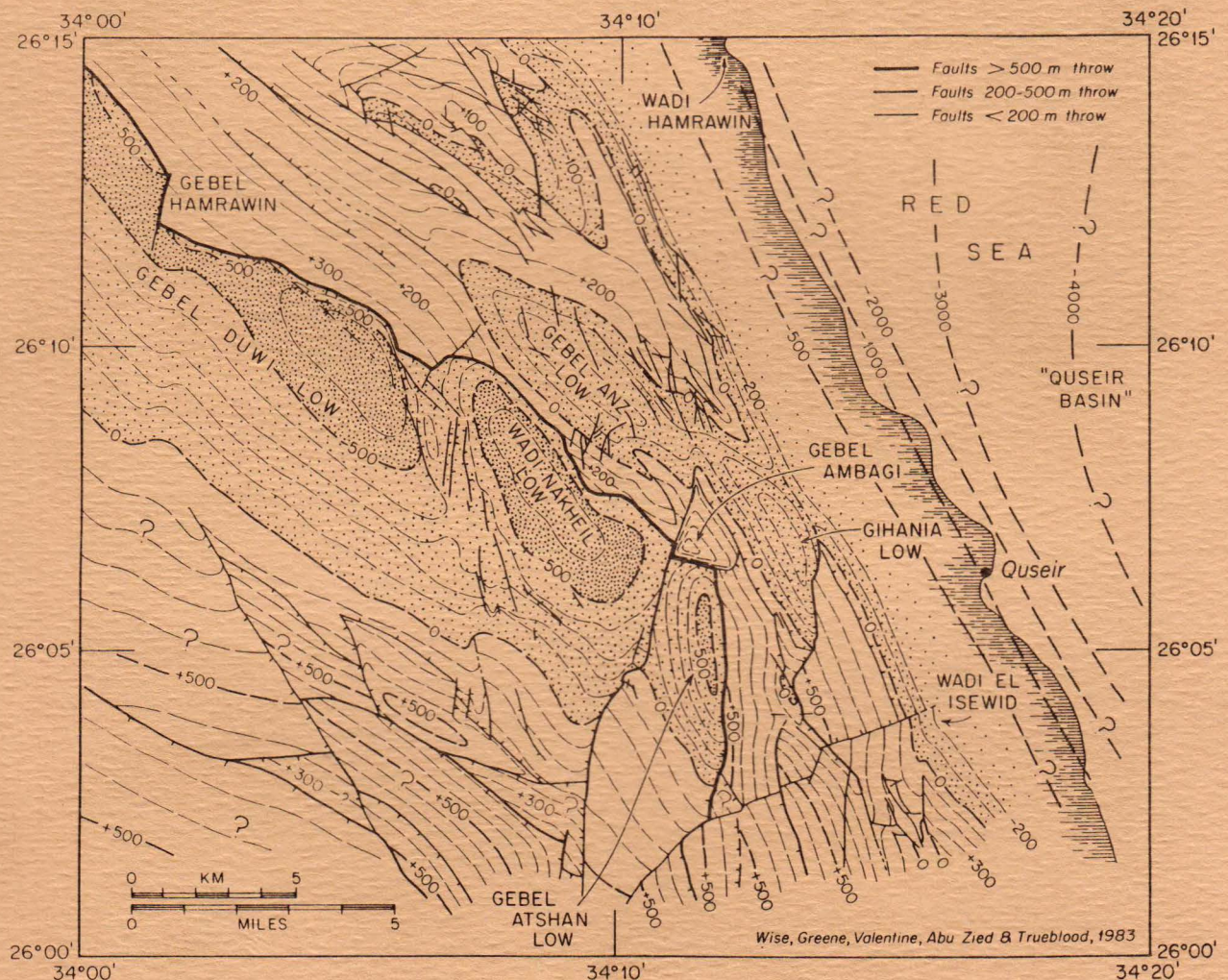


# STRUCTURE AND TECTONICS OF THE SOUTHERN GEBEL DUWI AREA, EASTERN DESERT OF EGYPT

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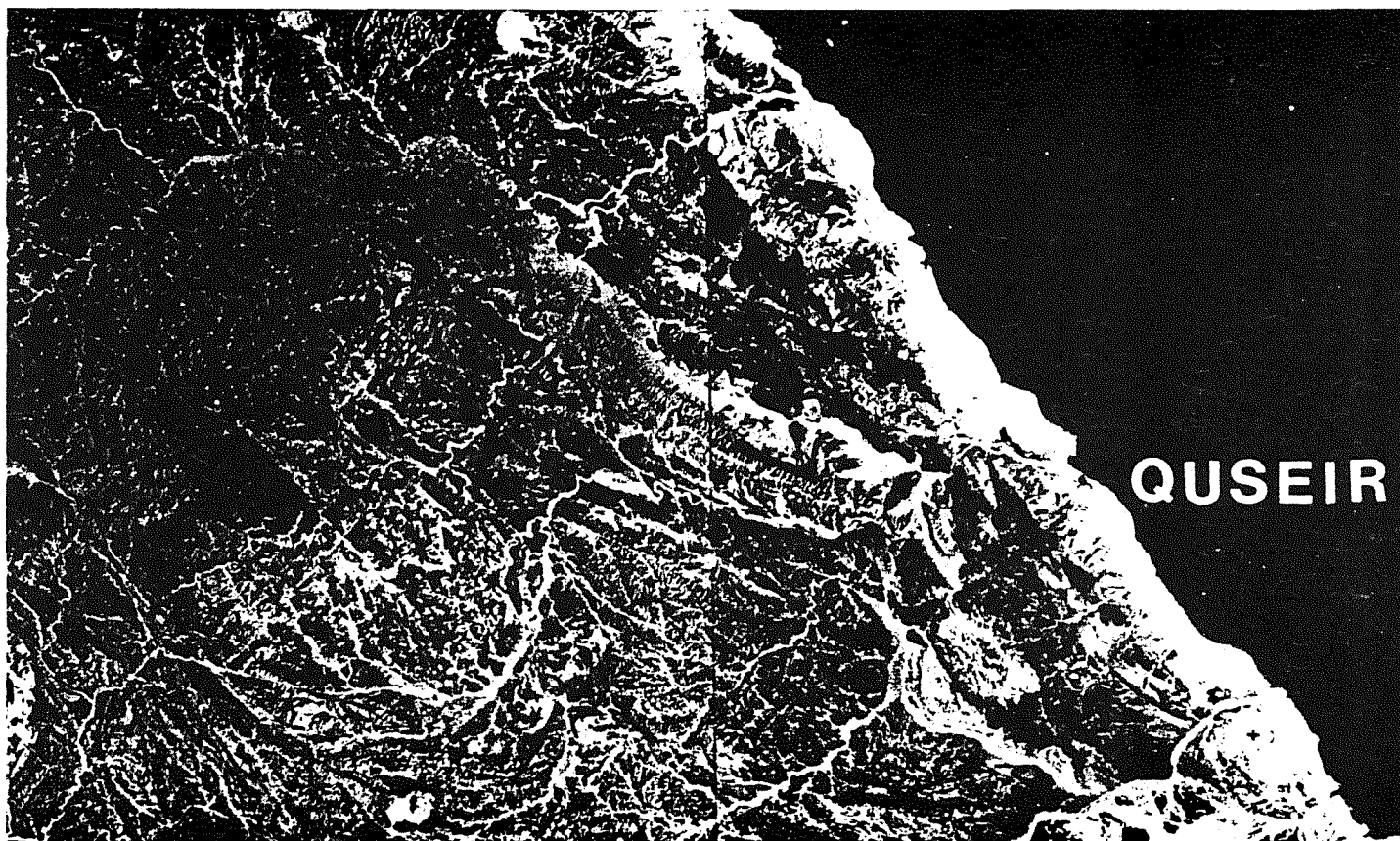
University of Massachusetts

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Prepared in cooperation with the  
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Frontispiece--LANDSAT return beam vidicon (RBV) image  
of the Gebel Duwi area.



## ABSTRACT

This study examines the Precambrian through Tertiary tectonic elements of an area of about 350 square km along the Red Sea coast utilizing geologic mapping and petrofabric work. The resulting data are used to test ideas concerning faulting, stress history, and the effects of older anisotropies. The study area, 500 km south of Suez and 10 km inland from the Red Sea, contains the largest preserved remnants of late Cretaceous to early Tertiary cover along the Egyptian Red Sea coast. These 600 meter-thick platform sediments are preserved as outliers downfaulted along trends atypical of the Eastern Desert. Fault trends are most prominent in the northwest-trending, 40 km long Gebel Duwi fault block and appear to be reactivated Precambrian structures: the northwest-striking, Eocambrian Najd strike-slip fault zone superimposed upon a north-northwest Proterozoic fold grain.

Red Sea-related structures began to disrupt the area in Oligocene to early Miocene time; a pattern of small conjugate strike-slip faults of that age suggests N25E compression. The Tertiary faulting hierarchy involves a pattern of northeast-tilted, northwest-trending blocks terminating against older north-south zones with some

suggestion of en echelon patterns of the younger blocks. Typical throws on major faults are 500-800 meters.

Tilting was followed by an eastward shift of tectonic activity to form the main Red Sea basin. A post-tilting regional erosion surface developed during mid-Miocene quiescence and has since suffered minor disruption.

Folding is minor except for drag folding along major fault zones and a 50 meter wavelength overturned fold atop Gebel Duwi, which may be the result of gravity tectonics.

The data suggest a multi-stage history for the Red Sea: 1) post-early Eocene uplift accompanied by N25E compression; 2) Oligocene to early Miocene major faulting, block tilting, and subsequent erosion; 3) early to mid-Miocene major activity to the east of the study area producing the main Red Sea trough while the regional erosion surface was enhanced along the shoulders; 4) post-mid-Miocene final adjustments producing coast-parallel horsts, with subdued tectonic activity continuing through the present.

Results of the study have implications for the evolution and style of deformation of the shoulders of developing ocean basins. Possible continuations of the same tilted fault block structural style controlled by basement grain along the zone of Najd trends should be of interest for offshore petroleum exploration.

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# C H A P T E R I

## INTRODUCTION

Much recent geologic interest in the Red Sea region has centered on mechanisms of continental rifting, small ocean basin formation, and the relation of these processes to offshore petroleum exploration and development. This study examines the mechanisms of deformation, stress history, influences of tectonic heredity, and the interplay of these elements in an area adjacent to the Red Sea.

The study area is near Quseir on the Red Sea coast of Egypt about 500 km south of Suez (Figure 1) and was chosen for its excellent exposure of tilted basement blocks and their Cretaceous to Tertiary cover. Gebel Duwi, the most prominent of the tilted fault blocks in that area, is the focus of the study. The area is characterized by divergence of structural trends from the typical Red Sea-parallel trends present along the Egyptian coast. The main objective of this study is a better understanding of the interaction of Tertiary stresses with pre-existing anisotropies to produce the unusual pattern of Red Sea-related structures present in the Quseir area.

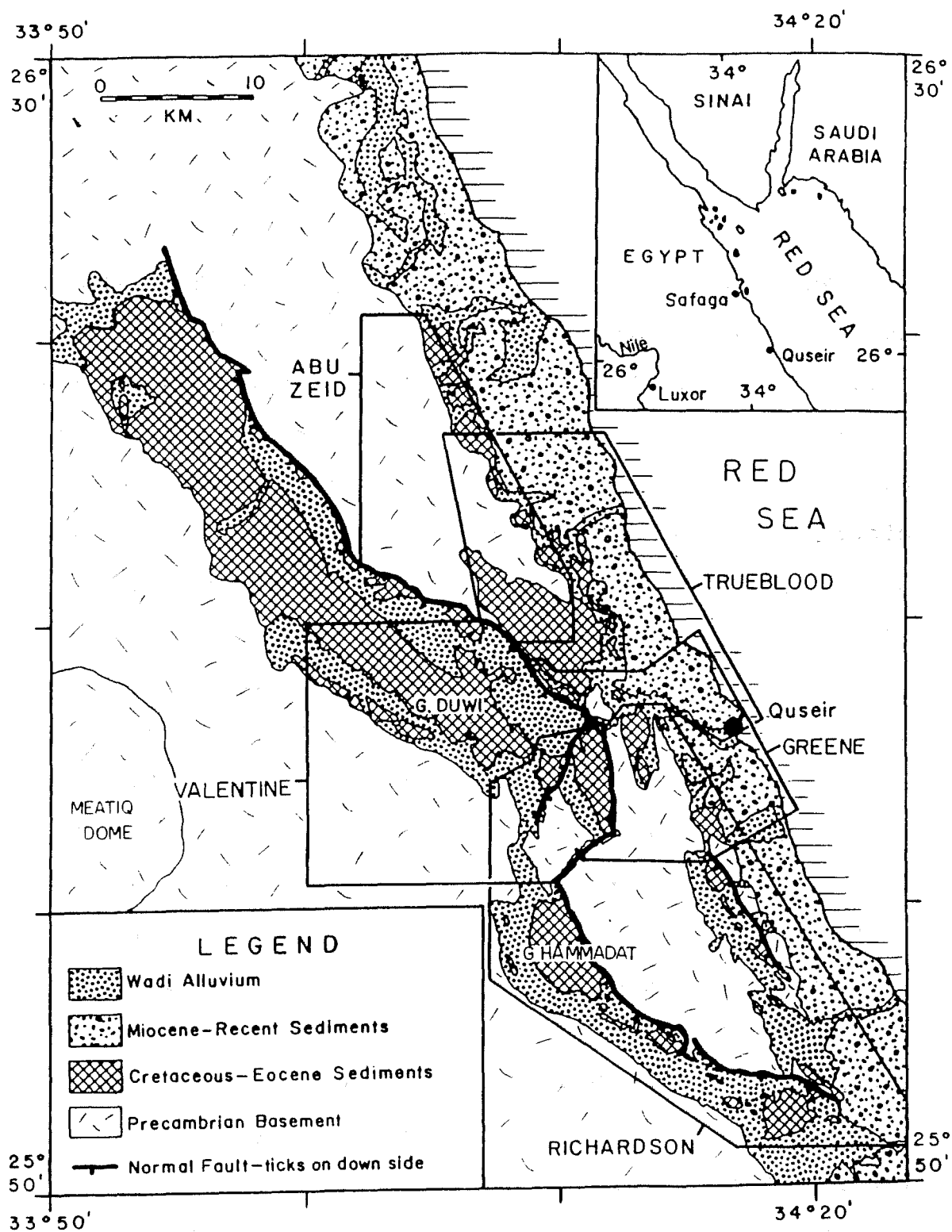


Figure 1. Map of the Quseir-Safaga region of Egypt showing location, general geology, and study areas of recent workers (geology after Said, 1962).



### Geographic Setting

The 17 by 20 kilometer area considered in this study lies about 8 kilometers west of the coastal town of Quseir along the Quseir-Qena road and is centered around the southeastern end of Gebel Duwi, the most conspicuous ridge in the Quseir area (Figure 1). The terrain is rugged, with over 300 meters of total relief (Figure 2). Access to the more remote areas can be gained from the main Quseir-Qena asphalt road via a series of dirt tracks maintained by the Quseir Phosphate Company (Figure 3). Several gebels (mountains), wadis (dry fluvial valleys), and birs (brackish-water wells) will be used as landmarks when discussing the geology.

### Regional Geologic Setting

The Eastern Desert of Egypt includes the area between the Nile River and the Gulf of Suez/Red Sea (Figure 4). Its most prominent feature is a north-northwest trending range of mountains that parallels the Red Sea coast. This Red Sea Range extends from Gebel Um Tenassib (latitude 28° 30'N) in the north, southeastward into Sudan forming a more-or-less linear series of mountain groups, rather than a true continuous chain. Sedimentary plateaus occur to

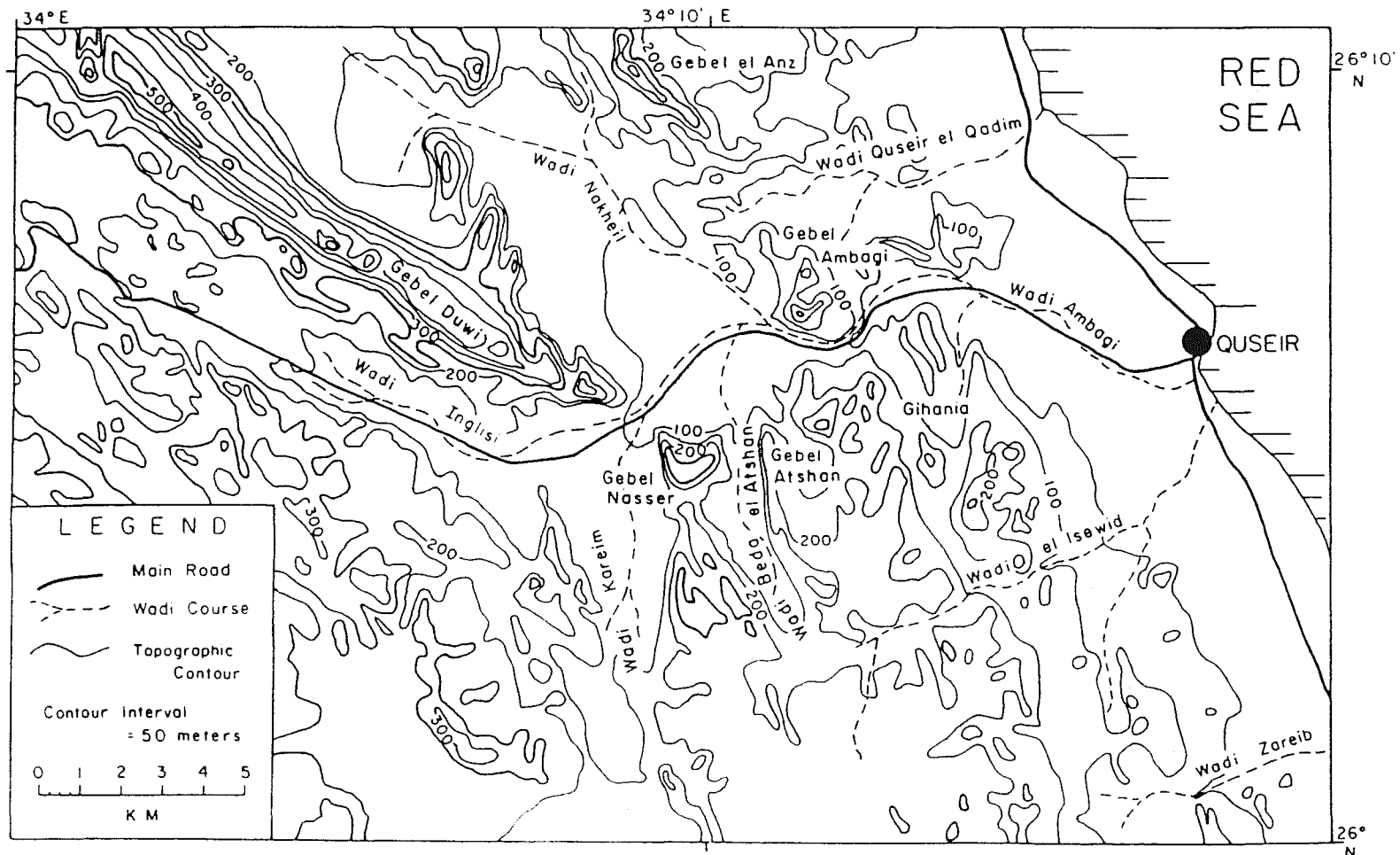


Figure 2. Topographic map of the southern Gebel Duwi area.

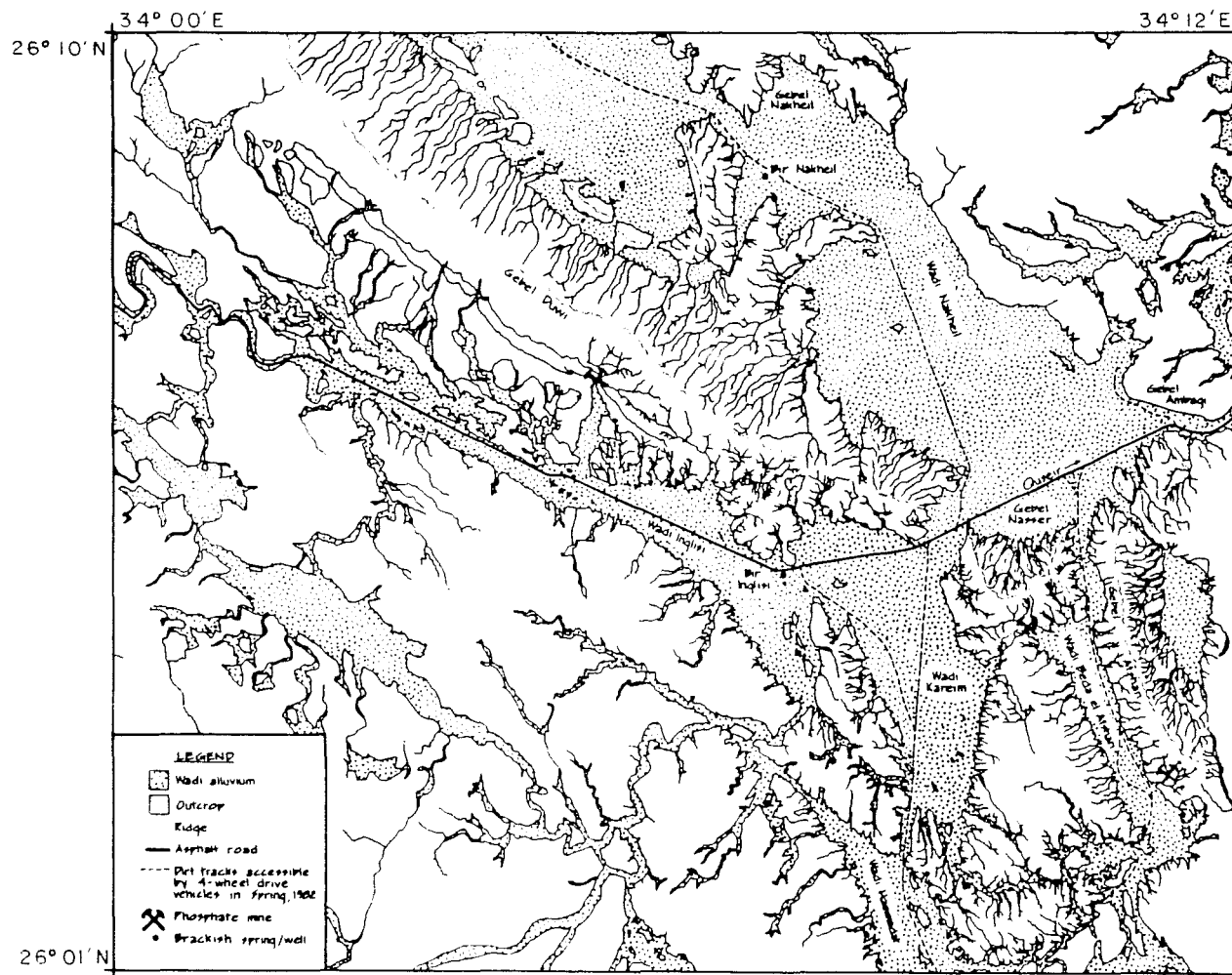


Figure 3. Main features of the southern Gebel Duwi area.



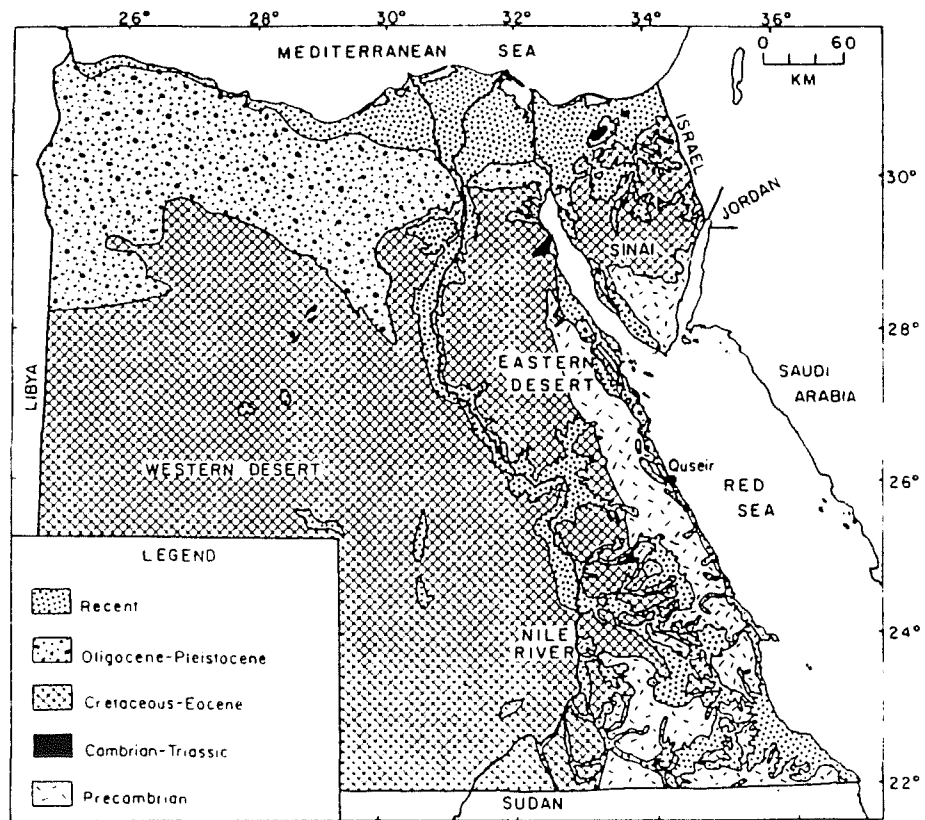


Figure 4. Geologic map of Egypt (after Said, 1962).

the north and west of these mountains, and a narrow coastal plain lies to the east. The mountains and plateaus are deeply dissected by a system of wadis that carries rare precipitation to the Nile, the Gulf of Suez, and the Red Sea.

The Red Sea Range is made up of late Precambrian crystalline rocks that underly the entire Eastern Desert (Figure 4). These rocks consist mainly of a layered sequence of greenschist-grade metavolcanics and volcanogenic metasediments intruded by granites (Sturchio, Sultan, Sylvester, et al., 1983). Engel et al. (1980) suggest that this greenstone belt resulted from the accretion of island arc systems in the late Proterozoic, unusual in that most greenstone belts are Archean in age. This Precambrian tectonic activity consolidated the Arabian-Nubian craton and resulted in a north-northwest trending basement fold grain (Engel et al., 1980; Greenwood et al., 1980). In the late stages of this Eocambrian cratonization, a pervasive northwest-trending fault fabric was superimposed on the area, a probable extension of the left-lateral Najd fault system of the Arabian Shield (Moore, 1979).

Following a long period of quiescence, Upper Cretaceous to Eocene platform carbonates and related sediments were deposited unconformably over the

Precambrian basement of the Eastern Desert. These sediments form the plateaus to the west of the mountains and are best exposed in the western part of the desert where erosion has produced a series of scarps stepping down into the Nile Valley. Uplift along the Red Sea Range during post-early Eocene time resulted in removal of the sedimentary cover by erosion except in isolated outliers preserved by downfaulting associated with Red Sea rifting. Much of this study is concerned with a group of these downfaulted sedimentary outliers in the Quseir area.

Middle Miocene and younger Red Sea-related sediments were deposited along the coastal plain unconformably over crystalline basement rocks and Cretaceous to Eocene sediments. These sediments are well preserved along most of the Red Sea/Gulf of Suez coast from the southern end of the Gulf of Suez to Ras Benas ( $23^{\circ} 09'N$ ).

#### Previous and Current Work

Barron and Hume (1902) studied the central Eastern Desert of Egypt and produced the first geologic map that included the Quseir area. Since then, interest in the phosphate deposits of the Cretaceous Duwi Formation has prompted more work in this area of the desert. Ball

(1913) examined and mapped the Um el Huetat area to the north, while Hume (1927) discussed the entire Quseir-Safaga district with respect to oil potential of the sediments.

Beadnell (1924) produced a series of four geologic maps of the coastal area between Quseir and Wadi Ranga at a scale of 1:100,000. These were the first good maps of the area produced at a useful scale. The sedimentary rocks were separated into two groups; the Cretaceous to Lower Eocene group and the "Newer Tertiaries and Pleistocene" group.

Youssef (1949; 1957) studied the Upper Cretaceous rocks in detail and divided them into four formations.

Said (1962) summarized the relevant literature and split the sedimentary rocks of the area into two subdivisions. Said's stratigraphy (Table 1), slightly modified and refined, is still in use.

Several studies in the Quseir area since that time (El Akkad and Dardir, 1966a; 1966b; Abd el Razik, 1967; Issawi et al., 1969; Issawi et al., 1971) have been concerned with the stratigraphy and general structure of the sedimentary cover. Naim and Ismail (1966) did a microfacies study of the Nakheil Formation (El Akkad and Dardir, 1966b) to determine the depositional environment of this conglomerate-sandstone series.

Table 1 Said's (1962) sedimentary cover stratigraphy.

Pleistocene	Terraces and Raised Beaches
Pliocene	Clypeaster-Laganum Series
Pliocene	Oyster and Cast Beds
Miocene	Evaporite Series
Miocene	Basal Lime-grits
Lower Eocene	Thebes Formation
:	Esna Shale
:	Chalk
:	Dakhla Shale
:	Duwi (Phosphate) Formation
:	Quseir Variegated Shales
Upper Cretaceous	Nubia Sandstone

Schurmann (1966) combined over 50 years of personal work in Egypt with prior studies into his comprehensive text on the Precambrian of the northern Eastern Desert and the Sinai. The stratigraphic sequence in that basement area and other related questions are still being debated. Data from recent studies (Akkad and Noweir, 1980; Dixon, 1979; Stern, 1979; Engel et al., 1980; Sturchio, Sultan, Sylvester, et al., 1983) and better radiometric dating may help to clarify the Precambrian history of the area.

Since the mid-1970's, the Egyptian Studies Group of the Earth Sciences and Resources Institute at the University of South Carolina at Columbia has been supporting studies in the Eastern Desert through various institutions. Much of the work has been concentrated farther to the west of the Quseir area or has involved larger areas. Of particular interest to the present work are studies of Trueblood (1981), Richardson (1982), and Greene (1984) as well as work in progress by Abu Zied (in preparation). All these studies involve areas directly adjacent to that considered in this study (Figure 1). Prior to these investigations, only scanty structural data were available for this part of the Eastern Desert.

Much work has also been done by the U. S. Geological Survey in Saudi Arabia. Most of this work has concentrated on the Precambrian basement of the Arabian

Shield (Greenwood et al., 1980; Moore, 1979; Schmidt et al., 1979) with individual mapping of quadrangles along the Red Sea coast (Smith, 1979; Davies, 1980; 1981). Some work has also been done in the Arabian Shield by the French Bureau de Recherche Geologiques et Minieres.

Numerous studies have also been done on the structure and evolution of the Red Sea (e.g. Lowell and Genik, 1972; Coleman, 1974; Girdler and Styles, 1974; Cochran, 1983). Several of these studies will be discussed in Chapter VII.

#### Geologic Map and Gross Structural Features

No suitable base maps were available at the outset of field work. However, the Egyptian government made available a series of high quality black-and-white air photos at a 1:40,000 scale. These photos, taken in 1955, are ideal for location in the field and tracings of them were used as a base for the resulting geologic map (Plate 1). The use of the air photos as a base resulted in some distortion around the edges of individual photos. As the photos were available only during my stay in Egypt, it was necessary to construct a best-fit map in the field (Plate 1) that has been adjusted subsequently using satellite imagery, but still contains minor distortions.

Most of the mapping northeast of the major fault bounding the northeast side of Wadi Nakheil, including Gebel Ambagi, is from Trueblood (1981) and Greene (1984). It is included in Plate 1 for the purposes of continuity and completeness.

The general structure of the map area results from interplay of three major fault groups striking N60E, N15W to N15E, and N50-60W. The faults break the area into two major blocks, the Gebel Duwi block and the smaller Gebel Atshan block (Figure 5). These blocks are, in turn, broken into smaller blocks by subsequent faulting. The "jagged" or "stepping" appearance of major N-S and N50-60W faults indicates possible reactivation of older fault trends by later stresses.

The Gebel Duwi block terminates to the southeast against the north-south Bir Inglisi, Gebel Nasser-Gebel Ambagi, and Gebel Atshan Fault Zones. Another tilted block with a trend similar to that of the Duwi block runs off the southern end of the Atshan block toward the Red Sea coast. This block is covered by the Cretaceous to Eocene sediments of Gebel Hammadat (Figure 1).

Other more-or-less north-south zones can be seen on satellite imagery to disrupt the Duwi block (see Frontispiece). These zones may also mark changes in the orientation of the Gebel Duwi block from Red Sea-parallel



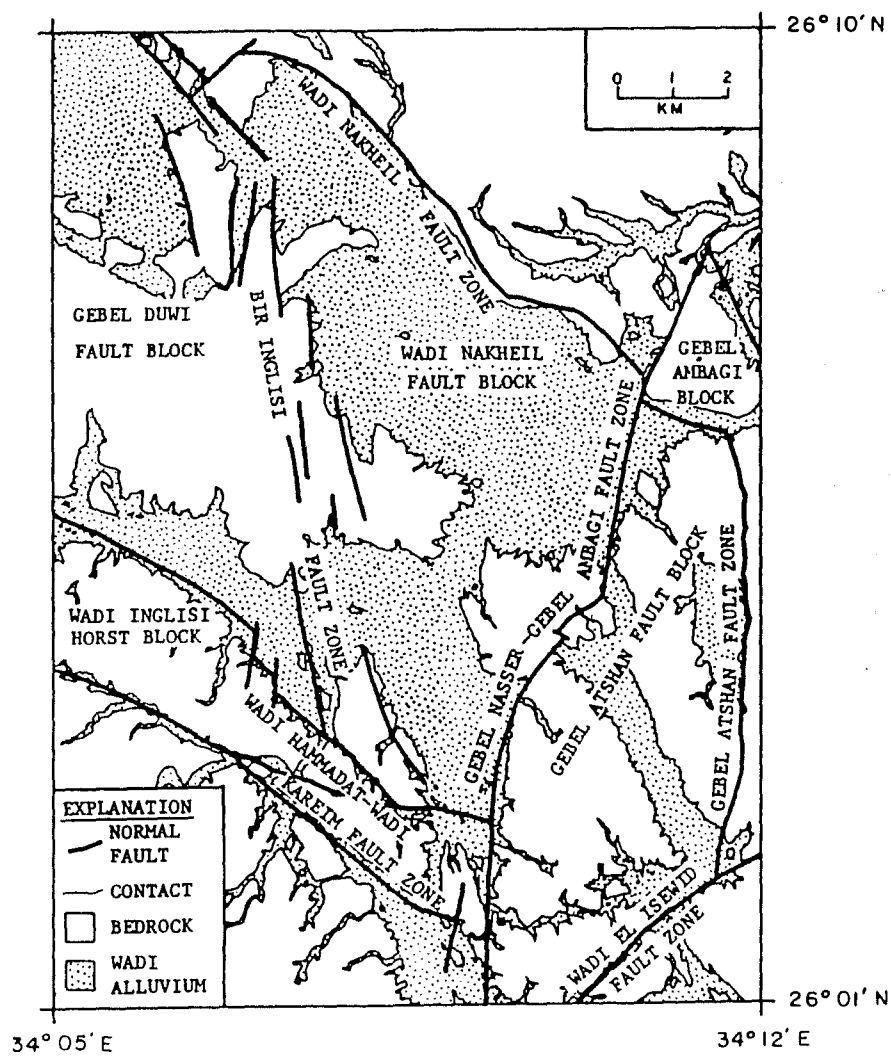


Figure 5. Major fault blocks and normal fault zones of the study area.

to a more westerly orientation. Figures 6 and 7 show the general fault block geometry of the Quseir-Safaga region.

The major faults generally dip  $50^{\circ}$  or more at the surface. Consistent northeast dips of the platform sediments suggest rotation of the tilted fault blocks and may indicate shallowing of listric fault dips at depth. This shallowing at depth is consistent with models for Red Sea extension. Greater than 600 meters of vertical displacement is indicated on portions of these faults where the upper Thebes Formation is in contact with the basement (Plate 2).

Most large-scale folds in the cover of the area trend parallel to, and are the result of, drag along post-Eocene faults. Examples of this style of deformation can be seen in the broad folding of the cover of the Gebel Duwi Block and in the open Gebel Nasser syncline. The only major exception to this style of folding is the large fold atop the ridge of Gebel Duwi (Plate 2), which is discussed in detail in Chapter V.

#### Acknowledgements

Dr. Donald U. Wise of the University of Massachusetts acted as advisor and provided much needed advice and assistance in all phases of the study. Three-and-one-half

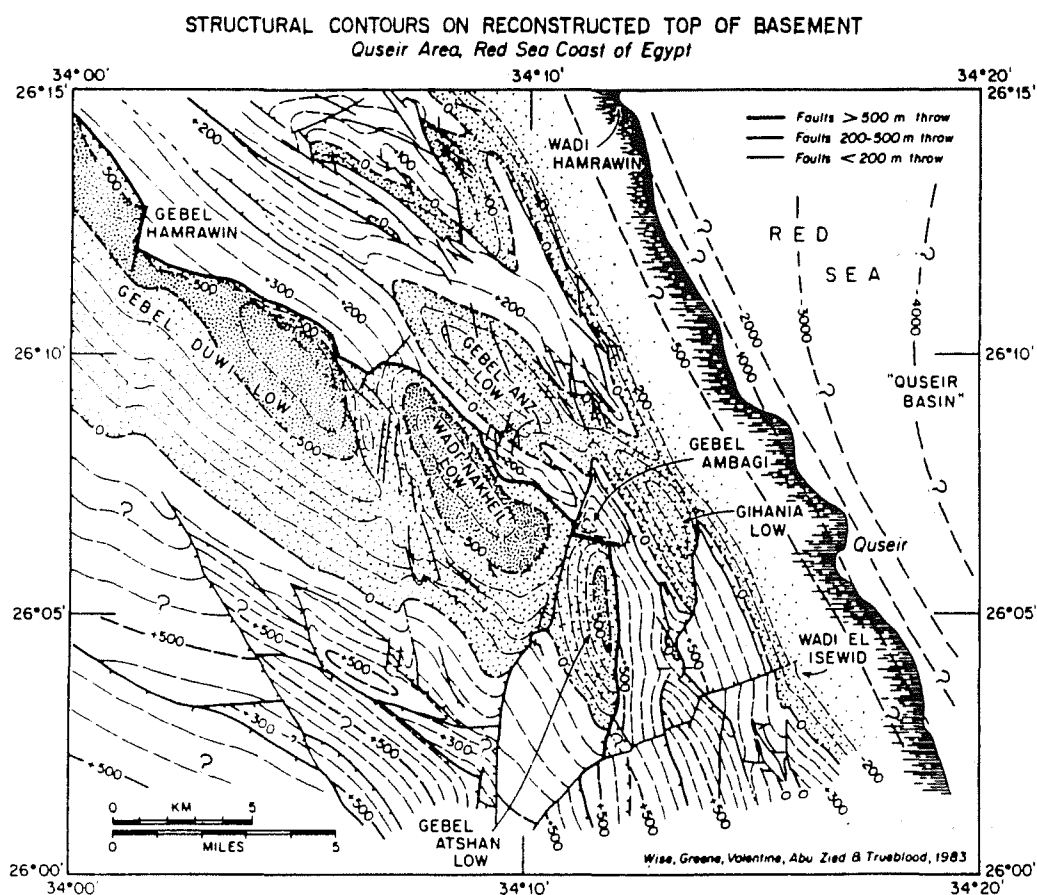


Figure 6. Structural contour map on reconstructed top of basement of the Quseir-Gebel Duwi area. Contour interval= 100 meters.

GENERALIZED STRUCTURAL CONTOURS ON RECONSTRUCTED TOP OF BASEMENT  
Quseir-Safaga Region, Red Sea Coast of Egypt

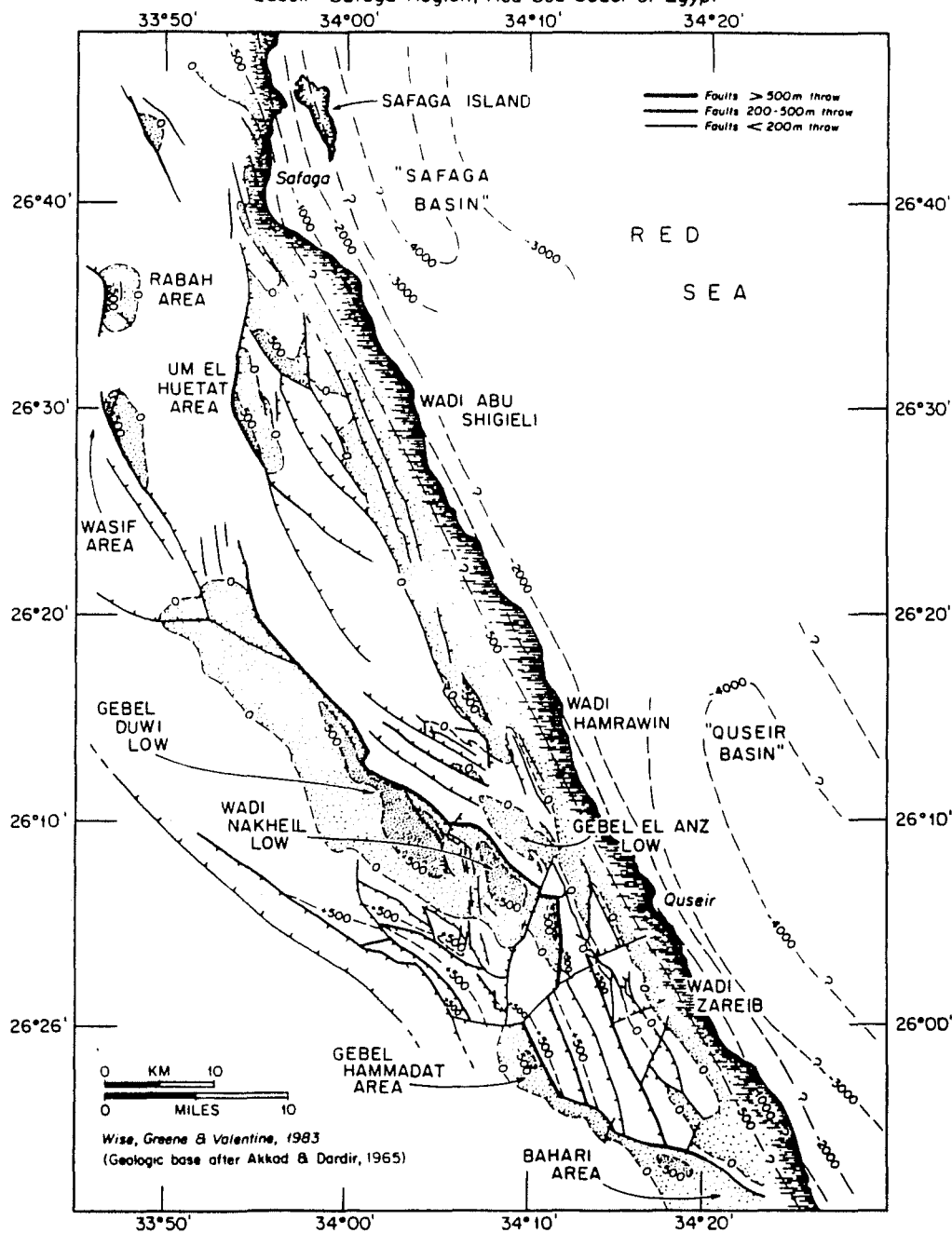


Figure 7. Structural contour map on reconstructed top of basement of the Quseir-Safaga region. Contour interval= 500 meters.

months of field work in the winter and spring of 1982 were funded by the National Science Foundation and the U. S. State Department. Professors W. H. Kanes, Steven Schamel, and Robert Ressetar of the Earth Sciences and Resources Institute at the University of South Carolina administered these funds and offered helpful advice.

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duration of this project. To all of the above, I express my thanks.

## C H A P T E R    I I

### PRECAMBRIAN BASEMENT STRUCTURE AND ANISOTROPY

Some Tertiary structures were probably controlled, in part, by basement anisotropy. This chapter is designed to establish the nature of this anisotropy, structural and compositional. Due to the complexity of basement fracturing patterns and their resemblance to those of the Cretaceous to Eocene cover, a fuller discussion of basement fracturing will be included in Chapter IV.

#### Basement of the Study Area

The basement of the study area, like most of the Eastern Desert basement, is dominated by a sequence of metavolcanics and volcanically derived metasediments. The volcanics are aphanitic to porphyritic in character; the volcaniclastic metasediments are generally coarse grained, commonly conglomeratic. Both types are highly fractured.

The metavolcanics and metasediments correspond to the upper part of Akkad and Noweir's (1980) Abu Ziran Group (Table 2). A few small exposures of serpentinite present south and southwest of Gebel Nasser may be part of the Rubshi Group (Table 2).

It will be shown that several periods of deformation at low, mainly greenschist, grade metamorphic conditions resulted in a pervasive northwest grain. Compositional layering is parallel to metamorphic foliation, suggesting near-isoclinal folding. Dips of these features are dominantly to the southwest.

Pink to gray granites intrude the folded volcanic sequences of the area. Granite-country rock contacts, examined at about a dozen places in the study area, vary from quite sharp to gradational across a zone of one to two meters. The granites appear to have been emplaced passively, possibly by processes akin to magmatic stoping, as large xenoliths of green metavolcanics are present around the edges of them. Further, foliation, volcanic layering, and other structures do not appear to be significantly deformed around their margins. These characteristics are in accord with Greenberg's (1981) description of the Egyptian Younger Granites.

Much of the basement west of Wadi Hammadat and south of Gebel Nasser is underlain by granite. The granite at the southern end of the Gebel Nasser block is in the process of erosional unroofing.

Basement foliations and crenulations were not observed in any of the granites. This is probably a reflection of their emplacement late in the Precambrian



		ROCK UNITS	
	SUPERGROUP & GROUP	FORMATION	MEMBER (and remarks)
ARABIAN DESERT SUPERGROUP		Kab Absi Essexite Gabbro Khors Volcanics	— (dislodging of contact between Nubia Sandstone and basement)
		Nubia Sandstone	— (regional unconformity)
		Younger Granites	Phase III South Eraddia pluton Phase II Gidami, Kab Amiri, Eraddia, Um Effein, Um Had, Um Hombos and Saneyat plutons Phase I Abu Qarahish, Sodmein, Kab Absi, Atalla El Murr, Atalla, Atalla gold mine, East Um Effein, Fawakhir and Arak plutons
		Post-Hammamat Felsites	Atalla, Rasafa-Shihimiya, Atshan, Qash, Mahdaf, Kohel, Arak and Zeidun members
		Qash Volcanics	—
			—
	HAMMAMAT GROUP molasse-type sediments	2. Shihimiya Formation	c. Um Hassa Greywacke Member b. Um Had Conglomerate Member — (local unconformity) a. Rasafa Siltstone Member
		1. Igla Formation	—
		Dokhan Volcanics (unmetamorphosed)	— (regional unconformity)
		Older Granites	— (transforming some Older Granites into cataclastic-mylonitic gneisses of Shaitian type or Shait Granites) Um Shager, Abu Ziran and N & E Eraddia plutons
		2. Sid Metagabbros	Hammuda, Khors, Fannani, Sid, Fawakhir, Esh El-Zarga, Eraddia, Saqia, Abu Diwan, Rubshi and Abu ziran complexes
	RUBSHI GROUP ultrabasic & basic	1. Barramia Serpentinities	Muweilih, Saneyat, Fannani, Atalla, Rubshi, Kab Amiri & Saqia ranges
		8. Abu Diwan Formation 7. Eraddia Formation 6. Sukkari Metabasalts 5. Um Seleimat Formation 4. Atalla Formation	—
	ABU ZIRAN GROUP eugeosynclinal filling	3. Atud Formation	— (local unconformity)
		2. Muweilih Formation	
		1. Hammuda Formation	d. Absi Metamudstone Member c. Khors Schist Member  b. Um Hombos Metapyroclastic Lentil a. Um Shager Metagreywacke Member
		Abu Fannani Schists	
	MEATIQ GROUP		Thick succession of high grade siliceous gneisses and schists. Subdivision into units in progress.

Table 2. Akkad and Noweir's (1980) stratigraphy and

Age	Stages of evolution	PRINCIPAL EVENTS
Lower Cretaceous	POST-GEOSYNCLINAL PHASE major block faulting & uplift. Red Sea rift, platform sedimentation, alkaline volcanicity & plutonism	<ul style="list-style-type: none"> <li>- Emplacement of alkaline plutonites</li> <li>- Explosive volcanism of trachyte lavas, pyroclastics and associated dykes</li> <li>- Rejuvenation of old N.W.-S.E. faults</li> <li>- Transgressive deposition of quartz-arenites and shales on stable shelf</li> <li>- Prolonged quiescence, erosion and peneplanation</li> <li>- Uplift and main rejuvenation of old N.W.-S.E. faults</li> </ul>
620-590 Ma	EPEIROGENIC PHASE uplift & andesitic volcanicity, molasse-type sedimentation, regional tilting & granite plutonism	<ul style="list-style-type: none"> <li>- Emplacement of granite plutons as final epeirogenic manifestation, associated with and followed by various dykes               <ul style="list-style-type: none"> <li>- Granite pluton cutting Phases I and II</li> <li>- Adamellite plutons cutting Phase I, Hammamat Group, Post-Hammamat Felsites and effecting pronounced contact metamorphism</li> <li>- Elongate granodiorite plutons along N.W.-S.E. trends</li> </ul> </li> <li>- Intrusion of felsites as huge bodies, sheets and dykes along N.W.-S.E. trends</li> <li>- Earliest indication of N.W.-S.E. dislocations controlling later emplacement of Post-Hammamat Felsites and Phase I of Younger Granites</li> <li>- Eruption of tuffs &amp; intrusion of subvolcanics into folded Hammamat Group</li> <li>- Folding &amp; faulting of Hammamat Group &amp; older rock units - second phase folding</li> <li>- Deposition of dark greywackes</li> <li>- Deposition of conglomerates derived from older units and reworked Igla Formation</li> <li>- Uplift in source area</li> <li>- Deposition of grey siltstones, minor greywackes and conglomerates</li> <li>- Deposition of primary red beds of purple siltstones, greywackes, minor arenites and conglomerates</li> <li>- Rapid severe erosion and peneplanation</li> <li>- Epeirogenic uplift accompanied by intrusion and eruption of andesites and porphyries. Subareal eruption of andesitic agglomerates and tuffs</li> </ul>
660-700 Ma		
900-1000 Ma	OROGENIC PHASE regional tilting, metamorphism & granite plutonism	<ul style="list-style-type: none"> <li>- Regional fault and thrust movements</li> <li>- Emplacement of tonalite, granodiorite &amp; monzonite during waning phase of orogeny</li> <li>- Emplacement of basic plutonites during orogenic folding and regional metamorphism affecting these and all older rock units</li> <li>- Recurrent intrusion of concordant ultramafic bodies at different horizons in the Abu Ziran Group, heralding main phase of orogeny</li> <li>- Intrusion of diabbases</li> <li>- Eruption and intrusion of andesites, andesitic tuffs and minor basalts</li> <li>- Effusion of basalts and basaltic tuffs</li> <li>- Intrusion and eruption of basalts, minor andesites and tuffs</li> <li>- Eruption of rhyolite, dacite, porphyries, acidic tuffs and minor interbedded mudstones, siltstones and arkosic greywackes</li> <li>- Deposition of alternating conglomerates and greywackes, minor siltstone, mudstone and intraformational breccia</li> <li>- Uplift in source area</li> <li>- Effusion of pillowed spilites, diabase flows, spilitic crystal tuffs, epiclastic andinole and intrusive andesites</li> <li>- Deposition of siliceous tuffaceous mudstones and minor greywacke</li> <li>- Deposition of alternating shales and calc-shales, minor siliceous limestone and carbonaceous chert</li> <li>- Eruption of lapilli-, lithic-, crystal-tuffs merging into epiclastic sediments</li> <li>- Deposition of alternating greywacke, mudstone, minor conglomerate and pelite</li> <li>- Deposition of successive quartz-arenites, calc-pelites and greywackes, transitional to proper turbidite facies</li> <li>- Extrusion of acidic tuffs and flows</li> </ul>
1300?? Ma	GEOSYNCLINAL PHASE flysch-type sedimentation & initial magmatic activity volcanicity & intrusion of ultrabasic & basic magmas	

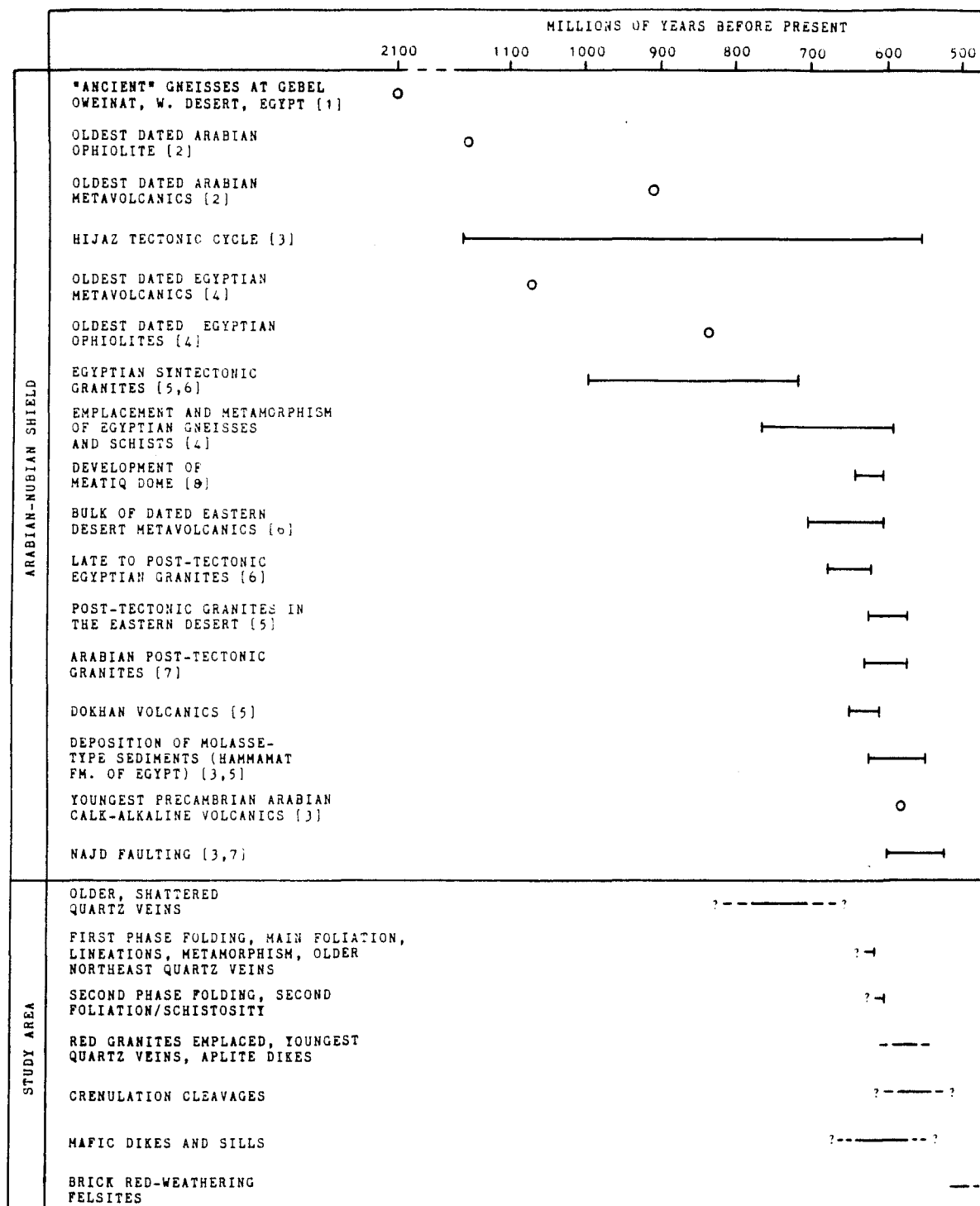
history of the Egyptian basement through the lower Cretaceous.

sequence of events, as opposed to some of the older, highly foliated and lineated granites of the Eastern Desert. Quartz veins, felsite dikes, and a single mafic dike were observed to cut the granites. Aplitic dikes were noted in the metavolcanics in close proximity to the large granitic body in the southeastern part of the area and will be discussed further. A summary of the Precambrian history of the study area is presented in Table 3.

#### Precambrian Tectonic Setting and Basement Correlations

The Precambrian basement of Egypt has been given serious study since the establishment of the Geological Survey of Egypt in 1896. In 1911, the first geologic map of Egypt was produced by the Survey with explanatory notes by Hume (1912). The map was based largely on reconnaissance geology and about one-third of the country remained "terra incognito". A revised edition of this map was later published in the Atlas of Egypt (Little, 1928).

Hume (1934), Andrew (1938; 1939), Neubauer (1962), and Schurmann (1966) developed Egyptian basement stratigraphies without the benefit of adequate radiometric dating. As a result, much confusion remained as to ages,



## REFERENCES:

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|-----------------------------|---|
| [1] Schurmann, 1974.        | [5] Ries et al., 1983.                        |
| [2] Fleck et al., 1980.     | [6] Engel et al., 1980.                       |
| [3] Greenwood et al., 1980. | [7] Schmidt et al., 1979.                     |
| [4] Hashad, 1980.           | [8] Sturchio, Sultan, Sylvester, et al., 1983 |

Table 3. Summary of Precambrian history.

origins, and regional correlations of units.

El Ramly (1972) published a basement map and stratigraphy of the central Eastern Desert and South-Western Desert of Egypt. Based on work since 1963 along the Qift-Quseir Road in the Hammamat-Um Seleimat District, Akkad and Noweir (1980) developed a basement stratigraphic sequence similar to El Ramly's (Table 2). All of the aforementioned authors placed the gneisses and schists of the Meatiq Group at the base of the column, making them the oldest exposed rocks in the Eastern Desert, with a tentative age of about 1300 M.y. (Akkad and Noweir, 1980).

Basahel (1980) and Greenwood et al. (1980) have attempted to correlate the basement stratigraphy of Egypt with other parts of northeast Africa. Although the lithologic units of the Arabian-Nubian Shield have been adequately described, there is even now much disagreement as to ages, origins, and regional correlations.

#### Volcanic Arc Accretion Model

Until relatively recently, it was thought that northeast Africa and Saudi Arabia were underlain by an ancient sialic crust like that of western and southern Africa. Many of the notions concerning the antiquity of the northeast African craton were based on the now

outmoded premise that the more highly tectonized and metamorphosed rocks are, the older they must be. With little or no radiometric dating to constrain the ages, it was assumed that the gneisses and schists of the basement were Archean in age, and they were correlated with similar rocks in other parts of Africa.

With the development and refinement of various radiometric dating techniques, absolute ages for basement rocks became available. The only reported Archean dates for basement rocks of the Arabian-Nubian Shield are Rb-Sr ages on microcline and whole rock from the gneisses of Gebel Oweinat in the Western Desert (Schurmann, 1974). Rogers et al. (1978) state that data were unavailable to evaluate the validity of these dates, and consequently, they do not accept them. If these dates are eventually borne out, these ancient rocks may represent a small block of sial "floating" in younger surrounding rocks. It has been proposed that ancient sial is present under much of northeast Africa, but it seems unlikely that it would be exposed only at Gebel Oweinat.

Many problems with the development of a model for the evolution of the northeast African craton have resulted from the lack of agreement on a stratigraphic sequence for the area. Ries et al. (1983) feel that they have solved this problem with a structural/tectonic sequence for the

shield, rather than a simple stratigraphic one. The contacts they see between the major rock types in the central Eastern Desert of Egypt are dominantly tectonic. They have therefore divided the basement rocks into four groups based on environment of development as outlined below.

Volcanic-Plutonic Rocks. The bulk of the Saudi Arabian and Egyptian basements consists of calcalkaline volcanics and volcanogenic sediments intruded by granites (Shackleton, 1979). The volcanics and granites are chemically similar to igneous products associated with present-day island arcs (Greenwood et al., 1980; Gass, 1977; 1979; 1981; Dixon, 1979; Stern, 1979; Engel et al., 1980); the associated sediments are very similar to those found in modern back-arc basins (Greenwood et al., 1980; Engel et al., 1980).

Radiometric ages for the metavolcanics and granites range from about 1000 M.y. to 450 M.y. (Greenwood et al., 1980; Gass, 1979; Hashad, 1980; Roobol et al., 1983) with most Eastern Desert dates at 700-600 M.y. (Engel et al., 1980; Ries et al., 1983). The rocks become younger to the east across the Arabian Shield and exhibit an eastward geochemical evolution suggestive of a maturing island arc (Fleck et al., 1980; Greenwood et al., 1980; Darbyshire et al., 1983; Roobol et al., 1983).

Ophiolite Melange. The existence of ophiolites in the Arabian-Nubian Shield has been recognized only recently (Bakor et al., 1976; Gass, 1977; 1981; Dixon, 1979; Engel et al., 1980; Shackleton et al., 1980). Complete ophiolite sequences are rare, but partial sequences are relatively common in the Arabian-Nubian Shield. These slivers of obducted sea floor are located in north-south and northwest trending discontinuous belts in the Arabian-Nubian Shield (Figure 8) and may mark old sutures. Radiometric dates of 825 M.y. and 860 M.y. were obtained for Egyptian mafic volcanics (Hashad, 1980) and a single date of 1165 M.y. was obtained from Saudi Arabia (Fleck et al., 1980). These rocks may have been erroneously classified as part of the Rubshi Group of mafic intrusives by earlier workers.

Gneisses and Schists. These rocks were originally termed the "fundamental" gneisses and were thought to be part of an ancient craton underlying northeast Africa. They have now been identified as metamorphosed younger plutonic and/or sedimentary rocks with dates of emplacement and metamorphism ranging from 763 M.y. to 584 M.y. (Schmidt et al., 1979; Hashad, 1980; Sturchio, Sultan, Sylvester, et al., 1983). In many places, volcanics have been thrust over the gneisses. The gneisses, in turn, rose diapirically, possibly during compressional episodes



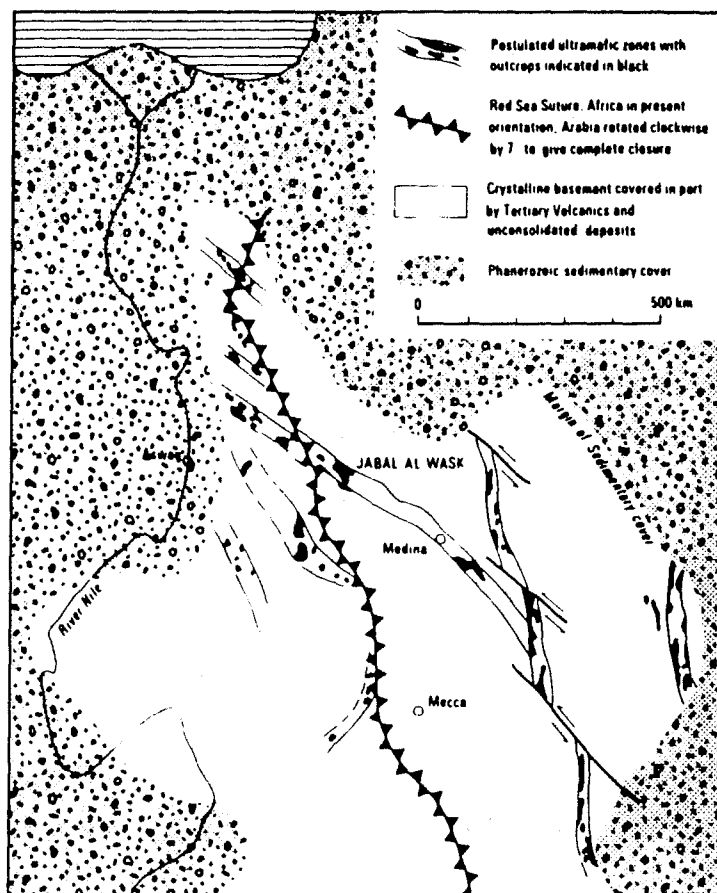


Figure 8. Distribution of mafic/ultramafic zones in the Eastern Desert of Egypt and western Saudi Arabia (Bakor et al., 1976).

(Greenwood et al., 1980) or during metamorphic core complex tectonics (Sturchio, Sultan, and Batiza, 1983), and were later exposed by erosion as mantled gneiss domes. Molasse-type Sediments. Stratigraphically, these are generally the youngest rocks in the structural/tectonic sequence. They include the Hammamat Group of Egypt dated at  $616 \pm 9$  M.y. to  $590 \pm 11$  M.y. (Ries et al., 1983) and the Murdama Group of Saudi Arabia. These sediments are clastic-dominated and are interpreted as being orogenic in origin (Greenwood et al., 1980; Schmidt et al., 1979; Ries et al., 1983).

#### Summary of Arabian-Nubian Shield Development

The chemistry, ages, and structure of rocks in the Arabian-Nubian Shield suggest that the craton formed through the accretion of island arc materials in the late Proterozoic. Single arc (Greenwood et al., 1980; Roobol et al., 1983) and multiple arc (Schmidt et al., 1979; Shackleton, 1979) models have been proposed; in the multiple-arc schemes, ophiolite belts mark the suture positions. Collisions along north-south to northwest trending lines produced mainly greenschist grade metamorphism, the Hijaz tectonic grain, dominant west to northwest trending lineations, and west to northwest fold

vergence seen in the shield. The gneisses and schists formed from sediments and/or plutons during collisional metamorphism, which locally reached amphibolite grade (Sturchio, Sultan, Sylvester, et al., 1983).

Uplift resulting from the collisions caused erosion and deposition of molasse-type sediments. At the same time, the last pulses of subduction-related magmatism cut all the pre-existing rocks to produce the Dokhan Volcanics of Egypt (Monrad and Ressetar, 1980) and minor andesites and rhyolites within the Murdama Group of Saudi Arabia (Greenwood et al., 1980). These events overlapped with intrusion of the collision-generated post-tectonic granites that stabilized and "cratonized" the new crust.

The Najd fault system developed between 520 and 590 M.y. ago (Greenwood et al., 1980; Schmidt et al., 1979) in response to the continuing collision of the Proterozoic African craton with the newly-created Arabian-Nubian continent (Greenwood et al., 1980; Fleck et al., 1980) or as the result of a collision with a continent to the east (Schmidt et al., 1979). A rigid indenter model similar to that of Molnar and Tapponier (1977) has been applied to both cases (Schmidt et al., 1979; Fleck et al., 1980).

During the hiatus in tectonic activity that followed the late Precambrian assembly of the Arabian-Nubian

craton, a widespread erosion surface developed over much of the craton. Cretaceous to Eocene platform sediments were subsequently deposited on this surface. This extensive older surface is preserved in the western Eastern Desert as a general concordance of basement peak elevations where the sedimentary cover has been removed. Within the study area, it can be seen as a weathered basement surface along the basal contact of the Nubia Formation.

Many details of this model need to be worked out, but the general scheme is gaining wide acceptance. The rapid development of this area, unusual mafic intrusions noted by Dixon (1979), the unusually young age of this greenstone belt, lack of arc-type blueschists, and the extent of the Pan-African tectono-thermal event all point to anomalous mantle conditions beneath Africa in the late Precambrian. This may prove to be a fruitful field for future investigation.

#### Regional Structural Grain

On the scale of LANDSAT imagery (Figure 9), areas bordering the edge of the Red Sea are seen to be dominated by more or less north-south braided structural trends and northwest structural trends (Greenwood and Anderson,

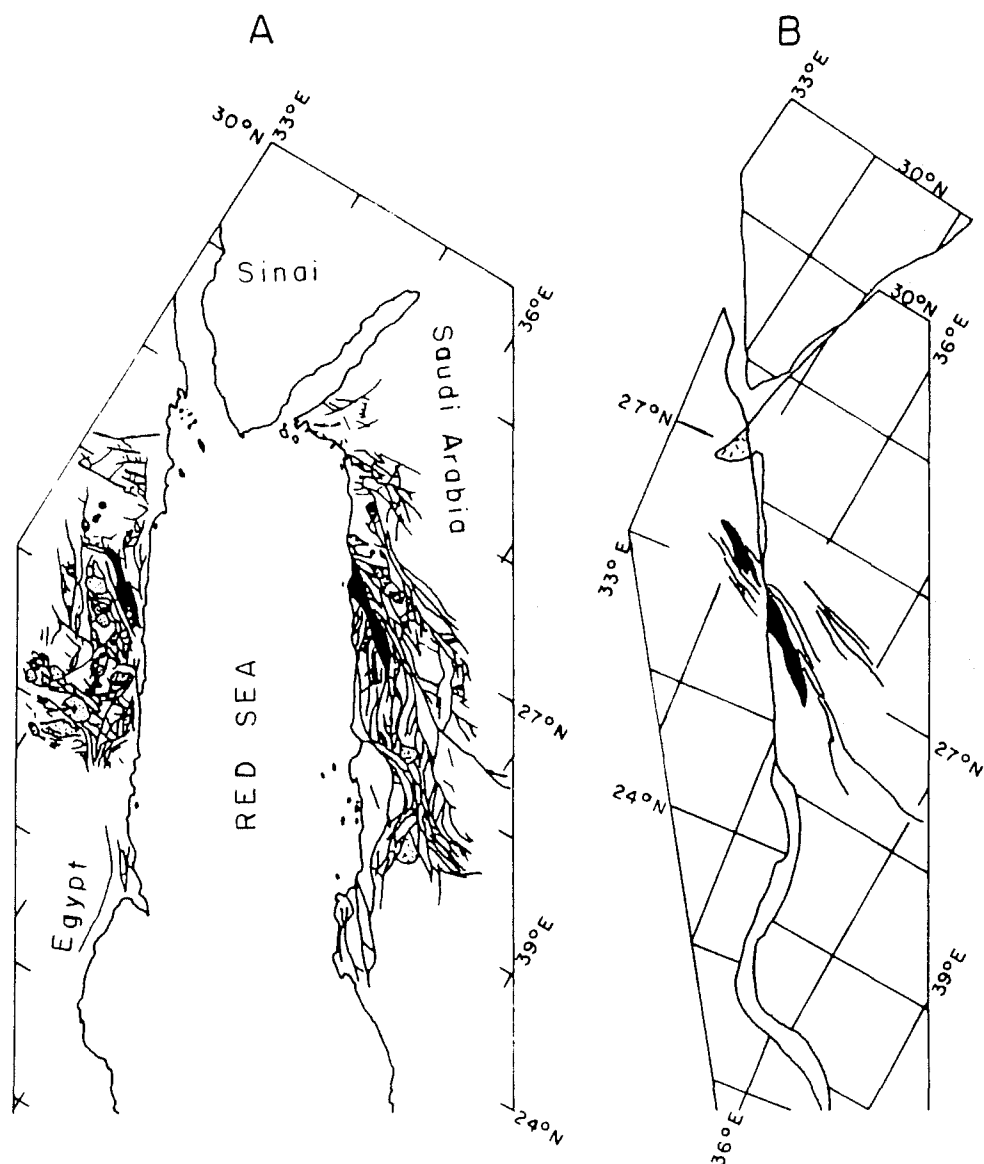


Figure 9. Palinspastic reconstruction of the northern Red Sea prior to Tertiary rifting (after Greenwood and Anderson, 1977): a) line drawing of the northern Red Sea showing lineaments visible on LANDSAT images; b) reconstructed Red Sea margins prior to rifting. Lines represent Hijaz- and Najd-parallel lineaments in Precambrian terrains. Note alignment of Gebel Duwi-Gebel Hammadat of Egypt and Wadi Azlam of Saudi Arabia (both in heavy black) prior to rifting.

1977). These can be associated with the Hijaz-Asir (N-S) and Najd (NW) tectonic provinces (Figure 10) of the Arabian Shield (Greenwood et al., 1980) and their extensions into northeast Africa. A third trend parallels the Red Sea and is associated with Tertiary rifting.

In the Arabian Shield, where extensive basement mapping has been done, structures paralleling the two dominant grain directions are well-known (Greenwood et al., 1980; Smith, 1979; Davies, 1980; 1981). Although published structural data for the Eastern Desert are somewhat sparse, north-south and northwest trends have been noted in the basement (Abdel Khalek, 1979; Engel et al., 1980; Gass, 1981; Ries et al., 1983). Minor groups of east-west and northeast trending faults have also been noted in Egypt (El Shazly, 1964; 1977; Garson and Krs, 1976; Abdel Khalek, 1979; Gass, 1981) and Saudi Arabia (Garson and Krs, 1976; Davies, 1980; 1981).

Northwest-southeast lineations are present throughout the Precambrian of the Eastern Desert and have shallow northwest or southeast plunges (Shackleton et al., 1980; Ries et al., 1983; Sturchio, Sultan, Sylvester, et al., 1983; Sturchio, Sultan, and Batiza, 1983). These are mainly stretched pebble and mineral smearing lineations that suggest northwestward tectonic transport. Similarly oriented lineations are present in the Saudi Arabian

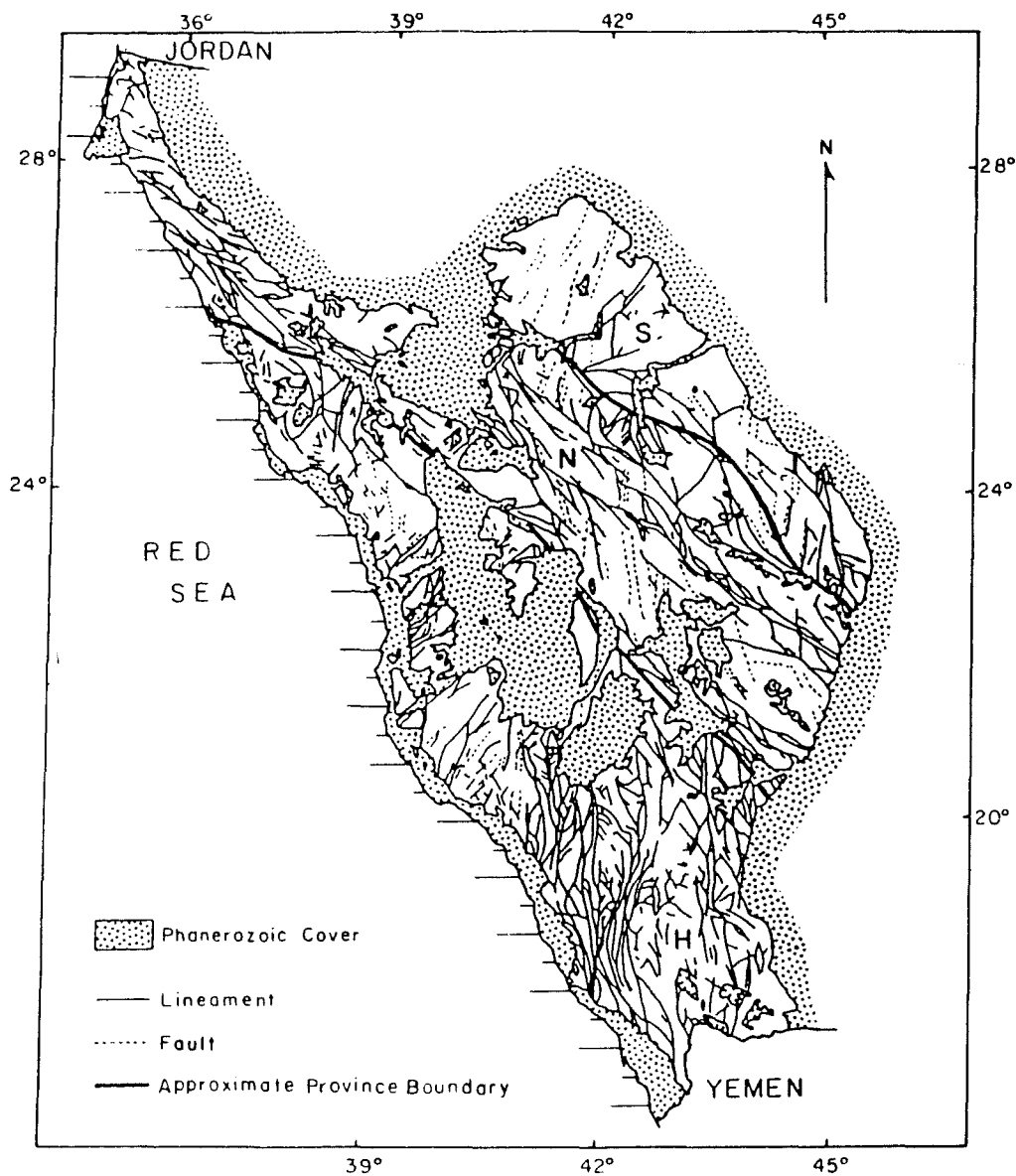


Figure 10. Structural grain of the Arabian Shield (after Greenwood et al., 1980). S= Shammar Province, N= Najd Province, H= Hijaz-Asir Province.

basement (Greenwood et al., 1980; Smith, 1979; Davies, 1980).

#### North-South Hijaz-Asir Grain

The braided nature of the north-south Hijaz fault grain (Figure 10) results from northwest, north-south, and northeast trending individual faults, folds, and plutonic belts. This pattern was produced by the complex tectonic events of the late Precambrian (Greenwood et al., 1980).

#### Northwest Najd Grain

Most important to the present study are the mostly northwest trending structures of the late Precambrian left-lateral Najd fault system (Figure 10) of the Arabian-Nubian Shield (Greenwood et al., 1980; Moore, 1979). Major right-lateral, north to northeast trending, strike-slip faults, which would be the theoretical conjugate complements to the northwest set, are rare. The Najd system is superimposed on and cuts the older Hijaz structures.

Najd faults in Saudi Arabia form a braided system at the surface with en echelon and curved faults converging and diverging (Moore, 1979). The pattern of the Najd



system is very similar to that developed in the experiments of Wilcox et al. (1973) in which wrench faulting of rigid blocks at depth resulted in the development of primary and secondary extensional and compressional structures in an overlying, less rigid medium.

The Najd fault system extends over 1100 kilometers across the Arabian Shield. Block motion in the Phanerozoic cover southeast of the Arabian Shield, along the extension of the Najd zone, may indicate a total length approaching 2000 kilometers (Moore, 1979). The zone narrows to the northwest as it approaches the Red Sea, where it is terminated and locally reactivated by Red Sea rifting. Possible extensions of the Najd zone can be found in similar trends on the western side of the Red Sea (Figure 9). Because some of the faults bordering Gebel Duwi parallel Najd trends, it is this northwest extension into the Eastern Desert of Egypt and possible later normal reactivations that are of particular interest in this study.

### Folding

There are at least three, perhaps four, phases of folding that have affected the basement rocks of the study

area. Only the granites, felsite dikes, and youngest quartz veins show no evidence of being affected. The three phases of folding are coaxial, producing shallow plunging, southeast-northwest to north-south trending fold axes (Figure 11a). Axial surfaces of the folds exhibit dominantly northwest-southeast strikes with variable southwest dips (Figure 11b).

The Meatiq Dome, about 10 kilometers west of the study area (Figure 1), has an overall double-plunging, north-northwest trending anticlinal form (Sturchio, Sultan, and Batiza, 1983) and exhibits related N35W/S35E, gently plunging minor folding. El Shazly (1964) also notes northwest trending folds in Egyptian basement near the Red Sea. Greene (1984) has mapped the large, S40E plunging, el Isewid synform in basement immediately east of Gebel Atshan, noting rare coaxial outcrop-scale folds. The large N60W trending Hamrawein Synclinorium lies in Abu Zied's area (Figure 1) to the north (Wise et al., 1983). The map pattern of planar features in the basement of the area of the present study (Plate 1) does not suggest any obvious major structures. Most minor folds noted in this study are subparallel to the axis of the el Isewid synform, and lie on the flanks of this larger structure.

Sturchio, Sultan, Sylvester, et al. (1983) have dated two late Proterozoic compressional events that affected

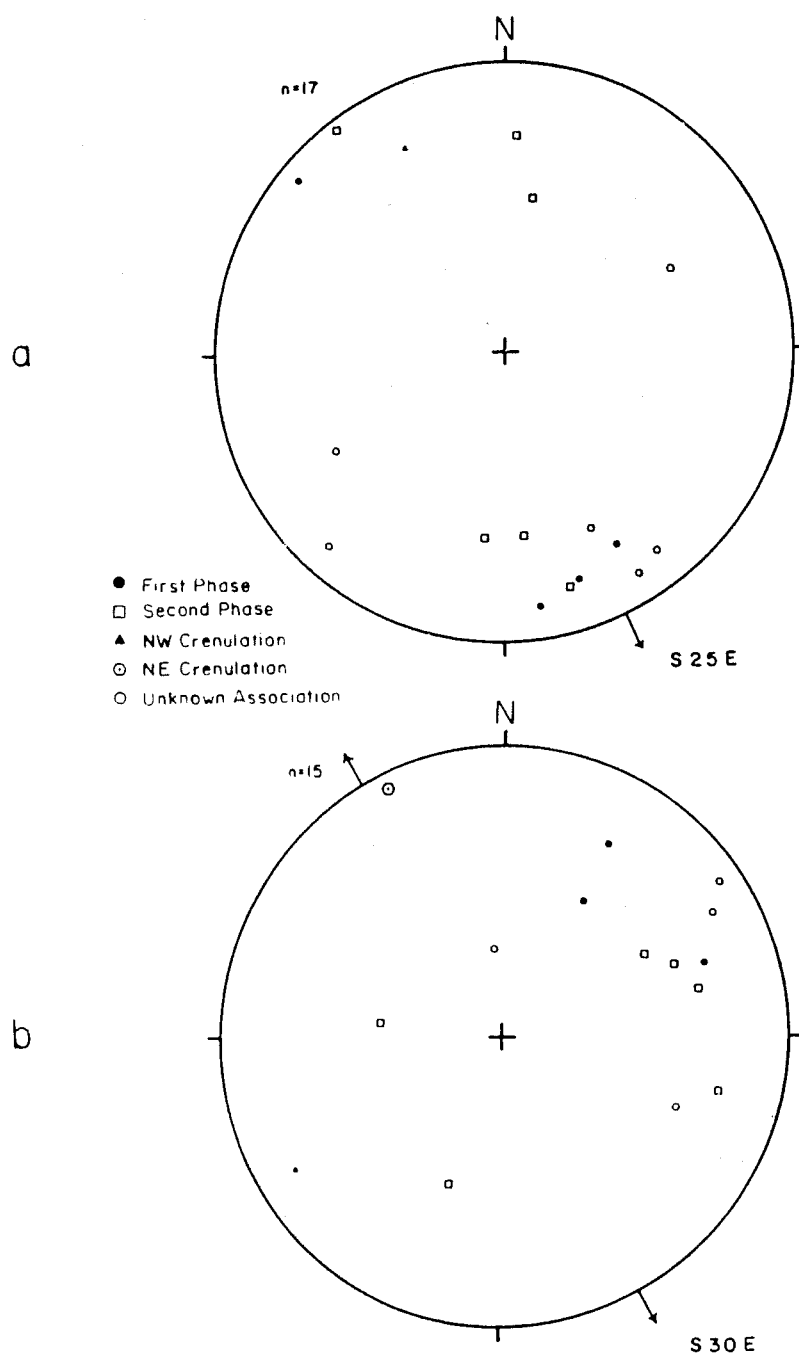


Figure 11. a) Fold axes the in Precambrian basement of the study area.  
 b) Poles to axial planes of folds in the Precambrian basement of the study area.

the Meatiq Dome. The first event resulted in metamorphism up to epidote-amphibolite grade and formed a low-angle ductile shear zone up to 1800 meters thick containing northwest trending lineations. The end of this event is dated at  $613 \pm 5$  M.y. by U-Pb dating of zircons from a syntectonic tonalite. Similar structures elsewhere in the Eastern Desert suggest the regional nature of this event.

The second tectonic event was the uplift that resulted in the deposition of the Hammamat sediments. This gave the Meatiq Dome its anticlinal structure and is dated at around 600 M.y. (Sturchio, Sultan, Sylvester, et al., 1983).

#### Bedding and Volcanic Layering

Much of the basement of the study area is faintly or indistinctly bedded with monotonous units. Further, it is commonly broken and jumbled to such an extent that consistent bedding orientations are not maintained over significant distances. Therefore, bedding/volcanic layering orientations measured in the field are comparatively rare. These orientations are plotted in Figure 12a and on the geologic map (Plate 1). Most beds dip moderately to the southwest. The remaining poles plot as a diffuse northeast-southwest girdle suggesting a gross

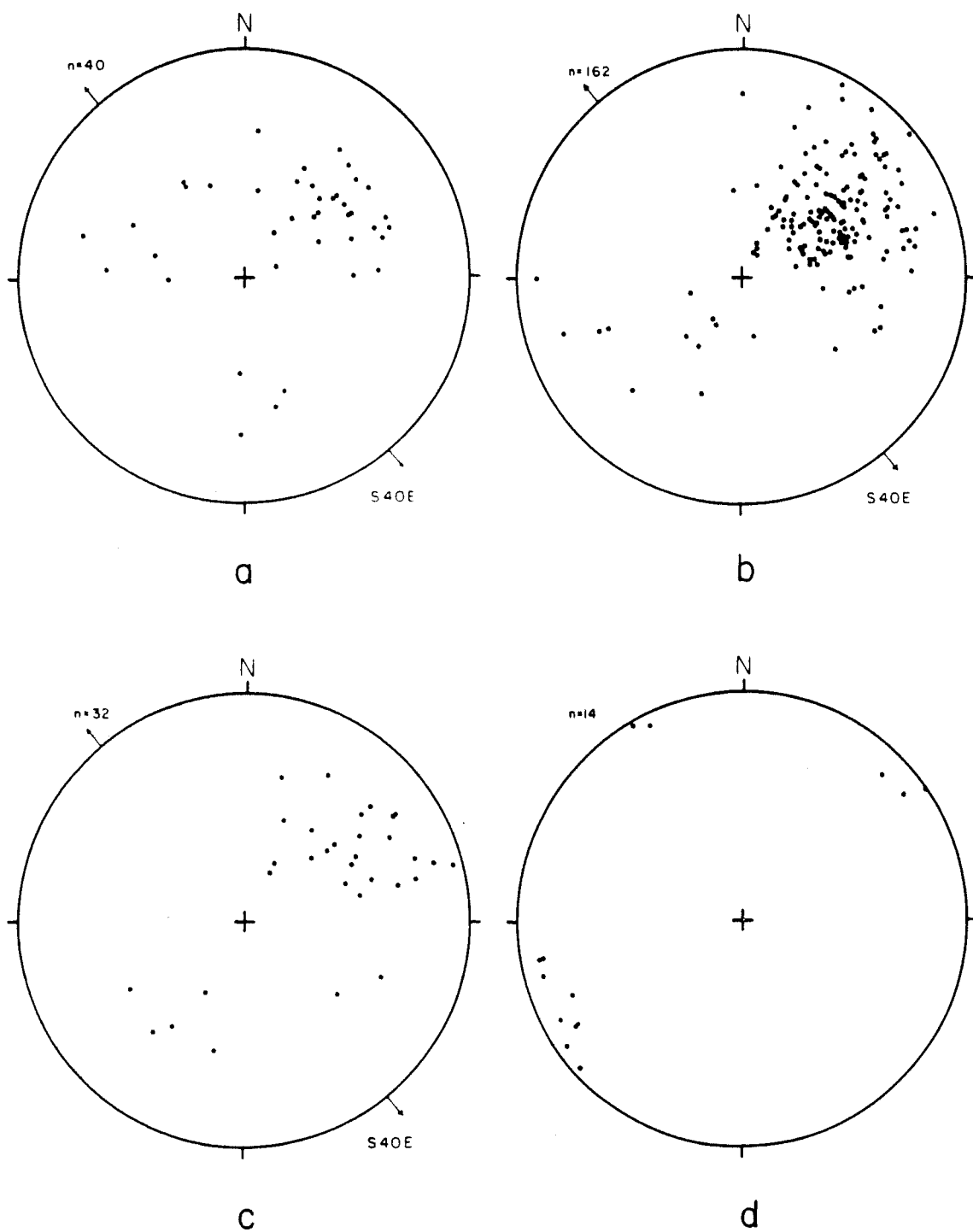


Figure 12. Precambrian basement fabric nets: a) poles to bedding/volcanic layering; b) poles to main foliation; c) poles to second foliation/schistosity; d) poles to crenulation cleavages.

south-southeast plunging fold system.

Foliations and Cleavages. Folds in the basement of the study area are associated with several basement foliations. The first recognized phase of folding produced the main basement foliation; a well-developed spaced cleavage which is present in almost all of the metavolcanics and metasediments. It is the most prominent fabric feature of the basement and dips predominantly southwest at moderate to steep angles (Figure 12b). A weak northeast-southwest girdle is defined by the remaining poles. Similar orientations of the main foliation have been noted to the north of the study area (Ries et al., 1983).

A second phase of folding affected bedding and the main foliation, producing a second basement foliation. It appears as a weaker spaced cleavage in the volcanic layers and as a schistosity in the fine-grained sediments and volcanic ash. The second foliation is commonly subparallel to the main foliation and, where strongly developed, may be indistinguishable from the main foliation. Northwest strikes and moderate to steep southwest dips are characteristic of the second foliation (Figure 12c). Again, a weak northeast-southwest girdle is defined by poles to this feature. Ries et al. (1983) note two cleavages with similar orientations in Wadi Um Esh to

the northwest of the study area.

Weak crenulation cleavage with a consistent northwest strike and very steep dips (Figure 12d) developed as a result of a third phase of deformation. This cleavage is present only locally and, even where best developed, is poorly expressed. This cleavage is seen to affect bedding and the two older foliations.

All three phases of folding are evident in an outcrop on the north side of Wadi Hammadat (Figure 13). Folding and coaxial refolding of bedding and early axial planar features by subsequent deformational phases may account for the variable orientations of these features as represented by the girdles that their poles form on stereonet. Tertiary faulting may also have affected the orientations of Precambrian foliations.

A second crenulation cleavage, which may be the result of a fourth phase of deformation, was noted at two stations in the basement between Wadi Kareim and Wadi Hammadat. This cleavage is very strongly developed with a N60-65E strike and a nearly vertical dip (Figure 12d). The second crenulation must be younger than the second phase, as it affects schistosity, but its age relative to the other crenulation is not known. Ries et al. (1983) note that post-cleavage crenulations and kink bands are common northeast of the study area.

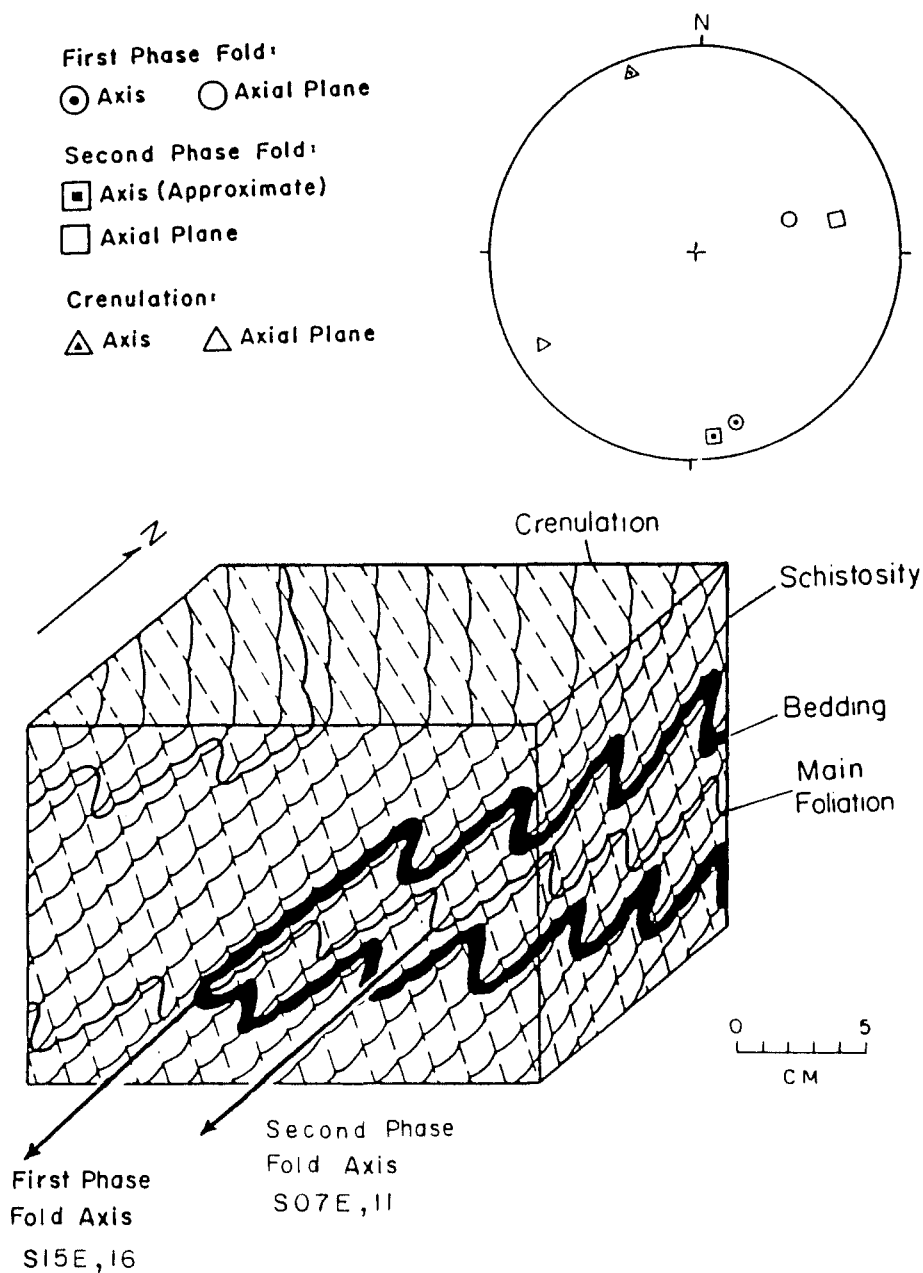


Figure 13. Block diagram and net showing three phases of folding of Precambrian basement as noted in an outcrop along the central southern edge of the Wadi Inglisi Horst Block. The fold affects a sandy bed within finer-grained metasediments.



Lineations. Lineations formed by the intersections of planar basement features are of various kinds. Intersections of the main and second foliations are most common. These features have systematic northwest-southeast to south-southeast trends and shallow plunges (Figure 14a), paralleling fold axes.

Smeared mineral lineations are found on first phase foliation surfaces, generally within volcanic layers, whereas stretched pebbles are found within conglomeratic layers. These features also have fairly consistent northwest-southeast to south-southeast trends and shallow plunges (Figure 14b). Ries et al. (1983) note northwest-southeast stretching lineations with very similar orientations in the plane of the main foliation in Wadi Um Esh (Ries et al. 1983, Figure 7b). They state that this northwest-southeast orientation is noted everywhere, even where the stretching is weakly developed. A pencil-like lineation parallel to the stretching lineation was also noted at several locations in their area. Sturchio, Sultan, Sylvester, et al. (1983) also note similarly oriented stretched pebble lineations at the Meatiq Dome.

Mineral and stretched pebble lineations are parallel to fold axes, yet appear to be, and have been proposed as, indicators of the direction of tectonic transport. This would require the rotation of early-formed fold axes into

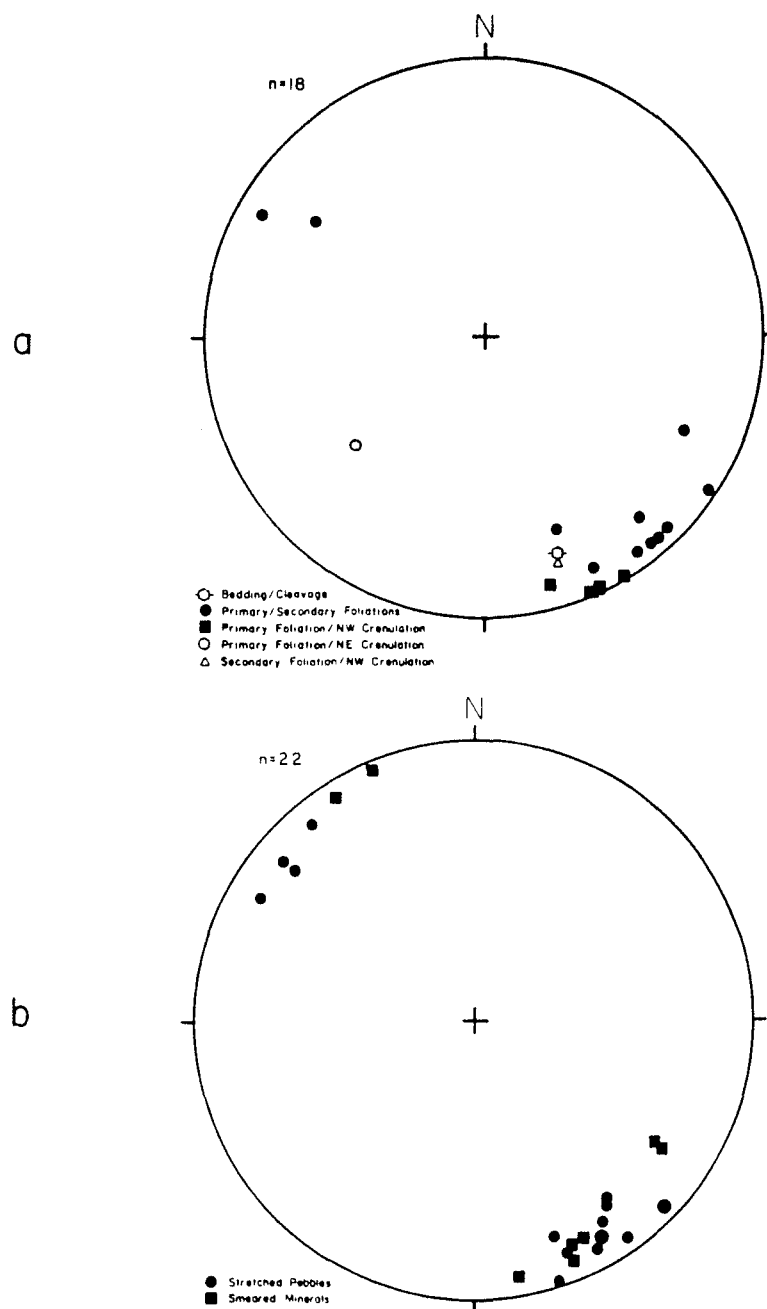


Figure 14. Precambrian basement lineations:  
 a) intersection lineations;  
 b) smeared mineral and stretched  
 pebble lineations.

parallelism with the transport direction, making them tectonic "a" lineations (Sander, 1930). Ries et al. (1983) suggest that the lineations do indicate transport direction, that folding occurred subsequent to lineation development, and that the existing lineations controlled the orientations of the developing folds. They see early, open folds with axes paralleling these lineations and find it difficult to believe that these could be sheath-like folds formed during the rotation of fold axes. The fact that the lineations consistently lie in the plane of the main foliation, an indication that the two features are genetically linked, seems to contradict their proposal. It may be that these are tectonic "b" lineations (Sander, 1930) paralleling fold axes of the first phase. Clearly, the solution to this problem lies outside the scope of this study.

### Dikes and Sills

Three types of small-scale igneous intrusions were noted in the basement of the study area. These features indicate a  $\sigma_3$  (direction of least compression or greatest extension) perpendicular to the plane of intrusion at the time of formation (Anderson, 1951). The first group consists of four granitic to aplitic

intrusions located around the borders of the granites in the southeastern portion of the area. They have no consistent orientation (Figure 15a) and are probably associated with the emplacement of the larger plutons. The intrusion of these small bodies caused minor perturbations of the main foliation.

Two groups of mafic intrusions were identified: west-northwest to north-northwest striking dikes and nearly horizontal sills (Figure 15b). They are fine-grained metabasalts with the exception of a large, coarse-grained, north-south striking dike which weathers to a dark olive green.

The mafic sills were intruded parallel to volcanic layering, and their orientations were probably controlled by the layering. The dikes are indicative of north-northeast to east-northeast extension. At least one is younger than the granite which it cuts, but others exhibit a weak foliation indicating an earlier origin. Several are cut by the youngest quartz veins.

North-northeast- to northwest-striking felsite dikes indicate west-northwest--east-southeast to northeast-southwest extension (Figure 15c). These dikes contain pink phenocrysts less than four millimeters in length in an aphanitic groundmass. Deep weathering to a brick-red color makes it almost impossible to obtain a fresh

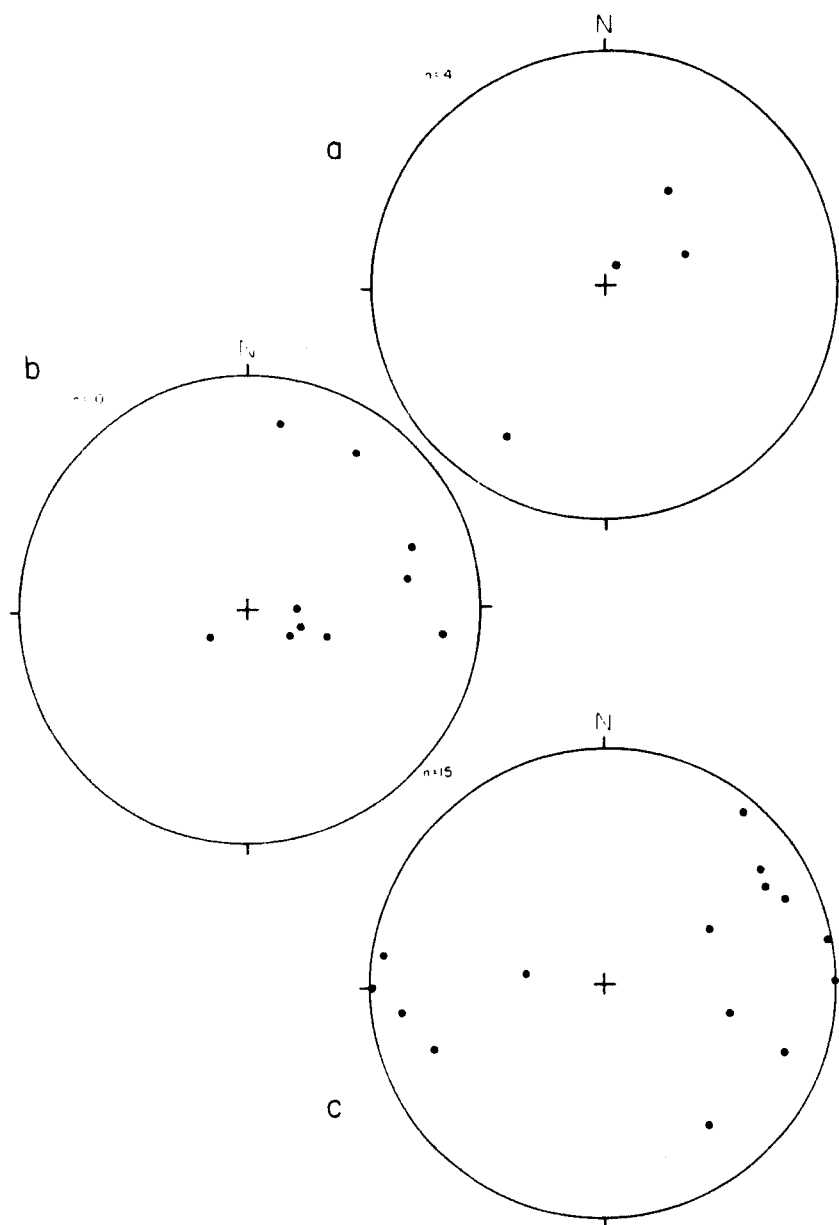


Figure 15. Poles to dikes and sills in Precambrian basement: a) aplitic dikes; b) mafic dikes and sills; c) felsite dikes.

sample. Similar dikes were noted in the basement immediately to the east of the field area (D. Greene, personal communication).

The brick-red felsite dikes are relatively young basement features and are not nearly as shattered as the bulk of the basement. They cut granites, mafic dikes, and shattered quartz veins; none was seen to be folded. Faulting did affect these features, but the age of the faults cutting them was not determined.

#### Quartz Veins

The orientations of 137 quartz veins were measured in the basement of the field area. Especially high concentrations occur in areas adjacent to the granitic bodies in the southeastern section of the area (Plate 1). The veins exhibit fairly consistent orientations, having northeast to north-northeast strikes and steep dips (Figure 16). A small population of northwest-striking, steeply dipping veins is also present.

Quartz veins also are interpreted as having developed under the influence of a stress field with  $\sigma_3$  oriented normal to the plane of the vein. Hence, the dominant northeast strike and steep dip indicate nearly horizontal northwest-southeast extension during quartz

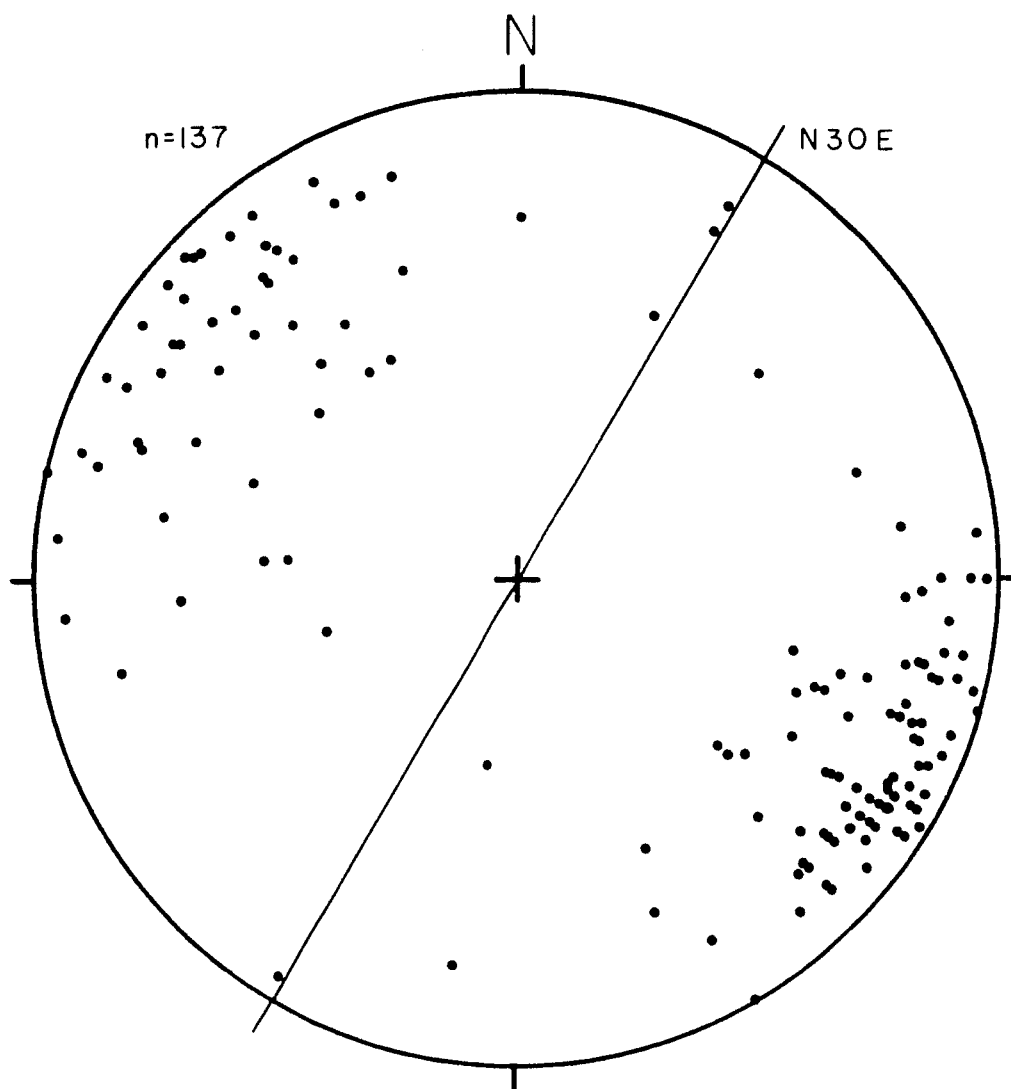


Figure 16. Poles to quartz veins in Precambrian basement.

vein development. The northwest-striking veins may have developed under local stress fields, in part associated with emplacement of the granites. The granites may also have provided a source for silica-rich solutions. Five of the northeast-striking veins with thicknesses greater than 20 centimeters have zones of pink to deep red feldspar within them, giving them a granitic appearance. This may be taken as a further indication that some quartz veining was associated with granite emplacement and with related stresses in the country rock roofing the plutons. Greenberg (1981) also associates quartz veining with emplacement of the Younger Granites of Egypt.

The northeast-striking veins apparently belong to at least two major subsets; older, commonly shattered veins and a younger group which is little affected by subsequent deformation. Some members of the older family exhibit the main foliation and are cut by felsite dikes and faults. Only one was observed to be folded. Younger quartz veins were not seen to be deformed, except by faulting, and show no evidence of foliation. None was seen to cut felsite dikes or significant faults.

The only quartz-bearing structural features in the platform sediments are microjoint fillings. This suggests a pre-Mid-Cretaceous origin for all quartz veins, most



probably in the late Precambrian. Older, shattered veins developed prior to, or during, the early stages of the first phase of folding, and their origin is unclear. The development of the younger, northeast striking veins has tentatively been linked to the first phase of folding, which also produced much of the metamorphism of the basement (Sturchio, Sultan, Sylvester, et al., 1983). The veins may have formed as A-C joints perpendicular to the regional sigma 3, with the metamorphism providing a source of quartz. Finally, quartz veins of various orientations were developed in association with emplacement of the granites.

## C H A P T E R    I I I

### STRATIGRAPHY OF THE SEDIMENTARY COVER

Two groups of Phanerozoic sedimentary rocks occur in Egypt's Eastern Desert. The older of the two groups consists of Cretaceous to Eocene platform carbonates and related clastics that were deposited unconformably on Eocambrian basement. Resting unconformably both on the basement and the older sediments is the second group: mostly littoral deposits associated with the formation of the Red Sea.

#### Cretaceous to Eocene Sediments

There are seven mappable formations throughout the area west of Quseir (Figure 17), deposited during a late Cretaceous through Early Tertiary southward transgression of the Tethyan Sea.

#### Nubia Formation

The Nubia Sandstone was a name applied by Russegar (1837) to sandstones cropping out along the Nile River south of Aswan. Since then, several variations of the

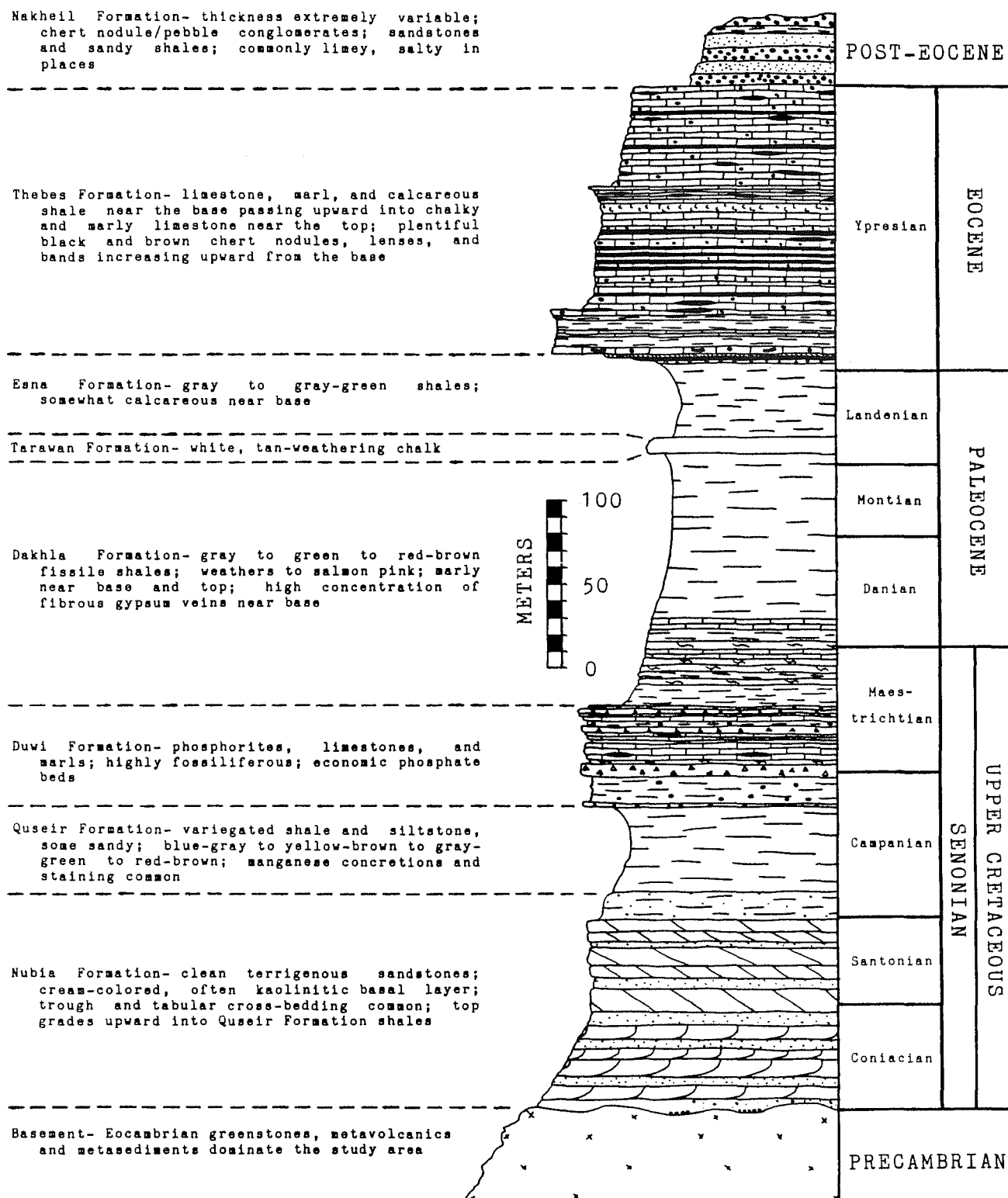


Figure 17. Stratigraphy of the Cretaceous to Eocene platform sediments.

name have been applied to sandstones and sandy shales over most of northeast Africa, often without regard to age or stratigraphic position. Throughout this study, use of the term Nubia Formation will conform to the usage of Youssef (1957) as applied to a predominantly nonmarine sequence lying unconformably on the Precambrian basement complex. Its upper boundary is marked by a transition to poorly consolidated, varicolored shales.

Based on sparse fossil evidence within the Nubia Formation and the overlying Quseir Formation, the Nubia in this region is tentatively dated as Coniacian to early Campanian in age. It has been considered by others to be as old as Cenomanian (Ward and McDonald, 1979; Van Houten, personal communication) and as young as early Maestrichtian (Issawi, 1972) in various parts of Egypt. It should be noted that northward, in the Sinai, an older "Nubian Sandstone" of Paleozoic age lies beneath units correlative with the Cretaceous formation of the map area.

The thickness of the Nubia Formation in the Eastern Desert is highly variable, thinning over basement topographic highs. Within the study area, its thickness varies from 70 to nearly 200 meters.

The Nubia can be divided into three distinct lithologic units in the Quseir area. These are, from oldest to youngest, trough-cross-bedded conglomeratic

sandstone, tabular-cross-bedded sandstone, and ripple-laminated siltstone and lenticular sandstone units as described by Ward and McDonald (1979).

The lowermost trough-cross-bedded sandstones rest unconformably on basement, which is often kaolinitized along the contact. Within the study area, the base of the Nubia is consistently marked by a light cream-colored coarse sandstone to pebble conglomerate exhibiting lavender and locally yellow staining. The basal zone is unbedded or poorly bedded. The remainder of the lowermost unit consists mainly of yellow-brown to red-brown, non-bedded to trough-cross-bedded sands. The basal unit attains a maximum thickness of about 80 meters in the vicinity of Quseir and is 50 to 60 meters thick at the southern end of Gebel Duwi. Great local thickness variations are observed due to basement topography. The characteristics of the lowermost unit are consistent with deposition on an alluvial plain (Ward and McDonald, 1979).

The second unit within the Nubia Formation is made up of broad lenses of nonbedded sands and spectacular tabular-cross-bedded sands that interfinger with ripple-laminated fine sands to silts. Cross-bedded sands account for more than half the thickness of this unit, which also was deposited on an alluvial plain (Ward and McDonald,

1979). A variable thickness of 50 to 140 meters is reported for this unit in the Eastern Desert (Ward and McDonald, 1979). At Gebel Duwi, it has a thickness slightly greater than the underlying trough-cross-bedded sands.

The third and uppermost lithologic subdivision of the Nubia Formation is dominated by dark brown to dark red-brown fine sandstones and sandy siltstones. Some of the sands are trough-cross-bedded, particularly near the base of the unit. An alluvial coastal plain/shallow marine environment is postulated for the deposition of this unit. The unit grades upward into the variegated shales of the Quseir Formation. Precise placement of a contact between the Nubia and Quseir Formations is difficult as there is a transitional zone where sandy silts and variegated shales are interbedded. A fairly subjective boundary was drawn where the variegated shales become dominant. The thickness of the upper unit varies from about 20 meters at Gebel Atshan to about 30 meters at Gebel Duwi.

#### Quseir Formation

The variegated shales of the Quseir Formation were long considered to be part of the upper Nubia Formation. Youssef (1949) described them in detail, calling them the

"variegated clays". The name Kossier Variegated Shales was later applied to them by Youssef (1957), but Ghorab's (1956) name, the Quseir Formation, has gained wider acceptance.

The Quseir Formation consists mainly of poorly consolidated shales, locally sandy, that vary in color from gray-green to blue-gray to red-brown with rare yellow-brown horizons. Manganese staining and concretions are common and some gypsum veining is evident. Local thin phosphate bands are present in the upper part of the formation.

Some workers (Abd El Razik, 1967; Trueblood, 1981) put the upper contact of the Quseir formation at the lowermost phosphate band. However, as the lithology continues to be dominated by variegated shales above these isolated bands, Youssef's (1957) placement of the contact at the base of a hard, brown, one meter phosphatic horizon will be used. Varicolored shales exist above this horizon, but are secondary. This placement of the contact yields a thickness of 50 to 75 meters for the Quseir Formation in the study area.

Many of the early fossil-based age determinations for the "Nubian Sandstones" were, in fact, based on evidence from the variegated shales. A Senonian age is indicated by these fossils and agreed upon by most authors (Said,

1962; Issawi et al., 1969). In the Quseir area, a more precise age determination of Campanian (Youssef, 1957; El Tarabili, 1966; Abd El Razik, 1967; El Dawoody, 1970) or possibly Campanian to early Maestrichtian (Issawi et al., 1971; Issawi, 1972) has been made on the basis of fossil gastropods and pelycypods from the Quseir and Duwi Formations.

Fossils found in the Quseir Formation are of marine and fresh water origin (Newton, 1909). Plant remains and fossil wood (Seward, 1935; Issawi et al., 1971) indicate a marginal marine to estuarine environment of deposition. The Quseir Formation marks an upward transition from a continental environment to the shallow marine environment that produced the remainder of the platform sequence.

#### Duwi Formation

Resting conformably on the Quseir Formation is the Duwi Formation. It was originally named the Phosphate Formation by Youssef (1949), and that name continues to be used by many workers, particularly along the Nile River and in the Western Desert. Ghorab's (1956) name, Duwi Formation, given for its type locality in the southern Gebel Duwi area will be used here. This name is used by



most workers in the Eastern Desert.

The formation consists mainly of hard, semi-crystalline or siliceous limestones, phosphatic beds, marls, and shales and contains chert bands, lenses, and nodules. The phosphatic beds are mined for tricalcium phosphate. Within the study area, the lower contact is marked by a series of hard porcellanite and siliceous phosphate bands interbedded with marls and coquina limestones.

The upper half of the formation is dominated by marls and oyster coquinas. Ostrea villae, with a ribbed, triangular shell, is the dominant fossil found throughout the formation. A one to three meter, soft, gray, phosphatic bed marks the top of the Duwi Formation. In the Quseir area, this formation is 50 to 70 meters thick.

Various workers (El Tarabili, 1966; Abd El Razik, 1967; Issawi, 1972) assign a Maestrichtian age to the entire Duwi Formation, based on fossil dating. However, Youssef (1957) dates the lower part of the formation as Campanian on the basis of fossil ammonites, gastropods, and oysters.

Bays connected to the open sea where strong currents reworked the bottom sediments are the environments suggested by Said (1962) for the deposition of the Duwi Formation. Nairn (1978) notes that the fossil assemblages

indicate an open shelf environment and suggests that the phosphates originated in shallow coastal basins behind shoals or bars, with coarser deposits forming during storms.

### Dakhla Formation

Conformably overlying the Duwi Formation is the Dakhla Formation, which is composed mostly of gray to green to red-brown shales. These weather to a salmon pink color characteristic of the Dakhla slopes. Youssef (1957) includes these rocks in the Esna Formation, but Said (1962) gives them separate formational status.

The lower part of the Dakhla Formation is marly with local limestone beds. Immediately above the lower contact are several meters of dark gray-brown shales with abundant, irregular, fibrous gypsum veins. These are known as the "gypsy shales" by the local miners and are used as an indication of proximity to the uppermost phosphate bed of the Duwi Formation. The balance of the Dakhla Formation is dominated by fissile shales, which terminate at the base of the chalk of the Tarawan Formation. The thickness of the Dakhla Formation ranges between 145 and 170 meters.

Fossils in the Dakhla have fixed its age as Maestrichtian at the base to early Landenian at the top (Issawi et al., 1969; Issawi, 1972). Other authors (Youssef, 1957; Said, 1962) assign a Danian age to the upper Dakhla. The fossils are of shallow-water marine organisms indicating near-shore deposition.

#### Tarawan Formation

The shales of the upper Dakhla Formation grade upward into the white marls and marly chinks of the Tarawan Formation. It is often called the Chalk Formation (Said, 1962) or lumped together with the overlying Esna Formation. Because these white, tan-weathering chinks are lithologically distinct from the shales above and below and have average thicknesses of 10 to 20 meters in the study area, they will be treated as a separate formation. However, because the outcrop pattern at the 1:40,000 scale of the original geologic mapping is very narrow, the unit is combined with the Esna Formation on the map (Plate 1).

On the basis of fossil foraminifera, a Landenian age has been assigned to this unit (Issawi et al., 1969; Issawi et al., 1971; Issawi, 1972). It was deposited in a shallow marine environment.

### Esna Formation

The Esna Formation rests conformably on the white chalks of the Tarawan. In the Quseir area, this unit consists of 50 to 60 meters of gray to green, thin-bedded shales with a few marly and silicic beds at the top. A brown silicified zone containing pelocypod fragments commonly forms the lowermost bed.

This unit is dated as Landenian to early Ypresian in age on the basis of fossil foraminifera (Issawi et al., 1971; Issawi, 1972). It was deposited in a near-shore environment and represents a temporary regression following the somewhat more distal deposition of the Tarawan.

### Thebes Formation

The uppermost unit of the Cretaceous to Eocene sequence is the Thebes Formation. It is also known in the literature as the "Operculina limestone", "lower Libyan", and "limestone with flint" (Said, 1962).

In the study area, the base of the Thebes Formation is generally marked by hard limestone with chert overlain by a hard, gray to brown-gray limestone containing Turritella casts. From the base to the top of the main

ridge of the Thebes, the lithology is dominated by chalky limestone interbedded with thin crystalline limestone, massive gray limestone, nodular, recemented limestone conglomerate, marl, and some shale. Dark brown, gray, and black chert is very common in the form of nodules, bands, and lenses. Above the main ridge-forming beds, the limestones tend to be more crystalline and thinly bedded, with chert slightly less common.

The thickness of the Thebes Formation in the study area is everywhere greater than 160 meters and can exceed 200 meters. The amount of erosion of the top of the unit controls its thickness.

Fossil foraminifera indicate a Ypresian age for this formation (Said, 1962; El Tarabili, 1966; Issawi, 1972) and its deposition marks a return to a more distal, deeper water environment. Uplift in the Eastern Desert during the early Eocene, possibly related to the early stages of Red Sea development, terminated its deposition and eventually brought the area above sea level, resulting in the subsequent erosion.

#### Topographic Expression

The units of the Cretaceous to Lower Eocene sequence exhibit characteristic topographic expressions which help

to identify them in the field and on air photos. The profile of the stratigraphic column (Figure 17) indicates each unit's relative resistance to erosion.

The Nubia Formation can be distinguished easily from the underlying basement by its brown color and its weathering pattern. The lower two subunits tend to form steep slopes, which are commonly covered with talus. The top of the second subunit is commonly present as a minor dip slope with the less resistant upper subunit stepping up to the overlying shales.

The Quseir Formation weathers relatively easily and develops gentle slopes between the two more resistant units that bound it. It is commonly covered with its own debris and that from the Duwi Formation. This makes it difficult, in places, to determine whether the material is in place or slumped.

The Duwi Formation, especially the resistant limestones and coquinas, forms cliffs and ridges that are easily identified in the field and on air photos. The uppermost coquina bed can be seen as a stripped dip slope that generally dips northeast in the study area. The Duwi-Dakhla contact is almost always covered with debris from the overlying strata.

The relatively soft shales of the Dakhla Formation

are eroded back from the Duwi ridges and slope gently up to the more resistant chalks of the Tarawan Formation. The slope steepens near the top where the shales are protected by the chalk, which forms a narrow, debris-covered ledge.

The soft Esna Formation slopes moderately up to where it, in turn, is protected by the limestones of the Thebes Formation. The protective cap of massive Thebes limestones forms ridges that are the most prominent topographic features of the Quseir area. The main ridge is formed at the boundary between the chalky lower half of the formation and the more crystalline limestones of the upper Thebes. A minor cliff is formed approximately a third of the way up from the base of the main ridge.

#### Post-Lower Eocene to Pre-Middle Miocene Deposits

##### Nakheil Formation

Over much of the area, the Nakheil Formation unconformably overlies the platform sequence. Along the northeast side of Wadi Nakheil it rests on basement. The bulk of the Nakheil deposits occur in the downfaulted troughs northeast of Gebel Duwi and east of Gebel Atshan.

Youssef (1949) first described these rocks as the

"Conglomerate and Sandstone Series" in the Quseir area. The sequence is extremely variable lithologically, consisting of chert nodule and limestone conglomerates, sandstones, sandy shales, and sandy limestones. The basal bed of the unit is usually a chert and limestone cobble conglomerate. The formation fines upward and in some instances appears to fine laterally with increasing distance from major faults. Several of its upper beds are similar in appearance to the shales of the Quseir Formation and can be gypsiferous and/or salty.

By strict definition, the Nakheil Formation contains no basement fragments (Trueblood, 1981) suggesting that basement was not exposed at the time of deposition of this unit. However, some quartz pebbles of possible basement origin were noted in the conglomerates in Wadi Nakheil. As basement is in contact with this unit in Wadi Nakheil, these pebbles may have come directly from this source. They may also have come via the platform sediments, however.

To date, the Nakheil Formation has proved completely unfossiliferous, even in thin section (Naim and Ismail, 1966). It is therefore very difficult to assign it a precise age. Said (1962) proposes an early Eocene age, while El Akkad and Dardir (1966b) and Issawi et al. (1969)



assign it to the Oligocene, and Abd El Razik (1967) calls it Middle Miocene. Similar conglomerates of Oligocene age occur in the Gulf of Suez with only slight angular unconformity with respect to the Thebes and older units (private communication from petroleum company sources). Limestone and chert conglomerates of pre-middle Miocene age are also exposed along the Gulf of Aqaba/Dead Sea rift (Garfunkel et al., 1974).

The thickness of this formation is extremely variable due to its deposition as a tectonically controlled unit. Multiple conglomeratic beds within the Nakheil Formation suggest several periods of tectonic activity during its deposition. It cannot be determined from this study whether major normal faulting disrupted the platform sediments prior to, during, or after deposition of the Nakheil Formation. A much more detailed study of facies, transport directions, and sources of clastic material would be necessary to determine whether it was deposited in downwarps or in fault-bounded troughs. El Akkad and Dardir (1966b), Issawi et al. (1971), and Richardson (1982) favor the fault-bounded trough origin, perhaps in a lacustrine environment. However, as these studies provide no concrete support for this preference, the validity of their conclusions is uncertain.

The lower conglomeratic beds tend to form low ridges,

readily identifiable on the ground and on air photos.

### Middle Miocene to Recent Deposits

A group of mostly littoral deposits of middle Miocene to Recent age lies unconformably over the basement and the aforementioned sediments. This group is associated, for the most part, with Red Sea formation and deposition in the resulting basin. These sediments crop out as a narrow strip along the western coasts of the Gulf of Suez and Red Sea (Figure 4). In the Quseir area, the strip is 5 to 10 kilometers wide and consists of five distinct units. With the exception of the recent alluvial deposits, they have only minor or no exposure in the mapped area (Plate 1). For a more detailed description, see Greene (1984).

### Recent Wadi Alluvium

The present wadi system in the Quseir area cuts across all of the other units seen in the Eastern Desert. Wadi floors are covered with a thin veneer of clastic sediments ranging in size from clay to boulders. These deposits cover large sections of the mapped area and are transported toward the Red Sea by catastrophic flooding of wadis following rainstorms.

## C H A P T E R IV

### STRUCTURAL FABRIC

Faults, folds, joints and a small number of veins were noted in the Cretaceous-Tertiary platform sediments. As previously mentioned, faults and joints in basement also are discussed in this chapter.

#### Faults

Most major fault surfaces in the study area are eroded and buried under talus. Consequently, inferences concerning regional fault motions are based on minor faults, which yield reasonably consistent results.

Attitudes of 190 faults were measured within the Cretaceous to Eocene platform sediments and the Nakheil Formation of the study area (Figure 18), 116 of which exhibit slickensides (Figure 18) and have an ascertainable sense of motion. Few of the fault surfaces show significant mineralization; calcite mineralization is most common, and some surfaces exhibit minor silicification. A single fault surface has chert developed along it and is associated with a set of chert-mineralized joints. Mineralization is probably the result of precipitation

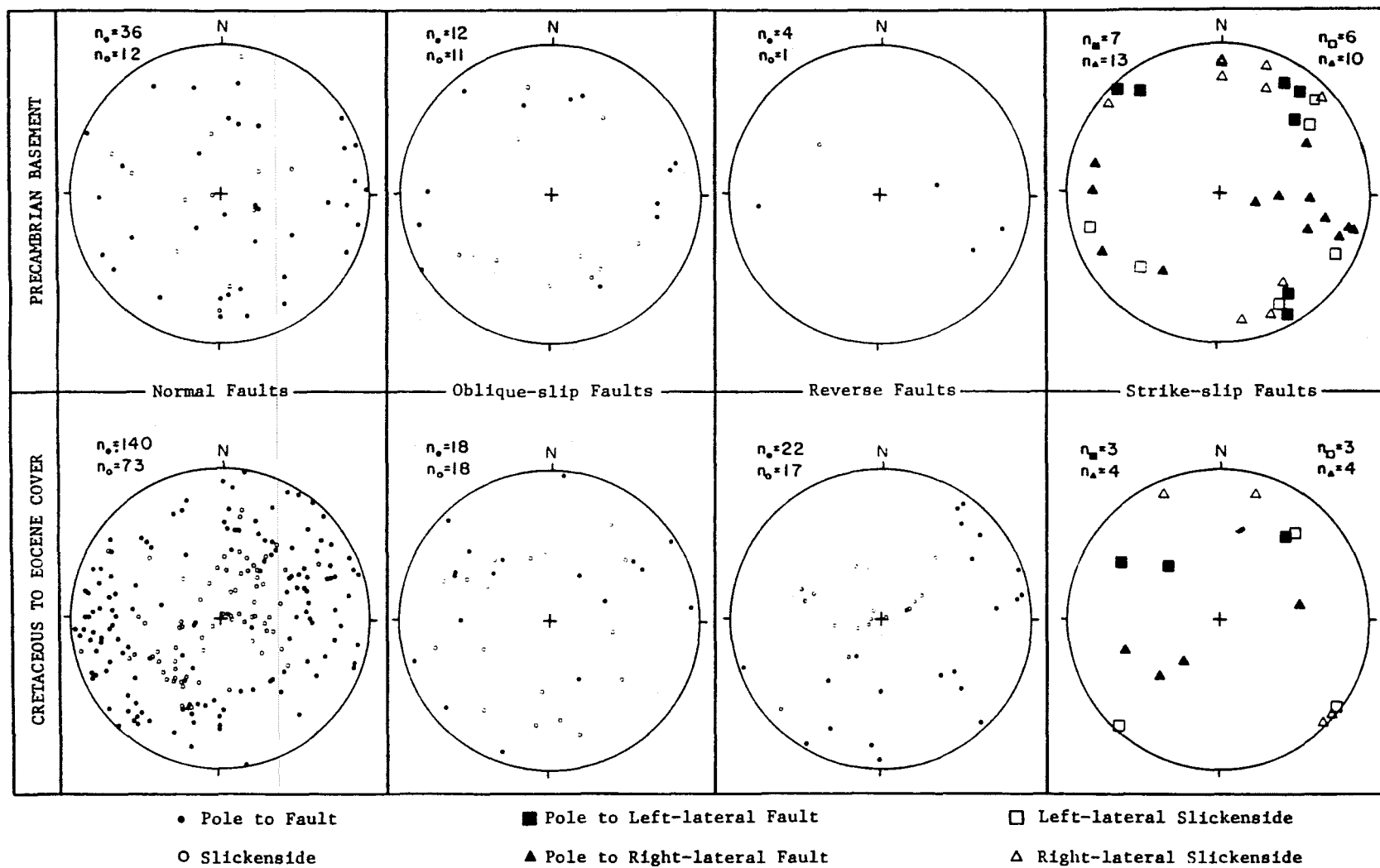


Figure 20. Poles to joints in the study area.

from groundwater circulating through the cracks.

Attitudes of 84 faults in basement rocks were measured (Figure 18). Minor chlorite was noted on a few of the surfaces and post-faulting silicification is fairly common. Thirty-seven of these fault surfaces exhibit identifiable slickensides (Figure 18).

The area is dominated by west-northwest- to north-northwest-striking, steeply to moderately dipping normal faults (Figure 18), as would be expected in an area that has undergone regional northeast-southwest extension in Tertiary time. These faults cut the entire platform sequence as well as basement, indicating their post-early Eocene age.

A small number of northeast-striking reverse faults in basement and cover (Figure 18) suggests possible northwest-southeast Tertiary compression while a larger number of northwest-striking reverse faults in the platform sediments (Figure 18) suggests northeast-southwest compression. Many of the moderately dipping, northwest-striking reverse faults are parallel or sub-parallel to bedding and are in close proximity to major normal faults. These reverse faults are probably the result of flexural slip out of drag-folded synclines.

Steeply dipping, northwest-striking minor reverse faults may have formed as normal faults prior to block

tilting.

A conjugate system of approximately north-south-striking right-lateral and northeast-striking left-lateral faults is present in all rocks from basement through Eocene (Figure 19). The development of this conjugate system is consistent with near-horizontal, north-northeast compression. Only four of these strike-slip faults cut Tertiary sediments. Therefore, a Tertiary age for the N25E compression would be rather tenuous based solely on these data. However, Greene (1984) notes a similarly oriented conjugate system of strike-slip faults cutting early Eocene strata directly to the east. Greene also notes that no similar structures were found in middle Miocene sediments. A tentative age for the N25E compression of middle Eocene to middle Miocene has therefore been assigned.

Similarly oriented strike-slip systems present in the Gebel Zeit area at the southern end of the Gulf of Suez (Perry, 1982) and in the Azlam Graben of western Saudi Arabia (Davies, 1981) suggest the regional nature of these stresses. Northwest trending folds in the Cretaceous to Eocene aged sediments of Gebel el Anz immediately to the northwest (Trueblood, 1981) may also be related to this compressional episode.

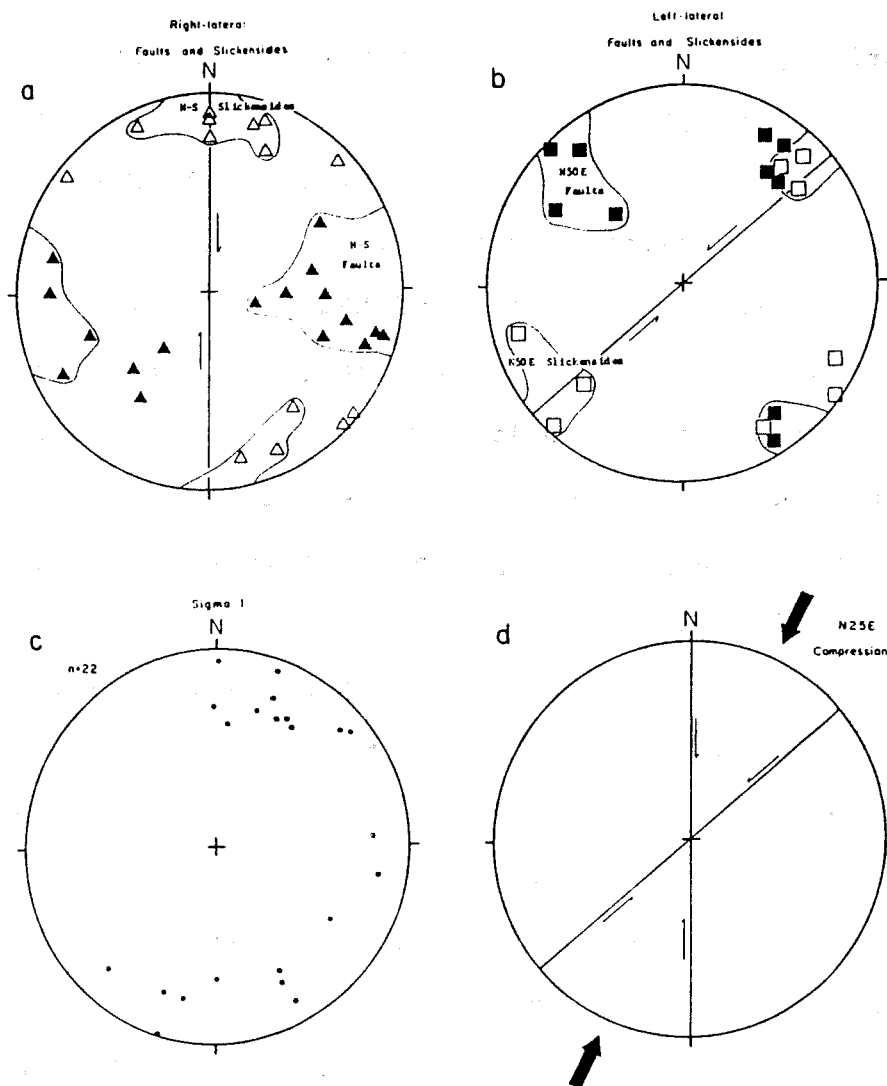


Figure 19. Tertiary N20E compression: a) and b) combined strike-slip fault data; c) calculated causal maximum compressive stress orientations; d) N20E compression and resultant strike-slip fault system.

Some segments of the major north-south normal fault zones may be reactivated right-lateral faults related to N25E compression. Four of the right-lateral faults, including a section of the northern end of the Gebel Atshan Fault Zone, have experienced both right-lateral and younger normal motion. Greene (1984) also notes numerous strike-slip faults reactivated as normal faults and tentatively associates this reactivation with the initiation of Red Sea rifting.

### Joints

Attitudes of 282 joints were measured in the study area; 117 in basement and 165 in the platform sediments (Figure 20). Two or three examples of each prominent joint set present at separate stations throughout the study area were measured to obtain these data. Both basement and cover display approximately east-west- and north-south-striking, steeply dipping major joint sets with some scatter. Steeply dipping, northeast-striking joints are present in both sequences, but are better developed in the cover.

A northwest-striking set with moderate to steep dips is better developed in cover. Joints of this set in basement have extremely variable dips, which may indicate



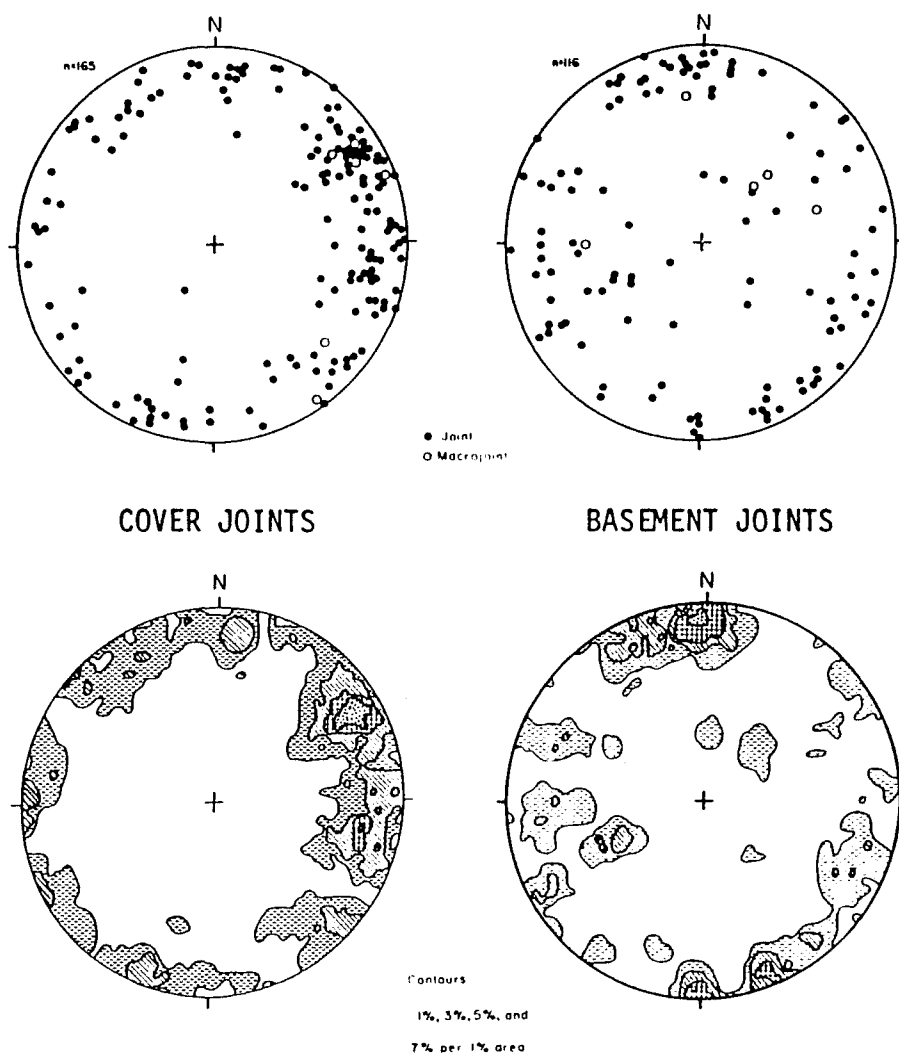


Figure 20. Poles to joints in the study area.

that they are old and have been folded prior to deposition of the platform sediments. They also appear very similar to the main spaced cleavage in the basement; hence some of these "joints" may actually be incorrectly identified cleavage surfaces.

The major north-south and east-west joint sets appear to bear little relation to any other observed structural grains, although some of the older north-south joints may be related to east-southeast extension which would have complemented N25E compression. Similarly, northwest-striking joints may be the result of northeast, Red Sea-related extension.

In most cases, joints are undeformed and cut all other structural features, indicating that they are among the youngest features in the study area. Age relations within and between joint groups are complex and commonly contradictory. At many locations, older, silicified sets parallel fresher, younger sets.

Much more detailed work specifically concentrating on joints is necessary to clearly understand the meaning of these features. However, based on a similarity of orientations and character of basement and cover joints, it is proposed that most jointing is post-early Eocene.

### Veins

Three northeast-striking, steeply dipping chert veins were noted in the upper Thebes Formation atop Gebel Nasser (Figure 21). They appear to have resulted from syn-sedimentary deformation in the Early Eocene and may be related to an early northwest-southeast extension. A small number of other veins were noted in the cover (Figure 21), but because of the small sample size, no useful information can be derived from them.

As previously stated, high concentrations of gypsum veins are located in the lower Dakhla Formation. Although no examination of these features was undertaken, they may prove a fruitful subject for future study.

### Lineaments

Basement Lineaments. Basement lineaments were drawn on LANDSAT return beam vidicon (RBV) images at two scales: 1:208,000 and 1:606,000. The 1:208,000 image (Figure 22) includes both Greene's (1984) area and the present study area (see Figure 1), whereas the 1:606,000 image (Figure 23) includes the entire Quseir-Safaga district. Both images show N30-70E trends of moderate intensity, which correspond to the major N60E faults of the study area.

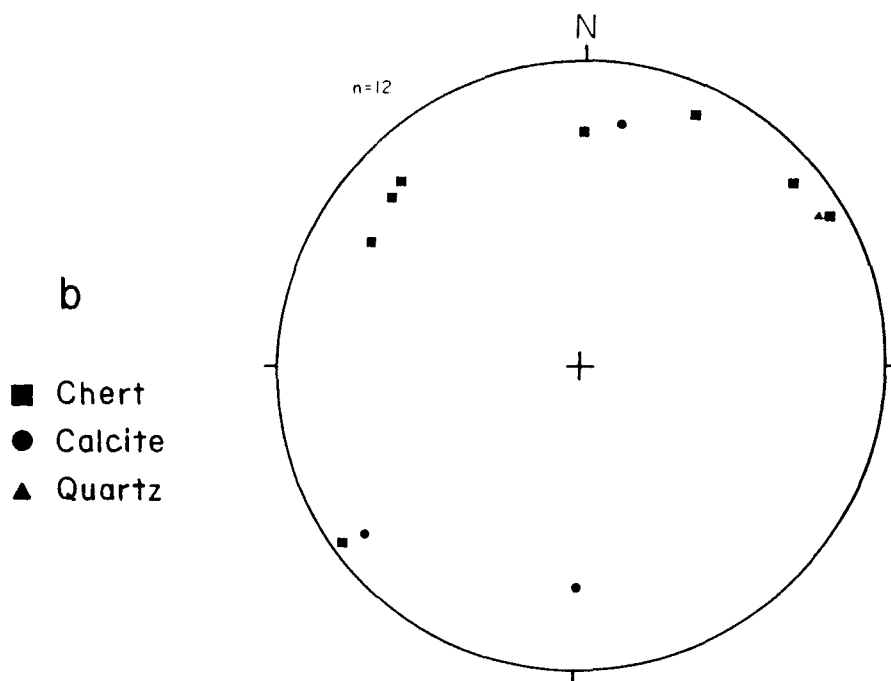
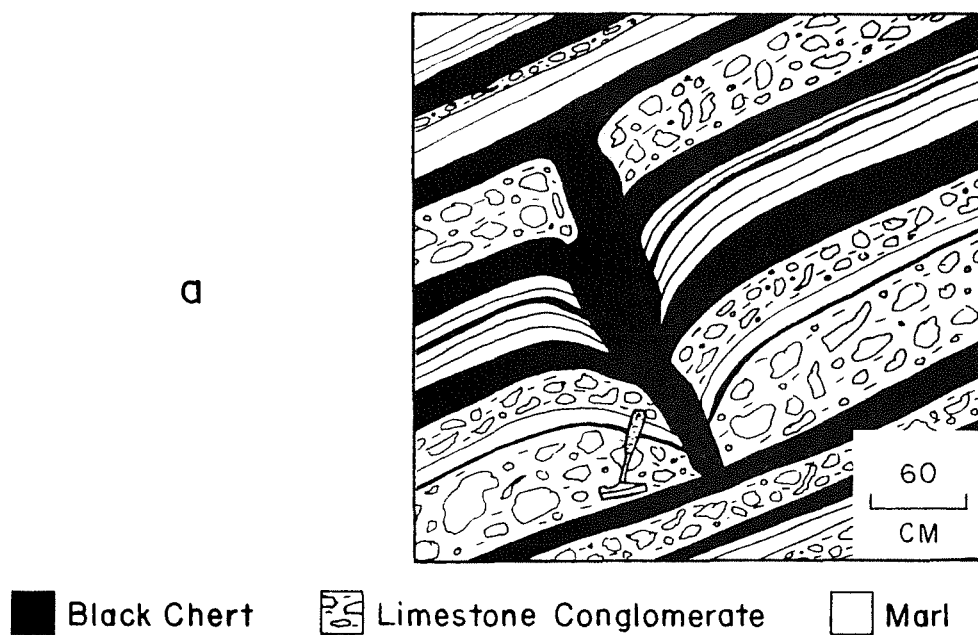


Figure 21. a) Sketch of black chert dike in the upper Thebes Formation of Gebel Nasser.  
b) Poles to veins and dikes in the sedimentary cover of the study area.

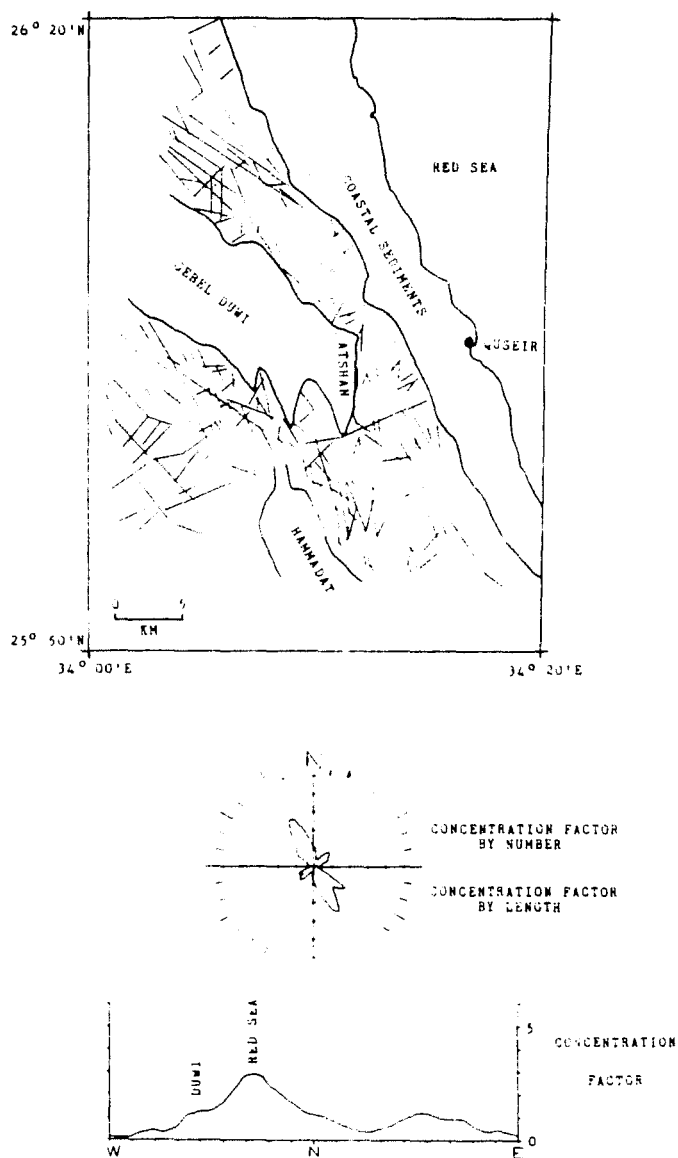


Figure 22. Lineaments in the basement of the study area.  
 TOP: Sketch map of the studied area with lineaments superimposed.  
 CENTER: Rose diagram of lineament azimuths.  
 BOTTOM: Histogram of lineament azimuths by number.  
 Rose diagram and histogram are twice smoothed using a ten degree running average calculated for every degree.

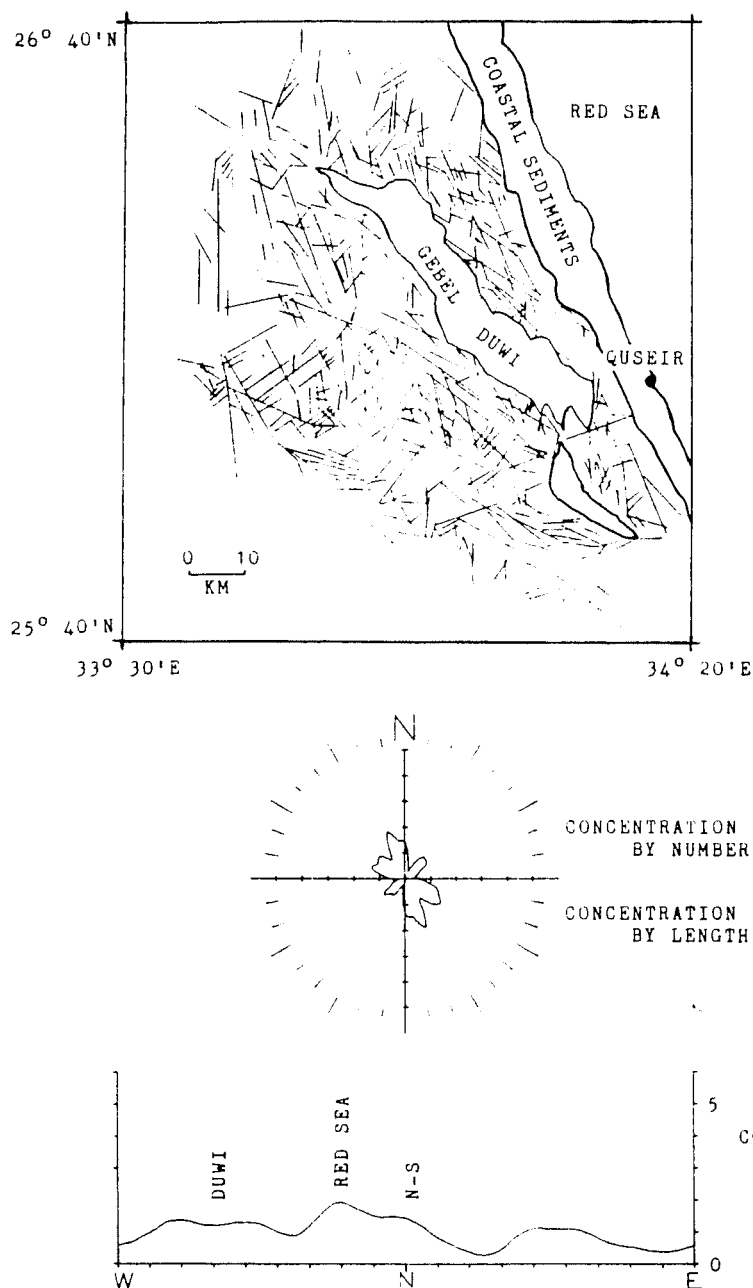


Figure 23. Lineaments in the basement of the Quseir-Safaga area.

TOP: Sketch map of the studied area with lineaments superimposed.

CENTER: Rose diagram of lineament azimuths.

BOTTOM: Histogram of lineament azimuths by number. Rose diagram and histogram are twice smoothed using a ten degree running average calculated for every degree.

North-south trends show up only weakly on the 1:208,000 image, but are stronger on the 1:606,000 image. This may be because they are overwhelmed on the 1:208,000 image by trends parallel to the Red Sea that are very prominent in the basement of the southern Gebel Duwi area. Although the Red Sea trends are present on the regional image, they are not as strong, perhaps due to greater coverage of areas at increased distances from the Red Sea.

Although the regional image exhibits more diffuse northwest trends, the N60W Gebel Duwi (Najd) trend is clearly present. Its presence is also evident on the 1:208,000 image as would be expected. The strength of the rose diagram peaks representing the length and number of Duwi-parallel lines indicates that, although the number of these lines does not approach the number of Red Sea-parallel lines, the total length of lines for these two groups is nearly identical.

Divergence of these results from data gathered in the field lies in the absence of east-west lineaments. East-west faults are relatively common in the basement of the study area and have also been reported in the literature (see Chapter II). East-west faults may be of diminutive size in the Quseir-Safaga region, being too small to be picked up on the RBV images.

Cover Lineaments. Lineaments in the Cretaceous to Eocene

cover were drawn on 1:47,000 copies of the air photos used during field work (Figure 24). Northwest trends, Duwi (Najd) trends, and Red Sea trends show weakly. Minor north-south trends are best represented in the southern end of Gebel Duwi and along the Bir Inglisi Fault Zone.

East-northeast and N20-30E trends are present along the northeastern dip slope of Gebel Duwi. Although neither of these trends is particularly well-expressed in field data for faulting (Figure 17) or jointing (Figure 19), they may be the result of structurally controlled drainage down the dip slope of Gebel Duwi. Several large joints paralleling wadis on the dip slope of Gebel Duwi were noted in the field, but as relatively few stations were located along the dip slope, these features may be underrepresented in the data.

With the exception of the dip slope lineaments, all of the lineament trends have corresponding fractures present in the ground data. Generally, these are the same trends noted by El Tarabili (1964; 1971) in the Quseir area. However, his study showed much stronger Red Sea-parallel trends based on ground data. Although fractures parallel to the Red Sea dominate the sedimentary cover (Figure 18), they must be relatively diminutive as they do not appear as strongly on the air photos.



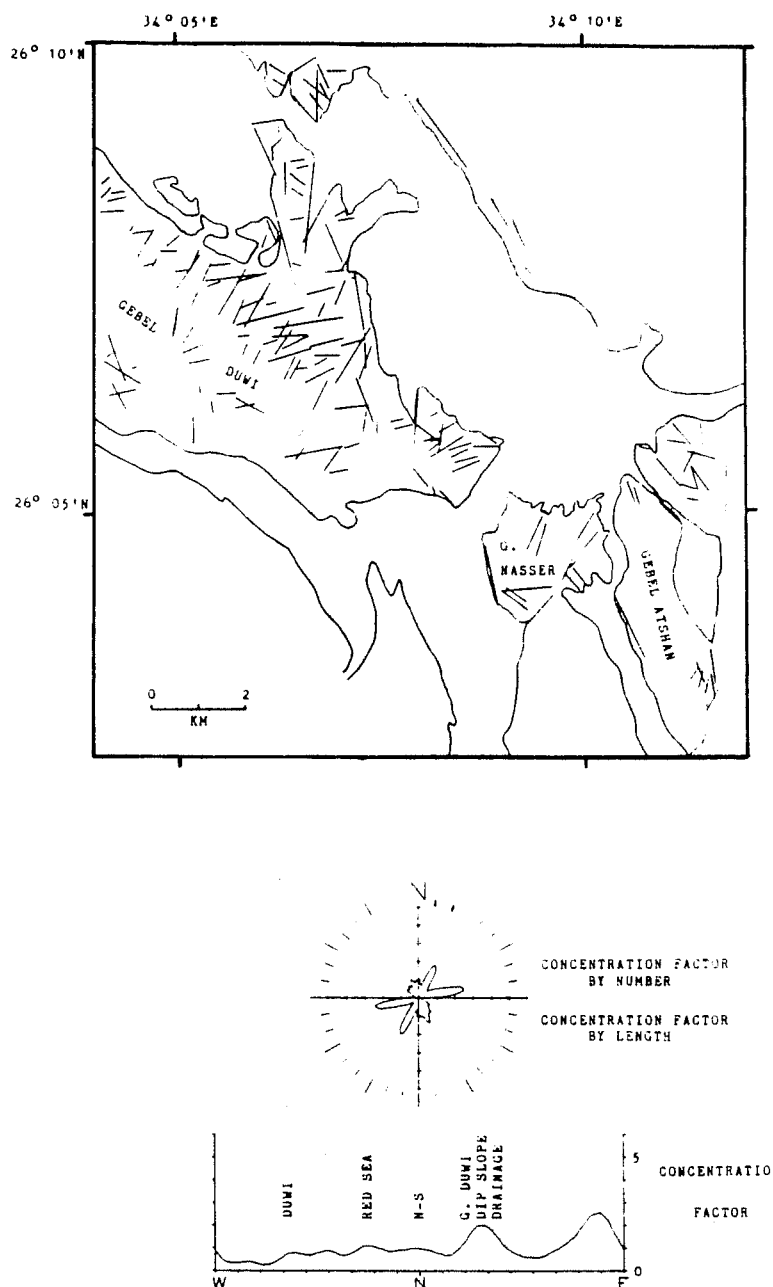


Figure 24. Lineaments in the sedimentary cover of the study area.

TOP: Sketch map of the studied area with lineaments superimposed.

CENTER: Rose diagram of lineament azimuths.

BOTTOM: Histogram of lineament azimuths by number.

Rose diagram and histogram are twice smoothed using a ten degree running average calculated for every degree.

## C H A P T E R V

### MAJOR FAULT AND FOLD STRUCTURES

#### Faults

Six major fault zones cut and bound the tilted blocks of the study area (Figure 7): 1) Wadi el Isewid Fault Zone, 2) Wadi Nakheil Fault Zone, 3) Wadi Hammadat- Wadi Kareim Fault Zone, 4) Bir Inglisi Fault Zone, 5) Gebel Nasser-Gebel Ambagi Fault Zone, and 6) Gebel Atshan Fault Zone.

#### Wadi el Isewid Fault Zone

The Wadi el Isewid Fault Zone forms the southern boundary of the Gebel Atshan Fault Block. The main fault zone is exposed in outcrop between the southern end of Wadi Beda el Atshan and Wadi Hammadat (Figure 3) where it is a highly brecciated, quartz-cemented zone with evidence of normal motion on it. The fault zone marks a sharp boundary between areas of moderate to extensive unroofing of the granite to the south and only initial unroofing of the granite to the north. The established north-side-down nature of the fault motion can therefore be inferred to

offset the granite in that fashion. Youngest quartz veining, which cuts the granites, may also have figured in the silicification of the breccia zone. Although Garson and Krs (1976) contend that N60E faults are the oldest in the basement, some normal motion occurred within the study area on this fault subsequent to the emplacement of the Younger Granites (see Table 3).

In the study area, evidence for Tertiary reactivation of this zone is lacking. However, Greene's central Nubia valleys, small downfaulted areas of preserved Nubia Formation, are bounded on their southern ends by northeastward extensions of the Wadi el Isewid Fault Zone. This suggests that at least those portions of the zone were active in Tertiary time.

#### Wadi Nakheil Fault Zone

The Wadi Nakheil Fault Zone bounds the northeast side of the Gebel Duwi Fault Block. An extension of this zone may also bound the northern end of the Gebel Atshan Block. This zone strikes approximately N55W and dips about 50 degrees to the southwest at the surface. Cretaceous to Eocene platform sediments of Gebel Duwi, which parallels the Wadi Nakheil Fault Zone, are preserved within the half-graben formed by normal motion on this zone.

A minimum of 600 meters of post-early Eocene throw places Thebes limestones against Precambrian greenstones and tilted basement and cover to the northeast. Total throw between Gebel Ambagi and Gebel Nakheil is probably substantially greater than 600 meters as the Thebes-basement contact lies below an undetermined thickness of wadi fill and Nakheil Formation. Drag along the fault folded the platform sediments of this monocline into a broad, open, synclinal form (Plate 2).

At Gebel Nakheil, the fault steps to the left where it is interrupted by and curves into a N60E fault segment that transferred normal motion from one section of the fault zone to another. Several such parasitic steps and changes of orientation of the northwestern border fault of the Gebel Duwi Block can be seen on regional LANDSAT imagery (Frontispiece).

To the southeast, the Wadi Nakheil Fault Zone may step to the southwest and continue to a termination against the Gebel Atshan Fault Zone. Alternatively, the fault between the northern end of Gebel Atshan and Gebel Ambagi may be an extension of the Gebel Atshan Fault Zone. The Thebes Formation at the northern end of Gebel Atshan appears to dip under the Precambrian rocks of Gebel Ambagi, which has a total topographic relief in excess of

100 meters. Therefore, total normal offset on the short northwest trending fault segment must exceed 700 meters.

#### Wadi Hammadat-Wadi Kareim Fault Zone

The southeastern end of the Gebel Duwi Fault Block is bounded along its southwestern edge by the Wadi Hammadat-Wadi Kareim Fault Zone. Faults dip northeast and southwest on either side of the Wadi Inglisi Horst Block. These faults terminate to the southeast against the Gebel Nasser-Gebel Ambagi Fault Zone.

Motions on these faults are less than those on faults bounding the opposite side of the Gebel Duwi Block. The minor offset of a north-northwest striking felsite body (Plate 1) indicates only slight motion on the northeast dipping fault. More substantial motion occurred on southwest dipping members. Approximately 300-400 meters of Cretaceous or later southwest-down throw is required across the entire zone.

#### Bir Inglisi Fault Zone

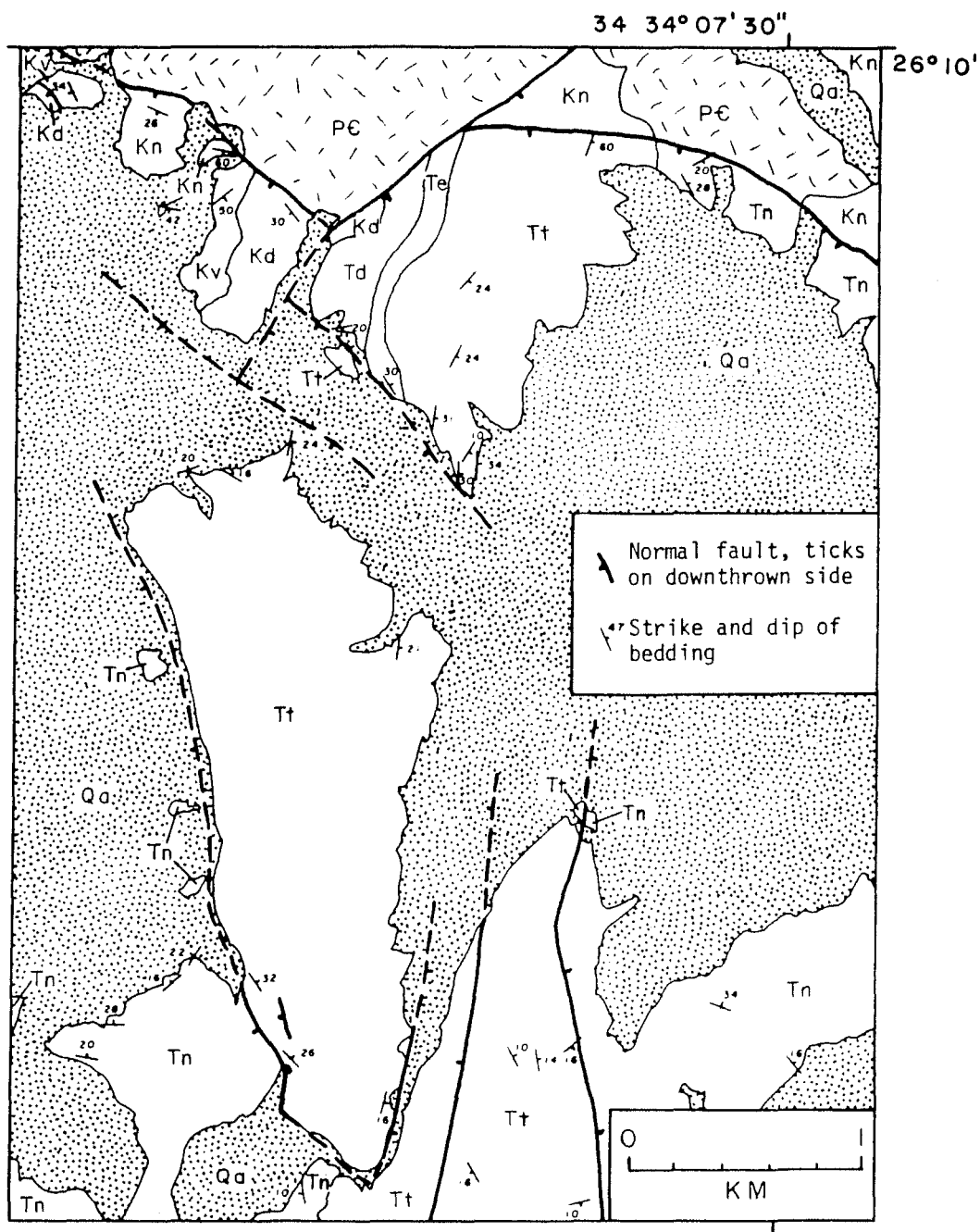
The northwest trending Gebel Duwi Block is broken by transverse zones trending approximately north-south, both within the study area and to the northwest. The north-

south ridges extending between the dip slope of southwestern Gebel Duwi and Gebel Nakheil developed in such a zone (Plate 1). These ridges consist of a series of horst-and-graben-like structures that are less dropped or tilted to the northeast than the areas on either side of them.

Faulting imparted a gross anticlinal structure to the north-south ridges. The ridges are bounded by hinge faults that exhibit increasing throw northward along their strikes. Nowhere is the throw on these faults greater than the thickness of the Thebes Formation. Displacements become negligible to the south where the faults die out as they intersect Gebel Duwi. The faults may be scissors faults as a series of similar structures present south of the main Gebel Duwi ridge exhibit increasing throw to the south.

Gebel Nakheil is a short north-south ridge of Cretaceous to Eocene sediments lying at the northern end of the Bir Inglisi Fault Zone (Figure 25) and, like the ridges to the south, has an anticlinal structure. It is located where the Wadi Nakheil Zone steps to the left at the intersection with the Bir Inglisi Fault Zone. The platform sediments of Gebel Nakheil dip east to the east of the step and west to the west of it.

Figure 25. Geologic map of the Gebel Nakheil area. PC= Precambrian basement; Kn= Nubia Fm.; Kv= Quseir Fm.; Kd= Duwi Fm.; Td= Dakhla Fm.; Te= Tarawan and Esna Fms.; Tt= Thebes Fm.; Tn= Nakheil Fm.; Qa= wadi alluvium.





It may be that the series of anticlinal ridges in the platform sediments result from drape folding over faulted basement blocks. The north-south zone is truncated against the step in the Wadi Nakheil Fault Zone and does not appear in the basement to the north (Abu Zied, in preparation). However, exposures of the Bir Inglisi Fault Zone south of Gebel Duwi suggest a structure of this kind. There, faults in basement form a graben that extends upward into the Nubia Formation, but the overlying Duwi and Dakhla Formations are folded into a broad syncline (Plate 1). A trend of N20W, 15NW was estimated for the axis of this fold by constructing a best-fit beta diagram using bedding orientations measured around the fold. The Bir Inglisi Fault Zone appears to be truncated to the south where it intersects the Wadi Hammadat-Wadi Kareim and Gebel Nasser-Gebel Ambagi Fault Zones.

#### Gebel Nasser-Gebel Ambagi Fault Zone

The Gebel Nasser-Gebel Ambagi Fault Zone forms the southeastern termination of the Gebel Duwi Block and its bounding faults, and also bounds the western side of the Gebel Atshan Block. The fault disappears under the Miocene and younger sediments to the north and under wadi fill to the south, where it may terminate against the Wadi el

Isewid Fault Zone.

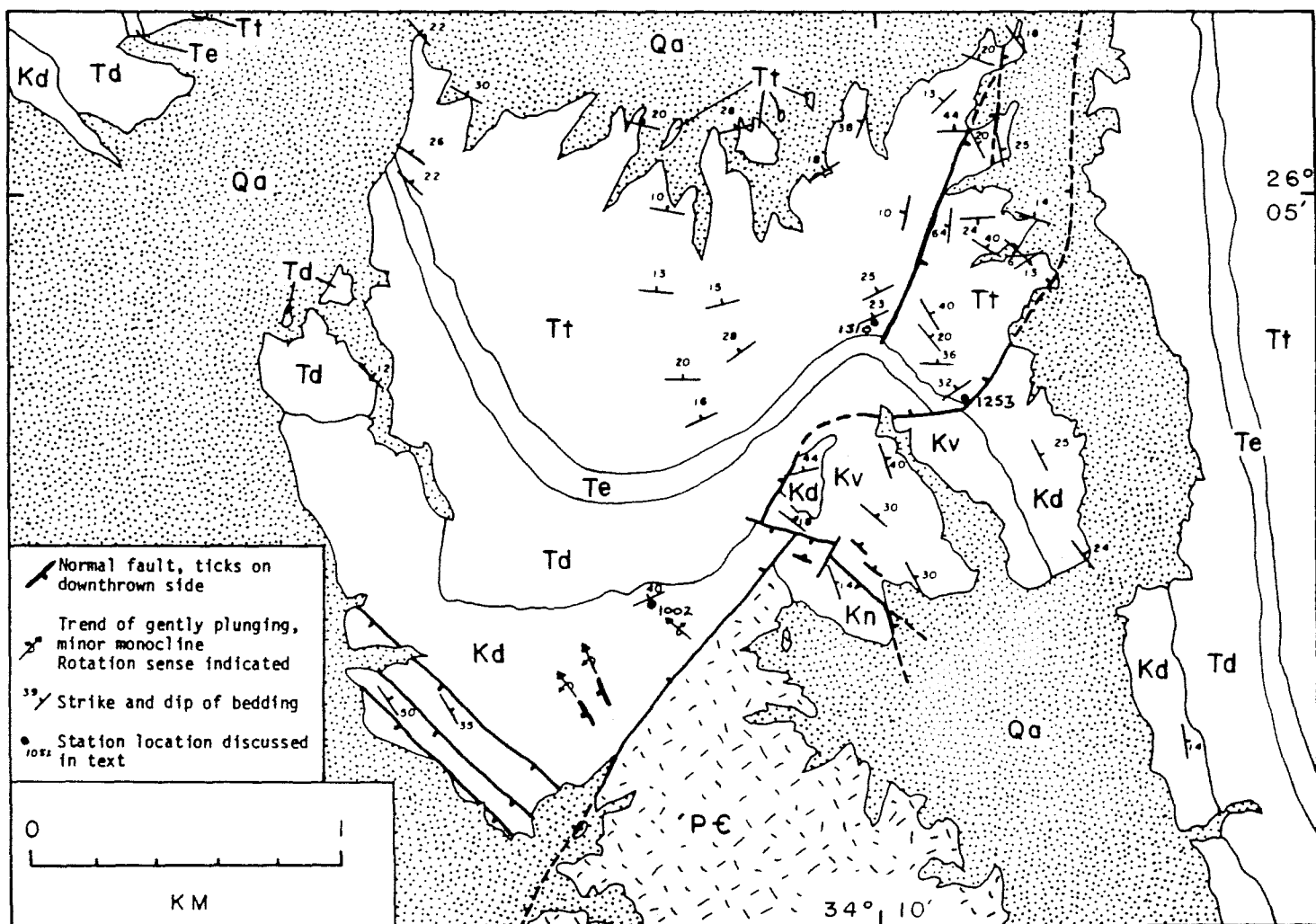
An exposure at the southern end of Gebel Nasser shows the fault zone dipping west-northwest at 45-50 degrees. Upper Thebes limestones are in fault contact with Duwi Formation along the eastern side of Gebel Nassser indicating a throw of over 300 meters at that location.

Topographically, Gebel Nasser resembles an amphitheater with its broadly curved, deeply dissected, north-facing dip slope. This shape is the result of open folding of the platform sediments where they have been dragged along the Gebel Nasser-Gebel Ambagi Fault Zone.

A beta diagram was constructed using bedding orientations measured around the "amphitheater" of Gebel Nasser's Thebes Formation. The axis is oriented approximately N10E, 20NE. Approximately east-west bedding plane slip noted in the Duwi Formation of southern Gebel Nasser is probably a result of this folding.

The eastern side of Gebel Nasser, along Wadi Beda el Atshan, was examined in some detail as it appears to involve numerous structural complexities (Figure 26). A sliver of this southeastern end of the Gebel Duwi Block apparently collapsed along the main fault to create a small, graben-like structure. A sketch of the ridge (Figure 27) between stations 1253 and 1310 (see Figure 26)

Figure 26. Geologic map of the Gebel Nasser area. PC= Precambrian basement; Kn= Nubia Fm.; Kv= Quseir Fm.; Kd= Duwi Fm.; Td= Dakhla Fm.; Te= Tarawan and Esna Fms.; Tt= Thebes Fm.; Qa= wadi alluvium.



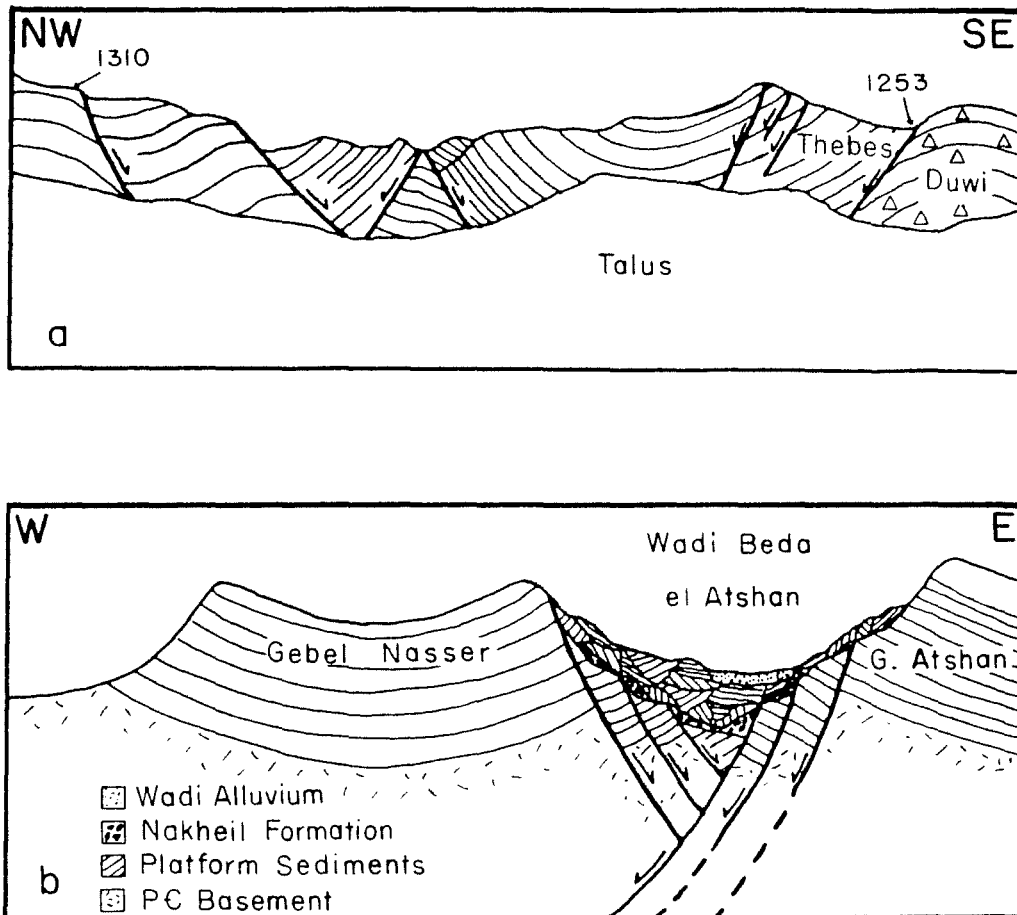


Figure 27. Gebel Nasser-Gebel Ambagi Fault Zone: a) sketch of view of the ridge between stations 1310 and 1253 showing style of deformation; b) sketch cross-section of Gebel Nasser showing faulting and extensional collapse along Wadi Beda el Atshan.

and a generalized cross-section of Gebel Nasser (Figure 27) illustrate the structural relations. Many of the "structural complexities" initially noted in this zone are the result of extensional collapse of large blocks between the two oppositely dipping normal faults.

Several minor southwest-down normal faults and folds are present in the Duwi Formation of southern Gebel Nasser (Figure 26). They are approximately parallel to the trend of the Gebel Duwi Block and the faults bounding it. Therefore, they may be associated with the faulting and tilting of this block. Age relations between these structures and north-south structures are uncertain. However, these features do not extend across the Gebel Nasser-Gebel Ambagi Fault Zone into the Precambrian basement south of Gebel Nasser; their termination suggests that the north-south zone may have existed prior to the development of the northwest-trending zone.

Other evidence suggests a greater antiquity for the northwest-trending structures. One mechanism for folding of the Duwi Formation along these northwest trends involves slip on joint surfaces. Gentle warping resulting from this mechanism was noted at station 1002 (see Figure 26). Joint surfaces at this location and slickensides on them are both perpendicular to now tilted bedding (Figure 28), suggesting that motion on the joints predates

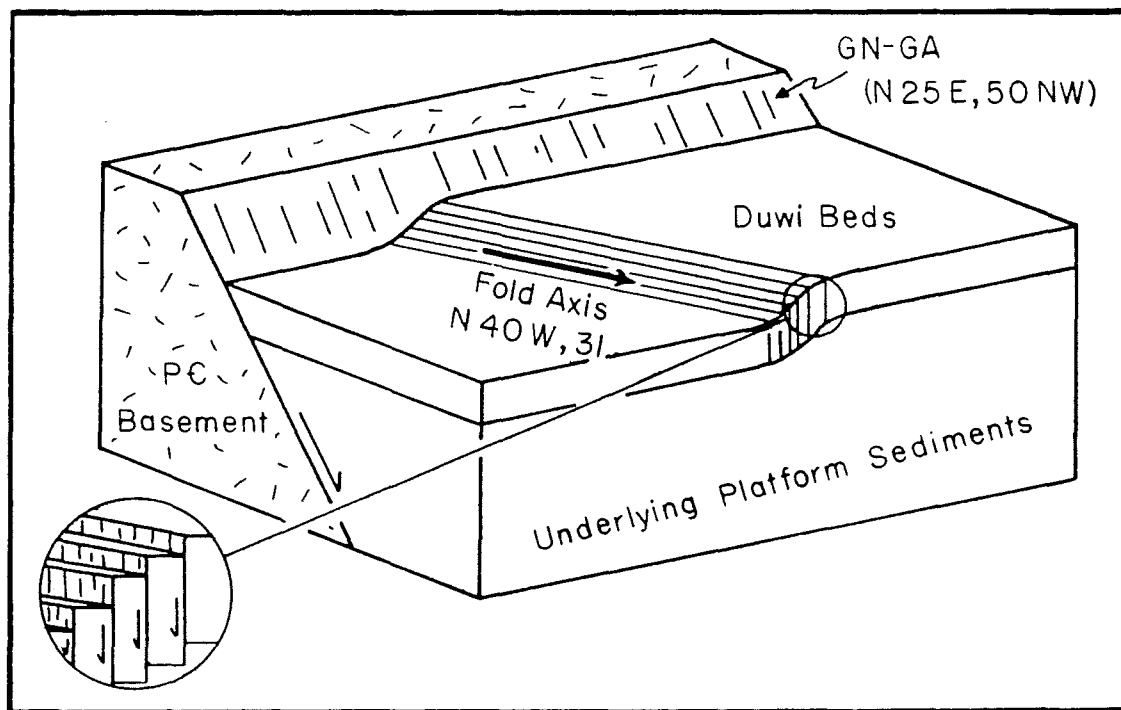


Figure 28. Slip on joints perpendicular to Duwi bedding as a mechanism of folding at station 1002, southeast Gebel Nasser. Flexure zone is approximately 3 meters across. GN-GA= Gebel Nasser-Gebel Ambagi Fault Zone.

tilting.

### Gebel Atshan Fault Zone

Gebel Atshan is an east-tilted block of platform sediments along the eastern edge of the study area. Quseir through Thebes Formations are exposed along its west facing erosional scarp; the main ridge, like Gebels Duwi and Nasser, is capped by Thebes limestones. A north-south fault zone with a dip of 60-70 degrees to the west at the surface bounds the Atshan block to the east. Surfaces within this zone near Wadi Ambagi exhibit early right-lateral slickensides and younger normal slickensides. The Thebes and overlying Nakheil Formations are dropped into contact with the basement along this fault indicating more than 600 meters of normal motion. Slivers of the platform sediments are exposed along the Gebel Atshan Fault Zone as a result of drag on the fault. Drag on a small, westward-projecting irregularity in the fault surface about one-half kilometer south of Wadi Ambagi resulted in a small-scale anticlinal upbulging (Plate 2). The fault zone terminates to the south against the Wadi el Isewid Fault Zone. Its northward termination is unclear.

An elongate, elevated basin is formed between the



main ridge of Gebel Atshan and the basement highlands to the east. An outlet of this basin into Wadi Nakheil cuts through the Thebes ridge at its northern end. Along the western margin of this basin, basal Nakheil conglomerate beds are nearly concordant with underlying Thebes limestone bedding. Dips of the two formations are within 8 degrees of one another. These Nakheil deposits fine upward to sands and sandy silts with a few coarse interbeds. The uppermost part of the Nakheil Formation, which largely underlies recent alluvium, approaches a horizontal attitude. Nakheil conglomerates along the eastern edge of the basin are also nearly horizontal. The geometry suggests that episodic motion and tilting continued during deposition of the Nakheil Formation.

### Folds

A small number of folds were noted in the platform sediments. Most are folds in the Thebes Formation; the three exceptions fold beds in the Duwi Formation. The folds are generally very open synclines formed by drag along normal fault surfaces. Therefore, their axes and axial planes tend to trend north-south to northwest-southeast, paralleling Tertiary fault strikes. Folds

range in size from regional features of 1-5 kilometers wavelength to outcrop-scale structures with wavelengths of less than a meter and amplitudes on the order of a few tens of centimeters. This relationship can be seen on a large scale in the broad, open folding of Gebel Nasser. It is also visible where the platform sediments of Gebel Duwi dip under the fill of Wadi Nakheil and reappear again 3 to 4 kilometers to the northeast along the fault bounding the northeast side of this valley (Plates 1 and 2).

A major exception to this style of folding is the large overturned fold in the Thebes Formation atop the main ridge of Gebel Duwi (Plate 2) and minor folds associated with it. The main fold has a wavelength and an amplitude greater than 50 meters, a nearly horizontal, northwest-southeast-trending axis, a gently southwest dipping axial surface, and a southwest-over-northeast rotation sense. Minor folds associated with this structure have approximately east-west striking axial surfaces and east-west trending, gently plunging axes. No evidence was seen to indicate that the strata below the Thebes were folded. To accommodate this folding in the Thebes limestones, bedding-plane faulting probably occurred in the underlying shales of the Esna Formation. As the shales could only be examined with binoculars from

the wadi floor below, the existence of these faults could not be confirmed.

Although the Thebes Formation as a whole was ductile enough to be folded, numerous minor faults are present. Many of the cherty and more brittle limestone beds involved in this large fold are broken. Depth of burial at the time of folding was probably less than 100 meters as the fold involves the lower half of the Thebes Formation. Thus, only the upper part of the Thebes would have overlain the observed folded strata at the time of deformation. Lower Eocene deposits can be several hundred meters thicker in other parts of Egypt (Said, 1962), but no evidence of thicknesses greater than 200 meters exists in the Quseir-Safaga region. Even if these thicker deposits were present, maximum depth of burial should not have exceeded 500 meters.

Two possible origins come to mind for this structure. First, it could be due to regional compression at a high angle to the fold axial trends. This compression could have produced folding in the limestone and bedding plane thrusts in the underlying shales. Strike-slip faulting provides evidence of late Eocene to early Miocene north-northeast compression that could have caused the folding.

A second possible mode of formation is by gravity

tectonics. Following the tilting of the fault blocks, the steepened Thebes Formation may have "slid downhill" to the northeast on the underlying, less competent shales causing folding and buckling. The main fold trends approximately parallel to bedding strikes in Gebel Duwi and has the proper transport sense for this mechanism.

Because the fold root lies to the southwest of the cliffs of the Gebel Duwi ridge and has been eroded away, the choice between the two possible modes of origin is not clear-cut. The fold was not followed out to its northwest termination due to time constraints and difficulties of access. The block tilting and gravity sliding origin is preferred as it seems more feasible. The lack of deformation of similar style in the area is the basis for this preference. Most of the significant deformation from the N25E compression was apparently brittle in nature. The only other folds not directly attributable to drag on fault surfaces are open, gentle warpings (Trueblood, 1981). However, it must be borne in mind that the large overturned fold, although a large and prominent feature, had not been previously reported. Others may yet remain undiscovered.

## C H A P T E R    V I

### REGIONAL TECTONICS

#### Phanerozoic History of the Study Area

Following the cratonization of northeast Africa at the end of the Proterozoic, the Quseir area became tectonically stable and remained so throughout the Paleozoic and much of the Mesozoic. During Late Cretaceous through Eocene time, a sequence of platform sediments was deposited as a result of the southward transgression of a shallow epicontinental sea over northeast Africa.

The relative stability of the Quseir area was disrupted in the middle Eocene by epeirogenic uplift, which resulted in the cessation of deposition. Regional north-northeast compression in the middle Eocene to middle Miocene resulted in the development of a conjugate system of strike-slip faults in the Quseir area (Figure 19) as well as in the Gulf of Suez region (Perry, 1982) and Saudi Arabia (Davies, 1981). Schamel and Wise (1984) note a similarly oriented compression of Eocene to Miocene age in the Sinai and tentatively relate it to the late stages of development of Syrian Arc structures. Further, they feel

that the system of conjugate strike-slip faults developed under the influence of this compressional episode later controlled the orientations of the Gulf of Suez/Red Sea and the Gulf of Aden. North-northeast to north-northwest-striking, right-lateral faults and northeast-striking left-lateral faults were produced in the Quseir area by this compression. N20E compression also may have resulted in folding noted by Trueblood (1981) and in downwarps within which the Nakheil Formation may have been deposited (Gebel Duwi, Wadi Nakheil, and Gebel Atshan lows, see Figure 6).

During Oligocene to early Miocene time, regional stresses changed resulting in northeast-southwest extension related to the early development of the Red Sea rift. A conjugate system of northwest-striking normal faults developed under these stresses, and appropriately oriented older faults were reactivated. This normal faulting dropped and tilted blocks of Cretaceous to Eocene platform sediments into troughs where they were subsequently preserved as outliers. The Nakheil Formation may have been deposited in these downfaulted troughs rather than in earlier downwarps.

The style of Tertiary deformation is clearly shown on structure contour maps for the top of reconstructed basement of the southern Gebel Duwi-Quseir area (Figure 6)

and the Quseir-Safaga region (Figure 7). These maps show that block faulting and tilting toward the Red Sea dominate the study area. This is noted in the field as a northeast tilt of the Nubia-basement contact.

In many parts of the world, reverse drag is commonly present in areas dominated by block faulting along listric normal faults. It seems unusual that this type of extensional structure is present only in eastern Gebel Nasser along the Gebel Nasser-Gebel Ambagi Fault Zone. Conversely, true drag can be seen along most of the major fault zones in the area.

Intersection relationships of most major faults could not be directly observed due to their burial beneath wadi alluvium. However, map patterns indicate that, generally, northwest-striking faults terminate against north-south faults. North-south faults terminate, in turn, against N60E faults. This suggests that N60E faults are the oldest in the study area and that northwest striking faults are the youngest. Relations in areas to the north (Abu Zied, in preparation) and to the east (Greene, 1984) are somewhat more ambiguous. Smaller-scale structures in this study area also provide inconclusive evidence.

Eocene to early Miocene uplift was apparently followed by a period of relative quiescence, with a middle

to late Miocene erosion surface developing along the Red Sea coast of Egypt and Saudi Arabia (Brown, 1970; Schmidt et al., 1982; Greene, 1984). The lack of major elevation differences across normal fault zones in the study area is a reflection of this erosion surface. Therefore, most of the motion on these faults predated this Late Miocene surface. Faults bounding Gebel Ambagi however, must have experienced substantial motion following the development of the mid-Tertiary erosion surface. The Miocene basal Gebel el Rusas Formation deposited on a segment of this erosion surface atop Gebel Ambagi now sits more than 100 meters above similar surfaces in the surrounding area. A regular decrease in basement peak elevation to the northeast across individual tilted blocks may also represent the slightly tilted mid-Tertiary erosion surface.

Erosion resulting from Eocene to Miocene uplift and faulting removed the bulk of the Cretaceous to Tertiary cover during creation of the mid-Tertiary erosion surface. The Nakheil Formation may well represent part of the material removed, but an enormous quantity of sediment must have been deposited in the proto-Red Sea rift. Johnson (1977) notes Oligocene to Lower Miocene redbeds deposited on Precambrian basement in the Ras Benas-Abu Ghussun area of the Red Sea coast (near  $24^{\circ}\text{N}$ ). Clastics



and boulder beds of Oligocene to Miocene age are found in drill cores offshore from Quseir and Safaga (Tewfik and Ayyad, 1982). Carella and Scarpa (1962) report similar deposits in southern Egypt and the Sudan. Pre-middle Miocene redbeds and boulder conglomerates also exist in the Gulf of Suez region (Garfunkel and Bartov, 1977). No similar redbeds were noted in the study area or in areas to the east (Trueblood, 1981; Greene, 1984).

With the exception of generally minor motion on faults that disrupted the mid-Tertiary erosion surface (e.g. the faults bordering Gebel Ambagi), the Quseir area has remained relatively quiet for the past 10 M. y. Upper Miocene evaporites along the Red Sea coast to the east of the study area are cut by some minor faults, but most of the deformation of these units is the result of flowage and tilting in a zone of coastal flexure (Greene, 1984). Tilting of the Miocene to Pleistocene sediments toward the Red Sea appears to have ended by the beginning of the Quaternary as Pleistocene and Recent deposits have barely noticeable dips. Hence, although uplift has resulted in the deep dissection of Upper Miocene and younger sediments and the creation of several terrace levels along the coast and in wadis, little faulting has occurred in the area since middle Miocene time. Table 4 summarizes the

Table 4. Phanerozoic history of the study area.

TIME PERIOD	SUMMARY OF EVENTS AND INTERPRETATION
Cambrian to Mid-Cretaceous	Tectonic stability. Peneplanation of Precambrian basement by erosion.
Mid-Cretaceous to Middle Eocene	Formation of large intracratonic basin over much of northeast Africa. Platform sediments deposited in this basin. This may be a precursor to Red Sea tectonics.
Middle Eocene	Uplift ends deposition of the platform sediments. Erosion creates an unconformity atop the Thebes Formation. Crustal doming is proceeding prior to rifting.
Late Eocene to Early Miocene	<p>1) N20E regional compression results in the development of a conjugate system of strike-slip faults: NNE to NNW trending right-lateral and NE trending left-lateral faults. This compression may also have warped the platform sediments. This may be an early stage of Red Sea-related tectonics.</p> <p>2) NE-SW extensional stresses become dominant resulting in new northwest striking normal faults. North to northwest striking preexisting structures are reactivated as normal faults, emplacing outliers of Cretaceous to Eocene sediments. This phase is related to initiation and widening of the Red Sea rift.</p> <p>Note: The Makheil Formation is deposited during this time either in downwarps created by N20E compression or in fault-bounded troughs associate with northeast extension.</p>
Early to Middle Miocene	Uplift and relative quiescence of the study area results in the development of the Mid-Tertiary erosion surface adjacent to the Red Sea. A few faults experience substantial motion, but major activity is centered closer to the rift.
Middle Miocene to present	<p>1) Deposition of coastal sediments in early Red Sea basin.</p> <p>2) Slow, gentle uplift presages break-up and active sea-floor spreading in the northern Red Sea. This results in the dissection of the Miocene erosion surface and creation of raised beaches and terraces along the Red Sea.</p>

Phanerozoic history of the study area.

### Tectonic Heredity

Obvious deviations from Red Sea fault trends occur in the Quseir-Safaga area. The most prominent is that which controls much of the orientation of the Gebel Duwi fault block. Another fault dropped and tilted the Gebel Hammadat-Bahari block to the southeast (Figure 1). It can be seen on LANDSAT imagery (Frontispiece) that the Gebel Duwi Fault Zone jumps from Najd-parallel segments to Red Sea-parallel segments as does the fault bordering the northeast side of Gebel Hammadat. Tertiary extension created Red Sea-parallel fault segments connecting reactivated Najd segments.

Garson and Krs (1976) note that several zones in Precambrian rocks along the Egyptian Red Sea coast parallel the Gebel Duwi trend and claim evidence for left-lateral motion on many of these zones. They feel that the movement was a secondary feature of left-lateral, strike-slip motion on the Red Sea rift during Cretaceous to Early Tertiary sea-floor spreading in the Gulf of Aden. Lacking evidence of Cretaceous to Eocene stresses in the study area that could have produced such motion, it is here proposed that any left-lateral motion on these faults is

more likely to be Precambrian in age and associated with Najd faulting.

Old Najd fault trends exert much control over fault orientations in this part of the Eastern Desert. As can be seen in Figure 6, many of the faults which dropped and tilted Cretaceous to Eocene sediments made use of both Red Sea-parallel and Najd-parallel fractures. These trends are, in turn, commonly disrupted by north-south faults. It is possible that the Red Sea faulting may have reactivated more ancient north-south Hijaz grain, although this grain does not appear strongly in the bulk of study area basement.

The idea of the reactivation of Najd trends by later stresses is further supported by Greenwood and Anderson's (1977) palinspastic reconstruction of the Arabian-Nubian Shield. This reconstruction (Figure 9) shows the Wadi Azlam graben of Saudi Arabia aligned with the Gebel Duwi-Gebel Hammadat fault blocks prior to separation. Although these authors push the Red Sea back together farther than may be warranted, this alignment of old Najd trends across the Red Sea is not unrealistic. Smith (1979) and Davies (1981) note reactivation of Najd trends to form the faults that bound the Azlam basin, and Smith (1979) also describes a Tertiary stratigraphy in the Wadi Azlam graben

of sandstone, gypsiferous, multicolored shales, and fossiliferous (abundant Ostrea) limestone very reminiscent of the platform sediments in the Quseir area. The similarities of the Tertiary histories of these basins suggest a similar origin and common control of their orientations by Najd trends in the basement.

At the northern end of the Gebel Atshan Fault Zone, right-lateral faults associated with Tertiary N25E compression are connected by younger normal fault segments with more northwest strikes. The later normal motion also reactivated the right-lateral fault segments and resulted in the jagged map pattern of the fault zone.

Typically, faulting and block rotation occur on normal faults that dip toward and step down into a developing rift. Red Sea-ward dipping normal faults appear adjacent to the Gulf of Suez (Schamel and Wise, 1984) and are responsible for the preservation of sedimentary outliers north of Quseir (Figure 7). The dips of major normal faults away from the Red Sea in the Quseir area and to the south as far as Mersa Alam (El Akkad and Dardir, 1966a) are unusual. It may be that this unusual geometry is related to the existence of steeply dipping planes of weakness, the strike-slip faults, at the onset of regional extension. Thus, both Najd faults and earlier Tertiary strike-slip faults may have exercised control

over not only the strike of later normal faulting, but also over dip directions of these faults.

### The Red Sea

Several models have been proposed for the structure and evolution of the Red Sea. The most widely debated question is the extent to which true sea-floor spreading has occurred and therefore, how much of the Red Sea is floored by true oceanic crust. Two schools of thought exist regarding this question: that the Red Sea is floored entirely by oceanic crust (McKenzie et al., 1970; Girdler and Styles, 1974) or that sea-floor spreading has begun relatively recently and that only the axial trough of the southern Red Sea is floored by oceanic crust (Hutchinson and Engels, 1972; Lowell and Genik, 1972; Coleman, 1974; Tewfik and Ayyad, 1982; Cochran, 1983). Although contradictory geological and geophysical data leave this question unsettled at present, the evidence favors the latter model.

Seismic reflection studies are inconclusive as basement is lost beneath thick, seismically opaque Miocene to Recent evaporites and marine sediments that cover much of the main trough of the Red Sea. Seismic refraction

work is also inconclusive, but yields variable velocities, most of which could be attributed to continental crust.

Evidence for an axial trough floored by oceanic crust comes from magnetic surveys. The axial trough clearly exhibits sharp, short-wavelength, high-amplitude, symmetrical magnetic anomalies characteristic of ocean crust (Girdler and Styles, 1974; 1976; Roeser, 1975). Broad, smooth, low-amplitude magnetic anomalies are associated with the main trough and shelves of the Red Sea. Girdler and Styles (1974) correlate these broad anomalies with the geomagnetic reversal scale of Heirtzler et al. (1968) for the period 41-34 M.y. ago. Based on this correlation, they propose a two-stage spreading history for the Red Sea with spreading arrested between 34 and 5 M.y. before present. Recent paleomagnetic work in the As Sarat Volcanics of southwest Saudi Arabia by Kellogg and Reynolds (1983) places constraints on models involving two stages of Red Sea-floor spreading. Their results indicate that most of the motion of Arabia relative to Africa has occurred since the eruption of these rocks. The Oligocene to Miocene ages (29-24 M.y.) of these volcanics would seem to preclude a major phase of Eocene to Oligocene sea-floor spreading.

Geologic studies along the shores of the Red Sea give no reason to believe that Red Sea-parallel normal faulting

and block tilting does not continue out under the Red Sea itself. Hutchinson and Engels (1972) propose this type of structure for the Danakil Depression. Lowell and Genik (1972) concur and show seismic and bathymetric evidence that this structural style continues northward to 19°N. Frazier (1970) interprets the magnetic pattern of the main trough as resulting from tilted fault block structures similar to those along the coast of the Red Sea. In addition, Hall et al. (1977) show Girdler and Styles' (1974) anomaly 15 (40 M.y. isochron) continuing over Precambrian basement of the Buri Peninsula.

The biggest problem with a model that proposes that only the axial trough is floored by true oceanic crust is the amount of separation between Africa and Saudi Arabia. A substantial amount of separation between the two land masses is required to account for the more than 100 kilometers of Cenozoic sinistral strike-slip motion on the Gulf of Aqaba-Dead Sea rift (Freund et al., 1968; Hatcher et al., 1981). Cochran (1983) shows however, that the separation need not be due to the creation of new crust under the Red Sea, but may be the result of crustal and lithospheric stretching and thinning due to block faulting and dike injection. Normal faults associated with block faulting may be listric at depth as in the Bay of Biscay



margin (de Charpal et al., 1978), which would imply block rotation and allow for sufficient separation without sea-floor spreading.

Cochran's (1983) model calls for an extended period of lithospheric rifting and attenuation over a diffuse zone prior to small ocean basin formation. A broad zone of crustal attenuation can account for the high heat flow of the entire Red Sea region (Girdler, 1970; Coleman, 1974) as well as sea-floor spreading can.

The spreading ridge seems to be extending itself northward from its present area of activity. Presently, active spreading can be documented between  $15^{\circ}30'N$  and  $21^{\circ}N$  (Cochran, 1983). Between  $21^{\circ}N$  and  $25^{\circ}N$ , axial deeps and hot brine pools suggest that a transition from crustal attenuation to true sea-floor spreading is taking place with no continuous, organized spreading center yet established. The northern Red Sea is still in the pre-spreading extension phase.

Crustal attenuation followed by eventual continental rupture and active spreading fits the geological and geophysical data with fewer problems than a Red Sea floored entirely by oceanic crust. Although the required amount of extension by block faulting and rotation is great, it is not unreasonable for this mechanism (see Watts and Steckler, 1979; Steckler and Watts, 1980; Keen

and Barrett, 1981; Watts, 1981) and can account for the Aqaba-Dead Sea fault motion.

### The Falvey Model

Falvey (1974) proposed a model for the development of ocean basins and continental margins that explains nicely much of what is seen in the study area and the Red Sea region. According to this model, the first sign of regional tectonic activity can be the development of a large intracratonic basin (or basins) 50 to 150 M. y. prior to continental break-up and the onset of actual sea-floor spreading. This basin accumulates fluvio-deltaic and shallow marine sediments. The Cretaceous to Eocene platform sediments of Egypt represent deposition in such a basin. Maestrichtian to Paleocene shallow marine strata along the Red Sea coast of Sudan (Carella and Scarpa, 1962) and similar deposits of the Asfar Series north of Jiddah, Saudi Arabia (Karpoff, 1957) indicate that the basin extended southward to at least 21°N.

A temperature anomaly in the asthenosphere results in thermal expansion and initial epeirogenic uplift about 50 M. y. prior to break-up. The result is erosion, crustal thinning, and the development of a widespread

unconformity. Swartz and Arden's (1960) paleogeographic reconstructions indicate that uplift began in the southern Red Sea in the mid-Cretaceous. As doming propagated northward, the shallow seas of the intracratonic basin retreated. Middle Eocene uplift and regression in the Quseir area are marked by the Nakheil unconformity atop the platform sediments.

Falvey predicts phase boundary migrations and resultant density and volume changes in the lithosphere about 40 M. y. prior to breakup. These changes result in collapse of an axial graben accompanied by alkaline volcanism. The rift valley thus formed is characterized by block faulting with en echelon horsts and grabens. Continental and deltaic sediments then begin to fill the rift valley basin. The rift valley continues to widen outward by block collapse until the initiation of sea-floor spreading. It should be emphasized here that in this discussion, rift valley formation and widening, which involve attenuation of continental crust, are not to be confused with later continental break-up/rupture and attendant sea-floor spreading.

The rift initiation and widening phase is represented by Oligocene to mid-Miocene faulting in the study area, northern Red Sea, and Gulf of Suez. Redbeds and boulder conglomerates were initially deposited in the widening

rift valley. These were followed by littoral and evaporitic deposits resulting from episodic invasion of the rift valley basin by waters from the Mediterranean Sea to the north. Oligocene evaporites in the southern Red Sea (Hutchinson and Engels, 1972) indicate that rift basin formation was initiated to the south and spread northward as northern Red Sea evaporites are Miocene in age (Tewfik and Ayyad, 1982).

Eocene to Oligocene plateau basalts of Ethiopia, Yemen, and Saudi Arabia (Coleman, 1974) accompanied rift formation and widening in the southern Red Sea. Middle Miocene alkaline basalts are present north of Jiddah, Saudi Arabia and in a north-south band between Amman, Jordan and Turayf, Saudi Arabia (Coleman, 1974). The Egyptian side of the Red Sea has few Neogene volcanics. However, Ressetar, Nairn, and Monrad (1981) report some Oligocene to Miocene basalts along the Red Sea coast of Egypt and in the Nile Valley that they tentatively associate with rift valley widening.

The Red Sea Hills appear to be the maximum westward extent of major Red Sea-related faulting or uplift in Egypt. The relative quiescence following initial faulting related to rift valley widening allowed for the development of the mid-Tertiary erosion surface, which may

reflect a proposed time lag. Once stresses had been relieved along the far edges of the affected area, tectonic activity was dominated by subsidence closer to the rift axis. This quiescence on the western side of the Red Sea is also evident in the sparsity of mid-Tertiary magmatism noted above. As heat built up sufficiently under the lithosphere, areas further from the axis once again began to experience renewed, but subdued, tectonic activity as indicated by minor fault motions and uplift.

Falvey proposes that rift valley development extends through actual continental break-up. In Pliocene time, major continental rupture initiated sea-floor spreading and new crustal generation in the southern Red Sea (Hutchinson and Engel, 1972; Lowell and Genik, 1972; Cochran, 1983). This resulted in a permanent connection between the Red Sea and the Indian Ocean through the Gulf Of Aden. As discussed previously, continental rupture has not yet occurred in the northern Red Sea. Post-Miocene uplift resulting in dissection of the mid-Tertiary erosion surface and the series of terraces and raised beaches along the northern Red Sea may be the result of slow, gentle, regional uplift preceeding continental break-up.

## C H A P T E R VII

### SUMMARY AND CONCLUSIONS

This is a case study of the effect of opening a continental-scale rift structure oblique to and superimposed on a San Andreas-scale strike-slip zone: Red Sea tectonic trends (N30W) are superimposed on late Precambrian Najd (N60W) strike-slip structures. In the Quseir region, the result is downfaulting and preservation of anomalously oriented fault blocks along master faults that dip away from the Red Sea rift. The final product is a jagged, sawtooth pattern characteristic of parasitic faulting. The results of this study may have implications for offshore structures under the Red Sea and for structure in similar settings elsewhere in the world.

#### History of the Study Area

The Arabian-Nubian Shield was assembled through the consolidation of island arc materials in the late Precambrian. In the study area, this Proterozoic activity resulted in three phases of coaxial folding. N25-30W fold axes and N40W axial planar cleavages produced by this

folding form the dominant basement grain of the study area. Precambrian N30E quartz veins and north-south felsite dikes are also present in basement.

The left-lateral Najd strike-slip fault system developed across the Arabian-Nubian Shield in latest Precambrian through Early Cambrian time, possibly as a result of a collision of the young craton with another continent to the east or west. Few minor structures related to this system were found in the study area, but Tertiary motion on the Wadi Nakheil and Wadi Hammadat-Wadi Kareim Fault Zones reactivated ancient Najd structures. The change of dominant basement grain to a N60W orientation north of the study area is related to the old Najd grain (Abu Zied, in preparation).

Quiescence in Cambrian through mid-Cretaceous time was followed by deposition of platform carbonates and related clastics in the Late Cretaceous through early Eocene. Middle Eocene uplift resulted in the development of the unconformity atop the platform sediments. The Nakheil Formation may have been deposited in downwarps at that time.

Post-middle Eocene, pre-middle Miocene, N25E compression caused the formation of north-south and northeast-striking strike-slip faults as a conjugate system. This compression may be related to an early phase

of Red Sea-related tectonic activity, but its meaning is unclear at present.

Following north-northeast compression, northeast-southwest, Red Sea-related extension became dominant, dropping and tilting northwest trending basement blocks and overlying sediment to the northeast. The Nakheil Formation may also have been deposited in fault-bounded troughs during this activity. Four major tectonic trends were active during that time:

- 1) N60E trends representing reactivated Precambrian faults;
- 2) N50-60W trends representing reactivated Najd grain control the orientation of much of the Gebel Duwi Block;
- 3) N-S trends terminating the Gebel Duwi Block to the southeast;
- 4) N25-30W trends associated with Red Sea rifting.

The north-south trend seems unusual in that Precambrian anisotropies do not seem to account for it and evidence for Tertiary causal stresses are lacking.

Intersection relationships of Tertiary faults in the Cretaceous-Eocene sediments suggest that N60E trends are oldest, followed by N50-60W, N-S, and N25-30W trends, in that order. However, these apparent age relations may reflect older basement age relations or dominance of anisotropies.



Middle Miocene quiescence resulted in the creation of a Mid-Tertiary erosion surface. Renewed, but much subdued tectonic activity has continued since the late Miocene through the present.

A second phase of motion on segments of Red Sea-related master faults supports the notion of a two-stage Red Sea history. This late motion may also have produced a coastal horst in the area with the Gebel Duwi and Gebel Hammadat lows forming small coastal basins. This horst-and-graben coastal structure may be part of a general style of deformation along the Red Sea, but may be visible only where outliers of covering sediments are preserved. Alternatively, this may be a unique situation resulting from the interplay of Najd and Red Sea trends. In either case, the existence of this kind of structure has implications for offshore structure, which may have particular importance to petroleum exploration efforts in the Red Sea.

#### Major Achievements of the Study

Major achievements of this study include the following:

- 1) creation of a detailed geologic map of the southern Gebel Duwi area;

- 2) recognition of major Precambrian basement anisotropies and their control over Tertiary structure;
- 3) filling of a gap in the structural-tectonic cross-section of the Eastern Desert at the latitude of Quseir, including the construction of a structural contour map of the area;
- 4) definition of the geometry and mechanisms of formation of Tertiary fault blocks;
- 5) provision of further evidence for Tertiary north-northeast compression noted by Greene (1984) and Schamel and Wise (1984);
- 6) discovery of large overturned folds in Thebes limestones atop Gebel Duwi, the only structures of this sort reported in the Cretaceous-Eocene sediments of the Eastern Desert;
- 7) tentative recognition of a class of horst-and-graben coast-parallel structures.

#### Future Work

Several areas of future investigation suggest themselves as a result of this study.

- 1) Further work is needed on basement anisotropy and how it controls the orientation of Tertiary faulting. Of particular interest are variations in the orientation of the Wadi Nakheil Fault Zone northeast of the study area, controls on the north-south trends, and the anomalous dips of faults away from the Red Sea.
- 2) Determination of the relationship between Gebel Duwi and Gebel Hammadat would be helpful. Are they en echelon zones?
- 3) Determination of the environment and timing of deposition of the Nakheil Formation could be accomplished through provenance, facies, and

paleocurrent studies.

4) More work on the extent and age of erosion surfaces would be helpful in elucidation of Red Sea history.

5) Determination of the areal extent of evidence for N25E compression and its relation to early stages of Red Sea tectonics would better the understanding of Red Sea development. Recognition of its presence or absence in the Nakheil Formation would help to tie down the timing of this compressional episode.

6) Location of more folds like that atop Gebel Duwi might tell us more about the origin of the folding.

7) The presence of a coastal horst-and-graben structure elsewhere in basement of the Eastern Desert could indicate a general deformational style for the Red Sea and other developing ocean basins.

It has been shown that the Najd fault system affects a zone greater than ten kilometers wide along the Egyptian Red Sea coast, controlling much of the Tertiary deformation there. The affected area straddles the main highway across the Eastern Desert, allowing easy access. It is hoped that this study will serve as a guide for field trips and visitors interested in the geology of this region.

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34°00'E

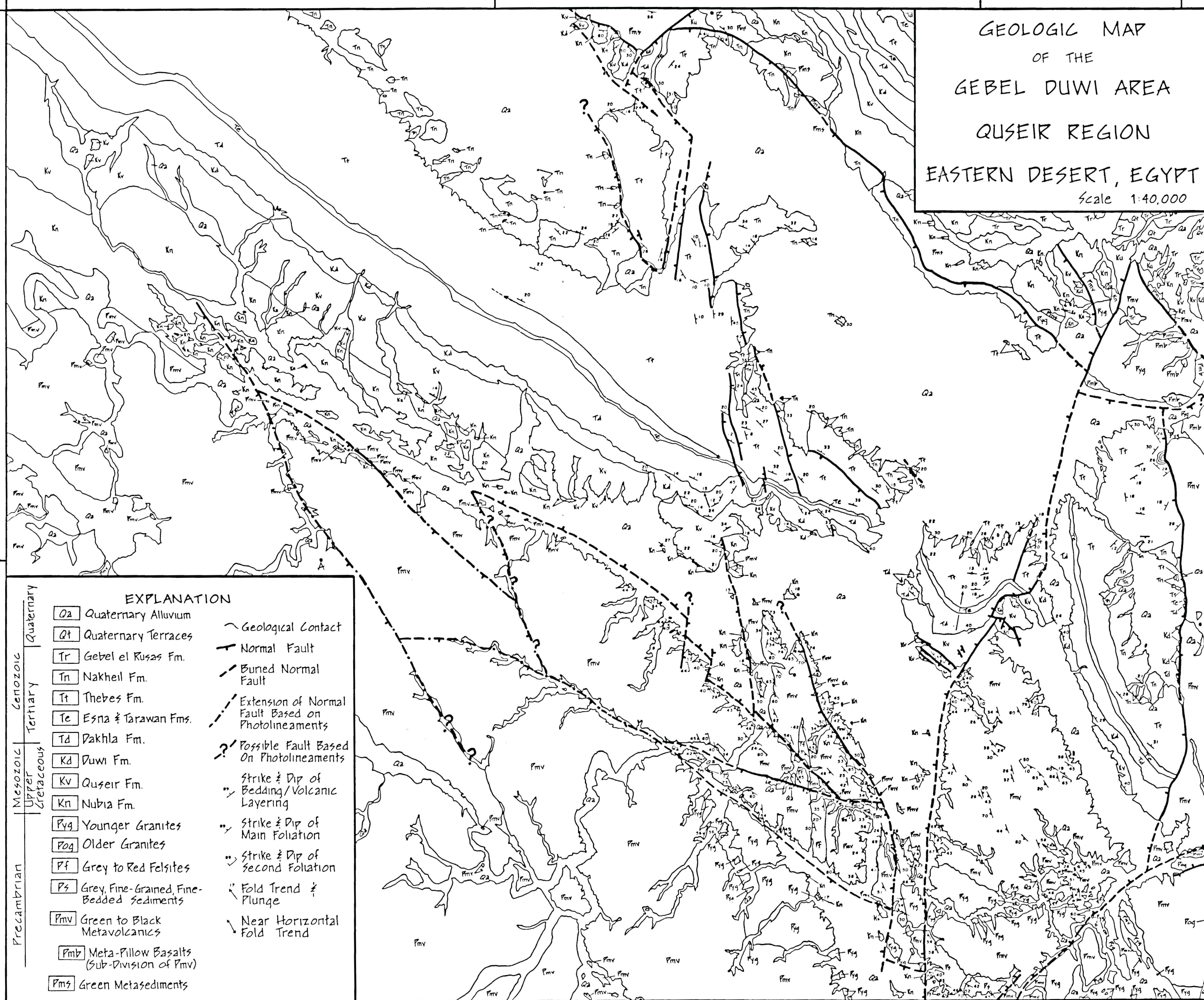
## PLATE I

34°12'E

26°10'N

26°10'N

GEOLOGIC MAP  
OF THE  
GEBEL DUWI AREA  
QUSEIR REGION  
EASTERN DESERT, EGYPT  
Scale 1:40,000



## EXPLANATION

Qa Quaternary Alluvium

Qt Quaternary Terraces

Tr Gebel el Rusas Fm.

Tn Nakheil Fm.

Tt Thebes Fm.

Te Esna &amp; Tarawan Fms.

Td Dakhla Fm.

Kd Duwi Fm.

Kv Quseir Fm.

Kn Nubia Fm.

Pyg Younger Granites

Pog Older Granites

Pf Grey to Red Felsites

Ps Grey, Fine-Grained, Fine-Bedded Sediments

Pmv Green to Black Metavolcanics

Fmb Meta-Pillow Basalts (Sub-Division of Pmv)

Fms Green Metasediments

Geological Contact

Normal Fault

Buried Normal Fault

Extension of Normal Fault Based on Photolineaments

Possible Fault Based on Photolineaments

Strike &amp; Dip of Bedding/Volcanic Layering

Strike &amp; Dip of Main Foliation

Strike &amp; Dip of Second Foliation

Fold Trend &amp; Plunge

Near Horizontal Fold Trend

1 0 1 2 3 4  
Kilometers

26°01'N

34°00'E

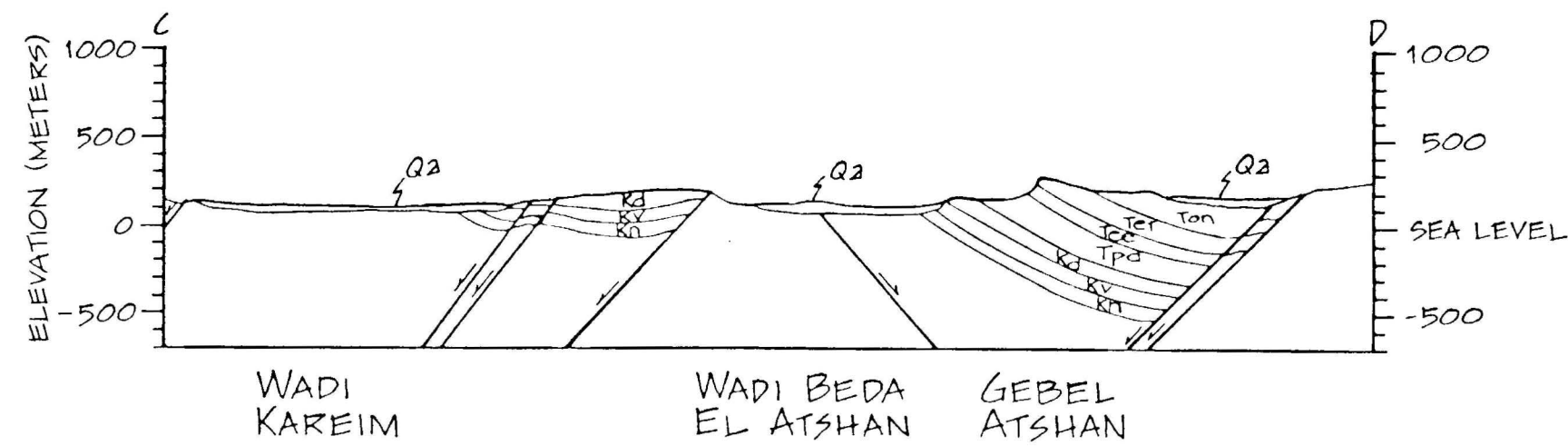
34°12'E

26°01'N



PLATE 2

Geologic Cross Sections  
Southern Gebel Duwi Area,  
Eastern Desert, Egypt



SCALE 1:40 000

