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Structural influence on the evolution of the pre-Eonile drainage system of southern Egypt: Insights from magnetotelluric and gravity data

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ABSTRACT

The Wadi Kubbaniya in the Western Desert of Egypt north of the City of Aswan has been interpreted as the downstream continuation of the Wadi Abu Subeira, comprising an ancient W- and NW-flowing river system originating from the Precambrian crystalline rocks of the Red Sea Hills which were uplifted during the Miocene in association with the opening of the Red Sea. This drainage system is thought to have been active before the onset of the N-flowing Egyptian Nile which started ~6 Ma with the Eonile phase; an event that resulted in carving of ~1000 km long canyon (the Eonile canyon) extending from the Mediterranean Sea in the north to Aswan in the south due to the Messinian Salinity Crisis. This study utilizes geophysical data to examine the role of regional tectonics and local structures in controlling the evolution of the pre-Eonile drainage system. Magnetotelluric (MT) and gravity surveys were conducted along two ~5 km-long profiles across the NW-trending Wadi Kubbaniya. Two-dimensional (2D) inversion of MT data and gravity models indicate the Wadi Kubbaniya is filled with loosely-consolidated sandstone and conglomerate that extend to a depth of ~150–200 m into Cretaceous sandstone formations which overlie Precambrian crystalline rocks. These results were evaluated in terms of two end-member models; an incision model in which the 150–200 m thick sedimentary rocks were considered as being deposited within an incised valley that was carved into bedrock, or a structural model in which the sedimentary rocks are considered as filling a NW-trending graben controlled by normal faults that deform the Cretaceous sandstone formations and the underlying Precambrian crystalline rocks. Geological observations as well as supporting seismic data favor the interpretation that the Wadi Kubbaniya is a NW-trending graben similar to other extensional structures found 400 km northwest along-strike of Wadi Kubbaniya. These structures are impressively parallel to the western shorelines of the Red Sea and the Gulf of Suez suggesting a regional tectonic link between them. Strain localization of these grabens (which are likely Miocene in age) might have been facilitated by inherited Precambrian and Jurassic – Early Cretaceous structures, such as the NW-trending Najd fault system, the most dominant regional structural grain in the Red Sea Hills of Egypt as well as the NW-trending grabens, such as the Kom Ombo graben located ~25 km to the northeast of Wadi Kubbaniya.

1. Introduction

The relative roles of tectonics and climate in shaping the Earth's landscape have received significant attention. However, many questions remain unanswered, such as what role pre-existing structures have in controlling the landscape and if these pre-existing structures are the most important factor in controlling the evolution of topography. The Nile River provides a unique opportunity to examine the interplay between tectonic processes and climate in continuously shaping the dynamic surface of the Earth (Goudie, 2005). The Egyptian Nile, the northernmost segment of the Nile River, is particularly important to answering some of these questions because it contains a record of over 20 Ma of geologic history displaying the relationship between evolving drainage systems, regional tectonics (the opening of the Red Sea and associated uplifting of the Red Sea Hills; (McCauley et al., 1986; Issawi and McCauley, 1992, 1993; Issawi et al., 1999; Issawi and Osman, 2008)), local structures (the presence of Cretaceous and younger faulting (Akawy, 2002; Thurmond et al., 2004)), and climate change (the Messinian Salinity Crisis and the emergence of the Sahara (Butzer and Hansen, 1968; Wendorf and Schild, 1976; Said, 1993)).

The onset of the N-flowing Egyptian Nile is suggested to have started ~6 Ma ago with the Eonile phase where a 1000 km long

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and 300–1000 m deep canyon (the Eonile canyon) was carved under the trace of the Modern Nile (Said, 1993). This event was linked to the desiccation of the Mediterranean Sea, resulting in the lowering of the river's baseline and allowing for deep headword incision. Prior to the Eonile phase, in what is referred to here as the pre-Eonile phase, numerous rivers flowed from the east across the Eastern Sahara originating from the uplifted terrain of the Red Sea Hills (Fig. 1; Said, 1993; Issawi and McCauley, 1993; El Bastawesy et al., 2010). The presence of these ancient rivers has been suspected for a long time, but they were not directly mapped until 1982 when images from the Shuttle Imaging Radar Mission (SIR-A) data revealed numerous channels buried beneath the sand shedding light on the fluvial past of the Sahara. Since this discovery much debate has centered on the age of these abandoned river channels. Several researchers (McCauley et al., 1982, 1986; Issawi and McCauley, 1992) suggested that these drainage systems were active starting in the Late Eocene while others (Butzer and Hansen, 1968; Said, 1993; Ghoneim et al., 2007; El Bastawesy et al., 2010) considered them to be relics from the Early to Middle Pleistocene.

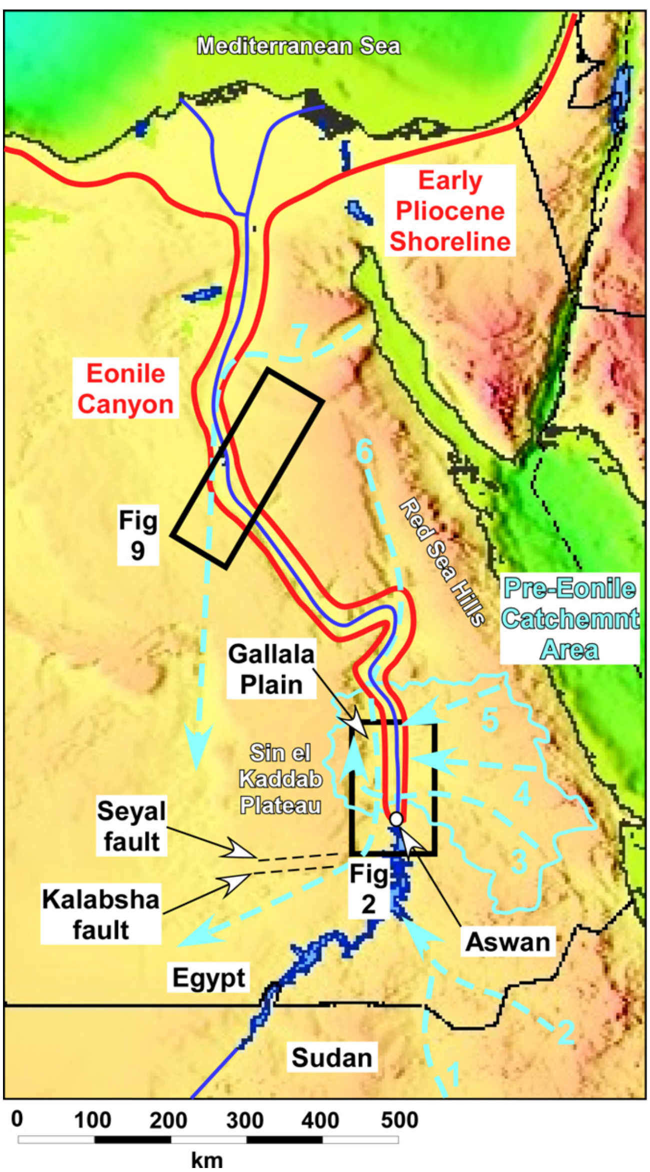

Fig. 1. Digital Elevation Model (DEM) of Egypt showing the Pliocene shoreline, the extent of the Eonile Canyon, pre-Eonile catchment area, and major paleo-rivers. (1) Wadi Gabgaba; (2) Allaqi; (3) Wadi Abu Subeira–Wadi Kubbaniya; (4) Wadi Shait – Wadi Natash; (5) Wadi Abad; (6) Wadi Gena–Radar Rivers; (7) Tarfa. Compiled from Said (1993), Issawi et al. (1999) and El Bastawesy et al. (2010).

The Wadi Kubbaniya and the Wadi Abu Subeira are part of these abandoned paleo-drainage systems located in southern Egypt (Fig. 1). The Wadi Kubbaniya has been interpreted by several researchers as representing the downstream continuation of the Wadi Abu Subeira forming a W- to NW-flowing river that existed prior to the Eonile phase. This wadi can be traced as far northwest as the Gallala Plain (Fig. 1) where it is buried under Quaternary gravel and sand deposits (Butzer and Hansen, 1968; Ghoneim et al., 2007; El Bastawesy et al., 2010). This paleo-drainage system was just one of many W-flowing rivers sourced from the east by the Precambrian crystalline rocks of the Red Sea Hills (Fig. 1) which were uplifted in association with the opening of the Red Sea. Fission track studies by Omar and Steckler (1995) suggested that the early stages of rifting in the Red Sea were characterized by two distinct episodes of uplift that occurred between ~34 (Oligocene) and 25–21 Ma (Miocene). However, structural and sedimentological studies (see summary in Bosworth et al., 2005) showed that Oligocene pre-rift formations were deposited in a marine setting indicating the absence of any significant uplift and the dominance of low relief prior to the Miocene epoch. This observation is in good agreement with stratigraphic data from the Gulf of Suez showing that syn-rift sedimentation and tectonic subsidence started in the Aquitanian between 23.0 and 20.4 Ma (Bosworth et al., 2005), apatite fission track and (U–Th)/He data from the Gulf of Suez indicating rift-flank exhumation at 23–21 Ma (Omar et al., 1989) as well as the presence of syn-rift volcanism in western Saudi Arabia that occurred between 27 and 20 Ma (Pallister, 1987).

This study focuses on using the geophysical techniques of magnetotellurics (MT) and gravity along with geological observations in the Wadi Kubbaniya to address the hypotheses that the Wadi Kubbaniya is a pre-Eonile phase drainage system that flowed northwestward and that it was controlled by NW-trending faults forming the Wadi Kubbaniya graben. Understanding this paleo-drainage system is important in examining the influence of regional tectonics and local structure in the evolution of drainage systems that pre-dated the Eonile phase. In addition, understanding ancient paleo-channels such as the Wadi Kubbaniya is important for locating a potential groundwater resource as recharge from the Nile may still occur, especially if the alluvial base is located at an elevation lower than the Modern Nile.

2. Geologic and geomorphological setting

Fluvial systems within Africa including the Nile River are relatively young, with many of the major rivers changing dramatically since the disintegration of Gondwana in the Cretaceous (Goudie, 2005). The Nile flows through five regions differing from one another in their geologic history and geomorphological features. Said (1981, 1993) described these regions as the Lake Plateau region in equatorial Africa; the Sudd and Central Sudan regions in southern and central Sudan, the Cataract region in northern Sudan, and the Egyptian Nile starting from the Sudanese–Egyptian border and ending at the Nile delta at the Mediterranean Sea. Gani and Abdelsalam (2006) proposed adding a sixth region by separating the Blue Nile in the Ethiopian Plateau from the Central Sudan region. The dating of the first appearance of fertile soil transported to the Egyptian Nile Valley from the Ethiopian Plateau and Equatorial Africa has shown that the Egyptian Nile did not connect with the sub-Sahara Africa Nile System until ~800 ka (Said, 1993). Before then, the Egyptian Nile evolved as an independent drainage system, the final geomorphological features of which were shaped by a number of events. Said (1981, 1993) has classified the evolution of the Egyptian Nile into seven stages beginning in the late Miocene ~6 Ma with what is referred to as the "Eonile phase". This phase was controlled by the Messinian Salinity Crisis, when the desiccation of the Mediterranean Sea resulted in carving of a ~1000 km long, ~300–1000 m deep canyon stretching in a N–S direction from the Nile Delta to the City of Aswan (Fig. 1; Said, 1981, 1993; Issawi and McCauley, 1992; Krijgsman et al., 1999). This was caused by uplift under the Strait of Gibraltar, cutting off the only connection the Mediterranean Sea had to the World's oceans, converting the sea into a great lake (Said, 1993). The other six phases of the Egyptian Nile evolution include the Gulf phase (5.4–3.3 Ma), the Paleo-Nile phase (3.3–1.8 Ma), the Desert phase (1.8–0.8 Ma), the Pre-Nile phase (0.8–0.4 Ma), the Neo-Nile phase (0.4 Ma-12 ka), and the Modern Nile phase (12 ka – Present). These phases are of less interest to this study since this work is concerned with the structural controls of the pre-Eonile drainage system.

This study examines the pre-Eonile phase by focusing in the region located along the Nile Valley close to the City of Aswan in southern Egypt. The geology of Aswan is dominated by outcrops of Precambrian crystalline rocks overlain by Cretaceous Nubian sandstone formations (Fig. 2; Lansbery, 2011). The two rock units are separated by a sub-horizontal unconformity. The Precambrian crystalline rocks in Aswan composed of greenschist to amphibolites facies quartzo-feldspathic schists and gneisses. These rocks represent metamorphic products of volcanic arc systems which were developed during the Neoproterozoic Pan African event resulting in the formation of the Arabian–Nubian Shield (Abdelsalam and Stern, 1996; Gindy and Tamish, 1998). They show well-developed NW-trending planar fabrics and folds, most likely related to the NW-trending, sinistral strike-slip Najd fault system. These layered rocks are intruded by un-metamorphosed and un-deformed granitoid bodies.

The Cretaceous Nubian sandstone constitutes three clastic formations with the Abu Aggag at the base overlying the Precambrian crystalline rocks followed by the Timsah formation which is topped by the Umm Barmil formation (Fig. 2; El Naggar, 1970; Tawardros, 2001; Lansbery, 2011). In the Aswan area the Nubian sandstone reaches a maximum thickness of ~160 m (Youssef, 2003).

The Wadi Kubbaniya extends from the western shore of the Nile River for ~20 km in a NW-direction (Figs. 2 and 3). It has been suggested that the depth of the wadi is ~5 m near the Nile River and

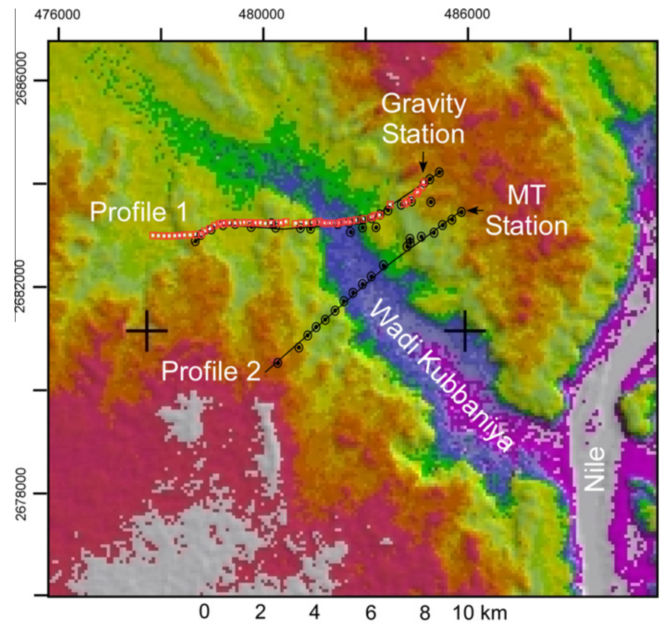

Fig. 3. Digital Elevation Model (DEM) of the study area showing the location of the MT and gravity data collected across Wadi Kubbaniya. The MT data were collected at a 250 m station spacing whereas the gravity data were collected at 100 m spacing. Poor contact or harsh terrain required some stations to be offset or moved closer to one another.

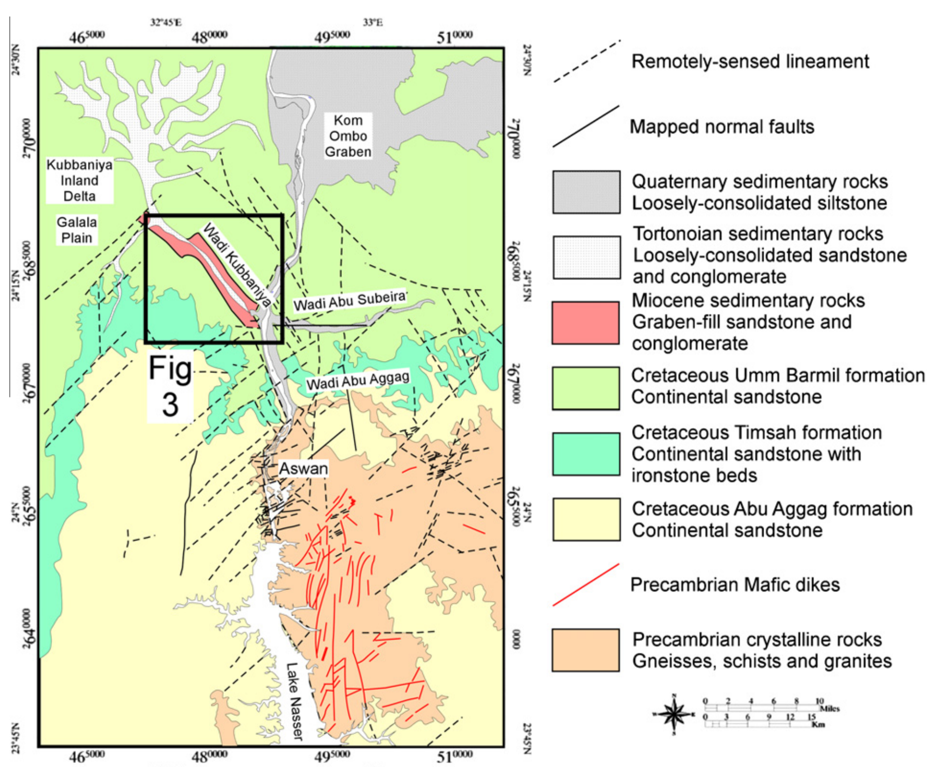

Fig. 2. Geologic map of the Aswan area. Modified after Lansbery (2011).

this depth increases to the northwest to reach ~40 m (Wendorf and Schild, 1976). This wadi is bounded to the northeast and southwest by subtle plateaus where the Umm Barmil formation is exposed at the surface (Fig. 2) indicating that the other Nubian sandstone formations are present in the subsurface. Geological observations from shallow trenches (~10 m deep) indicate that at least the upper part of Wadi Kubbaniya is filled with loosely consolidated coarse sandstone and conglomerate with a dominance of Precambrian crystalline rock clasts coming from the Red Sea Hills. Lansbery (2011) suggested that these sediments are Miocene in age (Fig. 2) based on the following considerations: (1) These sediments are restricted to Wadi Kubbaniya and they are clearly resting on top of the Umm Barmil formation; hence these sediments must be younger than the Cretaceous age. (2) The source of these sedimentary rocks was the Precambrian crystalline basement of the Red Sea Hills. Uplift associated with the opening of the Red Sea allowing for the exposure of the Precambrian crystalline rocks to the surface occurred in the early Miocene ~23 Ma ago (e.g. Bosworth et al., 2005). Hence, the supply of these sedimentary rocks to fill the Wadi Kubbaniya must have started shortly after the exposure of the Precambrian crystalline rocks to the surface. (3) The establishment of the Eonile phase during the Missinian Salinity Crisis ~6 Ma ago (which created a 170 m deep N-trending canyon between the Red Sea Hills in the east and the Sin el Kaddab Plateau to the west) would have necessary cut-off the supply of these sediments from the Red Sea Hills to Wadi Kubbaniya. Hence, Lansbery (2011) concluded that the age of the Wadi Kubbaniya-filling sedimentary rocks ranges between 24 and 6 Ma.

Issawi and McCauley (1992) suggested that during the Cenozoic Era, Egypt was likely dominated by at least three different major drainage systems which formed in response to tectonic uplifts and sea-level changes spanning the Late Eocene to the Late Pleistocene. Issawi and McCauley (1992) termed these three stages the Gilf System (40–20 Ma), the Qena System (20–6 Ma), and the Nile System (6 Ma to present). It is worth mentioning here that the lower age bracket (40 Ma) of the Glif System as proposed by Issawi and McCauley (1992) is significantly older to be associated with rift-flank uplift of the Red Sea which occurred at ~23 Ma (e.g. Bosworth et al., 2005). Rather, it is likely that the Gilf System might have only been active between 23 and 20 Ma. Hence, it is suggested here that the paleo-drainage system of Wadi Kubbaniya – Wadi Abu Subeira began developing during the Gilf System (23–20 Ma) due to uplift in the Red Sea Hills, and lasted through the Qena System. This paleo-drainage eventually evolved into one of many active alluvial river systems in the Tortonian (~11 Ma) and lasted until the start of the Nile system. The development of the Eonile Canyon during the Eonile phase resulted in the truncation of the W- and NW-flowing rivers including the Wadi Kubbaniya – Wadi Abu Subeira (Fig. 1). This truncation also resulted in a drainage reversal of Wadi Kubbaniya, which now flows in a SE direction towards the Modern Nile.

3. Structural setting

There are four regional tectonic elements that have contributed to shaping structures in southern Egypt. The first of these tectonic elements is the NW-trending Precambrian Najd fault system. This Precambrian fault system was developed between 620 and 540 Ma as a complex set of sinistral strike-slip faults and ductile shear zones (Abdelsalam and Stern, 1996). It is ~2000 km long and 400 km wide extending in the Arabian Shield of western Saudi Arabia and the Nubian Shield of the Eastern Desert of Egypt (Abdelsalam and Stern, 1996). Around the City of Aswan, the manifestation of the Najd fault system is in the form of strong NW-trending foliation and folding of the Precambrian quartzo-feldspathic schist.

Mesozoic rifting that affected northern and central Africa might be the second tectonic element that shaped the structure dominating southern Egypt today. Around the Aswan area, Schandelmeier and Reynolds (1997) showed in their regional synthesis of northern Africa that a NW-trending rift was developed during the Camanian–Maastrichtian time (~74 Ma). Subsequently, Bosworth et al. (2008) suggested that there are at least two NW-trending grabens (Asyut and Kom Ombo) formed in southern Egypt along the modern Nile Valley during the Jurassic – Early Cretaceous. Bosworth et al. (2008) suggested that these grabens were formed due to clockwise rotation in north and central Africa due to the opening of the South Atlantic Ocean.

The Nubian Swell represents the third regional tectonic element that has contributed to the geological architecture in southern Egypt (Stern and Abdelsalam, 1996; Thurmond et al., 2004). This swell is a ~400 km wide E-trending uplift that stretches for 800 km in southern Egypt and northern Sudan exposing Precambrain crystalline rocks, and in places a Paleozoic sedimentary section. The exposure of the Precambrian crystalline rocks around the City of Aswan is thought to be the result of uplift associated with the Nubian Swell and these exposures are included in what was termed by Thurmond et al. (2004) as the Gebel Uweinat-Bir Safsaf-Aswan Uplift. One of the characteristics of the Nubian Swell is the presence of numerous E-trending dextral strike-slip faults and less frequent N-trending sinistral strike-slip faults (Thurmond et al., 2004). Guiraud et al. (1985) related the E–W trending faults to the development of a major E–W trending lineament that extends across the entire African continent and was termed the Guinean–Nubian Lineament. In a subsequent regional synthesis, Guiraud et al. (2005) eluded to the fact that the E–W trending faults in southern Egypt were developed during the Late Santonian–Maastrichtian age (84–65 Ma). However, the regional synthesis of Schandelmeier and Reynolds (1997) shows these structures as being developed during the Chattian (24 Ma) suggesting that these might have formed as onland trans-current faults associated with the opening of the Red Sea. Alternative to these interpretations, Meshref (1990) related the development of the E–W trending faults in southern Egypt to Tethyan tectonics and referred to them as the E–W Tethyan trend.

The opening of the Red Sea represents the fourth regional tectonic element that has contributed to the structural evolution of southern Egypt. The evolution of the Red Sea started with outpouring of ~30 Ma flood basalts associated with the arrival of the Afar mantle plume at the base of the Arabian–Nubian Shield (Hofmann et al., 1997; Bosworth et al., 2005). At ~23 Ma, rifting across the Red Sea began as a new volcanic event occurred accompanied by strong rift-normal extension (Bosworth et al., 2005). At ~20 Ma, uplift and subsidence within the Red Sea occurred. Around 14 Ma, the extensional regime changed from orthogonal rifting (NE–SW) to a highly oblique rifting (N–S) that parallels the newly formed transform boundary (the Aqaba-Levant transform) resulting from the collision of Arabia and Eurasia. At 5 Ma, the south-central portion of the Red Sea experienced oceanic spreading. At 1 Ma, the southern plate boundary of the Red Sea joined the Gulf of Aden spreading zone (Bosworth et al., 2005).

4. Geophysical methods

MT and gravity geophysical methods were used to image the subsurface structure of the Wadi Kubbaniya using a Stratagem EH-4 MT system and a CG-5 gravimeter. The data were acquired over 14 days of field work conducted during the first half of January 2010. The MT and gravity methods were chosen due to the limitations imposed upon other electromagnetic geophysical techniques by the presence of a relatively thick and dry unconsolidated sandy layer, the time available for field work, and the desired depth for imaging the geological sub-surface features (>400 m). The Stratagem EH-4 MT system and the CG-5 gravimeter enabled the collection of geophysical data along long traverses in a relatively short amount of time due to quick set up and rapid acquisition of data.

In addition to the geophysical methods, sand samples were collected from the middle of Wadi Kubbaniya and these were used to determine the conductivity and major ion concentrations. Preweighed samples (31.5 and 30.7 mg) were placed into 50 ml of 18 MΩ deionized water in a centrifuge tube and mechanically shaken for 24 h. The samples were then centrifuged at 4500 rpm for 15 min to separate the solids. The conductivity and total dissolved solids of an aliquot of the supernatant were measured by microelectrode. In addition, the Cl^-, SO_4^{-2}, Ca^{+2}, Mg^{+2}, K^+ and Na^+ were measured by ion chromatography and the bicarbonate content was measured by sulfuric acid titration. The sand sample taken from the center of Wadi Kubbaniya resulted in a specific conductance of 2600 mS/m. The major cations measured in the samples included sodium and calcium with minor amounts of potassium and magnesium. The major anions found were chloride and bicarbonate, with minor amounts of sulfate.

Samples from each formation of the Nubian sandstone (Umm Barmil, Timsah, Abu Aggag) as well as the Precambrian crystalline rocks were collected in the field. The Umm Barmil samples were cut into 27 billets, Timsah into 19 billets, Abu Aggag into 12 billets and Precambrian crystalline rock into 11 billets. The density of each rock billet was measured. The average density was taken across the three different formations of the Nubian Sandstone resulting in an average of 2.4 g/cm^3 (Table 1). These densities were then used for the gravity model created in GYM-SYS in Geosoft's Oasis Montaj software.

4.1. MT data

The MT data were collected along two profiles across Wadi Kubbaniya (Fig. 3) using the Geometrics STRATAGEM EH4 unit. This unit is capable of measuring electrical resistivity to depths ranging from a few meters to more than 1 km with orthogonal electrical and magnetic field changes in the frequency range of 92 kHz and 10 Hz. These data were processed to provide tensor impedance measurements for interpreting complex 2D structures. This system is unique in that it uses both natural (in all measured frequency ranges) and controlled source electromagnetic signals. However, natural signals are generally weak in the higher frequency range. This problem was solved by using artificial signals generated from a transmitter located at least 250–300 m away from the receiver to "boost" the weak background field signals at these higher frequencies. To acquire soundings, the STRATAGEM EH4 was assembled at each station with a 50 m dipole length in the *X* and *Y* directions using 4 buffered electrodes with stainless steel stakes. The location of profile 1 was chosen due to the existence of an abandoned road which crosses and runs almost perpendicular to Wadi Kubbaniya. This profile is 5.2 km in length and comprised of 28 stations with 250 m station spacing (Fig. 3). The start of the second profile is ~3 km SE of profile 1 and was 5 km in length with 19 stations spaced at 250 m (Fig. 3). The *Y* direction dipole was oriented 45° and the *X* dipole 225° in order to keep the *X* dipole parallel to the strike direction of the geological structure.

The presence of a high tension power line running ~300 m to the west of the southwestern starting points of profile 1 and 1 km to the west of profile 2 has posed some challenges in processing the MT data. Other factors contributed to poor data quality in some stations include the presence of very dry yet conductive sand, which made it difficult in obtaining good contact between the ground and the electrodes. To overcome this problem, mud from the Nile River bank was collected and mixed with salt water and then poured into the electrode holes.

Table 1
Average densities and relative standard deviations measured from formation samples obtained from the Aswan area.

Average Umm Barmil density	Average Timsah density	Average Abu Aggag density	Average Precambrian crystalline rock density
2.69 g/cm^3 ± 9.0%	2.38 g/cm^3 ± 5.7%	2.13 g/cm^3 ± 18.1%	2.62 g/cm^3 ± 4.9%

4.2. Gravity data

The gravity data were collected over 62 stations across the Wadi Kubbaniya using a Scintrex CG-5 Gravimeter and a TopCon GPS system to record accurate elevations. The gravity measurements were carried out along the same direction and orientation of MT profile 1, but with a 100 m station spacing (Fig. 3). Many stations were measured repeatedly in order to assess the reliability of the readings. An average crustal density of 2.67 g/cm^3 was used as the slab density for the Bouguer correction. All gravity readings are only relative to the base station established in this study and were not tied to a known absolute gravity base station.

4.3. Data processing

All of the MT tensor data were downloaded from the STRATAGEM EH4 and processed using Geosystem's WinGLink software, which utilizes the 2D inversion algorithm developed by Rodi and Mackie (2001). The MT soundings were then edited and smoothed using two different smoothing algorithms resulting in two models for each profile (Fig. 4). The first method applied to the impedance and phase curves was a D+ smoothing algorithm. This algorithm examines the apparent resistivity and its corresponding phase to estimate the best fit of the 1D Earth (Beamish and Travassos, 1992). The second model was created from a 2D inversion of both the transverse electric (TE) and transverse magnetic (TM) modes using a numerical smoothing option of the sounding curves. This numerical smoothing model applies a fast fourier transform analysis of the soundings four components. An independent smoothed curve was then generated for each component. The D+ smoothing algorithm is preferred as it ensures all smoothed curves generated from the sounding data are in agreement with both the phase and apparent resistivity.

5. Results

Fig. 5A is a 2D inversion model of the MT D+ smoothed curves of Wadi Kubbaniya generated from profile 1 (Fig. 3). A ~1200 m wide low resistivity body of <5 Ω-m is apparent in this model extending in a NE–SW direction between the distances 2100 m and 3200 m of the profile (the southwestern end of the profile is assigned to the origin or distance zero). The deepest point of this anomaly, which extends to a depth of ~220 m, is near location 2650 m. This low resistivity zone is suggested to correspond to the extent of the loosely consolidated sedimentary rocks that fill Wadi Kubbaniya. Another boundary at the same location can be identified as the depth increases to ~305 m where the resistivity rises above 11 Ω-m. This resistivity boundary might be corresponding to the angular unconformity separating the Precambrian crystalline rocks and the Cretaceous Nubian sandstone formations. A low resistivity region is also apparent on the northeastern side of this profile between distances 3500 m and 4900 m. This anomaly is likely due to the presence of a small NE–SW sand-filled channel.

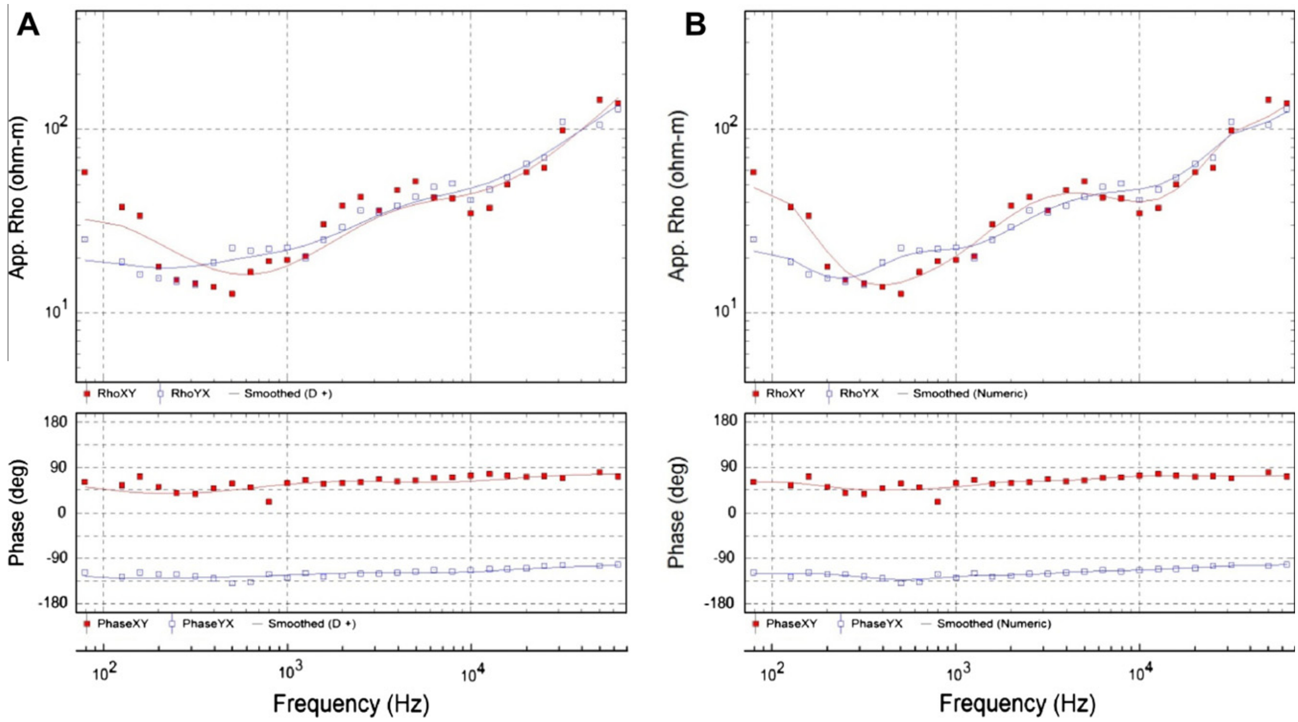

Fig. 4. Comparison of the smoothed curves generated from the two different smoothing methods on station S2. The smoothed curve in (A) is generated by the D+ algorithm whereas that of (B) is achieved through the numerical method.

Fig. 5B is a 2D inversion model of the MT numerically smoothed curves of Wadi Kubbaniya generated from profile 1 (Fig. 3). The numerically-smoothed inversion model is similar to the D+ inversion model in that the 5 Ω-m low resistivity boundary is also imaged at ∼220 m depth beneath location 2650 m. However, this model shows the low resistivity anomaly as being a broader feature encompassing a distance of ∼1700 m across the Wadi Kubbaniya. This model also differs from the MT D+ smoothed model in that the 11 Ω-m boundary appears to be 20 m shallower, located at a depth of ∼285 m. Similar to the D+ model, the MT numerically-smoothed model shows the eastern side of the profile between 4000 m and 4900 m as underlain by a relatively low resistivity anomaly.

Fig. 5C is a 2D inversion model of the MT D+ smoothed curves of Wadi Kubbaniya generated from profile 2 (Fig. 3). This model shows a ∼1000 m wide low resistivity zone of less than 5 Ω-m extending from distance 1600 m to 2700 m. This anomaly reaches a maximum depth of ∼164 m beneath the 2700 m mark. The 11 Ω-m boundary occurs at depth of ∼440 m. On the southwestern side of the profile, near the distance 500 m from the origin, the 11 Ω-m boundary shallows significantly to reach a depth of only ∼80 m suggesting that the Precambrian crystalline rocks are near the surface. A low resistivity zone of 3 Ω-m is located on the northeastern side of the profile between distances ∼4100 m and ∼4750 m. There is a 900 m long gap in the profile line due to the presence of a dissected alluvial fan containing large cobbles that prevented reliable soundings from being obtained at this location.

Due to the non-unique interpretation of gravity data, four different gravity models have been created. The first two models (Fig. 6) were constructed to depict the Wadi Kobbaniya as a graben using the gravity data with constraints from the D+ (Fig. 6A) and the numerically-smoothed MT model (Fig. 6B). The second two models (Fig. 7) were constructed to show the Wadi Kubbaniya as an incised valley with constraints from the D+ (Fig. 7A) and the numerically-smoothed MT model (Fig. 7B). All density values assigned to different rock units were from the values measured from rock samples obtained from the study area.

5.1. Modeling the Wadi Kubbaniya as a graben

Fig. 6B and C is a gravity model created using constraints provided by the D+ model in Fig. 6A. Additional constraint applied to this model was the adoption of a maximum thickness of 160 m for the Nubian sandstone formations as suggested by the surface exposures of these formations around the Aswan area. Modeling the Wadi Kubbaniya as a graben was further constrained by assuming that normal faulting post-dated the deposition of the Nubian sandstone formations and these formations were not deposited during the time when the graben was tectonically active. The model shows a 2200 m wide low density (2.1 g/cm^3) region extending between locations 2100 m and 4300 m with a maximum depth of ∼170 m beneath location 3210 m. This part of the gravity model, labeled as "Post-Cretaceous Fill", accounts for the presence of the loosely-consolidated sandstone and conglomerate that seem to fill Wadi Kubbaniya. This unit sits on top of the Nubian sandstone formations (modeled with an average density of 2.4 g/cm^3) which progressively deepen toward the center of Wadi Kubbaniya. The deepest part of the Nubian sandstone formations is present in the middle of the graben at location 3210 m with a thickness of ∼140 m. In this location, the Precambrian crystalline rocks, which are modeled with an average density of 2.62 g/cm^3, are predicted to be encountered at a depth of ∼310 m. At the southwestern and northeastern flanks of the wadi the Precambrian crystalline rocks are predicted to be encountered at a depth of only ∼80 m. In this model, a 24 m thick layer of 2.0 g/cm^3 is introduced to account for an exposed, but heavily disturbed Nubian sandstone unit resulting from bulldozing during road construction as well as the presence of large sand dunes. This unit extends in the southwestern side of Wadi Kubbaniya between locations 0 m and 750 m.

Fig. 6E and F are a gravity model created with the guidance of the numerically smoothed MT model in Fig. 6D. The 11 Ω-m boundary is selected as depicting the angular unconformity between the Precambrian crystalline rocks and the Nubian sandstone formations similar to what has been adopted for the D+ smoothed

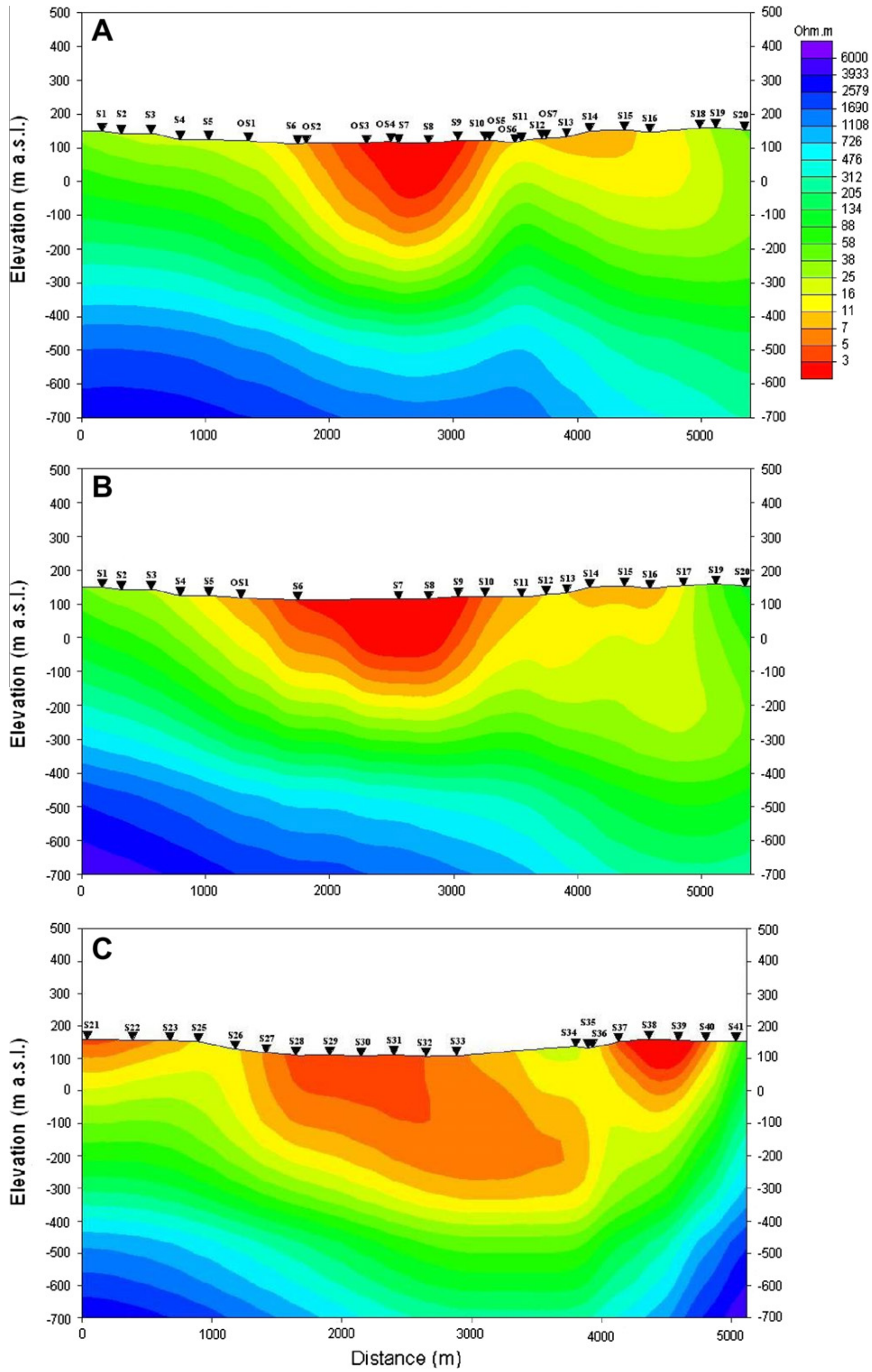

Fig. 5. Two-dimensional (2D) inversion of station soundings from Profile 1 smoothed using the D+ algorithm (A) and numerically smoothed (B). (C) 2D Inversion of station soundings from profile 2 smoothed with the D+ algorithm.

MT model (Fig. 6A–C). This model is similar to the gravity model that was constrained by the D+ smoothed TM model (Fig. 6A–C), especially at the northeastern and southwestern margins of Wadi Kubbaniya. However, it differs slightly from the previous model in estimating the thickness of the Post-Cretaceous Fill. In this model, the maximum thickness of the sedimentary fill was estimated to be ~150 m below location 3210 m. Also, at this location the thickness of the Nubian sandstone formation was estimated to be ~10 m thicker than that of the previous model, reaching a thickness of 150 m and the depth to the Precambrian crystalline rocks is shown to be ~300 m deep. In general, the two models in Fig. 6 are in good agreement with each other. However, the D+ smoothed MT model (Fig. 6A) appears to correlate better with the depth of boundaries between different geological units estimated in the gravity model (Fig. 6B and C).

It should be emphasized that the graben model only reflects predicted depth distribution of the Precambrian crystalline rocks, the Nubian Sandstone formations, and the Post-Cretaceous Fill based on their measured density values. The polygons of each unit have been smoothed and do not reflect the structural complexity of

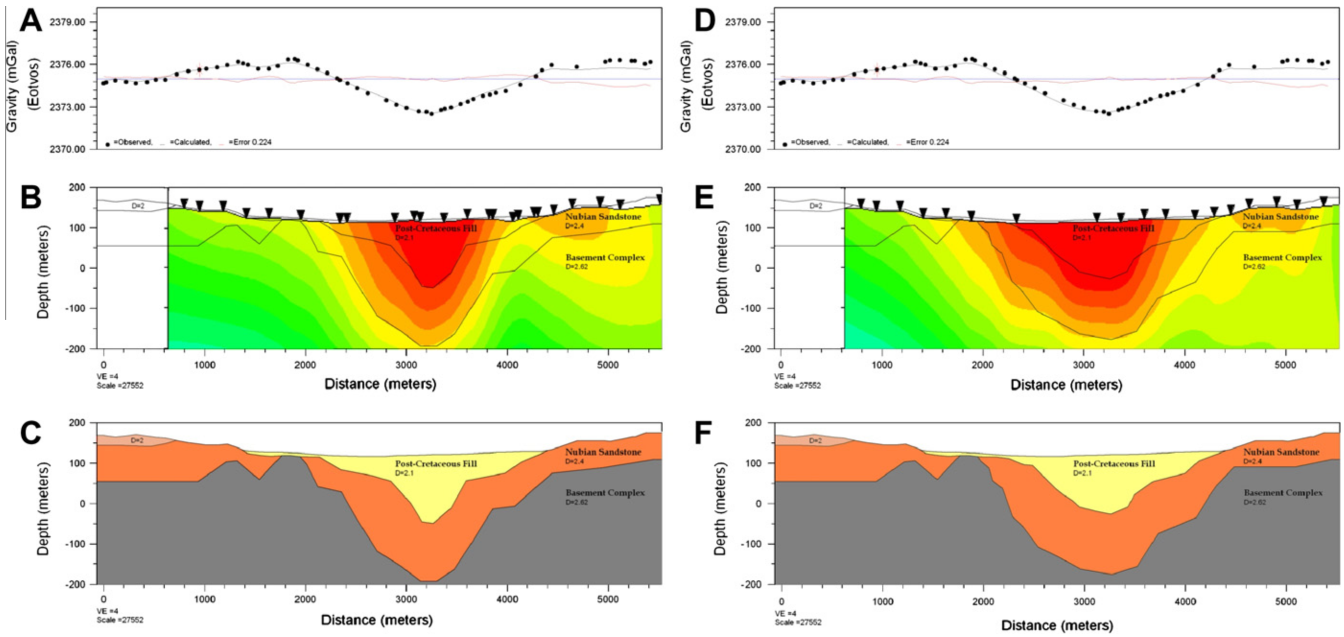

Fig. 6. Modeling the Wadi Kubbaniya as a graben structure using gravity data of profile 1 structured around the D+ smoothed (A–C) and the numerically smoothed MT model (D–F). (A) Observed and calculated gravity profiles and the error value between the two profiles. (B) Gravity model overlying the 2D inverted D+ model. (C) Final gravity model. (D) Observed and calculated gravity profiles and the error value between the two profiles. (E) Gravity model overlying the 2D inverted numerical model. (F) Final gravity model Nubian sandstone was assigned a density of 2.4 g/cm^3, basement complex was given a density of 2.62 g/cm^3, weathered Nubian sandstone was modeled with a density of 2 g/cm^3, and post-Cretaceous sedimentary fill density is designated a density of 2.1 g/cm^3.

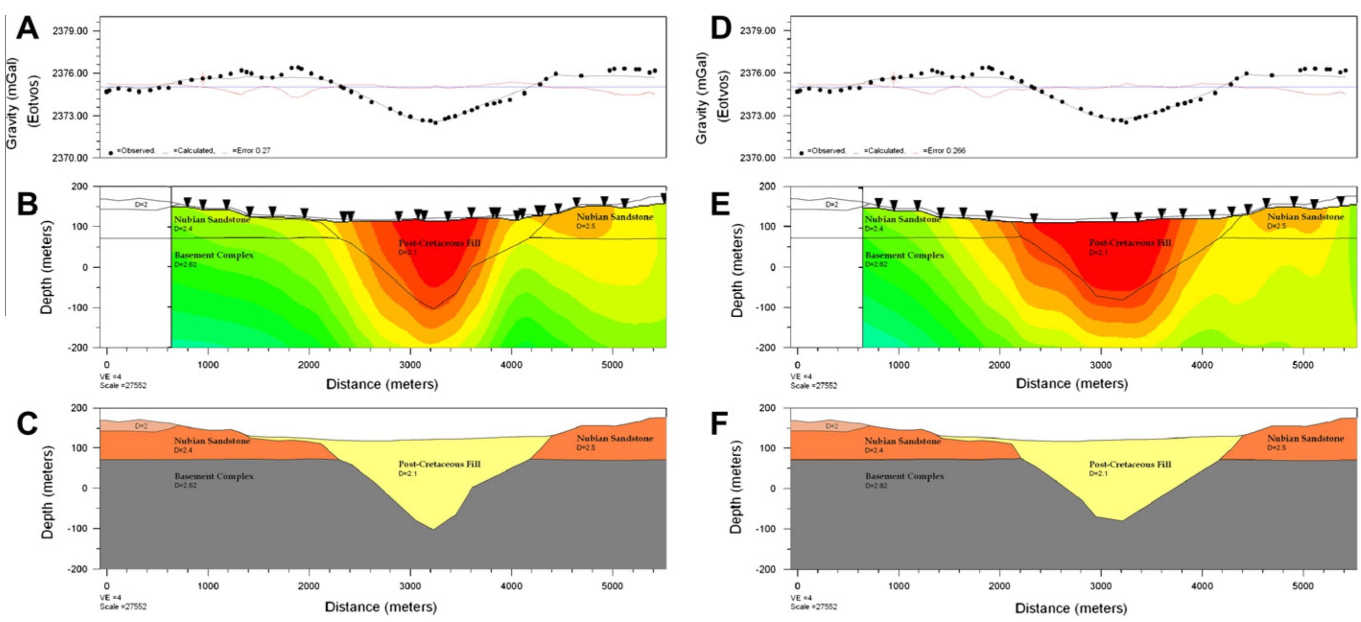

Fig. 7. Modeling the Wadi Kubbaniya as an incised valley using gravity data of profile 1 structured around the D+ smoothed (A–C) and the numerically smoothed MT model (D–F). (A) Observed and calculated gravity profiles and the error value between the two profiles. (B) Gravity model overlying the 2D inverted D+ model. (C) Final gravity model. (D) Observed and calculated gravity profiles and the error value between the two profiles. (E) Gravity model overlying the 2D inverted numerical model. (F) Final gravity model Nubian sandstone was assigned a density of 2.4 g/cm^3, basement complex was given a density of 2.62 g/cm^3, weathered Nubian sandstone was modeled with a density of 2 g/cm^3, and post-Cretaceous sedimentary fill density is designated a density of 2.1 g/cm^3.

the graben structure. A conceptual model for the Wadi Kubbaniya as a graben will be presented later by incorporating additional geological and refraction seismic data.

5.2. Modeling the Wadi Kubbaniya as an incised valley

The gravity data across the Wadi Kubbaniya can equally be modeled as resulting from a valley that has incised through the Cretaceous sandstone formations and the Precambrian crystalline rocks and later was filled with post-Cretaceous sedimentary rocks. Fig. 7B and C is a gravity model created using the D+ smoothed MT model (Fig. 7A) as a reference. This model predicts that the Nubian sandstone formations are only present at the northeastern and southwestern boundaries of Wadi Kubbaniya with an average thickness of ∼80 m keeping the depth to the top of the Precambrian crystalline basement consistent with the two graben models in Fig. 6. This model shows a 2300 m wide valley extending between locations 2100 m and 4400 m and reaching a maximum depth of ~220 m. Hence, the model necessitates the complete erosion of the Nubian sandstone formations during the valley incision. At location 3210 m (which corresponds to the deepest part of the valley) the top of the Precambrian crystalline rocks was predicted to be at ~220 m depth corresponding to the 5 Ω-m resistivity boundary on the MT model shown in Fig. 7A. This gravity model does not account for the two gravity highs at the 1300 m and 1850 m marks.

Fig. 7E and F are gravity models created by using the numerically-smoothed MT model shown in Fig. 7D as a constraint. The model is identical to the previous model, except for a slight discrepancy in the shape of the valley resulting in locating the depth to the Precambrian crystalline rocks at ~200 m. The gravity highs at 1300 m and 1850 m are not accounted for by this model.

6. Discussion

Results of this work are discussed to examine the plausibility of the incised valley versus the graben model for Wadi Kubbaniya, geographic extent of Wadi Kubbaniya as a graben, and strain localization resulting in the formation of the wadi as a graben.

6.1. Why the incision model cannot be supported?

The incision model in Fig. 7 clearly shows the Wadi Kubbaniya as a much deeper geological feature (reaching ~80 to 110 m below present day Mean Sea Level (MSL)) than the ~40 m incision depth estimated by Wendorf and Schild (1976). Such deep incision requires it to be accompanied by a comparable regional uplift or sea level drop. There is no evidence that post-Cretaceous regional uplift has affected the eastern half of southern Egypt (between the Sin el Kaddab Plateau and the Red Sea Hills; Fig. 1) other than the Miocene rift-flank uplift associated with the opening of the Red Sea. This uplift was restricted to the Red Sea Hills east of the Egyptian Nile and did not extend to the west as evidenced by the present day topography where the vastly expanding Gallala plain only rises to ~150 m above MSL.

Alternatively, it can be argued that such a deep incision of Wadi Kubbaniya may have been triggered by the sharp drop in base level during the Messinian Salinity Crisis. This event resulted in a rapid drop in base level by thousands of meters below MSL (Hsu et al., 1973) resulting in the carving of the Eonile Canyon. This canyon was subsequently filled with sediments during the early Pliocene when the Mediterranean Sea reestablished its connection to the Atlantic Ocean (Hsu et al., 1973). During this event the Eonile Canyon at Aswan incised a gorge ~200 m below MSL, 1250 km (Said, 1981, 1993). Hence, it can be argued that the ~200 m depth of Wadi Kubbaniya could have resulted from a rapid incision of a SE-flowing river draining into the Eonile Canyon which provided a local lower base-level. Additionally, it can be argued that the conductive signature of the sediments filling the wadi reflects an estuarine environment reflecting the deposition of evaporates as a result of back-flooding of Wadi Kubbaniya during the Gulf phase, which occurred between 5.4 and 3.3 Ma after the resumption of water circulation between the Mediterranean Sea with the Atlantic Ocean (Said, 1993). However, a major weakness of this explanation is that it requires large discharge sourced from the limestone exposures of the Sin el Kaddab Plateau to the west (Fig. 1). This is not supported by geological observations, which indicate that at least the upper part of Wadi Kubbaniya is filled with clastic sedimentary rocks sourced from the Precambrian crystalline rocks of the Red Sea Hills to the east and that the paleo-current data (Lansbery, 2011) clearly indicate that these sediments were deposited in a drainage system that was flowing to the northwest. Hence, the absence of any limestone clasts in the Wadi Kubbaniya rules out the possibility that the ~200 m depth of Wadi Kubbaniya was achieved through river incision.

6.2. Support for a graben model for Wadi Kubbaniya

It is suggested that widespread NW-trending normal faults were formed in northeast Africa during two episodes of tectonic activities. The oldest of these events occurred during the Jurassic – Early Cretaceous and was associated with the opening of the South Atlantic Ocean (Bosworth et al., 2008). Bosworth et al. (2008) suggested that this event resulted in the formation of two grabens (Asyut and Kom Ombo) in southern Egypt located under the modern Nile Valley. The youngest event occurred in the early Miocene when the Arabian plate began to move northeastward away from the stationary African plate (Makris et al., 1991; Tawardros, 2001; Bosworth et al., 2005). The Wadi Kubbaniya is likely an extensional feature that was formed in association with these tectonic events. However, because of sedimentological observations outlined above (see Section 2) it is likely that the extension across Wadi Kubbaniya was associated with the early Miocene tectonic event. The presence of this graben can effectively explain the abrupt NW deflection of the Wadi Kubbaniya-Wadi Abu Suberia paleo-drainage from a W-flowing direction east of the Modern Nile to NW-flowing west of the Nile.

The graben models shown in Fig. 6 suggest the presence of a Post-Cretaceous Fill reaching a depth of ~150 to ~170 m from the top of the Nubian Sandstone formations. This suggests the depth of the graben reached a depth of 25–50 m below present MSL. This topographic low would quickly become filled by sediments eroded and subsequently transported from the Precambrian crystalline rocks of the uplifted Red Sea Hills as well as the surrounding Nubian sandstone formations as the newly-formed drainage system moved toward achieving topographic equilibrium.

The gravity profile shows a gravity high feature of ~1 mGal between locations 1000 m and 2100 m (Figs. 6 and 7). This gravity anomaly cannot be modeled in terms of three layers constituting the Post-Cretaceous Fill, Nubian sandstone formations, and the Precambrian crystalline rocks. Rather, this gravity high feature can be modeled with the post-Cretaceous sedimentary fill sitting directly on top of the Precambrian crystalline rocks (Fig. 6). This structure is likely developed due to the superposition of at least two discrete phases of extension. The first phase dissected the Precambrian crystalline rocks and the overlying Nubian sandstone formations to form horsts and grabens with parts of the Precambrian crystalline rocks preserved on the horst structures at structurally-high levels. Subsequent erosion removed the Nubian sandstone formations from the top of the horst structures but these formations were preserved within the grabens. During the second phase of extension, the graben fill was deposited on top of the preserved Nubian sandstone formations as well as the uplifted Precambrian crystalline rocks. This interpretation is in good agreement with results of seismic refraction studies across the Wadi Kubbaniya (Fig. 8; Atef, 2011). Similar to the gravity model produced from the gravity and MT data (Fig. 8A and B), the seismic model also shows an uplifted block of Precambrian crystalline rocks on the southwestern side of Wadi Kubbaniya in which the Post-Cretaceous Fill directly overlies the Precambrian crystalline rocks (Fig. 8C). Fig. 8D is a conceptual model to illustrate the Wadi Kubbaniya as a graben structure.

6.3. Extent of Wadi Kubbaniya graben

Extensional features similar to the NW-trending Wadi Kubbaniya graben are apparent in Shuttle Imaging Radar C-band (SIR-C) X-band

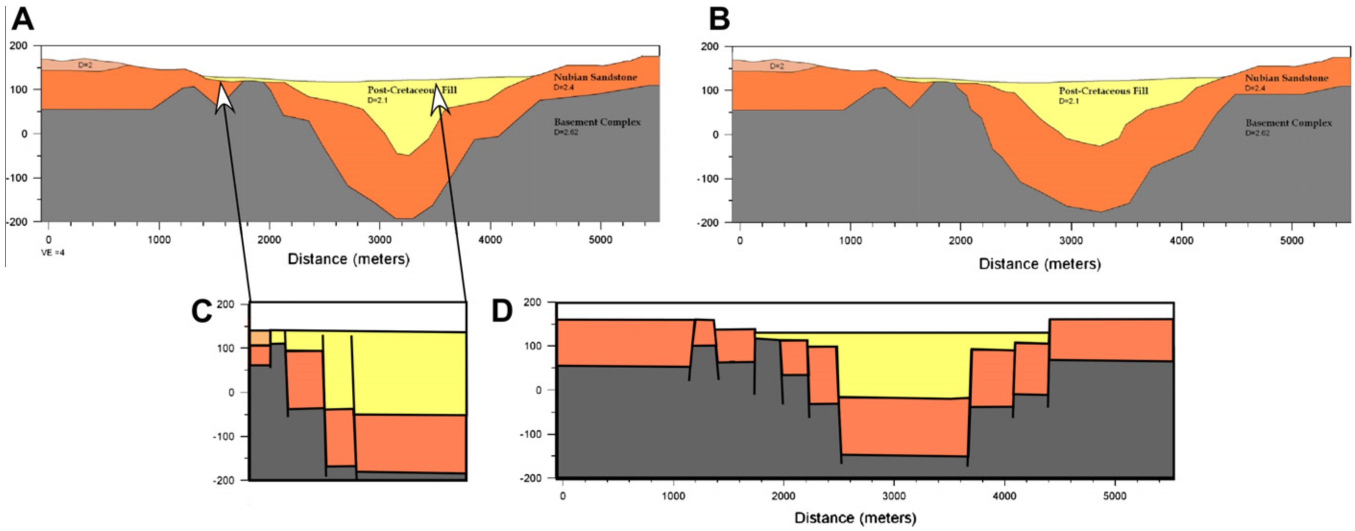

Fig. 8. (A) and (B) gravity models structured around D+ and numerically smoothed MT data, respectively. (C) Subsurface model of the western half of Wadi Kubbaniya from seismic refraction data. Modified after Atef (2011). (D) Conceptual model illustrating the Wadi Kubbaniya as a graben filled with post-Cretaceous sedimentary rocks.

Synthetic Aperture Radar (X-SAR) images as far northwest as ~400 km along-strike of the Kubbaniya graben close to the city of Assuit (Figs. 1 and 9). These extensional features which are interpreted as graben structures (Fig. 9C) are strikingly similar in their trend and width (3–4 km) to that of the Wadi Kubbaniya graben. These similarities are intriguing to suggest that the Wadi Kubbaniya graben might represent the southeastern extension of these structures.

6.4. Strain localization during the formation of Wadi Kubbaniya graben

Modeling the Wadi Kubbaniya as a graben predicts a total vertical displacement in excess of ~250 m. The lack of other known NW-trending grabens in the Aswan area, as well as the narrow width and relatively large displacement of the Kubbaniya graben, suggests strongly-focused strain localization within the NW-trending normal faults in southern Egypt. One explanation of such strong strain localization would be the presence of pre-existing structure. It is worth mentioning here that the Precambrian crystalline rocks in the Aswan area are dominated by strong NW-trending regional fabric that developed in association with the Neoproterozoic-aged sinistral strike-slip Najd fault system (Abdelsalam and Stern, 1996). The presence of such pre-existing structure in the region might have facilitated strain localization during the formation of the Wadi Kubbaniya graben. Additionally, Bosworth et al. (2008) pointed to the presence of the NW-trending Jurassic – Early Cretaceous Kom Ombo graben which is located ~25 km to the northeast of Wadi Kubbaniya. Normal faults that might have extended to the southwest of Kom Ombo graben might have also contributed to strain localization to form the Wadi Kubbaniya graben.

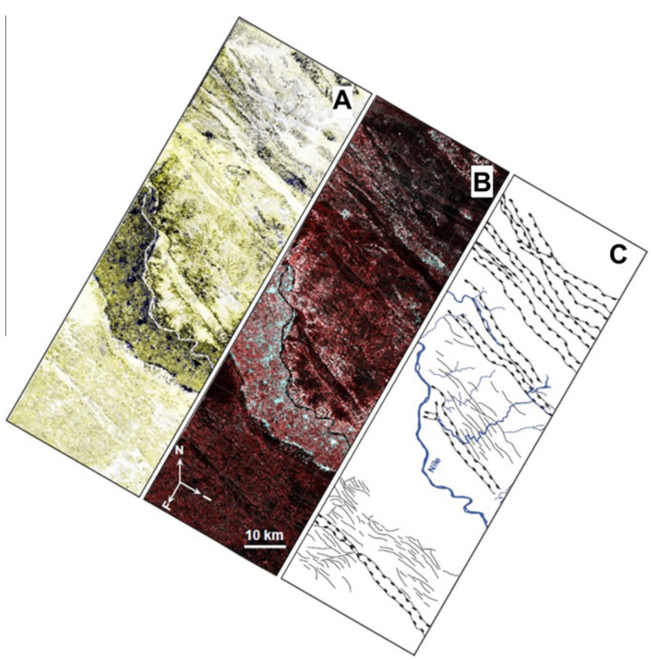

Fig. 9. Narrow NW-trending graben structures around the City of Assiut. (A) 1/Lhh-1/Lhv-1/Chv SIR-C/X-SAR image. (B) Lhh-Lhv-Chv SIR-C/X-SAR image. (C) Structural interpretation of the radar image in A. Lines with solid squares represents normal faults with the solid squares showing the throw direction of the hanging wall. Lines with no solid squares represent surface projection of fault heaves. The abbreviations in the arrow are: N = North, I = Radar illumination direction and F = Shuttle flight direction.

7. Conclusion and recommendations for future work

(1) Many W-flowing Miocene rivers in Egypt were sourced from the uplifted Red Sea Hills in the Eastern Desert. The Wadi Kubbaniya-Wadi Abu Subeira paleo-drainage was one of these W-flowing rivers which drained southern Egypt until the onset of the Eonile Canyon ~6 Ma ago.

(2) Models generated from MT and gravity data show the depth of Wadi Kubbaniya extends much deeper into the sub-surface than previously reported. These models prefer representing the Wadi Kubbaniya as graben structure bounded by NW-trending faults formed from extensional tectonics during the Oligocene time. The presence of this graben explains the sudden NW-deflection of the Wadi Kubbaniya-Wadi Abu Subeira paleo-drainage. The large normal displacement within the graben compared to its narrow width suggests that pre-existing structures might have facilitated strain localization.

(3) More potential field and seismic data, and sedimentological data from well cores are desired to constrain the geometry of the Wadi Kubbaniya graben. Additionally, comparing the architecture of the Wadi Kubbaniya graben with other grabens such as the Assuit grabens is desired to contribute to the understanding of strain localization during rifting processes.

(4) The depth of the Kubbaniya graben extends well beneath the current base of the Modern Nile; a scenario that favors the accumulation of groundwater far away from the rather crowded Nile Valley in southern Egypt.

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References

Abdelsalam, M.G., Stern, R.J., 1996. Sutures and shear zones in the Arabian–Nubian shield. Journal of African Earth Sciences 23, 289–310.

Akawy, A., 2002. Structural geomorphology and neotectonics of the Qina; Safaja District, Egypt. Neues Jahrbuch fuer Geologie und Palaeontologie 226, 95–130.

Atef, A., 2011. Apparent weekly and daily earthquake periodicities in the western United States, and evolution of Wadi Kubbania in Egypt. PhD dissertation. Missouri University of Science and Technology, Rolla, MO. p. 95.

Beamish, D., Travassos, J.M., 1992. The use of the D+ solution in magnetotelluric interpretation. Journal of Applied Geophysics 29, 1–19.

Bosworth, W., Huchon, P., McClay, K., 2005. The Red Sea and Gulf of Aden Basins. Journal of African Earth Sciences 43, 334–378.

Bosworth, W., El-Hawat, A.S., Helgeson, D.E., Burke, K., 2008. Cyrenaican ‘shock absorber’ and associated inversion strain shadow in the collision zone of northeast Africa. Geology 36, 695–698.

Butzer, K.W., Hansen, C.L., 1968. Desert and River in Nubia; Geomorphology and Prehistoric Environments at the Aswan Reservoir. University of Wisconsin Press, Madison, p. 562.

El Bastawesy, M., Faid, A., Gammal, E.S.E., 2010. The Quaternary development of tributary channels to the Nile River at Kom Ombo area, Eastern Desert of Egypt, and their implication for groundwater resources. Hydrological Processes 24, 1856–1865.

El Naggar, Z.R., 1970. On a proposed lithostratigraphic subdivision for the Late Cretaceous-Early Paleogene succession in the Nile Valley, Egypt. In: 7th Arab Petroleum Congress, Kuwait, pp. 1–50 B-53.

Gani, N.D.S., Abdelsalam, M.G., 2006. Remote sensing analysis of the Gorge of the Nile, Ethiopia with emphasis on Dejen-Gohatsion region. Journal of African Earth Sciences 44, 135–150.

Ghoneim, E., Robinson, C., El-Baz, F., 2007. Radar topography data reveal drainage relics in the eastern Sahara. International Journal of Remote Sensing 28, 1759–1772.

Gindy, A.R., Tamish, M.M., 1998. Petrogenetic revision of the basement rocks in the environs of Aswan, southern Egypt. Egypt Journal of Geology 42, 1–14.

Goudie, A.S., 2005. The drainage of Africa since the Cretaceous. Geomorphology 67, 437–456.

Guiraud, R., Issawi, B., Bellion, Y., 1985. Les Lineaments guineo-nubiens; un trait structural majeur a l’echelle de la plaque africaine. Comptes Rendus de l’Académié des Sciences, Paris 300, 17–20.

Guiraud, R., Bosworth, W., Thierry, J., Delplanque, A., 2005. Phanerozoic geological evolution of Northern and Central Africa: an overview. Journal of African Earth Sciences 43, 83–143.

Hofmann, C., Courtillot, V., Feraud, G., Rochette, P., Yirgu, G., Ketefo, E., Pik, R., 1997. Timing of the Ethiopian flood basalt event and implications of Plume birth and global change. Nature 389, 838–841.

Hsu, K.J., Ryan, W.B.F., Cita, M.B., 1973. Late Miocene desiccation of the Mediterranean. Nature 242, 240–244.

Issawi, B., McCauley, J.F., 1992. The Cenozoic Rivers of Egypt; the Nile problem. In: Friedman, R., Adams, B. (Eds.), The Followers of Horus. Oxford Monograph, Oxford, pp. 121–138.

Issawi, B., McCauley, J.F., 1993. The Cenozoic landscape of Egypt and its river systems. Annals of the Geological Survey of Egypt 19, 357–384.

Issawi, B., Osman, R., 2008. Egypt during the Cenozoic: geological history of the Nile River. Bulletin of the Tethys Geological Society 3, 43–62.

Issawi, B., El-Hinnawi, M., Francis, M., Mazhar, A., 1999. The Phanerozoic geology of Egypt–a geodynamic approach. The Egyptian Geological Survey Press, Cairo, p. 462.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Lansbery, L., 2011. Geological and geomorphological evolution of the Egyptian Nile between Aswan and Kom Ombo: A remote sensing and field study approach. MS thesis. Missouri University of Science and Technology, Rolla, MO, p. 83.

Makris, J., Henke, C.H., Egloff, F., Akamaluk, T., 1991. The gravity field of the Red Sea and East Africa. Tectonophysics 198, 369–381.

McCauley, J.F., Schaber, G.G., Breed, C.S., Grolier, M.J., Haynes, C.V., Issawi, B., Elachi, C., Blom, R., 1982. Subsurface valleys and geoarcheology of the Eastern Sahara revealed by shuttle radar. Science 218, 1004–1020.

McCauley, J.F., Breed, C.S., Schaber, G.G., McHugh, W.P., Issawi, B., Haynes, C.V., Grolier, M.J., El Kilani, A., 1986. Paleodrainages of the Eastern Sahara—the radar rivers revisited. SIR A/B implications for a mid-Tertiary trans-African drainage system. IEEE Transactions on Geosciences and Remote Sensing GE-24, 624–648.

Meshref, W.M., 1990. Tectonic Framework. In: Said, R. (Ed.), The Geology of Egypt. Balkema, Rotterdam/Brookfield, pp. 113–155.

Omar, G.I., Steckler, M.S., 1995. Fission track evidence on the initial rifting of the Red Sea: two pulses, no propagation. Science 270, 1341–1344.

Omar, G.I., Steckler, M.S., Buck, W.R., Kohn, B.P., 1989. Fission-track analysis of basement apatite at the western margin of the Gulf of Suez rift, Egypt: evidence for synchroneity of uplift and subsidence. Earth and Planetary Science letters 94, 316–328.

Pallister, J.S., 1987. Magmatic history of the Red Sea rifting: perspective from the central Saudi Arabian coastal plain. Geological Society of America Bulletin 98, 400–417.

Rodi, W., Mackie, R.L., 2001. Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics 66, 174–187.

Said, R., 1981. The Geological Evolution of the River Nile. Springer-Verlag, New York, p. 152.

Said, R., 1993. The River Nile: Geology, Hydrology, and Utilization, first ed. Pergamon, Oxford/New York, p. 320.

Schandelmeier, H., Reynolds, P.O., 1997. Palaeogeographic palaeotectonic atlas of north eastern Africa, Arabia, and adjacent areas. In: Schandelmeier, H., Reynolds, P.O. (Eds.), Palaeogeographic Palaeotectonic Atlas of North Eastern Africa, Arabia, and Adjacent Areas. Balkerma, Rotterdam, p. 160.

Stern, R.J., Abdelsalam, M.G., 1996. The origin of the Great Bend of the Nile from SIR-C/X SAR imagery. Science 274, 1696–1698.

Tawardros, E., 2001. Geology of Egypt and Libya. Balkema, Rotterdam/Brookfield, p. 468.

Thurmond, A.K., Stern, R.J., Abdelsalam, M.G., Nielsen, K.C., Abdeen, M.M., Hinz, E., 2004. The Nubian Swell. Journal of African Earth Sciences 39, 401–407.

Wendorf, F., Schild, R., 1976. Prehistory of the Nile Valley. Academic Press, New York, p. 404.

Youssef, M.M., 2003. Structural setting of central and south Egypt: an overview. Micropaleontology 49, 1–13.