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Structural setting and tectonic evolution of the Bahariya Depression, Western Desert, Egypt

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ABSTRACT

An integrated surface mapping and subsurface study of the Bahariya Depression aided the regional subsurface interpretation. It indicated that four major ENE-oriented structural belts overlie deep-seated faults in this part of the 'tectonically stable' area of Egypt. The rocks of the Bahariya area were deformed in the Late Cretaceous, post-Middle Eocene, and Middle Miocene-and subsurface data indicated an early Mesozoic phase of normal faulting. The Late Cretaceous and post-Middle Eocene deformations reactivated the early normal faults by oblique slip and formed a large swell in the Bahariya region. The crest was continuously eroded whereas its peripheries were onlapped by Maastrichtian and Tertiary sediments. The tectonic evolution of the Bahariya region shows great similarity to the deformation of the 'tectonically unstable' area of the northern Western Desert where several hydrocarbon fields have been discovered. This similarity may indicate that the same phases of deformation could extend to other basins lying in the 'tectonically stable' area, such as the Asyut, Dakhla, Nuqura, and El Misaha basins.

INTRODUCTION

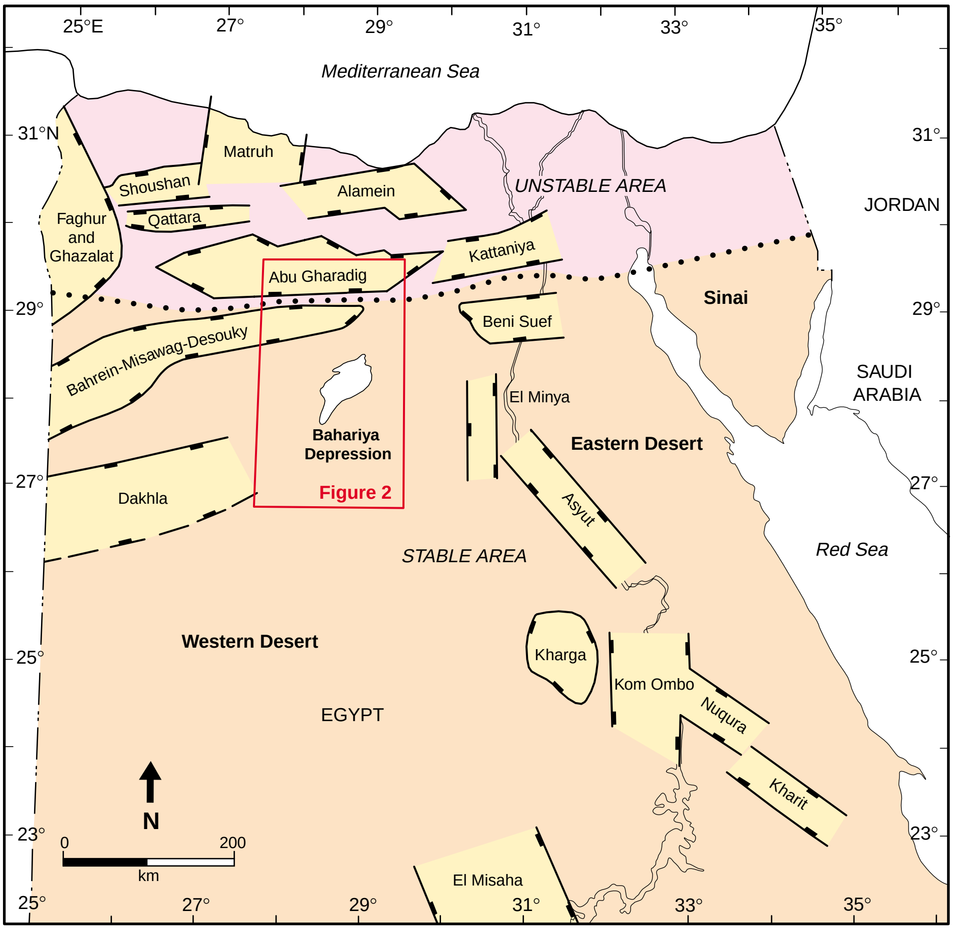
The Bahariya Oasis is a large, oval-shaped NE-oriented depression in the north-central part of the Western Desert of Egypt (Figures 1 and 2). It has a surface area of about 1,800 sq km and is surrounded by plateaus at about 250 m above sea level. Except for the Abu Roash area that lies to the southwest of Cairo, the Bahariya Depression is the only locality in the northern and central parts of the Western Desert where Cretaceous rocks are exposed as an inlier within the practically flat-lying Tertiary rocks.

The Oasis lies about 100 km south of the boundary between a northern tectonically unstable area and a tectonically stable shelf area to the south (Said, 1962, p. 30). The 'tectonically unstable' area in the northern Western Desert contains several sedimentary basins (Figure 1) (Shata, 1951; Kostandi, 1959; Gezeery et al., 1972; Deibis, 1976; and Abu El Naga, 1984). They were mostly formed by the Mesozoic rifting that affected northern Egypt during the opening of the NeoTethys (Biju-Duval et al., 1979; Argyriadis et al., 1980). Several ENE-oriented basins in the form of NNW-tilted fault blocks, such as the Kattaniya, Abu Gharadig, Alamein, Qattara, and Shoushan basins, occur in this area (Abdine, 1974; Abdel Aal and Moustafa, 1988; Abdel Aal et al., 1990; Hantar, 1990; EGPC, 1992; Taha and Halim, 1992; Nemec, 1996; Abd El-Aziz et al., 1998).

According to Said (1962), the 'stable shelf' is an area with ill-defined boundaries that is characterized by continental and epicontinental sedimentary rocks overlying a relatively shallow Precambrian basement. Gravity, magnetic, and seismic surveys, and a few boreholes drilled during the 1980s and 1990s, revealed Mesozoic rift basins such as Dakhla, Asyut, Nuqura, and El Misaha (Taha, 1992) within the 'stable shelf'' south of the Bahariya Oasis (Figure 1).

Studies of the geological and structural setting and tectonic evolution of the Bahariya Depression offer opportunities for understanding whether the deformations that affected the northern Western Desert extended into the 'stable platform' where rift basins with potential hydrocarbon reserves are located. Excellent coverage of 2-D and 3-D seismic data as well as the large number of boreholes in the northern Western Desert constrains the ages of deformation that affected the 'tectonically unstable area'.

Previous geological field mapping of the Bahariya Depression was by Ball and Beadnell (1903), Said (1962), El-Akkad and Issawi (1963) and Issawi et al. (1996). Geological mapping of selected parts of the Depression and its surrounding plateaus was by Issawi (1964), Said and Issawi (1964), Amer (1968),



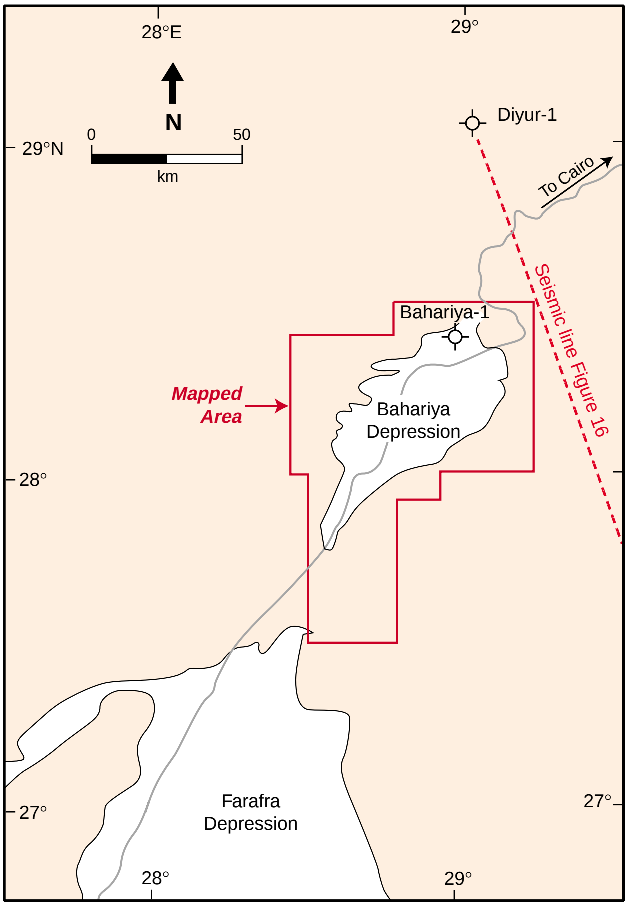


Figure 1: The Bahariya Depression in relation to the main Paleozoic-Mesozoic basins (yellow) of the Western Desert and Nile Valley (modified after Taha, 1992; and Dolson et al., 2001). The dotted line is the boundary between the unstable and stable shelf areas of Said (1962) after Meshref (1990).

Figure 2: Location map of the Bahariya area, and location of the seismic section of Figure 16.

Basta and Amer (1969), El Bassyony (1972), Amer (1973), El Bassyony (1978), Zaghloul et al. (1993), and Sehim (2000.) Only one previous attempt has been made to analyze the structure of the Bahariya area and the different phases of deformation. This was by Sehim (2000) and his interpretation is part of the Discussion section ('Tectonics of the Bahariya Region').

Our main objectives were to study and analyze the structures that have affected the rocks of the Bahariya Depression and nearby areas, to identify the phases of structural deformation, and resolve the tectonic evolution of this part of the northern Western Desert. These objectives were achieved by detailed field mapping of the Bahariya Depression and surrounding areas—including the northern part of the Farafra Depression (Figure 2)—at a scale of 1:20,000, and a study of the available subsurface data.

STRATIGRAPHIC SETTING

In the Western Desert, a variably eroded Paleozoic sedimentary section overlies Precambrian basement rocks of continental affinity and is, in turn, overlain by thick succession of Mesozoic to Cenozoic sedimentary rocks. Figure 3 is a simplified stratigraphic section for the northern Western Desert.

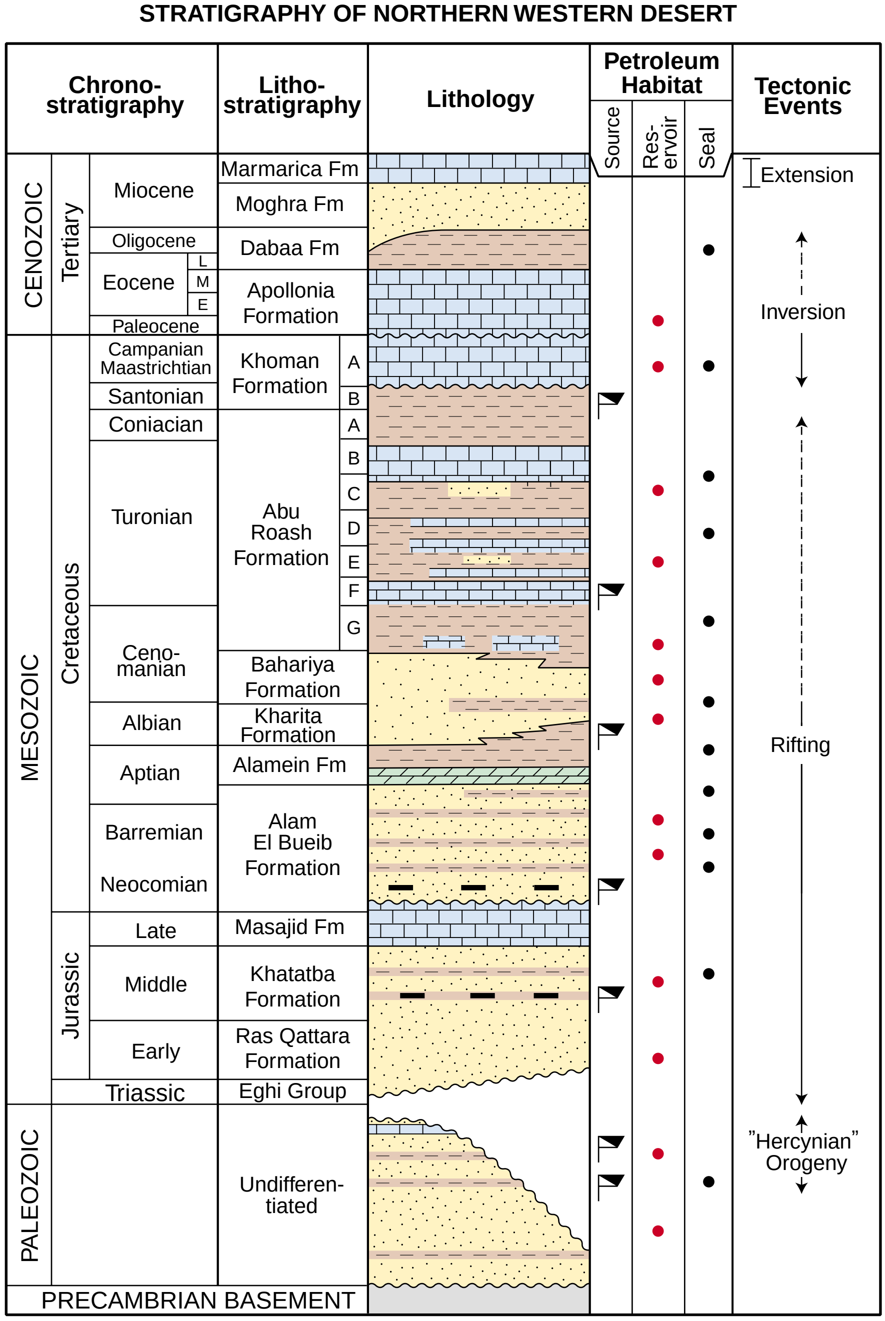


Figure 3: Simplified stratigraphic section of the northern Western Desert modified after Schlumberger (1984 and 1995) and EGPC (1992).

The thickest Paleozoic section in the Western Desert is in the Siwa area in the northwest where it exceeds 8,000 ft (about 2,440 m) (El Sweify, 1975; EGPC, 1992; Dahi and Shahin, 1992; and Fawzy and Dahi, 1992). The Bahariya-1 exploratory well (Figure 2) in the study area, intersected a Paleozoic section 1,024 m (about 3,350 ft) thick (Figure 4). A lower unit with abundant shale beds is 436 m thick and lies unconformably on the Precambrian basement rocks. It has been dated as Middle Cambrian. A 588-m-thick Late Carboniferous to Early Permian sandstone unit with some shale beds at the top unconformably overlies it.

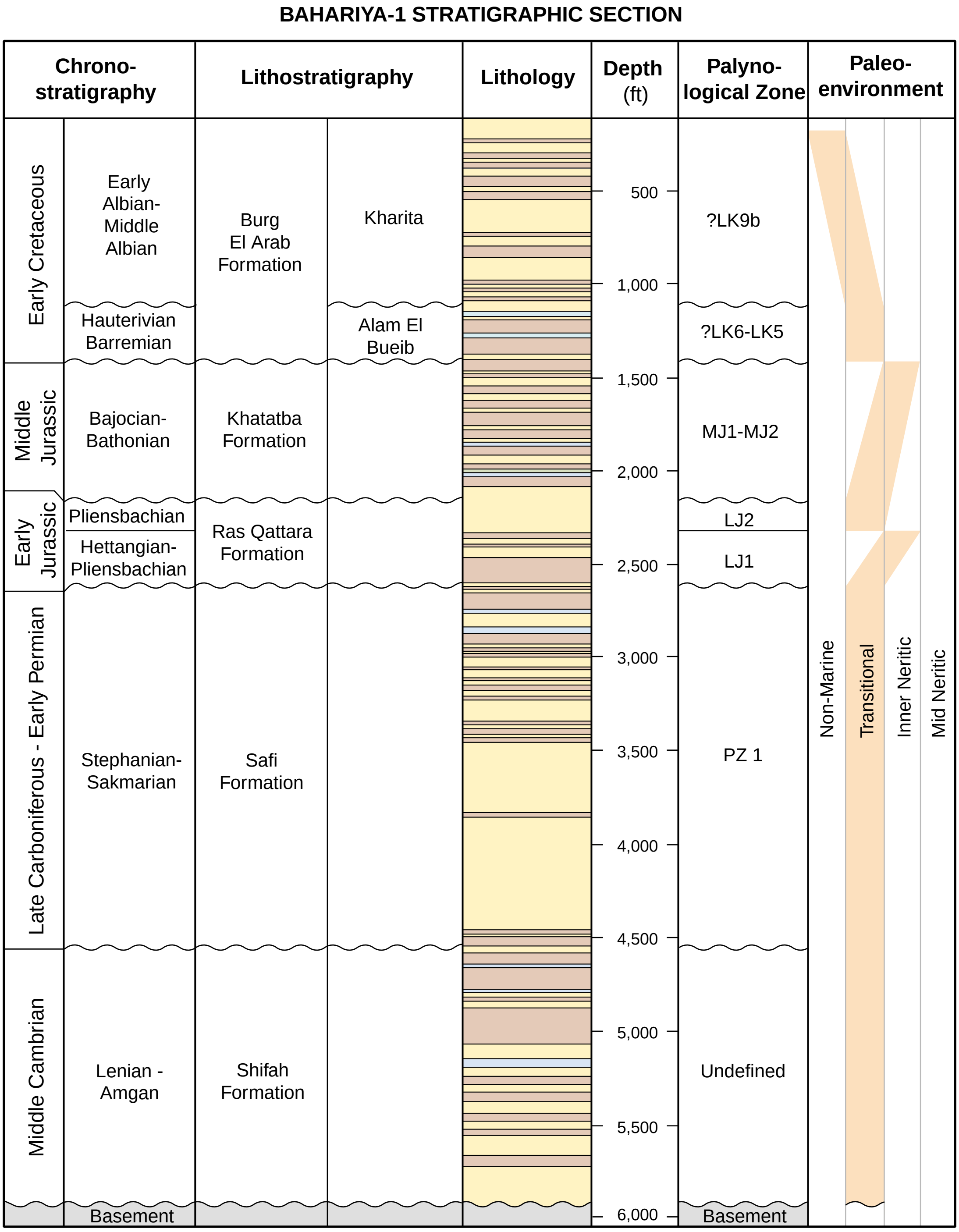


Figure 4: Stratigraphic section in the Bahariya-1 exploratory well after paleontologic checking by Devon Energy Egypt Companies.

Sultan and Halim (1988) divided the Mesozoic and Cenozoic section of the northern Western Desert into four major cycles, each terminated by a marine transgression.

1. The first cycle consists of Lower Jurassic non-marine clastics of the Ras Qattara Formation and the Middle Jurassic Khatatba Formation. Shallow-marine carbonates of the Masajid Formation were deposited in the Late Jurassic and represent the peak of the Jurassic marine transgression. The Masajid Formation was either not deposited on local highs, such as the North Qattara Ridge and the Umbarka Platform, or it was entirely removed by erosion.
2. The second cycle began in the Early Cretaceous with the deposition of shallow-marine clastics at the base of the Alam El Bueib Formation (units 6 and 5) followed by a marine shale unit (unit 4) and a succession of massive fluvial sand bodies separated by marine shale incursions (unit 3). Alternating shale, sandstone, and marine shelf carbonates (units 2 and 1) overlie these sand bodies and culminate in the Alamein Dolomite. The thin Dahab Shale marks the end of this cycle. A major unconformity separates the Masajid Formation of the first cycle from the Alam El Bueib Formation. Similarly, another unconformity separates the Dahab Shale from the Kharita Formation of cycle 3. The Alamein Dolomite was either not deposited on local highs or it was entirely removed by erosion.
3. The third cycle lasted from the-mid Cretaceous (middle Albian) to the early Tertiary. Continental and shoreline sands of the Kharita Formation represent the initial regressive period of sedimentation. The Bahariya Formation was deposited on a shallow-marine shelf during the early Cenomanian. A marked increase in water depth is reflected in the late Cenomanian Abu Roash G member. Widespread transgression and deepening of the sea led to the deposition of the Abu Roash F-A members. The Khoman Formation was deposited above the Abu Roash Formation and its upper member (Khoman-A) is separated from the lower member (Khoman-B) and locally from the Abu Roash Formation by an unconformity. This cycle ended with the deposition of carbonate rocks of the Eocene Apollonia Formation.
4. The uppermost cycle consists of the Dabaa and Moghra marine clastics that are capped by the Marmarica Limestone. The Dabaa Formation was not deposited over local highs and platforms.

The exposed rocks of the Bahariya Depression and its surrounding plateaus range in age from Cenomanian to Middle Miocene (Figures 5 and 6) and belong to the third and fourth sedimentary cycles. They are of sedimentary origin except for basalt flows and dolerite sills and dikes of Middle Miocene age. Part of the Cretaceous section was not deposited in the Bahariya area. A detailed description of the exposed rocks in the study area is given below. Some of the formation names used are informal and were proposed by P. Norton in 1967 in an unpublished report on the rock stratigraphic nomenclature of the Western Desert for the Pan American Oil Company, Cairo. Despite being informal, these formation names are used here because of their common usage by oil companies operating in the Western Desert of Egypt.

Bahariya Formation

The Cenomanian Bahariya Formation (Said, 1962) is the oldest exposed unit in the Bahariya Depression. It is one of the main reservoirs in the oil and gas fields of the northern Western Desert (El Ayouty, 1990); for example, the Razzak, Abu Gharadig, Qarun, and Khalda fields. The Formation has a maximum exposed thickness of 173.5 m and consists of a lower predominantly sandstone member and an upper member of sandstone and variegated shale. The upper member is well exposed in the northernmost part of the Depression at Gebel El Dist and elsewhere, where vertebrate and invertebrate fossils gave an early Cenomanian age (Stromer, 1914) and indicated a fluviomarine environment of deposition. Abdalla and El-Bassyouni (1985) and Soliman and Khalifa (1993) suggested that the depositional environment of the upper member of the Bahariya Formation is near-shore estuarine to subtidal and intertidal with intermittent subaerial exposure. The lower member of the Formation is well exposed in the Sandstone Hills area (Figure 6) on the southeastern edge of the Bahariya Depression, and at Gebel Miteilaa Radwan (western part of the Depression) where it is a highly ferruginous, dark-brown to black fluvial sandstone.

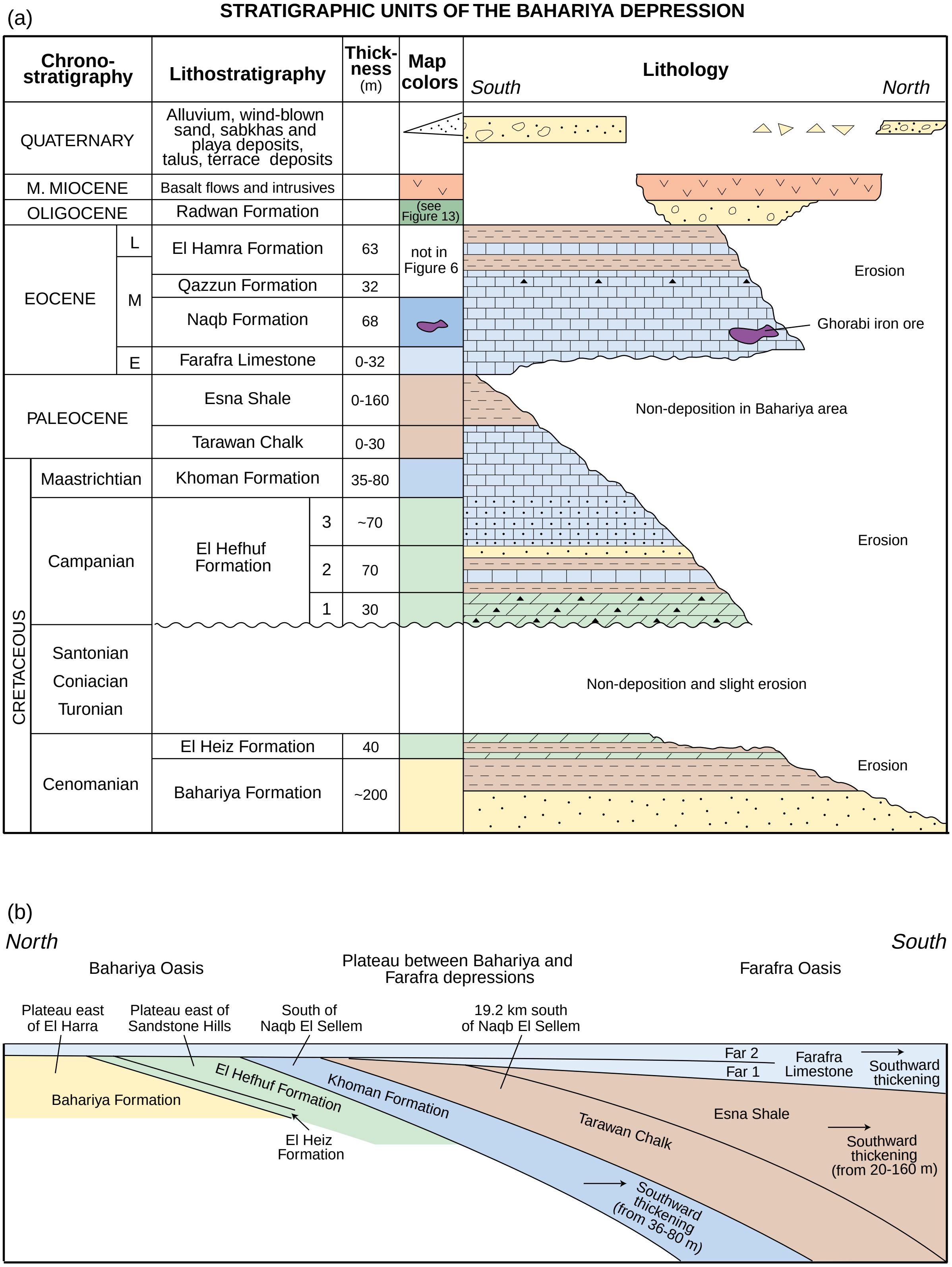


Figure 5: (a) Stratigraphic units exposed in the study area and their distribution in a N-S profile; (b) Schematic diagram (not to scale) showing the southward thickening of the Khoman Formation, Tarawan Chalk, and Esna Shale away from the Bahariya Depression.

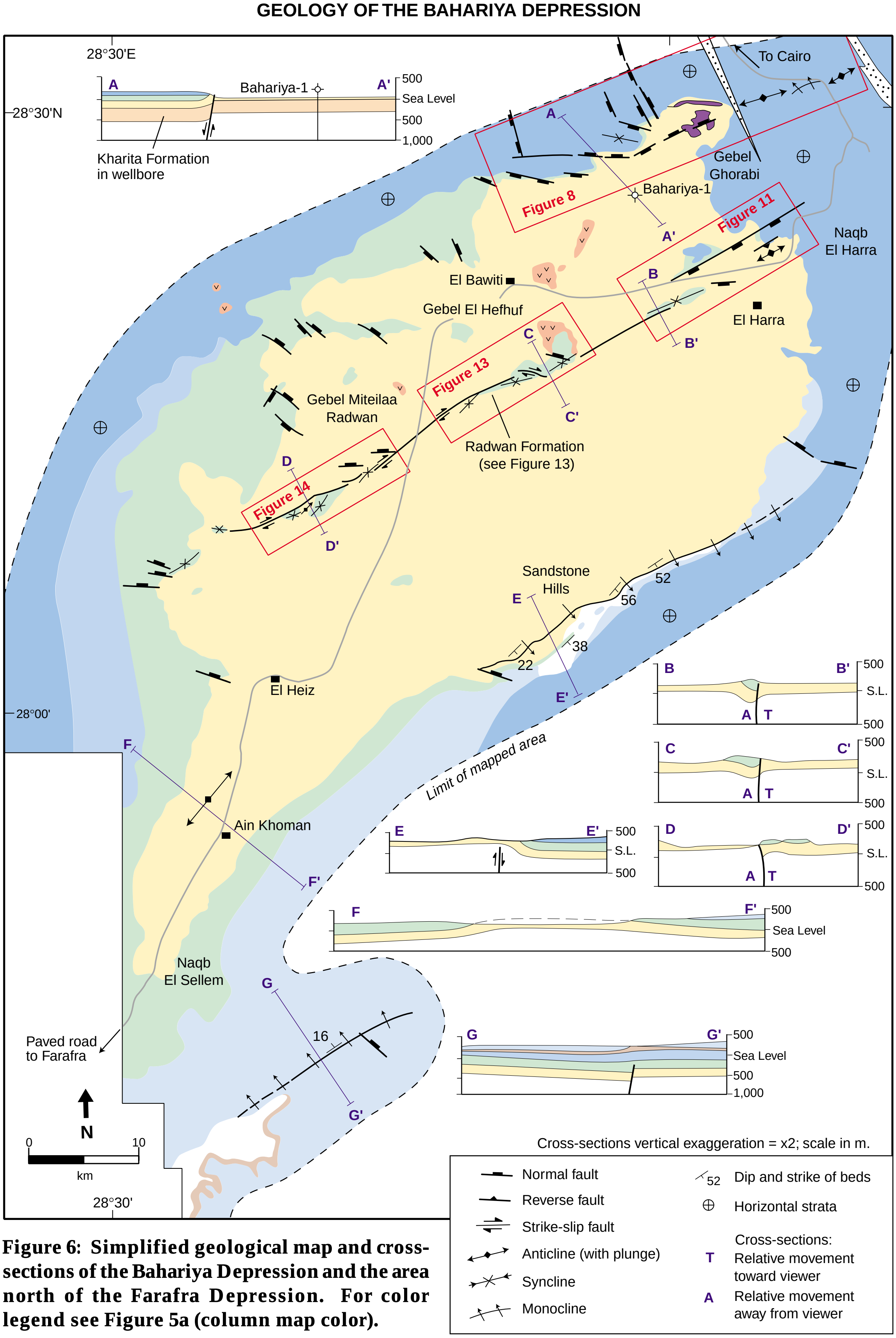


Figure 6: Simplified geological map and cross-sections of the Bahariya Depression and the area north of the Farafra Depression. For color legend see Figure 5a (column map color).

The Bahariya Formation is overlain directly by the Middle Eocene Naqb Formation in the northeastern scarps of the Bahariya Depression and by Middle Miocene basaltic rocks at Gebel Hefhuf and nearby hills in the northern part of the Depression. Elsewhere, the Bahariya Formation is conformable with the overlying upper Cenomanian El Heiz Formation, although El-Akkad and Issawi (1963, p. 19) argued for unconformable relationship between the two formations. Franks (1982) ruled out such an unconformable relationship and attributed the deposition of the El Heiz carbonates over different local lithologies of the underlying Bahariya Formation to the transgressive nature of the El Heiz Formation where it filled channels and channel margins at the top of the Bahariya.

El Heiz Formation

The upper Cenomanian El Heiz Formation (El-Akkad and Issawi, 1963) consists of clastics with occasional carbonate interbeds. A characteristic dolostone bed with calcite geodes marks the top of the Formation that was deposited in a shallow-marine environment. The El Heiz Formation is about 40 m thick at Naqb El Sellem in southernmost part of the Depression, but it decreases in thickness to about 12 m in the northern scarp. The Formation is stratigraphically equivalent to the Abu Roash ‘G’ member in the informal rock stratigraphic nomenclature of the northern Western Desert. Locally, it is overlain by the Middle Eocene Naqb Formation.

El Hefhuf Formation

The El Hefhuf Formation (El-Akkad and Issawi, 1963) is of Campanian age (Ball and Beadnell, 1903; Issawi et al., 1996). In this study it has been divided into the following three mappable units:

1. A basal 30-m-thick hard, light-brown siliceous dolomite that contains rounded chert concretions;
2. A middle unit (about 70 m thick) consists of interbedded yellow and brown limestone, marl, shale, and sandstone with a characteristic dark-brown phosphatic sandstone marker bed at the top; and
3. An upper unit (about 70 m thick) is a massive, grayish-brown to buff sandy, dolomitic limestone.

Stratigraphically, the Formation is equivalent to the lower part of the Khoman Formation of the northern Western Desert. The El Hefhuf Formation is unconformably overlain by Tertiary rocks except in southern escarpment where it is conformably overlain by the Maastrichtian chalk of the Khoman Formation.

Khoman Formation

El-Akkad and Issawi (1963) assigned the Khoman Formation (informally named by P. Norton in 1967 in an unpublished report to Pan American Oil Company, Cairo) to the early Maastrichtian. Subsurface sections of the Formation in the northern Western Desert have a Santonian to Maastrichtian age (Schlumberger, 1984). The Khoman Formation consists of massive white chalk and is 30 to 45 m thick in the western escarpment of the Bahariya Depression (Ball and Beadnell, 1903 and Zaghloul et al., 1993). Stratigraphically, the Khoman of the Bahariya Depression is equivalent to the Khoman-A member of the northern Western Desert. The Formation is widely distributed in the northern and central Western Desert and major variations in thickness are in response to Late Cretaceous deformation, as will be discussed later.

Tarawan Chalk

The Tarawan Chalk (Awad and Ghobrial, 1965) consists of chalky limestone and limestone and is of Early Paleocene age (Issawi et al., 1996). It is exposed to the south of the Bahariya Depression where it is 20 to 30 m thick. On the northern slope of the Farafra Depression the Tarawan Chalk lies between the Khoman Formation and the Esna Shale.

Esna Shale

The Esna Shale (Beadnell, 1905; Said, 1960) is of Late Paleocene age and is absent due to non-deposition in the Bahariya Depression and its bounding scarps. It is only exposed in the southern scarps of the plateau that separates the Bahariya and Farafra depressions (Figure 6) where it is about 20 m thick and is made up of a greenish-gray to gray shale. Farther south (outside the mapped area), the Esna Shale abruptly increases in thickness to be 120 to 160 m thick in the Farafra Depression (Said, 1962).

Eocene Succession

The Eocene rocks of the mapped part of the Bahariya Depression consist of the Farafra Limestone and the Naqb Formation. The Lower Eocene Farafra Limestone (Said, 1960) is exposed in the eastern and southern escarpments of the Bahariya Depression and farther south. It has a maximum exposed thickness of 34 m in the Farafra Depression (Said, 1962). It consists of two members in the plateau that separates the Bahariya and Farafra depressions but only the upper member (Far 2) is exposed in the Bahariya Depression.

The upper member of the Farafra Formation overlies several units in the mapped area (Figure 5b). It overlies the Bahariya Formation in the escarpment east of El Harra, rests on an eroded section of the El Hefhuf Formation on the plateau east of the Sandstone Hills, and overlies the Khoman Formation south of Naqb El Sellem. Farther south, the lower unit, Far 1, lies between Far 2 and the Tarawan Chalk. Southward again (at about 19 km south of Naqb El Sellem), Far1 rests on the Esna Shale.

The lower Middle Eocene Naqb Formation is 68 m thick and consists of pinkish-gray, hard, siliceous dolomitic limestone that is unconformable on various units in the Bahariya area (Said and Issawi, 1964). Iron-bearing solutions have replaced the carbonate rocks of the Naqb to form deposits of iron ore in the El Gedida, Gebel Ghorabi, Nasser, and El Harra areas of the northeastern Bahariya Depression (El Bassyony, 1980).

Outside the mapped area, the 32-m-thick Middle Eocene Qazzun Formation conformably overlies the Naqb Formation (Said and Issawi, 1964). It consists of white to gray chalky nummulitic limestone that contains spherical siliceous concretions at the top.

The Middle to Upper Eocene El Hamra Formation (Said and Issawi, 1964) is 63 m thick and conformably overlies the Qazzun Formation. Yellow to yellowish-brown, highly fossiliferous limestone beds with a few clastic intercalations have been eroded into isolated hills on the eastern plateau of the Bahariya Depression. The hills are formed from reefs built by pelecypods and gastropods and the upper beds dip inward at angles of up to 40° to form saucer-like outcrops.

The stratigraphic relationships and southward increase in thickness of the Khoman Formation, Esna Shale, and Farafra Limestone indicate that the southern and southeastern parts of the Bahariya Depression contain a thick Tertiary section that probably represents the northern rim of the Dakhla basin of EGPC (1992). Within this thick Tertiary section, all rock units lying between the base of the Khoman Formation and the top of the Farafra Limestone increase in thickness toward the south and southeast. The Khoman Formation is 35 to 40 m thick in the western escarpment of the Bahariya Depression but 80 m thick in the Farafra (Issawi et al., 1996). Similarly, the Esna Shale increases in thickness from 20 m at about 19 km south of Naqb El Sellem to 120 to 160 m in the Farafra Depression (Said, 1962). The Tarawan Chalk and Farafra Limestone also increase in thickness southward.

Radwan Formation

Flat-lying beds of the Radwan Formation unconformably overlie the Eocene rocks on the eastern plateau of the Bahariya Depression outside the mapped area. It also forms a small outcrop on the southern margin of the El Harra-El Hefhuf segment of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. The Formation is of Oligocene age (El-Akkad and Issawi, 1963; Said and Issawi, 1964) and is composed of ferruginous grits and beds of pale-brown to yellow sandstone and clayey sandstone.

Middle Miocene Igneous Rocks

Several small outcrops of basalt occur in the northern and central parts of the Bahariya Depression. The basalt in Gebel El Hefhuf is a large sill intruded at the contact between the Bahariya and El Heiz formations.

Basaltic rocks in the other localities may be remnants of the same sill. A WNW-oriented dolerite dike and a small laccolith also occur in Gebel El Hefhuf. Basalt flows overlie Eocene rocks to the north and northwest of the Bahariya Depression (El-Etr and Moustafa, 1978) and to the east (Amer, 1973).

Petrographically, the volcanic rocks are olivine basalts (El-Akkad and Issawi, 1963). They were assigned an Oligocene age by Ball and Beadnell (1903) and El-Akkad and Issawi (1963) based on their stratigraphic position and their similarity to the basalts of the Abu Roash, Gebel Qatrani, and El Bahnasa areas. However, potassium-argon dating by Meneisy and El Kalioubi (1975) and Meneisy (1990) indicated an age of 15 to 20 Ma (Middle Miocene).

Quaternary

Quaternary sediments in the Bahariya are gravel terraces, talus, sabkha and playa deposits, wind-blown sand, and alluvium. They occur within the Depression and scattered over the surrounding plateaus.

STRUCTURAL SETTING

Structural data were gathered during the detailed field mapping of the Bahariya Depression and the northeastern part of the Farafra Depression (Figure 6). A total of 93 mapped faults belong to two sets. The main set is oriented east-west to east-northeast (N70°–90°W and N50°–80°E), and a subordinate set is oriented northwest (N40º–60°W) (Figure 7a). The two have different senses of slip. The E-W to ENE-oriented faults had two phases of movement (to be discussed below). They consist of right-lateral strike-slip faults in addition to two reverse faults (Figure 7e), whereas the NW-oriented faults have normal slip. The measured data from 14 fault surfaces indicated a steep angle of fault dip that usually exceeded 60º (Figures 7b,e).

A total of 56 folds mapped in the Bahariya Depression have a predominantly northeasterly (N30°–70°E) orientation and a N40-50°E preferred orientation (Figure 7c). The largest are at Gebel El Hefhuf and in the area between El Heiz and Ain Khoman (Figure 6). The mapped folds generally have a right-stepped en echelon arrangement that indicates deformation by a dextral shear couple (Wilcox et al., 1973).

A total of 21 monoclinal segments was mapped in the study area and shows a predominantly east-northeasterly orientation (Figure 7d). Two major monoclines occur—one in the southeastern part of the Bahariya Depression (Sandstone Hills monocline) and the other in the northeast of the Farafra Depression (North Farafra monocline) (Figure 6). The steep flank of the Sandstone Hills monocline dips as much 56°SE, whereas that of the North Farafra monocline dips at up to 16°NW and affects the exposed Paleocene and Eocene rocks. The two monoclines overlie deep-seated faults.

STRUCTURAL BELTS

The structures of the Bahariya Depression and the northeastern part of the Farafra Depression form four distinct ENE-oriented structural belts (Figure 6). Of these, the Gebel Ghorabi, Gebel Radwan-Gebel El Hefhuf-El Harra, and Sandstone Hills structures define the shape of the Bahariya Depression. The fourth (southernmost) belt lies between the Bahariya and Farafra depressions and is named the Northeast Farafra structural belt.

Gebel Ghorabi Structural Belt

The Gebel Ghorabi structural belt extends in a east-northeasterly direction for about 36 km in the northernmost part of the Bahariya Depression (Figure 6). It affects the Eocene rocks of the northeastern plateau, and to the west-southwest it controls the northern scarp of the Depression (Figure 8).

The best-exposed part of the structure is an ENE-oriented fault that cuts the central part of Gebel Ghorabi. This fault displaces the southern part of Gebel Ghorabi downward and shows two phases of movement. The earlier movement is indicated by the southward dip of the Bahariya Formation on the

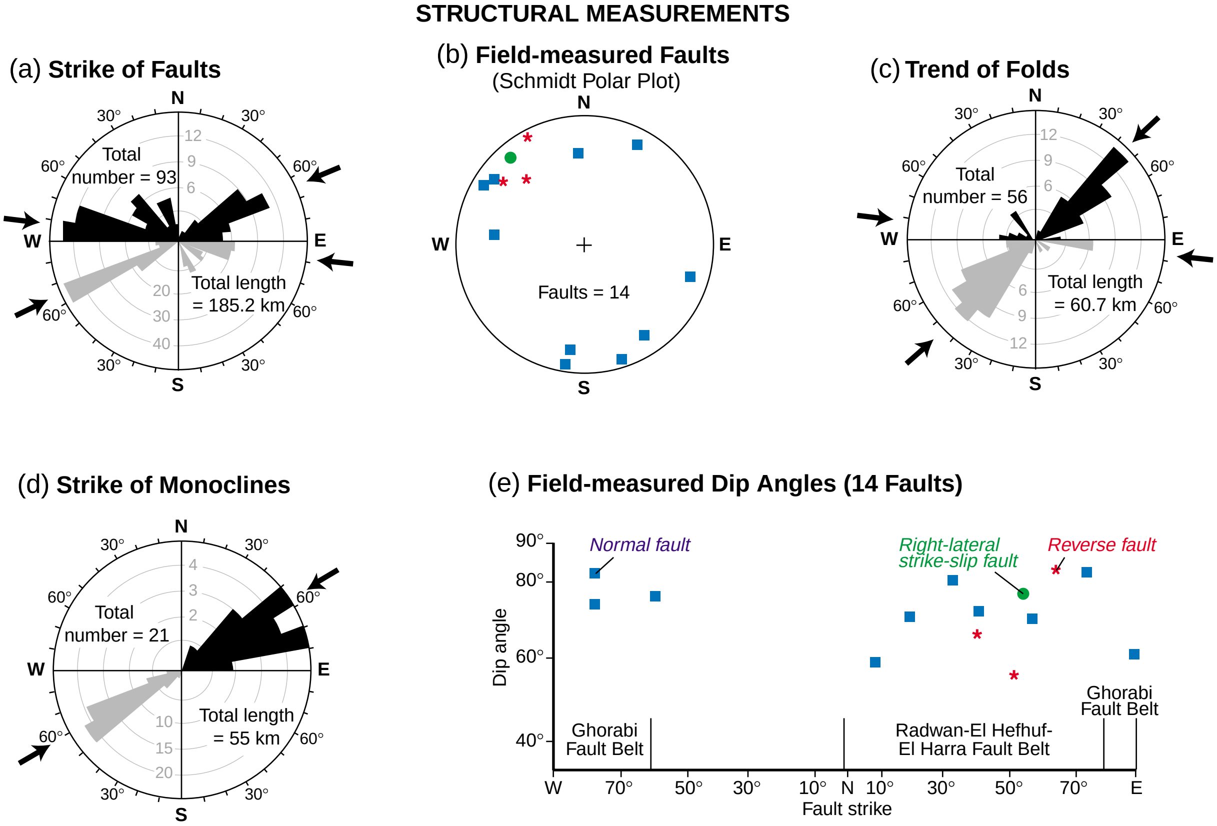


Figure 7: Attitude statistics of surface structural elements in the Bahariya depression. (a) Strike summary plot showing fault frequency distribution (black) and cumulative length distribution (gray); (b) Schmidt plot of measured fault attitudes (lower-hemisphere equal-area projection); (c) Strike summary plot of fold axis frequency distribution (black) and cumulative length distribution (gray); (d) Strike summary plot of monocline axis frequency distribution (black) and cumulative length distribution (gray); (e) Dip-angle versus fault-orientation diagram illustrating the regional distribution of the faults depicted in (b) above.

southern side of the fault due to drag. Iron-rich beds of the Middle Eocene Naqb Formation unconformably overlie the dipping Bahariya beds. This indicates that the early phase of slip movement was post-Cenomanian and pre-Middle Eocene. The second phase of movement was post-Middle Eocene and caused the southward displacement of the ironstones.

The Gebel Ghorabi Fault dips at 62°S. A steeply dipping reverse fault in the westernmost part of Gebel Ghorabi makes an acute angle with the Gebel Ghorabi Fault. To the southeast of this reverse fault, the Bahariya Formation has a southeastward dip whereas to the west of the reverse fault, it dips to the north-northwest (Figure 8). These opposing dip directions probably indicate the two flanks of a NE-trending anticline that is parallel to the reverse fault. The acute angle enclosed between the Gebel Ghorabi Fault and both the anticline and the reverse fault probably indicates that right-lateral strike-slip movement occurred in the first phase of movement on the Fault.

The eastern segment of the structure affects the Middle Eocene rocks on the eastern plateau of the Depression. It is represented by several folds and monoclines that have a right-stepped, en echelon configuration (Figures 8 and 9). The individual folds and monoclines have northeasterly to east-northeasterly orientations and generally gentle to moderate dips. The right-stepped en echelon arrangement of the folds indicates post-Middle Eocene right-lateral strike-slip movement on the Gebel Ghorabi structural belt. One of the en echelon folds of this belt is cut by an E- to ENE-oriented right-lateral strike-slip fault that has 150 m of horizontal displacement (Figure 9).

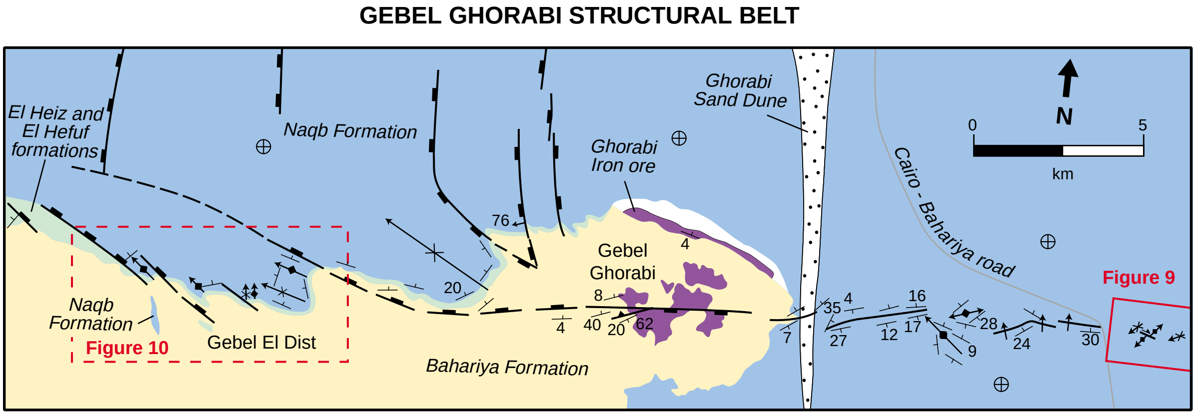


Figure 8: Simplified geological map of the Gebel Ghorabi structural belt. See Figure 6 for location and symbols.

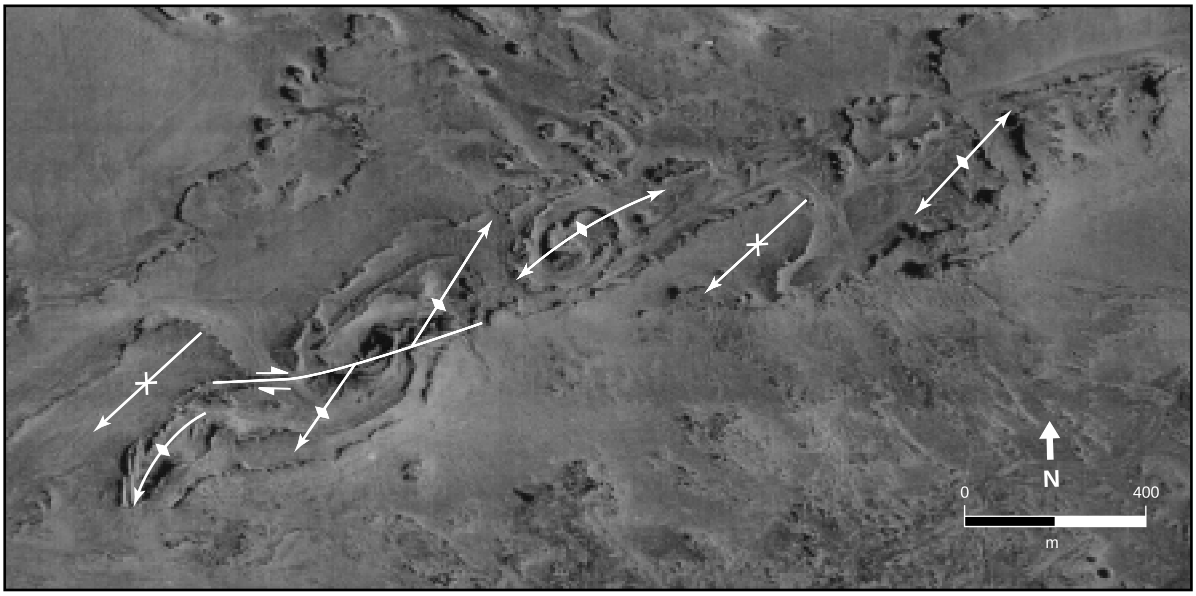


Figure 9: Vertical aerial photograph showing the right-stepped en echelon arrangement of doubly plunging folds affecting the Middle Eocene rocks at the northeastern part of the Gebel Ghorabi structural belt. Note the ENE-oriented right-lateral strike-slip fault that cuts one of the folds. See Figure 8 for location.

The western segment of the Gebel Ghorabi structural belt consists of W- to WNW-oriented, left-stepped en echelon faults (Figure 8). The faults have apparent normal slips and form horst-and-graben structures. Several anticlines and synclines that occur between the overlapping ends of the en echelon faults were formed by the drag of the beds in the vicinity of the faults. Thus, anticlines overlie horst blocks due to drag of the beds on the upthrown sides of the faults whereas synclines occur within the grabens due to drag on the downthrown sides of the faults. The plunge of the folds is related to a dip direction perpendicular to the faults themselves and represents relay ramps between the ends of the en echelon faults (Figure 10).

The structural data indicate that the first phase of movement on the Gebel Ghorabi structural belt was post-Cenomanian to pre-Middle Eocene and was followed by a post-Middle Eocene phase. Both phases consisted of right-lateral strike-slip movements. In the case of the second phase, it is indicated by the en echelon folds in the eastern segment of the belt and the en echelon faults in the western segment.

Gebel Radwan-Gebel El Hefhuf-El Harra Structural Belt

This structural belt is 65 km long and is the longest in the Bahariya Depression. It extends from the western plateau southwest of Gebel Miteilaa Radwan to the eastern plateau at Naqb El Harra (Figure 6). It has four main left-stepped en echelon ENE-oriented segments. From east to west they are the Gebel Tobog, El Harra-El Hefhuf, Gebel Radwan, and Western Plateau segments. The El Harra-El Hefhuf and Gebel Radwan segments are partly joined by a NE-oriented fault that extends southwest from Gebel Qalaa Siwa.

The structural belt includes several right-stepped en echelon folds that affected the Bahariya, El Heiz, and El Hefhuf formations and indicate an early phase of movement in the Late Cretaceous. A few related faults that also cut Eocene rocks on the eastern plateau to the north of Naqb El Harra indicate a second, but weaker, phase of tectonic activity.

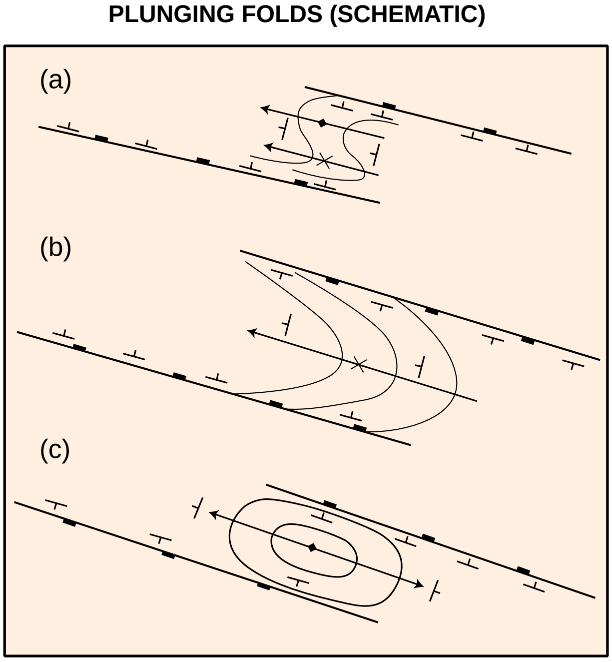


Figure 10: Formation of plunging folds (schematic) between the overlapping ends of left-stepped en echelon normal faults in the Gebel El Dist area of the Gebel Ghorabi structural belt. See Figure 8 for approximate location.

Gebel Tobog Segment

This fault segment extends from the southern side of Gebel Tobog to the eastern plateau of the Bahariya Depression. It has an east-northeast orientation and affects the Upper Cretaceous rocks of Gebel Tobog and the eastern scarp of the Depression as well as the Middle Eocene Naqb Formation on the eastern plateau (Figure 11). The Naqb Formation unconformably overlies the Bahariya Formation on the northern side of the fault and the El Hefhuf formation on the southern side of the fault, thus indicating two phases of fault movement. The first phase led to the relatively lower structural elevation of the El Hefhuf Formation on the southern side of the fault, whereas it was eroded from the northern (structurally higher) side before the deposition of the Naqb Formation. The second phase of movement took place after the deposition of the Naqb Formation and its effect is seen in the eastern plateau to the north of Naqb El Harra where the Naqb Formation is cut by the fault belt.

To the south of the Gebel Tobog Fault segment is a NE-oriented reverse fault that affects the Bahariya Formation west of Naqb El Harra (Figure 11). The reverse fault strikes N55°E and dips 72°SE. It is associated with a hanging-wall anticline and a footwall syncline in the Bahariya Formation. The steep flank of the footwall syncline is truncated and unconformably overlain by flat-lying to very gently dipping beds of the Naqb Formation (Figure 12) indicating a post-Cenomanian to pre-Middle Eocene displacement on the reverse fault. The amount of throw on the reverse fault is relatively large so that the lower member of the Bahariya Formation is juxtaposed against its upper member. El Bassyony (1978) mapped the same anticline, which he named the El Harra anticline, in the hanging wall of the reverse fault but without the reverse slip on the fault. He also mapped another anticline of the same orientation further to the northeast (his El Gedida anticline). The El Harra and El Gedida anticlines have a right-stepped en echelon arrangement perhaps due to the effect of a Late Cretaceous right-lateral shear couple.

El Harra-El Hefhuf Segment

This 23-km-long fault segment is the longest in the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt (Figure 6). At Gebel El Hefhuf, the fault segment is associated with ENE-oriented faults and related folds in the Upper Cretaceous rocks (Figure 13).

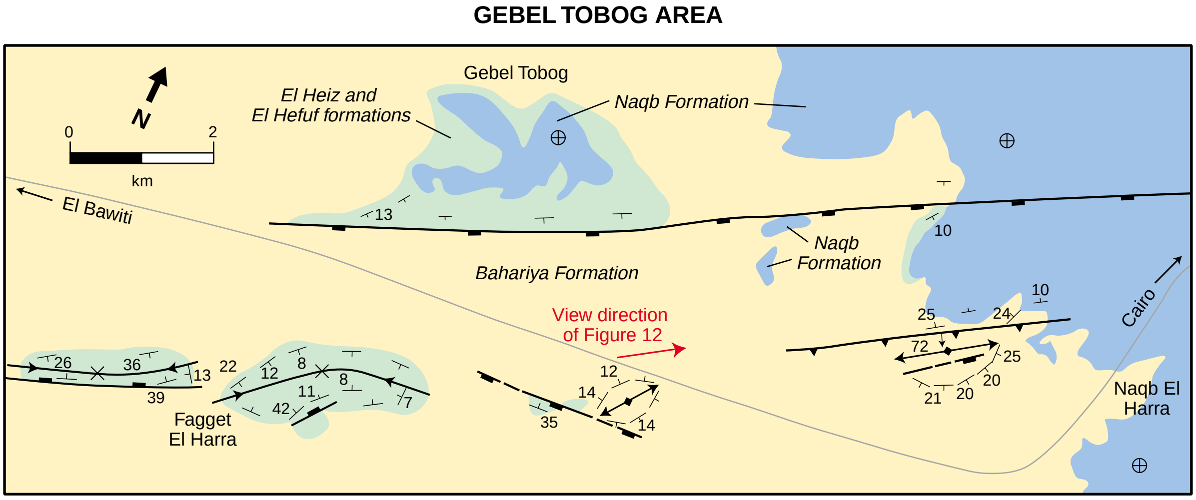


Figure 11: Simplified geological map of the Gebel Tobog segment and the eastern part of the El Harra-El Hefhuf fault segment of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. See Figure 6 for location and symbols.

The El Hefhuf-El Harra fault segment dips at 81°NW and its northern (downthrown) side is folded by a fault-drag syncline in which a complete section of the El Hefhuf Formation is preserved. The central part of Gebel El Hefhuf is also folded by a fault-drag syncline on the northern (downthrown) side of the fault. Farther to the west, the syncline lies within a graben.

The Gebel El Hefhuf syncline is oriented east-northeast subparallel to the fault but to the east it changes its orientation to northeast and makes an acute angle with the fault. To the east of the syncline is a southward plunging anticline that also makes an acute angle with the Gebel El Hefhuf fault. A WNW-oriented right-lateral strike-slip fault cuts the Upper Cretaceous rocks in the central part of Gebel El Hefhuf. This fault offsets an anticline and displaces its crest for about 500 m. To the southwest of Gebel El Hefhuf, the El Harra-El Hefhuf fault segment cuts the Bahariya Formation and on its southern side are three NE-oriented, right-stepped en echelon folds (Figure 13).

Several NW-oriented normal faults of short length and small throw are present in the northeastern part of Gebel El Hefhuf and indicate NE-SW lengthening. A large dolerite sill associated with a WNW-oriented dike and a small laccolith intrude the northeastern part of the gebel and are the result of Middle Miocene tectonic activity.

Gebel Radwan Segment

The segment is about 15 km long to the south and southwest of Gebel Miteilaa Radwan. It consists of two ENE-oriented parts and one oriented northeast (Figure 14). It is joined to the Gebel El Hefhuf segment by a NE-oriented fault that runs from Gebel Qalaa Siwa to the southern side of Gebel Miteilaa Radwan. This fault is generally oriented N49°E and dips at between 70°NW and 78°SE. Slickenlines on the fault surface plunge 7° toward S49°W which, in association with chatter marks, indicate a predominantly right-lateral strike-slip movement on the fault.

The Gebel Radwan fault segment is associated with several NE-oriented folds that have right-stepped en echelon arrangement at acute angles with the fault (Figure 15). As at Gebel El Hefhuf, the axes of the large folds are subparallel where they are close to the fault but away from the fault they are at acute angles. These and similar folds associated with strike-slip faults were named drag folds by Moody and Hill (1956) and renamed parafolds by Youssef (1968).

Western Plateau Segment

The southwestern segment of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt is about 4.5 km long and affects the Upper Cretaceous rocks of the western plateau of the Bahariya Depression

NAQB EL HARRA REVERSE FAULT

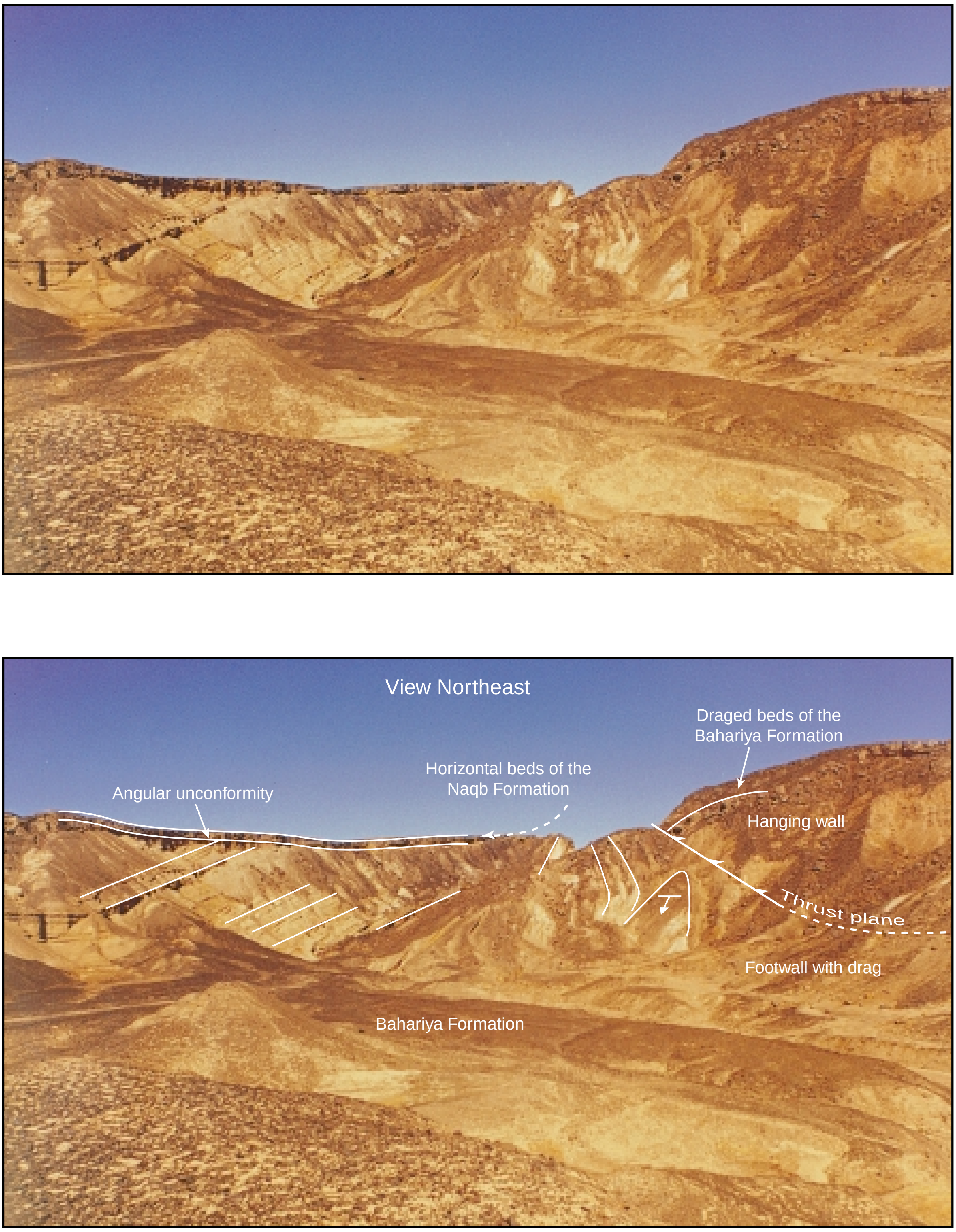


Figure 12: Field photograph showing the reverse fault in the vicinity of Naqb El Harra and east of Gebel Tobog. Steeply dragged beds of the Bahariya Formation close to the fault in its footwall are marked with a dip/strike symbol. Note the angular unconformity between the dragged beds of the Bahariya Formation and the horizontal beds of the Middle Eocene Naqb Formation indicating pre-Middle Eocene movement on the fault. See Figure 11 for location.

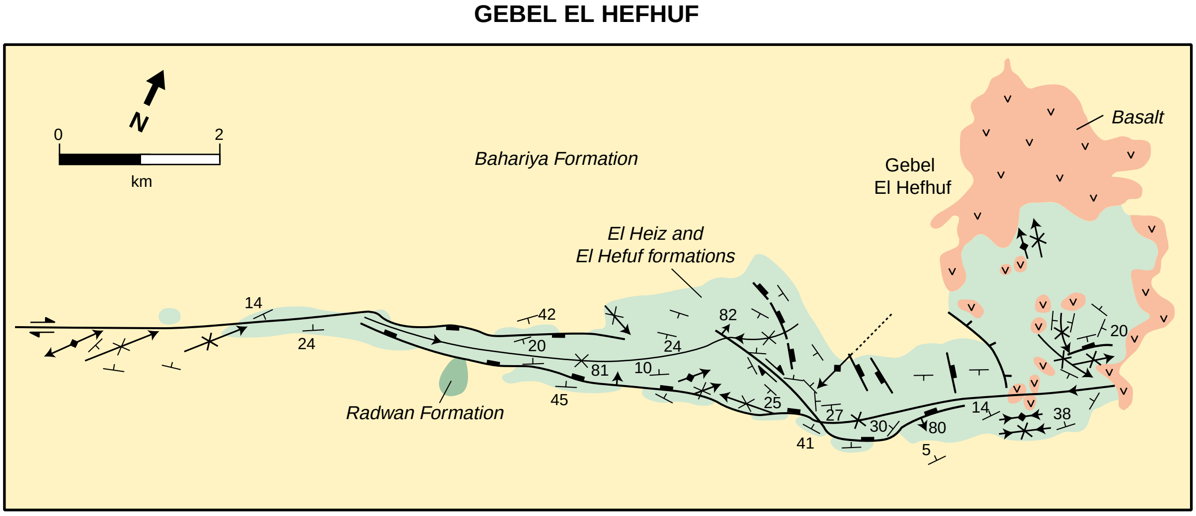


Figure 13: Simplified geological map of Gebel El Hefhuf. See Figure 6 for location and symbols.

(Figure 6). It is represented mainly by an ENE-oriented asymmetric syncline that has a gently dipping (5°) northern limb and a steeply dipping (35°-74°) southern flank. The syncline changes direction at its northeastern end to trend northeast where it becomes parallel to the folds associated with the Gebel Radwan fault segment. Several WNW-oriented normal faults lie to the west of the syncline and cut the Upper Cretaceous rocks of the western plateau.

Phases of Deformation

The data presented above indicated that two phases of deformation affected the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt as follows:

- The earlier phase was the stronger of the two and took place after the deposition of the El Hefhuf Formation and before the deposition of the Middle Eocene Naqb Formation; therefore it was post-Campanian and pre-Middle Eocene in age. This phase of deformation consisted of right-lateral strike-slip movement as indicated by the nearly horizontal slickensides on some faults in the structural belt, and by the right-stepped en echelon folds that make acute angles with the fault segments (Wilcox et al., 1973).
- The second phase of deformation was post-Middle Eocene in age as indicated at the eastern end of the Gebel Tobog Fault where the Naqb Formation in the eastern plateau to the north of Naqb El Harra is faulted. The sense of slip on the faults was not easy to determine because of the lack of Eocene exposures within the structural belt.

Sandstone Hills Structural Belt

The Sandstone Hills structural belt is a 32-km-long, ENE-oriented monocline on the southeastern side of the Bahariya Depression. The monocline controls the orientation of the southeastern scarp of the Depression (Figure 6) and has a relatively steep flank with an average dip of 30°SE and a maximum dip of 56° on the southeastern side of the Sandstone Hills. The monocline affects the Upper Cretaceous rocks that are unconformably overlain by the Lower Eocene Farafra Limestone, thus indicating post-Campanian-pre-Early Eocene folding (Figure 6, cross-section E-E'). The Sandstone Hills monocline is most probably underlain by a deep-seated ENE-oriented fault and was formed by the drape of the Cretaceous rocks over this fault (Stearns, 1971). A large NE-oriented doubly plunging anticline to the southwest of the Sandstone Hills monocline affects the Upper Cretaceous rocks in the southwestern part of the Bahariya Depression in the Ain Khoman area (Figure 6, cross-section F-F'). The fold makes an acute angle with the extension of the Sandstone Hills monocline.

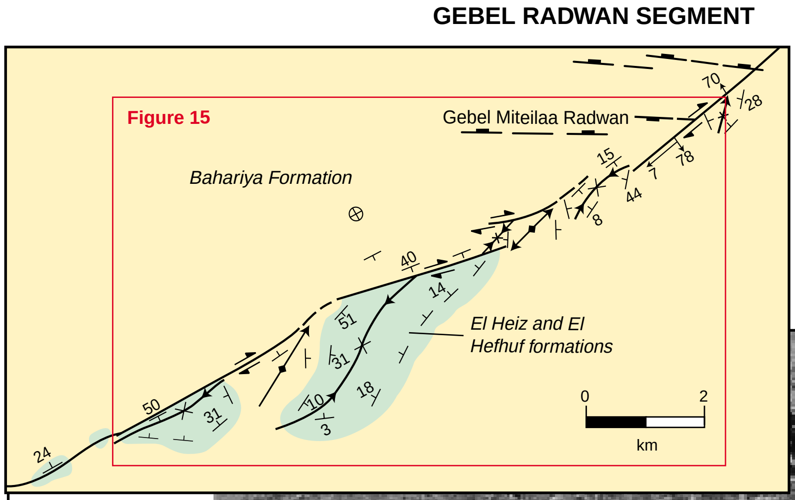


Figure 14: Simplified geological map of the Gebel Radwan segment of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. See Figure 6 for location and legend.

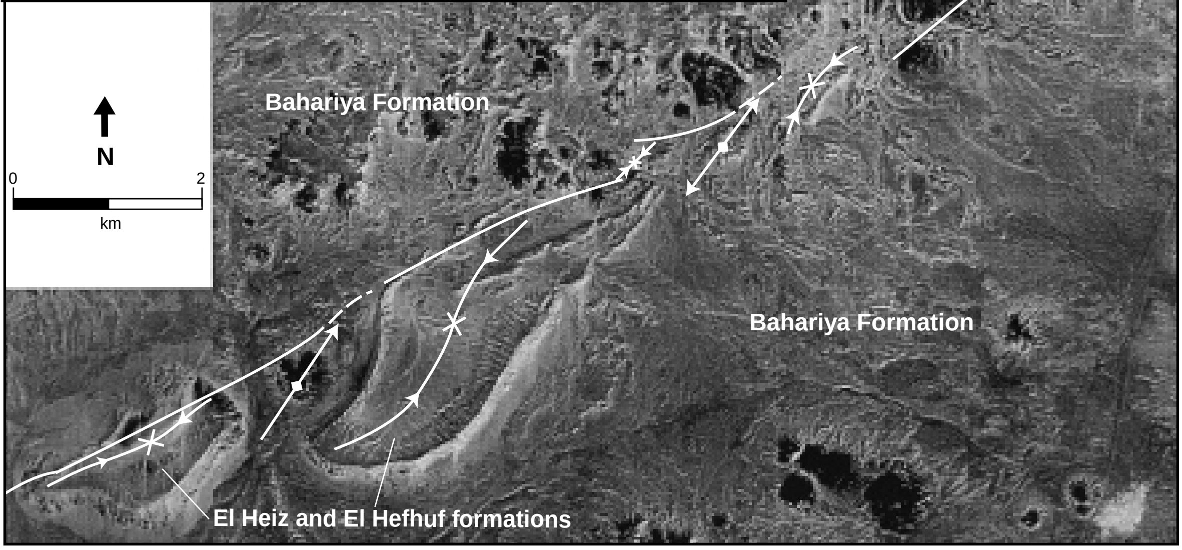


Figure 15: Vertical aerial photograph showing NE-oriented folds associated with right-lateral strike-slip faults in the Gebel Radwan segment of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. Note the right-stepped en echelon arrangement of the folds and the acute angles that they make with the faults.

Northern Farafra Structural Belt

The Northern Farafra structural belt is a 20-km-long, ENE-oriented monocline that affects the Paleocene and Lower Eocene exposures in the plateau between the Bahariya and Farafra Depressions (Figure 6). The steep flank of the monocline has a maximum dip of 16°NW. It occurs in a thick section of Upper Cretaceous (Khoman Formation), Paleocene, and Lower Eocene rocks. Landsat satellite imagery indicates that the monocline may extend southwestward for at least 100 km to the northern side of El Quss Abu Said at the northern scarp of the Farafra Depression (see Figure 2). The east-northeasterly orientation of this monocline, as with the other structural belts of the Bahariya Depression, suggests that it is underlain by an ENE-oriented fault. A minor NW-oriented normal fault on the southern side of the monocline indicates lengthening in a NE-SW direction, as elsewhere in the Bahariya Depression.

STRUCTURAL ANALYSIS

Most of the mapped structures in the Bahariya Depression are located within four ENE-oriented structural belts, whereas the intervening areas are undeformed or only slightly deformed. The four structural belts are controlled by deep-seated faults (see below).

Three phases of structural deformation affected the exposed Cretaceous and Eocene rocks in the Bahariya region and led to the rejuvenation of the deep-seated faults. They are post-Campanian to pre-Early Eocene (mostly Late Cretaceous), post-Middle Eocene, and Middle Miocene. Dating of the earliest deformation is based on the presence of an angular unconformity between the Eocene rocks (both Lower Eocene Farafra Limestone and Middle Eocene Naqb Formation) and the underlying Upper Cretaceous rocks, especially the Bahariya, El Heiz, and El Hefhuf formations. Additional data from the southwestern plateau of the Bahariya Depression constrain the age of this earliest phase of deformation. At that locality, the topmost part of the Campanian El Hefhuf Formation is eroded and is unconformably overlain by the Maastrichtian Khoman Formation. This indicates that the deformation is post-Campanian and pre-Maastrichtian and is therefore contemporaneous with the main phase of Late Cretaceous deformation in the northern Western Desert (Shukri, 1954; Said, 1962; Abdine, 1974; Sultan and Halim, 1988; Moustafa, 1988; Hantar, 1990). The second (post-Middle Eocene) phase of deformation is shown in the Gebel Ghorabi structural belt by structures that affect the Naqb Formation and older rocks. The third phase of deformation is contemporaneous with Middle Miocene igneous activity.

Late Cretaceous Deformation

Structures formed by the Late Cretaceous deformation are apparent in the structural belts of Gebel Ghorabi, Gebel Radwan-Gebel El Hefhuf-El Harra, and the Sandstone Hills. Two different structural styles affected the Upper Cretaceous rocks in these areas. The Sandstone Hills monocline shows deformation by fault-propagation folding over a deep-seated ENE-oriented fault, whereas Late Cretaceous deformation in the Gebel Ghorabi fault belt and the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt was related to right-lateral strike-slip movement. The strike-slip movement is indicated by:

- NE-oriented folds making an acute angle with the ENE-oriented right-lateral strike-slip faults as at Gebel Ghorabi, or having right-stepped, en echelon alignments as in the Gebel Radwan and Gebel El Hefhuf areas.
- NE-oriented reverse faults.
- WNW-oriented right-lateral strike-slip faults (Riedel shears) as in Gebel El Hefhuf.
- NW-oriented normal faults affecting the areas north of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt and north of the Gebel Ghorabi structural belt. El Bassyony (1978) also reported the presence of NW-oriented normal faults in the plateau to the southeast of Gebel Ghorabi where they affect the Bahariya and El Heiz formations but not the overlying Middle Eocene Naqb Formation.

These structures represent second-order wrench structures (Wilcox et al., 1973) related to the effects of an ENE-oriented right-lateral shear couple. The magnitude of the shear couple deformation in the Bahariya area was probably not large, as indicated by the lack of evidence for strong deformation between the long, en echelon fault segments of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. For example, if the magnitudes of strike-slip movement on these fault segments had been large, one would expect to find significant compressional (push-up) structures between the ends of the fault segments, but this is not the case.

Post-Middle Eocene Deformation

The effects of the post-Middle Eocene deformation are seen in the Gebel Ghorabi structural belt and the North Farafra monocline. The monocline was formed by the draping of the rocks over a probable deep-seated fault lying parallel to the monoclinal axis (Stearns, 1971). The structures in the Gebel Ghorabi structural belt are NE- to ENE-oriented, right-stepped, en echelon folds that have affected the Naqb Formation, and WNW-oriented, left-stepped, en echelon normal faults in the plateau on the northern side of the Bahariya Depression. These structures show that a dextral shear couple caused the post-Middle Eocene deformation in the Gebel Ghorabi structural belt. However, the absence of Riedel (R-) shears and conjugate Riedel (R'-) shears suggests that the shear-couple deformation was only in its early stages.

Late Cretaceous and Post-Middle Eocene Contrasting Structural Styles

The Late Cretaceous deformation formed a monocline in the Sandstone Hills area and second-order wrench faults in the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt. The post-Middle Eocene deformation also formed a monocline in the North Farafra area in contrast to the second-order wrench structures in the Gebel Ghorabi structural belt. These contrasting styles of deformation indicate that it was mainly fault-propagation folding that deformed the southern part of the Bahariya region (North Farafra area and the Sandstone Hills area). On the other hand, the northern part (the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt and the Gebel Ghorabi structural belt) was deformed by oblique-slip movement with a right-lateral strike-slip component. Such a contrast in structural styles is probably related to the following causes:

1. The thickness of the sedimentary section in the southern area is greater than in the northern area (see Figure 5b). The thicker sedimentary section responded to deformation by fault-propagation folding above deep-seated faults leading to the formation of monoclines, whereas the relatively thinner section in the north allowed shear-couple deformation to form second-order wrench structures.
2. The proximity of the northern part of the Bahariya region to the northern Western Desert where shear couple deformation was dominant during Late Cretaceous (EGPC, 1982; Moustafa et al., 1998).

Middle Miocene Deformation

A late phase of structural deformation affected the Bahariya region during the Middle Miocene (15-20 Ma) and was accompanied by igneous activity in its northern part. This igneous activity led to the development of several dolerite intrusions (sills and at least one laccolith) within the Cretaceous rocks and the extrusion of several basaltic flows onto Middle Eocene rocks, in addition to the intrusion of a WNW-oriented dolerite dike in Gebel El Hefhuf. The dike is probably one of several feeder dikes in the northeastern part of Gebel El Hefhuf. Other dikes may underlie the large basalt outcrop in this area. The direction of extension during this phase of deformation (measured normal to the orientation of the Gebel El Hefhuf dike) was NNE-SSW (N15°E–S15°W). Extension was only minor as dikes and NW-oriented normal faults are not common in the Bahariya region. This phase of deformation was contemporaneous with that in other parts of the northern Western Desert (Abd El Aziz et al., 1998; Moustafa et al., 1998) and was probably related to extension in the Gulf of Suez-Red Sea rift area.

SUBSURFACE GEOLOGIC SETTING

The subsurface geology of the Bahariya region was revealed by the drilling of the Bahariya-1 exploratory well (Bahariya-1) and the Diyur-1 well (see Figure 2 for well locations), and by 2-D seismic data from the area east of the Bahariya Depression.

Bahariya Depression Exploratory Well

Sahara Petroleum Company drilled the Bahariya exploratory well (Bahariya-1) in 1957 to the Precambrian basement. The location of the well was determined mainly from surface geologic mapping and gravity surveys. The well was spuded in at the base of the exposed Bahariya Formation and the drilled section ranges in age from Precambrian to Early Cretaceous. The Precambrian basement is at a relatively shallow depth equal to 1,718 m subsea. The sedimentary section is composed mainly of sandstone and shale (Figure 4).

Devon Energy Egypt Companies carried out a paleontologic analysis of the drilled section and the results are shown in Figure 4. The uppermost unit is an Albian non-marine to transitional sandstone and shale section of the Kharita Formation that is 286.5 m thick. It unconformably overlies a 91.5-m-thick Lower Cretaceous section of shale and sandstone beds of the Alam El Bueib Formation. The Alamein Dolomite is missing, probably due to non-deposition. A Bajocian-Bathonian shale unit with some sandstone and a few limestone interbeds underlies the Lower Cretaceous section. This is the Khatatba Formation (228.5 m thick) that was deposited in a transitional to inner-neritic marine environment and that, in turn, is unconformable on a Lower Jurassic clastic section (137 m thick) assigned to the Ras Qattara Formation.

Bahariya-1 drilled a thick Paleozoic section that consists of two rock units. These are an Upper Carboniferous-Lower Permian massive sandstone unit with a few shale interbeds (Safi Formation, 588 m thick) and a Middle Cambrian clastic unit of shales with some sandstone beds (Shifah Formation, 436 m thick). The unconformity between the two formations is most probably related to the late Paleozoic Hercynian Orogeny and a large thickness of Paleozoic rocks is thought to have been deposited above the Shifah Formation but was eroded as a result of this orogeny.

Diyur-1 Well

Amoco Petroleum Company drilled the Diyur-1 well (see Figure 2 for location) in 1968 to the Precambrian basement. As in Bahariya-1, the basement in Diyur-1 is at a relatively shallow depth of 1,391 m subsea. The basement is overlain by a Paleozoic section only 242.5 m thick. No paleontological data is available to show which part of the Paleozoic was penetrated by the well. A Jurassic section of the Bahrein and Khatatba formations unconformably overlies the Paleozoic rocks (Table 1). As with the Alamein Formation in Bahariya-1, the Masajid Formation is missing in the Diyur-1 well perhaps due to non-deposition. The Lower Cretaceous section overlying the Jurassic rocks in Diyur-1 is thin but includes the Alam El Bueib and the Kharita Formations that are 94.5 m and 30.5 m thick, respectively. The Diyur-1 well penetrated an Upper Cretaceous section represented by the Bahariya and Abu Roash formations that are 308 m and 241 m thick, respectively. The Khoman Formation is missing and the Abu Roash Formation is unconformably overlain by the Paleocene-Eocene Apollonia Formation. The latter is 409 m thick and is overlain by a relatively thin section of the Upper Eocene to Miocene Dabaa, Mamura, and Moghra formations (Table 1).

Table 1
Wells thickness of rock units in Diyur-1 and Bahariya-1 wells.

Rock Unit	**Diyur-1** Thickness (m)	**Bahariya-1** Thickness (m)
Moghra Formation	+ 21.0	-
Mamura Formation	46.0	-
Dabaa Formation	82.0	-
Apollonia Formation	409.0	-
Abu Roash Formation	241.0	-
Bahariya Formation	308.0	-
Kharita Formation	30.5	286.5
Alam El Bueib Formation	94.5	91.5
Khatatba Formation	101.0	228.5
Bahrein/Ras Qattara Formation	27.5	137.0
Paleozoic	242.5	1,024.0

Seismic Data

2-D seismic surveys have been made in the area to the east of the Bahariya Depression. The nearest seismic line passes through Diyur-1 (Figure 2). The corresponding seismic section (Figure 16) shows the structures that affect the Bahariya region and the surface-mapped structures of the Bahariya Depression can be traced along strike onto the section. It clearly shows the shallow depth of the basement reflector that has a consistent southeasterly dip and is cut by four faults dipping toward the north-northwest, two of which are on the extension of the Gebel Ghorabi structural belt and the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt.

The top basement and the top Paleozoic reflectors show normal slip on the four faults whereas the top Bahariya reflector shows reverse slip on three of them. This indicates that two phases of movement took place—an early phase of normal slip and a later one of reverse slip—indicating that the area was affected by positive structural inversion (Williams et al., 1989). The fourth (southernmost) fault does not intersect the top Bahariya reflector but is overlain by a southeastward-dipping Cretaceous section representing a fault-propagation fold on the extension of the steep flank of the Sandstone Hills Monocline.

The Mesozoic section lying between Diyur-1 and the nearby fault has a north-northwesterly dip that is probably related to drag on the hanging wall of the fault during its reactivation by reverse slip. The north-northwesterly dip in this area, together with the south-southeasterly dip on the Mesozoic rocks to the south of the fourth fault, indicates that an anticline having a broad crestal area occurs in the Bahariya region. This anticline is called here the Bahariya Swell and is a result of positive structural inversion. The Khoman Formation occurs only on the southern side of the Bahariya Swell and has a shallower dip than the underlying rocks. The top Khoman reflector shows stratigraphic onlap onto the southern flank of the Bahariya Swell. This indicates that the swell was formed before the deposition of the Khoman Formation and therefore that the positive structural inversion in the Bahariya region was pre-Maastrichtian in age (according to the dating of the Khoman Formation by El-Akkad and Issawi, 1963).

The seismic section also shows that the broad crestal area of the Bahariya Swell was affected by prolonged erosion, as the Bahariya and Abu Roash formations appear truncated in this area. The upper Apollonia Formation unconformably overlies the northern and southern edges of this eroded area whereas on the northern and southern flanks of the swell, continuous deposition of the entire Apollonia Formation (Paleocene to Middle Eocene) occurred. These stratigraphic relations are similar to those mapped on the surface in the Bahariya region where Middle Eocene rocks unconformably overlie an eroded section of the Bahariya, El Heiz, or El Hefhuf formations in the northern and southeastern scarps of the Bahariya Depression (Figure 6). Elsewhere, as in the plateau that separates the Bahariya and Farafra depressions, the El Hefhuf Formation is overlain by a complete uppermost Cretaceous, Paleocene, and Lower Eocene section that also shows a southward increase in thickness (Figure 5b).

The top Apollonia reflector also shows the anticlinal structure of the Bahariya Swell. The reflector is tilted toward the north-northwest on the northern flank of the swell and toward the south-southeast on its southern flank. This probably indicates that the phase of positive structural inversion continued into the post-Middle Eocene and was contemporaneous with the second phase of deformation identified by the surface study of the Bahariya region. The seismic section shows that the Late Cretaceous and post-Middle Eocene deformations in the Bahariya region proceeded by way of reverse slip on the inverted faults. However, the surface study of the Bahariya region indicated right-lateral strike-slip movement during both phases of deformation. These different senses of movement complement each other and the actual slip on the faults is oblique-slip with reverse dip-slip and right-lateral strike-slip components. The difficulty in identifying the strike-slip component on the seismic section is because the horizontal slip is normal to the section. In the case of the surface sections, the problem of identifying the reverse slip is due to one or more of the following reasons:

- In some cases, the fault is buried in the subsurface beneath a fault-propagation fold (e.g. the Sandstone Hills area).
- The change in the dip direction of the fault plane where it dips in opposite directions; for example, the faults on the southwestern side of Gebel El Hefhuf (Figure 13) and those on the southern side of Gebel Miteilaa Radwan (Figure 14).
- The generally horizontal to near-horizontal attitude of the rocks between the three main structural belts of the Bahariya Depression that represents the broad crestal area of the Bahariya Swell. Such an attitude makes it difficult to notice the drag that affects the hanging wall and footwall blocks of the inverted faults at the surface.

The seismic section shows a uniform thickness of rock units between the top basement and top Bahariya reflectors on the southern flank of the Bahariya Swell. This section includes the Paleozoic, Jurassic, and Lower Cretaceous rocks. The same units are relatively thicker on the downthrown sides of the four inverted faults. The Paleozoic section is very thin on the northern flank of the Bahariya Swell (as in Diyur-1; see Table 1) but the resolution of seismic section is too poor to show if all or only some of the Paleozoic units thicken in the middle part of the swell. It is not clear either if the Paleozoic section is thin in the Diyur-1 area due to erosion at the updip edge of the tilted Paleozoic section or because of non-deposition of some of the Paleozoic units. For these reasons, it is not easy to prove or disprove whether normal faulting began during or after the Paleozoic. The increase in thickness of the Paleozoic rocks on the downthrown sides of the faults could be attributed to active faulting during the Paleozoic where the downthrown sides received larger thickness than the upthrown sides. Conversely, the increase in thickness of the Paleozoic rocks on the downthrown sides of the faults could be due to post-Paleozoic faulting and tilting of the fault blocks followed by erosion of the updip edges of the fault blocks on the upthrown sides of the faults. We subscribe to the second interpretation because other parts of the Western Desert experienced normal faulting in the early Mesozoic rather than during the Paleozoic.

The increase in thickness of the section lying between the top Paleozoic and top Bahariya reflectors on the downthrown sides of the four faults indicates that normal slip on these faults continued into the Jurassic and Early Cretaceous. However, the fault movement must have been relatively slow because the increase in thickness across the faults is not great.

TECTONIC EVOLUTION OF THE BAHARIYA REGION

The information presented above was used to reconstruct the tectonic evolution of the Bahariya region. It is related to the following phases:

Paleozoic Evolution (570-245 Ma)

Very little is known about the Paleozoic history of the Bahariya region. What data is available comes from the Paleozoic section drilled in wells Bahariya-1 and Diyur-1, and the 2-D seismic section (Figure 16). Deposition of the Paleozoic rocks began in the Middle Cambrian in a transitional environment. An Upper Carboniferous to Lower Permian clastic unit unconformably overlies the Middle Cambrian deposits and the missing section was probably eroded during the late Paleozoic Hercynian Orogeny.

Triassic-Early Cretaceous Evolution (245–96 Ma)

The Bahariya-1 and Diyur-1 wells show that Triassic rocks were probably not deposited in the Bahariya region as Jurassic sediments unconformably overlie the Paleozoic rocks in the two wells. Prior to the deposition of the Lower Jurassic Ras Qattara Formation, normal faulting affected the Bahariya region and was associated with southeastward tilting of the Paleozoic rocks. We assume that the updip edges of the tilted fault blocks were eroded but that a thicker Paleozoic section was preserved on the downthrown sides of the faults. Normal faulting continued at a slow rate during the deposition of the Lower Jurassic Ras Qattara Formation and the Middle Jurassic Khatatba Formation in a transitional to inner-neritic marine environment. The absence of the Masajid Formation was probably related to non-deposition during the Late Jurassic. Deposition resumed in the Early Cretaceous and the Alam El Bueib Formation was deposited in a transitional environment followed by the deposition of the fluvial Kharita Formation. Normal faulting probably continued during the Lower Cretaceous but still at a slow rate. The Jurassic and Lower Cretaceous rocks are generally thicker on the downthrown sides of the normal faults (Figure 16).

Late Cretaceous Evolution (96–66.5 Ma)

Early to Late Cenomanian Fluvial to Marine Deposition

This phase of tectonic evolution in the Bahariya region started with the deposition of the Bahariya Formation during the early Cenomanian. The lower member of the Formation was deposited in a fluvial environment, whereas estuarine to subtidal and intertidal conditions (with some intermittent subaerial exposure) prevailed during the deposition of the upper member. This was followed in the late Cenomanian by the deposition of the marine El Heiz Formation.

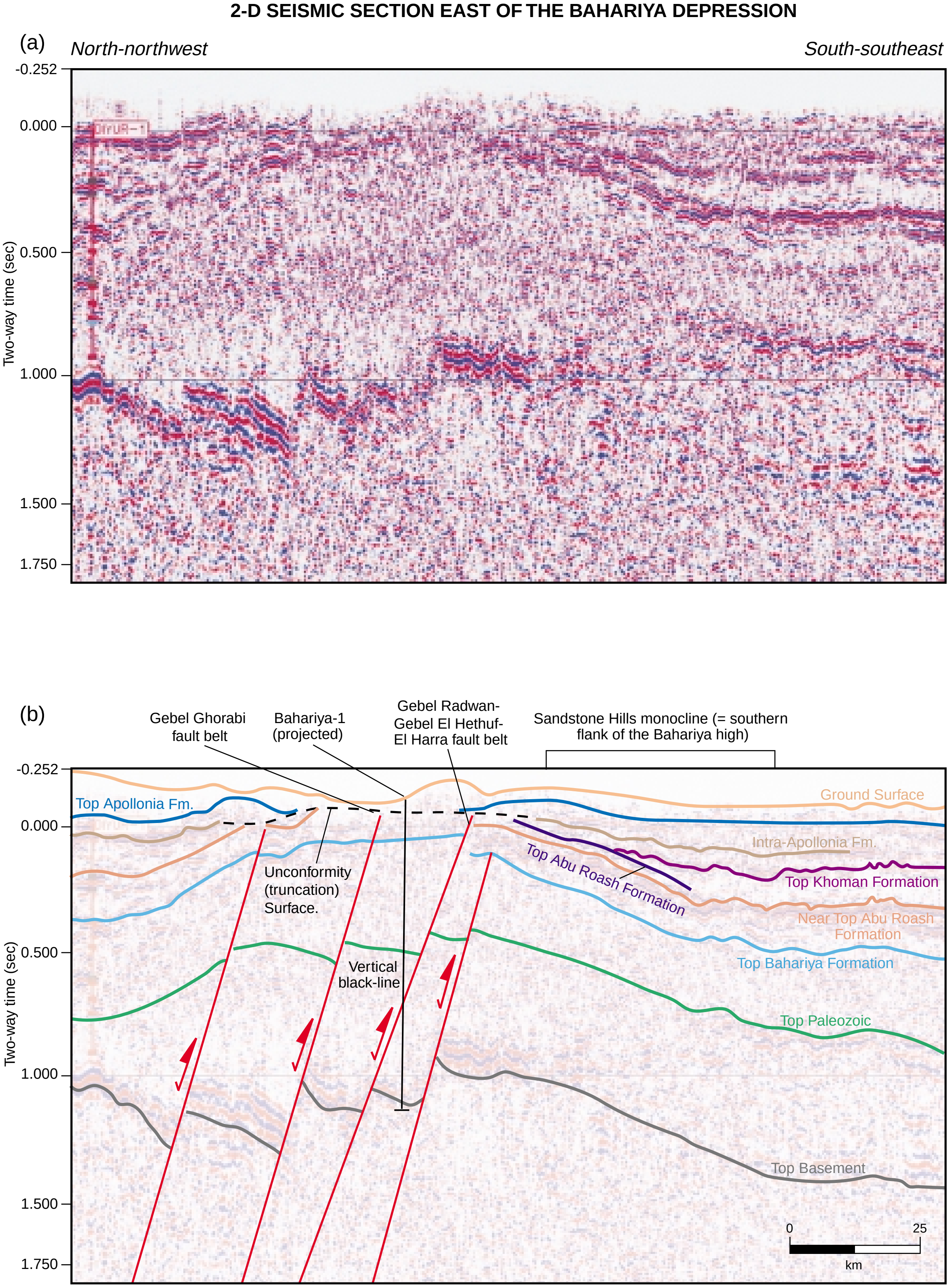


Figure 16: 2-D seismic section east of the Bahariya Depression (see Figure 2 for location). During the Jurassic-Early Cretaceous rifting normal faults developed. These faults were reactivated during the Late Cretaceous-Early Tertiary basin inversion as oblique-slip reverse faults.

Turonian to Early Senonian Non-deposition and Erosion

During the Turonian and early Senonian, the Bahariya region was a non-depositional stable platform probably above sea level that was related to the local northward retreat of the sea rather than to tectonic uplift. The Abu Roash section in the Diyur-1 well is not complete and the A, B, and C members were probably not deposited.

Campanian Transgression and Marine Deposition

Marine sedimentation was resumed during the Campanian in the Bahariya region and the El Hefhuf Formation was deposited in a shallow-marine environment.

Late Campanian to Early Maastrichtian Inversion, Swell Deformation, and Erosion

The Bahariya region was deformed by positive structural inversion in the late Campanian to early Maastrichtian. This led to the reactivation of the deep-seated ENE-oriented normal faults by oblique-slip (reverse dip-slip component and right-lateral strike-slip component). The northern part (Gebel Ghorabi area and the Gebel Radwan-Gebel El Hefhuf-El Harra area) developed second-order wrench structures above the deep-seated faults, whereas in the south (the Sandstone Hills) a large fault-propagation fold formed above a deep-seated fault. This Late Cretaceous inversion increased the structural elevation of the Bahariya region and formed a large swell around which sedimentation continued. Severe erosion affected the broad crestal area of the Bahariya Swell that underlies the central, northeastern, and northern parts of the Bahariya Depression, and removed the Upper Cretaceous rocks down to the upper part of the Cenomanian Bahariya Formation.

Maastrichtian Transgression and Marine Deposition

The margins of the Bahariya Swell were onlapped by Maastrichtian and Tertiary deposits (Figures 5b and 16) as had happened in the Abu Roash area southwest of Cairo (Faris, 1948; Jux, 1954; Moustafa, 1988; among others). The Khoman Formation was deposited during the Maastrichtian over an erosion surface on the southern flank of the Bahariya Swell (Figure 16).

Paleogene-Neogene Evolution (66.5–2 Ma)

Paleocene to Eocene Non-deposition to Shallow-marine Deposition

As with the Maastrichtian Khoman Formation, Paleocene and Lower Eocene sediments were also deposited on the margins of the Bahariya Swell. Paleocene rocks crop out only to the south of the present-day Bahariya Depression whereas Lower Eocene rocks are exposed both in the eastern plateau and in the area south of the Depression. The Paleocene and Lower Eocene units show a notable southward increase in thickness. Middle Eocene rocks were deposited across the whole area and unconformably overlie the eroded Upper Cretaceous section in the crestal area of the Bahariya Swell.

Post-Middle Eocene Deformation

Positive structural inversion continued into post-Middle Eocene time leading to the tilting of the Middle Eocene rocks on the flanks of the Bahariya Swell (Figure 16). On the surface, this deformation is shown by the development of en echelon folds and faults in the Gebel Ghorabi structural belt, and by the formation of the North Farafra Monocline.

Late Eocene Reefal Conditions

The El Hamra Formation was deposited in the Late Eocene as a shallow-water reefal facies on the periphery of the Bahariya region. Deposition of this unit might also have taken place before the second phase of deformation.

Oligocene-Miocene Fluvial Deposition

Deposition of the Oligocene and Miocene sediments took place in a fluvial environment, especially on the plateau on the eastern side of the Bahariya Depression.

Middle Miocene Extensional Deformation and Igneous Activity

NNE–SSW-oriented extension affected the Bahariya region during the Middle Miocene and was associated with igneous activity. It led to the intrusion of one or more WNW-oriented feeder dikes, dolerite sills, and a laccolith within the Cretaceous units, and the extrusion of basalt flows onto the Eocene outcrops. It is noticeable that the igneous activity mostly affected areas on the northern side of the Gebel Radwan-Gebel El Hefhuf-El Harra structural belt.

The carbonate rocks of the Naqb Formation were locally replaced by iron-bearing hydrothermal solutions that might have been associated with the Middle Miocene igneous activity (El Bassyony, 1980).

Quaternary-Holocene (2 Ma–present)

Continued erosion of the middle part of the Bahariya Swell has led to the present-day topographic features of the Bahariya region.

PETROLEUM HABITAT

Although petroleum exploration started in the Western Desert in the late 1930s, the first commercial oil discovery was made in 1966 in what became the Alamein field when oil was discovered in vuggy and fractured dolomite of the Alamein Dolomite. By 1985, a total of 20 fields had been discovered and in that year, exploration in the Western Desert reached a turning point with the discovery of oil in the Jurassic sands of the Khatatba Formation in the Salam field.

Most of the commercial oil and gas discoveries occur in the northern Western Desert, north of latitude 29°N in the Abu Gharadig, Kattaniya, East Beni Suef, Alamein, Shoushan, and Matruh basins (Figure 1). The hydrocarbons in these fields are trapped in reservoir rocks of Jurassic and Cretaceous age.

Petroleum Occurrences and Petroleum Habitat in the Western Desert

Petroleum discoveries in the northern Western Desert include both oil and gas. Some basins are characterized by one type of hydrocarbon; for example, the Kattaniya and Alamein basins that produce oil and the Matruh basin that produces mainly gas. Other basins, such as Abu Gharadig, contain both oil and gas fields.

Source Rocks

Petroleum source rocks occur in various parts of the sedimentary section of the northern Western Desert (Figure 3). They are common in Jurassic and Cretaceous deposits and may occur in Paleozoic (Parker, 1982; Sultan and Halim, 1988; El Ayouty, 1990; and EGPC, 1992) and Tertiary rocks.

Mahmoud et al. (2000) identified the Lower Silurian organic-rich black shales in paleo-depressions in the western and northwestern parts of the Western Desert as good potential source rocks. El Ayouty (1990) and EGPC (1992) considered Lower Devonian shales that are rich in waxy sapropelic kerogen in the northwestern parts of the Western Desert (west of the Umbarka area) to be fair-quality source rocks that could have generated oil. Gas-prone source rocks are present within Carboniferous sediments.

Source rocks of Mesozoic age in the Western Desert include the following:

- Jurassic sediments of the Khatatba Formation and Lower Cretaceous sediments of the Alam El Bueib Formation where carbonaceous shales and coals are predominant (Sultan and Halim, 1988). They include terrestrial plant material (kerogen type III), Parker (1982) and El Ayouty (1990).
- The thick Matruh shale (equivalent to the lower part of the Alam El Bueib Formation) in the Matruh basin is a type II source rock (El Ayouty, 1990) and a possible gas source (EGPC, 1992).

- The Kharita Formation includes several gas-prone carbonaceous shales with a good potential for gas generation (EGPC, 1992).
- The Cenomanian-Turonian sediments of the Abu Roash Formation (G, F, and E members) that contain type II kerogen (Parker, 1982 and El Ayouty, 1990).
- The lower part of the Khoman Formation (top part of Khoman-B and lower part of Khoman-A) that contain mixed type II-I kerogen (El Ghoneimy and El Gohary, 1988; May, 1991; EGPC, 1992).

Although it is unlikely that the Tertiary rocks in the Western Desert are mature enough for hydrocarbon generation, potential oil source rocks were identified in the Apollonia Formation. The Abu Gharadig-1 and BRE 27-1 wells intersected good-quality but immature oil-source rocks (EGPC, 1992). If such source rocks are deeply buried in certain basinal areas they could be oil-mature.

Of the various source rocks, perhaps the Jurassic Khatatba Formation and the Turonian Abu Roash-F member are the two main units in the northern Western Desert with potential for gas and oil generation. According to Sultan and Halim (1988), geochemical data and modeling indicated that the source rocks in this region reached peak maturity during the Late Cretaceous to early Tertiary.

Reservoir Rocks

Both sandstone and carbonate reservoirs occur in the northern Western Desert (El Ayouty, 1990). Hydrocarbon-bearing sandstone reservoirs are of Jurassic and Cretaceous age. Paleozoic sandstone units also have good reservoir quality but no hydrocarbons have been discovered in them so far. Carbonate reservoirs are also common in the northern Western Desert and include:

- The Alamein Dolomite that has good fracture porosity in association with reverse faulting (Sultan and Halim, 1988) and intergranular vuggy porosity (El Ayouty, 1990).
- Limestone reservoirs in the Abu Roash Formation also have good fracture porosity (El Ayouty, 1990).

Seals

Various shales and compact limestone and dolomite beds of Jurassic, Cretaceous, Eocene, and Oligocene age make efficient seals in the northern Western Desert (Figure 3). The Khatatba and Alam El Bueib formations have their own internal seals. Shales within the Alamein Dolomite are good seals to fractured and vuggy dolomite beds. Similarly, shales of the Abu Roash “G” member form the top seal of the Bahariya sandstone reservoir. Other potential seals are Paleozoic shales, the Khoman Chalk, and shales of the Dabaa Formation.

Traps

Structural traps are the main types of petroleum traps in the northern Western Desert. Late Cretaceous to Early Tertiary folds formed by basin inversion are the most common of these and consist of 3-way and 4-way dip closures. Local fault-block structures are another type of structural trap. Stratigraphic traps are also present but are less common than the structural traps. They include pinching-out sand bodies in the Abu Roash Formation and lateral facies changes from clastics to carbonates (El Ayouty, 1990).

DISCUSSION

Regional Tectonics

Guiraud et al. (1992) identified eight Mesozoic and Cenozoic tectonic and magmatic events in west and central Africa related to the break-up of Gondwana and the opening of the Atlantic Ocean. Guiraud (1998) noted that some of these events could also be recognized on the North African Tethyan margin. The eight tectonic and magmatic events are as follows:

1. Permo-Triassic rifting associated with Late Triassic-Early Jurassic magmatism.
2. Neocomian-early Aptian rifting.
3. Aptian-Albian rifting (associated with the extrusion of alkaline and transitional basalts).
4. Santonian compressive event ('Santonian event').
5. Cenomanian-Early Eocene sagging and basin deepening.
6. Intra-Eocene compression.
7. Late Eocene compression.
8. Neogene igneous activity.

No Permo-Triassic rocks are present in the Bahariya-1 well, and Lower Jurassic sediments unconformably overlie the Upper Carboniferous-Lower Permian rocks. The unconformity could be related to Permo-Triassic deformation.

Tectonostratigraphic rift assemblages in northern Egypt are probably related to the Permo-Triassic rifting event. As an example, red shale and sandstone of the Permo-Triassic Qiseib Formation crop out in the eastern scarp of the North Galala Plateau on the western side of the Gulf of Suez (Abdallah and Adindani, 1963). The Qiseib Formation is also exposed in Wadi Budra in west-central Sinai (Weissbrod, 1969) where it is underlain by an olivine basalt sill dated at 233 to 243 Ma (Middle Triassic) (Moussa, 1987 and Roufaiel et al., 1989). The Permo-Triassic section in the subsurface of the northern Western Desert (Eghi Group) shows widespread reddening (Keely et al., 1990; Hantar, 1990). Red clastics with thin coal beds in the Shoushan basin represent the base of the Jurassic section. They are exceptionally thick and are associated with weathered basalt in the Hazem-1 well (Keeley et al., 1990).

Guiraud and Maurin (1992) discussed the Early Cretaceous rifting events in detail. The first, second, and fifth events correspond to Late Carboniferous-Liassic, Late Jurassic and Early Cretaceous, and late Senonian rifting events on the North African Tethyan margin (Guiraud, 1998). According to Guiraud and Maurin (1992), Guiraud et al. (1992), and Guiraud (1998), no rifting took place during most of the Jurassic. However, Keeley and Wallis (1991) and Keeley and Massoud (1998) suggested that the Jurassic sediments in northern Egypt were deposited in westward-propagating rift basins. Nagati (1986), EGPC (1992), Taha (1992), and Moustafa et al. (1998) also defined Jurassic rifting in northeast Africa.

Guiraud and Bosworth (1997) recognized the late Santonian event in North Africa and mentioned that similar Santonian folding is local and gentle in most of northern Sinai. They considered that Campanian-Maastrichtian or Paleocene rifting in central North Africa and northern Arabia followed the Santonian compressive deformation. Bosworth et al. (1999) proposed that the Santonian deformation took place by way of dextral transpression in northeast Africa. Dextral transpression was also proposed for the Late Cretaceous deformation in northern Sinai (Moustafa and Khalil, 1989). According to Sultan and Halim (1988) strike-slip movement also took place on E-W oriented faults in the northern Western Desert at the end of the Cretaceous.

The detailed study of borehole and seismic data from the northern Western Desert showed the effect of three main phases of extension and shortening that affected the 'tectonically unstable' region. They are a Jurassic to Early Cretaceous rifting phase, Late Cretaceous to Early Tertiary basin inversion, and Miocene to post-Miocene extension.

Jurassic–Early Cretaceous Rifting

An early phase of rifting took place during the Jurassic and Early Cretaceous in the northern Western Desert (Keeley et al., 1990; Guiraud et al., 1992; Guiraud, 1998; Keeley and Massoud, 1998). It led to the development of ENE-oriented basins bounded by major normal faults of the same orientation. They have half-graben geometry with a northward tilt toward the boundary faults. The updip parts of the Jurassic-Early Cretaceous basins are shallow and have gentle dips and locally are platform areas, whereas the downdip parts are much deeper and have relatively steeper dips. As an example, the Abu Gharadig basin is bounded to the north by a major ENE-oriented fault that has a downthrow of about 6,000 m at the top Jurassic level (Abdel Aal and Moustafa, 1988). This asymmetric basin has a strong northward tilt. In contrast, the southernmost (updip) part of the basin is a very gently dipping, structural high known as the Diyur Platform. Similarly, the area lying north of the Abu Gharadig basin is another platform area (the Sharib-Sheiba platform) having shallow basement, a thin sedimentary section, and very gentle dips.

The detailed study of subsurface data from the northern Western Desert has indicated that the Jurassic-Cretaceous rifting took place in several pulses, as follows:

- Jurassic (ended in the Oxfordian);
- Neocomian-to middle Aptian;
- Albian; and
- Cenomanian-Turonian.

Late Cretaceous-Early Tertiary Basin Inversion

Basin inversion in the northern Western Desert started in the Late Cretaceous and probably proceeded by way of oblique-slip reactivation of old ENE-oriented basin-bounding faults (Sultan and Halim, 1988; Bosworth et al., 1999). These old faults had normal slip during the early rifting phase (Guiraud and Bosworth, 1997). The unconformity detected at the contact between the Khoman-A and Khoman-B members marks the climax of basin inversion in northern Egypt. According to Abd El-Aziz et al. (1998), basin inversion continued during and after the deposition of the Paleocene to Middle Eocene rocks, but its effect can only be seen in close vicinity of the basin-bounding faults.

Miocene to Post-Miocene Extension

Several NW-oriented normal faults with small throws cut the Dabaa Formation and younger rocks in the northern Western Desert, both in the surface and subsurface. They were formed in response to NE-SW extension in Miocene and post-Miocene times and might be related to the separation of Arabia from Africa and the opening of the Gulf of Suez-Red Sea rift.

Tectonics of the Bahariya Region

The Bahariya region is a large platform area with a relatively thin sedimentary section overlying a shallow Precambrian basement. The earliest deformation recognized in the Bahariya region is identified in the seismic section of Figure 16 and is contemporaneous with the Jurassic-Early Cretaceous rifting.

Surface studies of the Bahariya region shows evidence for the Late Cretaceous to Early Tertiary basin inversion as two distinct events—late Campanian to early Maastrichtian and post-Middle Eocene. In both the northern Western Desert and the Bahariya region, basin inversion proceeded by reactivation of the pre-existing ENE-oriented normal faults by oblique-slip movement having a right-lateral strike-slip and reverse dip-slip components. The Middle Miocene phase of extension in the Bahariya region is contemporaneous with the Miocene and post-Miocene extension in the northern Western Desert. Extension was toward the northeast or north-northeast in both areas.

Previous studies (e.g. El-Etr and Moustafa, 1980; Sehim, 2000) on the Bahariya Depression also recognized the ENE-oriented structural belts. However, the present study is at variance with some of the findings of Sehim (2000). For example, he assumed the coalescence of the controlling faults of the structural belts at depth, whereas they are steeply dipping and 15 to 20 km apart at the surface and seismic data (Figure 16) does not show such coalescence. He also inferred an ENE-oriented right-lateral strike-slip fault at outcrop in the Sandstone Hills but this has not been proved. His assumption that the Late Cretaceous deformation was due to divergent wrench faulting does not agree with the results of the present study and the interpretation of the seismic data that wrench deformation was convergent and led to the formation of the Bahariya Swell.

CONCLUSIONS

The integration of the detailed surface geologic mapping and subsurface data from the Bahariya region showed that this part of the 'stable shelf' area of Egypt has a shallow Precambrian basement overlain by a relatively thin sedimentary section. The area had several intervals of tectonic activity and related periods of non-deposition and/or erosion. The earliest identifiable phase of tectonic deformation was related to Jurassic normal faulting that continued into the Early Cretaceous. The slip rates on these ENE-oriented normal faults were slow and the resultant thickening of the Jurassic and Lower Cretaceous rocks across the faults was small. Normal faulting caused south-southeastward tilting of the Precambrian and Paleozoic rocks and erosion of the Paleozoic rocks on the updip edges of the tilted fault blocks.

The Bahariya region was affected by positive structural inversion in the Late Cretaceous to early Tertiary when the early normal faults were reactivated by oblique-slip with reverse dip-slip and right-lateral strike-slip components. The reverse-slip component caused a large anticlinal structure with a broad crestal area to form, known as the Bahariya Swell. The right-lateral strike-slip component led to the formation of second-order, NE-oriented, right-stepped en echelon folds in the Upper Cretaceous and Eocene rocks. Positive structural inversion started before the deposition of the Maastrichtian chalk. The margins of the Bahariya Swell were onlapped by this chalk and by Tertiary sediments. Inversion continued in post-Middle Eocene time as the Middle Eocene rocks were tilted in the flanks of the Bahariya Swell and deformed by small right-stepped en echelon folds and left-stepped en echelon normal faults. The last phase of tectonic deformation that affected the Bahariya region was related to Middle Miocene extension and associated mafic igneous activity. Continued erosion of the broad crestal area of the Bahariya Swell has formed the present-day Depression.

The similarities in the timing and styles of deformation between the northern Western Desert and the Bahariya region clearly indicate that the deformation that affected the 'tectonically unstable' area of the northern Western Desert also affected the northern part of the 'stable shelf' area. Sedimentary basins in the central and southern Western Desert can therefore be expected to have the same tectonic evolution as the hydrocarbon-producing fields in the basins to the north.

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