The uppermost deposits of the stratigraphic succession of the Farafra Depression (Western Desert, Egypt): Evolution to a Post-Eocene continental event

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Abstract

This paper gives insight into continental sedimentary deposits that occur at the uppermost part of the stratigraphic succession present in the north-eastern sector of the Farafra Depression (Western Desert, Egypt). Using space imagery to complete the field work, the geology of the area has been mapped and the presence of a N–S oriented fault system is documented. The analysis of the morphotectonic features related to this fault system allows reconstructing the structural and sedimentological evolution of the area. The study indicates that the continental deposits were accumulated in alluvial systems that uncon-formably overlie shale and evaporitic rocks attributable to the Paleocene–Eocene Esna Formation. The deposits of the Esna Formation show soft-sediment deformation features, which include slump associated to dish and pillar sedimentary structures and provide evidence of syndepositional tectonic activity during the sedimentation of this unit. The outcrops are preserved in two areas on separated fault-bounded blocks. Proximal alluvial fan facies crop out in a dowthrown block close to the depression boundary. The proximal facies are made up mostly by polymictic conglomerates which occasionally con-tain boulders. The conglomerate clasts are mainly quartz, carbonate, anhydrite satin spar vein, mudrock, ironstone and nummulite fossils. The mid-fan facies consist of trough cross-bedded, rippled and cross-laminated quartzarenites with reworked glauconite grains and carbonate rock fragments, interpreted as deposited by distributary streams. The distal alluvial fan deposits consist of sandy marls that evolve toward the top of the sections into root-bioturbated lacustrine limestone beds that are locally silicified. The limestones are biomicrites containing characea, ostracods and gastropods with fenestral porosity.

Keywords: Farafra Depression, Alluvial fans, Lacustrine deposits, Esna Formation, Seismites, Sabkha

1. Introduction

The Farafra Depression is a semi-closed basin situated within the Western Desert of Egypt (Fig. 1a). Structurally, the depression is included in the so called Stable Shelf (Said, 1962, 1990). The Sta-ble Shelf is located towards the south of the Unstable Shelf domain that forms part of the Syrian arc belt (Fig. 1a). This division into two geotectonic domains started during the Late Cretaceous and was synchronic with the closure of the Tethys Sea where the Cre-taceous sedimentation took place due to the convergence of the North-African and the European tectonic plates (El-Motaal and Kusky, 2003). The drift of the North-African plate caused uplifting and folding of the Cretaceous depression according to an ENE–WSW direction. Related faults follow the same pattern.

According to El-Motaal and Kusky (2003), the separation of the Arabian plate from Africa that initiated in Oligo-Miocene time through the Red Sea rift enhanced the intensity of the folding and thrusting of the study area. Additional shortening and left-lat-eral offset along the almost N–S oriented Dead Sea transform fault began in the Miocene and is still active at present.

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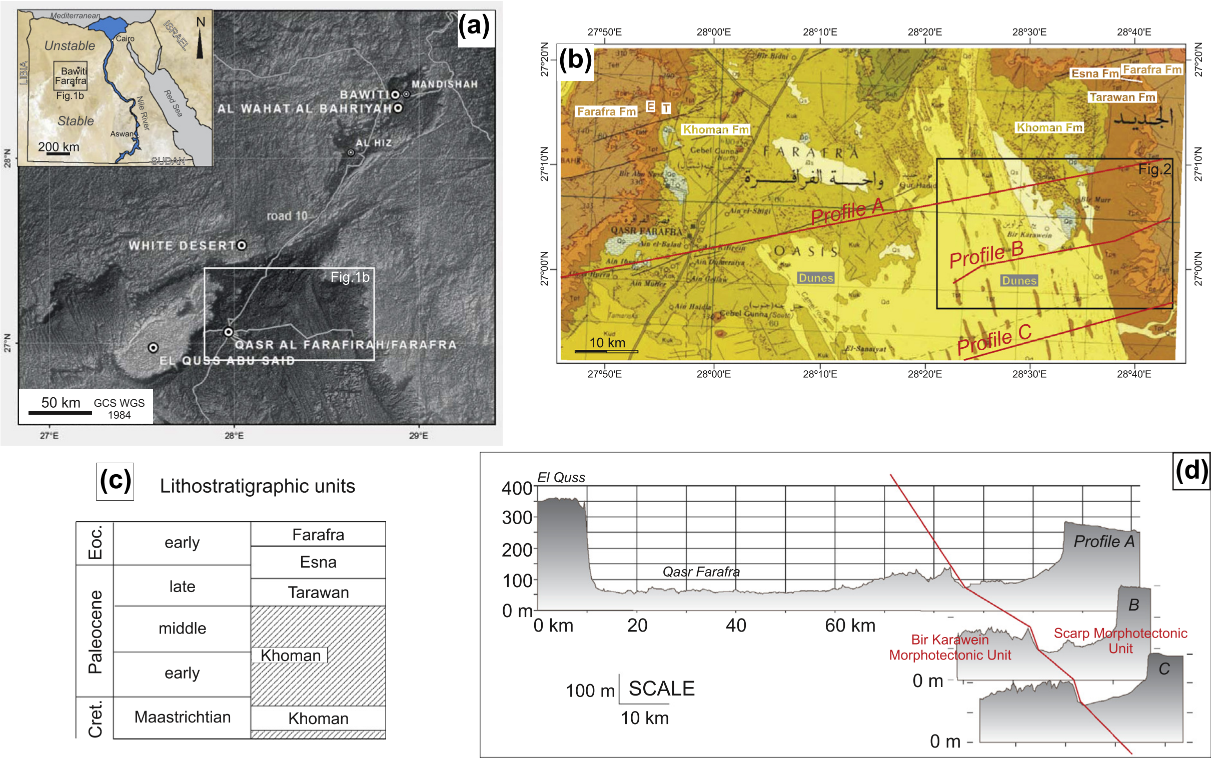

Fig. 1. (a) Location map of the study area. (b) Geological map of the northern part of the Farafra Depression (Conoco, 1987). (c) Upper Cretaceous to Paleogene lithostratigraphic units for the Farafra Depression after Hermina (1990). (d) Three profiles showing the different topographic features of the selected morphotectonic units. The trace of the profiles is shown in Fig. 1b. Profile b lies along the study outcrops.

After folding, there were periods of heavy rainfall during Oligocene (El Agami, 1989). The depression center was excavated due to the combined action of running water and wind, generating the Farafra Depression. The depression is limited by scarps and contains a record of the marine Upper Cretaceous to Eocene sediments (Fig. 1b and c) (Said, 1962; Youssef and Abdel-Aziz, 1971; Werner and Herrmann-Degen, 1981). The depression and its cliffs are sculptured in four marine sedimentary formations, namely the Maastrichtian Khoman Formation and the Paleogene Formations: Tarawan, Esna and Farafra (Fig. 1c). The Khoman Formation consists of chalk deposits that cover most of the depression area. The erosion of this carbonate formation has generated spectacular and geomorphologically attractive shapes, best represented in the White Desert Area National Park (Fig. 1a).

In the north-eastern scarp the sedimentary succession is composed of the Esna and Farafra Formations. The Esna Formation is widely distributed in Egypt and neighboring regions. It consists mainly of marine shales (Said, 1962) and is dated by planktonic foraminifera as late Paleocene, reaching the early Eocene in the area of Gebel Gunna (Abdel-Kireem and Samir, 1995), located 50 km towards the W of the study area. The Esna Formation is conformably covered by the Farafra fossiliferous limestones (Figs. 1 and 2).

Recently, in his study of the Farafra Depression, Wanas (2012) indicated the presence of continental deposits toward the upper part of the stratigraphic succession located at the eastern part of the depression. Despite the area has been object of different studies (Said, 1962, 1990; Issawi, 1972; Issawi et al., 1999; Tawadros, 2001), a geological framework for the continental record has been hampered by the lack of structural reconstructions, the poor age control as a result of a poor fossil record and the sparsity of the outcrops. The object of this study has been to place the uppermost deposits of the stratigraphic succession in a more specific geological context, and to get a better knowledge of the Post-Eocene evolution of the Farafra Depression and its possible relation to the Red Sea opening.

2. Methods

The study area (Fig. 1b) was recognized and 15 samples were collected from four representative stratigraphic sections (Fig. 2). Due to the area characteristics (a sand desert with scarce roads) we analyzed satellite images, and digital topographic models, which allowed us to cover more extensive areas and to complete the tectonic, geomorphologic and sedimentologic information available.

Three types of remotely sensed data were used: (1) Visible and infrared imagery of the Earth´ s land from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), sensor on board the satellite Terra that provide multiresolution (15, 30 and 90 m) and 14 wavelengths from visible light to thermal infrared bands; we used ASTER images acquired in years 2010 and 2011.(2) Digital topographic maps from the Shuttle Radar Topography Mission (SRTM) of the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). (3) Images of the surface of the Earth from July 1982 to November 2011 with a spatial resolution of 30 m, from the Landsat Thematic Mapper (TM) sensor on board Landsat 4 and 5. The data were integrated in a Geographic Information System, with WGS 84 as Coordinate System.

Thin sections of all samples were prepared and studied by standard petrography. Samples with high evaporite content were performed without water and were not covered with lack to avoid their alteration. The thin sections with carbonate were stained by using Lindholm and Finkelman (1972) method to facilitate carbonate distinction.

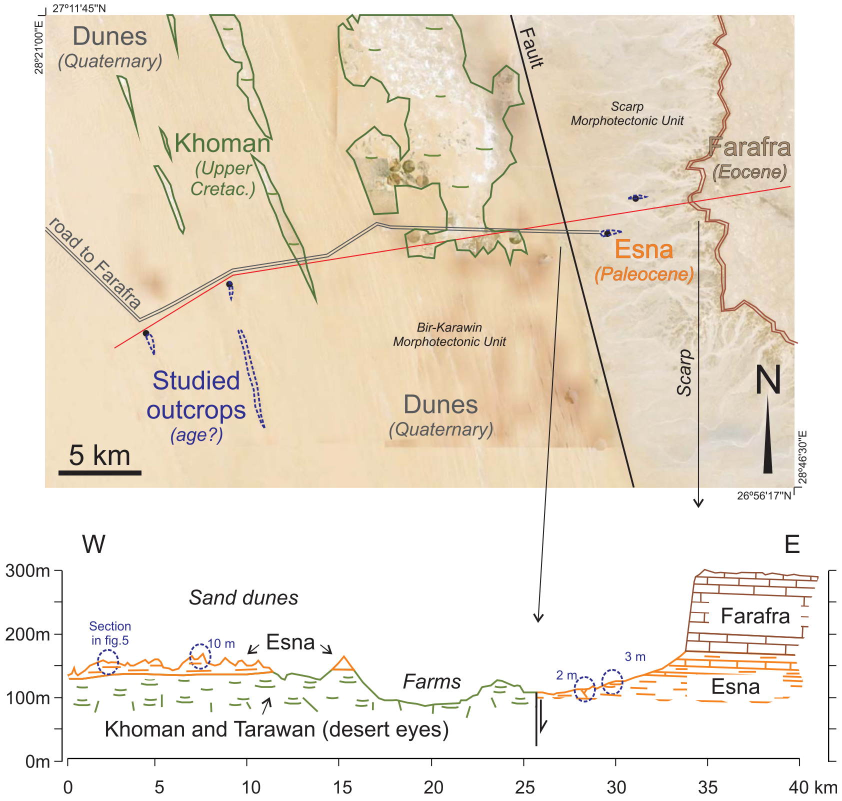

Fig. 2. Detailed geological map of the study area including satellite images that display the distinctive bedrock structures of the sedimentary formations in the vicinity. The derived geological section shows the fault zone that separates the morphotectonic units (MU): Scarp MU to the east and Bir-Karawein MU to the west. Dotted circles and numbers on the cross section indicate the position and thickness of the upper unit in the studied outcrops.

3. Results

In order to establish a more precise geological setting for the study succession, topographic profiles (Fig. 1b and d) and a geological map of the area were elaborated based on field observations and satellite images (Fig. 2) The geological mapping, together with the derived cross section, allowed to differentiate two morphotectonic contexts in the study area, which are described in the next subchapter. After this, the sedimentological features of the studied outcrops are presented.

3.1. Morphotectonic units

The studied outcrops are located in two separated areas, approximately 25 km far from each other (Fig. 2), which show quite different geomorphologic features. The first area is located in the vicinities of the scarp that limits the depression toward the east (Figs. 1b–d, 2 and 3a and b), whereas the second one spreads out near Bir Karawein, closer to the inner part of the depression (Figs. 1b–d, 2 and 3f). Both areas are separated by a main fault that is clearly visible by satellite imagery as a straight line with a NNW–SSE orientation (Fig. 2). The Bir Karawein area is around 50 m topographically higher than its equivalent in the scarp area (Figs. 1d and 2). These features allow to define two morphotectonic units (MU): Scarp MU and Bir Karawein MU.

The studied outcrops in the Scarp MU are distributed in scarce broadly elongated hills with an E–W orientation. The hills, usually less than 10 m high, are preserved among active endorheic channels flowing from the scarp toward the west (Figs. 2, 3c–e). Channel flows disappear where the channels reach the fault zone and the corresponding ridge (Fig. 2), approximately 10 km far from the scarp.

The outcrops of the Bir Karawein MU are located in □ 20 m high, elongate hills, systematically oriented along the direction NNW–SSE (Fig. 3f and g). The up-to 6 km long hills are isolated in the Quaternary sand field, in which every single dune is oriented parallel to the same direction (Fig. 2). As discussed below, the deposits that constitute the hills have been erroneously attributed to the Paleocene Tarawan Formation (Conoco, 1987 -Fig. 1b- and Said, 1990). Satellite imagery allows distinguishing between the unknown succession of the studied flat-topped hills (Fig. 3g) and the bedrock structures of the Khoman and Tarawan outcrops located in the proximities (Fig. 3h and i). Both formations are composed of white chalk and display a complex type of deformation pattern all over the Farafra Depression (Tewksbury et al., 2011). The lowermost part of the Khoman Formation occurs as a polygonal ridge terrain (Fig. 3i), while the upper parts show polka dot mesas and low relief eyes (Tewksbury et al., 2011). According to these authors, the sedimentary deposits of the Tarawan Formation somehow display circular structures of similar size as those of the underlying Khoman Formation. All these patterns seem to be related to polygonal fault systems and fluid escape structures and are never recorded in the overlying rocks (Tewksbury et al., 2011). The occurrence of these outstanding features in the satellite images allowed us to outline the outcrops of the main formations to complete the geological map and to estimate the amount of vertical displacement of the fault (Fig. 2), since the bedrock structures outcropping in the surroundings of the farms are distinctive of the lowermost part of the Khoman Formation (see cross section in Fig. 2).

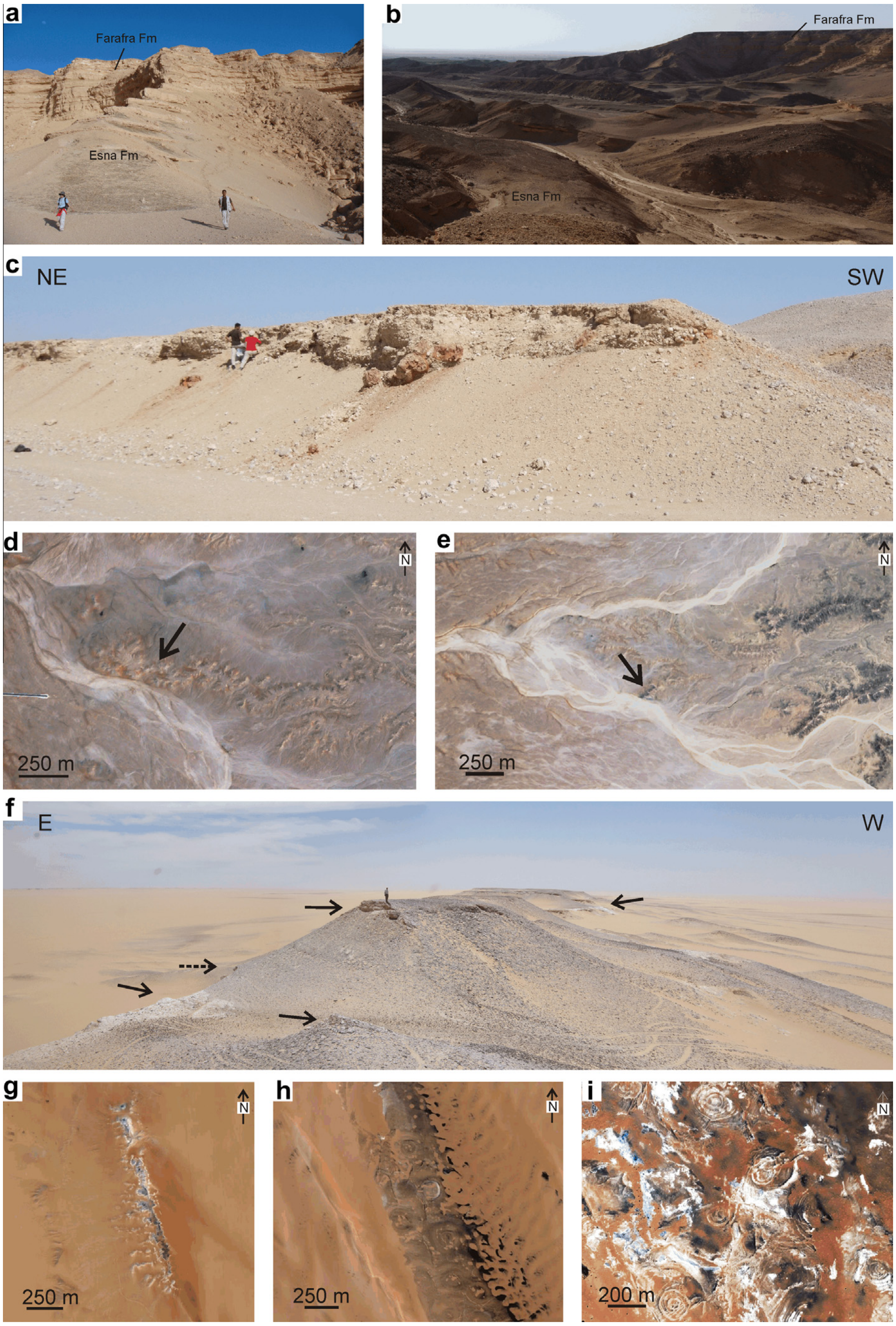

Fig. 3. (a–e) Scarp MU. (a) The lower part of the scarp shows the alternating shales and carbonates from the Esna Formation while the upper part consists of early Eocene carbonates from the Farafra Formation. (b) Typical landscape of the Scarp MU with Quaternary wadi eroding older Cenozoic deposits. (c–e) Outcrops in the Scarp MU are isolated low hills with a broad E–W orientation that remain in the middle of an active alluvial plain (in d and e, the arrows point to the studied outcrops on a satellite image).(f–h) Bir Karawein MU. (f) Typical landscape of the Bir Karawein MU. The outcrops are flat-topped isolated hills with a consistent NNW–SSE orientation. Arrows indicate the apparent dip of the beds. The dashed arrow points to the approximate location of the contact between the basal and the upper unit. (g) Satellite image of the flat-topped hill of Fig. 3f. (h and i) Satellite images of the distinctive circular bedrock structures recognizable in the outcrops from the Khoman Formation in the Bir Karawein MU. The structures are referred to as desert eyes by Tewksbury et al. (2011). (h) Isolated outcrop surrounded by sand dunes showing the low-relief eyes, and (i) View of the polygonal ridge terrain typical of the Khoman Formation close to the farms in the Bir Karawein MU.

3.2. Sedimentological and petrological analyses

3.2.1. Scarp area

The studied outcrops in the scarp area show two superimposed units. The lower one is constituted by shales, limestones and evap-orites that are unconformably overlain by the horizontal conglom-erate beds of the upper unit (Fig. 4a).

The exposures of the basal unit (at least 16 m thick) contain laminated dark shales cut by white satin-spar calcium–sulfate veins arranged in several directions (Fig. 4b). The shales contain perforate planktonic (Fig. 5a), occasionally benthic (Lenticulina) foraminifera (Fig. 5b) and iron concretions. The outcrop located closer to the scarp consists of thinly-bedded marls with shale intercalations that show soft-sediment deformation structures,

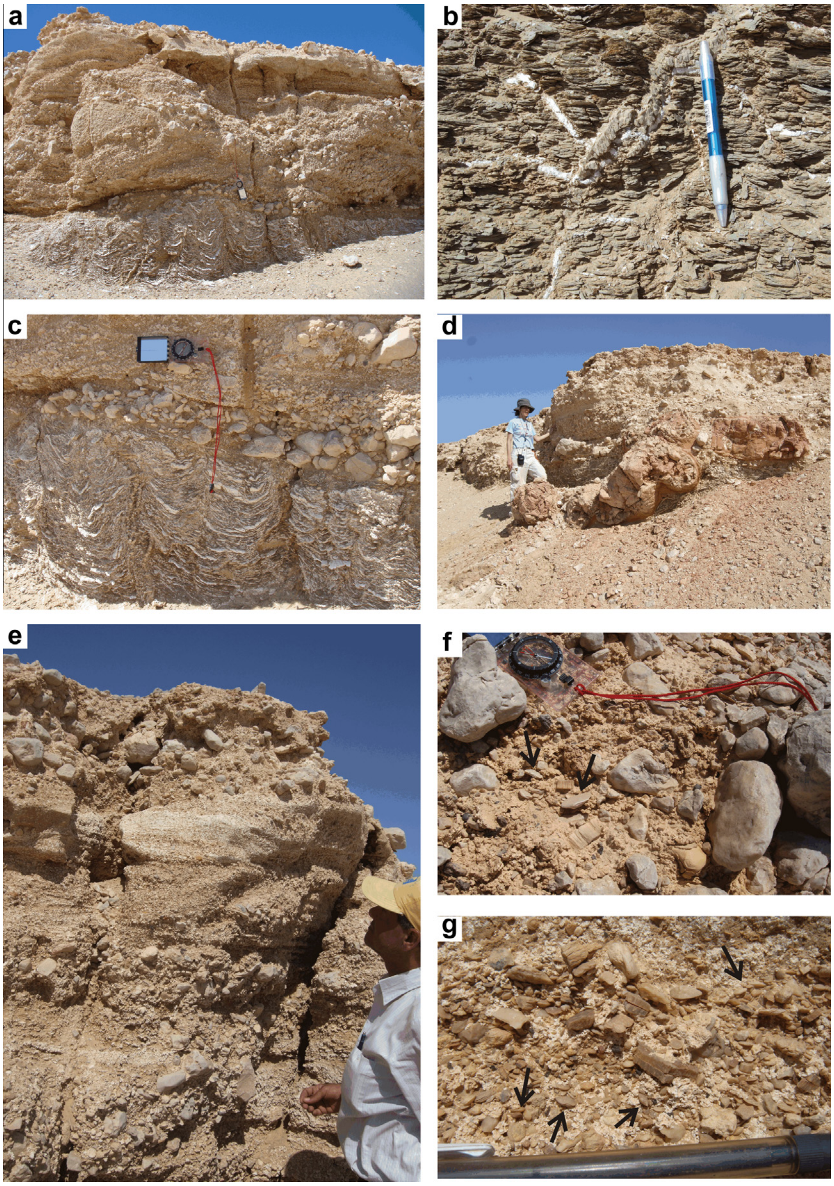

Fig. 4. Outcrop pictures in the Scarp MU. (a) Unconformity between the conglomerate unit and the underlying shales. See compass for scale. (b) Satin spar veins in shales. (c) Dish and pillar structure below the unconformity that is outlined by lag deposits. (d) Red carbonate slump associated with dish and pillar structures. (e) Graded conglomerates showing large scale cross-stratification. A debris flow deposit can be observed on top of the outcrop. (f and g) The polymictic conglomerates contain abundant fossils (mainly Nummulites), some arrowed, and fragments of satin spar veins and slumped carbonates similar to those of photograph (d). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Photomicrographs of the deposits in the scarp MU. (a) Planktonic foraminifera in shales from the Esna Formation. Notice the perforated walls and the abundance of iron concretions. Parallel nicholls. (b) Lenticulina foraminifera in same shales. Cross nicholls. (c) Operculina complanata in the conglomerates. Parallel nicholls.

i.e. dish and dish and pillar structures associated with slump structures (Fig. 4a and c). Dish structures consist of white concave-up laminae 15–20 cm across, in some cases separated by vertical pillars (Fig. 4a and c). Vertical spacing of the dishes varies between 2 and 10 cm. A red carbonate sediment interval, up to 1 m-thick, which extends laterally over hundreds of meters (Fig. 3c–e), disrupts the dish and pillar structures. The carbonate comprises contorted slumped beds and isolated spherical nodules (Fig. 4d).

The overlying unit consists of 2–3.5 m thick polymictic con-glomerates (Fig. 4a and e–g). The conglomerate consists of frag-ments of carbonate rocks, anhydritic satin spar, quartz, clay mudstones, ironstone and fossils. Fossils are mainly foraminifera (Nummulites and fragments of Nummulites, Operculina complanat-a, Fig. 5c), pelecipods (Lucina thebica), gastropods, echinoderms and bioturbation tubes (Fig. 4f and g). The conglomerates show different facies which include mostly lag (Fig. 4a and c) and channel-fill facies (Fig. 4e and f). Channel deposits comprise decimetre-sized graded beds with planar and trough cross stratifi-cation (Fig. 4e). The centile size of the carbonate clasts in this facies is 20 cm. Paleocurrents indicate a flow direction towards the W (N 120□W). The less common debris flow facies are matrix supported conglomerates (top of Fig. 4e).

3.2.2. Bir Karawein MU

In the Bir Karawein zone the succession consists of two sedimentary units separated by an angular unconformity (Fig. 6). The basal unit gently dips towards the west, whereas the upper silici-clastic–carbonatic unit lies horizontally (Fig. 3f).

The basal unit consists of dark greenish shales interbedded with evaporites in the lowermost part of the section (Figs. 6 and 7a and b). The evaporites comprise up to 5 cm-thick sulfate satin spar veins and up-to 15 cm thick beds of anhydrite intercalated with shale laminae (Fig. 7b and c). At the base, the evaporite sequence is made up of anhydrite laminite that locally exhibits undulating surfaces and teepee structures. The middle and upper parts of the evaporitic sequence are dominated by lenticular to prismatic crystals that are arranged vertically or coalesce to form rosette-like aggregates that show a bedded (Fig. 7c) or a brecciated structure.

Petrographic observation shows that the evaporite facies are made up of anhydrite and relics of gypsum crystals (Fig. 8a). Anhy-drite occurs as masses of fibers that locally exhibit fibroradiate morphologies. The sulfate is partially replaced by rounded calcite microcrystals.

The evaporite sequence is capped by a reddish surface (Fig. 6) covered by green shale interbedded with up to 5 cm-thick microsparite carbonate layers (Fig. 7d). The shales contain

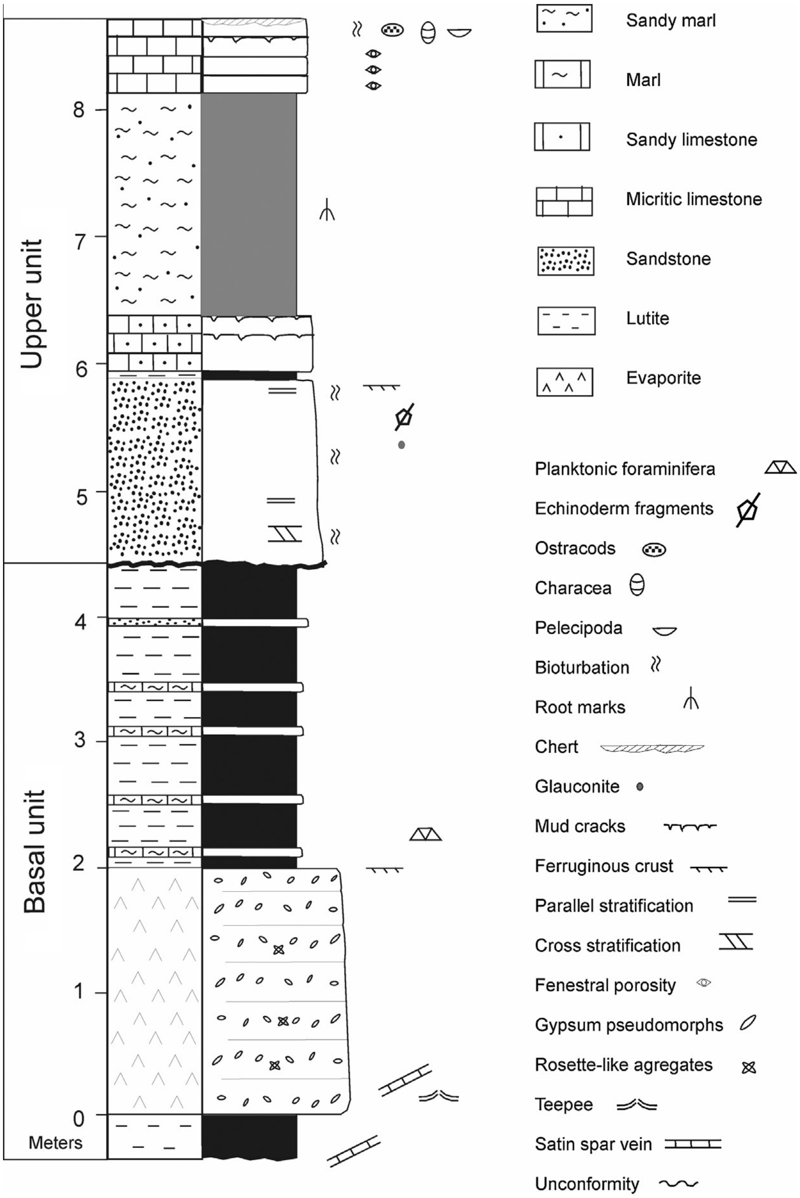

Fig. 6. Log of the sedimentary succession in the Bir Karawein area.

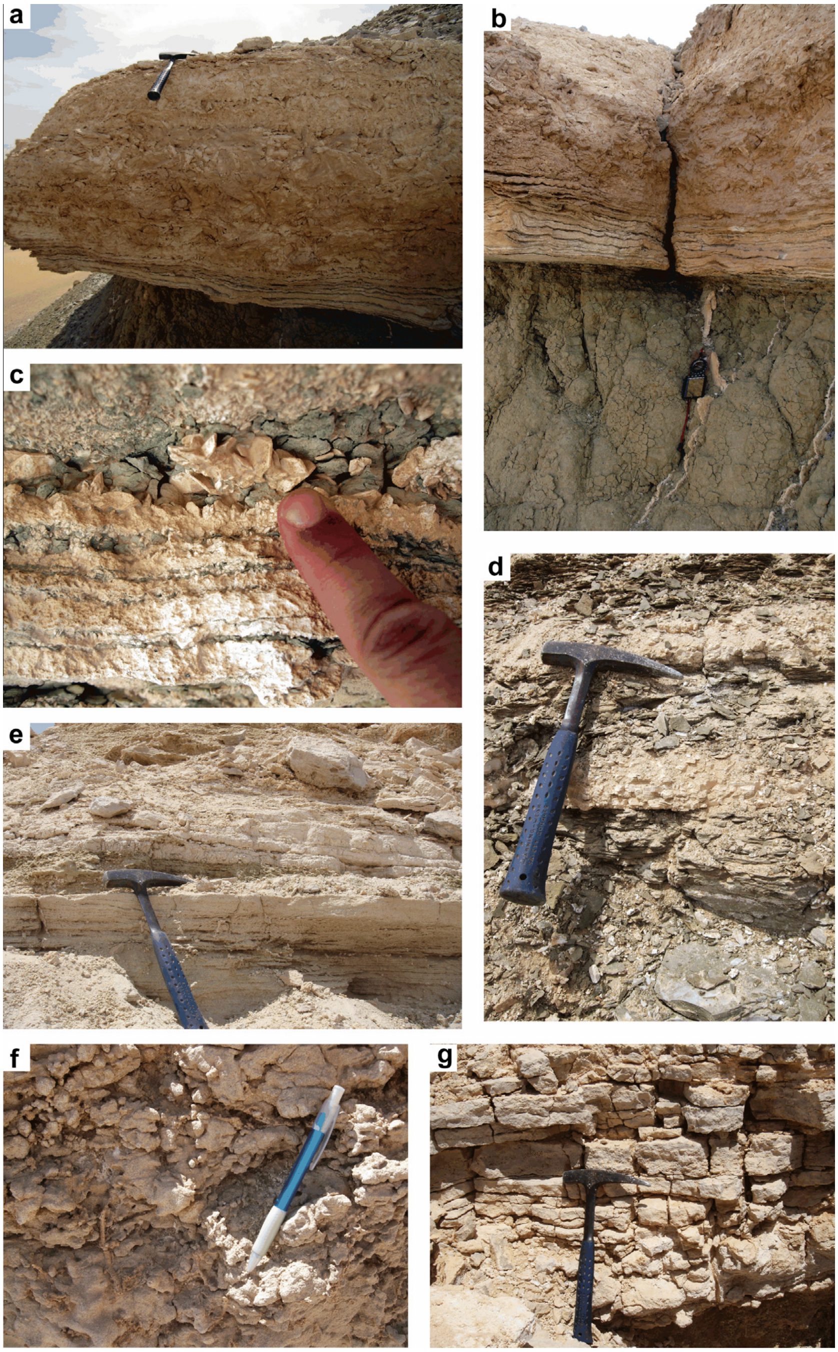

Fig. 7. Outcrop photos in the Bir-Karawein section (see Fig. 6). (a) Evaporite bed. (b) Satin spar veins cross cutting shale deposits below the evaporite bed. (c) Alternation of green shales and evaporites at the base of the thick bed of photograph 7a. The evaporite beds are formed by the coalescence of euhedric crystals of sulfates. (d) On top of the evaporites, alternation of green shales and brownish carbonates. (e) White sandstones with small scale cross stratification. (f) Densely bioturbated sandstones. (g) Laminated carbonates with fenestral porosity.

perforate planktonic foraminifera, thick-walled ostracods and de-formed pelecipod shells (Fig. 8b and c).

The upper sedimentary unit consists of a lower siliciclastic interval formed by siltstone and sandstone deposits that pass up-wards into carbonate beds thus forming a siliciclastic–carbonatic unit (Fig. 6). Sandstone facies comprise trough cross-bedded, rip-pled and cross-laminated structures (Fig. 7e). Paleocurrent mea-surements indicate a SW direction. Bioturbation structures, including root traces and nodulization, are mostly seen in the upper part of the sandstone beds (Fig. 7f).

The sandstone is quartzarenite and is mainly composed of rounded monocrystalline quartz and micritic and sparitic lime-stone and dolostone rock fragments, including echinoderm plates (Fig. 8d). Some glauconite rounded grains are present, along with minor polycrystalline quartz, K-feldspar and plagioclase grains. Accessory zircon and tourmaline minerals are also recognized. The grains are cemented by abundant non-ferroan calcite (Fig. 8d). The uppermost part of the succession is made up of gray lime-stone beds with lamination outlined by vuggy and fenestral poros-ity crossed-cut by open bifurcated tubes (root and rootlets). The

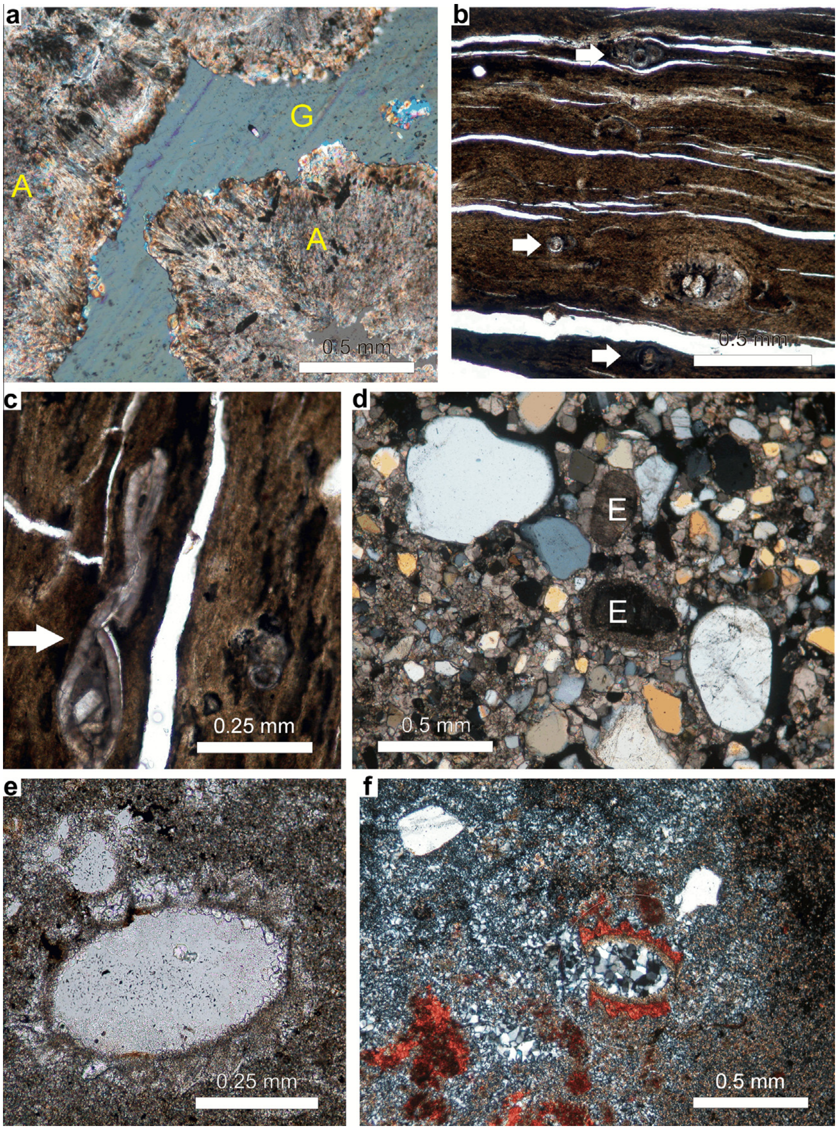

Fig. 8. Photomicrographs of the Bir Karawein area deposits. (a) Aspect of fibroradiate anhydrite (A) replacing a gypsum crystal (G). (b) Abundant planktonic foraminifera (arrows) in shales. (c) Delicate pelecipod shell (arrow) and planktonic foraminifera in shales. (d) Sandstones with grains of echinoderm plates (E) and abundant carbonate cement. (e) Gyrogonite of charophyte in limestones. (f) Partially silicified limestone and charophyte gyrogonite (stained in red and encircled). All samples are taken with cross nicholls, except a, d and e. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

upper part of the limestone beds is locally silicified (Fig. 6). The chert beds that occur at the top of the succession constitute a hard cap-rock that precludes further erosion of the hills.

This upper bed is composed of biomicrites that contain ostrac-ods, charophytes (Fig. 8e and f) and delicate pelecipod shells. Ce-ments made up of micro- to mesocrystalline quartz crystals are observed to fill the bioturbation, fenestral and intraparticle pores. Besides, irregularly-distributed microcrystals of quartz locally re-place the micrite matrix (Fig. 8f).

4. Discussion

The uppermost stratigraphic succession in the north-eastern sector of the Farafra Depression is constituted by two sedimentary units in each MU, preserved as isolated outcrops (Figs. 2, 6 and 9a). Our results concerning the morphosedimentary features, the lat-eral and stratigraphic arrangement and the type of facies associa-tions, allow to interpret that both successions are equivalent and, consequently, correlatable in the scarp and Bir Karawein areas. As discussed below, the basal sedimentary unit has been attributed in this work to the Esna Shale Formation and is overlain by the con-tinental deposits that we have defined as the informal Upper Unit (Fig. 9a).

4.1. Basal unit (Esna Formation)

The shale-bearing deposits recognized in the study outcrops of the scarp area are attributed to the Esna Formation, according to previous authors (Said, 1961; Conoco, 1987, Fig. 1). On the other hand, although this formation has not been identified previously in the Bir Karawein area, we interpret that the basal unit in these outcrops can be stratigraphically correlated to the same formation. This assumption is based on the similar lithologies (mainly shales and evaporites) and the presence of similar fossil content (Fig. 9a). This correlation allows to fill the gap of the Esna Formation in the central areas of the Farafra depression.

The Esna Formation in the Bir Karawein area is at least 50 m thinner than in the scarp area (Fig. 2) due to erosion processes

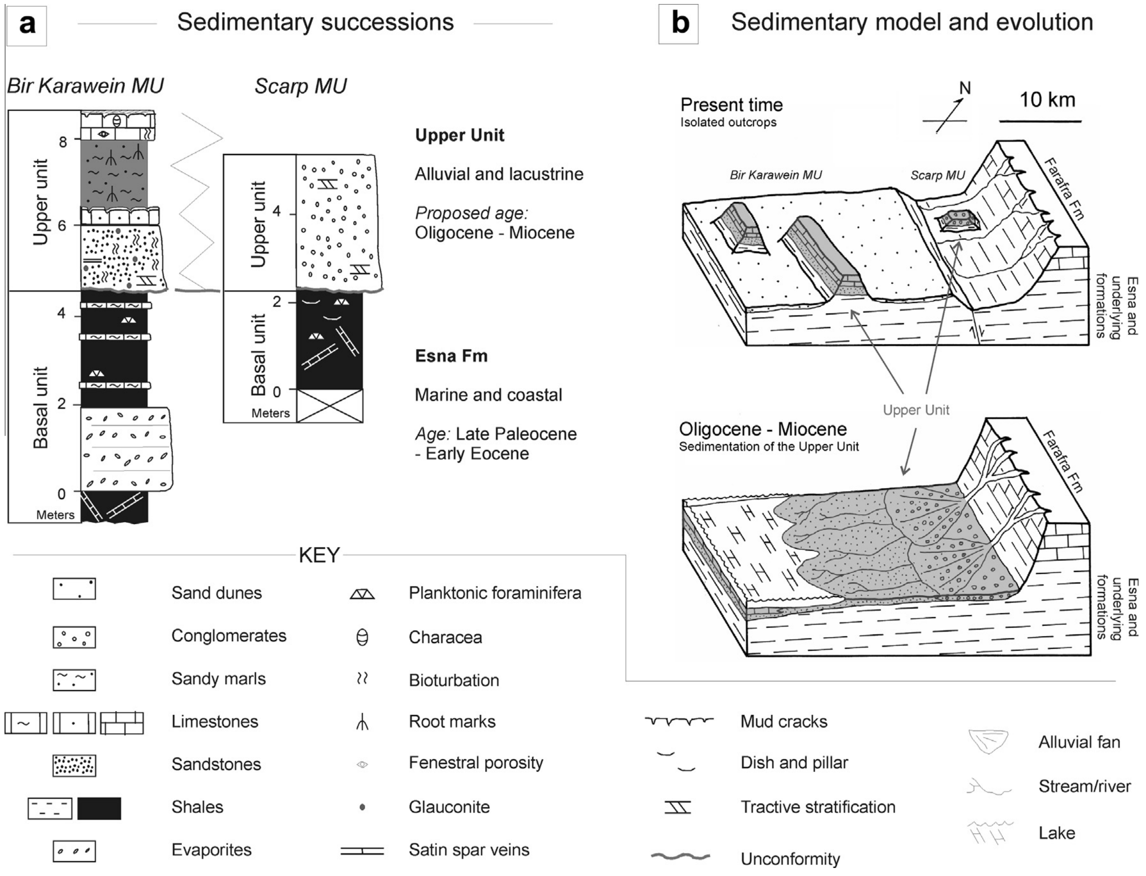

Fig. 9. (a) Main features of the basal and upper sedimentary units typically found in the defined Scarp and Bir Karawein MU. (b) Diagram blocks showing the sedimentary model and evolution for the continental record cropping out in the eastern sector of the Farafra Depression. The lower diagram displays the sedimentary environments for the Oligocene–Miocene period. The present time outcropping conditions are depicted in the upper block.

previous to the deposition of the Upper Unit. The erosion of the Esna Formation and its subsequent thinning can be considered as a widely developed event since it has been recorded elsewhere in the Eastern Desert of Egypt (Alsharhan and Salah, 1997). The latter authors interpreted that the erosion was simultaneous with the development of the Syrian arc system.

4.1.1. Paleoenvironment

The Esna Formation was deposited in a carbonate ramp devel-oped on a passive margin basin (El Ayyat, 2013). The soft sediment deformation structures recognized in the scarp area indicate a per-iod of tectonic instability. Dish and pillar structures (Fig. 4aa nd c) are due to elevated pore water pressure combined with fluidifica-tion, which is usually related to rapid deposition load (Collinson and Thompson, 1989). Slump folds are soft deformation structures that can be triggered by cyclic earthquakes (Leeder, 2011). In the scarp area, dish, dish and pillar and slump structures are present together indicating synchronicity and instantaneity of deforma-tion. This association of deformation structures further supports an earthquake shock (Bhattacharya and Bandyopadhyay, 1998). Accordingly, our findings show new evidence of syndepositional tectonic activity in the middle part of the Esna Formation, which was deposited in the late Paleocene-early Eocene interval coinci-dent with the development of the Syrian arc system (Alsharhan and Salah, 1997).

The evaporite facies found in the present study have hardly ever been reported in the Esna Formation before (Ahmad, 2012). Evap-orites preserved in the Bir Karawein area as anhydrite beds and pseudomorphs after gypsum interbedded with green shales (Fig. 4) are indicative of restricted sedimentary conditions typical of coastal evaporitic environments (Warren and Kendall, 1985). In those environments (sabkha), lenticular gypsum and gypsum roses are known to precipitate in interstitial pore space of inter-tidal sediments where microbial mats are very abundant (Schrei-ber and El Tabakh, 2000, and references therein). The coalescence of gypsum rosette-like aggregates precipitated in the water table leads to its bedded appearance. In addition, the growth of anhy-drite nodules and the replacement by anhydrite are observed to take place in the more arid zones of the sabkha environment (War-ren, 2006). The intercalation of sabkha deposits with planktonic-foraminifera-bearing shales reflects an event of marine regression recorded less than 20 m above the bottom of the Esna Formation in the Bir Karawein section (Fig. 2), followed by a marine transgression.

Shale facies are crossed cut by satin spar veins in both the scarp and the Bir Karawein areas. According to Shearman et al. (1972), hydraulic overpressure jacks-up the rock sequence to form this kind of veins. Then, the satin spar precipitates as fracture fillings. The calcium and sulfate ions have typically been interpreted to de-rive from the host rock by diffusion, or from overlying and/or underlying evaporite deposits. In the Farafra Depression satin spar crystals consist mainly of anhydrite, which is a mineral rarely found in these types of veins. The anhydrite can either be a primary precipitate (Machel, 1985) or a replacement of gypsum in fractures (Kendall, 1975).

4.2. Upper Unit (siliciclastic–carbonatic)

The deposits overlying the Esna Formation consist of conglom-erates in the scarp area and a siliciclastic–carbonatic unit in the Bir

Karawein area (Fig. 9a). The latter was briefly interpreted by Wa-nas (2012) as continental in origin.

4.2.1. Paleoenvironment

Conglomerate deposits have not been previously reported in the north-eastern part of the Farafra Depression. The debris flow and channelized facies association recognized in the conglomerates are typical of proximal arid alluvial fans (Schumm, 1977). A variety of features, namely the location of the conglomerates close to the scarp, as well as the paleocurrent directions toward the west, and the composition of the clasts, mainly including marine carbon-ates and fossils (chiefly Nummulites), and sulfate satin spar veins, suggest that the source area was likely the Paleocene–Eocene rocks located in the vicinity (mostly Esna and Farafra Formations, Fig. 9b).

Despite the lack of lateral continuity between these conglomer-ates and the sandstones of the Bir Karawein section, a number of features including the clast composition, stratigraphic position (unconformably overlying the Esna Formation), their horizontal arrangement and proximal–distal facies distribution that is consis-tent with paleocurrents, suggest that the scarp conglomerates can be correlated stratigraphically with the siliciclastic–carbonatic deposits of the Bir Karawein area (Fig. 9b). Accordingly, we inter-pret that the deposits in the two study areas were part of a sedi-mentary proximal–distal alluvial system draining to the west for tens of kilometres (Fig. 9b). The limestones associated to the silic-iclastic deposits would represent the distal facies in a closed lake basin. Limestones contain fresh-water biota with abundant charo-phytes, ostracods, and molluscs. The limestones display horizons with root traces, which is indicative of subaerial exposure in the marginal lacustrine (‘palustrine’) fringe (Wright et al., 1997; Alon-so-Zarza and Wright, 2010). Silica precipitation could be microbial-ly-mediated when water evaporates from plants (Bustillo, 2010) in the root tubes and the associated pores. Pervasive laminar fenestral porosity found at the base of the carbonate beds (Fig. 6) is typically attributed to the rotting of microbial material in microbial mats (Adams and Mackenzie, 1998) that presumably developed in the marginal areas of the lake.

4.2.2. Evolution

During the Miocene, the Farafra area was an inner depression that was not hydrologically linked to the major stream systems (Goudie, 2005). The overall vertical evolution of the continental succession from alluvial to fresh water lake deposits is consistent with a base-level rise in an endorheic basin controlled by climatic and/or tectonic factors. A similar sedimentary sequence composed of basal sandstone deposits evolving upward into lacustrine lime-stone deposits containing freshwater biota was described by Said (1962, p. 287) in the West of Farafra Depression as Minqar El Talh Fm. In addition, El-Ris Formation defined by Khalifa et al. (2003) in the upper part of the stratigraphic succession in the center of the Bahariya Depression (Fig. 1) shows a similar sedimentary evolu-tion. Wanas et al. (2009) and Pickford et al. (2010) attributed the lake expansion in the Bahariya Depression to the implementation of a humid climatic regime in the area during the Miocene and, specifically, during the continental Vallesian stage.

After the deposition of the continental Upper Unit, the study area was fractured and separated into two morphosedimentary do-mains (Figs. 2 and 9b). The almost N–S orientation of the faults is coincident with the Dead Sea fault system that has been active in the area since the Miocene (El-Motaal and Kusky, 2003).

Our overall results, concerning the fracturation pattern, the provenance of clastic deposits (mainly marine Paleocene and Eo-cene rocks), and the sedimentary and diagenetic features, suggest that the continental sedimentary deposits were probably accumu-lated during the Oligocene–Miocene interval.

5. Conclusions

The use of satellite imagery as a complementary tool is shown to be specially useful to delimitate formations, morphostructures, and to correlate sedimentary units in sand deserts as the Farafra Depression.

New evidence concerning sedimentologic, tectonic, paleonto-logic and stratigraphic data, suggests that an alluvial fan-lake sed-imentary complex developed in the Farafra Depression throughout portions of the Oligocene and the Miocene. During that time inter-val, the alluvial system evolved into a lake depositional system. This stage was more widely developed than previously thought as it is further recorded in western Farafra and in the adjacent Bahariya Depression.

The continental succession overlies the differentially-eroded Esna Formation. The horizons of seismite structures found in the Esna Formation give evidence for syndepositional tectonic activity during the deposition of the formation. In addition, the occurrence of evaporites in the lower deposits of the Esna Formation provides evidence of a drop in the relative sea level.

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