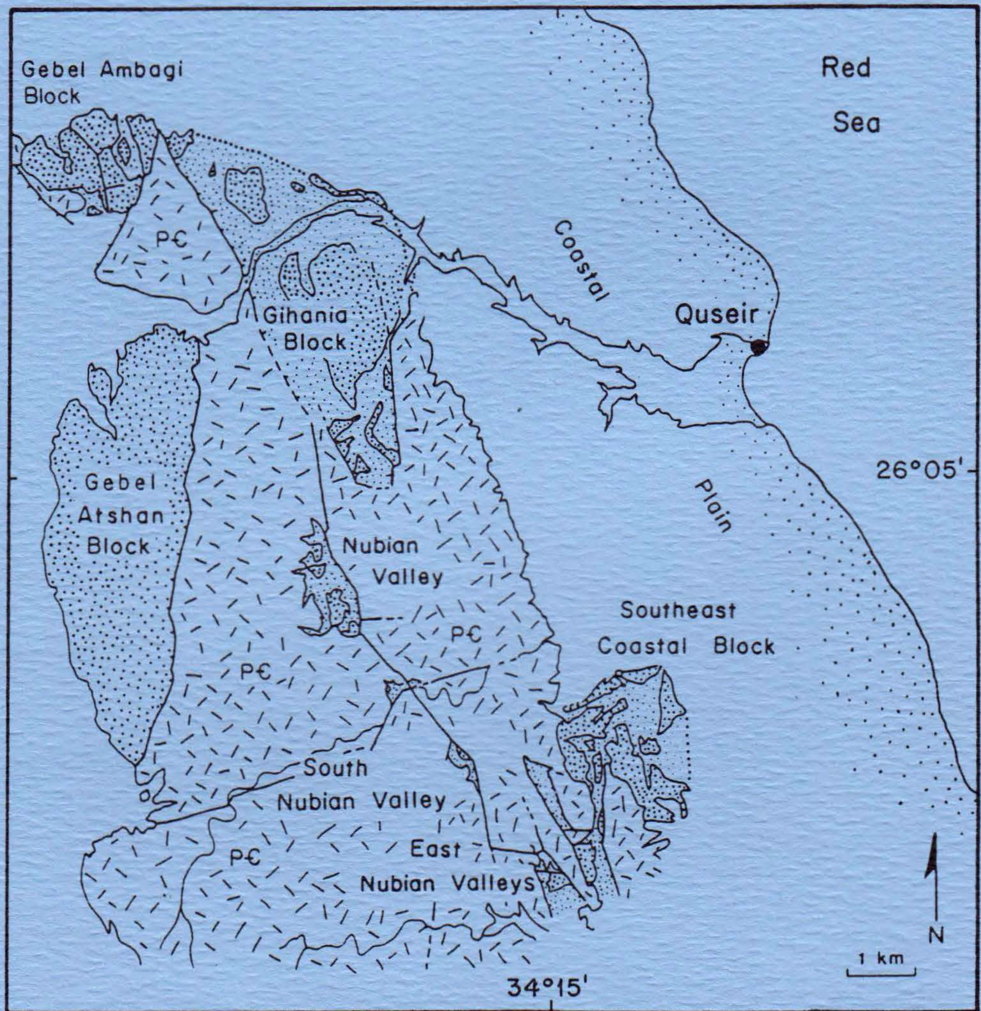
STRUCTURAL GEOLOGY OF THE QUSEIR AREA, RED SEA COAST, EGYPT

BY DAVID C. GREENE



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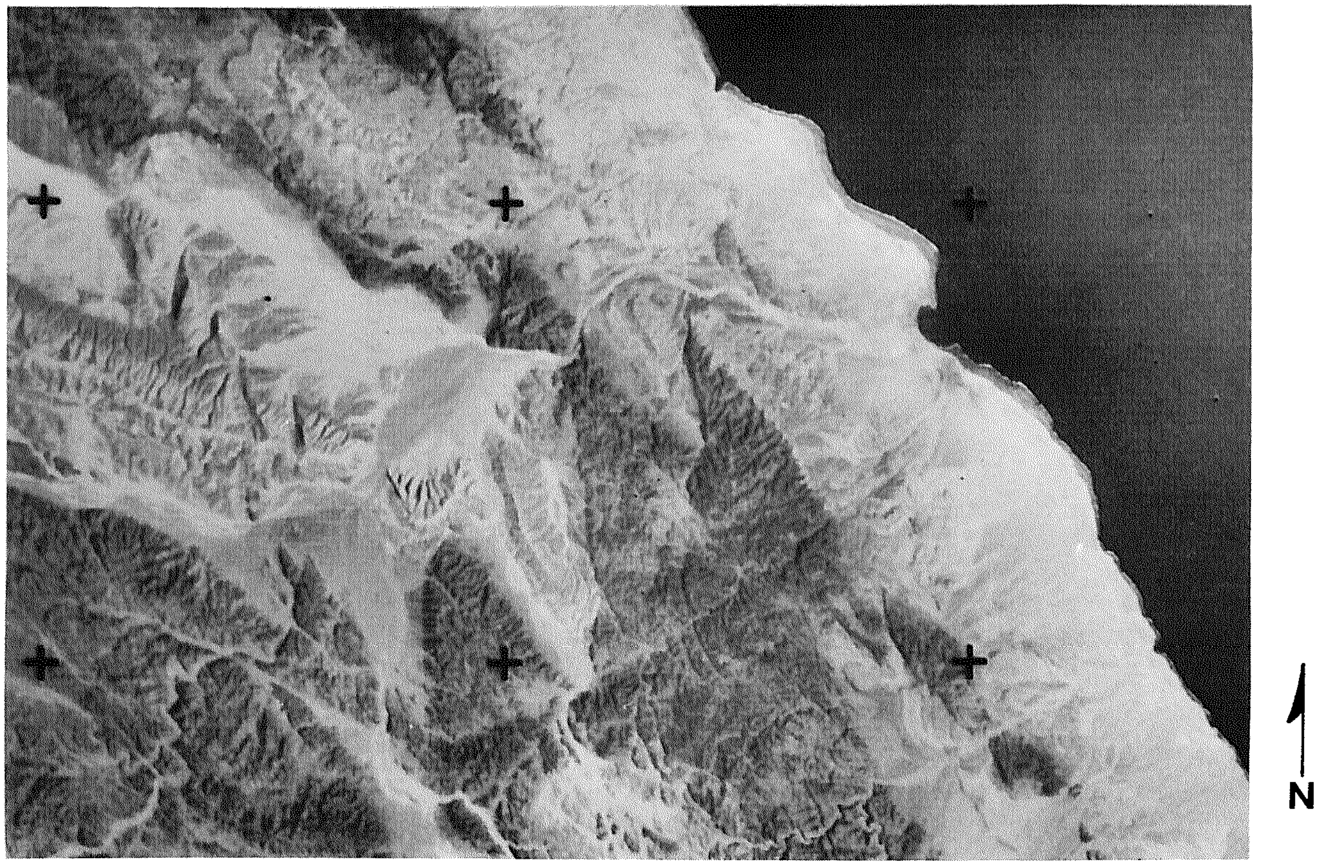

Figure 1. Return-beam vidicon image of the Quseir region. Precambrian basement is dark in color, with large granitic bodies slightly lighter. Platform sediment blocks and the Red Sea coastal plain are very light in color. The large block on the west is Gebel Duwi; the study area comprises the east-central portion of the image (see fig. 3).

ABSTRACT

The Quseir area of the Red Sea coast of Egypt (26° 01′N lat. to 26° 10′N lat.) includes three major lithologic groups: (1) a late Precambrian basement complex consisting of highly deformed volcanics and volcanogenic sediments metamorphosed to lower greenschist facies; (2) Cretaceous to early Eocene platform sediments consisting of up to 600 m of well-bedded sandstones, shales and limestones; and (3) Miocene to Recent Red Sea coastal plain sediments consisting of fanglomerates, marls, evaporites and calcareous reef deposits.

The Precambrian volcano-sedimentary units appear to have been deposited in an oceanic island-arc environment. Subsequent deformation by predominantly northeast compression resulted in development of a tight synform plunging approximately 60° toward S40E, axial planar regional foliation trending N35W, and a quartz vein set trending N45E. Major granitic intrusions were syn- to post-tectonic.

The unconformably overlying platform sediments are exposed as east-dipping tilted blocks and down-faulted inliers within the Precambrian basement. Emplacement and preservation resulted from 300 m to 1 000 m of motion on a system of west-dipping, north- to northwest-trending

normal faults, and from lesser motion on subsidiary east-dipping faults.

The coastal plain sediments, deposited at the margin of the developing Red Sea rift, thicken and dip eastward toward the rift axis. Abrupt vertical and lateral facies variations reflect syn-sedimentary faulting, coralline reef growth, and local variations in sediment supply.

Detailed study of Tertiary fault motions has documented a pattern of early strike-slip faulting with subsequent dip-slip reactivation. Right-lateral strike-slip faults trending N20W and left-lateral faults trending N60E form a conjugate system, indicating N20E compression in the Quseir region in middle Eocene to Oligocene time. North- to northwest-trending faults were reactivated in late Oligocene to early Miocene time as west-dipping normal faults, resulting in tilting and emplacement of the platform sediment inlier blocks.

Uplift and erosional truncation of fault blocks in the early Miocene culminated in development of a terminal erosion surface termed the mid-Tertiary pediplain. A second period of rift marginal uplift, active in post-Pliocene time, has elevated the mid-Tertiary pediplain and exposed Quaternary wadi and reef terraces on the coastal plain.

A five-phase Cenozoic evolution of the Red Sea rift in the Quseir region is proposed. Phase 1: north-northeast compression in middle Eocene to Oligocene time; Phase 2: continental margin extension and block rotation in late Oligocene or early Miocene time; Phase 3: formation of a proto Red Sea in middle Miocene time; Phase 4: quiescence during the late Miocene; and Phase 5: sea floor spreading, active from the Pliocene to the present.

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CHAPTER I

INTRODUCTION

Purpose of Research

The Red Sea Rift System includes one of the most recently rifted continental margins in the world. It is a region of fundamental importance for the study of the processes of rifting and continental break-up. The northeastern margin of the Red Sea has been much studied in the past decade, most notably by the various missions associated with the Saudi Arabian Deputy Ministry for Mineral Resources (Brown, 1970; Davies, 1980, 1981; Hadley et al., 1982; Schmidt et al., 1982). Substantial oceanographic work has been completed within the Red Sea basin (Degens and Ross, 1969; Whitmarsh et al., 1974; Ross, 1977). However, the Egyptian side of the Red Sea has received much less attention due to difficulties of access and the small number of workers in the region. The purposes of this study are: (1) to provide geologic maps (plates 1 and 2) and detailed structural information for an area of the western margin of the Red Sea in Egypt, (2) to correlate these data with structural information from other workers in Egypt and Saudi Arabia, and (3) to examine the implications of these data for the tectonics and development of rifting in the Red Sea region.

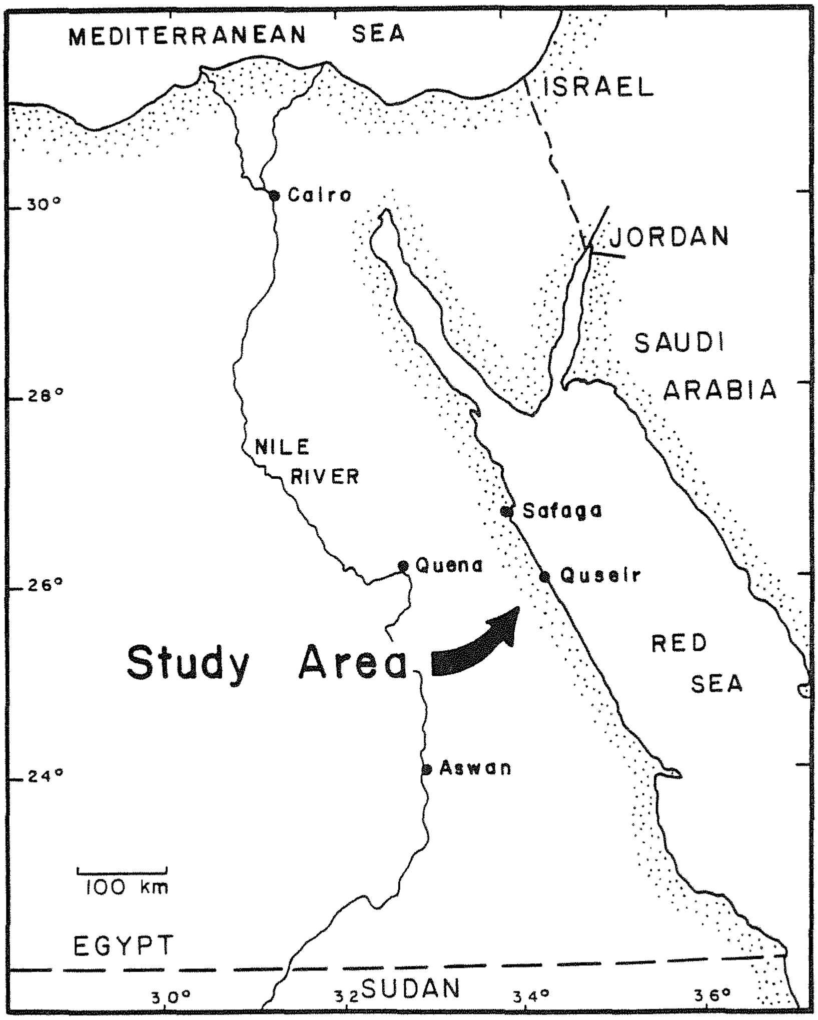


Figure 2. Index map of Egypt showing study area.

Description of Quseir Region

The study area is situated in Egypt, on the southwestern shore of the Red Sea, between 26° 01′ and 26° 10′ north latitude and 34° 09′ and 34° 19′ east longitude (figs. 1 and 2). It is 140 square kilometers in area, bounded by Wadi Quseir el Qudeim on the north, Wadi Nakheil and Wadi Beda el Atshan on the west, an east-west line approximately 4 kilometers south of Wadi el Isewid on the south, and by the Red Sea on the east (fig. 3). The only permanent settlement in the region is the town of Quseir, a small fishing and phosphate-mining community with a population of about 15 000(?).

Access to the area is generally adequate; a paved road runs north-south along the coastal plain, and another passes westward to Quena and Luxor in the Nile Valley. Most of the major wadis are passable in a four-wheel-drive vehicle, and many have remnants of former tracks constructed for phosphate exploration. Scattered anti-tank mine fields, and the use of the area south of Quseir as an artillery range, make access to the coastal plain somewhat more difficult.

The climate of the region is extremely arid, with rainfall averaging less than 1 cm. per year, and daytime

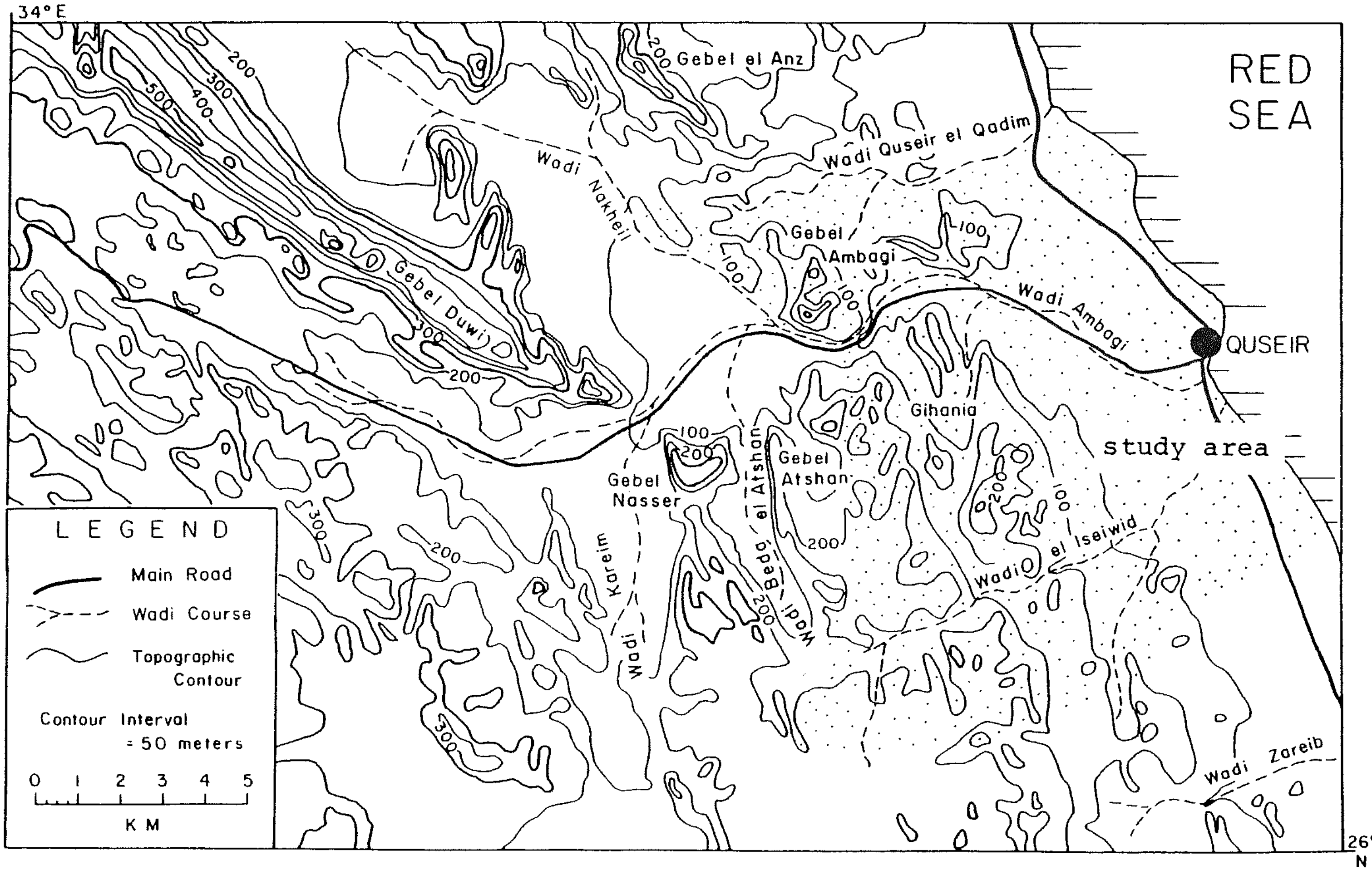


Figure 3. Geographic map of Quseir region. This study covers the eastern half of the region, a parallel study by M. Valentine covers the western half of the region. (Modified from Valentine, in preparation).

temperatures averaging 20° to 30° Celsius (Cohen, 1973). Vegatation is sparse, consisting of scattered small bushes and isolated acacia trees restricted to the major wadis. The only permanent water in the area is a brackish spring which occurs in the narrowest part of Wadi Ambagi, where it crosses a ledge of the Precambrian basement.

In general, the area consists of a flat coastal plain with uplifted, west-dipping plateaus of middle to late Tertiary sediments related to the Red Sea, and an elevated inland region. The inland region has a rugged topography, with several hundred meters of relief developed on highly deformed Precambrian basement, and local steeply tilted fault blocks of Cretaceous to Eocene platform sediments.

Several Arabic words are commonly used in the text: gebel=mountain, wadi=dry stream course or valley, and bir=well. The word "isewid" means black, thus Wadi el Isewid is "black valley". Qudeim means old, and Quseir el Qudeim is "old Quseir", the original site of the port of Quseir and an important trading post in Roman and medieval Islamic times.

Previous Work

Much of the early work on the geology of Egypt is summarized by Said (1962) in his excellent book The

Geology of Egypt. Currently available geologic maps include the Geologic Map of Egypt (Egyptian Geological Survey and Mining Authority, 1981), and the Geologic Map of the Quena Quadrangle (ibid, 1978) which includes the Quseir region.

An extensive study of the Precambrian basement rocks of the northern Eastern Desert of Egypt was published by Schurmann (1966). More recent work on the Precambrian rocks of the Eastern Desert has been carried out by Akaad and Noweir (1979), who published a detailed stratigraphy for an area between latitudes 25° 35′ and 26° 30′ N; by Dixon (1979) and Stern (1979) who studied the stratigraphy and geochemistry in the west-central Eastern Desert; and by Sturchio et al. (1983), who described the Meatiq Dome area west of Quseir. Recent ideas on the tectonic evolution of the Precambrian Shield are presented in Engel et al. (1980) and Ries et al. (1983).

Mapping and stratigraphic analysis of the Red Sea coastal-plain sediments has been undertaken by a number of workers, noteably El Akkad and Dardir (1966) in the area to the south of Quseir between Ras Shagra and Mersa Alam, and Issawi et al. (1971) in the area between Safaga (fig. 2) and Sharm el Qibili. More recently, Johnson (1977) completed a detailed study of the Miocene Gebel El Rusas Formation.

Most previous work in the Quseir region has been related to exploration and assessment of phosphate resources occurring in the Cretaceous Duwi Formation. The work resulted in a generalized regional geologic map at a scale of 1:100 000 (El Akkad and Dardir, 1965, unpublished), and numerous detailed maps and descriptions of phosphate localities (El Akkad and Dardir, 1966; Issawi et al., 1968, 1969; Glenn, 1980).

The first geologic map of the Quseir region to distinguish units within the Precambrian basement complex was El Akkad and Dardir´s "Geologic Map of the Coastal Strip Between Qena-Safaga Road and Sharm el Bahari", (1965, unpublished). Subsequently El Ramly, drawing on the work of El Akkad and Dardir, included the area in his "New Geological Map for the Basement Rocks in the Eastern and Southeastern Deserts of Egypt" (1972, scale 1:1 000 000). The "Geologic Map of the Qena Quadrangle" (Egyptian Geological Survey and Mining Authority, 1978; 1:500 000) is the most recent general geologic map of the region which includes the Precambrian basement complex.

In the Quseir region, Trueblood (1981) has mapped the

Phanerozoic sediments in an area north of Quseir, Abu Zeid (in progress) is mapping the Precambrian basement in an area to the northeast, and Valentine (in progress) has mapped an area to the west of this study area (fig. 4). These adjoining maps are being produced at the scale of 1:40 000, and collectively provide relatively complete geologic coverage of the region. In addition, Richardson (1981) has mapped the Mesozoic and Tertiary sediments in the region south of Quseir at a scale of 1:100 000.

Acknowledgements

This report is based on 3 months field work carried out in the spring of 1982. Field work was supported by the National Science Foundation through the Earth Sciences and Resources Institute at the University of South Carolina. Dr. William H. Kanes, Director, and Dr. Steven Schamel, Associate Director of the Institute, and Dr. E. M. El Shazley and Mr. Hafez Aziz of the Egyptian Project were all very helpful with many aspects of the project. Mr. Hassan Abu Zeid was of great assistance in the field, as were numerous members of the local staff. B. A. Greene assisted with petrographic analysis, and W. R. Greene provided computer support.

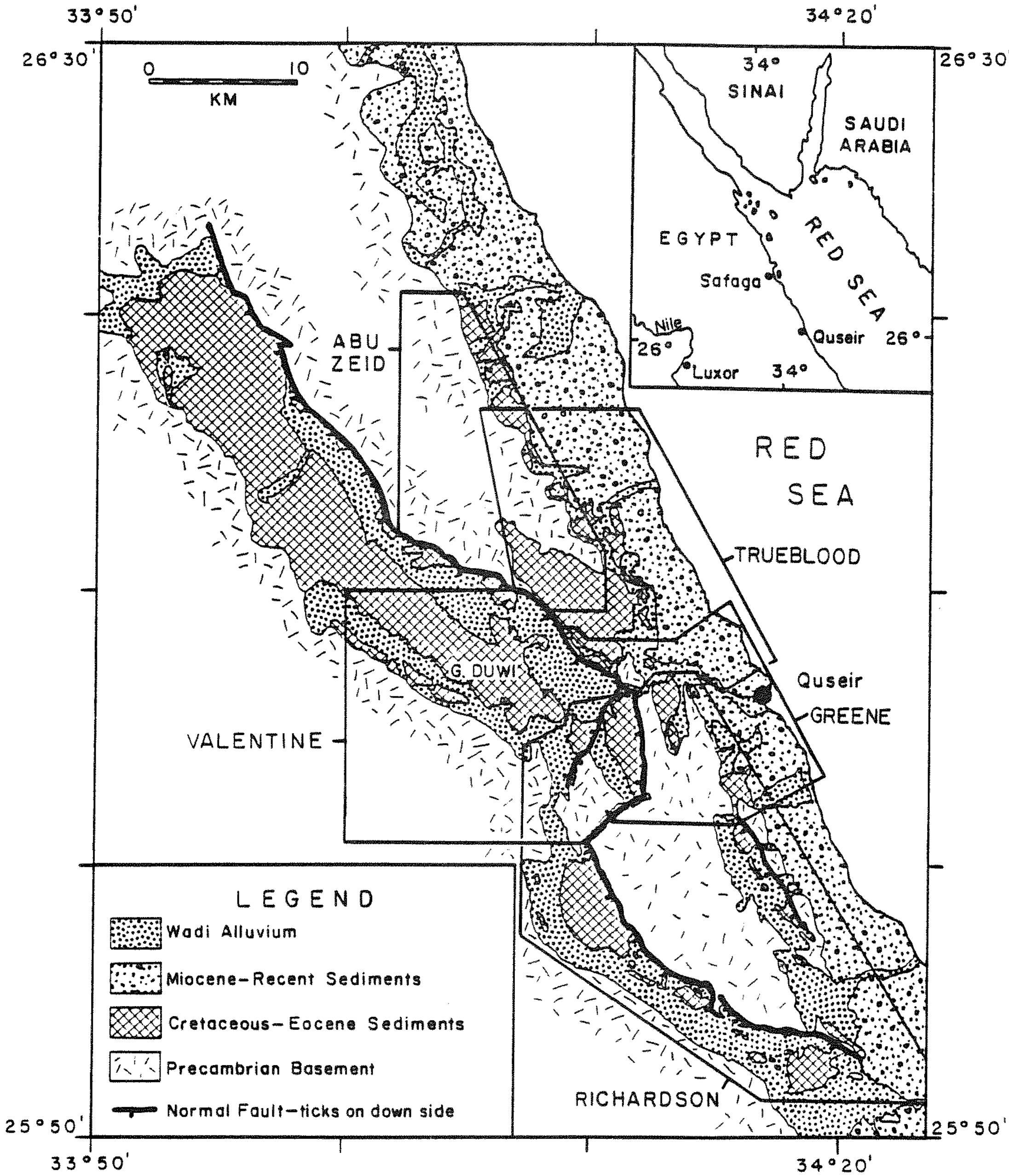


Figure 4. Index map of Quseir region (after Valentine, in preparation).

The manuscript has benefited from enlightening discussions with M. Valentine and R. C. Greene, and from the critical reviews of Prof. George E. McGill and Prof. Charles Pitrat. Prof. Donald U. Wise as thesis advisor provided guidance at all stages in the project. To all the above persons and organizations the author expresses his thanks and appreciation.

CHAPTER II

REGIONAL GEOLOGIC SETTING

Introduction

There are four major stratigraphic sequences exposed in Egypt (fig. 5): (1) a Precambrian basement complex of middle to late Proterozoic (Palmer, 1983) crystalline rocks, upon which is deposited (2) a widespread sequence of Cretaceous to lower Eocene epicontinental platform sediments. These are overlain in the east by (3) alluvial fan, littoral and near-shore marine sediments associated with the Red Sea basin, and in the north by (4) Miocene to Recent clastic and carbonate sediments related to the Mediterranean Sea.

Precambrian Basement Complex

Eastern Desert. A number of stratigraphic systems have been proposed for the Precambrian basement complex in the Eastern Desert of Egypt (El Ramly, 1972; Stern, 1979; Akaad and Noweir, 1980; Ries et al., 1983). A group of geosynclinal metasediments intercalated with mafic to intermediate metavolcanics and ultramafics is generally considered to comprise the oldest rocks in the region (Engel et al., 1980). Associated quartzofeldspathic gneisses (e.g., the Hafafit and Meatiq domes), previously

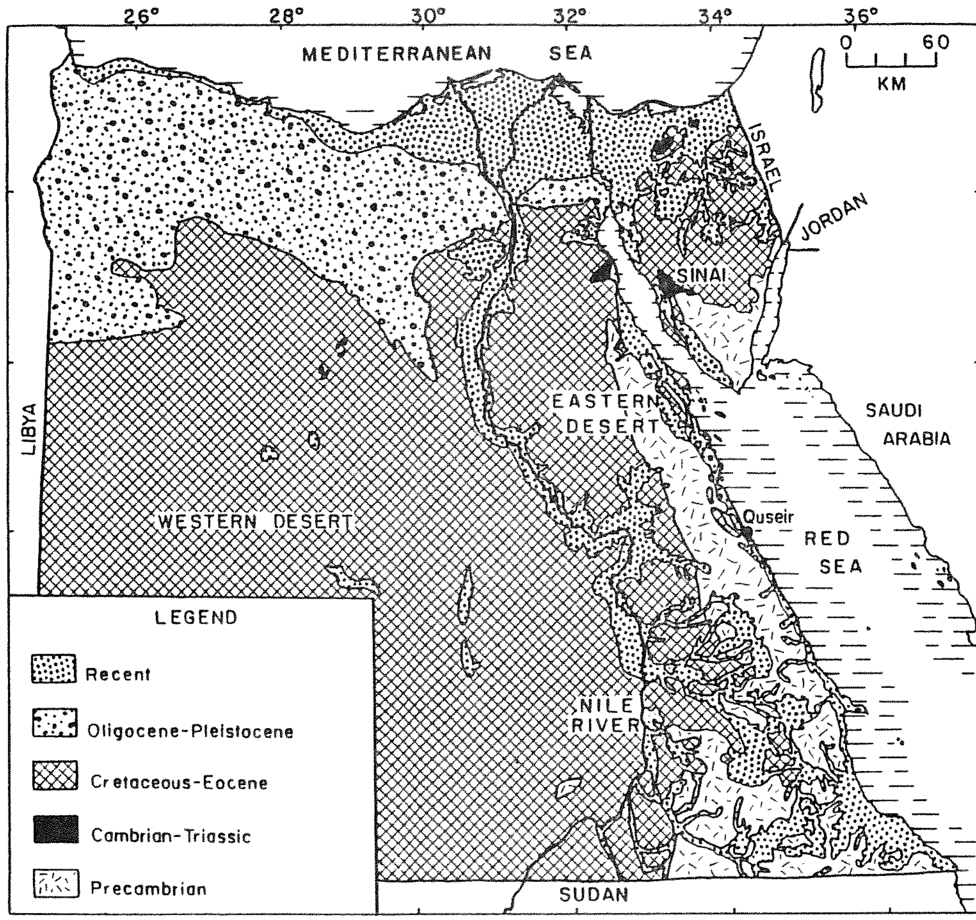


Figure 5. Generalized geologic map of Egypt (after Valentine, in preparation).

thought to be remnants of an older sialic basement (Akaad and Noweir, 1978), are now considered to be the result of late compressive deformation of granitic rocks intruding the metavolcanic/metasedimentary group (Sturchio et al., 1983).

The metavolcanic/metasedimentary group is intruded by granodiorites and quartz diorites of the syn- to late tectonic Older Granite Series (El Ramly, 1972). These are overlain by the Dokhan calc-alkaline volcanics and the Hammamat Group of molasse-type sediments, both much less metamorphosed and deformed than earlier units (Akaad and Noweir, 1978). Intruding the Hammamat Group and all previous units are voluminous post-tectonic granites and alkali granites of the Younger Granite Series (Greenberg, 1981), and subvolcanic rhyolites of the Post-Hammamat Felsite (Akaad and Noweir, 1978).

Arabian-Nubian Shield. The Precambrian basement complex in Egypt is part of the Arabian-Nubian shield, a region of middle to late Proterozoic crystalline rocks comprising the Eastern Desert of Egypt, southern Sinai, western Saudi Arabia, and northeastern Sudan (fig. 6). Three lithostratigraphic assemblages are recognized in the Arabian-Nubian Shield (Engel et al., 1980; Greenwood et al., 1980). The oldest rocks consist of a mafic and

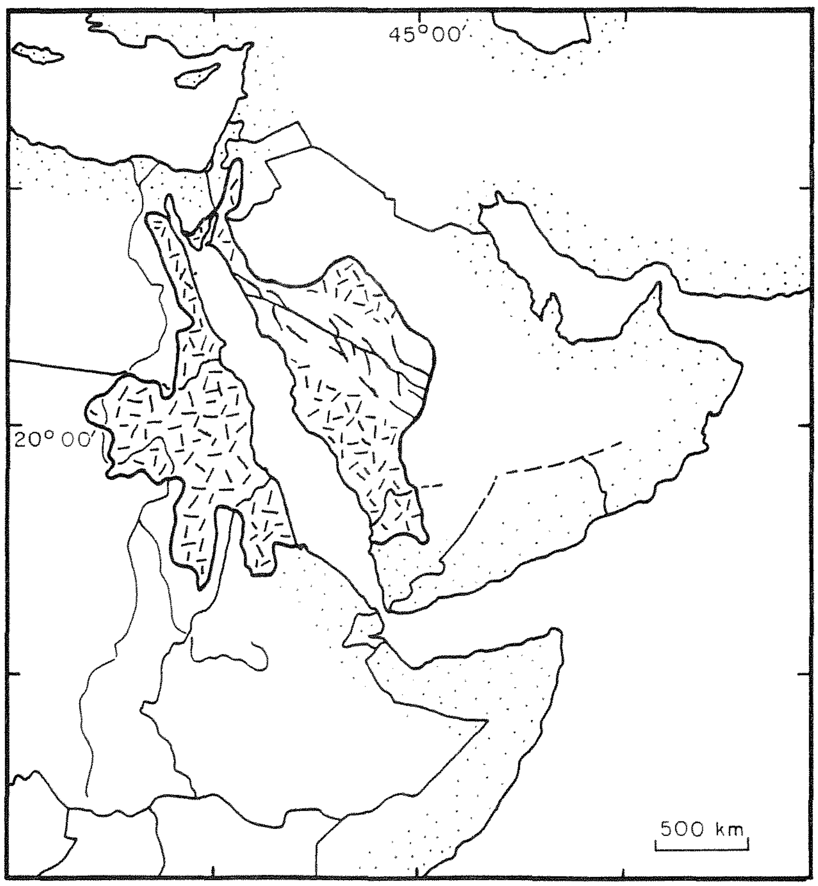


Figure 6. Generalized map of the Arabian-Nubian Shield, with Najd fault system.

ultramafic igneous complex, including tholietic basalts, gabbro, greywacke and chert. These are overlain by a thick sequence (up to 10 000 m) of calc-alkaline volcanics and immature volcanogenic sediments. Engulfing these assemblages are syntectonic to post-tectonic granitic intrusions with associated unmetamorphosed felsic volcanics.

There is general agreement that the Arabian-Nubian Shield was formed in an environment of plate subduction, where the mafic-ultramafic igneous assemblage consists of oceanic crust and immature island-arc material and the calc-alkaline volcanics are remnants of a mature island-arc complex (Schmidt et al., 1978; Engel et al., 1980; Gass, 1981). The granitic intrusions and felsic volcanics are thought to represent the collision of this island arc or arcs with the African craton.

The exact nature of the subduction system that produced the Arabian-Nubian Shield is speculative. A great variety of subduction zone models have been proposed, including single east dipping (Fleck et al., 1980; Greenwood et al., 1980; Ries et al., 1983), multiple east dipping (Gass, 1977), multiple west dipping (Schmidt et al., 1978), and multiple bidirectional (Gass, 1981). In addition, Stern (1979) and Engel et al. (1980) have proposed a modified Wilson-cycle evolution. Most investigators consider the Arabian-Nubian Shield analogous to the present day southwest Pacific region, with numerous island arc complexes of varying size developing in an intra-oceanic setting. Rogers et al. (1978) and Gass (1981) have noted that the whole of northern Africa between the Red Sea and the Archean West African Craton appears to be similar to the Arabian-Nubian Shield, and have suggested that the cratonized island-arc model may be applicable to the entire region.

The final Precambrian tectonic episode affecting the Arabian-Nubian Shield was the development of the Najd fault system (fig. 6) in late Proterozoic to early Phanerozoic time (Fleck et al., 1976). This system of left lateral strike-slip faults and related structures extends from the southeast edge of the Arabian Shield in Saudi Arabia northwestward to the Red Sea coast. The fault system is truncated by the Tertiary Red Sea rift, but probably extends into the Nubian Shield of Egypt at about 26° N lat. (Moore, 1979). The fault system has a total displacement estimated at 240 km (Brown, 1972), and may have developed as a result of the collision of a "rigid indentor" to the west of the Arabian-Nubian Shield (Fleck et al., 1980).

Platform Sediments

The Cretaceous to lower Eocene platform sediments form an extensive, uniform sequence of well-bedded alluvial plain to shallow water shelf sediments overlying a well-developed peneplain on the Precambrian basement. The sequence is exposed over a wide region in the Eastern and Western Deserts of Egypt, and in central Sinai (fig. 5). The rocks are virtually flat-lying over most of the region, but dip gently west off the Red Sea Hills, producing a series of spectacular east-facing erosional scarps with dip slopes dropping westward down to the Nile Valley.

The Egyptian region formed a stable continental platform during the entire period from the end of the Pan African orogeny in the early Cambrian to the beginning of pre-rift intraplate tectonics in the middle Tertiary (Said, 1962). The platform sediments were deposited during a period of epeirogenic downwarping and rising relative sea level which began in the Cretaceous. Epeirogeny culminated in a north to south transgression from the Tethys Sea, and the development of a shallow epicontinental sea across much of northeastern Africa. South to south-southeast directed regional compression in northeastern Egypt and the Sinai at the close of this period produced a system of broad northeast trending folds known as the Syrian arc (Said, 1962).

Red Sea Sediments

Miocene to Recent sediments related to the Red Sea are exposed along the margins of the Red Sea basin, forming a narrow coastal plain extending the entire length of the Red Sea and Gulf of Suez (fig. 5). These coastal plain sediments are primarily alluvial fan, littoral and near-shore-marine facies deposited at the margins of the evolving Red Sea basin.

Mediterranean Sediments

Sediments associated with the Mediterranean Sea basin are exposed predominantly in the northern portion of the Western Desert adjacent to the Mediterranean coast (fig. 5). They consist of generally flat-lying Miocene to Recent clastic and carbonate sediments overlying broadly folded Paleozoic through lower Eocene strata. Quaternary sediments of the Mediterranean coast and Nile delta are also included in this group. These units do not occur in the study area, and will not be discussed further.

CHAPTER III

STRATIGRAPHY OF THE QUSEIR AREA

Precambrian Basement Complex

Introduction. The Precambrian basement complex exposed in the Quseir area consists of highly deformed middle to late Proterozoic volcanics and volcanogenic sediments, pervasively metamorphosed to lower greenschist facies and intruded by major syn- to post-tectonic granitic plutons.

The volcanics are calc-alkaline, predominantly andesitic; although basaltic through dacitic and rhyolitic units are present. They occur as shallow intrusives, subareal and subaqueous flows, crystal and lithic tuffs, and various agglomerates and volcanic breccias. Complexly interbedded sediments are generally immature and of volcanic derivation. They range from shale through greywacke, arkose and lithic sandstone to volcanic breccia and boulder conglomerate. Intrusives include syntectonic tonalite, late tectonic granodiorite, and late to post-tectonic granite and alkali granite. The depositional style of these units is illustrated in figure 7, a pre-deformation cross-section of the south central map area.

The volcano-sedimentary units in the study area are metamorphosed to lower greenschist facies. Local metamorphism as high as amphibolite facies has been

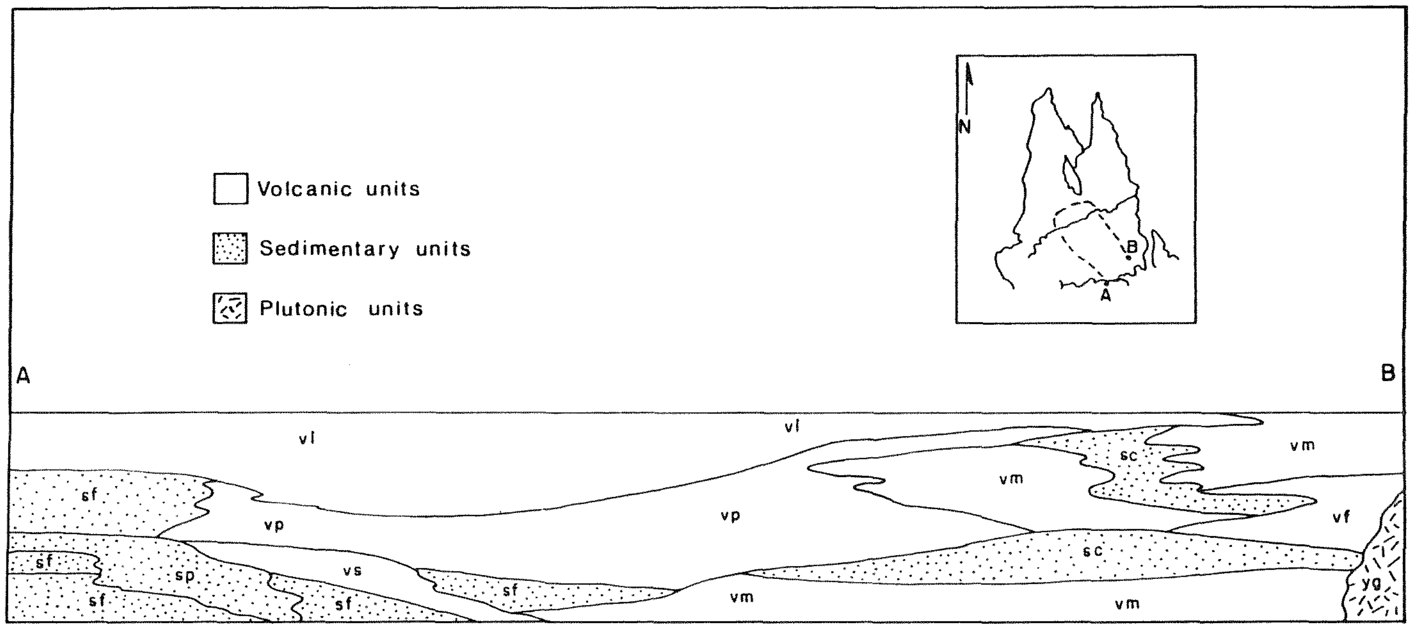


Figure 7. Interpretive cross section of the Precambrian basement in the vicinity of the el Isewid synform prior to regional deformation.

reported in the region (Stern, 1979), but was not observed in the study area. The predominant mineralogy is: albite, chlorite, quartz, epidote, and calcite, with accessory biotite, sericite, actinolite, and sphene. Plagioclase phenocrysts are commonly replaced by a mixture of albite, epidote, sericite, and calcite; mafic minerals are replaced by actinolite, epidote, and chlorite. Secondary quartz is common, especially in the groundmass. Relic sedimentary and igneous textures are usually well preserved. The greenschist metamorphic assemblage indicates temperatures during metamorphism of 400^{o} c to 550^{o} c, and pressures of 1 kb to 4 kb (Liou et al., 1974; Winkler, 1974).

A pervasive "layer cake" stratigraphy is not developed in the Precambrian of the area. Individual lithologies are generally of local extent, and abrupt vertical and lateral variations are common. At least 3 phases of deformation are recognizable in the region (Valentine, in preparation). Each of these phases probably included major episodes of faulting, resulting in many unit boundaries of tectonic rather than stratigraphic origin (Ries et al., 1983). The exposed thickness of layered Precambrian rocks in the map area probably exceeds 2 500 m. However, the stratigraphy has been so complicated by faulting and facies variations that no exact figure can be given.

The original tectonic/depositional environment was one of high topographic relief, with numerous local sources of volcanic and sedimentary material. The assemblage has a geochemical signature typical of an island arc complex (Engel et al., 1980), and was probably deposited in some form of intra-oceanic island arc/back arc setting, subsequently accreted to the African craton through subduction and collision.

Present Study. Precambrian geology was not the primary focus of this project. The Precambrian portion of the geologic map presented here is the result of approximately 3 weeks of field work. Fourteen units have been distinguished within the map area (plate 1); these units are generalized, and are recognized on the basis of dominant or characteristic lithologies. The unit descriptions that follow are based primarily on field descriptions, with a minimum of subsequent petrographic analysis. In general, complexly interbedded metavolcanics and volcanic-derived metasediments in the southern portion of the map area are exposed in a south-plunging regional synform here named the el Isewid synform. The synform is intruded in the southeast and southwest corners of the map area by late to post tectonic granitic plutons (see cross section A-A´, plate 3). In the northern portion of the map area metavolcanic and metasedimentary units are in fault contact with pillow basalt and diorite emplaced along a major northwest trending shear zone. This complex, of possible ophiolitic origin, was subsequently intruded by the late tectonic Gebel Ambagi granodiorite (see cross section B-B´; plate 3).

The units of the Precambrian basement complex within the study area are separated into two groups: (1) older metavolcanic and metasedimentary units, intruded by (2) a younger group of subvolcanic and plutonic units. Age relationships within the younger intrusive group are fairly clear, but the relative ages of the older units are obscure.

Metavolcanic/Metasedimentary Group.

Mafic volcanic unit (vm). The mafic volcanic unit (vm) crops out extensively on the south side of Wadi Ambagi, and locally on the north side, where it has been intruded by the Gebel Ambagi granodiorite. A similar lithology is exposed in the extreme southeast of the study area, in contact with the southeast alkali granite.

The unit consists of grey-green to dark green, fine- to medium-grained mafic meta-igneous rocks, predominantly basalt and diorite. The unit is commonly massive and structureless, with the notable exception of the exposures on the south wall of Wadi Ambagi, which are prominently pillowed.

Porphyritic volcanic unit (vp). The porphyritic volcanic unit (vp) crops out in a large zone on the west side of the map area, where it is in fault contact with the mafic volcanic unit (vm), and in apparent conformable stratigraphic contact with the silicic volcanic unit (vs). The unit also crops out in the east central part of the map area, and as a stratigraphically distinct unit within the el Isewid synform to the south.

The dominant lithology within this unit is a very hard, massive, black, fine-grained dacite porphyry, with variably altered white euhedral plagioclase phenocrysts, now mostly albite, sericite, and calcite. The volcanics are locally vesicular, and some interbeds of coarse volcanogenic sediments are present, especially in the north.

The porphyritic volcanic unit (vp) contains one of the few useful marker horizons in the area, a distinctive, bright green, fine- to medium-grained porphyritic andesite with very prominent white tabular phenocrysts comprising up to 50% of the rock. This marker horizon (mapped locally on plate 1) is approximately 30 m thick, and occurs near the contact between the porphyritic volcanic unit (vp) and the intermediate volcanic unit (vi). It can be traced nearly continuously around the axial region of the el Isewid synform for a total distance of greater than 4 km.

Mixed sediments and volcanics unit (sv). The mixed sediments and volcanics unit (sv) is exposed north of Gebel Ambagi, where it is intruded by the Gebel Ambagi granodiorite; east of Gihania Valley, where it is in conformable contact with the porphyritic volcanic unit (vp); and southeast of Gihania Valley, where the southern part of the unit is conformable with the northernmost unit of the el Isewid Synform (vm).

The mixed sediments and volcanics unit (sv) contains a great variety of volcanic and sedimentary rocks. Medium- to coarse-grained volcanogenic sediments, (lithic sandstone, arkose and volcanic breccia) are the predominant lithologies, interbedded with intermediate to mafic volcanics. A distinctive medium-bedded pillow basalt sequence is exposed on the east side of Gihania Valley.

The southernmost exposures of this unit are well-bedded, coarse-grained sediments, conformable with the el Isewid Synform. However, the northern contact of this exposure appears to be faulted, and stratigraphic relationships in the other outcrop areas are uncertain.

Silicic volcanic unit (vs). The silicic volcanic unit (vs) crops out in the west of the map area, separating the porphyritic volcanic unit (vp) from the el Isewid Synform.

The unit consists predominantly of light green, fine- to very fine-grained rhyolitic and subsidiary intermediate volcanics. Subhedral to subrounded white albite phenocrysts are common, variously altered to calcite, sericite and epidote. Interbedded sediments consist of fine- to medium-grained schists and volcanogenic sandstones.

Fine sediments unit (sf). The fine sediments unit (sf) crops out adjacent to the central Nubian valley, on the west side of the el Isewid Synform, and east of Wadi Nakheil in the extreme northeast portion of the map area.

The unit is characterized by highly foliated, silvery green to light orange, fine- to medium-grained terrigenous sediments; predominantly sandy shale, arkosic sandstone, and quartz-pebble conglomerate. Fine-grained felsic to intermediate volcanics and volcanic breccia are interbedded locally. The unit generally has a high albedo and a fine drainage network, giving it a characteristic air photo signature.

Mafic volcanic flows unit (vf). The mafic volcanic flows unit (vf) is exposed at two stratigraphic levels within the el Isewid synform: (1) immediatly south of the central fault valley, where it crops out as a continuous horizon outlining the northern edge of the synform; and (2) south of Wadi el Isewid toward the southeastern fault valleys, where it is interbedded with the porphyritic volcanic unit (vp) and the conglomerate unit (sc).

The unit consists of dark green, thick-bedded, locally vesicular basalt flows; interbedded with light green, fine-grained (in the north) to orange conglomeratic (in the south) sediments. Layers with stretched amygdules at various levels indicate subaerial eruption of the volcanics. The volcanic flow units are resistant, and form locally prominent dark bands visible on hillsides in the outcrop area.

Conglomerate unit (sc). The conglomerate unit (sc) crops out within the el Isewid synform, in association with the mafic volcanic flows unit (vf).

The unit consists predominantly of orange weathering cobble to boulder conglomerate (avg. dia. 10 cm to 25 cm), with subsidiary volcanic breccia. The dominant clasts are hard, well rounded, dark grey to black, very fine grained hornfels, probably of volcanogenic origin. These clasts are commonly flattened, and stretched in the direction of tectonic transport (NNW).

Intermediate volcanic unit (vi). The intermediate volcanic unit (vi) is exposed in the center of the el Isewid synform. It is a large unit of mixed lithologies, consisting predominantly of thick-bedded to massive, grey-green, fine- to medium-grained intermediate volcanics, with subsidiary interbedded porphyritic volcanics, mafic volcanics, and fine- to medium-grained volcanogenic sediments. This unit is generally resistant to erosion, and two of the highest peaks in the map area occur within the unit.

White quartz porphyry unit (vw). The white quartz porphyry unit (vw) crops out in the southeast part of the map area, interfingering to the north and west with sediments of the intermediate volcanic unit (vi) and the conglomerate unit (sc). The unit consists of massive, white, fine-grained dacite quartz porphyry, with rare intercalations of chlorite sericite schist.

Grey phyllite unit (sp). The grey phyllite unit crops out on the southwest edge of the el Isewid synform, where it is interbedded with members of the fine sediments unit (sf). The unit is a well foliated, dark grey phyllite, with pebble conglomerate layers and rare well rounded cobbles of quartzite and hornfels.

Schistose phyllite unit (ss). The schistose phyllite unit (ss) is exposed along the southern border of the map area, and is transitional northward into the grey phylite unit (sp). It is a well foliated, dark grey schistose phyllite, commonly with pebble conglomerate interbeds of quartzite, hornfels and volcanic rock fragments.

Subvolcanic/plutonic group.

The units of the subvolcanic/plutonic group intruded the older metavolcanic/metasedimentary group during and immediately following regional metamorphism. The group consists of:

1. biotite tonalite of the Older Granite series (og) (El Ramly, 1972; Akaad and Noweir, 1980; Greenberg, 1981);
2. granodiorite, granite and alkali granite of the Younger Granite series (yg) (El Ramly, 1972; Rogers et al., 1978; Akaad and Noweir, 1980; Greenberg, 1981);
3. subvolcanic quartz porphyry probably equivalent to the Post-Hammamat Felsite (ph) (Akaad and Noweir, 1969; El Ramly, 1972; Akaad and Noweir, 1980); and
4. mafic dikes, felsic dikes, and quartz veins.

The units are described below in order of presumed age.

Older Granite (og). The Older Granite (og) unit crops out in two bodies in the southwest of the map area. The unit is generally intrusive, but a locally faulted contact is present on the south side of Wadi el Isewid.

The Older Granite (og) is a grey, medium to coarse grained biotite tonalite. It is syntectonic, and has been subjected to low grade metamorphism, with biotite altering to chlorite, and feldspars to sericite. Contacts with the country rock are sharp, but substantial alteration of both the intrusive and the country rock is common.

Post-Hammamat Felsite (ph). The Post-Hammamat Felsite (ph) crops out in a generally northeast trending zone of irregular shallow intrusions in the central map area. The unit consists of a massive, light brown to pinkish brown, fine-grained rhyolite porphyry, with phenocrysts of quartz, potassium feldspar, and sodic plagioclase. Contacts with the country rock are uniformly sharp, unaltered and intrusive. The unit weathers to a brick red, which is in marked contrast to the dark green color of the surrounding country rocks (fig. 8).

Younger Granite (yg). Three plutons of the Younger Granite series are present in the map area: the granite at Gebel Ambagi in the north, a small body of alkali granite in the southeast, and the northern edge of a very large

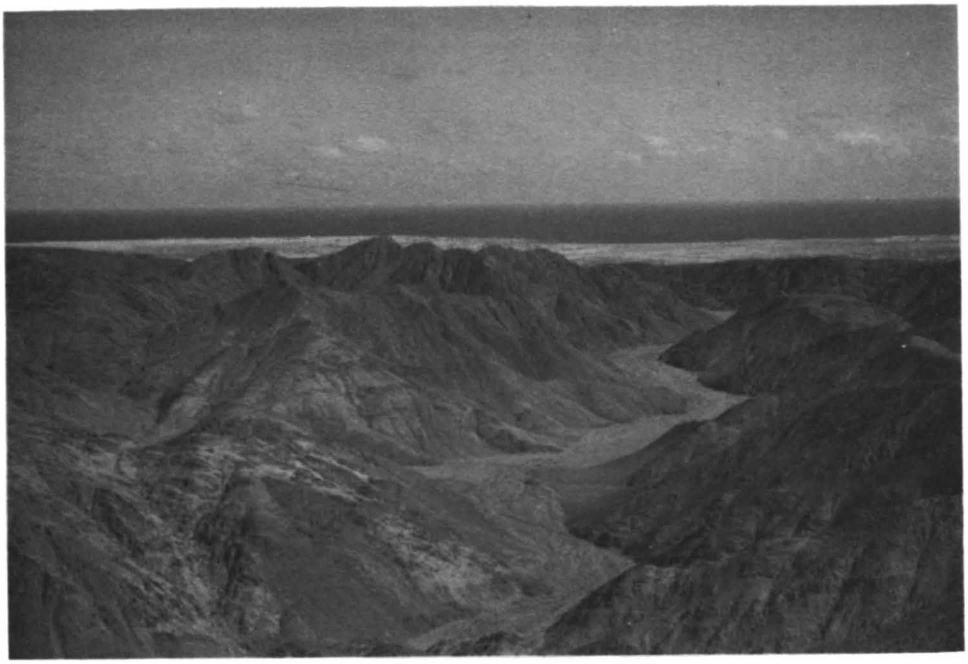


Figure 8. Photograph of the Precambrian basement looking east toward the village of Quseir. Greenstone metasediments in foreground, Post-Hammamat Felsite in middle ground, Red Sea coastal plain in background.

body of biotite granite in the southwest.

The Gebel Ambagi granodiorite is probably the oldest of the three; it appears to correspond to the type III Younger Granites of Greenberg (1981; see also Akaad and Noweir, 1978). It is a greyish-pink, medium- to coarse-grained biotite granodiorite, showing the effects of minor low grade metamorphism. Various subordinate lithologies are also present within the pluton, notably a grey to dark grey, very fine-grained, white feldspar porphyry.

The granodiorite generally has sharp intrusive contacts with the surrounding country rocks. Chilled margins are locally present, but no contact metamorphic effects were observed. Small mafic xenoliths are common locally near the contacts, and the pluton is cut by a few mafic dikes.

Gebel Ambagi, the main massif of the Gebel Ambagi granodiorite, is the most prominent mountain in the map area. It has a gentle east slope, but precipitous south and west sides dropping down to Wadi Nakheil and Wadi Ambagi. Post-emplacement shearing and mylonitization of late Precambrian age occur along the pluton boundaries northwest of the main Gebel Ambagi massif, indicating that later faulting has been localized along the margins of the pluton. Most of the present relief, however, is due to

Cenozoic faulting, accentuated by the erosional resistance of the granodiorite.

The biotite granite in the southwest part of the area is similar to the type I and type II Younger Granites of Greenberg (1981). It is pink, coarse grained, and deeply weathered. Contacts with the country rock are uniformly sharp and intrusive, with little evidence of chilled margins. The exposures of the southwest biotite granite are at the northern edge of a large pluton located to the south of the map area. The unit weathers rapidly, producing a broad plain of coarse-grained, light colored, granite derived sand (grus), with inselbergs of residual granite. Exposures within the map area are near the roof of the pluton. Dikes and fingers of granite in the country rock and abundant large spalled blocks of country rock in the granite indicate emplacement at a high crustal level, probably by magmatic stoping.

The southeast alkali granite corresponds to the Type I Younger Granites of Greenberg (1981). It is pink and medium to coarse grained, with iron alteration common locally. Towards the northern tip of the body the rock is transitional to a fine-grained, iron stained microgranite. The contacts with the country rock are generally sharp and intrusive, and no inclusions were observed.

Dikes and Veins. Three types of intrusive dikes and veins were observed in the map area: (1) mafic dikes, (2) quartz veins, and (3) felsic dikes.

The mafic dikes are syn- to late tectonic, and consist of highly altered diabase. They average 1 m to 5 m in width, and 200 m to 500 m in length. The dikes are generally irregular and discontinuous in outcrop, and show the same regional foliation as the country rock.

The quartz veins consist of white milky quartz, and occur in veins and vein swarms averaging 5 cm to 20 cm in width, and 10 m to 100 m in lengh. They are probably late tectonic in age, as they are oriented generally perpendicular to the regional extension direction, and do not show the regional foliation.

The felsic dikes are post tectonic, younger than both the mafic dikes and the quartz veins. The felsic dikes consist of brick red, fine-grained, alkali trachyte with a well developed flow-parallel foliation. They form a remarkably uniform set of regional dikes, averaging 1 m to 2 m in width and greater than 1 km in lengh. The felsic dikes are generally parallel to the regional foliation, and may be a late magmatic self-intrusive phase associated with the emplacement of the Younger Granites.

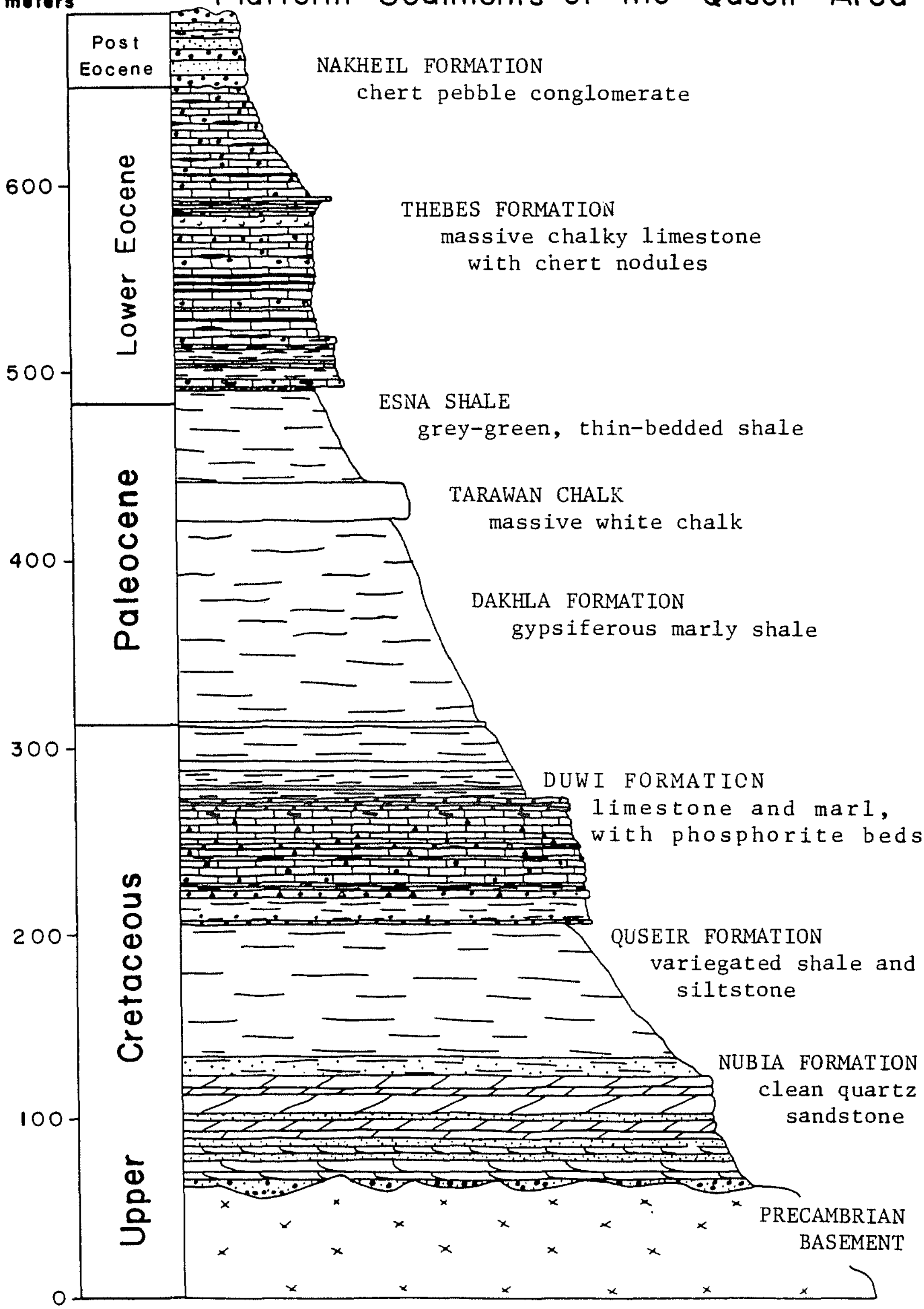
Late Mesozoic/early Cenozoic Platform Sediments

Nubia Formation. The Nubia Formation lies unconformably on the Precambrian basement complex, and forms the basal unit of the platform sediments section (fig. 9). The name is derived from the term "Nubian Sandstone", first used by Russegar in 1837 to describe the massive sandstones exposed in the Nile Valley south of Aswan (the ancient region of Nubia). The term "Nubian Sandstone" has since been applied to numerous sandstone units of similar stratigraphic position throughout North Africa and the Sinai, without regard to age or provenance (Pomeyrol, 1968). The name Nubia Formation is here used, after Ward and McDonald (1979), to distinguish the unit as originally defined from subsequent usage of the term. The Nubia Formation has been studied in detail by Van Houten et al. (in press) and Ward and McDonald (1979).

The Nubia Formation is generally considered to be Late Cretaceous (Said, 1962) on the basis of sparse pelecypods; Abbas (1962) considers it Cenomanian, while Ghanem et al. (1970) place the upper member in the Campanian. The thickness of the Nubia Formation in the Eastern Desert is highly variable, depending on the topography of the underlying Precambrian basement. Within

Figure 9. Stratigraphic column of the Mesozoic/Cenozoic platform sediments in the Quseir area (modified from Valentine, in preparation).

Platform Sediments of the Quseir Area



the study area, the thickness ranges from approximately 120 m to 180 m.

The Nubia Formation can be divided into three lithologically distinct members within the study area (not distinguished on plate 2): a lower trough cross-bedded member, a middle tabular cross-bedded member, and an upper fine sand and silt member.

The basal member typically consists of light yellow to reddish-brown, well sorted, medium- to coarse-grained, clean quartz sandstone and quartz pebble conglomerate. Trough cross-bedding is present locally, as are white, lavender and yellow stained kaolinitic horizons. Thickness of this member is variable, controlled at least in part by relief on the Precambrian depositional surface, but averages 50 m to 80 m in the Quseir region.

The middle member of the Nubia Formation is a brown, fine- to medium-grained quartz sandstone with prominent tabular cross-bedding in sets averaging less than 0.5 m in thickness. This member is fairly resistant to weathering and is the most conspicuous unit in outcrop, commonly forming prominent cliffs. Its thickness averages 60 m to 70 m in the Quseir region.

The upper member of the Nubia Formation consists of dark brown to dark red-brown, very fine-grained sandstone, sandy siltstone and shale. The member is commonly iron stained, and locally exhibits well developed ripple marks. This member is transitional upward to the variegated shales of the overlying Quseir Formation. Its thickness in the Qusier region averages 20 m to 30 m.

The lower and middle members of the Nubia Formation are predominantly fluvial sediments deposited across a wide alluvial plain. The upper member consists of coastal plain and delta plain deposits which grade upward into the coastal and near shore marine deposits of the Quseir Formation (Ward and McDonald, 1979). The Nubia/Quseir contact marks the transition from subaerial to shallow marine deposition as the Tethys Sea transgressed southward across the continental platform.

In outcrop, the basal trough cross-bedded member of the Nubia Formation is generally subordinate to the middle tabular cross-bedded member. The low cliffs and blocky weathering pattern of this middle member dominate the outcrop pattern within the study area. A stripped dip slope commonly occurs at the top of the middle member. Where present, the upper fine sand and silt member forms shallow talus slopes transitional upward into the shales of the Quseir Formation.

Quseir Formation. The variegated shales of the Quseir Formation are transitional between the underlying Nubia Formation and the overlying Duwi Formation. The Quseir Formation was originally described and separated from the Nubia Formation by Youssef (1957). The formation is considered to be Senonian (Said, 1962; Issawi et al., 1968). The thickness of the formation in the Quseir region is 50 m to 75 m.

The Qusier Formation consists of brown to grey siltstone and fine silty sandstone at the base, grading upward to varicolored clayey shales of grey, yellow, brown, and dark red color. Thin phosphatic interbeds occur locally toward the top of the formation, and are transitional upward into the Duwi Formation.

The Quseir Formation was deposited in a low energy, shallow marine and estuarine environment, with brackish lagoons transitional to shallow bays and mud flats (Ward and McDonald, 1979). The formation represents the transition from terrigenous dominated coastal deposits to a fully marine shelf environment.

The Quseir Formation is generally observed in the study area as rubble covered slopes separating the Nubia Formation from the irregular cliffs and ledges of the lower Duwi Formation.

<u>Duwi Formation</u>. Conformably overlying the Quseir Formation is the Late Cretaceous Duwi Formation; named for Gebel Duwi, the prominent ridge west of the study area (see M. Valentine, in preparation). This formation is equivalent to the Phosphate Formation of Said (1962) and others, but the name Duwi Formation is preferred in the Eastern Desert.

The age of the Duwi Formation is Campanian to Maastrichtian (Youssef, 1957), or strictly Maastrichtian (El Ṭarabili, 1966; Issawi, 1972). The thickness of the formation in the Quseir area is 50 m to 70 m, but large variations in thickness have been reported from other areas (C. Glenn, personal communication, 1982).

The Duwi Formation consists of white to yellow marls, chert, banded shales, coquina limestone, siliceous limestone, and phosphatic beds. The local stratigraphy is highly varied, with many lateral stratigraphic variations, but in general a lower zone of thin phosphatic bands in variegated shales and marls gives way upward to a carbonate-dominated zone consisting of shales and marls with thin interbeds of chert. These are overlain by hard phosphatic layers interbedded with siliceous coquina limestone and chert bands, and capped by a resistant 1 m to 3 m oyster coquina bed containing abundant articulated

Ostrea villae. This capping bed commonly forms a prominent ledge and dip slope; it is overlain by 1 m to 5 m of white to yellow marl and grey friable phosphates which mark the top of the Duwi Formation.

The Duwi Formation contains a number of phosphatic horizons, which are mined locally for tricalcic phosphate. All of the mines within the study area are currently inactive, but well-developed phosphate horizons were formerly mined at El Gihania and Gebel Atshan, with grades in the range of 65% to 75% $Ca_3(PO_4)_2$ over mineable thicknesses averaging 1 m to 2 m (Youssef, 1957).

The Duwi Formation was deposited in a varied shallow marine shelf environment, possibly in bays connected to the open sea (Said, 1962), or in shallow coastal basins behind shoals and barrier bars (Nairn, 1978).

The Duwi Formation crops out as a prominent band of regular cliffs and ridges between the shaley slopes of the underlying Quseir Formation and the overlying Dakhla Formation. A prominent dip slope of grey-brown limestone commonly occurs near the top of the formation. The formation as a whole, and especially the upper dip slope, is commonly disrupted due to shearing and slumping in the underlying shales of the Quseir Formation.

<u>Dakhla Formation</u>. The Dakhla Formation conformably overlies the Duwi Formation and underlies the Tarawan Chalk and the Esna Shale. Although the Dakhla, Tarawan, and Esna Formations are normally separable in the field, their individual outcrop areas are not easily resolvable at the 1:40 000 scale used for mapping, and consequently all have been combined into one map unit.

The Dakhla Formation is recognized throughout the stable shelf region of Egypt (Said, 1962), with the type locality at the Dakhla Oasis in the central Western Desert. The Dakhla Formation is predominantly Paleocene in age (Issawi, 1972). The thickness of the formation is variable, ranging from less than 50 m near Safaga to as much as 165 m at Gebel Atshan (Youssef, 1957).

The Dakhla Formation consists of light pink weathering calcareous and gypsiferous shales and marls, grading upward to grey and brown highly fissile shale. It was deposited in a deepening near-shore marine shelf environment. The formation generally forms the base of the rubble covered slopes leading up to the cliffs of the Thebes Formation.

<u>Tarawan Chalk</u>. The Tarawan Chalk has a transitional contact with the underlying Dakhla Formation and a sharp conformable contact with the overlying Esna Shale, with

which it is sometimes grouped. The formation is late Paleocene in age (Issawi, 1972), and varies in thickness from 5 m to 15 m.

The Tarawan Chalk is a massive, white, tan-weathering chalk, which commonly forms a prominent band of outcrop in the shaley slopes beneath the Thebes Formation. It was deposited in a distal shallow marine shelf environment.

Esna Shale. The Esna Shale conformably overlies the white chalk of the Tarawan Chalk, and underlies the Thebes Formation. It is predominantly late Paleocene in age (Issawi, 1972), and is 20 m to 50 m thick in the Quseir area.

The Esna Shale consists of light grey to greenish-grey finely fissile shales. It generally forms steep, loose slopes leading up to the cliffs of the Thebes Formation. It was deposited in a shallow marine environment during a temporary regression, prior to the deeper water conditions which prevailed during deposition of the overlying Thebes limestones.

Thebes Formation. The Thebes Formation conformably overlies the Esna Shale, and is unconformably overlain by the Nakheil Formation. The Thebes Formation is recognized throughout the central region of Egypt and the Sinai; its type locality is the huge cliff exposures on the west side of the Nile Valley near the ancient city of Thebes (now Luxor). The Thebes Formation is considered to be early Eocene in age (Said, 1962; Issawi, 1972).

The thickness of the Thebes Formation can reach 300 m (Said, 1962); however, its full thickness is not preserved within the study area. Approximately 50 m of Thebes Formation is present at El Gihania, and about 160 m at Gebel Atshan.

The Thebes Formation consists of light grey to light brown, thick-bedded, chalky limestone with abundant chert bands and nodules. Towards the top of the thicker sections (e.g. Gebel Atshan, and the east side of Wadi Nakheil), the formation is characterized by more thinly bedded, recrystalized and siliceous limestone.

The Thebes Formation was deposited in a distal, open marine shelf environment, and marks the culmination of the southward transgression of the Tethys Sea in Egypt. Deposition was terminated by uplift in the Eastern Desert region, possibly combined with a general lowering of sea level, which eventually resulted in subaerial erosion and the deposition of the Nakheil Formation.

The Thebes Formation is the most distinctive unit within the map area. It caps the platform sediments section, and is extremely resistant to erosion. Commonly it forms large, light colored, west-facing cliffs with long east-northeast dip slopes.

Nakheil Formation. The Nakheil Formation disconformably overlies the platform sediments section, and underlies the middle Miocene Gebel el Rusas Formation. It is named for Wadi Nakheil, on the west edge of the study area, where the formation is particularly well developed. It is non-fossiliferous, and can only be dated as post- early Eocene and pre-middle Miocene (Trueblood, 1981). Its thickness is highly variable within the study area, ranging from 5 m to greater than 75 m. The Nakheil Formation consists of massive, poorly consolidated, commonly yellow-brown iron-stained limestone and chert nodule conglomerate; locally overlain by sandstones and sandy shales. Precambrian basement was not breached during deposition of the Nakheil Formation in this area, as no basement fragments are found within the section.

The Nakheil Formation was derived from subaerial weathering of the platform sediments, especially the Thebes limestone. It is preserved in fault-bounded troughs, generally on the east side of major down faulted blocks of the platform sediments. Early alluvial and colluvial deposition of conglomerate apparently gave way to deposition of poorly sorted sandstones and shales in shallow lakes within downwarps or fault troughs.

The Nakheil Formation is exposed in low ridges on lower dip slopes of the Thebes Formation, and along east edges of major fault bounded basins. In this area, it can be distinguished from the similar appearing basal Gebel el Rusas Formation by the fact that the Nakheil Formation contains no Precambrian basement fragments.

Red Sea Coastal Plain Sediments

Gebel el Rusas Formation. The middle Miocene Gebel el Rusas Formation rests with angular unconformity on the Precambrian basement complex and the Cretaceous to lower Eocene platform sediments (fig. 10). It is conformably overlain by the middle Miocene Evaporite Formation. The type locality is at Gebel el Rusas, south of Quseir near Marsa Alam, where the formation contains lead-zinc mineralization (El Akkad and Dardir, 1966). A detailed discussion of the Gebel el Rusas Formation along the .cp4 entire Red Sea Coast of Egypt can be found in Johnson (1977).

The thickness and lithology of the Gebel el Rusas Formation are extremely variable, due to a combination of irregular original depositional topography, synsedimentary tectonic activity, and local variations in sediment

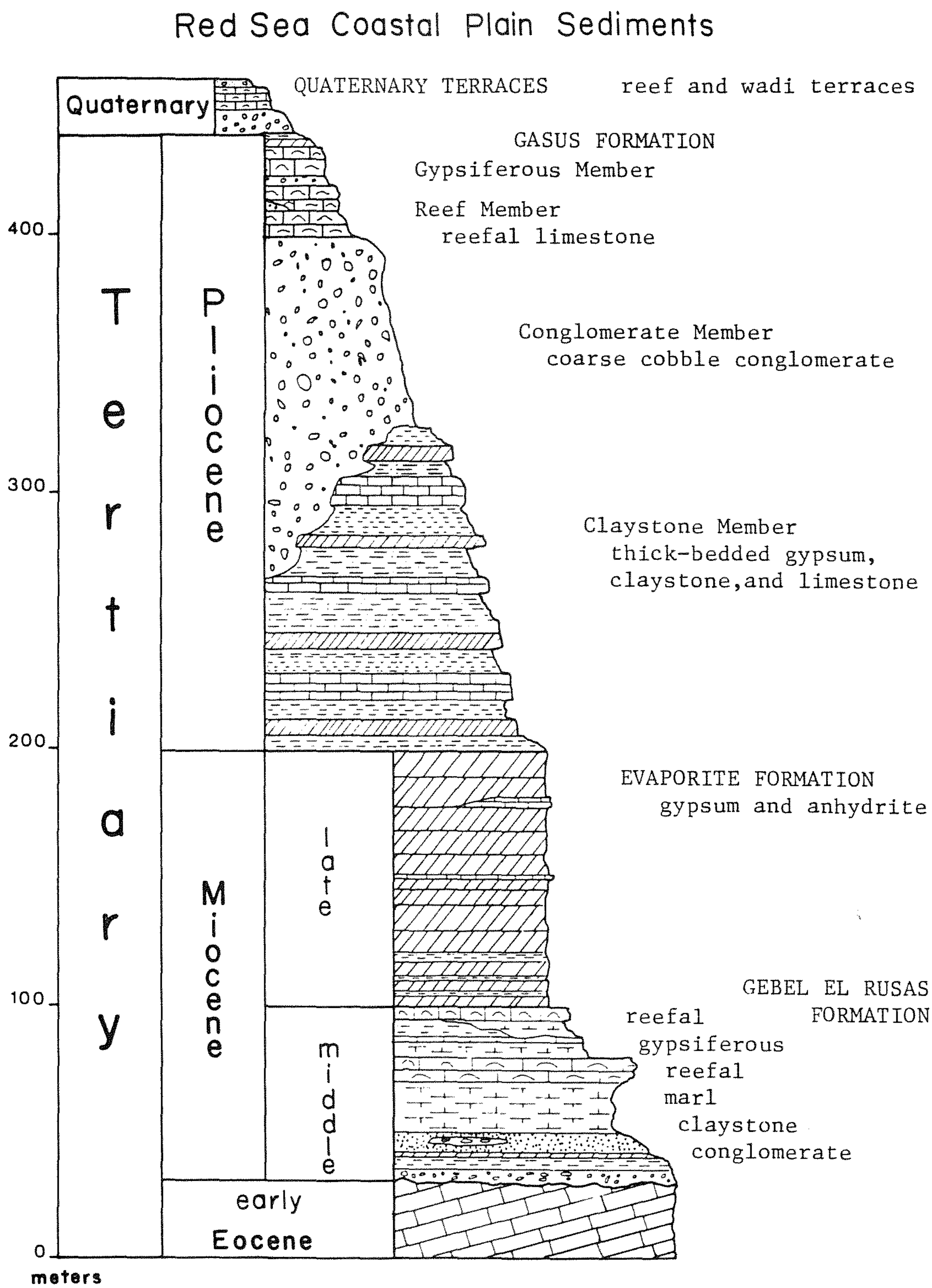


Figure 10. Stratigraphic column of the Red Sea coastal plain sediments in the Quseir area.

supply. Within the map area the formation varies in thickness from approximately 25 m to 60 m.

The author has divided the Gebel el Rusas Formation within the study area into six locally occurring members on the basis of lithology and stratigraphic position. On the geologic map, the formation has been separated into the lower predominantly terrigenous group (conglomerate member, claystone member, and marl member) and the upper reefal group (main reef member, gypsiferous member, and upper reef member).

The conglomerate member, the basal unit, is a grey to brown, polymictic pebble to cobble conglomerate, with rounded clasts of greenstone metavolcanics and granite of the Precambrian basement complex, and chert and rare limestone clasts from the platform sediments. The matrix varies from coarse-grained calcareous sand to grey-green silty marl and grey sandy limestone. This basal conglomerate member may be indicative of the first stages of formation of the Red Sea basin. The conglomerate member is up to 5 m thick in the study area.

The claystone member conformably overlies the conglomerate member. It consists of a light grey-green to grey-brown, thick-bedded to massive, silty calcareous claystone, locally gypsiferous; varying to marly coarse sandstone with pebble size intraclasts and conglomerate lenses. This member is 10 m to 15 m thick, and was deposited in a shallow water terrigenous-dominated environment.

The marl member conformably overlies the claystone member, and consists of light grey to light yellow, light brown weathering, massive to thick-bedded, marly chalk to fine shell hash limestone; it is porous, recrystalized, and cavernous weathering. This member is 10 m to 20 m thick, and commonly crops out as irregularly sculpted and undercut cliffs below the protecting cap of the main reef member. This unit was probably deposited in a back reef lagoonal environment.

The main reef member overlies the marl member, and consists of light yellow, light brown to grey weathering, massive coralline limestone; highly recrystalized, very porous, and abundantly fossiliferous. Yellow to red iron staining and black manganese staining are common locally. This member is 4 m to 10 m in thickness, and is highly resistant to erosion. It forms flat, steep-sided plateaus capping most of the major outcrops of the Gebel el Rusas Formation in the study area. This member developed as a coral reef facies fringing the middle Miocene shoreline of the Red Sea, much as the present shoreline is fringed by modern coral reefs.

The gypsiferous member and the upper reef member are observed only on the Ambagi Reef block, where they conformably overlie the capping reef of the main reef member. The gypsiferous member consists of light yellow marl and marly chalk with interbedded intraformational breccia, finely laminated algal mat limestone, and Precambrian basement-derived pebble conglomerate. This varies laterally to medium- to thin-bedded grey-green silty claystone with interbedded gypsum. This member is 5 m to 15 m thick, and formed in a hypersaline back reef lagoonal environment, probably caused by local block faulting in the Wadi Ambagi area.

The upper reef member is similar to the main reef member, a light yellow, light brown to grey weathering, massive, rubbly, coralline reefal limestone, highly recrystalized and abundantly fossiliferous. It differs from the main reef member in containing more common intraformational breccia horizons, and local Precambrian-derived pebble conglomerate interbeds. It is 2 m to 5 m in thickness, and like the main reef member is a capping reefal limestone, probably indicating reequilibration of the Ambagi block with sea level.

A more terrigenous equivalent of the gypsiferous and upper reef members was deposited on a flat, mid-Tertiary erosion surface developed on the Precambrian basement. The outcrops consist of thin-bedded sandy limestone with pebble conglomerate interbeds; and medium to coarse cobble conglomerate with mixed Precambrian and Thebes Formation clasts. This facies has a preserved thickness of 5 m to 10 m.

Deposition of the Gebel el Rusas Formation was primarily structurally controlled, and is discussed more fully in Chapter IV.

Evaporite Formation. Deposited conformably on the Gebel el Rusas Formation is a thick sequence of middle to late Miocene evaporites generally referred to as the Gypsum Formation (El Akkad and Dardir, 1966; Issawi et al., 1971; Trueblood, 1981), or the Evaporite Formation, Series, or Group (Said, 1962; Stoffers and Ross, 1974; Johnson, 1977; Schmidt et al., 1982). While not in conformity with normal stratigraphic nomenclature, these are the terms customarily used to describe this unit, and the name Evaporite Formation will be adopted here as the most widely used and generally descriptive term for the unit.

The Evaporite Formation consists of white, tan weathering, thin- to medium-bedded gypsum and andydrite. Grey-green silty claystone interbeds are common near the base of the unit. Rare, thin (0.3 m to 1.0 m) continuous interbeds of dark grey recrystalized limestone, and thicker (1 m to 3 m) locally fossiliferous dark grey algal mat and coralline reefal limestone patches occur higher in the section.

The exposed thickness of the Evaporite Formation varies from less than 10 m to greater than 100 m within the study area. These thickness variations are due in part to early post-depositional erosion of the Evaporite Formation by streams issuing from the major wadis (e.g., Wadi Ambagi and Wadi el Isewid), and in part to plastic flow of the evaporites away from areas of high overburden pressure.

The Evaporite Formation as exposed on the Egyptian coastal plain is the on-shore equivalent of a major evaporite sequence which occurs throughout the Red Sea basin, and is correlated with a similar sequence in the Mediterranean Sea (Stoffers and Ross, 1974). Seismic reflection data and exploratory drill holes have indicated thicknesses in excess of 3 000 m for this evaporite sequence in the Red Sea basin (Carella and Scarpa, 1962; Ahmed, 1972; Lowell and Genik, 1972).

The Evaporite Formation was probably deposited in a shallow water or sabkha environment (Stoffers and Ross, 1974) in an early Red Sea basin connected to the Mediterranean Sea, but not to the Indian Ocean.

Occasional periods of deeper water and more normal salinity resulted in the deposition of fine terrigenous and calcareous interbeds. Evaporite deposition was apparently halted in the early Pliocene by the opening of the Straits of Bab al Mandab and the influx of normal salinity marine waters from the Indian Ocean.

The Evaporite Formation forms large, light brown weathering outcrop zones with very white fresh surfaces. The outcrop zones are commonly dissected by a system of narrow, steep sided canyons. Outcrop surfaces are very rough and jagged, with a characteristic ribbed "brain coral" type weathering pattern.

Gasus Formation. The Gasus Formation is Pliocene in age (Issawi et al., 1971) and conformably overlies the late Miocene Evaporite Formation. The formation is named for the Wadi Gasus locality, near Safaga, where the section is particularly well developed. The thickness of the formation is variable, but generally ranges from 200 m to 250 m. The Gasus Formation was apparently deposited in an environment very similar to the present shoreline, with abrupt lateral facies changes indicating along-shore variations in depositional environment.

The Gasus Formation is divided by the author into four separately mapped members within the study area. The claystone member consists of thick (1 m to 3 m) interbedded gypsum, grey-green marly claystone, brown limestone, and calcareous sandy siltstone. The member was deposited in a predominantly shallow water, near shore marine environment, and represents the transition from hypersaline conditions to more normal marine sedimentation. The claystone member is best developed in the north and south of the study area, where it attains a maximum thickness of approximately 200 m. It is replaced in the vicinity of Wadi Ambagi by the conglomerate member.

The conglomerate member is a light brown, coarse, polymictic cobble conglomerate, with well rounded clasts of metavolcanics, granite, chert, and limestone in a silty calcareous sandstone to coarse sandy limestone matrix. Interbeds of siltstone and silty coarse sandstone are common. The member crops out as low, dark, cobble-covered ridges, which are parallel to bedding and form a marked contrast to the underlying Evaporite Formation. The conglomerate member is an alluvial fan facies, analogous to Holocene alluvial fan deposits which have developed around the mouth of Wadi Ambagi. The Pliocene Gasus Formation can be distinguished from the Holocene deposits by the common seaward dip of the former. The conglomerate member is best developed in the vicinity of Wadi Ambagi, where it attains a thickness of over 200 m; it thins to the north and south and is replaced by the claystone member.

The reef member consists of a light grey, coralline reefal limestone with abundant megafossils and sparse pebble to cobble conglomerate interbeds. This member also includes a locally developed, brown, well-sorted, coarse-grained, calcareous cemented, lithic sandstone with abundant rounded shell fragments. The reef member is developed only in the northeast corner of the study area, where it attains a maximum thickness of approximately 35 m. It was deposited as a fringing reef complex which developed on a local structural high.

The gypsiferous member consists of grey-green, thin-bedded, gypsiferous claystone and thin-bedded gypsum, with locally developed conglomerate and silty coarse sandstone interbeds. This member is also restricted to the northeast corner of the study area; and is at least in part laterally equivalent to the reef member. The gypsiferous member was deposited in a sabkha-type back reef environment, with a maximum thickness of about 5 m.

Quaternary back-reef deposits. Two members were recognized within the Quaternary back-reef deposits in the study area, deposited with minor angular unconformity on the Gasus Formation. The terrigenous member consists of up to 15 m of brown, recrystalized, fossil-fragment limestone; grey, calcareous-cemented conglomerate; brown, calcareous-cemented, coarse-grained sandstone to pebble conglomerate; and minor marly claystone. The evaporitic member consists of up to 2 m of thin-bedded gypsum with interbedded grey-green claystone. The terrigenous member probably represents a lagoonal back-reef environment, while the evaporitic member represents a sabkha-type back-reef environment.

Reef terraces. Two distinct Quaternary reef terraces are present in the study area. R1, the lower terrace, is a fringing reef complex rising directly from the shoreline to a height of 5 m to 7 m above sea level. R2, the upper terrace, occurs as irregular linear and patch reef developments further from shore, at a height of 10 m to 15 m above sea level. The stratigraphy of both terraces is similar, consisting of 3 m to 5 m of light grey to light brown, recrystalized, abundantly fossiliferous, coralline reefal limestone; overlain by appproximately 2 meters of well rounded, calcareous-cemented, pebble to cobble conglomerate. These reef terraces are the seaward lateral equivalent of the back-reef deposits described above.

Wadi terraces. Dissected terrace deposits of unconsolidated to poorly consolidated wadi alluvium form a prominent sedimentary unit within the study area. A number of terrace levels are developed, particularly in Wadi Ambagi. The most prominent of these are at approximately 4 m, 7 m, and 12 m above wadi level. In addition, remnants of a highly dissected terrace at approximately 20 m above wadi level are present.

Active wadi alluvium. Overlying all other units in the study area is a thin veneer of unconsolidated wadi alluvium. It consists of clay, silt, sand, and well rounded pebbles, cobbles, and boulders of all underlying units; with clasts of Precambrian crystalline rocks predominating.

Fringing Reef Complex. A modern fringing reef complex is developed offshore, with a 100 m to 400 m wide terrace at approximately mean sea level. This terrace is partially wave cut and partially depositional, and ends in a steep active reef front and talus slope.

Erosion Surfaces

Introduction. Two major erosional episodes are recorded within the study area. A pre-Cretaceous erosion surface formed as a peneplain on the Precambrian basement complex prior to the deposition of the Cretaceous Nubia Formation. A second erosion surface formed during the mid-Tertiary as a regional pediplain and wave cut terrace superimposed on the tilted and block faulted remnants of the older peneplain surface and its covering sediments.

Pre-Cretaceous Erosion Surface. The pre-Cretaceous erosion surface is observed most clearly in outcrop at the base of the Nubia Formation, and as flat topographic surfaces in areas where the Nubia Formation has been recently stripped from the Precambrian basement. This erosion surface is particularly well exposed northwest of Gebel Ambagi, where it is tilted toward the northeast, and overlain by remnant blocks of the Nubia Formation. A saprolitic horizon 0.5 m to 1.0 m thick is commonly observed in outcrop at the Precambrian basement/Nubia Formation contact, and a rounded quartz pebble conglomerate, probably derived from the saprolite, occurs in the basal Nubia Formation.

Mid-Tertiary Erosion Surface. The mid-Tertiary erosion surface is well developed on the Precambrian basement complex over the entire central Precambrian horst north of Wadi el Isewid, and forms the summit plateau of Gebel Ambagi. The erosion surface is best exposed along the east side of the central Precambrian horst, south of Gihania Valley. It is highly dissected, and is characteristically observed as a regional accordance in elevations of peaks and ridge tops. Through much of the area it forms a flat, sub-horizontal surface 100 m to 150 m above sea level, with a dip of about 2° to the northeast. Minor outcrops of the Gebel el Rusas Formation occurring on the erosion surface indicate that the surface was at one time below sea level, and suggest that the surface may be partly wave cut.

CHAPTER IV

STRUCTURE OF THE QUSEIR AREA

Precambrian Basement Complex

Folding. The Precambrian structure of the study area is dominated by the el Isewid synform, a large southeast plunging fold exposed in the southern part of the map area. The fold is relatively tight, with a near vertical axial surface trending N40W. A well-developed regional foliation, axial planar to the synform, probably developed during the same deformational episode.

Minor outcrop-scale folds are not common, and where present appear coaxial and contemporaneous with the large scale folding. Rare outcrop-scale folding of the regional foliation was observed, indicating a later phase of relatively minor folding. M. Valentine (in preparation) has reported three phases of coaxial folding in the Precambrian basement immediatly to the west of the study area.

Faulting. Faulting is widespread in the Precambrian basement, but is difficult to map in detail. Irregular, highly foliated zones with evidence of shearing are common within the map area. It is difficult, however, to differentiate schistose stratigraphic units with minor shearing from mylonitized shear zones, and few attempts were made to do so during this study. For this reason few Precambrian-age faults are mapped, although they may be quite common within the map area.

One exception is the major northwest-trending fault zone exposed within the mafic volcanic unit (vm) on the south side of Wadi Ambagi (plate 1). This is a 500 m wide zone consisting of multiple shear surfaces showing evidence of major horizontal motion, including mylonitization, shear foliation, and pencil cleavage. The faults in this zone are terminated by north-northwest-trending Tertiary faults involved in the development of the Gihania valley.

In general, the field evidence suggests that regional compressive shearing was pervasive during late Precambrian time, occurring simultaneously on multiple horizons that were commonly localized within the schistose stratigraphic units.

Foliation. A well developed regional foliation is present in the map area, with an average orientation of N35W 80°NE (fig. 11). The foliation is remarkably uniform throughout the map area, and is developed in all units except the younger intrusives. Rare outcrop-scale folds with wavelengths of 1 m to 5 m were the only deformation of the

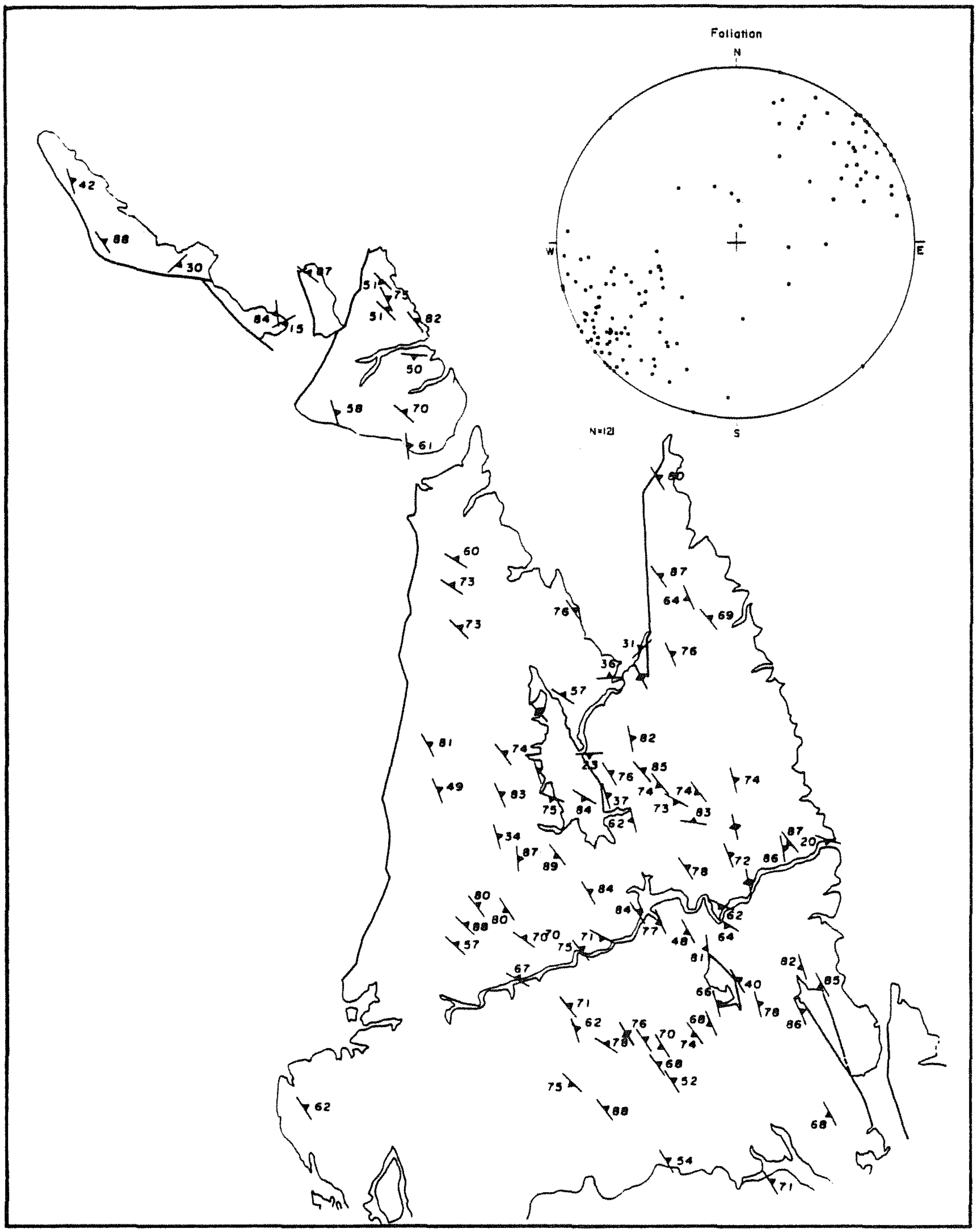


Figure 11. Foliation in the Precambrian basement, Quseir area.

foliation observed.

Three fracture cleavage sets are also developed, cutting the foliation (fig. 12). The dominant set, particularly well developed in the south of the map area, has an average orientation of N60E 90^{o}, parallel with the el Isewid lineament. The second set, reported to be dominant in the basement rocks to the west of the map area (M. Valentine, personal communication, 1983), has an average strike of N30W, sub-parallel to the regional foliation. The third fracture cleavage set, developed especially in the east of the map area, has an average strike of N05E with steep dips.

<u>Dikes and veins</u>. Two types of Precambrian dikes are present in the map area; felsic dikes and mafic dikes. The mafic dikes are earlier, probably syntectonic, and as a result of deformation and metamorphism they are irregular and dificult to measure in the field. The felsic dikes, on the other hand, are extremely uniform, and form a consistent sub-vertical set with an orientation of N25W (fig.13a). This orientation is parallel to the regional foliation, which may have controlled the orientation of felsic dike emplacement.

A third type of late fracture filling present in the study area is quartz veins. The orientation of these

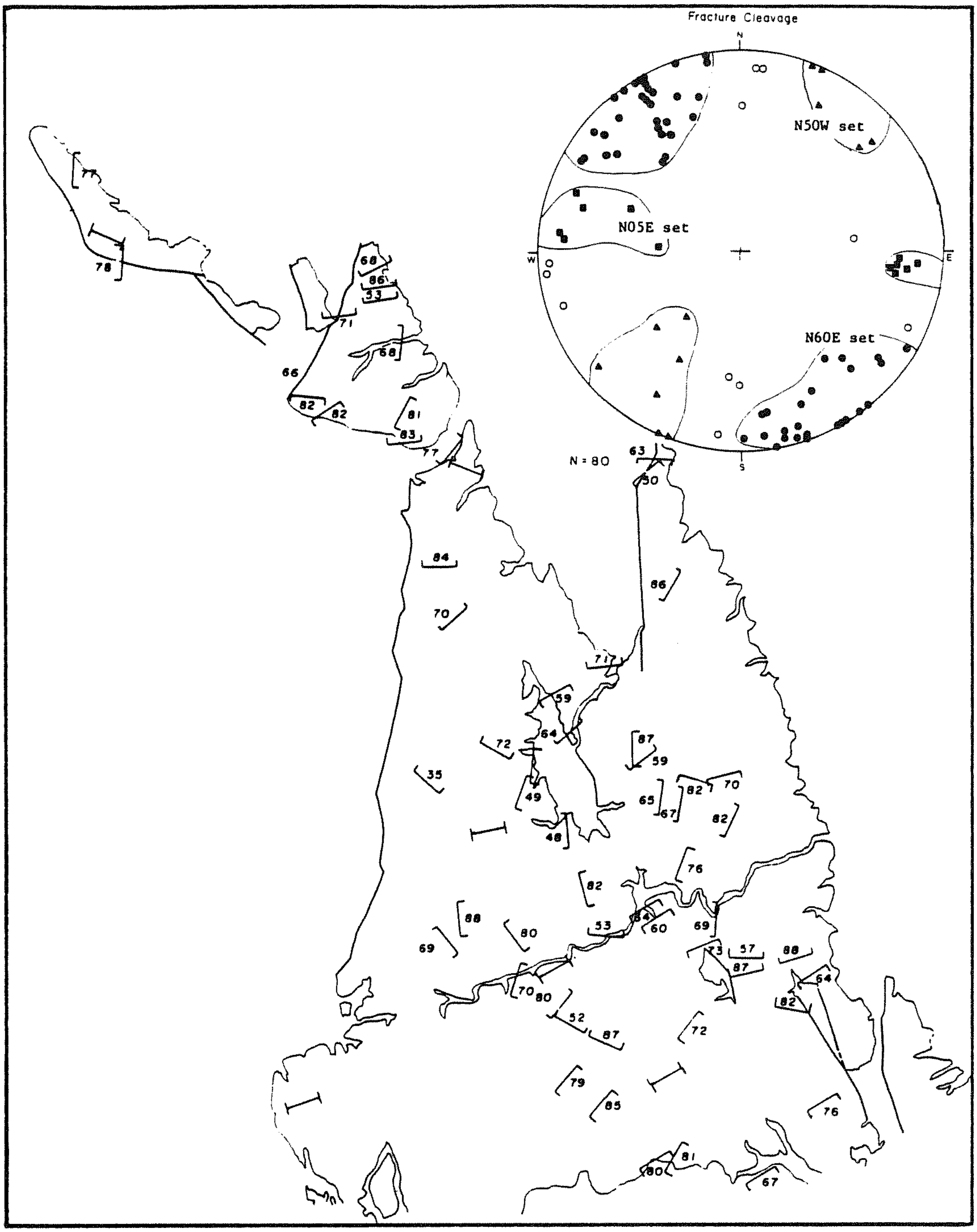


Figure 12. Fracture cleavage in the Precambrian basement, Quseir area.

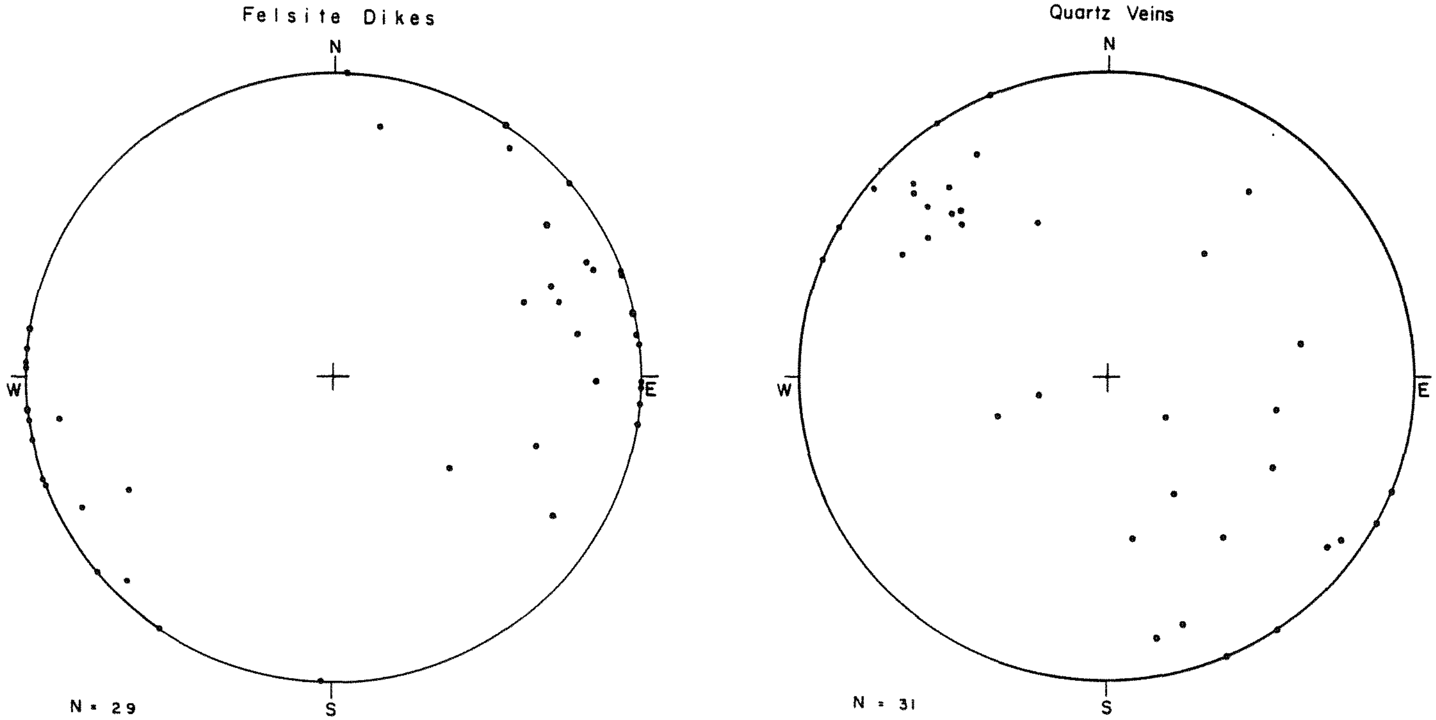


Figure 13. Orientations of (a) felsite dikes, and (b) quartz veins in the Precambrian basement, Quseir area.

quartz veins is irregular in detail, but averages N45E 80°SE (fig. 13b), perpendicular to the regional foliation. These quartz veins were probably emplaced during the last phases of tectonism, perpendicular to the least compressive stress direction (sigma 3).

Late Mesozoic/early Cenozoic Platform Sediments

Introduction. Four areas of major down faulting and platform sediment preservation are present: (1) the Gebel Ambagi area, (2) the Gihania valley, (3) the southeast coastal area, and (4) a number of related shallow valleys within the central Precambrian horst (fig. 14). Gebel Atshan, included on the maps for completeness, was studied in detail by M. Valentine (in preparation). The platform sediment blocks characteristically form north-south elongate valleys within the surrounding uplifted Precambrian basement, with steep valley walls on the east and locally on the west. Topography within the valleys tends to be linear, controlled by the distribution and erosional resistance of individual units within the platform sediments. The fault blocks were emplaced by generally north- to northwest-trending normal faults, with displacements in the range of 300 m to 1 000 m. The

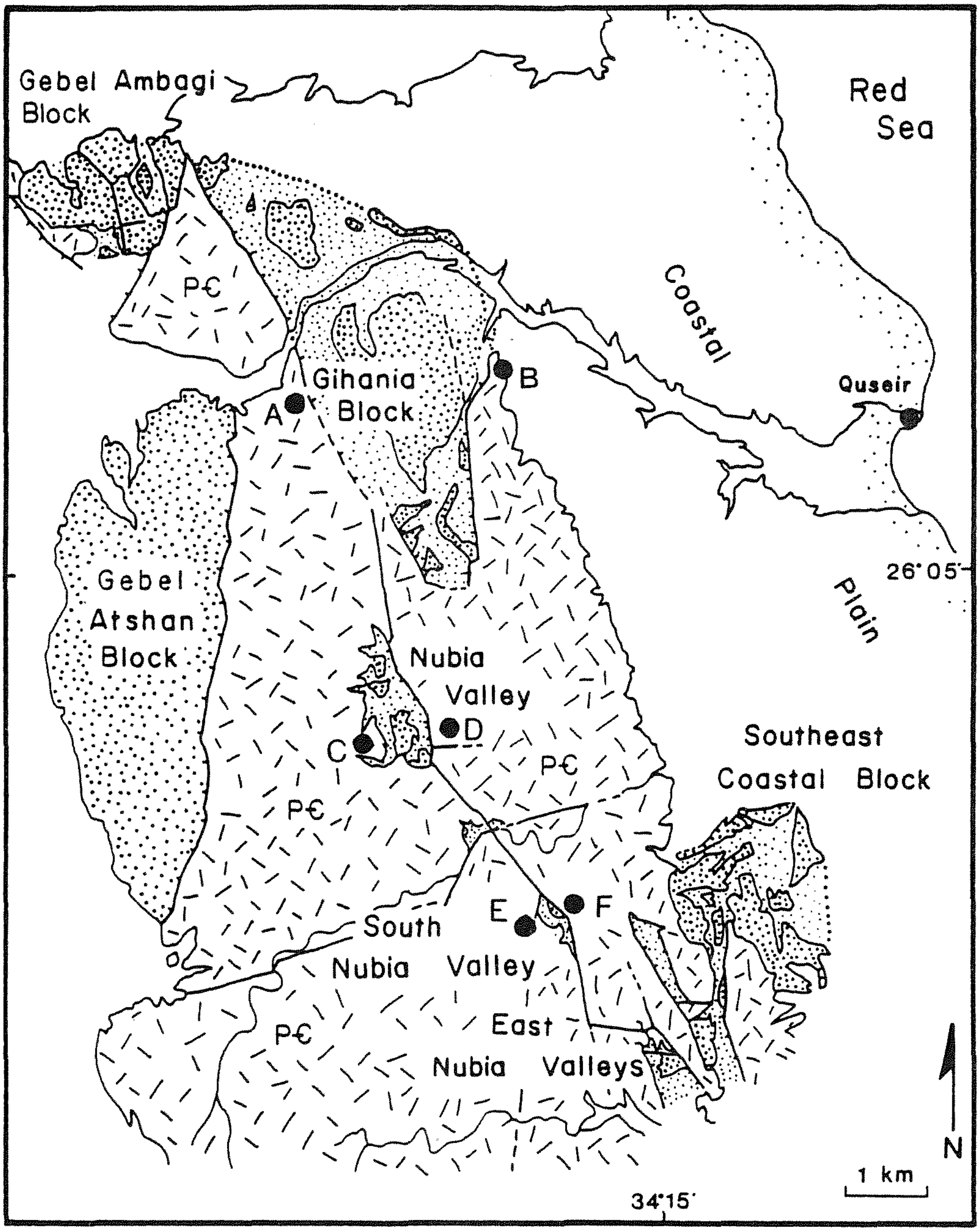


Figure 14. Faulted inlier blocks of platform sediments, with cross section locations.

blocks are all tilted to the northeast, with dips ranging from 10^{o} to 30^{o}.

Gebel Ambagi Area. The platform sediments preserved in the Gebel Ambagi area consist of a number of prominent erosional remnants of Nubia sandstone and overlying Quseir variegated shale, resting unconformably on a tilted Precambrian erosion surface of very low relief. The fault blocks form distinct, steep-sided plateaus, dipping from 10^{o} to 30^{o} northeast. They were emplaced through west-down dip-slip motion on a major northeast-trending normal fault which forms the northwest edge of Gebel Ambagi, plus similar motion on a subsidiary northwest trending fault (see cross section B-B´, plate 3). Internal deformation within these fault blocks is very minor. A northwest-trending fault within the Precambrian in this area shows no signs of reactivation during the emplacment of the blocks.

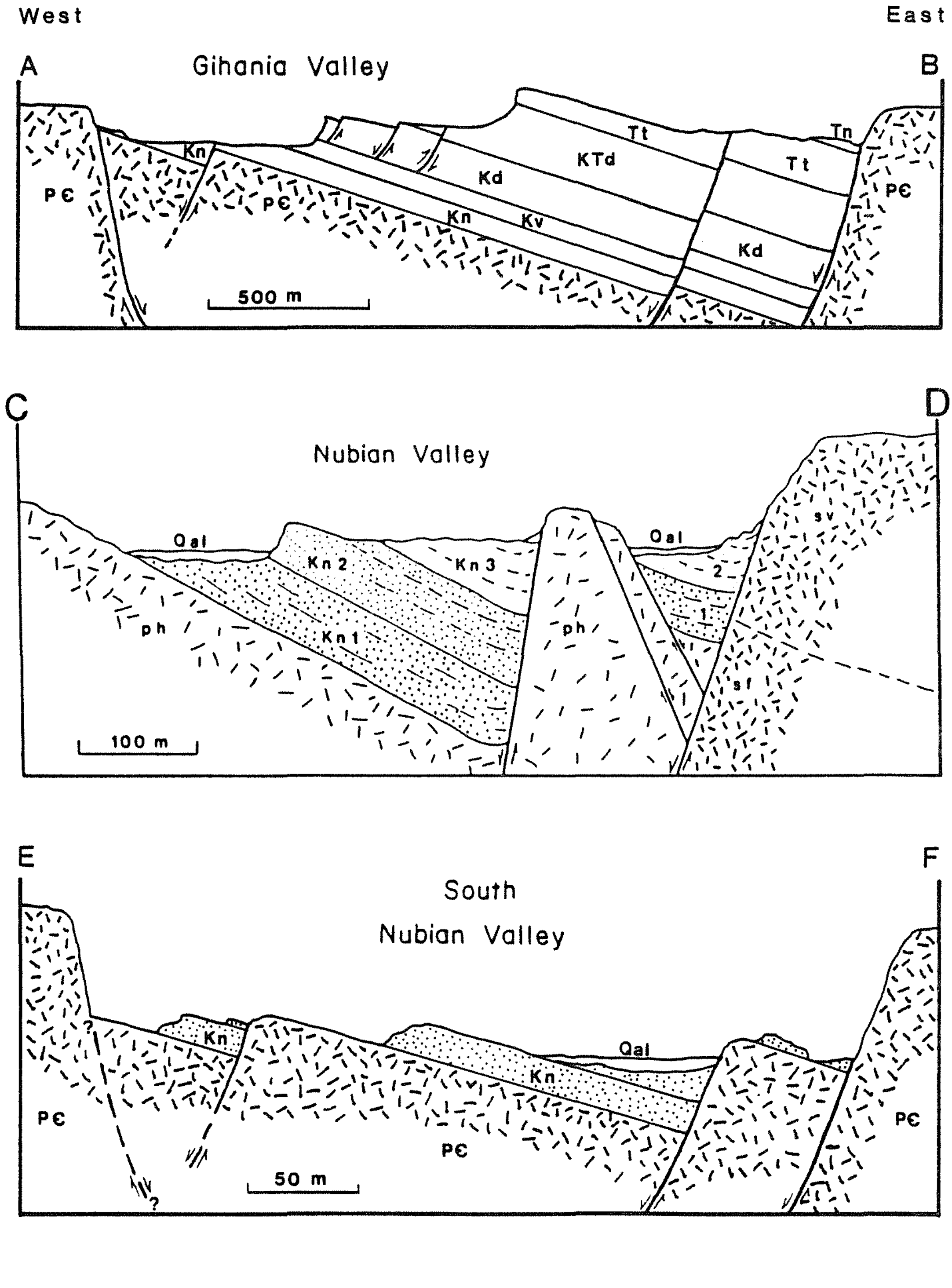
Gihania Valley. The Gihania Valley contains the largest exposure of platform sediments in the map area, and is the only fault block which includes a complete Cretaceous through lower Eocene section. It consists of a large triangular block south of Wadi Ambagi between two prongs of the Precambrian basement complex, a smaller block of Quseir and Duwi formations north of Wadi Ambagi, and scattered outcrops of Nubia sandstone along the west margin of the valley (plate 2). The main block crops out as two prominent linear ridges, with steep west-facing scarps and dissected east-facing dip slopes (fig. 15). The lower ridge is underlain by Duwi Formation, and the higher by the Thebes limestone. At the north end of the valley, north of Wadi Ambagi, the Thebes limestone is present as chaotic subcrop beneath the fringing reefs of the Miocene Gebel el Rusas Formation.

The Gihania block is bounded on both the east and the west by normal faults, separating the platform sediments from the Precambrian basement (fig. 16a). The block was emplaced by west-down motion on the major N05W trending normal fault that forms the east boundary of the valley. Vertical displacement on this fault, as estimated from the offset of the platform sediments, is approximately 600 meters. The less important west boundary fault has an orientation of N30W, and a vertical offset of 50 m to 100 m.

Substantial minor faulting and slumping have occurred within the Duwi Formation in this area, probably as a result of rigid blocks of Duwi Formation sliding on low strength Quseir Formation shales. Drag folding is also common, both within the Duwi Formation and where the Nubia

Figure 15. Photograph of the Gihania block, looking north. Ridge on right is Thebes Formation, ridge on left is Duwi Formation. Right foreground and left background are Precambrian basement.

Figure 16. Cross sections of Gihania block (A-B), Nubia Valley (C-D), and South Nubia Valley (E-F).


West
East
A
Gihania Valley
B
Kn
Tt
Tn
KTd
Tt
Kd
PЄ
PЄ
PЄ
Kn
Kv
Kd
500 m
C
D
Nubian Valley
sv
Qal
Qal
Kn 2
Kn 3
2
1
ph
Kn 1
ph
sf
100 m
E
F
South
Nubian Valley
Kn
Qal
Kn
PЄ
PЄ
PЄ
50 m

and Thebes formations come into contact with the boundary faults.

Southeast Coastal Block. The southeast coastal block is an area of gently dipping Nubia sandstone and Duwi Formation cropping out on the west edge of the coastal plain. Nubia sandstone unconformably overlies the Precambrian basement to the west. To the east and north the Duwi Formation is overlain by reefal limestone of the Gebel el Rusas Formation. The original emplacement and preservation of this block was due to west-down movement on normal fault parallel to the Red Sea, now obscured by more recent sediments of the coastal plain. Subsequent exposure of this block above the coastal plain appears to be the result of a transverse basement horst bounded by northeast- to north-northeast-trending normal faults, developed largely beneath the coastal plain south of Wadi el Isewid.

Central Nubia Valleys. The central Nubia valleys comprise a set of shallow topographic lows, occurring entirely within the Precambrian, related to a through-going system of north-northwest-trending faults. Unlike the previously described fault blocks, the rocks underlying these valleys are highly disrupted, with extensive minor faulting and cross-faulting. Vertical offset on the main bounding faults is less, generally 100 m to 300 m, and only the Nubia Formation is preserved.

There are four main valleys of this type; all are formed by major north- to northwest-trending normal faults along their east edges, with west down dip-slip motion (figs. 16b and 16c). Minor valley-parallel step faults are common, as are east-west to northeast-southwest cross faults (fig. 17). Slivers of Precambrian basement are commonly faulted into contact with the Nubia Formation within these valleys, forming low, weathered outcrops. The valleys appear to be the result of the interaction of a major system of north-northwest through-going faults with a lesser system of N60E to N90E cross faults.

Details of Fault Movements. In order to characterize the stress systems operating during formation of these tectonic blocks, a detailed study was made of fault motions associated with their emplacement. It was rarely possible to make direct measurements of the major fault surfaces. Preferential weathering has obscured them, and in many cases completely eroded the fault zones into linear valleys. However, multiple measurements were made of orientations and slickenside directions on minor fault surfaces bordering the major fault zones, and these give a reasonably consistent indication of the regional movement

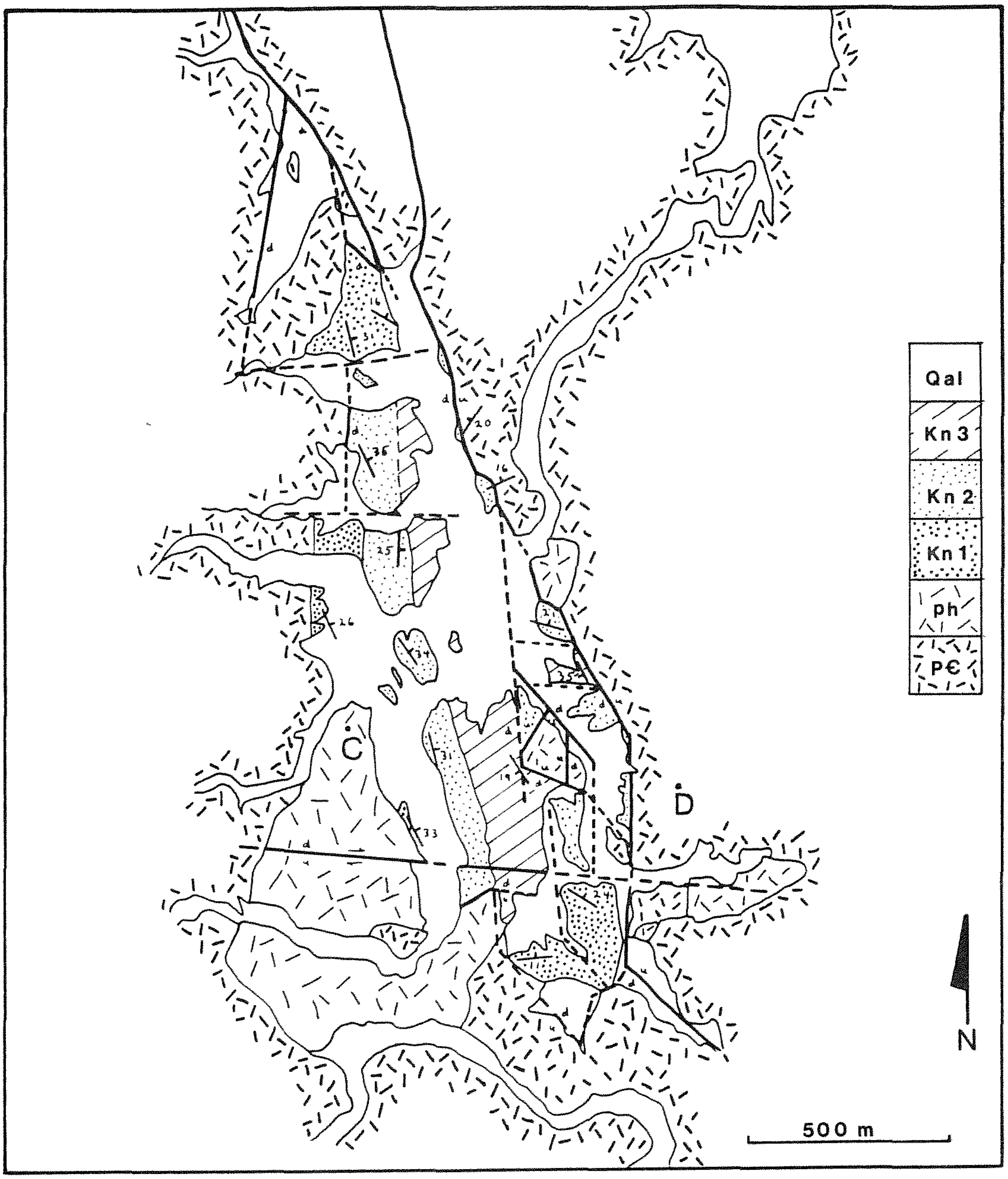


Figure 17. Detail map of Nubia Valley.

patterns.

Figure 18a is an equal area plot of poles to Tertiary faults associated with emplacement of the platform sediments blocks. Little can be discerned from this plot, except that moderate to steeply dipping fault planes predominate, as would be expected in an area of regional extension.

Figure 18b is a cumulative plot of all slickenside orientations measured within the study area. Dip-slip normal fault motions predominate, but a substantial number of strike-slip fault motions were also observed. These strike-slip faults can be readily separated into two distinct sets, a predominantly northwest-trending set showing right-lateral motion, and a predominantly northeast-trending set showing left-lateral motion.

In the field, many of the Tertiary fault surfaces were seen to have two superimposed movement directions; an early strike-slip motion, overprinted by a later dip-slip motion (fig. 19). In figure 20, all the measured slickensides from faults with two movement directions have been plotted. The open symbols represent early motion, while the closed symbols represent superimposed later motion. The figure clearly shows the predominance of early strike-slip motion with later dip-slip reactivation.

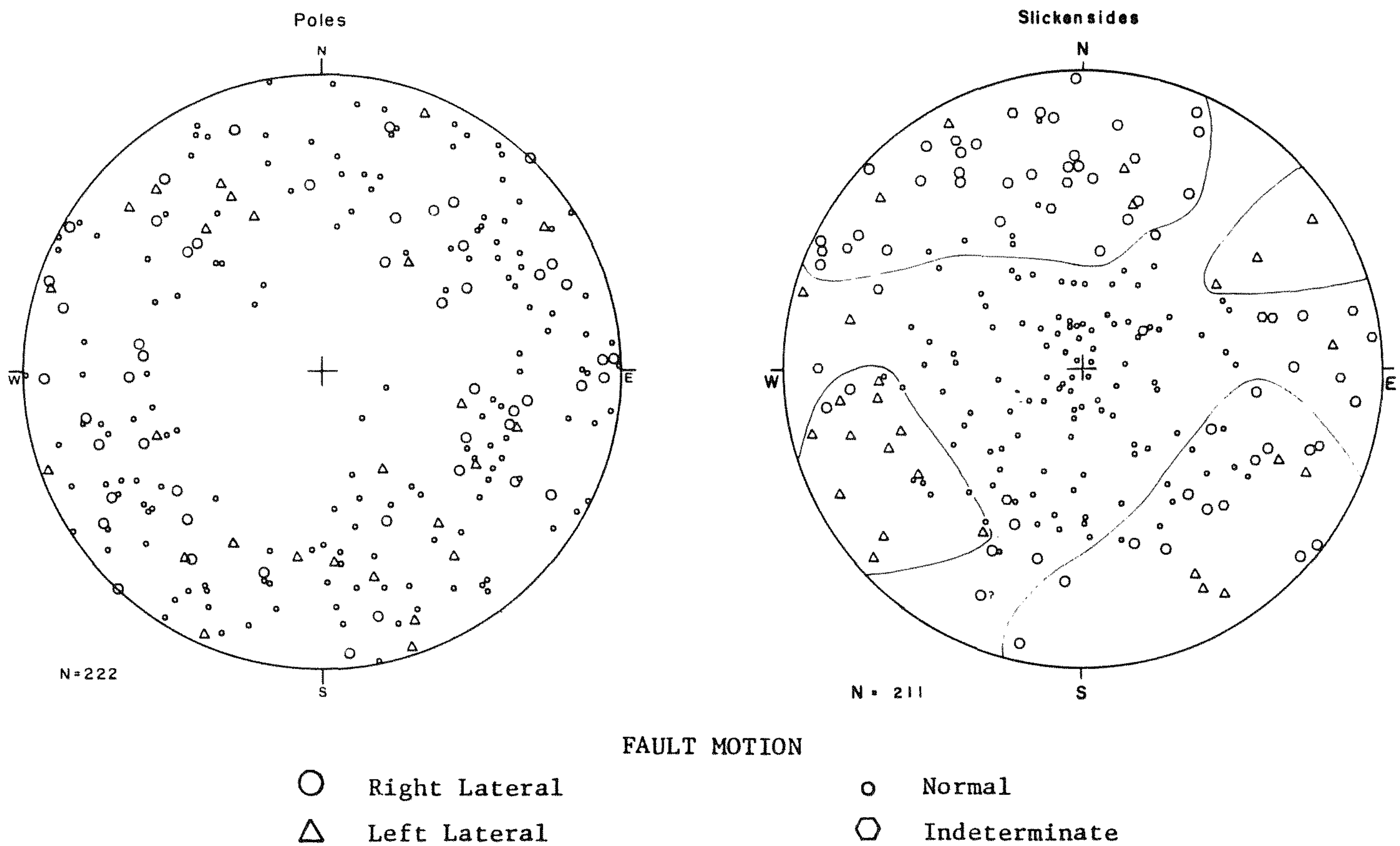


Figure 18. Orientations of (a) fault planes and (b) slickensides of Tertiary faults measured in the Quseir area.

Figure 19. Detail photograph of fault plane showing dip-slip slickensides (parallel to pencil) superimposed on strike-slip slickensides (parallel to jacknife).

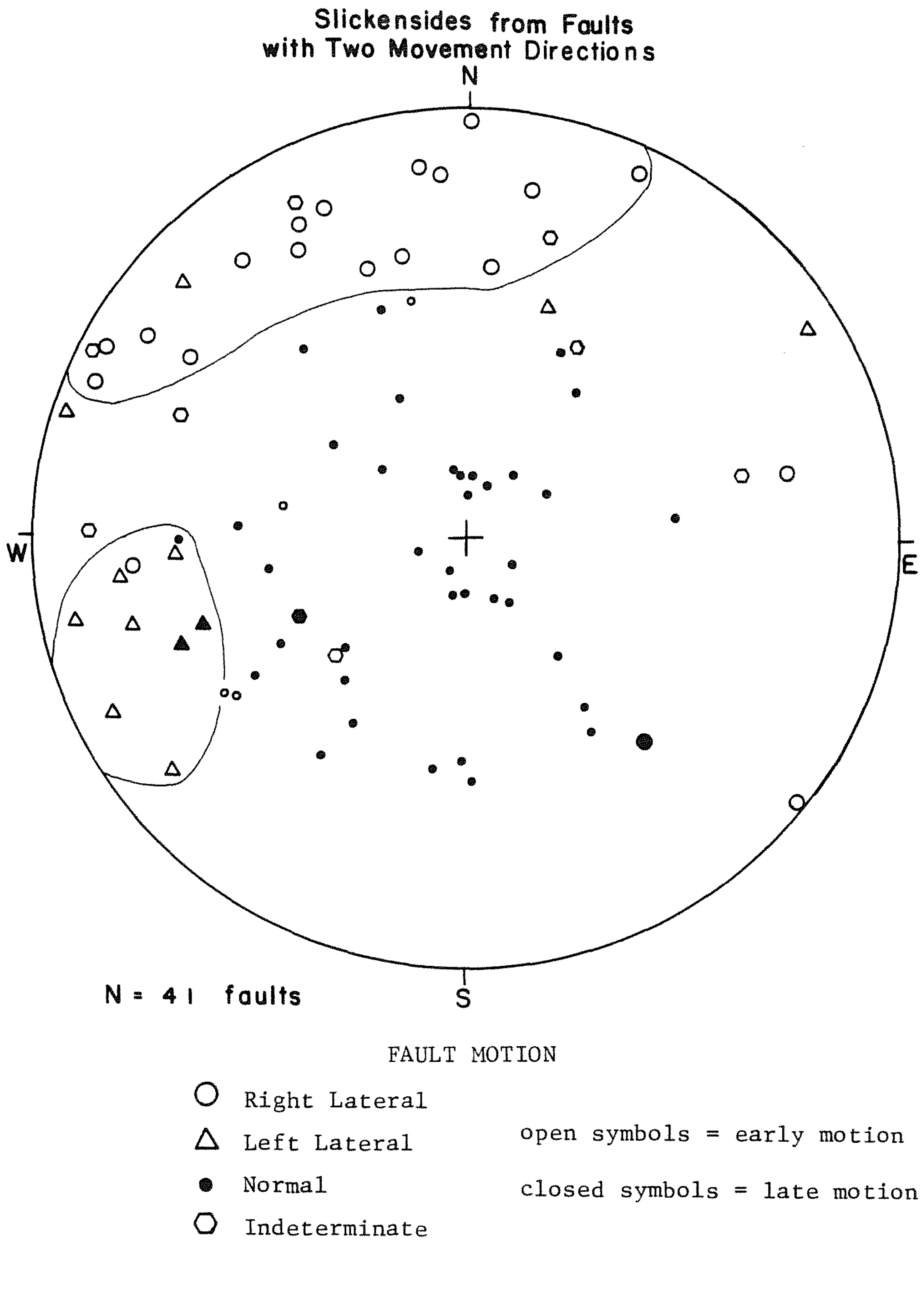


Figure 20. Orientations of slickensides from faults with two movement directions.

When the faults with strike-slip motion are plotted separately a number of subsets emerge. Figure 21a shows poles to faults with right-lateral motion, and figure 21b the orientation of slickensides indicating right-lateral motion. These are separated into three subsets; the predominant northwest-trending set, a minor east-west-trending set, and a minor northeast-trending set. The plots of poles to faults with left-lateral motion, and slickensides indicating left-lateral motion (figs. 22a and 22b), show the predominant N60E fault set, and a scattering of other orientations, but no identifiable subsets.

The two predominant early fault sets are a right-lateral set with an average orientation of N20W, and a left-lateral set with an average orientation of N60E. These two strike-slip fault sets form a conjugate system with sigma 1, the maximum compressive stress, oriented at approximately N20E; and sigma 3, the minimum compressive stress, oriented at approximately N70W. A plot of calculated stress field orientations for each individual fault measurement (fig. 23a and 23b) agrees reasonably well with these average orientations. Individual discrepancies are probably related to:

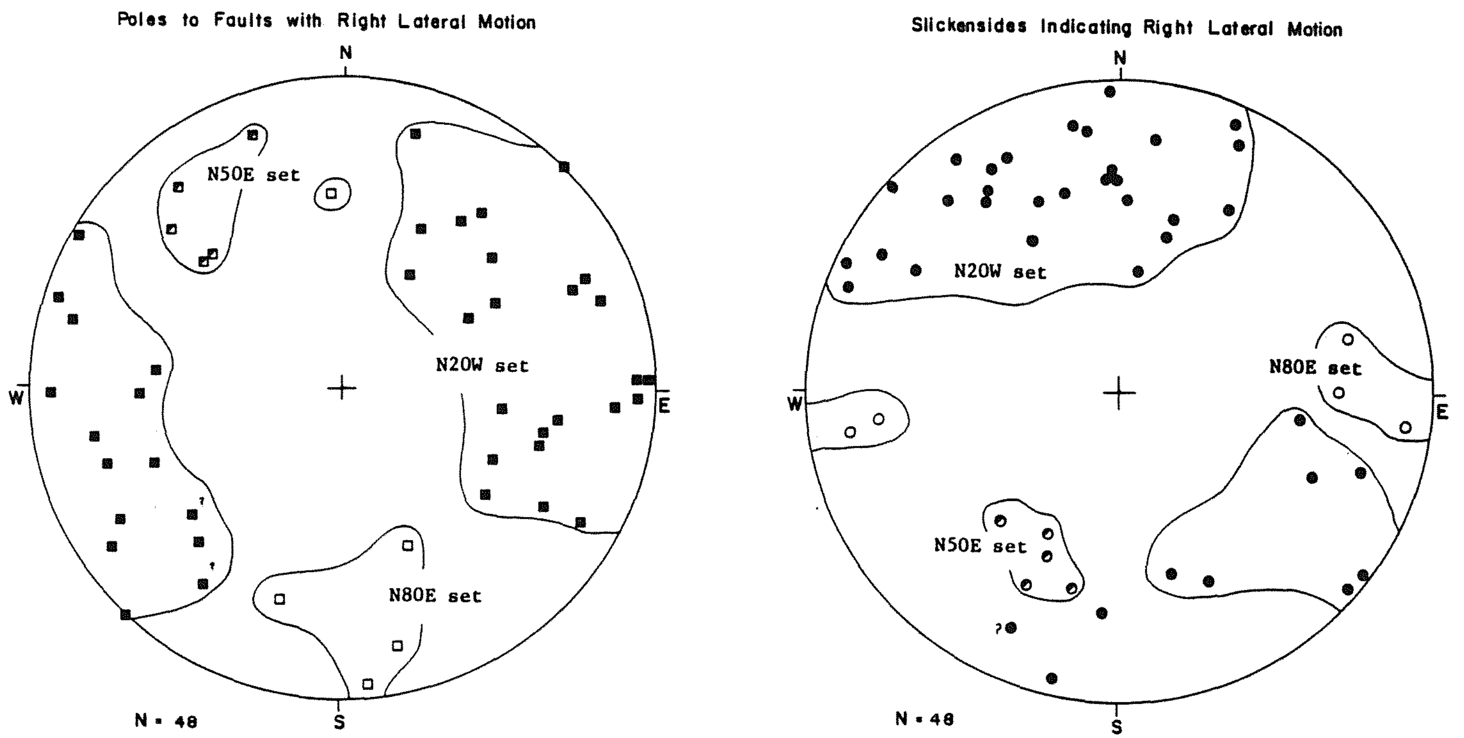


Figure 21. Fault plane and slickenside orientations of Tertiary strike-slip and oblique-slip faults with right-lateral motion.

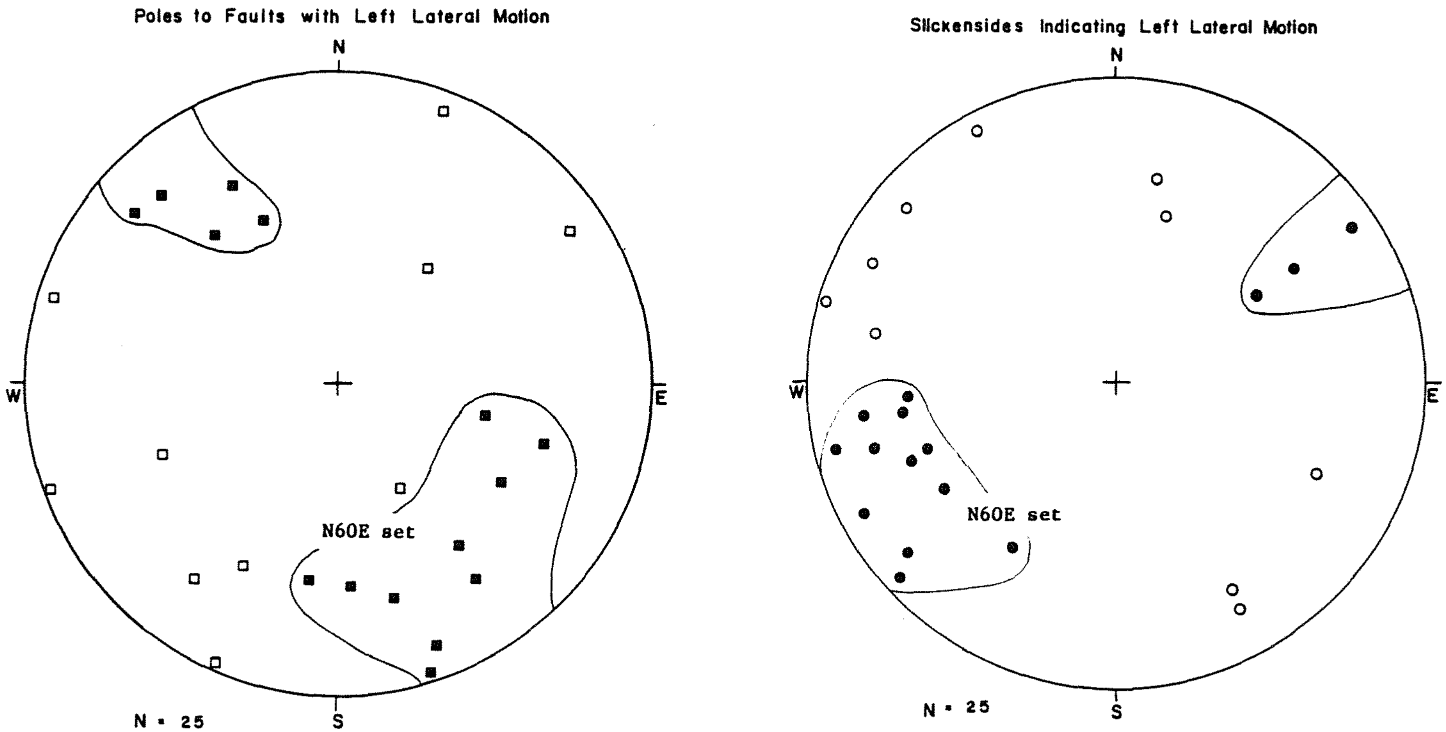


Figure 22. Fault plane and slickenside orientations of Tertiary strike-slip and oblique-slip faults with left-lateral motion.

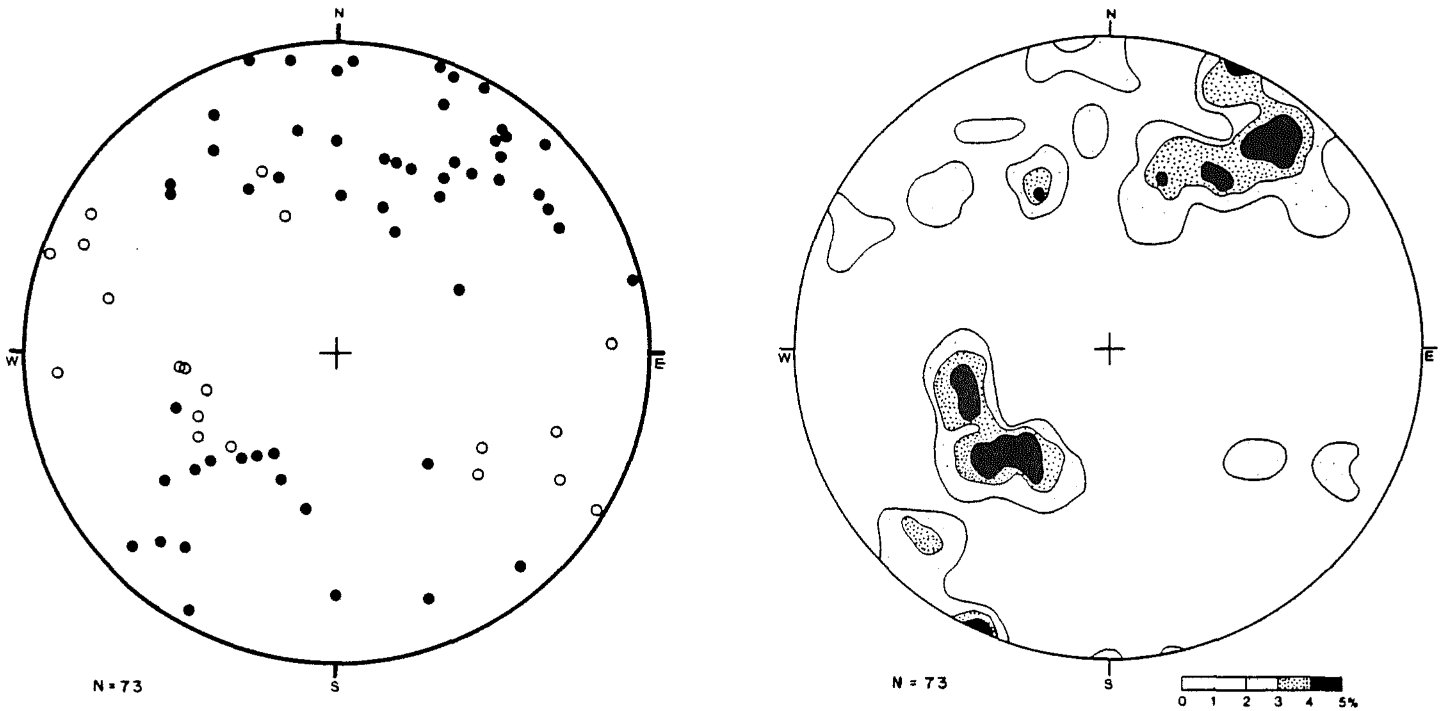


Figure 23. Sigma 1 orientations of Tertiary strike-slip and oblique-slip faults. (a) Sigma 1 orientations from individual fault planes. Solid dots represent sigma 1 orientations from faults in main sets, open dots represent sigma 1 orientations from faults in minor sub-sets. (b) Contour plot of sigma 1 orientations from individual fault planes.

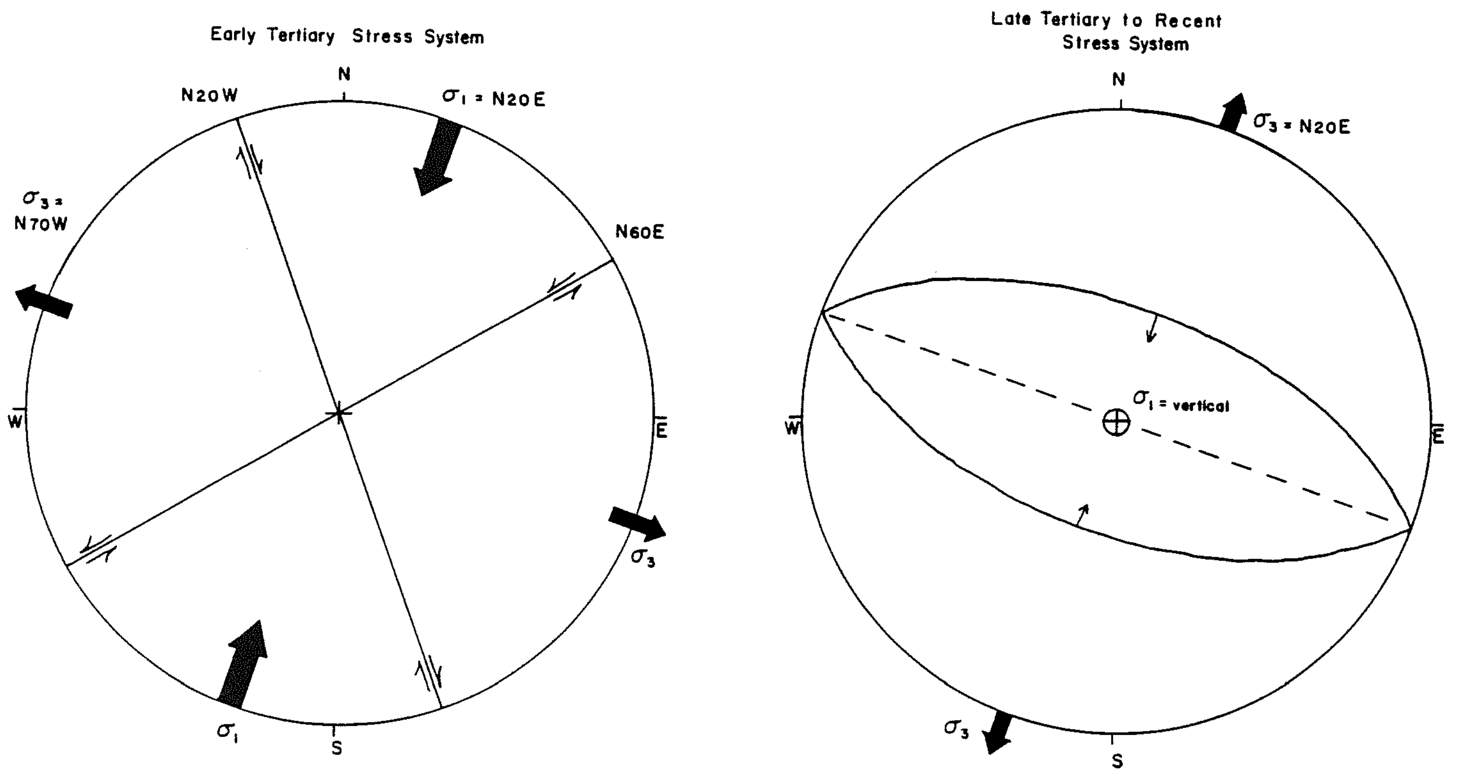


Figure 24. Tertiary stress systems in the Quseir area. (a) Pre-rifting N20E compressional phase, (b) Rift and post-rift N20E extensional phase.

1. subsequent block tilting during the onset of northeast extension,
2. local variations in the stress field, and
3. previous zones of weakness in the underlying Precambrian basement acting to control later fault orientations.

This stress system is indicative of an early phase of north-northeast compression (fig. 24a), active prior to the development of the present extensional stress regime associated with the opening of the Red Sea (fig. 24b).

Summary and Interpretation. In the Quseir region a stable tectonic regime was disrupted sometime during late Eocene to Oligocene time by the onset of north-northeast compression, producing regional uplift and the cessation of sedimentation. This was accompanied by the development of a conjugate system of north- to northwest-trending right-lateral strike-slip faults and northeast-trending left-lateral faults.

The north- to northwest-trending fault set was strongly affected by the northwest structural grain of the underlying Precambrian basement, which accentuated development of through-going faults, and in particular favored the development of faults trending northwest. The stress system, however, appears to have favored more nearly north-south right-lateral faults, and the results of this interaction can be seen in the common segmented pattern of the right-lateral fault set, in which northwest-trending fault segments alternate with more northerly segments (e.g., the Gebel Atshan fault, plate 2).

Elements of the northeast-trending left-lateral fault set appear to control many of the transverse topographic features in the region, including the terminations of a number of the fault block valleys in the south, the orientations of Wadi el Isewid and Wadi Quseir el Qudeim, and the orientation of the transverse topographic high upon which the Pliocene Gasus reef structures are developed. Garson and Krs (1976) identify regional transverse fractures averaging N60E in both Egypt and Saudi Arabia. They suggest that major fractures of this orientation may have first developed during the Precambrian, a suggestion possibly supported by the N60E fracture cleavage set noted in the Precambrian basement in the Quseir area.

A system of broad folds and arches developed concurrently with the strike-slip faulting to the north of the study area, in the vicinity of Gebel el Anz (Trueblood, 1981). These folds have axes oriented approximately N40W, also indicative of northeast compression.

During the Oligocene or earliest Miocene, the stress regime changed to one of northeast extension. This resulted in an episode of northeast tilting, and the reactivation of the early northwest strike-slip fault set as west-down normal faults. Some form of regional tilting associated with this period of fault reactivation is implied by the predominant southwest dip of the faults as presently exposed. The early strike-slip faults would normally have developed vertically; requiring tilting either prior to or during reactivation to reach their present orientations. Dip-slip movement on these northwest-trending faults resulted in substantial tilting and down faulting of isolated blocks of platform sediments, and the emplacement of these blocks as inliers within the Precambrian basement. Erosion during this period stripped the uplifted areas of their sediment cover, leaving the Precambrian exposed in all areas except the down-faulted inliers.

Red Sea Coastal Plain Sediments

Gebel el Rusas Formation. The middle Miocene Gebel el Rusas Formation has a highly irregular outcrop pattern, with abrupt lateral facies variations reflecting the irregular topography of the original Miocene basin edge, now exhumed due to a combination of marginal uplift, basin subsidence, and/or sea level fall. It occurs in three distinct structural settings within the study area (fig. 25):

1. as a large barrier reef development on a local horst block (the Ambagi reef),
2. as fringing reefs developed against a fault scarp of the Precambrian basement (the Rusas/ Precambrian reefs), and
3. as a reefal cap on exposed platform sediments (the Isewid reef).

Ambagi Reef. The Ambagi reef is an excellent example of the interaction of sedimentation, local tectonics and sea level changes. It is located at the north end of the Gihania valley, on the north bank of Wadi Ambagi, and is visible just north of the main highway, 7 km west of Quseir. It formed along the south side of a marked indentation in the Miocene coastline (fig. 26), associated with an area presently bounded by Wadi Ambagi and Wadi

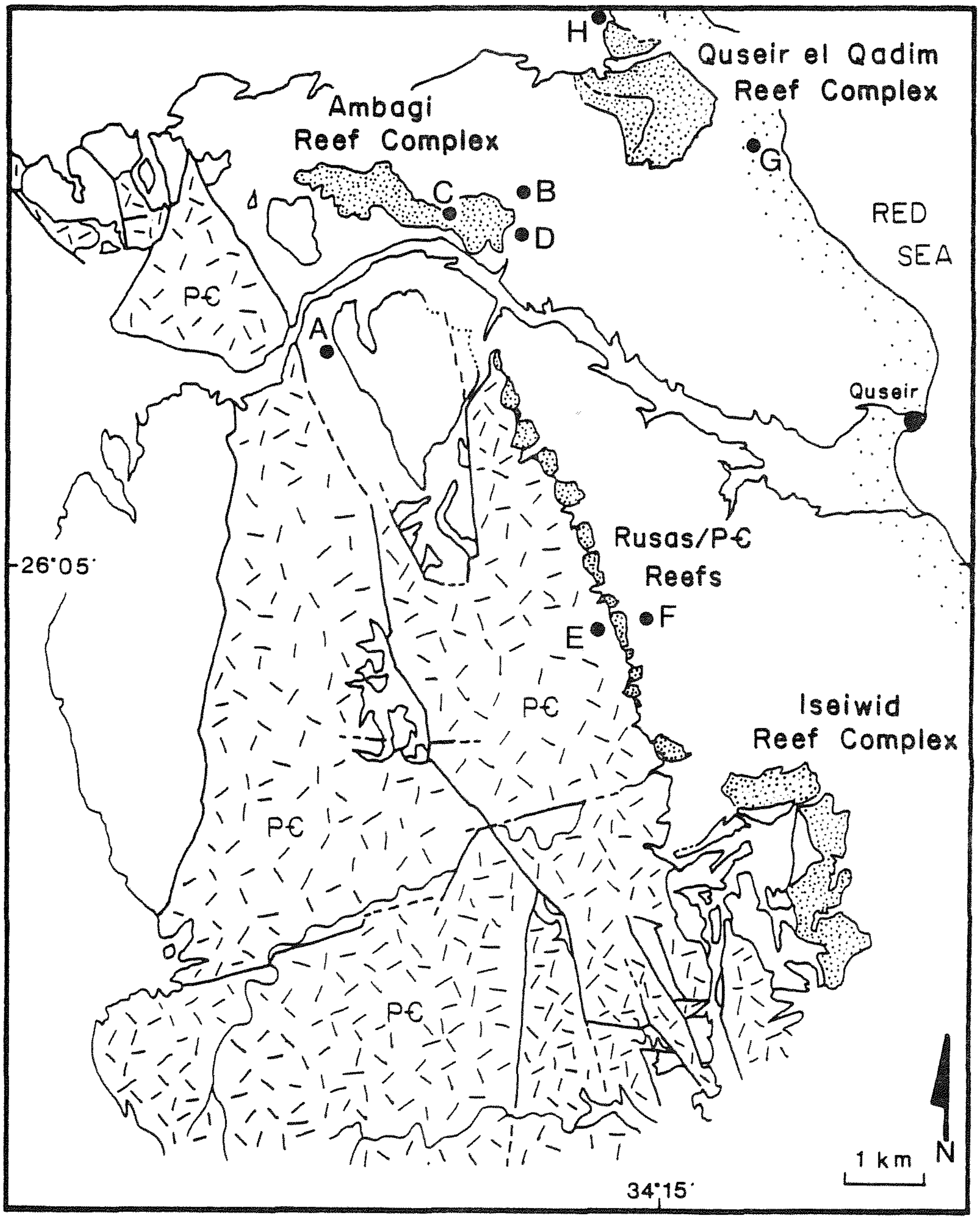


Figure 25. Coastal plain reef complexes, with cross section locations.

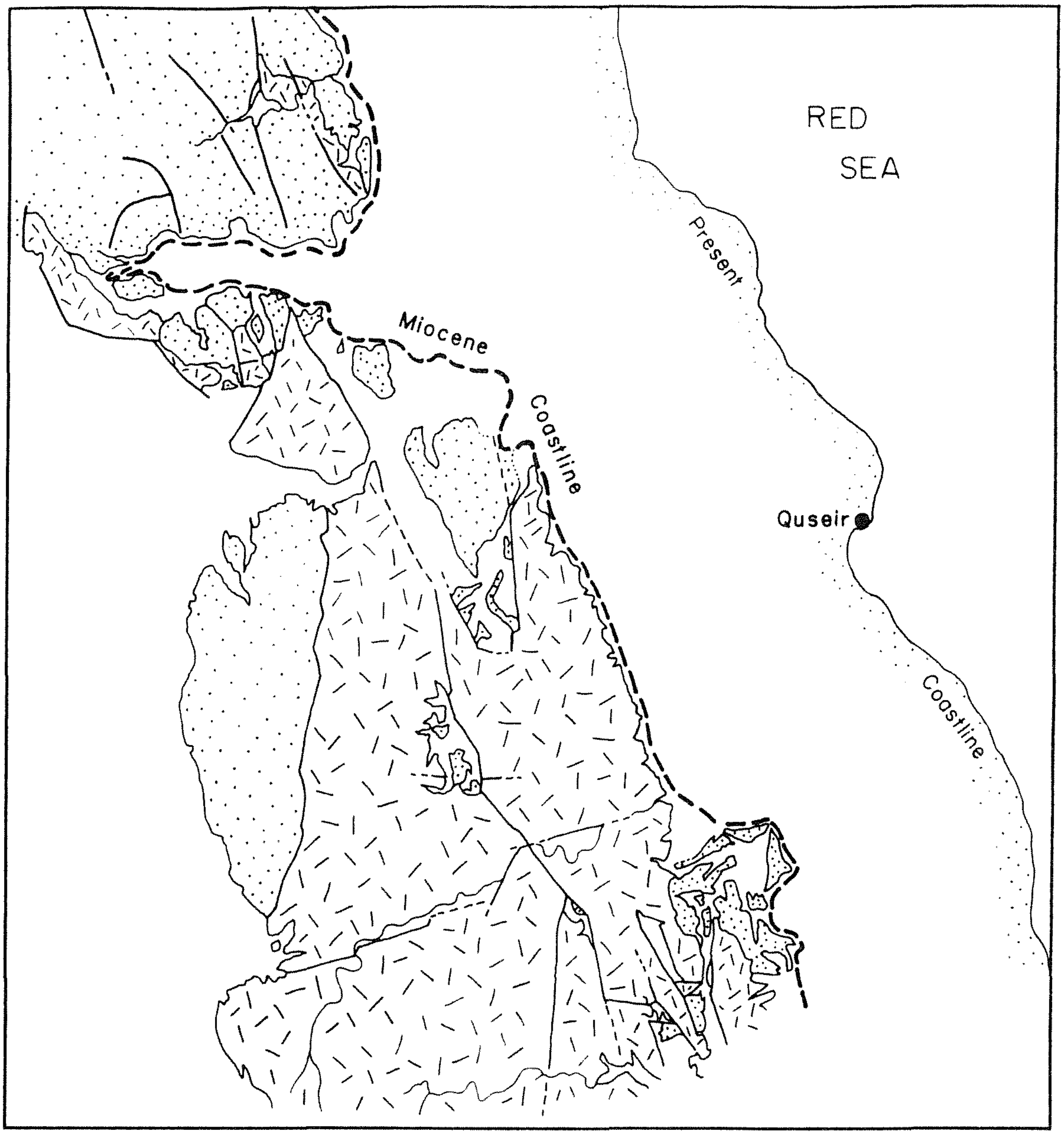


Figure 26. Map showing Red Sea coastline during middle Miocene time.

Quseir el Qudeim. The reef complex is developed on a substrate of chaotic Thebes Formation, with numerous disturbed blocks and slump structures indicating highly active local faulting.

The exposure of the Ambagi reef complex (fig. 27) is steep on all sides, and with the adjacent Evaporite Formation stands as a prominent topographic high above the surrounding coastal plain. Two capping reef terraces (the main reef and upper reef members) are flat, undeformed, and dip approximately 2^{o} to the northeast. Coarse Precambrian-derived pebble conglomerates form an off-block equivalent to the upper reef member north of the reef complex, while local outcrops of thin-bedded to massive gypsum of the late Miocene Evaporite Formation overlie the reef plateau. Individual units within the reef complex dip steeply and thicken dramatically off the east and northeast edges of the block, indicating substantial synsedimentary faulting.

The underlying structure of the Ambagi reef is an uplifted horst block developed within a zone of coastal flexure. The horst is formed by the interaction of a major flexure zone parallel to the Red Sea with a zone of west-northwest faults, possibly related to the old Precambrian structural grain (fig. 28). The interaction

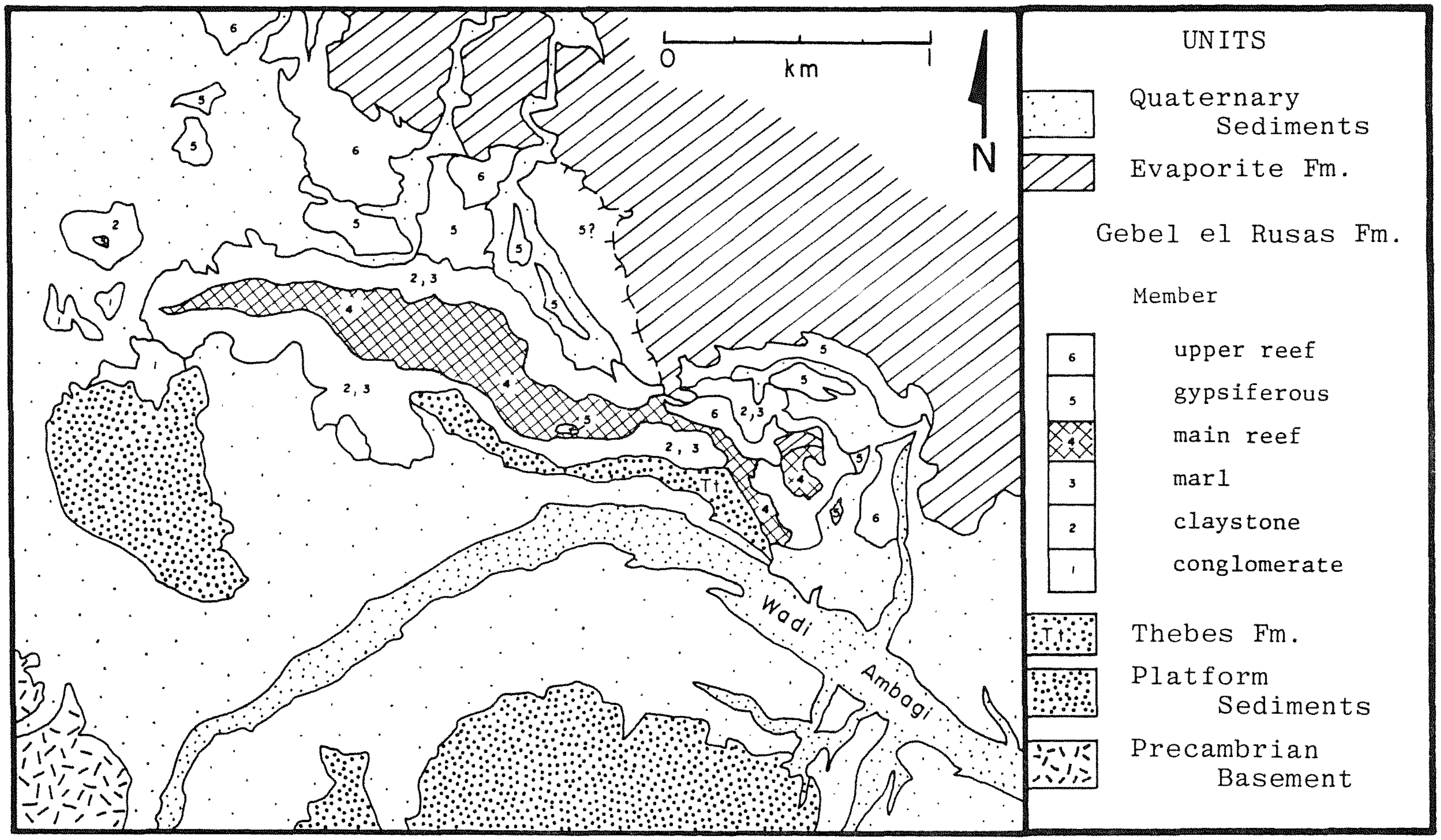


Figure 27. Detail map of the Ambagi reef complex.

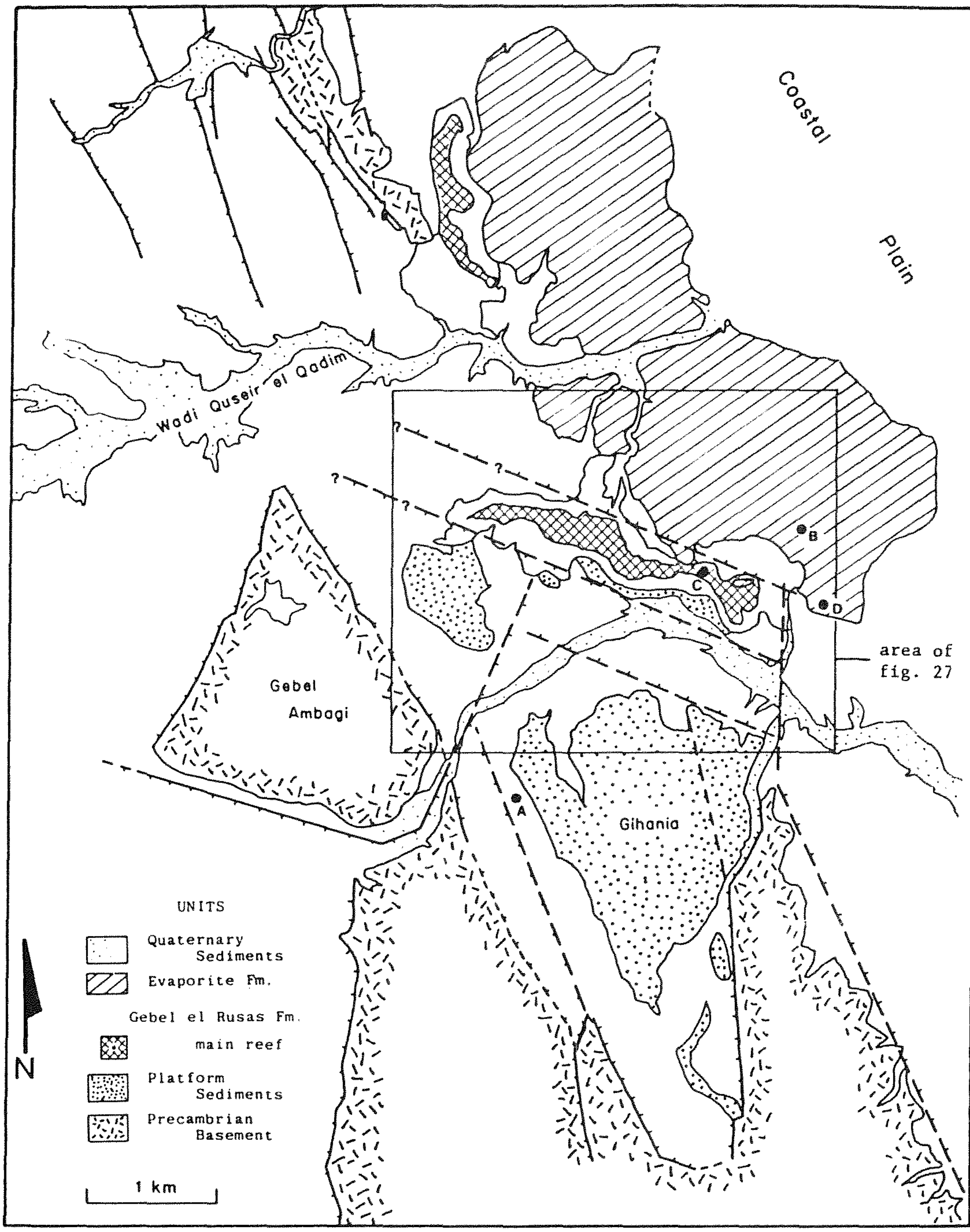


Figure 28. Faults in the Ambagi reef area, showing interaction of northwest-trending fault set parallel to the Red Sea with west-northwest trending set parallel to the Precambrian structural grain. (Geology north of Wadi Quseir el Qudeim from Trueblood, 1981).

has resulted in the isolation of this block as an independant fault sliver within the main flexure zone (fig. 29a).

Uplift of the horst block was episodic and synsedimentary. It was probably already a local topographic high in the middle Miocene, when the basal conglomerates of the Gebel el Rusas Formation were deposited in surrounding areas. Continued uplift and/or basin subsidence during deposition of higher stratigraphic units resulted in tilting and substantial off-block thickening of the claystones and marls that form the base of the reefal succession (fig. 29b). As the uplifted block neared sea level, a resistant cap of reefal limestone (main reef member) developed, prograding seaward across its talus debris. A lowering of the horst block relative to sea level, possibly combined with increased salinity of the sea water, killed the reef organisms, and resulted in the deposition of 10 m of fine terrigenous sediments and evaporites (gypsiferous member) overlying the reef horizon. This in turn gave way to another episode of reef development (upper reef member), before the block was finally inundated by evaporites of the Evaporite Formation in the late Miocene.

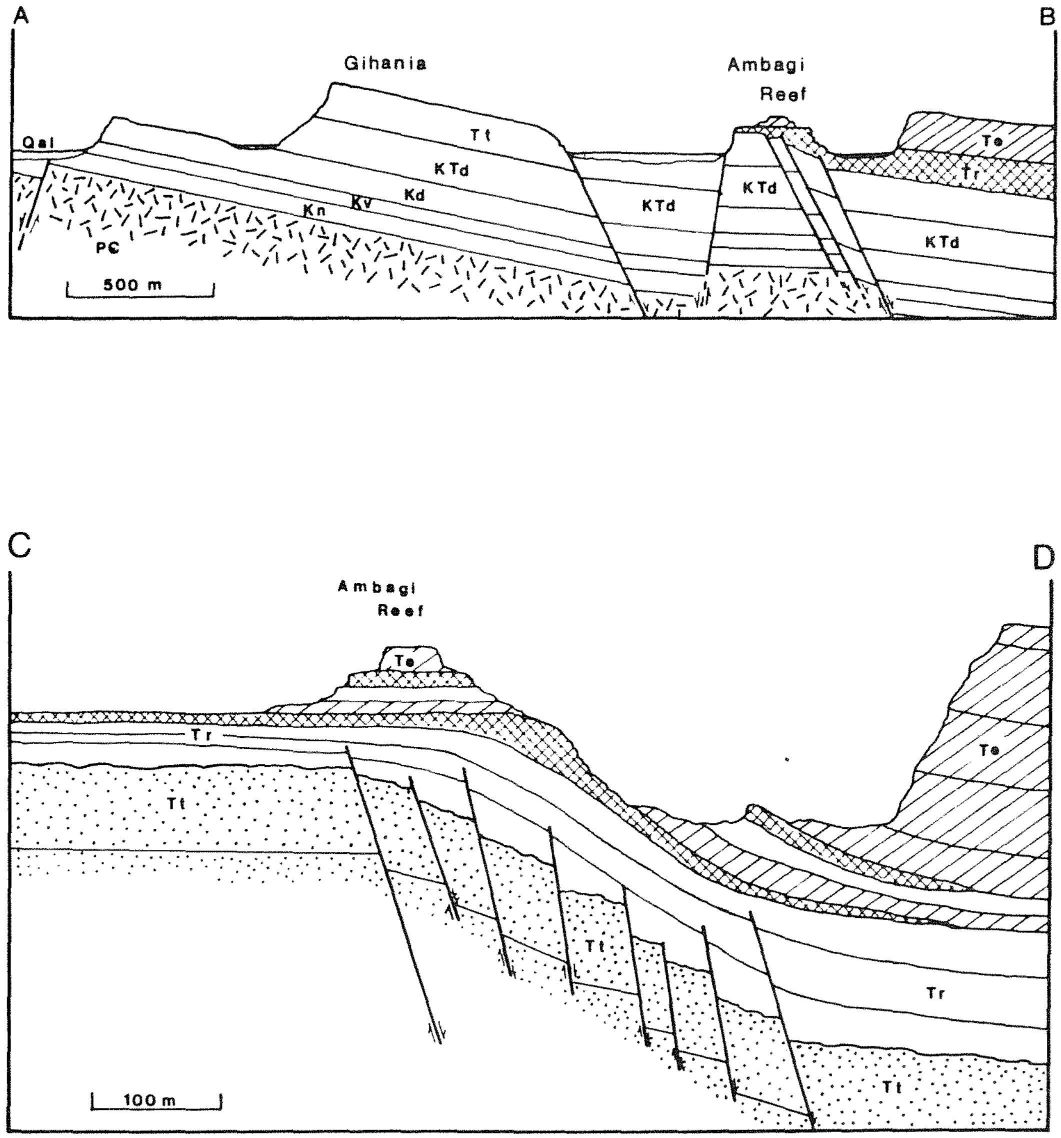


Figure 29. Cross sections of the Ambagi reef.

Isewid reef. The Isewid reef is located on the coastal plain in the southeast corner of the study area, immediately south of the mouth of Wadi el Isewid. It unconformably overlies northeast-tilted sediments of the Duwi Formation, and must have formed a prominent point on the Miocene coastline (fig. 26).

The Isewid reef complex is developed over a transverse basement high bounded by a N60E ("transverse trend") fault on the north side, and a N10E ("Aqaba trend") fault on the southeast side. The N60E fault forms a continuation of the Wadi el Isewid lineament, while the N10E fault possibly continues under the coastal plain to control the bend in the coastline which forms Quseir harbor. A tilted prong of the lower platform sediments is preserved on the structural high formed by these faults; the Isewid reefs have developed as fringing reefs around this structure.

Rusas/Precambrian reefs. The Rusas/Precambrian reef complex is a series of fringing reefs developed against the steeply tilted and faulted Precambrian basement between Wadi Ambagi and Wadi el Isewid. The reefs are strikingly visible from the coastal plain. They appear as flat-topped plateaus uplifted with the Precambrian above the coastal plain. Their light brown color contrasts sharply with the predominantly dark green color of the Precambrian basement (fig. 30).

The reef complex originally formed a continuous band along the seaward margin of the Precambrian basement; later dissected by numerous wadis draining the uplifted interior. While some faulting and substantial synsedimentary tilting of the underlying marls and terrigenous sediments have occurred, the present outcrop pattern is a primary depositional feature produced by coralline reef growth against a steeply shelving, tectonically active shoreline.

Remnants of the pre-Cretaceous surface dip under the Rusas reef complex at an angle of 25^{o} to 30^{o}, and form the original surface upon which the Miocene sediments of the reef complex were deposited. Early, primarily terrigenous sediments are sub-parallel to this surface, but overlying units have progressively shallower dips and exhibit pronounced seaward thickening. Coralline reef horizons are present at a number of levels within the section, interbedded with the clastic facies (fig. 31).

The complex is capped by a major coralline reef horizon, with a flat to very gently sloping (2^{o}) plateau top which merges into the mid-Tertiary erosion surface developed on the Precambrian basement. This capping reef horizon thickens substantially seaward, and has formed a

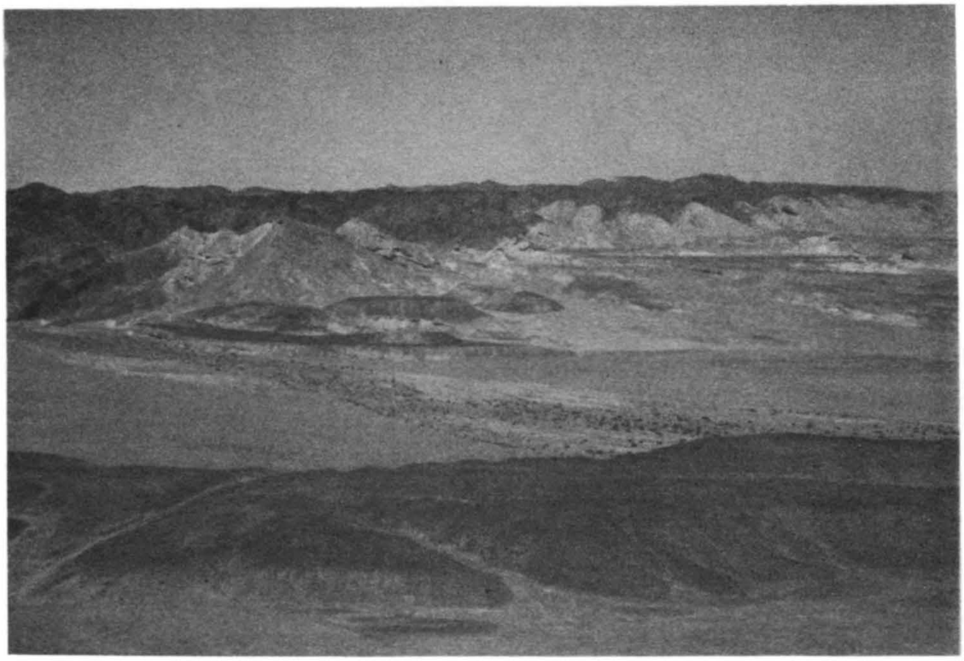


Figure 30. Photograph of the Rusas/Precambrian reef complex (light colored) on the edge of the uplifted Precambrian basement (dark colored). Note flat mid-Tertiary erosion surface developed on the Precambrian, and Quaternary wadi terraces in foreground.

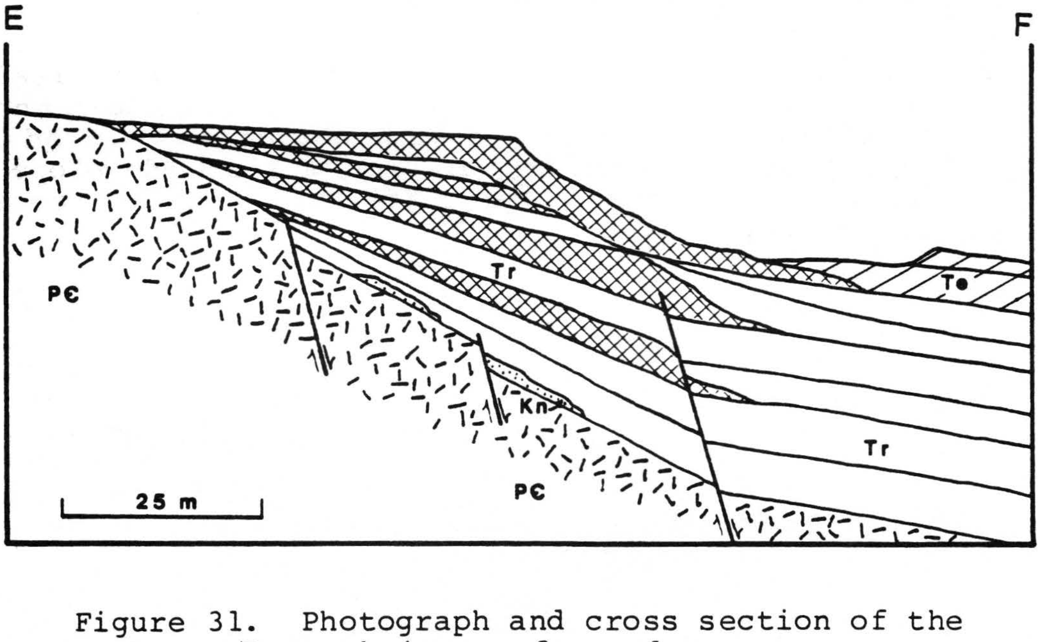


Figure 31. Photograph and cross section of the Rusas/Precambrian reef complex.

thick talus wedge at the seaward edge of the outcrop zone.

Evidence of minor normal faulting is locally present at the Miocene/Precambrian contact, with slump structures and minor angular unconformities common within the section. However, no indications of large-scale fault displacements are present.

The Rusas/Precambrian reefs have developed as fringing reefs on a steeply shelving basin margin. The basin margin in this area is formed by the edge of the Precambrian basement, which has been tilted and down-faulted contemporaneously with reef development.

Initially, terrigenous and shallow marine sediments were deposited on a flat Precambrian surface, which had been stripped of its cover of platform sediments by previous erosion. Progressive tilting of this surface, with continuing deposition of coarser terrigenous sediments, resulted in a sequence of east thickening terrigenous and shallow marine facies, with beds deposited at increasingly higher angles to the original Precambrian depositional surface. Periodically, sedimentation caught up with tilting and a coralline reef formed, to be subsequently drowned and covered by the next layer of clastic sediments. The last and best preserved stage is a major coralline reef horizon (the reef member), which represents a period of structural stability toward the end of the middle Miocene.

Remnants on the mid-Tertiary erosion surface. On top of Gebel Ambagi, and in several locations west of the Rusas/Precambrian reef complex, terrigenous equivalents of the gypsiferous and upper reef members are preserved as erosional remnants of what was probably once an extensive, thin sheet of sediments overlying the Precambrian basement. On Gebel Ambagi, the unit dips approximately 15^{o} to the north-northeast, while on the central Precambrian horst, the unit is flat lying. On the central Precambrian horst the unit is only slightly higher than, and is clearly associated with, the Rusas/Precambrian reef complex. However, the outcrops of this unit on Gebel Ambagi are 50 m to 100 m higher than the surrounding Precambrian terrain, or the top of other Rusas reefs in the area.

During the waning phase of Gebel el Rusas Formation deposition, the mid-Tertiary erosion surface was apparently covered by this sheet of thin-bedded back-reef and near-shore lagoonal facies. The cover probably never amounted to more than about 25 m of poorly indurated material, largely removed by subsequent erosion.

On the central Precambrian horst, where the Rusas/Precambrian reefs are developed directly on the

Precambrian basement block, this unit has maintained its topographic relationship with the reefs through all subsequent deformation. However, Gebel Ambagi has been sharply uplifted relative to surrounding areas. The north-northeast tilt of the Miocene sediments on Gebel Ambagi suggests that this uplift occurred primarily on the N75W fault which forms the southern boundary of the mountain.

Other outcrop areas. Isolated outcrops of the Gebel el Rusas Formation are observed at a number of other locations in the map area. Silty pebble to cobble conglomerate, and thin-bedded, poorly indurated marls and gypsiferous claystones are exposed north of the Ambagi reef in the Miocene Quseir el Qudeim embayment (fig. 26), now Wadi Quseir el Qudeim. A small algal-mat reef is developed against the Thebes Formation in Wadi Ambagi, just south of Gebel Ambagi, indicating Miocene marine intrusion at least to this point.

Evaporite Formation. There are two major outcrop areas of the Evaporite Formation in the study area:

1. north of Ambagi reef, where a very thick evaporite section forms a distinctive topographic high, and

2. east of the el Isewid reef, where a broad, low, prominently folded outcrop area occurs.

Between Wadi Ambagi and Wadi el Isewid a zone of scattered subcrop connects these two major outcrop areas.

The Evaporite Formation was deposited conformably on the Gebel el Rusas Formation, but the extremely irregular coastal plain topography formed by the reef complexes of the Gebel el Rusas Formation, combined with local intercalation of gypsum with the upper Rusas reef horizons, has resulted in contacts that are complex in detail.

Johnson (1975) has suggested that the Gebel el Rusas Formation and the Evaporite Formation were contemporaneous, or at least were deposited alternately for a considerable period. However, in this study evidence was found for only one cycle of alternate deposition of gypsum and Gebel el Rusas Formation (at the Ambagi reef). It is considered that most of the complications of the Gebel el Rusas/Evaporite Formation contact are due to the depositional topography.

Outcrops of the Evaporite Formation are prominantly folded, both on outcrop scale and map scale. Map scale folds appear to follow subsurface topography (see for example the Wadi el Isewid area). They are probably the result of differential flow of the evaporites toward subsurface highs, driven largely by the load of overlying sediments in adjacent basins.

A set of small lineaments trending N10W is developed at the east edge of the Evaporite Formation outcrop zone south of Quseir el Qudeim. Elements of this lineament set can be traced into the adjacent Gasus Formation to the north, and lineaments of similar trend were observed to the south near Wadi Ambagi. No bedding offset is detectable across the lineaments in the north, though the lineaments farther south in the Gasus Formation apppear to be associated with minor tilting and bedding disruption. The lineaments probably reflect minor movements on an underlying zone of coastal flexure.

Both major outcrop areas of the Evaporite Formation have well-developed joint systems. In the northern outcrop area these are especially prominent, as they have controlled drainage patterns and given the wadi networks an orthogonal form.

Gasus Formation. The Gasus Formation conformably overlies the Evaporite Formation, and is tilted and folded with it. Dips range from 5^{o} to more than 40^{o}, but average about 30^{o}.

The conglomerate member of the Gasus Formation is generally coincident with present wadi mouths (e.g., Wadi

Ambagi), suggesting that the present wadi system was developed at least as early as the Pliocene. Near the mouth of Wadi Ambagi, the underlying Evaporite Formation is substantially thinned, and the conglomerate member overlies the Evaporite Formation with apparent minor angular unconformity. It seems likely that stream flow from Wadi Ambagi partially eroded the upper Evaporite Formation in this area prior to deposition of the Gasus Formation.

At Quseir el Qudeim, in the northeast corner of the study area, a small reef complex developed over a structural high (fig. 32). The structural high forms a small transverse block with an orientation of about N60E. Beds of the Gasus Formation dip off the structure on the northwest and southeast sides, and are truncated on the northeast (seaward) side by Pleistocene coral reefs. The truncation is highly linear, and probably represents a subsurface Red Sea-parallel normal fault of late Pliocene or Pleistocene age. The structure must have been uplifted during the Pliocene, to form the topographic high which localized coralline reef growth. Uplift continued during and immediately after deposition of the Gasus Formation, as the reefal beds of the Gasus Formation are tilted outward from the center of the structure. Two

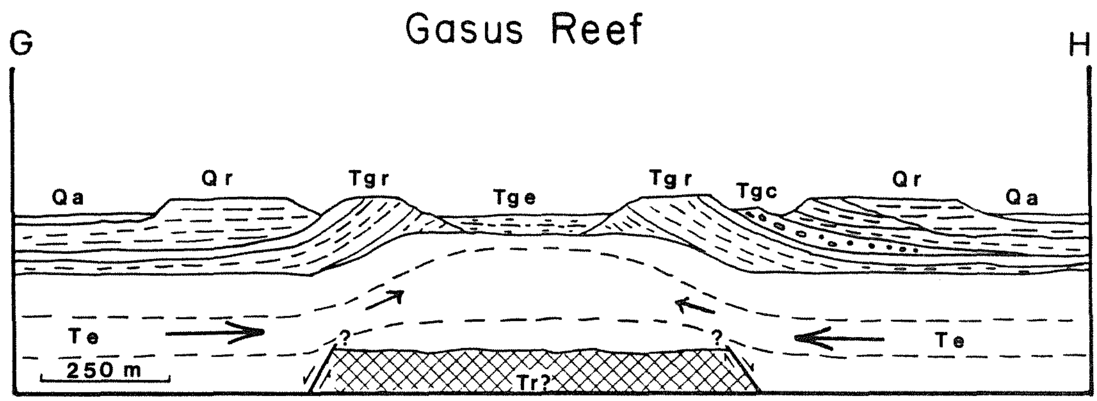


Figure 32. Cross section of the Gasus reef complex.

possibilities for the underlying nature of this structure present themselves:

1. the structure may be related to differential movement of a subsurface block controlled by N60E "transverse trend" faults, or
2. the structure may be caused by upward flow of the underlying Evaporite Formation, up dip from the Red Sea Basin and laterally away from terrigenous depocenters at the mouths of Wadis Ambagi and Quseir el Qudeim.

Much of the bedding in the Gasus Formation appears to have been tectonically steepened, especially in the vicinity of the large Evaporite Formation outcrops. Dips of 30° or more are not uncommon in the Gasus Formation, and if these dips are extrapolated into the subsurface, extremely large (> 500 m) stratigraphic thicknesses must be presumed. In these cases bedding attitudes may reflect oversteepening due to upward flow and outward expansion of the Evaporite Formation.

An unknown but probably significant amount of block faulting has occurred beneath the coastal plain, primarily parallel to the Red Sea. Evidence includes local lineaments and linear zones of bedding disruption, and minor faults and fault zones observed within the coastal plain sediments. This fault activity probably also contributed to the disruption of flat lying bedding, and the local steepening of bedding orientations.

The tilting episode that affected the Miocene and Pliocene coastal plain sediments must have occurred toward the end of the Pliocene, prior to the development of the overlying Quaternary wadi and reef terraces. These Quaternary units, while sharply uplifted above present sea level, show seaward tilts of no more than 1^{o} or 2^{o}, and thus could not have been involved in the Gasus Formation tilting event.

Quaternary Sediments. Two Pleistocene reef terraces are well developed along the Red Sea coast in this area. The contact between coralline reef rock and conglomerate in each terrace is considered to represent former mean sea level. R1, the lower terrace, indicates a former sea level approximately 4 m higher than present sea level, while R2, the upper reef terrace, indicates a former sea level approximately 10 m above the present level. The R2 terrace has been dated at 90 000 years bp, and occurs along the entire Egyptian shore of the Red Sea (Veeh and Giegengack, 1970).

Wadi terraces at 4 m, 7 m, 12 m, and 20 m above present wadi level are well developed in the study area. The terraces are apparently depositional, and represent dissected remnants of higher base levels of erosion. They were probably formed in response to the same sea level changes responsible for the development of the reef terraces. All of these terraces, while sharply uplifted above present sea level, show seaward tilts of no more than 1^{o} or 2^{o}, and little sign of other deformation. Similar wadi and reef terraces have been described by Veeh and Giegengack (1970) and El Akkad and Dardir (1966), indicating that this coastal terrace system is of regional extent. The undeformed nature of these terraces, and their apparent correlation for hundreds of kilometers along the coast, indicate that the Quaternary tectonic history of this area has been characterized by relatively uniform regional uplift, with very little deformation.

Erosion Surfaces

The pre-Cretaceous and mid-Tertiary erosion surfaces in the Quseir area act as stratigraphic markers, and can be used to date the deformational events affecting the region. The relationship between these two erosion surfaces can be clearly seen at Gebel Ambagi. The east side of Gebel Ambagi is a dissected dip slope of the pre-Cretaceous erosion surface, with conformable Nubia Formation remnants cropping out at the base. This dip slope is tilted 25° to the northeast. On top of Gebel Ambagi is a superimposed remnant of the mid-Tertiary erosion surface, which is sub-horizontal, and overlain by thin-bedded, sandy limestone and conglomerate of the middle Miocene Gebel el Rusas Formation.

A regional structural contour map has been constructed on the pre-Cretaceous erosion surface (fig. 33). This surface is equivalent to the pre-erosion Precambrian basement/Nubia sandstone contact. The most prominent features on this map are the northwest-trending structural lows formed by the Gebel el Anz-Gihania Valley and Gebel Duwi-Wadi Nakheil-Gebel Atshan areas. The map shows the style and extent of post-lower Eocene deformation in the region, and highlights the fact that the predominant deformational pattern in this region of the Red Sea coast has been one of down-faulting and seaward tilting of Precambrian basement blocks and their overlying sedimentary cover.

The history of deformation in the Quseir area, as deduced from the pattern of exposure of these two erosion surfaces, is as follows:

1. A long period of apparent structural stability prior to the middle Cretaceous resulted in the development of an extensive peneplain, the pre-

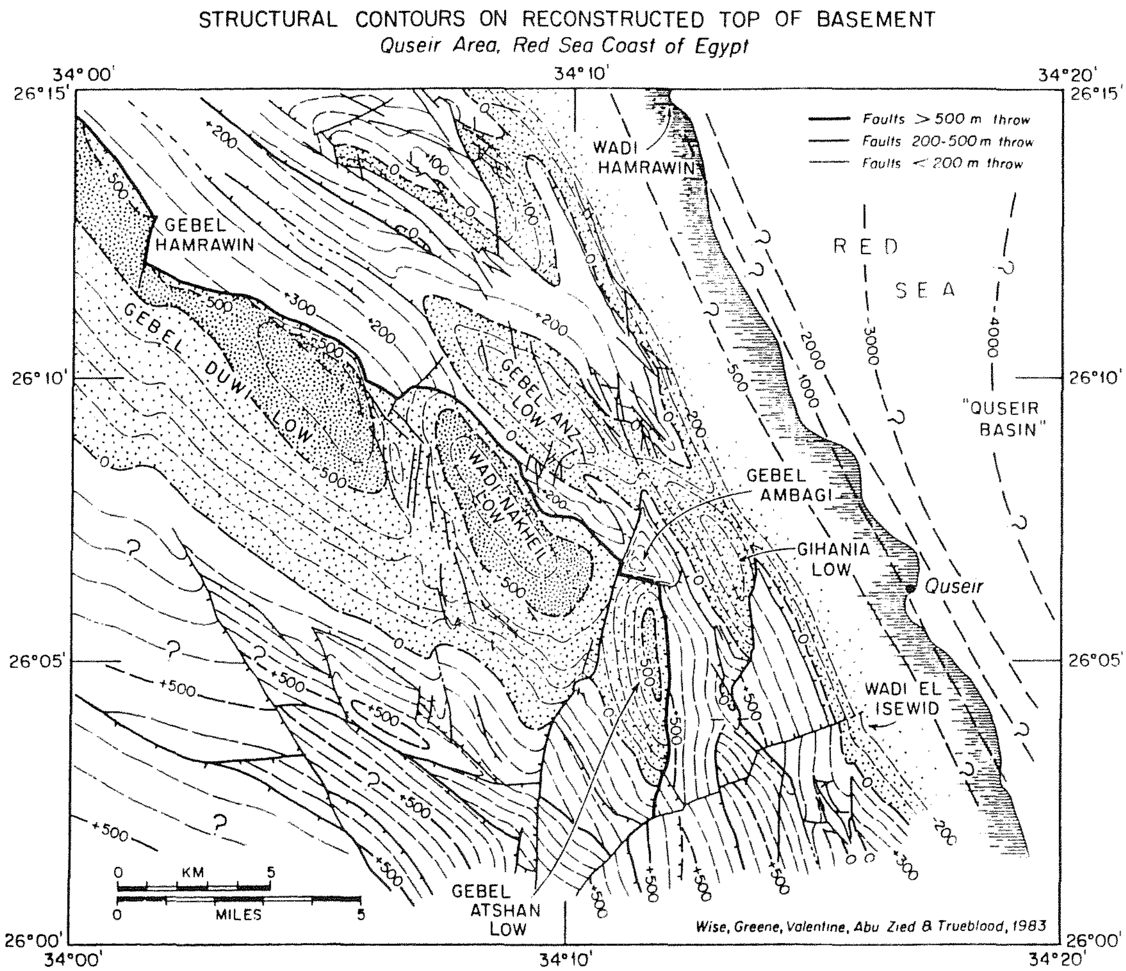


Figure 33. Structural contour map on reconstructed top of Precambrian basement, Quseir area, Red Sea coast, Egypt. (Combined work of D.U. Wise, D.C. Greene, M.J. Valentine, H. Abu Zied, and P.M. Trueblood).

Cretaceous erosion surface, on the Precambrian basement.

2. Block faulting and northeast tilting sometime during late Eocene to Oligocene time resulted in break up of the pre-Cretaceous erosion surface.
3. Differential erosion in Oligocene to early Miocene time stripped the platform sedimentary cover from topographic highs, and superimposed a second erosion surface, the mid-Tertiary pediplain, on the tilted fault blocks.
4. This mid-Tertiary erosion surface was subsequently uplifted, and dissected by the present wadi system.

Inland from the continental margin the Oligocene(?) episode of seaward tilting and block collapse seems less important, and it is probable that the pre-Cretaceous peneplain is the dominant control on peak elevations.

CHAPTER V

PHANEROZOIC REGIONAL TECTONICS

Introduction

The Phanerozoic tectonic history of the Quseir region has been dominated by the development of the Red Sea rift system. From the end of the Pan African orogeny in early Cambrian time to the early Tertiary, the region was a stable continental platform. Periodic epeirogenic movements occurred, including the late Mesozoic/early Cenozoic downwarping during which the platform sedimentary sequence was deposited. However, no major tectonic activity is apparent prior to the development of the Red Sea rift system in late Oligocene to early Miocene time. In the following sections the geology of the Red Sea rift system and adjacent areas will be summarized, and current models for the formation of the Red Sea will be discussed. In the succeeding chapter, the observed local tectonics of the Quseir area are related to the evolution of the Red Sea rift.

The Red Sea Rift System

The Red Sea rift system consists of the Red Sea, the Gulf of Suez, the Gulf of Aqaba-Dead Sea rift, and the

Gulf of Aden. The Red Sea and Gulf of Aden are small ocean basins with active oceanic spreading centers (Cochran, 1983); their junction with the East African rift system forms the Afar triple junction, a structurally complex area dominated by basic volcanism and continental rifting (Pilger and Rosler, 1976). The Gulf of Suez is a continental rift of small displacement (Garfunkel and Bartov, 1977), while the Gulf of Aqaba-Dead Sea rift is a left lateral transform fault system (Ben-Avraham et al., 1979).

The Red Sea is commonly considered the type example of an early stage of ocean basin formation (LePichon and Francheteau, 1978). However, despite many years of study, there is still considerable controversy over the details of how and when the Red Sea was formed (Cochran, 1983). Central to this controversy is the fundamental question of whether the majority of the basin is underlain by continental or oceanic crust; that is, whether the basin was formed primarily by down faulting and subsidence of continental crust, or by creation of new oceanic crust at a spreading center.

Morphology. The Red Sea occupies an elongate, escarpment-bounded depression, 2 000 km long by 250 to 450 km wide. The Red Sea morphology is characterized by shallow continental shelves, a broad main trough, and a narrow, steep-sided axial trough with very rough bottom topography. A 10 km to 50 km wide coastal plain, consisting of late Oligocene to Recent rift-related sediments and volcanics, is developed over much of the basin between the escarpments and the sea.

Stratigraphy. The earliest sediments associated with the Red Sea basin are thick (2 000 m to 3 000 m) Miocene clastics, which are found both onshore on the coastal plain (this study; Brown, 1970) and offshore in drill cores (Ahmed, 1972; Lowell and Genik, 1972). These are overlain by and locally interfinger with 3 000 m to 4 000 m of upper Miocene evaporites (Coleman, 1974), the top of which form a prominent seismic reflector known as reflector S. The reflector S horizon, which occurs at a sediment depth of 0 m to 500 m, is correlated with the begining of the Pliocene (Stoffers and Ross, 1974). Marine oozes, marginal clastics and carbonate reefs have been deposited continuously since the Pliocene.

The original Miocene marine invasion of the Red Sea came from the Mediterranean (Dubertret, 1970), and Reflector S in the Red Sea appears to correlate with Reflector M in the Mediterranean (Ross and Schlee, 1973; Stoffers and Ross, 1974). A second marine invasion, which terminated evaporite deposition, occurred in the Pliocene. However, this Pliocene marine invasion originated in the Indian Ocean, rather than the Mediterranean. The Mediterranean Sea was permanently separated from the Red Sea during early Pliocene time by uplift in the Suez region (Swartz and Arden, 1960).

Axial Trough. The axial trough of the Red Sea is best developed in the south, extending from just north of the Straits of Bab al Mandab to about $20^{\circ}\ 30'$ N latitude. Northward it becomes discontinuous, consisting of isolated deeps, commonly containing hot brine pools and hydrothermal sediments, separated by broad intertrough zones. The axial trough is characterized by steep-sided walls, and very irregular bottom topography. It is floored by Pliocene to Recent subalkaline tholeitic basalt, and is associated with a high positive gravity anomaly and large-amplitude magnetic anomalies identified as sea floor spreading anomalies (Drake and Girdler, 1964; Vine, 1966; Coleman, 1974). There is general agreement that the axial trough of the Red Sea is underlain by oceanic crust formed over the last 3 my to 5 my by sea floor spreading (Cochran, 1983).

Main Trough. The nature of the crust underlying the main trough and shelves is much less certain. The thick Miocene clastic and evaporite section, and the prominent seismic reflector (Reflector S) at the top of the evaporites effectively mask the geophysical signature of the underlying basement. Conventional seismic reflection techniques are unable to penetrate the basement, and the limited seismic refraction studies are inconclusive. These have been interpreted to indicate the existence of both oceanic crust (Tramontini and Davies, 1969; Davies and Tramontini, 1970; Healy et al., 1982), and continental crust (Drake and Girdler, 1964; Knott et al, 1966; Coleman, 1974). Magnetic anomalies away from the axial trough are diffuse and of low amplitude, and have proved difficult to correlate with the magnetic polarity time scale (Cochran, 1983).

These ambiguities have led to the development of two conflicting hypothesies regarding the evolution of the Red Sea. One hypothesis, generally emphasizing plate kinematic, seismic, and geomagnetic evidence, suggests that the Red Sea is floored entirely by oceanic crust (e.g. McKenzie et al., 1970; Girdler and Styles, 1974; Schmidt et al., 1982). The other hypothesis, emphasizing plate geometries, onshore geology and seismic reflection data, maintains that the Red Sea is primarily floored by extended continental crust, with new oceanic crust being restricted to the axial trough (e.g. Ross and Schlee, 1973; Coleman, 1974; LePichon and Francheteau, 1978; Cochran, 1983).

The distinction between these two conflicting theories is of fundamental importance for the interpretation of the evolution of mature continental margins. If the Red Sea is floored entirely by oceanic crust, then the 100 km to 150 km wide transition zone between continental and oceanic crust usually observed at a mature continental margin may develop in a later phase of the opening of an ocean, possibly by subsidence due to cooling and sediment loading, or by hot creep at the base of the crust. If the Red Sea is floored primarily by continental crust, then the transitional zone at a mature continental margin may develop in the early phases of rifting by tectonic and volcanic modification of the continental crust. Possibly only after the maximum extension has occurred in the continental crust does a spreading center develop and new oceanic crust appear (LePichon and Francheteau, 1978).

The oceanic crust hypothesis assumes sharp boundaries at or near the coastline between relatively undeformed continental and oceanic crust, and maintains that the entire Red Sea basin is floored by oceanic crust generated at a spreading center. This theory explains the excellent geographic fit of the coastlines in the Red Sea and the shelf edges in the Gulf of Aden (McKenzie et al., 1970; Greenwood and Anderson, 1977), and the agreement of movement directions calculated by shoreline fit with present day instantaneous spreading velocities (LePichon and Francheteau, 1978). Basement seismic velocities characteristic of oceanic crust have been found within the rift (Tramontini and Davies, 1969; Davies and Tramontini, 1970), and Girdler and Styles (1974, 1976) and Hall et al. (1977) have identified magnetic anomalies which they interpret to be sea floor spreading anomalies over the entire width of the southern Red Sea. Gravity studies (Gettings, 1977) and a seismic refraction profile (Healy et al., 1982) across the southeastern margin of the Red Sea in the vicinity of Jizan (aprox. 17^{o} N lat) and the Farasan Islands, have been interpreted to indicate the existence of oceanic crust beneath the Farasan Islands, and an oceanic/continental crustal boundary beneath the Saudi Arabian coastal plain (Schmidt, 1982).

However, with the oceanic crust hypothesis serious geometric dificulties arise at both ends of the Red Sea. If the Red Sea is entirely closed, the southwestern corner of the Arabian Penninsula overlaps the Afar triangle (LePichon and Francheteau, 1978), implying that the whole of the Afar triangle to the base of the Ethiopian escarpment is oceanic crust. This assumption ignores the Danakil horst, a 110 km wide area of Jurassic basement exposed in the northeastern Afar. In the northern Red Sea, the displacement on the Dead Sea transform is well constrained at approximately 105 km of left lateral motion (Quennel, 1959; Freund et al, 1970). The Gulf of Suez is underlain by partially extended continental crust, with total extension of approximately 20 km (Garfunkel and Bartov, 1977). Thus the total northeastward displacement of Arabia relative to Africa at the northern end of the Red Sea appears to be constrained to approximately 125 km, which is insufficient to completely close the Red Sea, as required if the entire sea floor is underlain by oceanic crust.

Frazier (1970) and Cochran (1983) have shown that the long, low amplitude magnetic anomalies characteristic of the southern Red Sea (Girdler and Styles, 1974; Hall et al., 1977) can be modeled as tilted basement fault blocks, rather than sea floor spreading anomalies. This interpretation is strengthened by the presence of linear zones of salt diapirs parallel to some of these magnetic anomalies, a characteristic feature of linear fault blocks in the Gulf of Suez (Garfunkel and Bartov, 1977) and the Gulf of Aqaba (Ben-Avraham et al., 1972). It has also been observed (Cochran, 1983) that one of the sea floor spreading anomalies described by Girdler and Styles (1974) can be traced onshore into an area of Precambrian basement. The high seismic velocities attributed by Davies and Tramontini (1970) to oceanic crust could also be caused by Precambrian greenstone belts, which are common within the continental basement in this region (Coleman, 1974).

The continental crust hypothesis maintains that the main trough and shelves of the Red Sea formed by the same processes of block faulting, subsidence, and rotation that characterize the rift margins. This theory is not contradicted by the plate geometries, as the pre-drift configuration does not require complete closure to the present shorelines of the Red Sea. However, the theory does require substantial extension and consequent thinning of the continental crust under the Red Sea. Extension of 70% to 130% is necessary to open the main trough and shelves to their present width (Cochran, 1983).

Several lines of evidence are used to support the contention that continental crust exists beyond the margins of the Red Sea. Two exploratory wells drilled approximately 20 km off the Saudi Arabian coast at 28 N latitude bottomed in granite, while a well drilled 100 km off the Ethiopian coast bottomed in metamorphics (Coleman, 1974). Seismic reflection and gravity studies indicate that the shelf floors of Sudan (Sestini, 1965) and Egypt (Tewfic and Ayyad, 1982) consist of steep sided platforms separated by large troughs, suggesting a horst and graben structure. This structural pattern appears to occur for at least 40 km off the Egyptian coast. Seismic refraction studies indicate widespread occurrence of seismic velocities characteristic of continental crust, as well as those characteristic of oceanic crust (Drake and Girdler, 1964). It has been suggested (Coleman, 1974) that high seismic velocities are observed in areas underlain by Precambrian greenstone belts, whereas lower values more characteristic of continental crust are observed in areas of felsic or granitic rocks.

<u>Summary</u>. It will be noticed that most of the evidence for the main trough of the Red Sea being oceanic crust comes from work in the southern Red Sea, while much of the evidence for a floor of continental crust comes from the northern Red Sea. This is probably not entirely fortuitous, and may represent fundamental differences in the structures of the two regions. While the axial trough

in the southern Red Sea is very well developed, with steep walls, rough bottom topography, high heat flow, and large linear magnetic anomalies, these characteristic features of an oceanic spreading center are not observed in the northern Red Sea. Instead, the region is characterized by an irregular, broken bottom topography; intensely fractured but with no evidence of a morphologically distinct axial trough. Magnetic anomalies are smooth, of low amplitude, sometimes circular in plan, and commonly associated with positive gravity anomalies; suggesting the possibility that they are caused by isolated intrusions rather than systematic sea floor spreading (Cochran, 1983). In the central Red Sea, the sea floor is characterized by isolated deeps showing all the characteristics of the axial trough, separated by broad, smooth intertrough areas more typical of the main trough.

This structural pattern suggests that sea floor spreading, or at least the most recent phase of spreading, has not yet begun in the northern Red Sea. Active sea floor spreading is taking place only in the southern Red Sea, south of 21° N lat, while the northern Red Sea appears to be undergoing a process of diffuse extension, with a transitional zone in the central Red Sea, between 21° N lat and 25° N lat, in which isolated actively spreading segments are separated by transform faults and zones of diffuse extension (Cochran, 1983). The rotational nature of the motion of Arabia away from Africa suggests a possible reason for this pattern, in that significantly more displacement has occurred in the southern Red Sea than the northern Red Sea. In addition, higher than normal heat flow and tectonic activity would be expected in the southern Red Sea as a result of its proximity to the Red Sea-Gulf of Aden-East African Rift triple junction.

While no definite conclusions can be drawn, the present author favors the hypothesis that the main trough and shelves of the Red Sea are floored by extended and intruded continental crust (Coleman, 1974; Cochran, 1983). This hypothesis allows for the progressive south to north development of recent sea floor spreading in the axial trough as a natural consequence of the rotational movement of Arabia away from Africa. It seems to explain best the observed onshore and offshore geology, especially the occurrence of granitic and metamorphic rocks in offshore wells, the apparent continuation of onshore fault block deformation patterns into the offshore region, the lack of conclusively identifiable magnetic anomalies, and the plate geometric problems associated with fully closing the Red Sea.

Geology of Saudi Arabia

Introduction. Until the initiation of substantial rifting and subsidence in late Oligocene to early Miocene time, the Quseir area was adjacent or subjacent to northwestern Saudi Arabia and southeastern Sinai (Greenwood and Anderson, 1977). Consequently, these areas should have an older sedimentary and tectonic history similar to that of eastern Egypt.

Stratigraphy. Possible equivalents to the Egyptian Cretaceous to Eocene platform sediments sequence are very sparse in Saudi Arabia, consisting of rare outcrops of limestone, fine sandstone and mudstone of the Usfan, Um Himar and Shumaysi Formations of Paleocene to middle Eocene age (Schmidt et al, 1982). A thick (1 500 m to 2 000 m) Cretaceous to Eocene sedimentary section possibly analogous to the Egyptian platform sediments is preserved in the Azlam graben, a major north-northwest-trending fault-bounded trough occuring north of Al Wajh (Davies, 1981). This structure appears to be analogous to the Gebel Duwi/Wadi Nakheil fault block valley in the Quseir region of Egypt, and may in fact be a continuation of the same structure (M. Valentine, in preparation). No

Cretaceous to Eocene platform-type sediments are exposed in southern Saudi Arabia, and it is inferred that the epicontinental extension of the Tethys Sea in which these sediments were deposited reached no farther south than the latitude of Jeddah.

Of the middle Miocene to Recent sediments of the Red Sea coastal plain, the Gebel el Rusas Formation of Egypt is clearly equivalent to the Raghama Formation of northwestern Saudi Arabia and the Bathan Formation of southwestern Saudi Arabia (table 1). However, the late Miocene and Pliocene section, equivalent to the Evaporite and Gasus Formations of Egypt, is poorly developed in northwestern Saudi Arabia, and for this reason many authors include it in the upper Raghama Formation (Brown et al., 1963; Alabouvette and Pellaton, 1978).

Two erosion surfaces are commonly recognized in western Saudi Arabia, an early (probably pre-Cretaceous) peneplain surface, now primarily preserved as a high uniform elevation of summits in the Precambrian basement, (Davies, 1980; Alabouvette and Pellaton, 1978), and a mid-Tertiary pediplain (Brown, 1970; Alabouvette and Pellaton, 1978; Schmidt et al., 1982). Schmidt et al. (1982) describe (after Overstreet et al., 1977) a 20 m to 30 m thick saprolite horizon developed on the Precambrian crystalline basement in southwestern Saudi Arabia, which

Table 1. Correlation of Cretaceous and Tertiary Sediments in the Red Sea Region

Egypt	SE Sinai/Gulf of Aqaba	NW Saudi Arabia	SW Saudi Arabia
Gasus Fm.	no equivalents	locally included in	Evaporite Series
Evaporite Fm.			
Gebel el Rusas Fm.		Raghama Fm.	Bathan Fm.
Nakheil Fm.	Raham Conglom.	local equivalents only e.g. Usfan Fm. Shumaysi Fm. Um Himar Fm. and the Azlam Graben fill	no equivalents
Thebes Fm.	Mor Fm.		
Esna Shale	Taqiya Fm.		
Tarawan Chalk	Ghareb Fm.		
Dakhla Fm.			
Duwi Fm.	Sayyarim Fm.		
Quseir Fm.	Zihor Fm. Gerofit Fm. Ora Shales(?) Hazera Fm.		
Nubia Fm.	Nubian Sandstone (locally)		

References:
Alabouvette and Pellaton, 1978.
Hildebrand et al., 1974.
Garfunkel et al., 1974.
Issawi, 1972; ...et al., 1971
Said, 1962.
Brown, 1970.
Schmidt et al.,1982
Davies, 1980, 1981.

probably correlates with the early (pre-Cretaceous) peneplain of northwestern Saudi Arabia and Egypt. Brown (1970) notes the development of widespread playa lakes on a "terminal mid-Tertiary pediplain", while Schmidt et al., (1982) correlate this period with a "broad valley erosional stage" associated with a hiatus in rift activity during the late Miocene.

Structure. The mid-Tertiary conjugate fault system characteristic of the Quseir region of Egypt appears to have equivalents in western Saudi Arabia. Davies (1981) in particular notes the existence of a system of conjugate faults of early Tertiary age in the Wadi Thalbah Quadrangle (26^{o} 30′ to 27^{o} 00′ N lat) of northwestern Saudi Arabia. This system consists of right-lateral strike-slip faults with orientations of N10W to N10E, and left-lateral strike-slip faults with an average orientation of N60E. Contemporaneous with this fault system was the development of a broad coastal arch and synclinal basin with west-northwest axes oblique to the Red Sea coast. Davies (1981) ascribes these features to an early phase of compression perpendicular to the present Red Sea trend. This compressive phase was followed by regional extension, during which a set of normal faults developed with an average orientation of N45W, dipping 60^{o}

to the southwest or northeast. On the coastal plain of the Red Sea in southwestern Saudi Arabia, Schmidt et al. (1982) have described a similar orthogonal fault system, with fault sets trending north-northwest and east-northeast, and bedding of sediments in the late Oligocene to early Miocene Jizan Group dipping an average of 30^{o} southwest, toward the Red Sea.

Geology of Sinai

In the Sinai, block faulted erosional remnants of platform sediments and syntectonic conglomerates very similar to the Egyptian platform sediments are present along the Gulf of Aqaba coast (table 1) (Garfunkel et al., 1974; Hildebrand et al., 1974), indicating the close geologic affinity of these two areas. As in Saudi Arabia and Egypt, mid-Tertiary faulting, seaward tilting, and block subsidence were followed by a period of quiessence (BenAvraham et al., 1979). During this period erosion truncated the structural relief, forming a flat terminal erosion surface which was subsequently uplifted and deformed by the present phase of rifting.

The Gulf of Suez, on the west side of the Sinai penninsula, is dominated by normal faults and tilted blocks. It is floored by continental crust, is quite shallow. The Gulf of Aqaba, in contrast, is dominated by en echelon left-lateral strike-slip faults forming deep, fault bounded basins (rhombochasms) with structural relief in excess of 5 km (Ben-Avraham et al., 1979).

CHAPTER VI

EVOLUTION OF THE RED SEA RIFT

Relation of Observed Local Tectonics to the Evolution of the Red Sea Rift

Introduction. The Cenozoic structural geology of the Quseir area reflects the evolution of the Red Sea rift, and provides useful insights into rift development. In this chapter aspects of the geology of the Quseir area with implications for the development of the Red Sea rift are discussed.

Origin of main trough. The hypothesis that the entire Red Sea, shoreline to shoreline, is new oceanic crust, has been suggested by some authors (McKenzie, 1970; Girdler and Styles, 1974; Schmidt et al., 1982). This assumes that the Quseir region of northern Egypt (26° 05´ N lat) and the Duba region of northwest Saudi Arabia (27° 30´ N lat) were directly adjacent prior to the begining of the Miocene, and implies that these regions had similar sedimentary histories. However, equivalents to the Egyptian platform sediments are almost totally lacking in Saudi Arabia, suggesting that (a) the Arabian side of the Red Sea has undergone a different tectonic history, including more vigorous uplift with less concurrent block faulting than the Egyptian side of the Red Sea; and/or (b) that the Red Sea is in fact floored by continental crust, and the abrupt sediment variations observed across the present Red Sea actually took place over a considerable distance.

Red bed sediments. Large volumes of sediment would have been produced during erosion of the platform sediments from the Egyptian side of the Red Sea. Sediments correlative with this event (e.g., the Nakheil Formation) are volumetrically small in the Quseir area, suggesting that a depositional sink for the units must exist in the Red Sea basin.

The earliest well developed sedimentary unit associated with the Red Sea basin is the Gebel el Rusas Formation, but the basal member of this formation consists of Precambrian basement-derived cobble conglomerate, commonly deposited on an eroded Precambrian surface. This formation was deposited after the stripping of the Egyptian platform sediments from the Precambrian basement, and could not be the depositional sink of the platform sediments. However, a coarse red-bed sedimentary unit underlying the Gebel el Rusas Formation has been reported from rare exposures on the coastal plain in southern Egypt and the Sudan (Johnson, 1975; Carella and Scarpa, 1962), and in drill cores from the northern Red Sea near the Gulf of Suez (Tewfik and Ayyad, 1982). If this unit is widespread in the subsurface under the main trough of the Red Sea, it may contain the bulk of sediments derived from erosion of the Egyptian platform sediments. It would indicate deposition in a continental rift environment, prior to marine innundation.

Two phase extension. Regardless of the origin of the crystalline basement underlying the main trough of the Red Sea, the very different characters of the main and axial troughs make it clear that the geologic processes and/or timing of events which produced the main trough were different from those which produced the axial trough. It has been suggested that the Red Sea rift evolved in two distinct phases, with a period of quiescence between (Girdler and Styles, 1974). Recent studies, particularly from the Gulf of Aqaba-Dead Sea rift region, have lent support to this idea (Zak and Freund, 1981); however, the hypothesis is still debated (Cochran, 1983).

In the Quseir region, evidence for a two phase history for the Red Sea rift comes from the pattern of regional uplift and erosion. As noted earlier, two distinct periods of Tertiary uplift and erosion are observed in the Quseir region, separated by a mid-Tertiary pediplain. The first phase of erosion occurred during the interval between the late Eocene and the middle Miocene; probably predominantly during Oligocene to early Miocene time. Rift marginal extension, block rotation and subsidence continued through the middle Miocene, as indicated by the progressive tilting of basal units in the Gebel el Rusas Formation, but there is no evidence of major tectonic activity during the late Miocene. This early period of tectonic activity corresponds to the first phase of development of the Red Sea rift, the formation of the main trough.

During the late Miocene, tectonic stability is indicated by the formation of a terminal erosion surface, the mid-Tertiary pediplain, which developed across the Precambrian basement along the rift margin. Schmidt (1982) recognizes an equivalent period of tectonic stability in southern Saudi Arabia, which he refers to as the "broad valley erosional stage". During this period restricted circulation in the Red Sea and a lack of detrital sedimentation resulted in the deposition of a very thick evaporite sequence, exposed as the Evaporite Formation in the Quseir area. It seems probable that this period of tectonic stability on the rift margins and restricted circulation within the rift corresponds to a cessation of extension within the rift, as postulated for this same time on the basis of independent evidence in the Gulf of Aqaba-Dead Sea rift region (Zak and Freund, 1981).

A second phase of rift marginal uplift in the Quseir region began in the early Pliocene, and continues to the present day. The renewed deposition of terrigenous sediments in a normal marine environment is indicated by the Pliocene Gasus Formation, while the elevation and subsequent dissection of the mid-Tertiary pediplain, as well as numerous Pleistocene and Recent wadi and reef terraces, indicate the extent of post-Miocene uplift. This phase of uplift corresponds to the second phase of extension of the Red Sea, which began with the development of an oceanic spreading center in the southern Red Sea in early Pliocene time.

Rift development. The predominant Cenozoic deformational pattern in the Quseir region is one of fault block rotation toward the rift axis (fig. 33). Large fault blocks elongate in a rift-parallel direction exhibit a pronounced seaward tilt of 20° to 30° (e.g. Gebel Atshan, Gihania). This pattern of seaward tilted fault blocks is also observed along the southern Arabian coastline, where Oligocene volcano-sedimentary rocks of the Jizan Group are intricately block faulted and tilted an average of 30° toward the Red Sea (Schmidt et al., 1982). The widespread dominance of this structural pattern suggests that it may be a fundamental aspect of rift evolution.

The Red Sea rift appears to have developed by a process of progressive subsidence and block rotation toward the rift axis. This suggests that the loss of lateral support, due to extension and tectonic thinning of adjacent continental crust, may be a key element in the evolution of the rift margin. This is contrary to many theories of rift evolution that emphasize initial doming and uplift of the continental crust (Falvey, 1974; Gass, 1976). Initial doming, followed by rifting at the dome axis is usually considered to produce marginal blocks tilted away from the rift axis; a deformational pattern not generally observed in the Red Sea region.

Transverse faulting. An important structural feature in the Quseir region is the el Isewid lineament, which extends in a southwesterly direction for greater than 50 km (fig. 1). This lineament has a trend of approximately N60E, parallel to a Precambrian fracture cleavage set, and to the left lateral fault set of the Oligocene(?) compressive phase. Garson and Krs (1976) have used geophysical, geological, and remote sensing data from the northern Red Sea region to delineate a set of major transverse block faults of this orientation, which they consider to be of Precambrian age. They suggest that these large transverse fractures may have acted as zones of crustal weakness in the Precambrian basement, and localized transform fault offsets in the developing Red Sea rift. The Brothers, a small gabbroic island (Nesteroff, 1955) probably representing a fault sliver of the underlying crystalline basement, is located near the center of the Red Sea at 26° N lat, on the extension of the el Isewid lineament. Adjacent to The Brothers is Oceanographer´s Deep, a hot brine pool similar to those associated with known transform faults in the central Red Sea. It seems probable that an incipient transform fault is developing in this region, localized by the structural weakness of the el Isewid lineament.

<u>Recent uplift</u>. Characteristic features of the Red Sea coastal plain in the Quseir area are the Pleistocene to Recent wadi sediment and reef terraces. Multiple terraces are not immediately evident along the Arabian coast, but a 3 meter littoral reef surface dated at >40 000 years (Brown, 1970) is well developed along much of the northern Arabian shoreline. The underformed nature of these terraces and their regional distribution indicate that the Quaternary history of the northern Red Sea region has been characterized by relatively uniform regional uplift, with little local deformation. This regional uplift may be due

to increased heat flow in the region as active oceanic spreading progresses northward from the southern and central Red Sea.

C H A P T E R V I I

GEOLOGIC HISTORY OF THE QUSEIR AREA

Precambrian Geologic History

The Precambrian evolution of the Ambagi area began with the deposition of a thick sequence of interbedded volcanic and volcanogenic sedimentary rocks (table 2).

The depositional environment of this group of rock units was characterized by varied terrain, rapid deposition, both subaerial and subaqueous depositional sites, high topographic relief, and numerous local sources of volcanic and sedimentary material. These characteristics are typical of an oceanic island-arc complex.

The deposition of these volcano-sedimentary units was followed by an extended period of orogeny, during which the entire region was deformed and metamorphosed to lower greenschist facies. The orogeny included a phase of major northeast regional compression which resulted in:

1. the folding episode that produced the el Isewid synform,
2. the development of a regional foliation, and
3. northwest regional extension, including the emplacement of a set of northeast trending quartz veins perpendicular to the extension direction.

Table 2. Precambrian History of the Quseir Area

Lithologic Units	Orogenic Events	Tectonic Setting
Metavolcanic/Metasedimentary Group		
1. deposition of volcanic and volcanogenic sedimentary units (vm, vp, sv, vs, sf, vf, sc, vi, vw, sp, ss)	1. minor syndepositional faulting and metasomatism.	Oceanic Island Arc
	Period of Main Orogeny	
Subvolcanic/Plutonic Group 2. intrusion of mafic dikes(?) 3. intrusion of Older Granite (og) 4. intrusion of Post-Hammamat Felsite (ph)	2. major NE directed compression results in: a) regional folding to produce the el Isewid synform b) development of regional foliation c) NW extension and emplacement of quartz veins perpendicular to sigma 3	Arc/ Continent Collision
5. intrusion of Younger Granites (yg) a) Gebel Ambagi granodiorite b) southwest granite c) southeast alkali granite	3. pervasive lower greenschist facies regional metamorphism	Craton-ization
6. intrusion of felsic dikes	4. development of cross-cutting fracture cleavage sets 5. continued faulting and minor folding deforms foliation and fracture cleavage	

Major faulting episodes probably also occurred during this period. The orogeny may have resulted from some form of collision between the early island arc complex and the African craton.

During and immediatly following the main orogeny, the members of the subvolcanic/plutonic group were intruded into the deformed volcano-sedimentary pile. Tonalite of the Older Granites series was probably emplaced during the main orogeny, whereas rhyolite porphyry of the Post-Hammamat Felsites (ph) and granodiorite to alkali granite of the Younger Granite series were late to post-tectonic intrusions. This period of increasingly fractionated granitic intrusion may represent the final stages of cratonization of the region following arc-continent collision.

Phanerozoic Geologic History

Erosion of Precambrian. The Quseir area was tectonically stable during most of the early Phanerozoic, as indicated by a regional peneplain which is developed on the Precambrian basement (table 3). The peneplain is overlain by a saprolitic horizon, forming the flat, low-relief surface upon which the Cretaceous to Eocene platform sediments were deposited. Some Paleozoic or early

Table 3. Phanerozoic History of the Quseir Area

Tectonic Phase	Time Period	Units Deposited	Tectonic Events
Erosion of Precambrian	Cambrian to middle Cretaceous	1. kaolinized saprolitic horizon 2. possibly some Paleozoic sediments, subsequently eroded	1. epeirogenic uplift, erosion, and peneplaination of the Precambrian basement
Platform Sediment Deposition	middle Cretaceous to middle Eocene	3. deposition of the platform sediments sequence: a) Nubia Fm. b) Quseir Fm. c) Duwi Fm. d) Dakhla Fm. e) Tarawan Chalk f) Esna Shale g) Thebes Fm.	2. epeirogenic downwarping, and a progressive north to south marine transgression from the Tethys Sea 3. epeirogenic uplift and/or lower sea level results in marine regression and end of deposition in middle Eocene.

Table 3. Phanerozoic History of the Quseir Area (page 2)

Tectonic Phase	Time Period	Units Deposited	Tectonic Events
North-Northeast Compression	middle Eocene to late Oligocene		4. north-northeast regional compression results in development of a conjugate system of N to NW trending right lateral faults, and NE trending left lateral faults
			5. broad folds (e.g. Gebel Anz) in the platform sediments may also have formed during this period
Continental Margin Extension	early Miocene		6. development of a NE extensional stress regime
		4. deposition of Nakheil Fm. in fault-bounded depressions	7. reactivation of strike-slip faults as west dipping normal faults
			8. emplacement of down faulted platform sediment blocks (e.g. Gebel Atshan, Gihania) in asymetric grabens in the Precambrian basement
		5. development of a terminal erosion surface, the mid-Tertiary pediplain	9. uplift in coastal region combined with differential subsidence results in erosion of platform sediments cover from topographic highs

Table 3. Phanerozoic History of the Quseir Area (page 3)

Tectonic Phase	Time Period	Units Deposited	Tectonic Events
Formation of Proto Red Sea	middle Miocene	6. deposition of Gebel el Rusas Fm. in the developing Red Sea basin	10. continued regional extension, down faulting, and possibly sea floor spreading results in development of Red Sea marine basin
Quiescence	late Miocene	7. deposition of Evaporite Fm. in Red Sea basin	11. hiatus of tectonic activity
Sea Floor Spreading	Pliocene to Present	8. deposition of Gasus Fm. 9. deposition of wadi sediment and reef terraces	12. beginning (or resumption?) of sea floor spreading in Red Sea 14. minor block faulting and flow of underlying gypsum results in seaward tilting of the coastal plain sediments 13. second phase of coastal up-lift begins, and continues to present

Mesozoic units may have been present, but if so these have been subsequently eroded away, and the superposition of middle Cretaceous Nubia Formation on peneplained Precambrian basement indicates relative tectonic stability for this entire period.

<u>Platform Sediment Deposition</u>. Epeirogenic downwarping in the middle Cretaceous resulted in a north to south transgression of the Tethys Sea and the deposition of a widespread and uniform sequence of platform sediments across the region. Fluvial and fluvio/deltaic sands of the middle Cretaceous Nubia Formation are overlain by littoral and shallow marine shelf sediments, culminating in the Thebes limestone of lower Eocene age. The regional extent of these units, and their lithologic and stratigraphic similarities, indicates that no major tectonic activity occurred during the period of their deposition.

<u>North-Northeast Compression</u>. During the period from middle Eocene to late Oligocene, a north-northeast compressional stress regime developed, resulting in the formation of a conjugate system of north- to northwest-trending right-lateral strike-slip faults, and northeast-trending left-lateral strike-slip faults. Broad folds in

the platform sediments (e.g., Gebel Anz) may also have formed during this period. Northeast-trending faults of this system appear to have been affected by earlier Precambrian trends averaging N60E, and together these structural elements may have played a role in the subsequent localization of transform faults in the Red Sea rift. This fault system cuts the Thebes Formation and all older units, but does not affect the Miocene and later sediments related to the Red Sea, thus bracketing the age of the stress system as post-lower Eocene and pre-Miocene.

Continental Margin Extension. In the early Miocene, a regional northeast extensional stress regime developed. This resulted in the reactivation of strike-slip faults as west-dipping normal faults, and the emplacement of down-faulted platform sediment blocks (e.g., Gihania and Gebel Atshan) in asymmetric grabens in the Precambrian basement. Characteristic of this period was extensive block tilting toward the evolving rift valley, possibly as a result of a loss of lateral support as the crust in the vicinity of the rift was thinned and extended. Contemporaneous uplift of the rift margins, possibly due to increased heat flow in the vicinity of the active rift, resulted in rapid erosion of the platform sediments from topographic highs in the Precambrian basement. Sediments derived from this period of rapid erosion were the Nakheil Formation, deposited in local downwarps and fault-bounded depressions, and voluminous sediments probably deposited as coarse red beds in the evolving rift valley. Erosion of the rift marginal fault blocks culminated in the development of a flat terminal erosion surface, the mid-Tertiary pediplain.

Formation of the proto Red Sea. During the middle Miocene, continued regional extension, normal faulting and/or sea-floor spreading resulted in subsidence to the east and the formation of the Red Sea marine basin. Sea-floor spreading may have begun during this first phase of extension, or the continuing regional extension may have been accommodated by listric normal faulting, block subsidence, and thinning of the continental crust. The first unit deposited on the margin of the developing basin was the middle Miocene Gebel el Rusas Formation. The basal member of this formation, a coarse Precambrian derived-conglomerate, is deposited directly on stripped Precambrian basement and highly eroded or down-faulted platform sediment blocks.

Quiescence. A hiatus of tectonic activity during the late Miocene indicates a relaxation of the northeast extensional stress regime. During this period the Red Sea became hypersaline, and a thick sequence of evaporites, the Evaporite Formation, was deposited.

Sea floor spreading. A second phase of extension at the beginning of the Pliocene resulted in the initiation (or resumption?) of sea floor spreading in the Red Sea basin. This coincided with a second phase of coastal uplift and/or basin subsidence, the connection of the Red Sea basin to the Indian Ocean, and a return to normal marine conditions of sedimentation with the deposition of the Gasus Formation. Minor block faulting and flow of the underlying Evaporite Formation in the coastal plain resulted in northeast tilting and the development of northeast transverse highs within the coastal plain sediments. Pleistocene to Recent wadi and reef terraces have developed as a result of continued uplift of the coastal plain.

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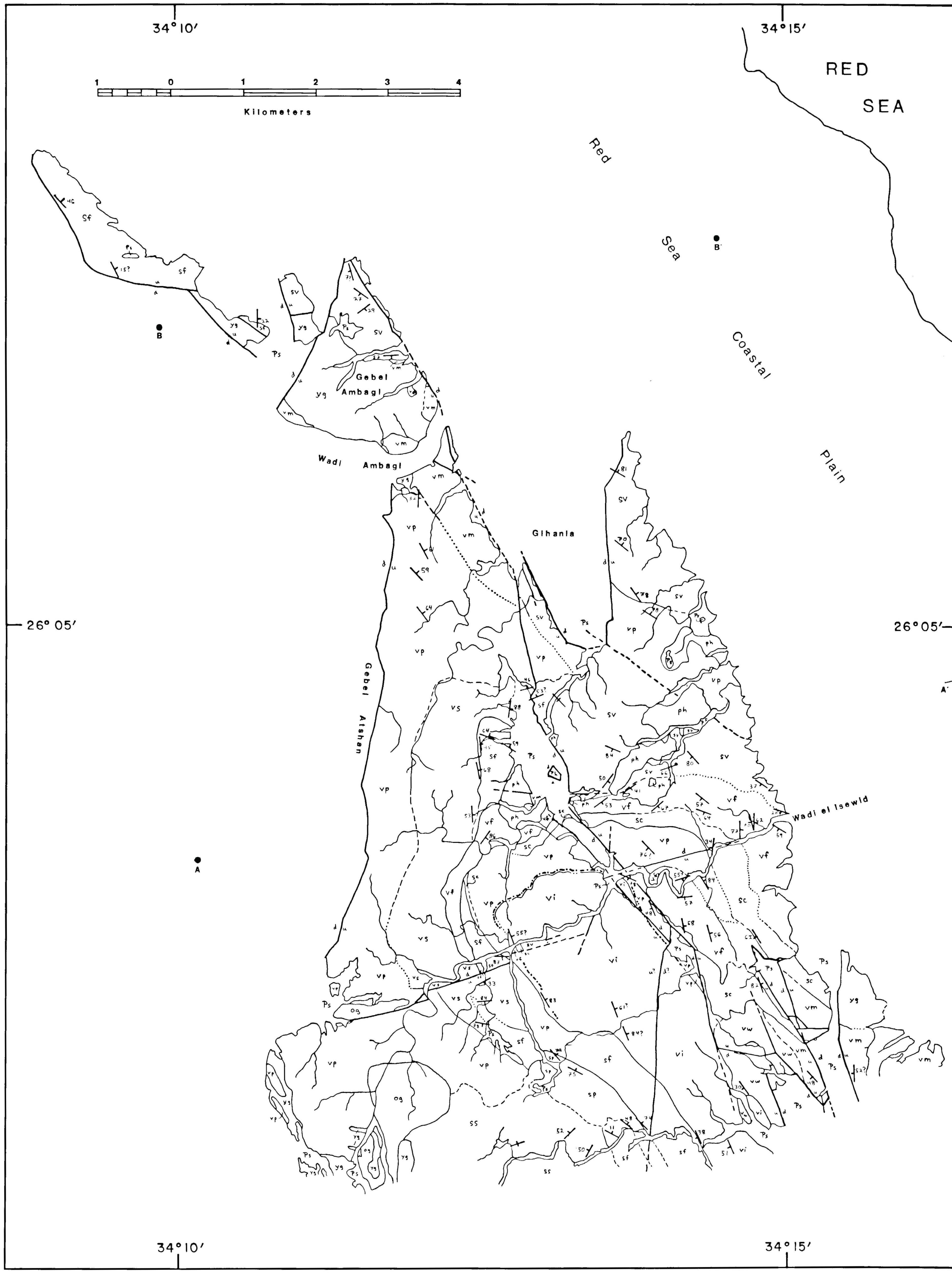
PLATE I

PRECAMBRIAN GEOLOGIC MAP OF THE QUSEIR AREA, RED SEA COAST, EGYPT



EXPLANATION

Scale = 1:40 000

PRECAMBRIAN

Ph	Phanerozoic Sediments
	Subvolcanic/Plutonic Group
yg	Younger Granite
ph	Post-Hammamat Felsite
og	Older Granite
	Metavolcanic/Metasedimentary Group
ss	schistose phyllite unit
sp	grey phyllite unit
vw	white quartz porphyry unit
vi	intermediate volcanic unit
sc	conglomerate unit
vf	mafic volcanic flows unit
sf	fine sediments unit
vs	silicic volcanic unit
sv	mixed sediments and volcanics unit
vp	porphyritic volcanic unit, with locally mapped marker horizon
vm	mafic volcanic unit

contact

fault

contact, location approximate

fault, location approximate

contact, location inferred

fault, location inferred

strike and dip of bedding

David C. Greene 1984

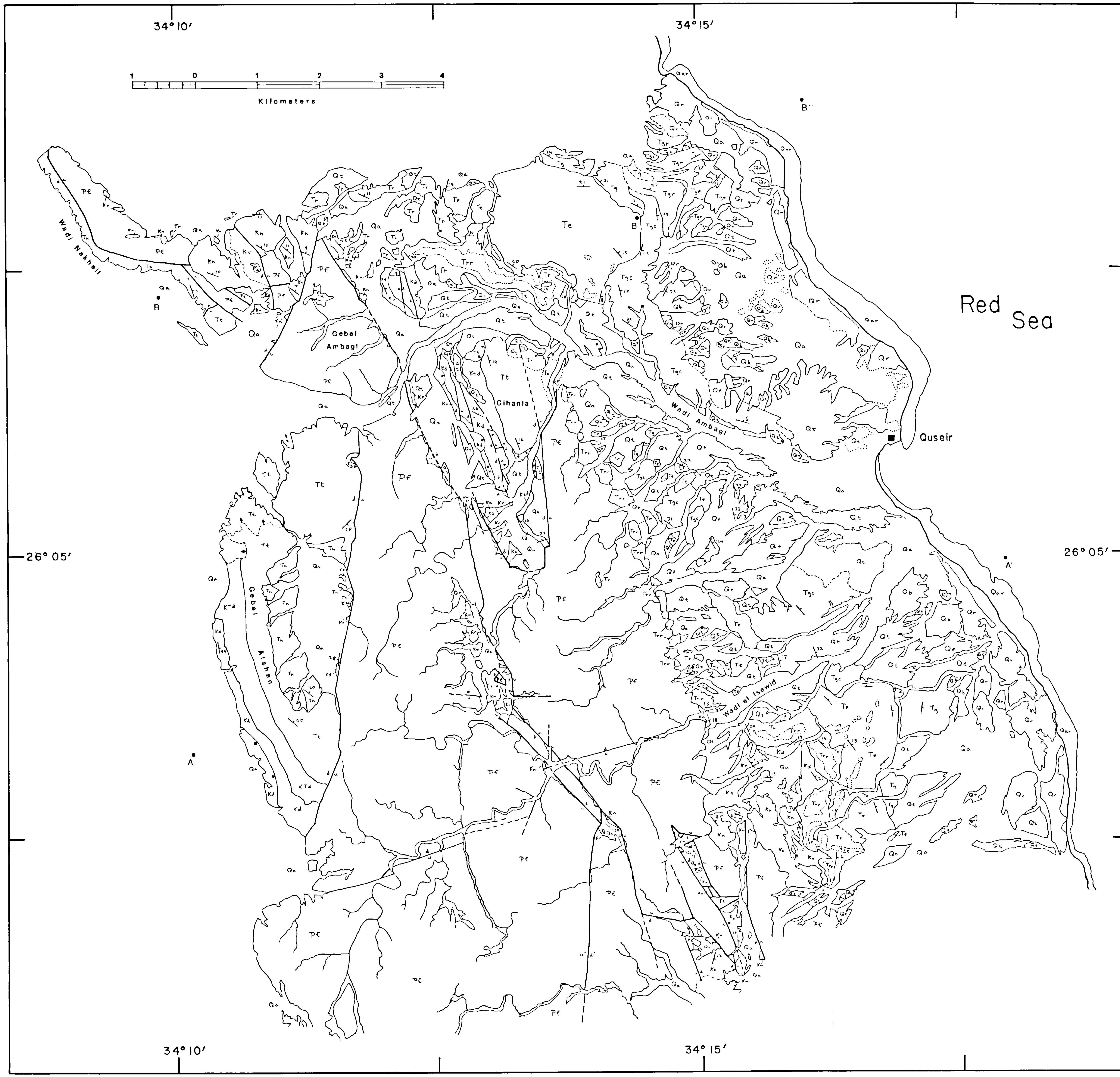


PLATE 2

PHANEROZOIC GEOLOGIC MAP OF THE QUSEIR AREA, RED SEA COAST, EGYPT

EXPLANATION

Scale = 1:40 000

QUATERNARY	RECENT	Qa	ACTIVE ALLUVIUM
		Qar	ACTIVE REEF
		Qt	WADI TERRACES
	PLEISTOCENE	Qr	REEF TERRACES
		Qe	BACK REEF DEPOSITS : evaporitic
		Qb	BACK REEF DEPOSITS : terrigenous
TERTIARY	PLIOCENE	Tge	GASUS FORMATION : Gypsiferous Member
		Tgr	GASUS FORMATION : Reef Member
		Tgc	GASUS FORMATION : Conglomerate Member
		Tg	GASUS FORMATION : Claystone Member
	MIOCENE	Te	EVAPORITE FORMATION : with locally mapped reef facies
		Trr	GEBEL EL RUSAS FORMATION : Reefal Group
		Tr	GEBEL EL RUSAS FORMATION : Terrigenous Group
	OLIGOCENE?	Tn	NAKHEIL FORMATION
	EOCENE	Tt	THEBES FORMATION
LATE CRETACEOUS		KTd	ESNA SHALE, TARAWAN CHALK, DAKHLA FORMATION – undifferentiated
		Kd	DUWI FORMATION
		Kv	QUSEIR FORMATION
		Kn	NUBIA FORMATION
PRECAMBRIAN		P€	PRECAMBRIAN BASEMENT : undifferentiated

contact

fault

contact, location approximate

fault, location approximate

contact, location inferred

strike and dip of bedding

intraformational contact, locally mapped

slumped area

Gebel Atshan mapped by M. Valentine

David C. Greene 1984

PLATE 3

CROSS SECTIONS OF THE QUSEIR AREA, RED SEA COAST, EGYPT

SCALE 1:40 000