An Overview of the Phanerozoic Geology in Egypt

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Abstract

Egypt is located in northeastern portion of Africa and extends into the Asian near East. It is susceptible to many local and global tectonic events with sea-level changes during deposition of the Phanerozoic sediments. The Paleozoic history of Egypt showed that the sediments were meagerly comparing with the Mesozoic and Cenozoic. The most important structures which had a great effect on the stratigraphy of Egypt stretched from the northern shores of Egypt to its extreme southern part. The controlling factor in the development and distribution of the Paleozoic is rolled by several high arcs which stretch from south to north, irregularity with Pre-Cambrian and Paleozoic plumes (541–431 ± 20–30 Ma). Important glaciation sediments were recorded during the infra-Cambrian of the Hammamat sediments and Late Ordovician–Early Silurian Gabgaba Formation at southeast Egypt and Al Gilf Kebir which stretching from the northwestern part of Africa to the Arabian Plate. The Mesozoic deposits in Egypt are very unequally distributed. Marine Triassic is only known from the Arif El Naga dome in northeast Sinai, where continental Triassic covers more areas in Egypt. Marine Jurassic deposits were recorded from the north and northeast Sinai as well as from the western side of the Gulf of Suez. The best and most complete section of the Jurassic is exposed at Gebel Maghara North Sinai. On the other hand, Jurassic fluvio-marine and fluviatile sections were mapped from the southern parts of the country as far as lat. 23° 30′ N. Subsurface marine and continental sequences were identified in the subsurface of the north Western Desert. The transition from Jurassic to Cretaceous history was marked by a major and widespread hiatus in Egypt due to Cimmerian Event. Cretaceous deposits are widely distributed on the surface and subsurface covering about 40% of the total area of Egypt extending from north Sinai to the Egyptian–Sudanese border. Remarkable facies and thickness variations are noted in Egypt. Where Egypt was covered by a thin blanket of Mesozoic sediments in paleo-high areas, thick sections were deposited in trough areas in-between the arcs. The Early Cenozoic marine transgression covered most of Egypt and even penetrated inside Sudan. The history of the Cenozoic in Egypt witnessed three major events named: (1) closure of the Neo-Tethys; (2) rifting of the Gulf of Suez associated with the gradual uplift of the Red Sea Basement Mountains; and (3) Messinian Crises leading to the desiccation of the Mediterranean.

Keywords

Global events • Phanerozoic • Paleozoic arcs • Cimmerian event • Messinian crises • Neo-Tethys

1 Introduction

Africa was a part of Gondwana during the end of the Precambrian period, and the South Pole was placed just north of where the African Plate is now. The plate moved northward over and away from the South Pole throughout the Phanerozoic (Siegesmund et al., 2018). This was succeeded by a period of relative stability with the only slow rotation of the plate at about the same latitude for the past ~ 200 m.y. as neighboring plates within Gondwana dispersed (Burke et al., 2003). The end of the Pan-African orogenic events rendered present-day African Plate was positioned inside of Gondwana, bordered to the west by the South American Plate and to the east by Arabia, India, Madagascar, and Antarctica. Therefore, only regions of the African Plate that were at the boundaries of Gondwana, i.e., the far northern and far

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southern sections, are registered for subsequent orogenic events during the Phanerozoic (Bumby & Guiraud, 2005).

The evolution of African basins must be considered in view of periodic plumes rising under the African Plate and also the climate that changed with sea-level changes accompanying the northward drift of the supercontinent during the transgressions–regressions Phanerozoic cycles, which have a direct influence on basin fill. The majority of the Phanerozoic tectonism and magmatism within the African Plate can be considered to have occurred along broad lineaments, which represent the reactivation and exploitation of earlier Late Proterozoic Pan-African sutures (Merdith et al., 2017; Unrug, 1997). Several Phanerozoic magmatic events have been identified (Issawi & Gayed, 2011; Fig. 1) as postdating the Precambrian (620–570 Ma) Dokhan Volcanics in different parts of Egypt, including the Paleozoic cycle I (541–431 ± 20–30 Ma) in southwestern Egypt known as the Katherina event. The Permian–Triassic–Jurassic cycle II (216–145 ± 5–3 Ma), a rejuvenation of cycle I, has also been identified in southwestern Egypt as a circle extending eastward. Eruptions of the same age were also recorded in the Eastern Desert and Sinai. The Cretaceous cycle III (14,274 ± 3 Ma) has been identified in many parts of Egypt where new eruptions took place rejuvenating the older cycle and in new areas. Cycle IV (46–22 ± 1 Ma) occurred in the Cenozoic and has been recorded across most of Egypt, including the areas of the Cretaceous cycles.

Although the spatial distribution, the fauna, and sedimentological characteristics of the Phanerozoic deposits are well scrutinized in Egypt, their integration in the global framework and the events which prevailed before and during the Phanerozoic are lacking. One of the targets, which the present study aims at, is to fit Egypt's Phanerozoic history into a regional picture as far as the global changes in the sea level, the rifting episodes, the history of the global events, and their effect on Egypt's sedimentation sequences and the main magmatic events are concerned. As many stratigraphic sequences are adopted by different groups working on the Phanerozoic sequences, the result is a labyrinth of formational names, which confuse the younger generations who have the stamina for developing and enriching the geology of Egypt. Enough has been given on the identification of a formation and the interest in the following pages is focused on the global events, which had a great bearing on the history of the Phanerozoic geology of Egypt.

2 Paleozoic Arcs and Basins

The large number of faults that crosscut the Precambrian Shield regions of the Gondwana supercontinent in general, and Egypt in particular, is the controlling factor in the Paleozoic sedimentation.

The faults led to the uplift of several plutonic arcs that crossed Egypt in a general northeast–southwest direction and along the margins of the intracratonic basins. The larger arcs, within the covered basement rocks, dissect Egypt into several high narrow blocks and between-blocks low areas, which became sites of thick sedimentation. The Phanerozoic section accumulated conformably and unconformably in thin to thick sequences characterized by facies shifts between the highs (arcs) and lows (basins). The identification of the arcs helps in solving many of the tectonostratigraphic problems in Egypt. Many arcs dissecting Egypt into multiple highs and lows, trending generally northeast–southwest during the Pan-African and Paleozoic times, were covered by a thin blanket of Mesozoic sediments, and thick sections were deposited in trough areas between the arcs. The most important arcs in Egypt during the Paleozoic were the Umbark, Sharib–Shiba, Uweinat–Bahariya–Port Said, Tarfawi–Qena–southern Sinai, Chephren–Kom Ombo, El Nashfa–El Balliyna, Suez–Cairo–Dabàa, and Gharib–Raqaba–Taba (Fig. 2). However, intracratonic basins related to stresses within the shield are also important in Egypt; for instance, they include the many small basins within the Red Sea Mountains.

In Egypt, the Pan-African tectonics produced a geologic setting characterized by a crescent-shaped exposure of basement rock, a basin filled with sedimentary deposits, and extruded volcanics to the north and west of the outcropping basement, amounting to a total cumulative thickness assumed to be 25 km. The frequent rejuvenation of these faults was also control for local or regional tectonic evolution, with various behaviors in magmatic eruptions, delineation of the basin size coupled by rise and fall of sea-level change.

Deposits of the Precambrian–Cambrian transition are distinguished by a bedded clastic sequence, locally including a conglomerate bed and unmetamorphosed sediments except near a granitic intrusion (e.g., Gebel Umm Had in the central Eastern Desert and at Wadi Lithi in southwestern Sinai). U–Pb ages of the Hammamat Series refer to 585 ± 13 Ma (Wilde & Youssef, 2002). Deposition of the Hammamat Series occurred from braided alluvial-fan streams with some marine paleoenvironment pulses (indicated by microfossils together with the mineral chamosite) (Grothaus et al., 1979; Khalifa et al., 1988; Wilde & Youssef, 2002). The fluviatile conditions of the Hammamat end phase continued through the Cambrian. The Infracambrian Hammamat sediments are coarse-grained clastics, which could be partly coeval with the Taba Formation in Sinai west of the Gharib–Raqaba–Taba arc. The 8-m-thick Hammamat here consists of conglomerate, sandstone, and minor siltstone. The Hammamat and the feldspathic sandstone of the Araba Formation are known to be deposits overlying basement along the east and south sides of the Egyptian Basin.

Paleozoic deposition took place in intracratonic basins delineated by basement-exposing high arcs, which generally crossed Egypt in a north-northeast–south-southwest direction.

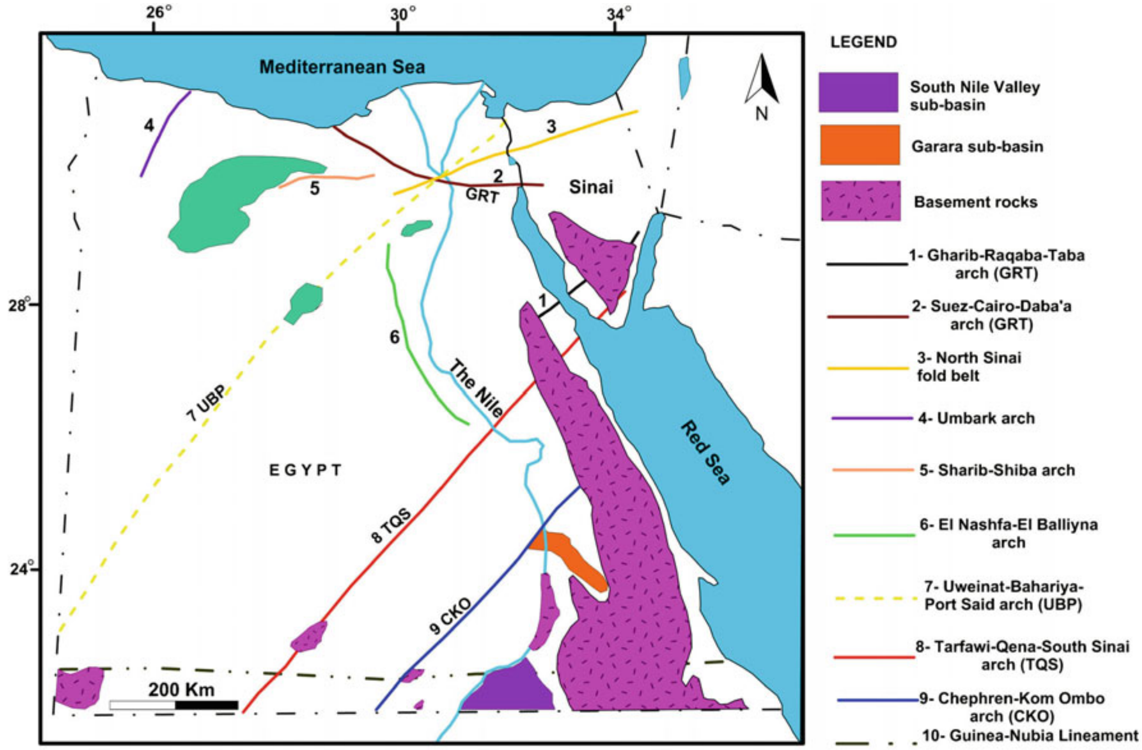

Fig. 1 Paleozoic arcs in Egypt (Issawi et al., 2009)

Sedimentation was influenced by global climate, sea-level changes, and periodic flooding by the Paleo-Tethys Ocean southward over newly assembled northern Africa. Generally, braided river deposits in the south (southern Nile and Dakhla Basins) pass into tidal and shallow-marine facies toward the north (Gulf of Suez, Sinai, and Siwa Basins) where the Paleo-Tethys Ocean had transgressed: (1) the southern Nile Basin including the Araba, Gabgaba, Naqus, Wadi Malik, and Gilf Formations; (2) the Dakhla Basin (including the Araba, Naqus, Wadi Malik, and Abu Ras Formations); (3) the Gulf of Suez Basin (including the Araba, Naqus, Rod El Hamal, Abu Darag, Aheimer, and Qiseib Formations); (4) the Sinai Basin including the Taba, Araba, Naqus, Wadi Malik, Um Bogma, Ataqa, Abu Durba, and Aheimer Formations; (5) the Siwa Basin including the Shifa, Kohla, Basur, Zeitoun, Desouqy, Dahiffan, and Safi Formations. Figure 3 shows the coeval units in different basins.

2.1 The Cambrian Deposits

In the subsurface Siwa Basin, the 300–1500-m-thick Cambrian Shifa Formation consists of heterogeneous sandstones with interbedded conglomerate, claystone, and commonly dolomitized skeletal carbonate (Keeley, 1989). The Shifa is coeval with the Araba Formation which recorded in different parts of Egypt (Fig. 3). The middle part of the Araba Formation contains *Cruziana* and *Skolithos* ichnofacies, which refer to the Cambrian (Elicki et al., 2013; Khalifa et al., 2006; Wanas, 2011).

The pediplain, which dips away from central, northeastern, and western African orogens and over which the Cambrian was deposited, started to rise during the Cambrian–Ordovician transition (Sardinian and pre-Caradoc) tectonic event (Table 1). During both times, this event was responsible for the limited accumulation of sediments and hence the many unconformities. Thick deposits are found only on the passive margin of northern Africa (Siwa Basin), with the exception of an area in the northeast part of the Egyptian Basin that was blocked by the Turkish Plate. For this reason, the Lower Paleozoic pedimentation in this part of the Egyptian Basin was quite limited.

2.2 The Ordovician Deposits

The low sea level during the Early Ordovician coupled with a general uplift of Egypt along the arcs generally reflected the Taconic movement in northern Africa (Table 1). Ordovician marine sediments are almost totally absent, although they are found on both sides of Egypt as well as in Libya and Saudi Arabia. The Taconic movement was well recorded in Wadi Gabgaba, where the tilting of the Cambrian Araba Formation is as described in southwestern Libya (in the Uweinat area); in

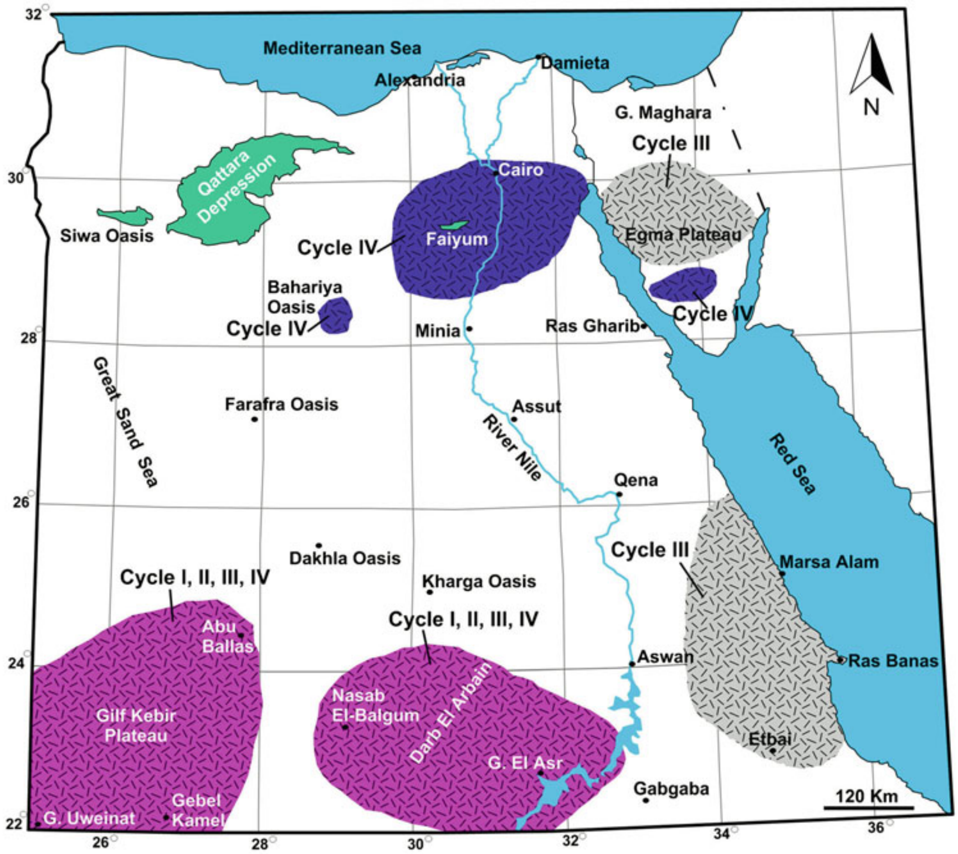

Fig. 2 Anogenic and orogenic plumes in Egypt (Issawi & Gayed, 2011)

the Gilf Kebir in Egypt, two faults bound its scarp on the west side (Issawi et al., 2009). By the Late Ordovician, Gondwana had drifted northward over the South Pole, which was then located in an interior position in what is now northwestern Africa. Late Ordovician glacial deposits (sandstone and tillite) are thus widespread through northern Africa. By correlation with similar facies in Arabian Plate (e.g., Saudi Arabia, Jordan, Iraq), a fluvioglacial mode of deposition is substantiated for the Naqus Formation in Egypt. The Naqus Formation lies unconformably on top of the Araba Formation separated by a paleosol layer. A fluvioglacial origin of the Naqus Formation depends largely on the presence of dropstones or erratic pebbles (Issawi et al., 2009).

The fissures, cracks, and faults in the Gabgaba area led to degradation and deepening of the wadis at the base of the Archean igneous and metamorphic units in the hills bordering the east side of the wadis. These paleovalleys later were the sites of deposition of the Gabgaba Formation, glaciogene conglomerates that resulted from the Ordovician glaciation (Issawi, 2000). The next phase in the glaciation history was the complete melting of the ice and the deposition of the Naqus Formation during the Early Silurian. Glaciogene diamictite deposits are common in many parts of Egypt extending from Sinai through Wadi El Dakhl in the northern Eastern Desert to Wadi Gabgaba in the southern Eastern Desert to Gilf Kebir in the southern Western Desert. Issawi's (2005) detailed study of Gabgaba geology revealed four glacial phases and four interglacial paleosol layers. The Ordovician unit in the Siwa Basin is the 80–600-m-thick Kohla Formation, which consists of fluvioglacial tidal-flat sandstone and mudstone deposits.

2.3 The Devonian–Silurian Deposits

The Late Caledonian uplifts during the Early Devonian were accompanied by the continuous regression of the sea and by progradation of braided plains over large areas in southern Egypt. The Late and Early Devonian registered a brief marine transgression during the Emsian with the deposition of the ~ 750-m-thick Zeitoun Formation as shallow-marine sandstone and offshore marine mudstone all along the northern Africa platforms (Carr, 2002) and conglomerate in the Siwa Basin. In southern Egypt, erosion of the high land as a result of the Caledonian movement resulted into significant thinning of the outcropping clastic parts of the Devonian Wadi Malik Formation (80–100 m) in the Dakhla Basin near the west side of the Gilf Kebir; in Sinai, the Wadi

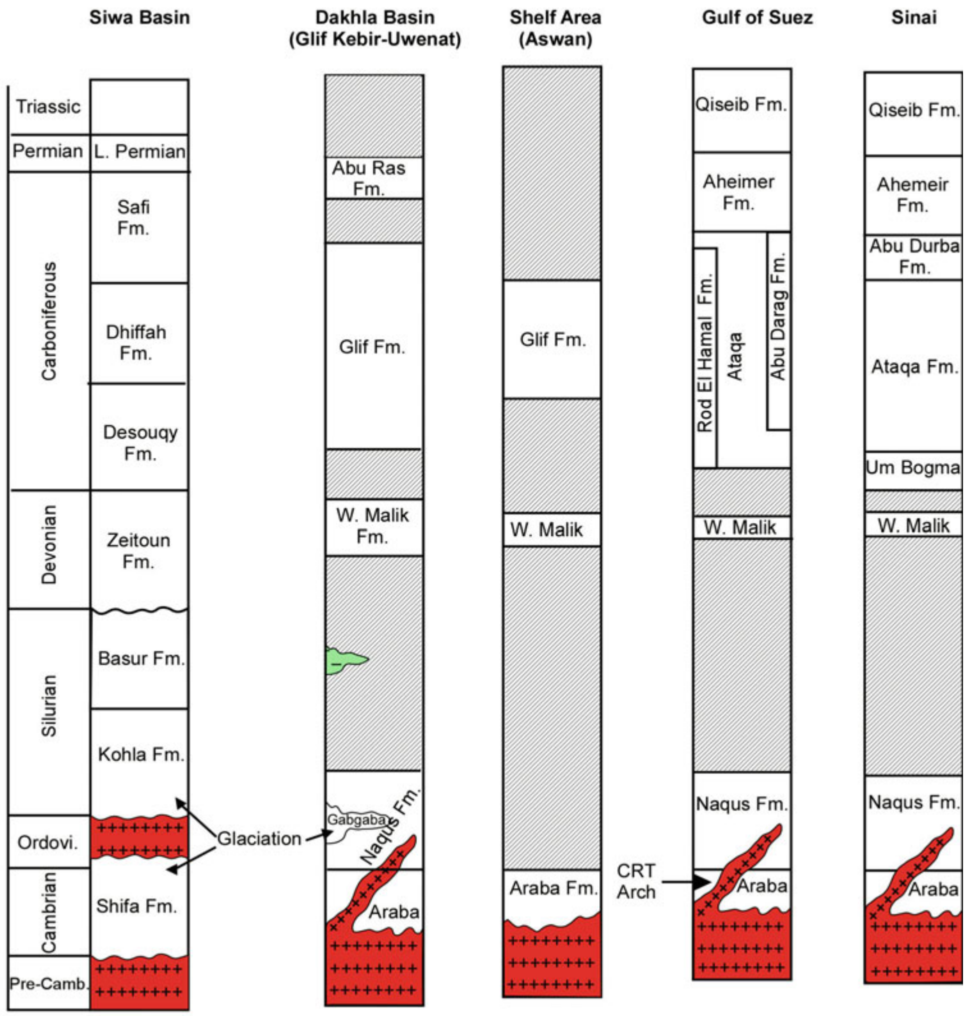

Fig. 3 Paleozoic rock units in Egypt

Malik section is only 15 m thick and consists of sandstone. Devonian rocks are also of record in eastern Aswan at Wadi Abu Agag, in southeastern Aswan at Wadi Gabgaba, and in southwestern Aswan at Um Shagir Hill. On the basis of subsurface data from both the Hurghada oilfield and the Zaafrana drillhole, Devonian sediments are likely extend below the confirmed Carboniferous section.

In Wadi Gabgaba, Late Ordovician Gabgaba conglomerates and the Naqus Formation were tilted 10–35, indicating a second uplift reflecting the Erian phase of the Caledonian orogeny. The Devonian sediments were again tilted in response to the Late Devonian–Early Carboniferous uplift known as the Bretonian or Late Acadian movement representing the first phase of the Hercynian orogeny. Block tilting of the Carboniferous sediments, domal uplift, and folding are clearly evident in the Lower Paleozoic sediments in Sinai, in the Wadi Gabgaba area, and in the Gilf–Uweinat stretch. Minor deformation in northern Africa strata in the Late Devonian (the Bretonian event) is associated with the initial northward subduction of the Paleo-Tethys.

During the Late Silurian, the deposition of the 400–700-m-thick Basur Formation (sandstone, minor interbedded siltstone, and conglomerate) occurred in the Siwa Basin (Issawi et al., 2009; Keeley, 1989; Fig. 3). The Silurian hot shale rich in organic matter provided good sources for the petroleum systems adjacent to Egypt—the Libya–Algeria basins to the west and the Arabian basins to the east. Because the Turkish Plate dammed the northern shores, no rich organic matter of marine origin comparable to that in the surrounding countries has been found in Egypt.

2.4 The Carboniferous–Permian Deposits

The Early Carboniferous witnessed globally high sea levels and warm temperatures with the sea invading northern Africa over the pre-Carboniferous deformed surface. Although deformation led to the inversion of the Siwa Basin, in other parts of this basin, thick deposits of sediments accumulated, thereby forming the 100–300-m-thick Tournaisian–Early

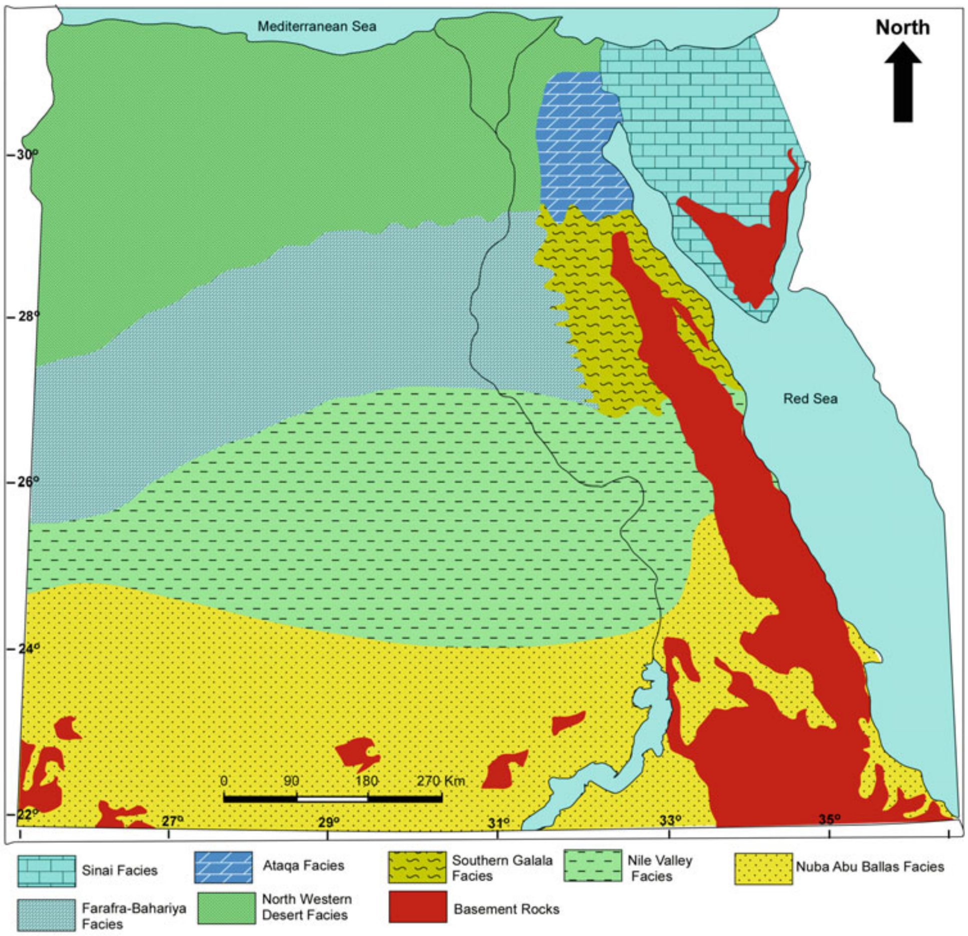

Fig. 4 Different cretaceous facies in Egypt (after Issawi et al., 2009)

Visean Desouqy Formation (bedded sandstone with minor intercalated siltstone). To the south, in the Uweinat–Gilf Kebir stretch, the Gilf Formation unconformably overlies older Paleozoic units in an area stretching from the southern Western Desert to the high basement rocks of the present Red Sea Hills.

In Sinai, the area north of Gharib–Raqaba–Taba received a thick succession of Carboniferous deposits including the Um Bogma and the Abu Durba Formations, mainly clastics and minor carbonates that host the well-known manganese–iron ore deposit. South of the arc, the inversion of the basin during post-Naqus Formation time continued in response to the Hercynian–Variscan orogeny. The Hercynian orogeny, which dates back to 350–280 Ma (Early Carboniferous–Early Permian) (Coward & Ries, 2003), was responsible for intraplate deformation throughout the entire Sahara platform (Haddoum et al., 2001), often by reactivation along the Pan-African suture zones such as the northeast–southwest-trending arcs crossing Egyptian basins. All these features involve Paleozoic sediments, but most of the Mesozoic units (Triassic and Jurassic) are missing or are represented by continental lithofacies.

Sea-level oscillation in the Late Carboniferous was associated with the early stages in the opening of the central Atlantic Ocean and resulted in lithofacies changes varying from shallow to deep marine in northern Egypt. The many unconformities within the Carboniferous marine section were due to these transgression–regression phases as well as the many deformations resulting from the Westphalian–Stephanian Asturian event of the Variscan orogeny and generally may have been synchronous with or may have postdated a rapid cooling phase in the global climate, which reached its maximum during the Late Carboniferous–Early Permian glaciation (Klitzsch, 1983). At the time, most of Egypt was paleo-highs except probably its northern part, where the Aheimer Formation formed. Inland, the 30–40-m-thick Abu Ras Formation (conglomerate) unconformably overlies the Carboniferous Gilf Formation. Both the Aheimer and the Abu Ras Formations are considered to be Upper Carboniferous to Permian (Kora, 1998).

The progressive fragmentation of Gondwana began during the Late Carboniferous–Early Permian and continued through the Early–Middle Mesozoic. In the first stage of rifting, consequent escape structures resulting from

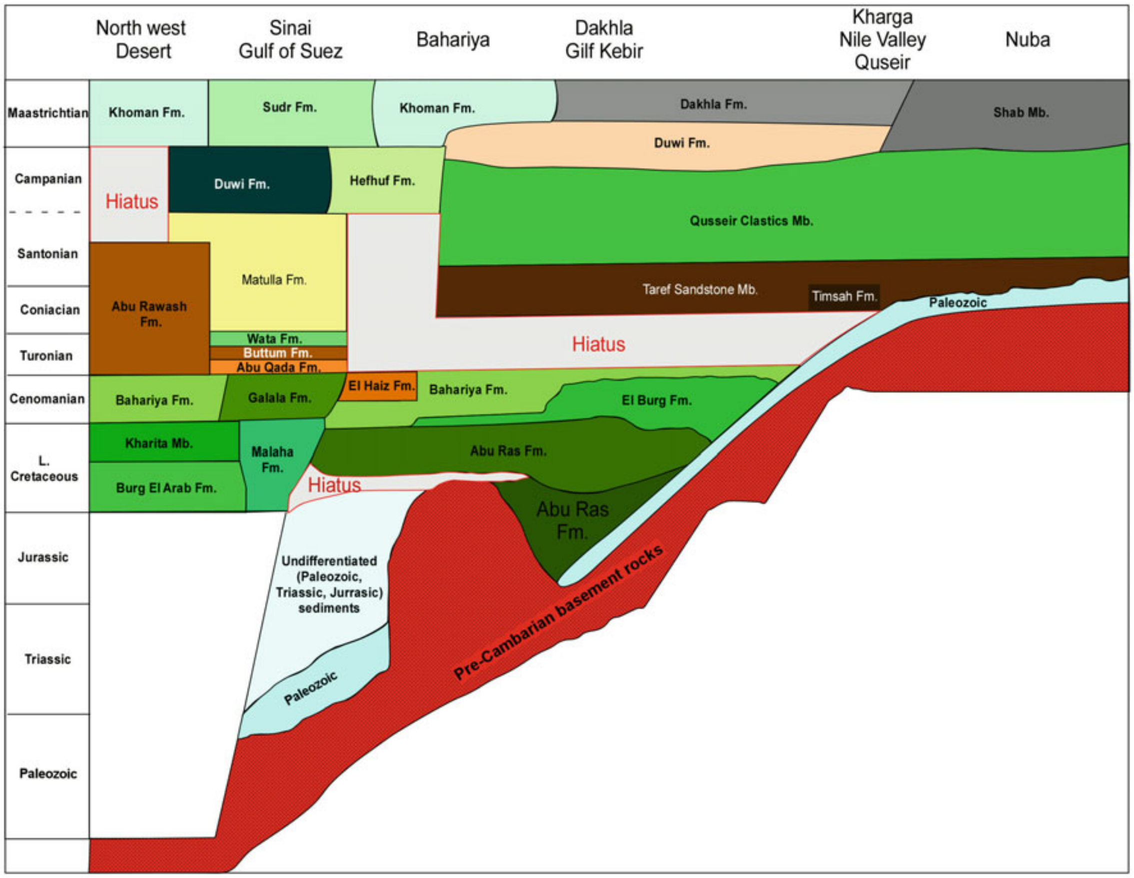

Fig. 5 Cross sections and distribution of Cretaceous rock units in Egypt (after Issawi et al., 2009)

fragmentation processes (or vice versa), the northern and eastern margins of Africa, were greatly affected.

2.5 The Permian / Triassic Transition

The northern margin of Africa changed from being a convergent margin associated with the closure of the Paleo-Tethys Ocean to a passive margin during the Permian and Triassic, as the Neo-Tethys began to open (Wilson et al., 1998). Rifting occurred by reactivation of Hercynian faults under a purely extensional regime along the passive margin (Pique et al., 2002). Large-scale transcurrent fault zones, such as the Newfoundland-Azores-Gibraltar and Guinea-Nubia fracture zones, which acted as northern and southern transform faults, respectively, enclosing the central Atlantic during crustal separation, allowed for the opening of the central Atlantic (Bumby & Guiraud, 2005). The clockwise rotation of Africa (Fairhead et al., 2013) during the process of separation of South America from Africa led to the positioning of the southern rift of the northern fracture zone to be in northern Africa. The zone includes the Syrian Arc System and associated structures, such as along the northern Egypt fracture zone (Issawi et al., 2009) between Taba (on the north end of the Gulf of Aqaba) and Suez and through Cairo to the Mediterranean. Farther west, the presence of sinistral strike–slip faulting and associated flower structures in parts of the Atlantic trough attests to this transgressive movement (Pique et al., 2002). However, the passive margin of Egypt's African Plate seems to have not been much affected by the suturing phase of the plates, and the Triassic heralded the onset of thick Jurassic and Cretaceous sediments in the northern Egyptian Basin, together with subsidence that affected the eastern Mediterranean margin in conjunction with the opening of the Neo-Tethys (Stampfli & Boreal, 2002).

2.6 The Triassic Deposits

The Triassic section at Arif El Naga (northeastern Sinai) comprises the 50-m-thick basal Anisian Qiseib Formation (fine- and coarse-grained clastics), which is overlain successively by the 19-m-thick Anisian Arif El Naga Formation (lumachels in a gypseous or marly matrix) and the 50-m-thick Ladinian–Carnian Abu Nusra Formation (fossiliferous massive limestone and dolomite with interbedded

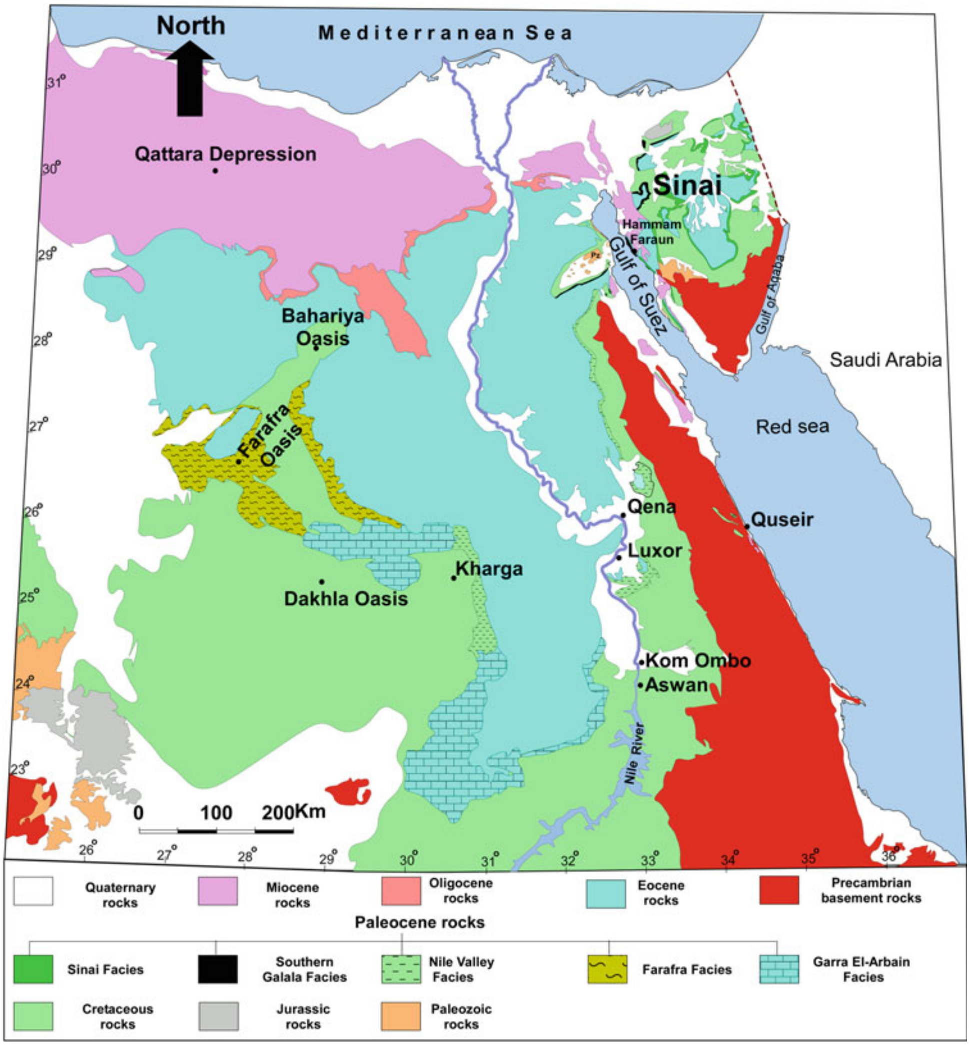

Fig. 6 Paleocene facies distribution in Egypt (Farouk, 2016)

gypseous clay and marl). The marine Triassic sediments are known from most wells drilled in northern Sinai between Arif El Naga and the Gulf of Suez, whereas continental conditions prevailed in the high area south of Lat 30°N in both the Eastern Desert and Sinai.

In the northern Western Desert, the subsurface sandstones above the Carboniferous and below the Jurassic might belong to both the Permian and the Triassic, while in the southern Western Desert, the 50-m-thick Abu Ras Formation (sandstone, shale, and grit) is thought to be of Triassic age. Volcanic activity peaked at $\sim$ 200 Ma (Guiraud, 1998), which is near the Triassic–Jurassic contact, when extensive alkaline basalt flows were emplaced in northern and central Africa and in the Levant, preceding the separation between northern Africa and Europe (Table 1).

2.7 The Triassic–Jurassic Transition

A major unconformity representing the Triassic–Jurassic transition is known from the Egyptian successions and in Sinai is marked by a gypseous clay and conglomerate horizon at the top of the Triassic section. The hiatus followed the rifting and basin-development episode, which was terminated by volcanic eruptions. Tectonic instability had increased from Middle Triassic time and was underscored by block tilting and local uplifts along the Africa–Arabia Neo-Tethys margins, as reported by frequent unconformities and hiatus in the Triassic–Jurassic sediments and also by the complete lack of Triassic marine deposition apart from the Arif El Naga area. These deformations represent the distal effect of the Eo-Cimmerian orogenic event.

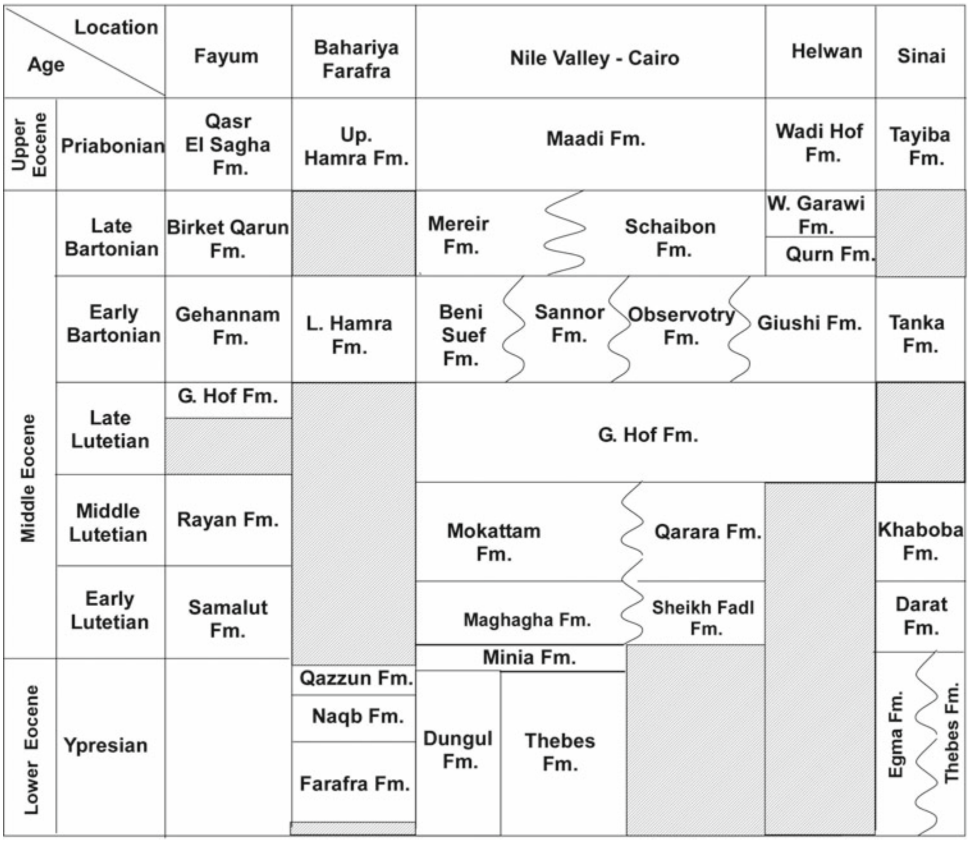

Fig. 7 Distribution of eocene rock units in Egypt

2.8 The Jurassic Deposits

In northern Sinai, Jurassic sediments attained a thickness of > 1800 m through three marine and three continental sedimentary-facies cycles, each of which incorporated a minor cycle of the other facies (Al-Far, 1966). The Gebel Maghara Facies characterize the sediments into three marine and three continental cycles. Each cycle carried a minor second-order cycle, and thus, the marine cycle has a minor representation of the continental facies vice versa. The Gebel Maghara Facies started at base with the continental Mashaba Formation followed by the Marine Rajabiah, Continental Shusha, marine Bir Maghara, continental Safa, and marine Masajid Formation at top. Though the Safa Formation includes coal beds, it is hard to apply the term cyclotheming to the whole section; it may be referred to as "poor cyclotheming."

However, in Khashm El Galala exposed section on the west side of the Gulf of Suez has the same Gebel Maghara units but is much reduced in thickness (220 m). The line along which the Gebel Maghara Sinai Facies changes to Khashm Facies is now the Gulf of Suez. The continual sinking of Sinai and rising of Khashm during the Jurassic led to the initiation of the Gulf of Suez.

Guiraud et al.'s (2005) interpretation of the geodynamic events during the Jurassic does not fit with field observations. We do not concur with a high sea level in the Late Kimmeridgian, the reduced intracontinental fluviatile–lacustrine basins, and the development of the alkaline anorogenic intrusions in Nubia. The Kimmeridgian Masajid Formation is a shallow-marine unit, both in the subsurface of the Western Desert (Hantar, 1990) and in the Gebel Maghara section (Al-Far, 1966); the Dakhla Basin is distinguished by its fluviatile and shallow-marine Jurassic sediments (Issawi et al., 2009); and the Jurassic intrusive rocks in Nubia, southern Egypt, are of minor importance relative to the Oligocene volcanics extending from west of the Nile to Gilf–Uweinat in the far west.

The subsurface Jurassic sediments in the northern Western Desert are assumed to be as thick as 1524–1828 m, but they average 600 m farther south; in the Dakhla and Kom Ombo Basins, the Jurassic comprises mainly clastics, as proven by drilling in the western Kom Ombo area. The Late Jurassic–Early Cretaceous Abu Ballas Formation is exposed in the Dakhla Basin as a 20–53-m-thick unit of sandstone and clay. The sandstone in Kharga Oasis was described in part by palynological studies of drill core. Also, palynology

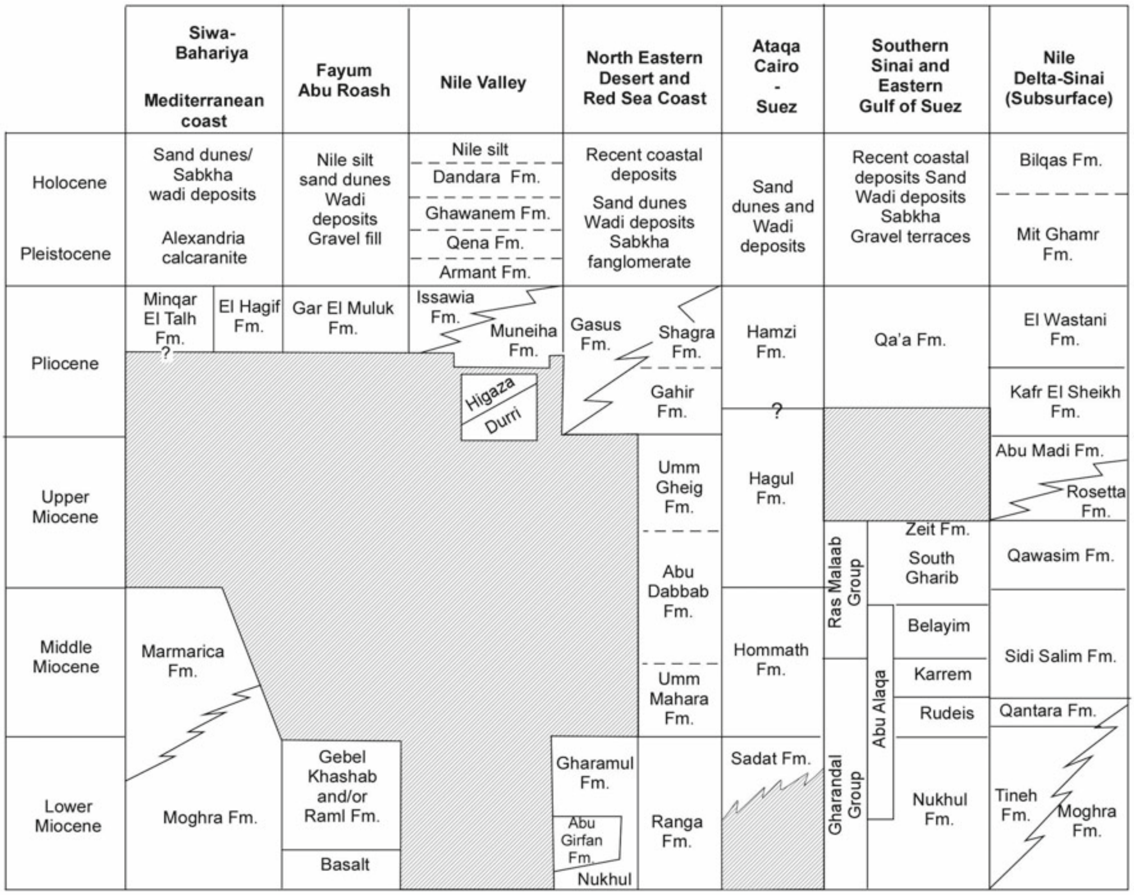

Fig. 8 Distribution of the Neogene rock units in Egypt

studies of the sandstones in Foram-1 and Ammonite-1 wells in the west-central Western Desert revealed 273 m and 105 m thicknesses, respectively (Schrank, 1987). A Jurassic 120-m-thick marine-sediments section, composed of interfingering limestones and sandstones, was cored in the Nile Delta (Schlumberger, 1984).

2.9 The Jurassic–Cretaceous Transition

Within many basins in north, west, and central Africa, the Jurassic–Cretaceous transition exhibits hiatuses and unconformities associated with Late Tithonian sharp drop in sea level and also with uplift, block tilting, and slight folding caused by local transpression from the tectonic Cimmerian event near the end of the Late Jurassic that has been throughout much of the Middle East (Fourcade et al., 1993). These deformations represent the distal effect of strong tectonic activity, including thrusting that occurred in southeastern Europe, known as the mid-Berriasian orogenic event (Nikishin et al., 1998). Stresses during these events caused many rift stages in eastern and northern Africa margins and in the eastern Mediterranean in general, with many east–west-trending rifts, especially along the northern margins of Egypt. These rifts' depocenters in the main Egyptian Basin became wider and larger, ready to be covered by Cretaceous seas and thick Cretaceous deposits. The Jurassic–Cretaceous transition was marked by a major and widespread hiatus in Egypt. The top beds of the Masajid Formation in the Gebel Maghara Facies belong to the Barthonian–Kimmeridgian, whereas the overlying Malha Formation is commonly dated as Aptian–Albian; the topmost Jurassic (Tithonian) and the basal Cretaceous (Berriasian to Barremian) are missing in most of the sections analyzed. However, Aboul Ela et al. (1989–1991) identified 25 species of pollen and spores from the kaolin bands within the Malha Formation from the west side of the Gulf of Suez, which relegates the lower part of this unit to the Barremian or possibly older.

The buildup of many domes along the Syrian Arc belt started by rifting and initiation of the basins in northern Egypt in general, during the Triassic–Lias associated with the widening of the Neo-Tethys. The main structural configuration of this belt developed in the Late Jurassic through the Cimmerian event and continued intermittently during the Cretaceous, reaching its acme during the Santonian.

In southern Egypt, the opening of the Indian Ocean around the Horn of Africa happened ~ 156 Ma (Middle–Late Oxfordian) (Rabinowitz et al., 1983), and most probably, the resulting escape structures mobilized to southern Egypt intracratonic basins, which have different orientations: northwest–southeast (Garara and Kom Ombo Basins) and northeast–southwest (southern Nile and Dakhla Basins). Among the structural features that are considered to be more important in the geologic history of Egypt are the widening of the Gulf of Suez, the renewable uplift of the Pan-African arcs that generally trend northeast–southwest, and the northwestward movement of the Arabia–Nubia block. This second stage of Late Jurassic–Early Cretaceous rifting followed a Late Carboniferous–Middle Jurassic initial stage of rifting and strongly affected the development of Karoo Basin, which stretches from southern Africa to Kenya–Somalia and Ethiopia in the north (Bumby & Guiraud, 2005). The first stage of rifting was the initial movement stage in the breakup of Gondwana at ~ 180 Ma, which separated West Gondwana (Africa, Arabia, and South America) from East Gondwana (India, Madagascar, Antarctica, Australia, and New Zealand). Both of these rifting phases and a third Late Eocene–Early Miocene rifting phase resulted in the gradual breakup of Gondwana, the beginning of the opening of the Neo-Tethys, basin development on this supercontinent, and the activation of Pan-African sutures and arcs. Because these events corresponded to a general sea-level rise and fall, both widespread marine-sediment accumulation through transgressions and accumulation hiatuses occurred within the basins. These effects were most important on the high arcs in the Egyptian Basin. During the Jurassic–Cretaceous within the African Plate, superimposed on the main regime of extensional tectonics were compressional events believed to have been linked to a change in the spreading direction and rate within the Indian and Atlantic Oceans.

3 The Cretaceous Deposits

A bird's eye view over Egypt makes it possible to identify the following seven facies: (1) Sinai (including Aptian–Albian Malha, Cenomanian Galala, Lower Turonian Abu Qada, Middle Turonian Buttum, Middle to Lower Turonian Wata, Coniacian–Santonian Matulla, Campanian Duwi, Early Maastrichtian Qadiera, and Maastrichtian Sudr Formations); (2) Ataqa (including Malha, Galala, Turonian Maghra El Hadida, Santonian-Campanian Adabiya, and Maghra El Bahari Formations); (3) Southern Galala (Malha, Galala, Abu Qada, Wata, Matulla, Southern Galala, and Sudr Formations); (4) Nile Valley (including Nubia Formation, Taref Sandstone Member, Qusseir Clastic Member, Duwi, and Dakhla Formations); (5) Nuba Abu Ballas (including Abu Ballas, Burg, Timsah, Taref Sandstone, Qusseir Clastic, and Shab Members); (6) Farafra–Bahariya (including Bahariya, Heiz, Hefhuf Formations, and Khoman Chalk); and (7) subsurface northern Western Desert Facies (including: Burg El Arab Formation, Alam El Bueb Clastic, Alamein Dolomite, Dahab Shale, Kharita Clastic Members, Bahariya, Abu Roash, and Khoman Chalk). Each of these facies is further classified into several rock units, and some of the units cross over to another facies type. The differentiation between the facies is controlled by the surface of depositional basins, the degree of marine flooding, and structural deformation before and during deposition. Figures 4 and 5 show the coeval units in different basins.

Marine incursions covered northern Egypt depositing sediment units that vary by lithology and thickness. Transgression reached southern Egypt in the Dakhla Basin and in extreme southeastern Egypt (Abraq), where the Abu Ballas Formation is found and is assumed to be in the subsurface of the Garara Basin. Deposition of this unit took place as a reflection of the Middle to Late Aptian and Albian dextral-transform movement along the Equatorial Atlantic fractural system (Gulf of Guinea). The escape structures of this movement led to widening (resulting in pull-apart basins) and subsiding of subbasins within the Egyptian Basin, and the movement certainly was accelerated by the constant opening of the Indian Ocean.

The final separation between Africa and South America occurred during 105–100 Ma (Albian–Cenomanian), although the Atlantic was completely opened in the Santonian (Nurnberg & Muller, 1991; Jolivet et al., 2016), coinciding with the closure of the Neo-Tethys. These movements resulted in seafloor spreading in western Africa and in intracratonic basins, the Cenomanian high sea-level stand, and the establishment of a marine connection between the Neo-Tethys and the Gulf of Guinea (Atlantic Ocean). Because the Cenomanian sea-level rise covered all of Egypt, Cenomanian marine beds are known from the southern Aswan Abu Rawash near Cairo. Over the high arcs, the Cenomanian is poorly represented or partly absent, but the high seawater masked all the structures in the Egyptian Basin. The widespread Cenomanian over Africa is an expression of the Cretaceous Normal Magnetic Quiet Zone recorded worldwide that was initiated at ~ 120 Ma (Early Aptian) and ended at 83.5 ± 0.5 Ma (latest Santonian) (Ziegler, 1990, 1992). The Turonian events that are by far the most active in Cretaceous time occurred during the closure of the Neo-Tethys, although it probably was initiated during the Cenomanian (Guiraud et al., 2005; Issawi et al., 2009). The huge volcano mountain in southeastern Egypt, the presence of a 15-m-thick gypsum section of Buttum Formation, the Turonian section in Sinai, the northward retreat of the Turonian shoreline from the Cenomanian shoreline (~ 400 km between 22° 30′ N and 26° 30' N), and the closure of the trans-African seaway connecting the

Tethys with the Atlantic are among the important events characterizing this stage.

This rather-uneventful period was interrupted by the development of two major regional unconformities, one of them Albian–Cenomanian and the other Turonian. The duration of these hiatuses, maturation of the paleokarst features, and the presence of kaolin both in western Sinai and on the west side of the Gulf of Suez (northwest of Zaafarana) point to exposure that was not just brief or transient. Thus, unconformities were tectonically rather than eustatically controlled (Farouk, 2015; Farouk et al., 2017).

In Egypt, the Cenomanian sediments are mostly clay and limestone, but sandstone and clay with rare carbonate (increasing northward) are found in the area south of 26°N. In Gebel Halal, the Cenomanian consists of a 350-m-thick limestone. Shallowing conditions of deposition dominated during the Turonian, but generally the sediments are shales and marls in Sinai with gypsum in the middle and carbonate at the top. The Turonian is missing south of Qena and farther west, in Farafra and Bahariya Facies. Accessed by drilling, the subsurface of the Western Desert was found to include an 1800–1900-m-thick Turonian–Senonian section of fine-grained clastics and clean carbonates.

The Coniacian, which is not well defined in Egyptian stratigraphy, consists mostly of sandstone of the Nubia Formation in the southern and middle latitudes of Egypt. Mountains in southeastern Egypt provided felsic-volcanic source rock for this unit; the volcanogenic sediments were brought to the basins by rivers mostly flowing from these high mountains toward the north, east, and west in a centripetal drainage system. The Nubia Formation is divided into the Taref Sandstone Member at the base (~ 80–150 m thick; Coniacian–Santonian), the Qusseir Clastic Member in the middle, and the 54-m-thick Shab Clastic Member. Found only in extreme southwestern Egypt, the Shab is coeval with the Maastrichtian–Early Paleocene Dakhla Shale in the north. In the Farafra–Bahariya Facies, the Campanian is represented by 120-m-thick Hefhuf Formation (dolomitic limestone at the top and base and argillaceous sandstone in the middle). Turonian–Santonian strata are missing in these facies.

The most important unit in the Late Cretaceous is the Upper Campanian Duwi Formation as it includes Egypt's economically viable phosphate beds, extending from the Red Sea (Safaga–Qusseir) through the Nile Valley (Qena to Edfu) and farther west within the Kharga–Dakhla stretch up to the Libyan–Egyptian border through the Sand Sea (Ahmad et al., 2014). The phosphate horizon in southern Egypt forms the south boundary of the Upper Cretaceous marine sedimentary units in the north and the north boundary of the Upper Cretaceous continental sedimentary units in the south.

The Santonian events are clearly reflected in the inversion of the Syrian Arc basins forming many domes in northern Sinai through constant rifting and drifting, uplift, gliding of the mostly Cenomanian upper carbonate units, and steeply tilting the half domes (Issawi et al., 2009). Dipping of the Santonian Matulla Formation together with the angular unconformity between the Matulla and the overlying Duwi and Sudr Formations is proof of the Santonian inversion of these features.

The Africa–Arabian Plate's strong rotation in an anticlockwise direction resulted in collision with the Eurasian Plate (Reilinger & McClusky, 2011). The collision is expressed in northern Egypt by increased faulting and accentuation of the old structures on the surface or in the subsurface of the northern Western Desert. The activated northeast–southwest arcs in the Egyptian Basin exhibit well-defined courses, especially in Bahariya Oasis, where the Cenomanian Bahariya and Heiz Formations are steeply tilted with an angular unconformity. The overlying units (Turonian, Coniacian, and Santonian sediments) are not present in the Bahariya Oasis. In the Eastern Desert, the Santonian is missing in Gebel Shabrawet and in most of Gebels Ataqa and Northern Galala but is found in Southern Galala (Farouk, 2015). Active block movements started before the Santonian and became more pronounced with time until the Middle Miocene opening of the Red Sea.

The Campanian transgression reached south–southwestern Aswan, where the Duwi Formation (a clastic phosphate–carbonate unit) was deposited; the Duwi gradually reflects deeper marine conditions northward and is part of the Southern Galala and Sinai Facies. Also representing the Campanian transgression is the Hefhuf Formation in Bahariya. The shallow conditions prevailing over much of the Egyptian basins, associated with tranquil tectonic events, gave way to more marine transgression during the Early Maastrichtian, when the basal part of the Dakhla Formation was deposited as far south as Lat 23° N and northward in Sinai; it is also found at the surface and in subsurface sections of the northeastern and northern western deserts. The Maastrichtian Dakhla Shale is well exposed above the Duwi Formation east and west of the Nile, along the Sin El Kaddab scarp, through Darb El Arbain to the Kharga–Dakhla oases and Lat 26° 45′ N (Hatyet El Sheikh Marzouk south of Farafra Oasis but gradually changing to Khoman Chalk to the north). In the northern Western Desert, the chalk reaches a considerable thickness (1814 m), as observed in the Betty well and in many oil wells in the northern Egyptian basins. Issawi and Osman (2002) consider the Farafra Oasis latitude to be a boundary between platform (Dakhla Shales) and ramp (Khoman Chalk) environments of deposition. Such platform–ramp conditions extended eastward to where, in the southern Galala Facies, deeper conditions of deposition prevailed during the Maastrichtian and the ~ 88-m-thick Sudr Chalk (chalky limestone) formed, and in the Ataqa Facies, because block faulting caused a disturbance in the depositional regime in the north, the 80-m-thick Maastrichtian Maghra El Bahari Formation (sandstone, marl, limestone, and conglomerate). The high sea level during the Maastrichtian penetrated the high uplifted blocks in the north, thereby causing a reversal of the ramp–platform relationship.

In southern Egypt, in the Nuba–Abu Ballas Facies, the Campanian Duwi Phosphate is largely missing: It is represented only by thin fossiliferous phosphatic lenses along Darb El Arbain (Issawi et al., 2009). The Maastrichtian Dakhla is replaced by minor shale beds (Shab Clastic Member at the top of the Nubia Formation; Fig. 5). Repeated major sedimentary cycles from continental and marine facies were observed at least three times from the Late Jurassic through the Late Cretaceous in southern Egypt. Each of these cycles (as follows, from top to base) includes basal continental sediments overlain by transitional deltaic rocks and marine deposits: The Nubia Formation includes the Santonian Qusseir Clastic Member (dominantly shallow-marine to deltaic facies) and the Coniacian Taref Sandstone Member (dominantly continental facies). The Early Senonian Timsah Formation consists mainly of iron-bearing beds, clay, and sandstone of lacustrine and deltaic facies intercalated with marine sediments. The Albian–Cenomanian Burg Formation consists mainly of fluviatile and deltaic continental deposits on-lapped with sediments from marine incursions, such as the Upper Cenomanian Heiz or Maghrabi Formation (shallow-marine facies). The Lower Cenomanian Bahariya or Sabaya Formation consists of shallow-marine to continental and deltaic facies (Catuneanua et al., 2006.). The Lower Cretaceous (Aptian) Abu Ballas Formation consists of continental sediments at the base (named Six Hills Formation by the Germans), overlying Upper Jurassic shallow-marine deposits (called the Abu Ballas Formation by the Germans). The end of the Cretaceous in Egypt is marked by a retreat of the sea, with a wide unconformity representing the Cretaceous–Paleogene boundary.

4 Cenozoic

After the closure of the Neo-Tethys at the end of the Mesozoic, the Cenozoic witnessed two major events, with many structural and stratigraphic consequences: the appearance of the Red Sea in the Middle Miocene and the desiccation of the Mediterranean during the Messinian. These occurred as brief but very important events in the geologic history of Egypt, which were unequaled by any events during earlier times.

Along the northern African–Arabian Plate, the basins recorded strong subsidence through rifting during the Paleocene–Early Eocene, a continuation of the general subsidence during the Jurassic and the Cretaceous. Strong faulting and folding happened in Egypt from the Syrian Arc System in the north to the Guinea–Nubia lineament far to the south; compression collision occurred in the Zagros and the Oman Mountains in the northeast; folding happened along the Central African Rift System and the Horn of Africa in the south and southwest; and deformation occurred in northwestern Africa. The effects in Egypt manifested as a general Cretaceous–Paleogene unconformity (between the Dakhla and Kurkur conglomerates), the gradual upheaval of southern Egypt associated with block faulting (especially in the Gulf of Suez and in Sinai), and the extensive folding along the northeast-oriented arcs dissecting the Egyptian Basin.

4.1 The Paleocene–Eocene Successions

The Paleocene five age-coeval facies associations from south (shallower) to north (deeper) are: (1) Garra El Arbain; (2) the Nile Valley; (3) Farafra; (4) Galala; and (5) Sinai (Fig. 6). The Paleocene reefal Kurkur Formation in southern Egypt gave way to the more marine Tarawan Formation in the middle latitudes, overlying deep-marine facies of the Dakhla Formation, which extends from the Red Sea in the east to the Sand Sea in the west. The uneven Cretaceous surface over which the Cenozoic sediments were deposited displayed several facies varying from quiet deep marine (Nile Valley Facies) in the eastern and central parts of Egypt to reefal facies in the southern and western parts (Garra El Arbain Facies), where many Cretaceous–Lower Paleocene unconformities were recorded in the top strata.

The sea-level stand reached southern Egypt and penetrated a few hundred kilometers into Sudan during the Paleocene and Early Eocene. Deposits during these times overlie a very irregular surface caused by the above-mentioned movements; as a result, units are quite variable in thickness and are commonly missing altogether. The Paleocene is totally missing in Bahariya area in spite of the northern location (where Paleocene sediments are common), 500 km to the south (in Sin El Kaddab scarp) and 35 km north of the Egypt–Sudan border (Lat 22°N) at Bargat El Shab.

In the northern Farafra area, the Paleocene Tarawan Chalk is only 2.5 m thick, and an unconformity separates the underlying Khoman Chalk; also, the Paleocene gradually thins out toward the north Farafra Oasis owing to the effects of the Syrian Arc System (Farouk, 2015; Farouk et al., 2019). In the Red Sea area, the Paleocene transgression reached Lat 26° N, most probably owing to sea-level rise rather than structural conditions as in the Nile Valley and the Western Desert, where the sea covered more areas toward the south. The most-probable explanation relates to the beginning of the uplift of the Red Sea Mountains and the consequent westward tilting of the Egyptian basins.

In the northern Eastern Desert, many unconformities are known from the Paleocene–Lower Eocene sequence, together with lateral facies changes (Farouk, 2016). This evidence plus the idea presented earlier that the Gulf of Suez formed during the Jurassic indicates that the Red Sea and the Gulf of Suez opened from north to south. Since the Paleozoic tectonic pulses led to the uplift of the Red Sea Mountains. This area also has witnessed active block movements recorded along the Wadi Gabgaba in southwestern Egypt.

In Sinai, the Paleocene is represented by the 40–50-m-thick Esna Shale unconformably overlain by 200-m-thick Lower Eocene limestone with chert. To the north, at the Syrian Arc fold belt, the Paleocene is generally missing (Farouk, 2016). In the subsurface of the northern Western Desert, different thicknesses were recorded for the Paleocene–Eocene sediments in oil wells drilled in the many subbasins or depocenters of the Egyptian basins which reflect the interaction among and instability of the blocks. Since the Late Cretaceous, the Farafra Oasis area stood on the downward edge of the continental slope of the Egyptian basins. It is in this area that the Maastrichtian Dakhla Shale is replaced by thick Khoman Chalk in the subsurface of the northern Western Desert. The Paleocene in the subsurface is commonly made up of limestone alternating with thin shale layers in the deeper parts of the subbasins. The undivided Eocene Apollonia Formation (550–1788-m-thick limestone) is generally unconformably overlain by the Tarawan Formation and the thick Paleocene–Eocene Ain Dalla Formation. To the south (Farafra), deeper sediments of the Paleocene–Eocene are replaced by a shallow facies comprising the Esna and the Farafra Formations. This supports the assumption that the Farafra area was a transition zone between a platform in the south and a ramp in the north during Late Cretaceous–Early Eocene time (Hewaidy et al., 2006, Farouk et al., 2019). To the north, in the Bahariya eastern scarp, the Lower Eocene Farafra Formation (limestone) is interdigitated with the 68-m-thick Naqb Formation (limestone), which makes up the Bahariya eastern and northern scarps and part of the western scarp and also covers many of the isolated hills in the northern part of the depression (Fig. 7). The Naqb Formation conformably underlies the 32.7-m-thick Qazzun Formation (limestone) deposited during the Late Ypresian under relatively quiet conditions in contrast to the oscillating and turbulent conditions during Naqb time (Issawi et al., 2009).

A conglomerate bed forms the contact between the Middle–Upper Eocene Lower–Upper Hamra Formations (together 63 m thick) and the underlying Qazzun Formation. The Lower Hamra Formation is Bartonian in age while the Upper Hamra Formation is Priabonian; the Lutetian is totally missing, indicating an uplift pulse in the Uweinat–Bahariya–Port Said arc, reflecting Late Lutetian Pyrenean movement. The 45-m-thick Qazzun Formation is of record to the north and northwest of El Quss Abu Said in the Farafra depression, reflecting a major detour in the sea north, west, and south of Bahariya Oasis. The Qazzun Formation consists of a sequence of marl and limestone including abundant chert pebbles and reworked carbonates with a 4-m-thick gypseous shale layer at the top. The shale is highly fossiliferous; *Nummulites cailliaudi* is most common in the formation at Bahariya in the northern plateau, although patches of *N. gizehensis*-bearing limestones were recorded from the west-central part of the Bahariya depression. The limited Eocene section in the vicinity of Bahariya slopes and dips eastward toward the Nile Valley, where very thick units are known, besides some newly discovered units that outcrop in places within the Lutetian gap to the west.

In the Nile Valley between Qena and Cairo, the Lower Eocene Esna Shale is overlain by a 200-m-thick Paleocene–Lower Eocene limestone (Farouk, 2016). A 1-m-thick chert-bearing conglomerate bed is found at Darb Gaga west of the Nile opposite Qena between the Esna and Ypresian Thebes Formations (El-Azabi & Farouk, 2011). Farther north, at the latitude of Minia, the 80-m-thick Minia Formation (limestone) from the top of the Ypresian is overlain by the 80-m-thick Lower Lutetian Samalut Formation (limestone bearing *N. gizehensis*), which underlies the Middle Lutetian Mokattam or the coeval Rayan Formation (Fig. 7). This sedimentary sequence comprises 100-m-thick sand and sandy-clay beds, which unconformably overlie the 50-m-thick Lower Bartonian Giushi Formation or the coeval 80-m-thick Observatory Formation, both of which are fossiliferous limestones with marl and dolomite intercalations (Fig. 7).

In the Mokattam area, the Giushi Formation and the coeval Wadi Hof Formation are unconformably overlain by the Priabonian Maadi Formation, which is coeval with the Qasr El Sagha Formation in the Faiyum area (Issawi et al., 2009). To the south, in the Helwan area, the basal 97-m-thick Qaurn (limestone) and the overlying 25-m-thick Wadi Garawi Formation (clay and marl) are considered Late Bartonian (although unconfirmed, pending further paleontological work) (Fig. 7). These two units are coeval with the well-dated Birket Qarun Formation in Faiyum. The Garra El Arbain Facies in southern Egypt comprise the $\sim$ 100-m-thick Late Paleocene–Ypresian Upper Garra beds (limestone), overlain by the 127-m-thick Ypresian Dungal Formation (limestone on top of shale) (El-Azabi & Farouk, 2011).

In northeastern Egypt, many unconformities distinguish the Paleocene–Eocene section from Wadi Qena in the south through southern and northern Galala and the Ataqa and Shabrawet Mountains. A 90-m-thick Lower Eocene limestone unconformably underlies Middle Eocene limestone with a 20-m-thick conglomerate bed between the two units in the St. Paul area on the southern Galala Plateau; Upper Eocene beds have not been confirmed in the area.

Table 1 Summary of global events during the Phanerozoic showing the resulting features and the response in Egypt

Global events	Resulting features	Response in Egypt
Major craton forming events in the Archean followed by a complex history of mountain building and rifting that culminated with the Pan-African Orogeny	Tectonic magmatic episodes of Late Proterozoic–Early Paleozoic age. The resulting basement rocks are classified into several units: gneisses and migmatites to younger granitoids and post-granitic dykes. Uprising of acidic magma. In Egypt, the oldest rocks in Gebel Ouwinat are 2656 + 71 Ma; the rocks become younger eastward extended between 1000 and 550 Ma	– Emplacement of the main basement rocks and their faults and arcs along the Red Sea and South Western Desert. – Faults and arcs delineated the troughs in-between which became later the main basins in Egypt during the Phanerozoic. – The arcs were either due to plumes along fracture zones or due to normal tectonic movements marking the plates and subplate boundaries
Cambrian–Ordovician–Pre-Caradoc tectonism; Early Caledonian Orogeny	Uplifting of the main orogenic belts in west, central, and south Africa associated with faulting and compressive stresses	• Uplifting and igneous intrusions in most regions in Southern Sinai and southern Egypt (especially arcs areas) • Unconformities, cracks, faults in most sedimentary successions during this period
Late Ordovician–Early Silurian Taconic Orogeny	Low sea level spread of glaciers from west Africa to Saudi Arabia and Iran passing by Egypt. South pole located offshore of Algeria (west Gondwana)	• Thick conglomerate diamictic glaciogene sediments in the cracks along the present Wadi Cabgaba (Gabgaba Formation) • Second pulse in the rising Red Sea Hills in south Egypt
• Late Silurian–Erian; last phase of the Caledonian Orogeny • High sea level	Acadian collision between Gondwana and Laurasia–Deposition of rich graptolitic shale in Libya and Saudi Arabia; petroliferous source rocks	• Stream deposits of the Naqus Formation • Four glacial periods were identified in Gabgaba area, separated by 3 interglacial periods plus a fourth one at the base of the section • Third pulse in the rising Red Sea Hills in southern Egypt. Each pulse is represented by an angular unconformity in the basal unit
• Early Devonian • Rapid marine transgression • Bretonion (Late Acadian) first phase of Hercynian Orogeny	• Deformation, plutonic, and metamorphic events in Laurasia, prolonged over a more extended period dated 330 and 360 Ma. The Acadian had best been regarded, not a single orogenic episode, but as an orogenic era • Northward subduction of Paleo-Tethys • Subsidence and rifting along the plate margins	• Inversion of Siwa basin and the basin south of GRT in south Sinai • Thick unit in the north sub-basin of the Egyptian Basin (Siwa) duo to rifting • Tilting of pre-Carboniferous (Cb) sediments in Cabagaba area • Uplifting in south Egypt and deflation of much of Devonian sediments • Gulf of Suez basin received Devonian sediments, kept Intact by block movement
• Early Carboniferous • High sea level • Austrian Event (Orogeny) • (Westphalian–Stefanian)	Transgression–regression phases in the marine section along the North Africa–Arabia plate	– Deposition of marine-continental section in north Egypt, and fluviatile section in the south – In Gabagaba area, the Carboniferous Gilf Formation overlaps older Paleozoic units with pronounced unconformities
Late Carboniferous–Early Permian • Variscan Orogeny • Drop in sea level and glaciation • Early stages in the opening of the Paleo-Tethys closing and opening the Neo-Tethys	• Sharp cooling associated with drop in sea level. Progressive fragmentation of Gondwana • Rifting occurred as escape structure for this fragmentation along the north African–Arabian Plate • Clockwise rotation of Africa	Major uplift of most Egyptian basins associated with low marine transgression – Continental sediments are common with fluvio-marine intercalations – Initiation of the Syrian Arc folded belt in response to the opening of the Central Atlantic and the rotation of Africa
Permian–Triassic • Break up of Gondwana • Neo-Tethys was born • Eo-Cimmerian Events • Transit process	– Rifting increased along N. Africa passive margin and in general in the Tethys domain Rifling. Propagated rapidly from the N. Arabian Plate westward – Plates accreted to EuroSLA, detached from African Gondwana (transit process)	– Marine and continental sediments were deposited in NE Sinai and in the subsurface of the Western Desert – Tectonic instability increased from Mid Tr., underscored by block tilting and local uplifts; a distal effect of the EO-Cimmerian Events

(continued)

Table 1 (continued)

Global events	Resulting features	Response in Egypt
Triassic–Jurassic transition	• Break in sedimentation • Volcanic extrusions terminated basins development	• A major unconformity is known in between the Triassic and Jurassic – Continental sediments represent this transition time and even extended through the Early Jurassic time in the N. Western Desert subsurface sections • Rifting continued and the north basins kept widening • Volcanic extrusions were dominated
Middle Jurassic Separation between north Africa and Europe	– Along the NW margin of Africa, rifting continued. – Rifting terminated with the more crustal separation between Africa and S. America around 180–175 Ma: Toarcian/Bajocian – Rift-related magmatism peaked within Central Tethys during Late Triassic /Early Jurassic (Morocco, Algeria, and Libya)	• Rifting in the north Egypt led to the accentuation and extension of the old basins which were filled by Jurassic and Cretaceous sediments • Deposition of thick Upper Jurassic marine section alternates with three continental units • Magmatic intrusions
• Late Jurassic–Early-Cretaceous Cimmerian Event: the distal effect of the stronger Mid-Berriassian Orogenic event • Continuous opening of Central and South Atlantic Oceans • Split of Gondwana into western and eastern parts. – Opening of Indian Ocean during the Oxfordian • Tithonian drop in sea level	• Second stage rifting, uplifting, and block tilting initiated at the transition from Late Jr. to Early Cretaceous following the Mid-Jurassic separation between Northern Africa and Europe • Rifting affected large areas including the South and Equatorial Atlantic margins, the West and Central African Rift Systems, and the Northern Africa margin from Tunisia to Egypt • Atlantic rift system propagated southward in the S. hemisphere and northward in the N. Hemisphere toward a land bridge created by the Pan-African orogenic belt in the equatorial region	• Omission of the Upper Jurassic sediments in south Egypt. Activation of the Garara basin which was received Upper Jurassic and Cretaceous sediments • Widening and activation of highs of the south subbasins
– Neocomian–Early Aptian – Progressive northward crustal separation between Africa and S. America and sea floor spreading in the newly opened S. Atlantic – Early Aptian Normal Magnetic Quiet Zone	– Rifting was accentuated inside Africa leading to the development of internally rigid continental blocks within the African Plate namely West Austral and Arabia-Nubia; the latter could be separated into central and eastern blocks. The boundaries between the blocks correspond to zones of crustal weakness inherited from the Pan-African Orogeny – Beginning of the closure of the Neo-Tethys	• Northern Western Desert basins were more developed in some of them Late Jurassic magmatic phases preceded the rifting. In the Eastern Desert: the Lower Cretaceous sediments are partly marine with thick continental sediments
End of Aptian till Late Albian Rapid opening of Equatorial Atlantic Ocean. Differential rates of sea floor spreading	• Very active strong phase of magmatic activity. -Linking of the Central and South Atlantic ○ Rejuvenation of the crustal weakness zones in Africa (those between the blocks) ○ Important lateral displacements along these zones ○ Basins were pulling apart in response to dextral and sinistral or strike slip movements • Basins continued to evolve	○ Rejuvenation of the old arcs—hence the adjacent basins become more widespread receiving more sediment. The unequal filling of basins led to their pull apart and in response to the movements which accentuated the uplift of the arcs ○ Basins continued to evolve in north Egypt as anticipated from the following thick Up. Cretaceous section • Intrusion of syenite, gabbro, and basalt in the Eastern Desert took place as huge (in area and thickness) ring complexes, dykes, and silts • Polyphase rifting was common during many episodes in the Cretaceous

(continued)

Table 1 (continued)

Global events	Resulting features	Response in Egypt
• Late Cretaceous (Laramide = Getic movement) • Collision between Africa and Europe • High stand of sea level during the Cenomanian, a connection was established between the Tethys and the Gulf of Guinea • Late Santonian: end phase of the Normal Magnetic Quiet Zone and the collision between African, Arabian, and European plates	• Compressional forces leading to shortening in N. Africa and South Europe, during the Santonian (Guiraud et al. 1992) or during the Cenomanian (Philip, 1993) • Major hiatus within the Up. Cretaceous sediments, associated with structure features • The continuous development of Syrian Arc System along the North Africa margin • Polyphase rifting, folding, and basins inversion along Africa margin and inside the continent associated with many volcanic eruptions	○ Deposition of thick Cenomanian marine section in North Egypt, continental on the arcs (Bahariya Formation) with thin marine incursions • A major hiatus at the Cenomanian / Turonian contact in Egypt, uplift in South Egypt leading to the missing of Turonian beds and very shallow conditions dominated in Sinai (Buttum Formation) ○ Santonian carbonates were still high and received clastics-fine and coarse (Qusseir Clastic Member of the Nubia Formation) ○ Campanian carbonates in north Egypt are shallow in central Egypt giving rise to phosphate beds and neritic carbonates, continental in South Egypt (Nubia Formation)
• Campanian relaxation of global tectonics which extended through the Early Maastrichtian	○ Rifting episode followed the Santonian folding event • Several rift basins rejuvenated or were initiated by the Campanian–Maastrichtian times; some of them carrying on through the Paleocene	• Development of the phosphate basin stretching between the Red Sea and the Libyan border
○ Late Maastrichtian • The Mediterranean Seuil carrying on through the Paleocene	• Many basins along African–Arabian Plate margin in the Palmyrides, the Abu Gabra, the Muglad, the White Nile, the Blue Nile, and many others inside Africa and along its northern western and eastern margins were reactivated, some of them carrying on through the Paleocene	○ Injection of quartz vein in the phosphate bed at Darb El Arbain • Unconformities within many parts of Egypt • Missing of the Paleocene in Bahariya area, and partly missing in east Farafra along the Uweinat–Bahariya–Port Said arc
• Late Ypresian–Lutetian • Drop in sea level and tectonics paleo-highs	Retreat of the Early Eocene sea towards the north	– Moving of the shore-lines during the Lutetian, Bartonian, and Priabonian reaching its acme during the Oligocene – Facies of different became younger north ward – Unconformities are known from the Eocene section, e.g., the Lutetian missing in Bahariya area, in Ataqa, and in many parts in Sinai and along the Gulf of Suez
• The Late Lutetian • Pyrenean Atlasic compression event	Dextral transpression along Africa, Arabia, Eurasia plate frontiers—Opening of NNW to NNE Oligocene rifts	○ Activation of the Guinea–Nubia Lineament ○ Uplift of basement rocks in south Egypt through the thin sedimentary cover, developing centroclinal folds ○ Development of Trans North Egypt Fracture Zone with eastwest faults • Many dome and basin structures along fault planes
Oligocene uplift in east Egypt with basalt plumes during the initial rifting of the Gulf of Suez	• Gradual rise of the Red Sea Hills in pulses started in the Priabonian • Developing of many Oligocene rifts along the Mediterranean and inland. Volcanic eruptions were common	○ Reversal of slopes of the main part of Egypt—nearly south of latitude 29º 0′ N • Development of hinges along the western side of the uplifted basement rocks • Many fissures and cracks developed parallel to wadis • Deposition of dominantly fluviatile continental section in the inland rifts with some marine sediments especially in the northerly developed basins. The Fayium delta with vertebrate fossils

(continued)

Table 1 (continued)

Global events	Resulting features	Response in Egypt
– Early Miocene to Middle Miocene the Red sea came into existence – Collision of Alpine and Himalayan plates – Plume activities preceded the breakup of E. Mediterranean	Faults along the Red Sea coast rifts developed creating local basins in the Red Sea mega-rift and along the Mediterranean coast – Reorganization of the convection system within the upper mantle across the Africa, Arabia, and Europe margins	Deposition of thick Miocene sediments in the rift basins in the sea and the Mediterranean and of shallow continental, shallow marine, and evaporites on the shoulders of the rift. Evaporite was also common in the rift – Hot brines gushed along the axis of the Red Sea. – Volcanic eruptions in many parts of Egypt
– The place of the present Nile Delta began to build up during the Early Miocene	A thick section in the place of the Nile Delta, sediments brought from inland by northerly flowing rivers most probably emanating from northeast high plateaus, e.g., Gebel Ataqa and Northern Galala. The southern Galala-Minia high area formed a water divide between north and central Egypt, where some rivers, e.g., Tarfa, flowed southward. Migration of the Oligocene Fayiurn delta to Moghra area in the northeast	
– Messinian desiccation of the Mediterranean	Formation of saltwater lagoons in the Qattara, forming a Salt Mesa at m depth, means that the Qattara was hewed to this depth between the Serravallian—the last sea transgression—and the Messinian—the time of the Salt Mesa, i.e., between 11.7 and 7.1 Ma; Tortonian time	
– Zanclean transgression	Transgression of the Mediterranean through the many gorges along its southern coast, in case of Egypt, transgression reached Aswan and Wadi Haifa in Sudan. Marine sediments were deposited in the deep part of the estuary, cascading sediments were known from the foot of the eastern cliffs bordering the estuary. Continental sediments were recorded inland away from the Pliocene Gulf. The main delta of Egypt took its present shape, supplied by local Egyptian rivers and marine sediments. Third location of the main Egyptian delta	
– Piacenzian regression	Rivers started to adjust their courses to cope with the new base level in the Mediterranean. The welding of the many rivers along the present Nile, the course took place only when the Pliocene Gulf invaded Egypt. Though the E- W rivers resumed their courses during the Piacenzian regression, the drastic changes in the climate of Egypt from wet to dry gradually changed these rivers from being active to sluggish which were easily captured by the flood of the Ethiopian waters during the Middle to Late Pleistocene	

In Sinai, the 200-m-thick Lower Eocene Egma Formation (chert-bearing limestone) shows varied gradation including siliceous, dolomitic, chalky, and marly limestones. The Egma is overlain by the 98-m-thick Darat Formation (green and brown shale, marl, and limestone), which in turn is topped by the 93-m-thick Khaboba Formation. The Darat and Khaboba are coeval with the Middle Lutetian Rayan or Mokattam Formation (the Early Lutetian is missing). The 180-m-thick Middle–Late Eocene Tanka Formation consists of clayey limestone and salty dark shale at its base, which is Late Bartonian; the top beds might be Late Eocene in age, whereas the overlying 20-m-thick Tayiba Formation (marl and clay) is Priabonian. The Tayiba Formation is unconformably overlain by Miocene sediments along the east coast of the Gulf of Suez. The many unconformities in the Paleocene–Eocene sediments in general and the uplift in southern Egypt associated with the continuous retreat of the Paleocene–Early Ypresian seas off Egypt from south to north led to the many facies described above. The sea regression coupled with the activation of the northeastern arcs in many parts of southern and eastern Egypt (especially in the vicinity of the Red Sea and the Gulf of Suez and in Sinai) reflected the Pyrenean–Atlasic compression event. This represents a major stage in the collision of Arabia–Nubia and European plates as a result of the changes in the rate and direction of the opening of the central, southern, and northern Atlantic Ocean (Fairhead et al., 2013). The activation of block movements in northeastern Egypt is clearly evident in the interplay and hierarchy among the blocks in this area, resulting in the total absence of the Lutetian in Gebel Ataqa and also probably in Shabrawet. The unconformity there is represented by 5-m-thick paleosol between the Ypresian Suez Formation and the overlying Middle Bartonian Ramiya Formation (Osman, 2003).

The interior basins among the basement rocks in Safaga and the southern Qusseir stretch (e.g., Mohamed Rabah, Wasif, Hamrawein, Duwi, and Hamadat) were dragged eastward toward the Red Sea (in the Safaga area) or westward (in the Qusseir area) forming very asymmetric synclines. The longer flank with the Thebes massive limestone at the top was tilted eastward (or westward), gliding on the underlying shale of the Esna and Dakhla, which lubricated the movement for considerable distances (2–4 km) before another short flank (a few hundred meters in length) overrode the basement rocks while dipping in the opposite direction to that of the longer flank. The movement is certainly post-Ypresian and probably related to the Pyrenean–Atlasic movement. After this movement, volcanic eruptions through the Oligocene and younger sediments were very common.

In Sinai, along the trans-Egypt fracture zone, a number of significant highly tilted domal structures are found between Taba in the east (on the Gulf of Aqaba) and Cairo in the west, especially in the Sudr El Heitan area, east of the Gulf of Suez, and along the Suez–Cairo stretch. The area of Sudr El Heitan is probably one of the most structurally complicated areas in Egypt. The dominantly Cretaceous and Eocene rocks involved in this area are related to the Lutetian Pyrenean–Atlasic movement.

4.2 The Eocene/Early Oligocene Transition

The Late Eocene–Early Oligocene transition witnessed the rise of the Red Sea Hills, most probably coinciding with the opening of Gulf of Aden. This rifting developed large basins along the gulf and also inside the Africa Lakes region, which resulted in the gradual separation and the northward drift of the Arabian subplate, enabled by sinistral movement along the Dead Sea–Levant transform fault.

The constant movement of the Red Sea Hills during the Oligocene formed escape structures for the northward-moving Arabia subplate and the widening of the Gulf of Aden. The resulting uplift in eastern Egypt changed the slopes in the region to be east–west rather than south–north and, coupled with 1500-mm rainfall during the Oligocene, caused major wadis to become important rivers in the Egyptian geomorphic landscape. The master stream was the Qena River, initiated along the cracks and faults that resulted from the uplift movements. The southern Galala Plateau became a high catchment area for the Qena River headwaters and formed a water divide where from which the Qena flowed southward and the Bown and Karus Rivers flowed westward to the Faiyum depression, thereby building a huge fan with fluviatile and deltaic deposits in which lived various vertebrates since the Late Eocene and the Oligocene. The area is now considered to be one of the biggest graveyards for these animals in Africa and probably in the world.

4.3 The Oligocene Deposits

The main Oligocene deposits in Egypt are of fluviatile to deltaic origin. The marine sediments are confined to far northern Egypt along an exposed strip extending from Risan Aneiza in northern Sinai and passing by El Arag south of the Qattara Depression to Siwa Oasis in the far west. Most noteworthy among the deltaic Oligocene units is the 340-m-thick Gebel Qatrani (sandstone, sandy mudstone, limestone, and shale) north of Faiyum, where important and unique vertebrate fossils are very common. Other Oligocene units include the 50-m-thick fluviatile section (vividly colored sandstone) known as the Gebel Ahmar Formation, near Cairo; the 120-m-thick Nakheil Formation (coarse-grained breccia and conglomerate) in the Qusseir–Safaga stretch; and the 40-m-thick Radwan Formation (ferruginous sandstone) in the Bahariya Oasis. The subsurface 1086-m-thick Tineh Formation (shale and sandstone, as observed in Qantra-l well) has been drilled through east of the Nile Delta and in northern Sinai; the top of the Tineh is Early Miocene. On the Mediterranean coast, the Daba'a well penetrated the 442-m-thick Daba'a Formation (shale and limestone).

The 60-m-thick Oligocene Wadi El Arish Formation in Risan Eneiza (Kuss & Boukhary, 2008) consists of basal marine sandstone, clay in the middle, and massive limestone at the top. At El Arag, this formation (only 7-m-thick) comprises sandy calcareous clay and limestone. In the Gulf of Suez, drilling opposite the Northern Galala Plateau revealed a thick Oligocene section: 690-m-thick shales interbedded with sandstones and limestones overlying 300-m-thick argillaceous limestones, shales, and sandstones. Associated with the Red Sea uplift were 31–23.2-Ma flood basalts on the rift shoulders along the coast and also inland (Abu Zaabal, Bahariya, El Bahnassa, and many other areas).

4.4 The Oligocene–Miocene Transition

The Oligocene–Miocene transition involved significant movements in the Mediterranean region from its far west end in southern Spain to the Levant passing by all of northern Africa. In the Levant and Anatolia, collision among African, Arabian, and Eurasian plates significantly intensified from the very Early Miocene when the Arabian Plate constantly moved northward along the Dead Sea Transform where the northern part of this plate crops out in southeastern Turkey (Kissel et al., 2003). In Egypt, as a result of the tectonic events briefly summarized above, linear topographic scarps and deeply incised valleys developed along active faults. The Red Sea Mountains kept rising during the Miocene, while the east–west-trending rivers (especially in the Qena System) deepened their channels, and the two main plateaus of central Egypt became conspicuous geomorphic features. Minor thrusts have been recorded in Sinai (Issawi et al., 2009) and along the still-active Kalabsha Fault in southern Egypt, which is part of the reactivated Guinea–Nubia lineament (Bumby & Guiraud, 2005). Strong magmatism predated and accompanied the rift tectonics, mostly along the Red Sea shoulder in the Nubia area, along the reactivated northeast-trending arcs (Bahariya, trans-northern Egypt fracture zone, and in Suez–Cairo areas). The stresses exerted by the Oligocene–Miocene tectonics favored extension by weakening the lithosphere (Bosworth, 2015).

4.5 The Miocene Deposits

The Miocene sediments in Egypt are classified into Red Sea, Mediterranean, and Inland Facies. The Early Miocene Red Sea Facies protorift sedimentation started with a continental sequence: sandstone, siltstone, grit, and coarse-grained fanglomerate in the 70-m-thick Ranga, 37-m-thick Gebel El Russas, and 40-m-thick Abu Gerfan Formations. Northward at the foot of Gebel Ataqa, the marine unit coeval with these formations is the 52-m-thick Sadat Formation (Fig. 8).

Facies of the Lower–Middle Miocene basin include the basal 460–490-m-thick Nukhul Formation (calcareous shale, marl, and limestone) and the overlying 600–800-m-thick Rudies Formation (shale and sandy shale, with minor limestone). The Gharmoul Formation in the Eastern Desert and the Qabeliyat Formation in Sinai are shallow-marine equivalents capped by the Rudies in the basinal area.

The Serravallian Kareem Formation consists of 120–135-m-thick Rahmi evaporite overlain by 186–221-m-thick Shager open-marine sediments (calcareous sandstone and shale). The overlying Belayim Formation comprises the Baba (a 54–126-m-thick evaporite), the Sidri (a 9–100-m-thick open-marine shale, the Feiran (a 40–60-m-thick evaporite), and the Hammam Faraun (a 44–84-m-thick open-marine phase including shale, marl, and sandstone). The $\sim$ 50-m-thick Abu Dabbab (or Gypsum) Formation is coeval with the Kareem Formation that is exposed along the Red Sea coast along the Egypt–Sudan border (almost 800 km to the north). Overlying the Abu Dabbab Gypsum is the 35-m-thick Samh Formation (marl, shale, and sandstone), the topmost middle unit along the Red Sea coast (Fig. 8).

In Sinai, the 120-m-thick Sarbut El Gamal Formation (conglomerate and limestone) forms the top of the Middle Miocene section and is coeval with the Qabeliyat Formation. Both these are coeval with the 6–12-m-thick Upper Burdigalian–Langhian Gharmoul Formation (sandy and argillaceous dolomitic limestones) exposed along the east coast of the Gulf of Suez. The overlying sediments are classified into the 0–1650-m-thick South Gharib Formation (anhydrite with shale bands) and the overlying 27–900-m-thick Zeit Formation (shale with thin intercalated anhydrite lenses). The 22-m-thick Upper Miocene Hagul Formation at the entrance of the Gulf of Suez consists of shale overlain by a chalk bed.

Differences in thickness locally are explained by the absence of some units. For instance, the range of thickness of the South Gharib (0–1650 m) is in part attributable to the absence of units such as the Rahmi Anhydrite Member, which is missing in the Morgan-1 well. This contributes to the very uneven surface of the floor of the Gulf of Suez, which is also due to the (210-m-thick) Kareem Formation carbonates' unconformably overlying basement rocks in the central part of Gebel El Zeit Bay. Another factor is the havoc imposed by the many blocks in the gulf owing to faulting, which also explains many unconformities among the units.

Messinian sedimentation was a fluviatile phase in many parts along the Red Sea and the Gulf of Suez coasts, where sand section rich in fossil wood and gravels covers the older Miocene units. This section is widespread as patchy outcrops unconformably overlying Oligocene and Eocene sediments along the Suez–Cairo road. In the Mediterranean Facies, a 200-m-thick Miocene section includes clastics with minor carbonates and conglomerates as well as lenses of gypsum; the unit is known as the Moghra Formation and belongs to the Aquitanian–Burdigalian. The top 70–160-m-thick Marmarica Formation (Langhian–Serravallian) consists of limestone and calcarenite beds that change laterally to 6–10-m-thick gypsum at the Hagif scarp. The Tertiary section drilled offshore from the Mediterranean revealed a 287-m-thick Early–Middle Miocene shale unit.

The desiccation of the Mediterranean Sea during the Messinian led to many salt layers in dry depressions across the dry seabed. In the Qattara Depression, the southwestern parts of the Salt Mesa are at a 100-m depth, which means that the depression formed during the period between the last marine transgression over the area, i.e., in the Serravallian (11.2 Ma), and the time of the Salt Mesa. Thus, the depression was excavated to a depth of 100-m below sea level during the Tortonian. The subsurface basal Miocene section in the Nile Delta is composed of the 300-m-thick Moghra Formation (open-marine shale) overlain by the 130-m-thick Langhian–Tortonian Sidi Salem Formation (shale, dolomitic marl, and rare sandstone). Above that is the 280-m-thick Tortonian–Messinian Qawasim Formation (conglomerate and sandstone), which in turn is overlain by the 2040-m-thick Rosetta Anhydrite in the eastern and northern Nile Delta but is missing in the western part of the delta. Where present, the Rosetta is an expression of the general desiccation of the Mediterranean during the Messinian. The uppermost Miocene in the delta subsurface is represented by the 222-m-thick Abu Madi Formation, which formed by continuous deposition during the Messinian to the Zanclean and laterally is coeval with the Rosetta Anhydrite.

In the Sinai subsurface, the 1086-m-thick Oligocene–Miocene Tineh Formation (shale and sandstone) is overlain by the 533-m-thick Burdigalian–Langhian Qantara Formation (intercalated marl and sandstone) (Farouk et al., 2014). The Qantara Formation in turn is successively overlain by the 552-m-thick Langhian–Tortonian Sidi Salem Formation (banded shale and sandstone), the 185–258-m-thick Qawasim Formation, and the 992–1400-m-thick Abu Madi Formation (Farouk et al., 2014). The Gebel El Khashab Formation is represented by the 40–90-m-thick (sandstone and gypseous clay) in the northern Western Desert (Fig. 8).

The rate of tectonic activity in the Red Sea and the Gulf of Suez rifts was reduced considerably since the Late Miocene (Segev et al., 2017; Steckler, 1985) concurrently with the dislocations and cracks along the Gulf of Aqaba. However, the connection of this Gulf with the Red Sea never happened except during the Pleistocene contrary to what many foreign scholars believe. The axial basins in the place of the Gulf of Aqaba and its margins kept extensively lowered and uplifted, respectively, most probably as escape structures to what we're happening in the Red Sea and the Gulf of Suez plus of course the northward moving of the Arabian Plate.

The drop in the Atlantic Ocean water and the close of Gibraltar during the Messinian led to a break in communication between the Ocean and the Mediterranean Sea, hence the desiccation and disintegration of the sea into a number of isolated sea lakes which became the sites of the Messinian Rosetta Anhydrite.

4.6 The Pliocene Deposits

During the Early Pliocene, a major transgression of the Mediterranean through the many gorges along its southern coast, in case of Egypt, transgression reached Aswan and Wadi Haifa in Sudan (Table 1). Marine sediments were deposited in the deep part of the estuary; cascading was the opening of Gibraltar and the filling of the sea in which the water level was 110—120 m above the present sea level. The sea thence transgressed inside Africa and Europe filling the Late Miocene degraded channels which the rivers in response to the lower base level during the Messinian. The seawater invaded Egypt to south Aswan crossing a water divide in the area of South Galala and a promontory coming down the western scarp in southwest Faiyum area (Issawi et al., 2009). That incident represents the first time for a continuous water body located at the place of the present Nile River. The cracks and faults in this part of the country were formed in consequence to the uplift of the Red Sea basement rocks. The contact between the base of Gar El Muluk Fm. (Zanclean) with the underlying Miocene Raml Fm. and Gebel El Khashab Formation is marked by 2.5 m conglomerate composed of angular quartz and chert gravels. This unconformity was named Mikheimin conglomerates after a locality carrying the same name west of Wadi El Natrun. The unconformity is believed to have more than local significance since it recorded from Sinai.

In the deeper part of the Pliocene Gulf, which has a width of 60 km north of the water divide or what is known as the neck, 1458 m thick Lower Pliocene shale section was deposited and known as Kafr El Sheikh Fm. South of the neck at El Minshah, south of Sohag, the formation is 12 shales and limestone at top; the base was not exposed. At the subsurface in Aswan, the Lower Pliocene marine section is montmorillonitic clay with lenses of fine-grained micaceous sands including ostracodes. When the Gulf marine waters reached -21 m below the present sea level, the Gar El Muluk Fm. was deposited at the area of Wadi El Natrun, consisting of 27 m deltaic and lacustrine gypseous sandstones, clays, and minor limestones. The section includes both freshwater vertebrate faunae and marine ostracodes.

The Middle and Late Pliocene witnessed a retreat of the Gulf marine waters to the north. During this phase, the water halted in Kom El Shelul area of the neck depositing the formation with the same name. This formation is made of ≈ 25 m coquina limestone and sandstone highly laden with pelecypod shells. In the east side of the Gulf where high mountains are common with fluvial drainages, the marine water cascaded over the Gulf bank and both marine and freshwaters fill topographic low depressions. In there, Umm Raqaba Formation (23.85 m) was deposited composed of alternating conglomerate and sandstone beds. The inland continental Pliocene sediments in the Upper Nile Valley are known as the Muneiha Fm. (14.6 m sandstones) at the latitude of Kom Ombo area and the Issawia Fm., 15 m brecciated limestones, east of Sohag. Both units belong to the Middle Pliocene.

In the Red Sea near Mersa Alam, the Pliocene section is divided into Gahir Fm. (944 m sandstone, marls, and conglomerates) of Early Pliocene age and the overlying Shagra Fm. (80 m sandstones, marls, and reefal limestones) dated Middle Pliocene to Pleistocene. In Safaga area, both units, Gabir and Shagra, are lumped together under the name Gasus Formation with the Samh Formation (late Miocene) at base. In Sinai, the undifferentiated Pliocene sediments in the west are described under the Qa'a Fm. (52 m grits, sandstones, anhydrite, and shelly limestones). The formation is 100 m in the drilled oil wells.

In the Nile Delta basin, the Pliocene–Pleistocene succession starts by the sandy deposits of the upper part Abu Madi Formation and followed by fine clay deposits of the Kafr El Sheikh Formation and attains about Kafr El 120–259 m in the oil wells in the Nile Delta, only 23 km south of Giza, represented by sandstones and clay pockets. The Pleistocene section in Nile Delta and Mediterranean Sea consists of fluvial-deltaic the Wastani, Mit Ghamr, and Bilqas Formations which consist dominantly of thickly bedded silty sands with clay streaks, overlying the El Wastani Formation (Fig. 8).

5 Surface Water Resources in Egypt

During the Phanerozoic, Egypt was a rainy country and many older rivers were flowed into present-day deserts. This was best recorded in southeast Egypt at Abraq and Hodain where freshwater fossils were recorded during the Mesozoic and Cenozoic (Issawi et al., 2009). Also, at Bahariya and Kharga oases, dinosaur fossils were described from the Upper Cretaceous deposits. In Faiyum, a major collection of Oligocene freshwater fossils was collected by many scientists (Simons & Rasmussen, 1990). One of the oldest major rivers in Egypt was the Qena river as a result of the uplift of the Red Sea Mountains in pulses, during the Late Eocene up to the Early Miocene. The Qena River collected all the Egyptian waters from the Southern Galala Plateau to the extreme southwest of Egypt. The Pleistocene deposits of the Nile Valley are represented by lower Pleistocene conglomerates of the Armant Formation and Middle Pleistocene sands of the Qena Formation which represented the oldest Quaternary deposits in the Nile Valley resulted from the Qena River (Issawi et al., 2009). The Pleistocene oldest sediment is the Qena Sand which has a suite of minerals specific to Egypt's Eastern Desert including opaque minerals rich in zircon and epidote with a relatively high abundance of amphiboles (Omar, 1996). To the south in Egypt, in the Gabgaba area, the Gabgaba River started its course in Sudan near the Dungola loop and flowed northward along cracks developed on the west side of the hills exposing basement in southern Egypt. The Gabgaba then joined the Allaqi River and the system is now known as the Gabgaba–Allaqi River; flowing northward and westward, it was captured by the Qena River flowing from the north to the southwest below the westward-diminishing Sin EI Kaddab scarp. Thus, a huge amount of water was flowing in southwestern Egypt, including now-defunct streams that were braided in some places and had conspicuous banks in others, all covered by thick deflated sands during the arid phases that have been dominant across Egypt in the Middle-Late Quaternary. This drainage system, known as the Radar Rivers or the trans-African drainage system, reached the Atlantic during the Oligocene and later times. Another older river, the Gilf, was also important during the Oligocene; it was formed in the north and flowed through southwestern Egypt while building the Siwa deltaic sediments.

The Nile River is applied to the south-north a river which has its upstream from two locations: Victoria Lake (Uganda, the White Nile) and Tana Lake (Ethiopia, Blue Nile). Both Niles meet at Khartoum. The important diagnostic characteristics distinguishing Nile sediments from other riverine systems are their inclusions with an Ethiopian heavy minerals suite (e.g., pyroxenes mainly augite, amphiboles, strongly dwindled zircon accompanied by an intermediate epidote contents). These heavy minerals are only recognized in the Dandara Formation which is well exposed in both banks of the Nile in Upper Egypt. It is believed that the sediments of the Dandara Formation are the first deposits of a river coming into Egypt from Ethiopia heading toward the Mediterranean. In between both units, i.e., Qena and Dandara Formations, the Ghawanem Formation was recorded including both minerals of Qena and Dandara Formations with the Egyptian and Ethiopian suites indicating that the Qena System was partly active even when the Ethiopian water reached Egypt. The top third of the Dandara Formation is 210 ka which gives an approximate age for the Ethiopian water with its special mineral suite at least ½ million years—the age of the present Nile. The presence of Nilotic fishes and crocodile remains in Tarfawi, Sahara area 300 km west of the Nile, is a proof for a connection between the Nile and the site of the fauna. The age of the fauna is 174 ka and elevation is ca 247 m a.s.l. With this connection, water must have covered a huge stretch in the south Western Desert. Remnants of this water can be seen in the many and extensive playas south of Sin El Kaddab and at Bir Tarfawi–Bir Sahara stretch. The playas down the Darb El Arbian, Kharga, and Dakhla scarps have elevation less than 200 m a.s.l. This tells that the Nile water once flowed into these depressions during the Late Pleistocene.

The most important problem facing many African countries north of the equator is the lack of freshwater taken with construction of dams from upstream countries with a rapid increase in population, which could lead to increased death rates and the lake of enough water to sustain irrigation and economy. Such limited water inevitably leads to conflicts such as the tribal war in Darfur and the confrontation between Sudan and Chad, not to mention the dispute between Ethiopia on the side and Sudan and Egypt on the other, about construction of a huge dam on the Blue Nile just upstream from the Sudan border, in a seismically active region close to the Ethiopian rift. It is surprising, therefore, to realize that large amounts of water originating in Central Africa and Congo were trapped in the swamps of the Bahar El Gebel and Bahar El Zaraf depressions in west South Sudan. This suggests that the channels of the ancient Cenozoic river system, which flowed naturally from the southern region across what is now the Sahara Desert could be used with relatively little expense to transport freshwater to the populated territories of northeastern Africa. Some of the northern feeders of the Congo River near Buta, or near Ueley further north, are low-gradient streams that could be reversed to flow into these natural collectors. From here, the old Radar Rivers' channels could transport water to the sand-filled Gilf River channel, or further west into the ancient Chad-Libya mega system. The main trunk of the rejuvenated channel would run from the swampy areas in western South Sudan to Darfur near El Fasher, and further north through Lagiet Arbain and Lagiet Omran to reach the Wadi Magrur and Wadi Howar. At Merga, 100 km further north, a reservoir could be developed to supply two main systems, the paleo-Gilf flowing into Egypt across the Sudan border east of Gebel Kamel and the paleo-Kufra flowing past west Gebel Uweinat into north Chad and south Libya. In all these swathes, the suggested new canals would take advantage of the existing excavation provided by the ancient river systems, to develop a new life in a dead desert.

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