Structural setting of the Giza pyramids plateau and the effect of fractures and other factors on the stability of its monumental parts, Egypt

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STRUCTURAL SETTING OF THE GIZA PYRAMIDS PLATEAU AND THE EFFECT OF FRACTURES AND OTHER FACTORS ON THE STABILITY OF ITS MONUMENTAL PARTS, EGYPT

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ABSTRACT

The Eocene carbonate rocks forming the bulk of the Giza Pyramids Plateau are highly fractured by west-northwest, northwest, and northeast trending fractures. These exhibit an excellent example of mechanical layering that influences fractures continuity, shape, and trends. The left-stepped, en echelon, northwest oriented normal faults affecting the plateau area are interpreted to overlie a deep-seated, N 52° E oriented fault. The latter fault is thought to have been rejuvenated by right-lateral wrenching after the deposition of the middle member of Mokattam Formation (Early to Middle Lutetian). Deep-seated faults in the study area and in Abu Roash area could have been reactivated during the Syrian Arc deformation in Early Turonian, Early Senonian, Late Maastrichtian, Paleocene, and Early to Middle Lutetian times. The kinematic analysis of fault slip data indicates that the stress and strain axes are coaxial.

The fractures in the Eocene rocks play the main role in karst formation and rock instability of the Giza Pyramids Plateau. Karst cavities exist in four forms which are surface, pocket, bedding plane, and fracture cavities. Bedrock settlement and fragmentation are the main risk factors affecting the plateau. Bedrock settlement is diagnosed as falling of the roof beds in the karst cavities. Injections by shotcrete and use of rock bolts are recommended for supporting the foundation beds and stopping the settlements.

INTRODUCTION

The Giza Pyramids represent the most famous monumental site and one of the ancient Seven Wonders of the World. They lie on top of a nearly leveled plateau called the Giza Pyramids Plateau which lies to the west of Cairo, at the northeastern part of the Western Desert (Fig. 1). The Sphinx body was carved in a part of the eastern edge of this plateau.

The Giza Pyramids Plateau is made up of the Eocene carbonate rocks. The stratigraphy and rock erosion of the plateau were studied by Omara (1952); Knetsch and Mazhar (1953); Said (1962); Aigner (1983); Gauri (1984); Strougo (1985); Gauri et al. (1990); Kholief and Barakat (1992); Soliman (1996, 1997); and Barakat et al. (1997).

The main objectives of this study include studying the fractures affecting the Giza Pyramids Plateau, local and regional structures, determining the paleostress and strain directions, and indicating the impact of some geological features on the stability of the plateau. In order to achieve these goals, detailed geologic field mapping of the Giza Pyramids Plateau was carried out on a scale of 1: 2,500 by using vertical aerial photographs enlarged from an original scale of 1: 20,000 and topographic base maps on a scale of 1: 4,000.

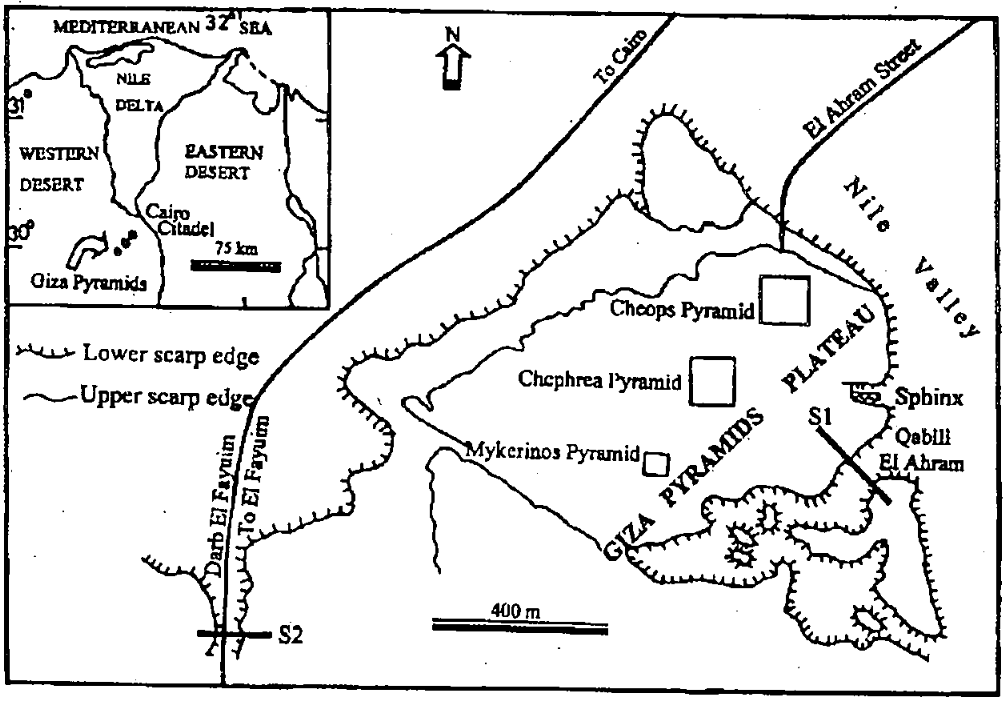


Fig. (1). Location map of the Giza Pyramids Plateau. S1 and S2 are the stratigraphic sections in Fig. 2.

STRATIGRAPHY

The formal Eocene stratigraphic units of Strougo (1985) are used in the present study. The exposed Middle Eocene rocks of the Giza Pyramids Plateau are subdivided from base to top into the Mokattam, Observatory, Qurn, and Wadi Garawi Formations; whereas the Upper Eocene rocks are represented by the Wadi Hof Formation. Two stratigraphic sections were measured in the study area (Fig. 2). The first is a composite section was measured at the eastern part of the plateau and Qabili El Ahram hill whereas the second section was measured at Darb El Fayuim, on both sides of the road. Oligocene, Pliocene, and Quaternary sands and gravels unconformably cover the Eocene rocks in several parts of the mapped area (Fig. 3). The Pliocene-Quaternary sands, gravels, and clays of the Nile Valley outcrop at the footslopes of the eastern edge of the plateau. The Oligocene and/or Pliocene sands and gravels fill some fractures, holes and depressions on the upper surface of the plateau. Some of these filling sediments are highly ferruginous forming several clastic dikes and pockets. The outcrops of the Eocene rock units are controlled mainly by the gentle, south to southeastward general dip of the plateau. The Qurn, Wadi Garawi, and Wadi Hof Formations are exposed in the southern part of the plateau whereas the Mokattam Formation is exposed in the northern part of the plateau (Fig. 4 and cross section Y-Y' in Fig. 5). Therefore, very steep scarps characterize the northern and eastern edges of the plateau, where the hard limestones of the Mokattam Formation exist. On the other hand, the softer rocks in the southern part of the plateau have gentler slopes.

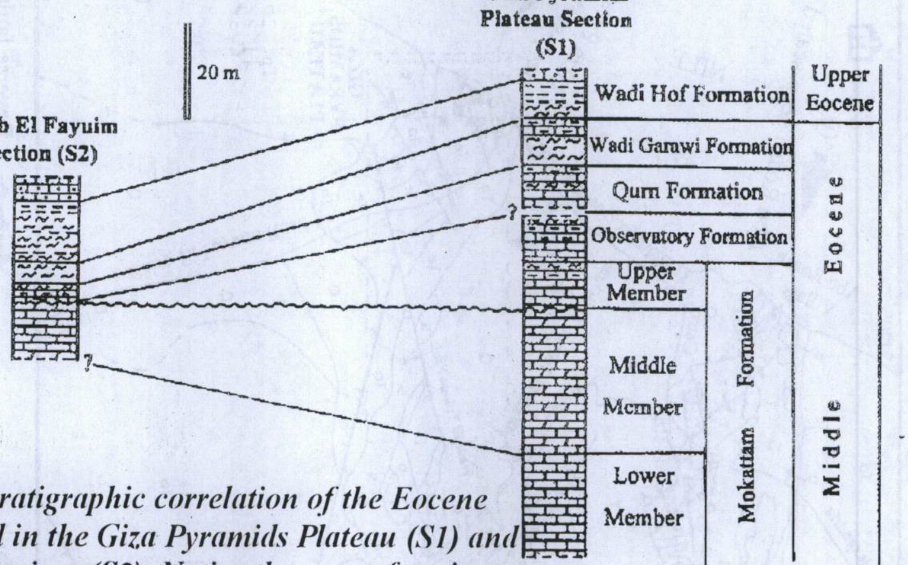


Fig. (2). Stratigraphic correlation of the Eocene units exposed in the Giza Pyramids Plateau (S1) and Darb El Fayium (S2). Notice the unconformity between the middle member of the Mokattam Formation and each of the upper member of the Mokattam Formation (S1) and the Qurn Formation (S2). See figure 1 for locations of these sections.

The complete Middle-Upper Eocene sequence is well exposed in the southeastern part of the plateau (section S1 in Fig. 2). The hard nummulitic limestones and dolomitic limestones of the lower and middle members of the Mokattam Formation are exposed in the northeastern and northern parts of the plateau. The softer nummulitic limestones of the upper member are exposed in the central part of the plateau. The argillaceous limestones and marls of the Observatory Formation occupy the southwestern part of the plateau. The marls, shales and sandy limestones of the Qurn, Wadi Garawi and Wadi Hof Formations, which form the Qabili El Ahram hill, are down-faulted against the Observatory Formation (Fig. 4). The Wadi Hof Formation is capped by a very highly fossiliferous, sandy and dolomitic limestone bed (Ain Musa Bed of Barron 1907) forming a thick hard ledge underneath the Pliocene rocks of Qabili El Ahram hill.

In the Darb Al Fayuim area (section S2 in Fig. 2), the marls, argillaceous limestones, and shales of the Qurn, Wadi Garawi, and Wadi Hof Formations unconformably overlie the dolomitic limestones of the middle member of the Mokattam Formation. This unconformity (Strougo 1985) is characterized by a tilted irregular surface.

STRUCTURES

1- Fractures:

All joints and minor faults are herein named fractures. Because maintenance blocks and/or talus cover several parts of the plateau, fractures were only measured where the Eocene

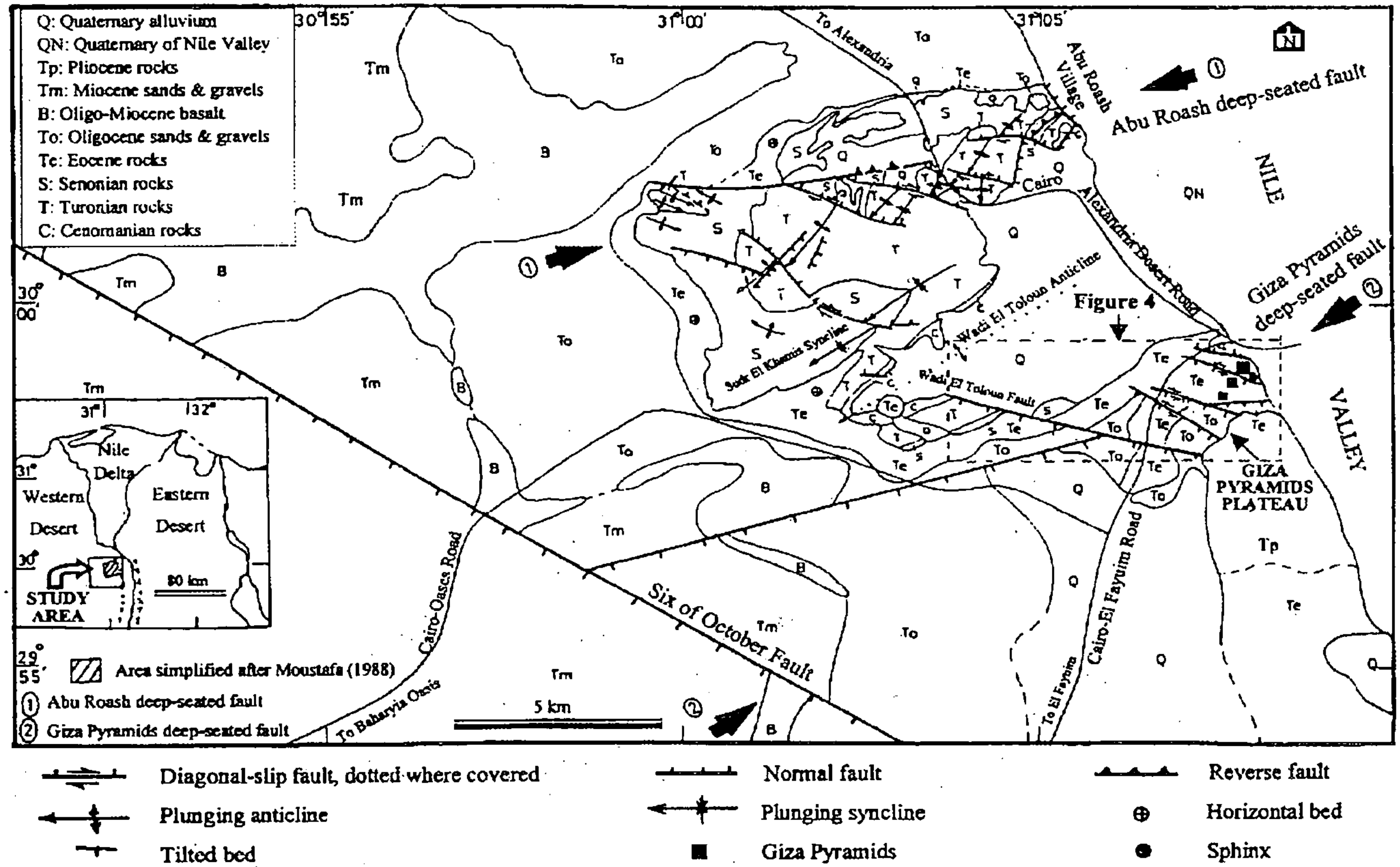


Fig.(3). Geologic map of the Giza Pyramids Plateau-Abu Roash district. The structures of Abu Roash area compiled from Moustafa (1988).

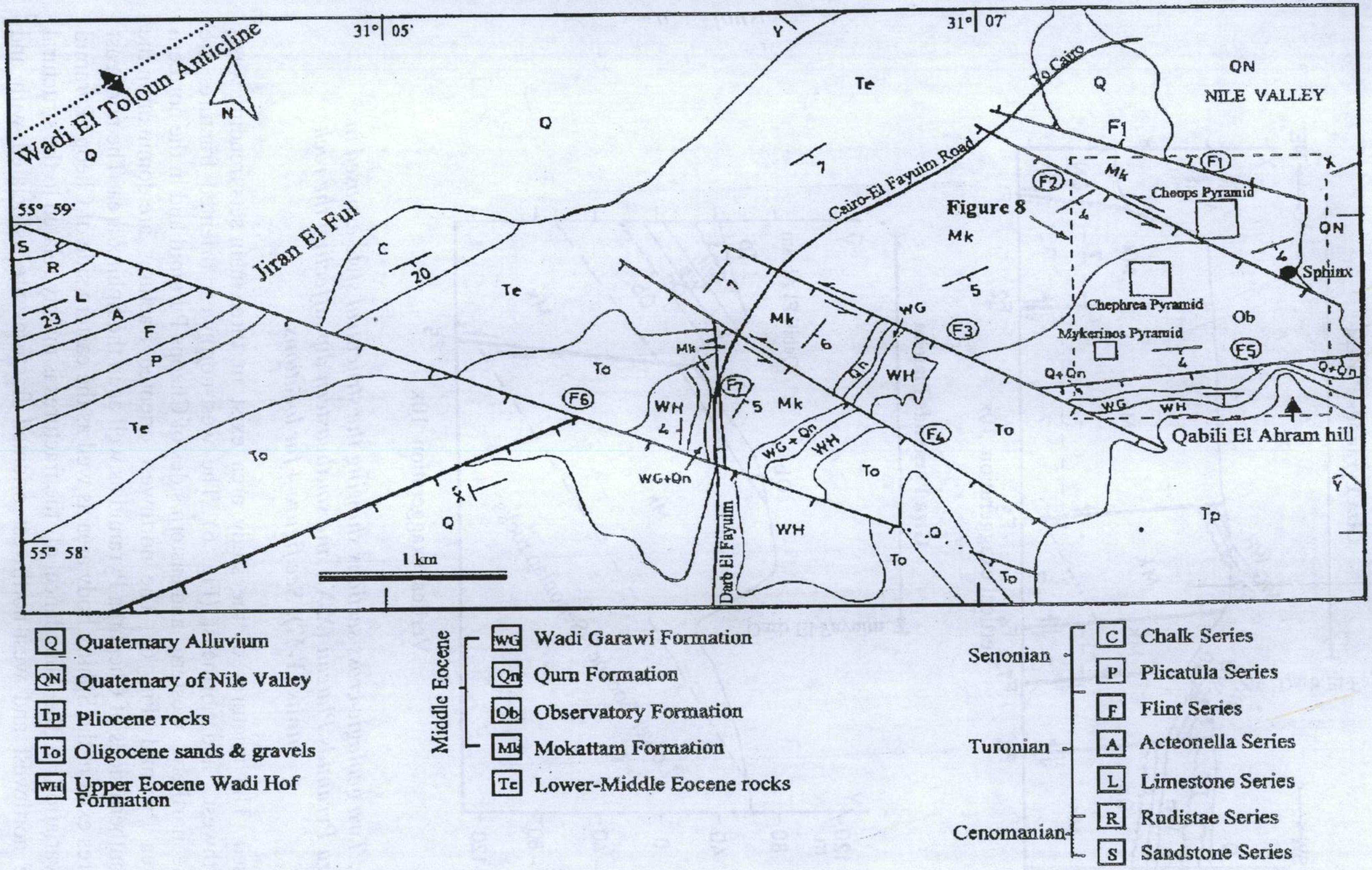


Fig. (4). Detailed geologic map of the Giza Pyramids Plateau area. Structure symbols as in figure 3. X-X` and Y-Y` are cross sections of Fig. 5.

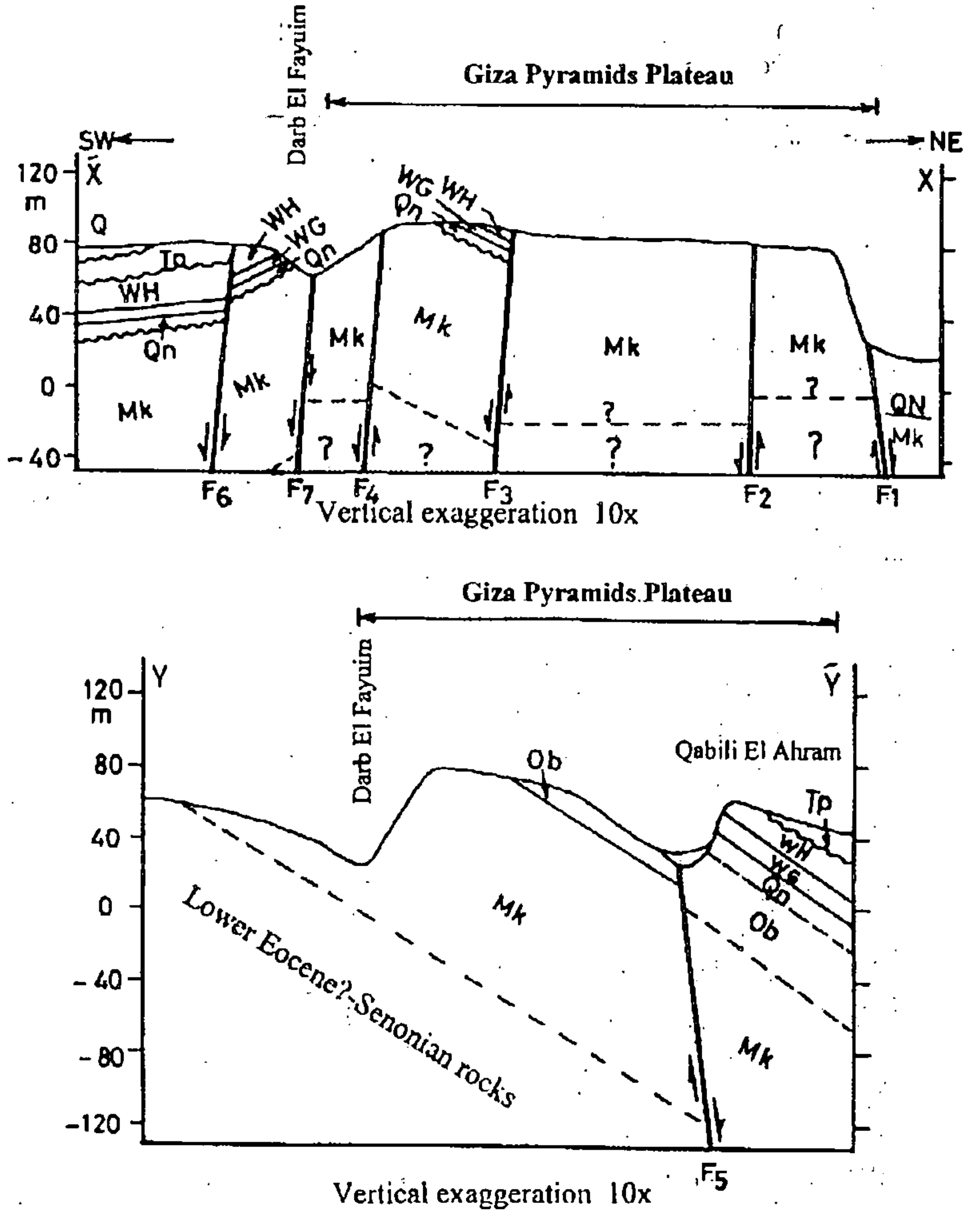


Fig. (5). Two geologic cross sections showing the structural style exposed in the Giza Pyramids Plateau (X-X') and southeastern dip affecting the rock units (Y-Y'). See figure 4 for locations.

beds are exposed. The fractures of the study area exist in three main sets trending west-northwest, northwest, and northeast (Fig. 6). The west-northwest oriented fractures are dominant in the northern, western and eastern sides of Cheops Pyramid and in the northern side of Chephrea Pyramid (Fig. 6). The northwest oriented fractures are dominant in the western and southern sides of Chephrea Pyramid as well as in the Sphinx area. The northeast oriented fractures exist in the Sphinx body area as well as the eastern side of Cheops Pyramid (Fig. 6). The variation in the abundance of the fractures is mainly related to the structural positions. The northwest and west-northwest oriented fractures are associated with and parallel to the mapped northwest and west-northwest oriented faults. Willemse et al. (1997) indicated that some larger scale faults appear to nucleate along pre-existing joints.

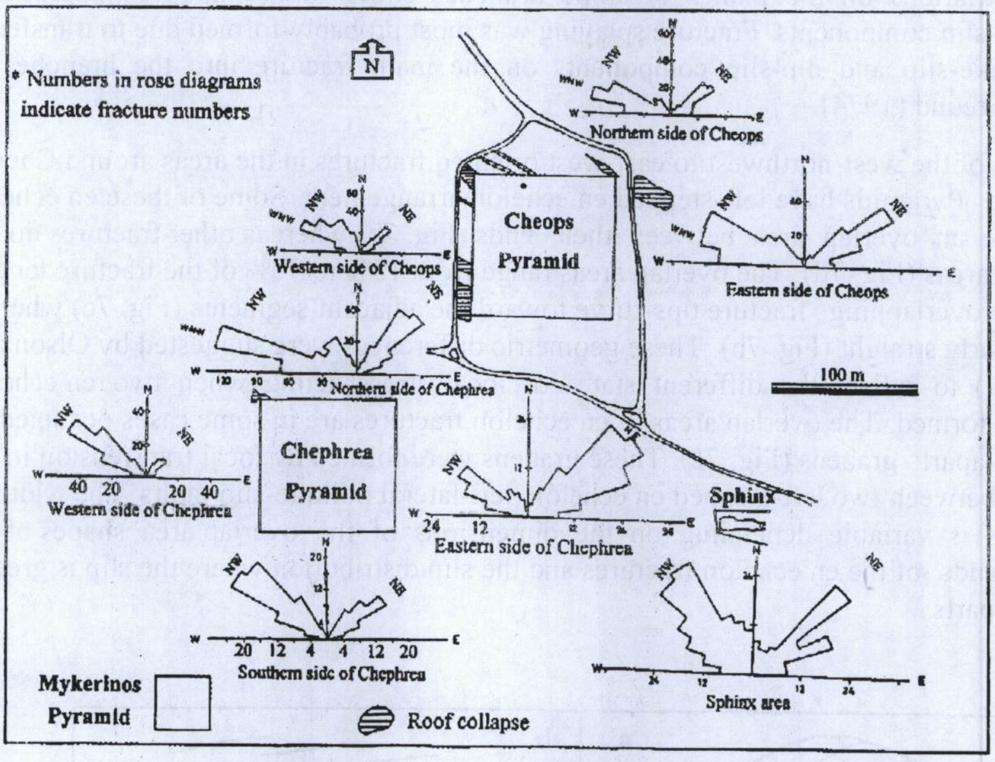


Fig. (6). A general plan of the Giza Pyramids Plateau showing the locations of roof collapse and the rose diagrams of the measured fractures.

Fractures affecting the Giza Pyramids Plateau have several patterns. Most of the fractures affecting the hard limestone beds of the Mokattam Formation in the area around Cheops Pyramid have nearly straight traces both on map and in vertical views. They have a nearly constant fracture spacing, except in the areas close to fault planes. All of these parameters indicate that, the brittle rocks of the Mokattam Formation were deformed by homogenous strain. On the other hand, the presence of ductile marl and argillaceous limestone intervals in the Observatory Formation around Chephrea Pyramid and the Sphinx cause the fractures to have slightly curved traces but still with a nearly constant fracture spacing. Therefore, the curved fracture traces would be related to the presence of ductile intervals in the deformed section whereas the constant spacing indicates homogeneous strain. The brittle intervals exceed the ductile intervals in the Observatory Formation which behaves as a brittle section. Therefore, the carbonate rocks of the Mokattam Formation are more brittle than the Observatory Formation. The ductile marls and shales of the Qurn Formation, Wadi Garawi Formation, and Wadi Hof Formation show excellent examples of mechanical layering. The fractures affecting this sequence are characterized by discontinuous traces on both map and vertical views and by obvious abundance in the more brittle interbeds. During the deformation, the brittle beds were deformed by jointing whereas the ductile beds behaved as a plastic materials.

Some fractures splay and terminate into several branches which have similar length and trend (Fig. 7a). These branches have smaller fracture aperture than the main fracture. Slickenside striations on the planes of some branches show subordinate right and/or left-lateral strike-slip components. Fracture splaying was most probably formed due to transfer of both the strike-slip and dip-slip components on the main fracture into the branches as proposed by Freund (1974).

Some of the west-northwest to east-west oriented fractures in the areas around Cheops and Chephrea Pyramids have left-stepped en echelon arrangement. Some of these en echelon fractures have an overlap area between their ends (Fig. 7b) whereas other fractures do not have overlap areas (Fig. 7d). The overlap areas range from 15% to 90% of the fracture length. Some of the overlapping fracture tips curve toward the adjacent segments (Fig. 7c) whereas others are nearly straight (Fig. 7b). These geometric differences were suggested by Olson and Pollard (1989) to reflect the different states of local stress acting when two en echelon fractures are formed. The overlap areas of en echelon fractures are in some cases occupied by rhombic pull-apart grabens (Fig. 7e). These grabens were formed by local transtension in the overlap area between two left-stepped en echelon, left-lateral oblique-slip faults. The width of these grabens is variable depending on the dimensions of the overlap area, shapes of the overlapping ends of the en echelon fractures and the slip distribution where the slip is greater in the widest parts.

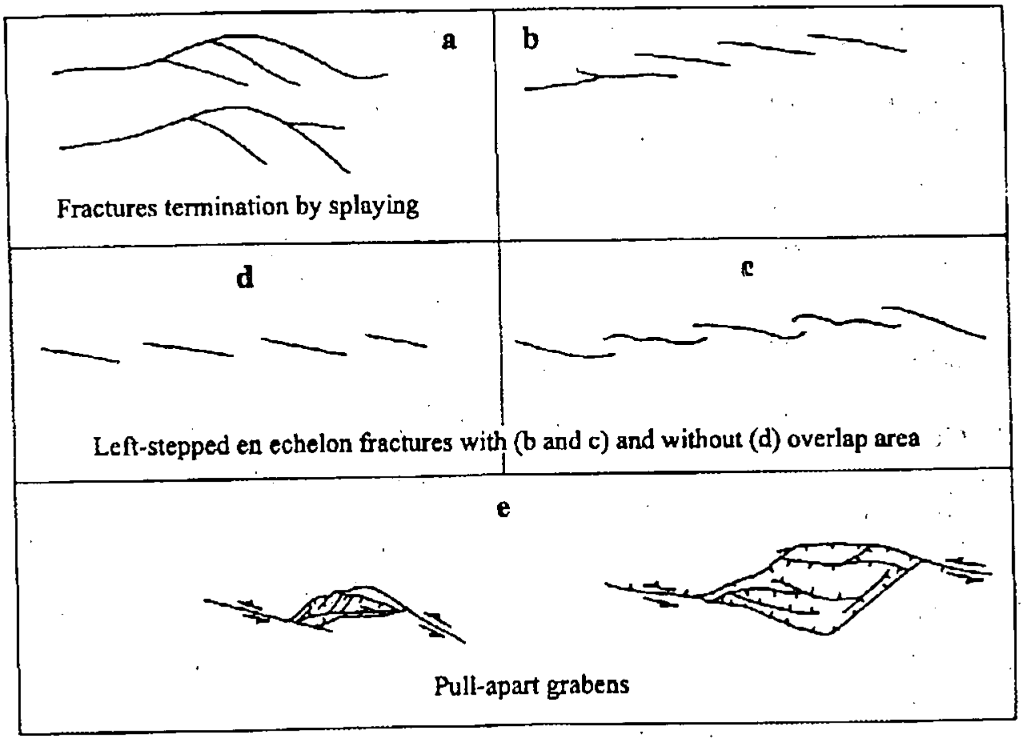


Fig. (7). Different fracture patterns found in the study area. See text for details.

2- Local Structures:

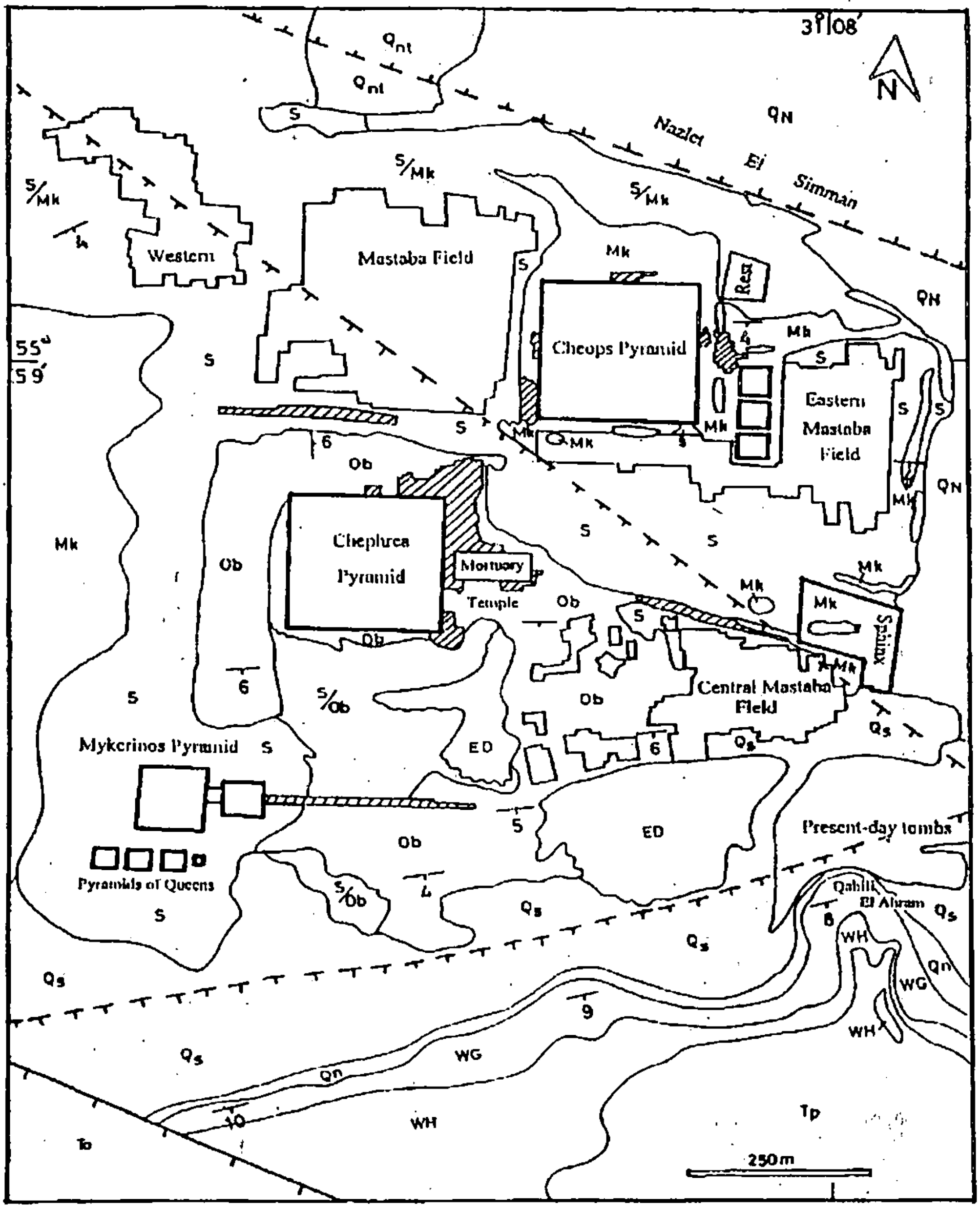
A few structural studies were carried out on the Giza Pyramids Plateau. Omara (1952) showed that the plateau represents an anticline, its axis has N 60° E-S 60° W orientation and plunges west-southwest. Yehia (1985) considered the structure of the plateau as a southeast facing, northeast oriented monocline that is dissected by northwest to north-northwest oriented normal faults.

Detailed field mapping of the Giza Pyramids Plateau area (Fig. 4) indicates that the Tertiary rocks are dissected by five northwest oriented faults as well as three east-west, north-south, and east-northeast oriented faults. Slickenside striations found on three planes of the northwest oriented faults (F2, F3 and F4) indicate predominant normal-slip components and subordinate left-lateral strike-slip components (slickenside striations rake 76°-81°). The northwest oriented faults have left-stepped en echelon arrangement (Figs. 3 and 4). All the planes of these faults have southwest dip except one fault (F1) that has northeast dip. The latter fault has a maximum amount of throw of about 140 m. Faults number F2, F3, F4 and F6 form step faulted blocks in the southwestern part (cross section X-X\` in Fig. 5).

The south to southeastward dip of the Eocene rocks forming the plateau is related mainly to the southeast dip of the southeastern limb of the Wadi El Toloun anticline (Fig. 4) which exists in the southern part of Abu Roash area (Fig. 3). This anticline lies to the northwest of the Giza Pyramids Plateau. The dip amounts of the Middle Eocene rocks forming the plateau range between 4° and 7° whereas those of Upper Eocene rocks range between 8° and 10° on the downthrown side of the F5 fault (Fig. 8). The changes in the dip amount and direction are attributed to the influence of the faults. The nearly east-west oriented fault (F5) changed the southeastward dip of the plateau into southward dip in its hangingwall, it also caused the steeper dip (up to 10°) in its footwall. Also, the Middle and Upper Eocene rocks in the hangingwall of the north-south oriented fault (F7) have westward dip (Fig. 4).

3- Regional Structures:

The study area lies at the boundary between the stable and unstable shelves of Egypt (Said 1962). The Giza Pyramids Plateau is bounded on the west and north by the Upper Cretaceous Syrian Arc deformation of the Abu Roash area (Fig. 3). Beadnell (1902), Faris (1948), Jux (1954), El-Etr and El Baz (1979), Moustafa (1988), and Abdel Khalek et al. (1989) studied these structures. Different structural models are proposed for the deformation of the Abu Roash structures. These models are vertical movement (El-Etr and El-Baz 1979), right-lateral wrenching on deep-seated, east-northeast oriented faults (Moustafa 1988), and horizontal compression associated with wrenching and assisted by vertical radial stresses (Abdel Khalek, et al. 1989). The structures of the Abu Roash area consist of east-northeast to northeast oriented folds which are dissected by several west-northwest, north-northwest, and north-south oriented faults (Fig. 3). Moustafa (1988) interpreted these folds and faults to have been formed by right-lateral wrenching on east-northeast oriented deep-seated fault. This wrenching took place at the beginning of the Turonian and reached its acme after the deposition of the lower part of the Senonian chalk.



Boat Pit
Qnt Quaternary Nile terraces
Qs Quaternary sands
Blocks for maintenance and pavement
S Soil
ED Excavation Dumps

Figure 8: Very detailed geologic map showing the faults affecting the rock units of the plateau. Notice that the limestone of Observatory Formation form the head of Sphinx. The dashed fault traces indicate concealed faults, the other rock units and fault symbols are as in Fig. 4.

The left-stepped en echelon, northwest trending normal faults affecting the Giza Pyramids Plateau are herein interpreted to overlie a deep-seated, east-northeast oriented fault called the Giza pyramids fault (Fig. 3). This deep-seated fault has been rejuvenated by right-lateral divergent wrenching after the deposition of the middle member of Mokattam Formation (Early to Middle Lutetian) representing the first phase of the Tertiary deformation. The age of this deformation is indicated by the presence of an unconformity between the middle member of the Mokattam Formation and the Qurn Formation in Darb Al Fayuim area (Fig. 2). Second order structures contemporaneous with this right-lateral divergent wrenching include northwest to west-northwest oriented faults having subordinate left-lateral strike-slip components (conjugate Riedel shears) and northeast oriented minor faults having subordinate right-lateral strike-slip components (Riedel shears).

The Eocene beds forming the Giza Pyramids Plateau have the same southeast dip direction like the Cretaceous beds on the southeastern limb of the Wadi El Toloun anticline (Fig. 4). These Cretaceous beds have dip amounts ranging between 20° and 23° whereas the Eocene beds have gentler dips ranging between 4° and 7°. Based on the similarity in the dip direction, the Eocene rocks forming the Giza Pyramids Plateau represent the outer part of the southeastern limb of Wadi El Toloun anticline. Also, the east-northeast oriented deep-seated faults (Abu Roash and Giza Pyramids faults in Fig. 3) could have been reactivated during the Syrian Arc deformation in Early Turonian and Early Senonian. The same faults were rejuvenated again after the deposition of the Upper Maastrichtian nodular chalk in Jiran Al Ful area. This chalk underlies unconformably the Paleocene Chalk and both are separated by a thin conglomerate bed (35cm thick). Strougo and Haggag (1983), Haggag (1986), Strougo and Hottinger (1987), and Anan (1987) studied the Upper Maastrichtian, Paleocene, and Lower Eocene rocks in Jiran Al Ful area. These authors indicated two other unconformities, the first one lies between the Middle and Upper Paleocene rocks whereas the second one lies between the Upper Paleocene rocks (chalk and matrix supported conglomerates) and the Lower Eocene limestones which are rich in alveolinids. The Upper Paleocene conglomerates represent some kind of submarine mass flow at the base of a significant slope (Strougo and Haggag 1983 and Strougo 1986). These two unconformities are most probably equivalent to two phases of rejuvenation of the deep-seated faults in the Giza-Abu Roash district. These faults were also reactivated after the deposition of the middle member of the Mokattam Formation as indicated by the presence of an unconformity at the top of this member in Darb Al Fayuim. The upper member of the Mokattam Formation and all the Observatory Formation (Fig. 2) represent the hiatus of this unconformity. This hiatus decreases to the east where Strougo (1985) pointed out that the middle and upper members of the Mokattam Formation are separated by a disconformity in the Sphinx ditch. At the Citadel area (east), there is a sharp contact between the algal limestones of the middle member of the Mokattam Formation and the *Nummulitic gizehensis* bank of the upper member of the same formation (Strougo personal communication). Strougo (1985) showed that the area of Kait Bey lies on top of a deep-seated ridge.Therefore, the area between the Darb Al Fayuim and Sphinx was uplifted after the deposition of the middle member. This uplifting may have be extended into the Citadel area. The uplifting was higher toward the Wadi El Toloun anticline (in the west) and seems to have been very mild in the Citadel area.

In the present study, the Syrian Arc deformations include all the tectonic movements (deep-seated fault reactivations) which took place in the Late Cretaceous time and extended into Paleocene, and Early to Middle Lutetian times. The Syrian Arc renewed deformations during the Maastrichtian, Paleocene, and Early Eocene times was reported by Hussein and Abd-Allah (2001) in the district between the southern Galala Plateau and the Manzalah Lake, to the east of the present study area.

The Tertiary deformations in the Giza-Abu Roash district are supported by the rejuvenation of the northwest oriented, Six of October fault (Fig. 3). Geoelectric studies (by the second author) indicate that this fault juxtaposes the Oligocene basalts against the Lower Miocene Moghra Formation. This fault is also found on the Upper Cretaceous structure map of Nemec (1996). The displacement of the Wadi El Toloun fault (F6) is transferred into the Six of October fault through a northeast oriented fault which acts as synthetic transfer zone (Fig. 3). Field evidence indicates that the second phase of Tertiary deformation was at the beginning of the Oligocene time. Moustafa et al. (1985) also proposed this deformational phase for the formation of the faults in the area east of Cairo, Maadi, and Helwan (east of the study area).

4- Stress and Strain Analysis:

The data of twenty eight fault planes measured in the Giza Pyramids Plateau are used to estimate the orientation of the stress and strain that affected this plateau. These data include some of the mapped faults as well as minor faults.

a- Stress

The method of Aleksandrowski (1985) is used to determine the orientation of the stress axes in the study area. The slip-linear plot for thirteen slickenside striations indicates two clusters of west-northwest oriented faults (Fig. 9). The first fault cluster has south-southwest dip whereas the second fault cluster has north-northeast dip. The majority of these faults show normal right and left-lateral oblique-slip movements. The strike-slip components (arrows parallel to the primitive) are less than the dip-slip components (radial slip linear). The pattern of the slip linear shows N 18° E - S 18° W oriented extension ($\sigma 3$) and N 74° W - S 74° E oriented compression ($\sigma 1$). These trends of extension and compression are compatible with the directions of lengthening and shortening that resulted from the right-lateral wrenching on the east-northeast oriented deep-seated fault in the study area. The analysis of the trends of the lengthening and shortening in relation to the right-lateral wrenching in figure 9 indicates that the deep-seated fault affecting the plateau area is expected to have N 52° E - S 52° W orientation.

b- Strain

The three dimensional strain axes are determined by using the Odd-axis model proposed by Krantz (1988). The attitudes of the fault planes and their slip vectors are used in the construction of this model (Fig. 10). This model shows three fault sets which are east-west, west-northwest, and northwest. Faults of these sets are conjugate and have two opposite dip directions. The rakes of the slickenside striations vary from 63° to 90° with an average of 78°. In the present study area, the nearly vertical Odd axis must be Σz ($\lambda 1$) and the other two maximum and minimum axes match the Σx ($\lambda 3$) and Σy ($\lambda 2$) respectively.

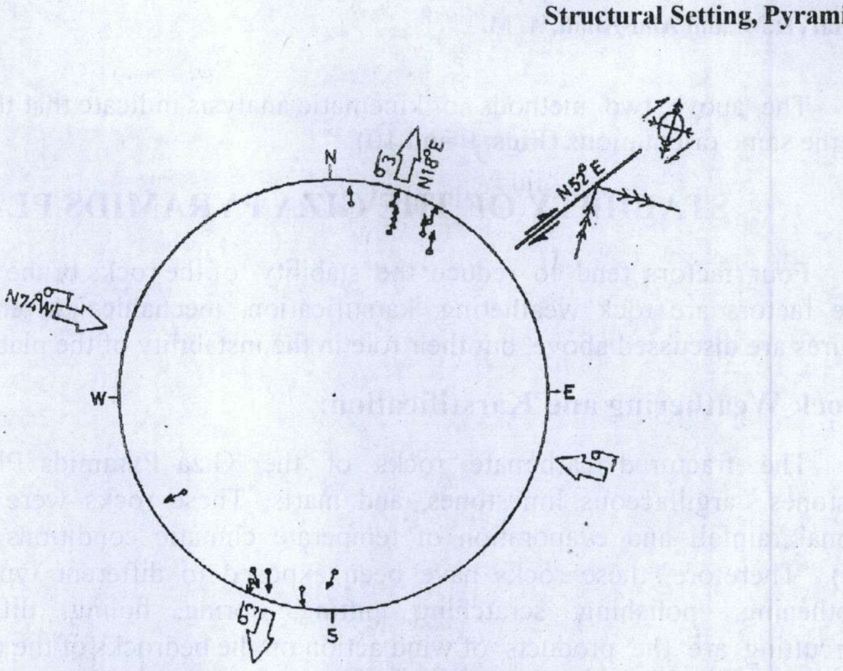


Fig. (9). Slip linear stereographic plot for 13 faults affecting the study area. The stress axes analysis indicates that the slip linears point toward σ 3 and away from σ 1. The radial slip linears perpendicular to the primitive indicate dip-slip faults whereas the arrows parallel to the primitive are strike-slip faults. The inset diagram shows the relation between the stress axes (σ 3 and σ 1) and the lengthening and shortening that resulted from the right-lateral wrenching on the N 52° E oriented deep-seated fault.

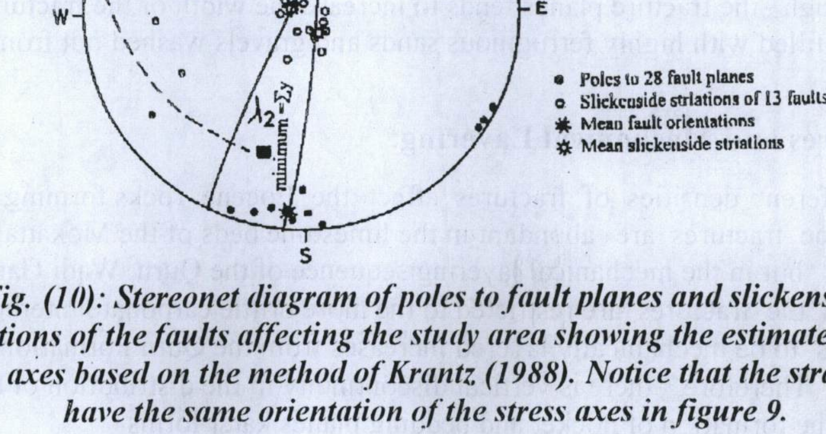


Fig. (10): Stereonet diagram of poles to fault planes and slickenside striations of the faults affecting the study area showing the estimate of the strain axes based on the method of Krantz (1988). Notice that the strain axes have the same orientation of the stress axes in figure 9.

The above two methods of kinematic analysis indicate that the stress and strain axes have the same orientations (Figs. 9 and 10).

STABILITY OF THE GIZA PYRAMIDS PLATEAU

Four factors tend to reduce the stability of the rocks of the Giza Pyramids Plateau. These factors are rock weathering, karstification, mechanical layering, and fractures. The fractures are discussed above, but their role in the instability of the plateau is indicated below.

1- Rock Weathering and Karstification:

The fractured carbonate rocks of the Giza Pyramids Plateau are made up of limestones, argillaceous limestones, and marls. These rocks were subjected to intensive seasonal rainfall and evaporation of temperate climatic conditions (El Aref and El Refai 1987). Therefore, these rocks have been exposed to different types of weathering. The smoothening, polishing, scratching, pitting, boring, holing, differential erosion, and undercutting are the products of wind action on the bedrocks of the plateau (Soliman 1997). The study of Barakat et al. (1997) on the bedrocks of Sphinx indicates human pollution in the surrounding area and the natural forces resulting from wind, rain, dew, humidity, and temperature affect the Sphinx bedrock. The degree of weathering varies from extremely high and high in the fractured parts of the plateau to moderate and low in the other parts. The dump materials (Fig. 8) that cover several parts of the plateau surface prevent the successive weathering. Rainwater dissolves the carbonate rocks to form several cavities and karst forms. The insoluble materials like clays, sands, and iron oxides fill partially the resulting cavities.

Geometrically, the resulting karst cavities exist in four forms which are surface, pockets, bedding planes, and fractures. The surface forms include the pits, holes, and depressions resulted from the drainage of the running water in the low parts of the plateau surface. The pocket forms comprise cavities, of different sizes in the thick carbonate beds, where the surface water percolated through the fracture planes and dissolved the carbonate material. On the other hand, the bedding plane forms resulted where the percolated water reached the bedding plane of two carbonate beds. The fracture zone is highly porous and has easier water flow and percolation causing intense karstification and forming pipe-like cavities. These cavities are widely distributed and have variable width (0.2-2.6 m). The percolating water through the fracture planes tends to increase the width of the fracture aperture. Several pipes are filled with highly ferruginous sands and gravels washed out from the top surface of the plateau.

2- Fractures and Mechanical Layering:

Different densities of fractures affect the Eocene rocks forming the Giza Pyramids Plateau. The fractures are abundant in the limestone beds of the Mokattam and Observatory Formations but in the mechanical layering sequence of the Qurn, Wadi Garawi and Wadi Hof Formations the fractures are restricted to the more brittle carbonate interbeds. The affinity of these rocks to be mechanically layered increases from the Qurn Formation into the Wadi Hof Formation. Therefore, there is vertical discontinuity in the distribution of the fractures which facilitates the formation of pocket and bedding planes karst forms.

The majority of the fractures affecting the Eocene rocks of the Giza Pyramids Plateau have steep dip between 62° and 90° with an average of 79°. Steeper planes found in the brittle rocks compared to those affecting the ductile rocks. The Ancient Egyptians used the vertical fracture planes affecting the Mokattam and Observatory Formations in carving of some tombs and the body of Sphinx. The wall rocks of the majority of the fractures are extremely highly to highly weathered. Both the high-angle fracture planes and weathered rock walls tend to reduce the rock strengths. High angle fracture planes have low shear strength, thus the blocks bounded by these planes are potentially unstable and easy to slide under small seismic shaking and/or intense water dissolution or even under the influence of their own weight. Block sliding may occur into the karst cavities and/or into the slope and scarp faces.

Based on the fracture trends and spacings, the bedrocks of the Giza monuments are fragmented into several blocks of different sizes and shapes. The fractures affecting the foundation bedrock of Cheops Pyramid belong to two sets trending west-northwest to northwest and northeast (Fig. 6). The average fracture spacings of these sets are 0.45 m and 1.15 m respectively. In the northeastern corner of the Cheops Pyramid, the northwest oriented fractures have steep northeast dip and dissect the elevated foundation bed (bedrock above the plateau surface). These fractures are filled with highly ferruginous sands and fragmented the foundation bedrock into several blocks that can easily slide (Fig. 11). The foundation bedrock of the Chephrea Pyramid is also fragmented into several blocks by the northwest to west-northwest and northeast oriented fractures (Fig. 6). In order to support the blocks in Cheops and Chephrea areas, rock bolts of different lengths and diameters are recommended (Fig. 11).

The northwest oriented fractures dissecting the foundation bedrock of the northeastern part of the Cheops Pyramid splay into several branches that enclose a subsided rhombic block (Fig. 11c). This block is internally affected by fractures of curved traces which are downthrown toward the central part of the block. The measured amounts of settlement of this block increase toward its central part to be 0.46 m. According to the curved traces of the fractures, most of these fractures might have been formed during the settlement. This settlement is diagnosed as roof collapse of the upper bed (forming the plateau surface) over karst cavity that resulted from the dissolution of the underlying carbonate bed by the action of the percolated water through the fractures (Fig. 12). The continued water percolation led to increase in the size of the karst cavity until failed the rock strengths of the overlying roof bed by its own weight and collapsed inside the cavity (Fig. 12). Other roof collapse areas are observed at the northwestern and southwestern parts of Cheops pyramid as well as the northwestern part of Chephrea Pyramid (Fig. 6). Maintenance of some of these parts was done by filling them with cube-shaped carbonates blocks. The present authors recommend the use of injected shotcrete that is more favorable and has several advantages. These advantages are the shotcrete reaches narrow cavities, it is an insoluble material, and it seals completely and blocks the cavities. Thus, the injected shotcrete is preferred for supporting, stopping, and filling these collapses and karst forms. It should be noted that the shotcrete is assumed to be impermeable by using fine grained sands and much cement to prevent water percolation and must be injected under high-pressure. Finally, the abundance of fractures, weathering processes, and karst forms would result in significant reduction in the strength of the rock forming the plateau leading to instability of the plateau. In addition, the Giza Pyramids Plateau suffers greatly from seismic shaking (Gauri 1992).

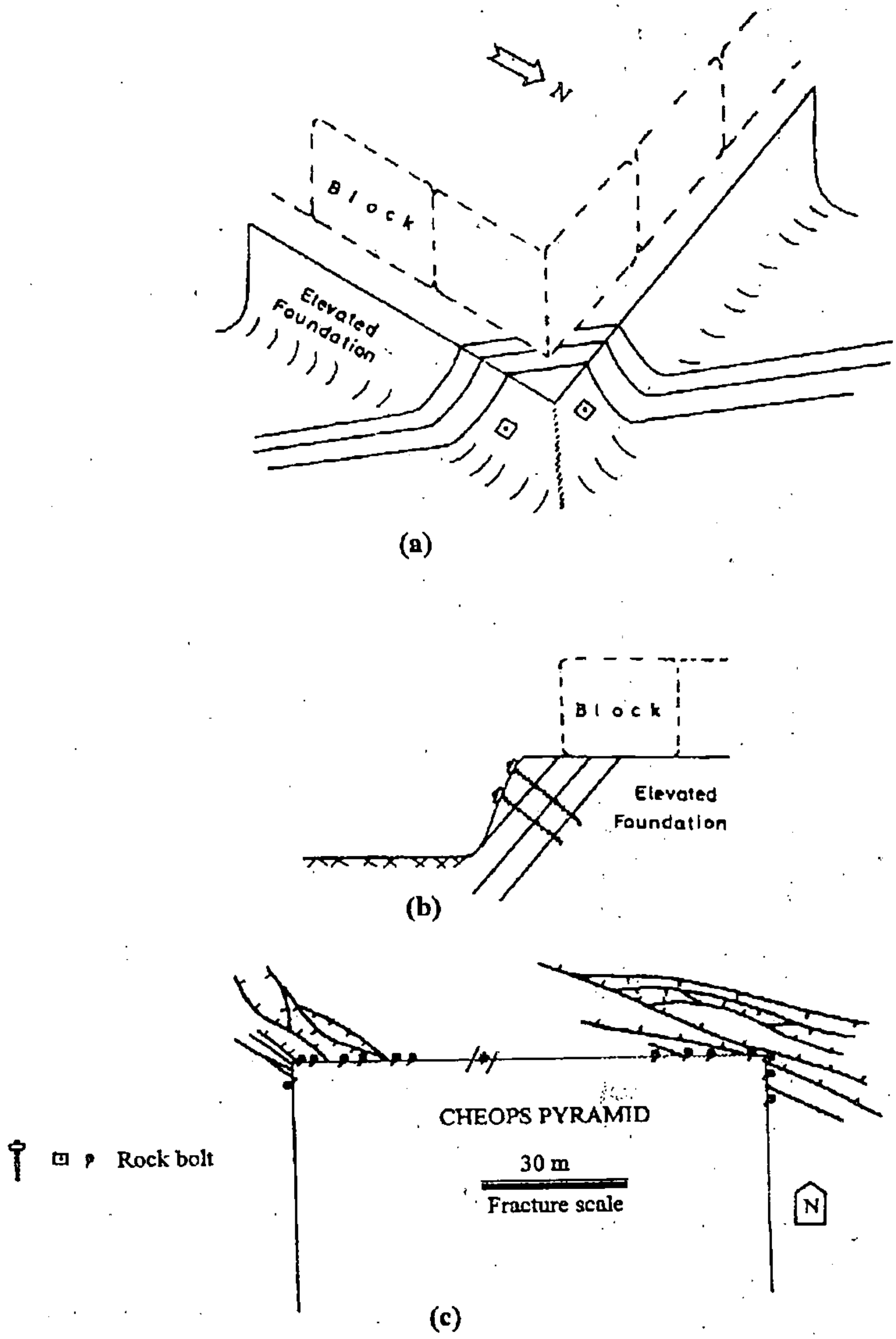
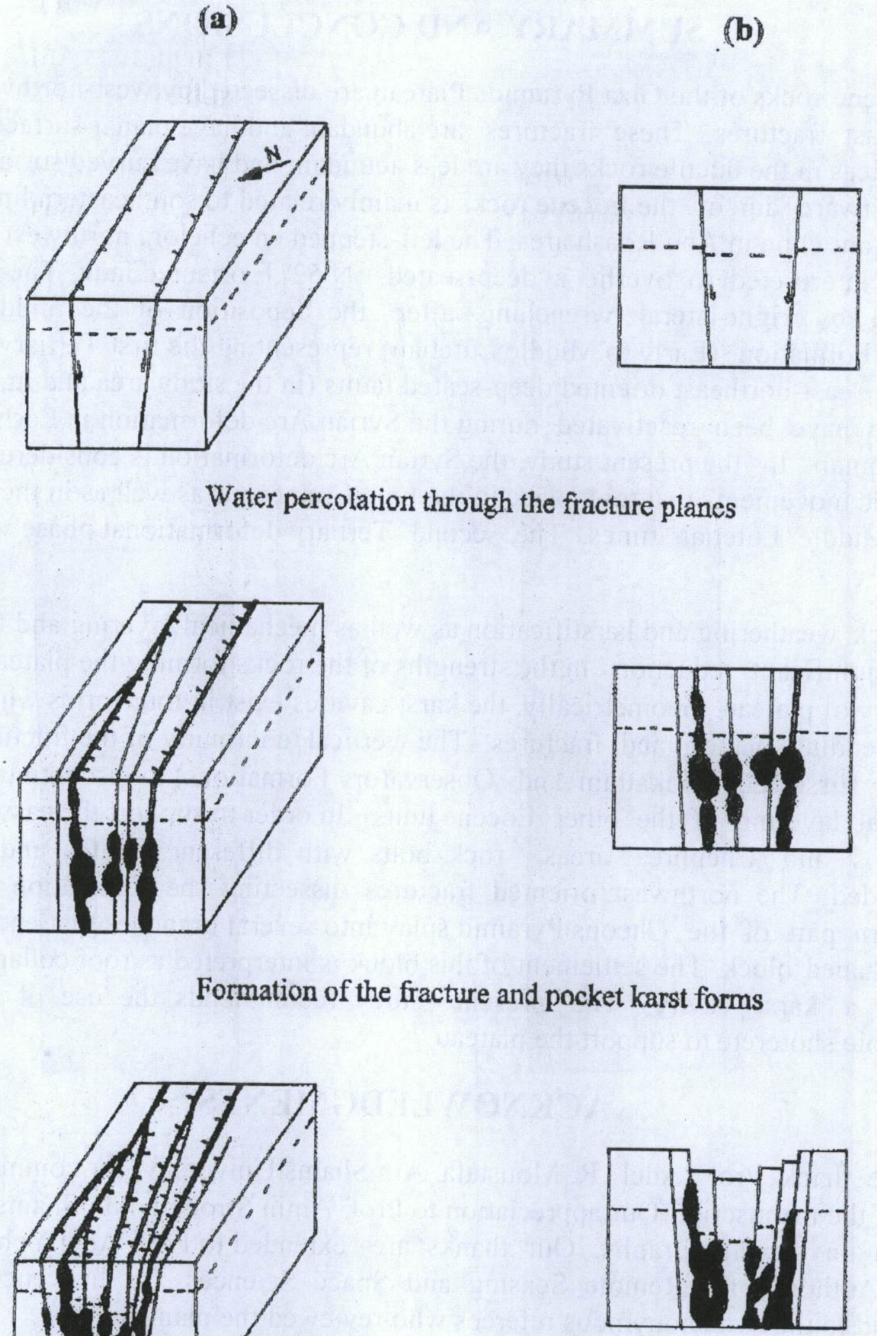


Fig. (11). (a) Block diagram showing the influence of the northwest oriented fractures on the elevated foundation bedrock in the northeastern corner of Cheops Pyramid. (b) Cross section perpendicular to these fractures shows the proposed design of rock bolts for supporting the fractured blocks. (c) Map view of the fractures affecting the northeastern and northwestern sides of Cheops Pyramid and the proposed pattern of rock bolts.



Increaseing the volume of the karst forms by continuous water percolation and collapse of the roof bed into the karst cavity and formation of new fractures

Figure 12: Successive block diagrams (a) and cross sections (b) showing the formation of the roof collapse in the Giza Pyramids Plateau.

SUMMARY AND CONCLUSIONS

Eocene rocks of the Giza Pyramids Plateau are dissected by west-northwest, northwest and northeast fractures. These fractures are abundant and have planar surfaces in the brittle rocks whereas in the ductile rocks they are less abundant and have curved surfaces. The south to southeastward dip of the Eocene rocks is mainly related to southeastern limb of the Wadi El Toloun anticline in Abu Roash area. The left-stepped en echelon, northwest oriented faults are herein interpreted to overlie a deep-seated. N 52° E oriented fault. The latter fault was rejuvenated by right-lateral wrenching after the deposition of the middle member of Mokattam Formation (Early to Middle Lutetian) representing the first Tertiary deformational phase. The east-northeast oriented deep-seated faults (in the study area and in the Abu Roash area) could have been reactivated during the Syrian Arc deformation in Early Turonian and Early Senonian. In the present study, the Syrian Arc deformation is considered to include all the tectonic movements that took place in the Late Cretaceous as well as in the Paleocene and Early to Middle Lutetian times. The second Tertiary deformational phase was at the Early Oligocene.

Rock weathering and karstification as well as mechanical layering and fractures would result in significant reduction in the strengths of the rocks forming the plateau and decrease the stability of plateau. Geometrically, the karst cavities exist in four forms which are surface, pockets, bedding planes, and fractures. The vertical continuity of the fractures varies from completely dissected (Mokattam and Observatory Formations) to discontinuously dissected (mechanical layering of the other Eocene units). In order to support the easy slide blocks in the Cheops and Chephrea areas, rock bolts with different lengths and diameters are recommended. The northwest oriented fractures dissecting the foundation bedrock of the northeastern part of the Cheops Pyramid splay into several branches that enclose a subsided rhombic-shaped block. The settlement of this block is interpreted as roof collapse of the upper bed over a karst cavity. The present study recommends the use of highly injected impermeable shotcrete to support the plateau.

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