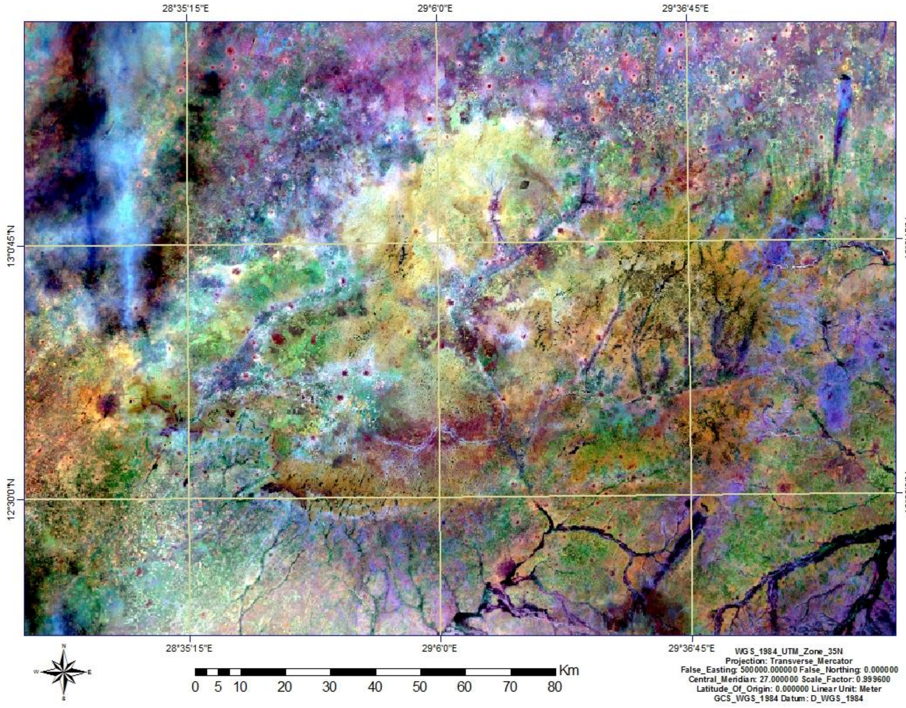


Fig. 15: The Basin Area as A Distinct Geological Unit in the Landsat Image.

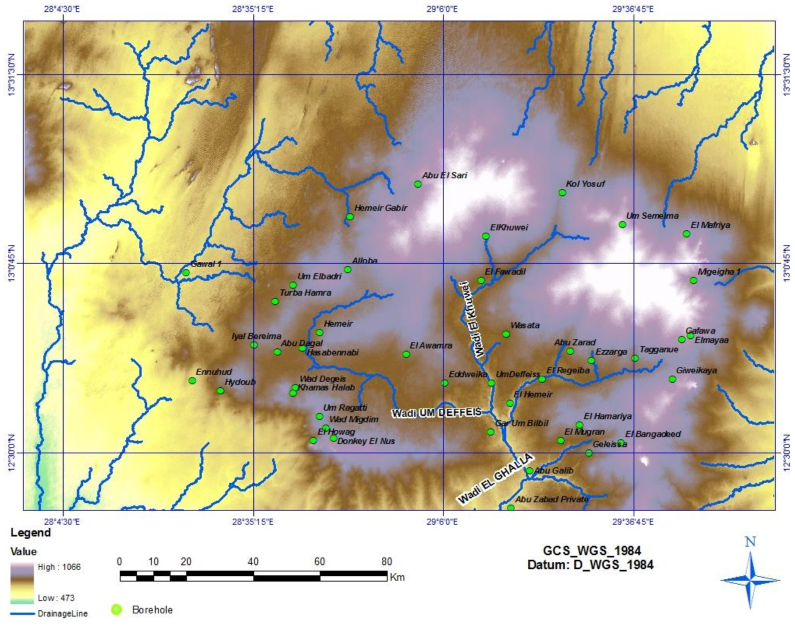


Fig. 16: Digital Elevation-Drainage Map Illustrates the Elevation of the Study Area.

On both sides of the suture, collision resulted in thickening of the crust, transcurrent faulting on a major scale, and wide spread magmatism expressed in numerous late to post-tectonic igneous complexes with ages between 660- 600 my. They also correlated the collision in Arabia with the "Pan-African event" recognized in over two third of Africa continent a concentration radiometric dates in the range of 650- 450.

Ahmed (1982) in his study of the Precamberian lineaments in NE Sudan, conclude that besides the curvilinear features, strong pattern Precamberian structures trending mainly in N-S, NNW- ENE, and less distinct, poorly exposed E-W and NW-SE were developed. Furthermore, faults along the lineaments' zones seem to have been rejuvenated several times during the subsequent tectonic events which were active since post-Cretaceous until recent (Vail, 1978 and Whiteman, 1971). In Sudan, large transcurrent faults include the NW trending Aswa fault (Almond 1982), and its possible extension northward into Sudan (Salama, 1985a).

Salama (1985a) suggested that, following the Pan-African event (950-500 Ma), Harms, U, et al. (1990) and before the end of Mesozoic, there began long succession of warping, rifting and volcanism, which preceded and followed the opening of the Red Sea oceanic rift. These tectonic events in central Sudan are related to the same forces causing the opening of the Red Sea.

The Upwelling of the Darfur Dome (NE-SW trending), at the end of the Mesozoic and continued to tertiary, is enough to cause tensional forces which caused fracturing and faulting perpendicular to the direction of stress, creating the extensive NW faulting system, Salama (1997). At the same time the spreading of the Red Sea 65-56.5 Ma, Kennett (1982), produced another tensional field which caused the N-NE fracturing and faulting patterns. The intersecting normal faulting systems led to the formation of blocks, which were continuously subsiding. This subsidence was accompanied by uplift on the flanking sides. This in turn led to creation of another compressional field, which in turn created its own fracturing system, Salama (1985a, b).

According to Gridler and Daracot (1972), the separation of Arabia from the Africa plate along the Red Sea with its rotation poles in North Africa 5.2-3.4 Ma, Kennett (1982), created NE tensional stress fields and NW structures in Sudan. This statement can be supported by the note of Salama (1997) that based on the length, depth and width of the Sudanese Rift System. It is clear that the forces which caused the rift are more prominent in the western side and seem to fade away towards the east; the stress in the Sudanese Rift System increases from east to west.

Bailo et al. (2003) stated that the Keraf Shear Zone of NE Sudan formed in the Neoproterozoic time due to crustal shortening when the Arabian Nubian Shield collided with the reworked older crust of the Saharan Metacraton (Fig. 5.2). Abdelsalam et al. (1998) stated that the Keraf deformation took place between 640 and 589 Ma. The sharing was characterized by N-NNW trending faults.

According to the review and discussion of many of the main local and regional tectonic events and the characteristics of the structural features developed as a result of these events, temporal and spatial relationships of En Nuhud Basin to surrounding tectonic events and structural features are conceivable and can be deduced.

The structures that more affected the basin building as they described before have the dominant trends NNW-SSE and E-W, (Fig. 8). These trends assimilate trends related to many events and major structural features.

The NNW-SSE fracture set can be attributing to Precamberian (Neoproterozoic) deformation, collision of Arabian and African plates (Tertiaty), tensional forces resulting from the up welling of Darfur Dome in the Mesozoic era (Cretaceous), or to the clockwise rotation of the African plate during the separation of the Arabian plate from the African continent during the last 10 million years. For the E-W fracture set, similar structures are noticed only with the Precamberian (Neoproterozoic) deformation where E-W fractures are included. Nevertheless, it is not necessary all these events fit the time conditions of the evolution of these fracture sets.

The second explanation for the formation of these structures is that the area was subjected to approximately directed NW-SE compression stresses, and crustal shortening, where as a result, two sets of fractures are produced, and hence strike slipping along these fractures took place. This postulated is supported by the acute angle between the two sets of fractures as around 60 degrees (Fig. 8), the case which usually characterizes the fractures produced by compression stresses, Billings (1972).

The mechanism of such action requires the state of regional and far-field stresses feeding, the source of which can be compared to tectonic activity occurred in east and central Africa during the Mesozoic and early Tertiary, Bosworth (1992), which resulted into the formation of the Central African Rift System, that spanned from central Sudan to southern Kenya, or it can be compared to any displacement of rock blocks around the area due to the different tectonic events that took place around.

Whatever the way of the formation of these fractures the area was subjected to tensional forces during the following periods, and hence a pull-apart basin is formed. Salama (1985a) stated that Cainozoic up-doming, volcanism and tensional stress associated with the movement of the African plate create rift structures, which were formed by successive block faulting along palaeotrends. These were followed by subsidence and linear uplift to create the Sudanese Rift System.

Some geological evidence from the study area indicated the presence of active rifting during the subsequent time; this is deduced from that the Superficial Deposits are thicker above the relatively subsided zones within the basin; the subsidence continued during the deposition of these sediments or syn-tectonic deposition is present. On the other hand, the digital elevation map with drainage shows that the study area is clearly elevated above the surroundings where the area is drained outwards. This case gives a sense of inversion stage for the basin; basin inversion can take place if compressive events are going on; presence of far-field effects is suitable for the case. Localized basin inversion during the Tertiary is revealed in the eastern Anza Basin in south Sudan and Kenya (Bosworth, 1992 and Bosworth and Morley, 1994). Confirmation of such as assumption needs correlation of events across the surrounding areas that may be involved in the same events as well as detailed data on associated structures such as folding, strike-slip faults and thrusting, in addition to chrono-stratigraphic data.

5.3. Discussion

An important thing that to be in mind is that presence of unbalanced forces or forces acting in different planes on rock masses, can cause some deviation or even a rotation in the structural trends affecting these rock masses; that is, the present position of the structural features may not be the initial position. This can be agreeable in view of the irregularity of En Nuhud basin in respect to the surrounding structural features.

NE-SW trending structures are not clear in the formation of the basin; maybe they belong to recent events. These structures are deduced from a citation on the drainage pattern; some of the water cources seams to be controlled by a NE-SW trend. Master faults are expected cross-cut the area and they may be masked by post-displacements along the intersected fractures; some fault structures affecting the basin are seem to have outside extensions or relations to neighbor geologic units and possibly are parts of master faults. Such cases can be revealed by accurate and detailed work, and when this is true, minor rift structures are expected at the intersections of these structures and can be of an economic importance.

Wide spread geophysical work (gravity, seismic, and magnetic), remote sensing analysis, subsurface sampling and chronostratigraphic studies are necessary to answer the question of the structural relation of En Nuhud Basin to the central African Shear Zone and to the neighboring rift structures (White Nile and Baggara rift structures).

6. Conclusion

The interpretation of geophysical measurements integrated with borehole data geological observations gave a good diagnosis for the structural setting and geological conditions in the study area. The gaps due to lack or inadequate control data in some parts of the area, are completed by correlation with the adjacent areas or comparisons to similar conditions or areas around the world. In spite of all, it is still there are some questions in respect to the geometry of the through structures and the geological boundaries in some parts of the basin, especially at the eastern and northern portions where additional geologic work is needed for more accurate mapping to the boundary. The area at the east-central part of the basin, between Nasharbo and Megeigha villages, where no drilling or geophysical data are available to reveal the geological conditions there, is represented on contour maps by contours referenced to surrounding conditions.

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