SUBMARINE GEOLOGY OF THE RED SEA

by

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ABSTRACT

A literature survey has been done on the regional geology of the Red Sea to summarize the factors which have been effective in the development of Red Sea submarine structure. Recent geological and geophysical work in the Red Sea itself has been consulted. Previous theories regarding Red Sea evolution and structure are reviewed.

A new model for the structural evolution of the Red Sea basin and its consequent submarine features together with the supporting evidence is presented.

The model proposes Paleozoic development of the basin as a shallow trough which subsided through the agency of semi-plastic spreading and thinning. In contrast, most writers have considered the basin a fracture feature of mid-Tertiary age. The suggestion is made that Tertiary faulting and subsidence represent a second phase of basinal development; this latter activity was dominated by the development of a transcurrent fault zone which passes through the sea.

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The Red Sea trough separates the ancient crystalline highlands of Arabia on the east from their counterparts on the western Nubian shores. Lacking the central trough, the two crystalline areas together form a nearly circular Precambrian shield. The so-called Arabo-Nubian Shield extends from the Nile to central Arabia. It domes up toward the middle, and is overlain on its periphery by an offlapping succession of Paleozoic sediments.

The Sea is nearly 2000 kms. long from Bab el Mandab in the south to Ra's Muhammad in the north; the width converges from a maximum of 350 kms. at Massawa to about 190 kms. in the northern reaches. (Figure 1). A most striking characteristic is the nearly exact match in shape of the opposite shores, and the even better match of opposite basement boundaries.

A band of mainly littoral-facies sediments up to 50 kms. wide lines the Red Sea shores. In some places the beds are reported to lie unconformably upon the basement. In other areas, the contact is reported as a great boundary fault, or fault zone. Correspondingly, the shield topography rises slowly in some areas and steeply in others. It reaches its maximum height of about 3 km. in the south Arabian and Ethiopian Highlands. Mean elevation of the hinterland through the main body of the Sea is 1-1.5 km. (Figure 2).

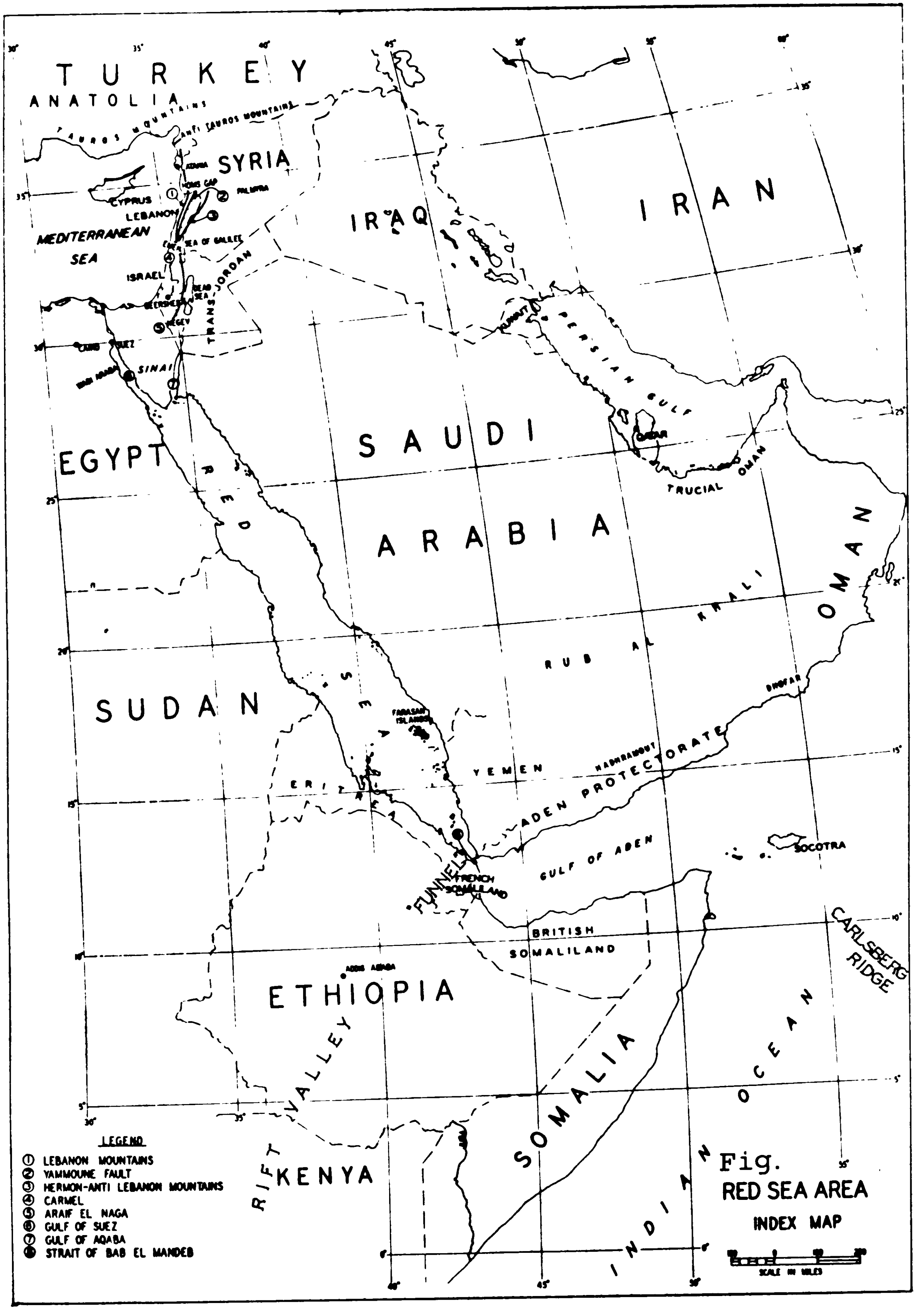


Figure 1 Red Sea area index map.
(after Swartz and Arden.)

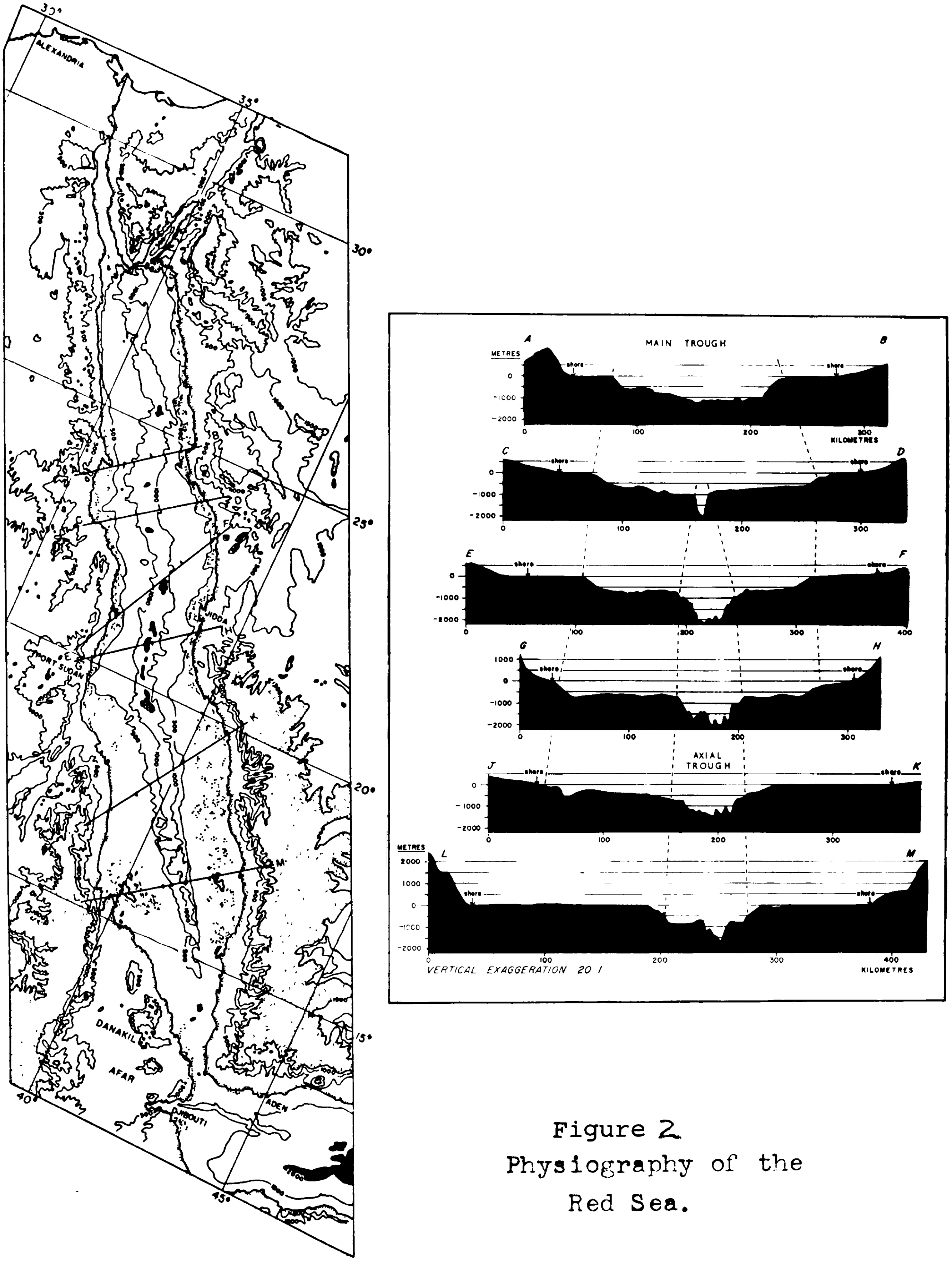


Figure 2
Physiography of the
Red Sea.

In the north, the topography again rises steeply above the shores of Gulf of Aqaba. The bottom topography of the Gulf is irregular; depth reaches 900 fathoms. The Gulf of Suez, by contrast, is filled with sediments to a depth of about 50 meters. Its shores are bordered by a sedimentary lowland similar to that of the Red Sea.

The only major inconsistency in the borderland pattern of the Red Sea itself is the Afar Plain, an extrusive igneous lowland which borders the southwestern shore. This plain fills a large triangular area between the sea and the highlands of Ethiopia and Somalia. The two highlands join at the southwest corner of the plain and then continue inland toward the east African rift zone. An important interruption of the Afar Plain is a horst of basement rocks and Mesozoic sediments which runs parallel to the Red Sea coast. Toward the east, the Gulf of Aden shores diverge toward the Indian Ocean at a small angle (6-9 degrees) like that of the Red Sea shores.

The Red Sea bottom topography is rough except below the shelves. It has a distinguishable pattern of depth--wide trough and narrow shelves in the north; wide shelves and narrow median valley in the south. The mean depth is on the order of 500 meters. Sediment thicknesses range up to several kilometers where measured below the shelves and trough. They are much disturbed by faulting below the trough. Magnetic, gravity, and seismic measurements indicate the presence of basic intrusive rocks in the form of a massive dike below the median valley. The presence of numerous volcanic islands in the southern parts of the valley agrees with this finding.

II. INTERPRETATIONS

A. History of theoretical developments

The Red Sea has been characteristically interpreted as a rather simple geologic structure--most typically as a graben or as a gap between separated crustal blocks. Lack of complication in theories of its origin has most probably been due to a shortage of detailed geological information about either the sea or its borderlands. Until recently, very little direct information about the submarine geology has been available, except for several oil well logs, mainly from the Gulf of Suez. Most writers have assumed the Red Sea structure is continuous with that of rifts described on land at either end. Thus, the interpretation of the connecting structures has been quite critical. This is especially true of the Gulf of Aqaba--and its counterpart the Gulf of Suez--because of their relative accessibility. For this reason, and also because the geology of the area is better known, the northern end of the Red Sea will be emphasized in the present study.

The structure of Gulf of Aqaba is somewhat controversial. It has been variously interpreted as a graben, a normal fault, a crustal separation, a transcurrent fault, or an intermediate combination. Even whether it has been under tension or compression is not resolved in the current literature.

The Gulf of Suez, by contrast, has been agreed by most writers to be a subsidence trough or some kind of tensional separation which has been continuously filled with sedimenrs and faulted on the sides, however, whether the faulting is a cause or effect of subsidence is not agreed. Although the structure is superficially simple, it is in fact rather complicated, and has not been given detailed treatment in theoretical writings (Tromp, 1950). The same is to some extent true of the Red Sea proper (Owen, 1938). Much controversy appears to have carried on because particular points of view or types of information have not been reconciled.

Subsidence

The oldest and most durable structural argument holds that the Red Sea subsided en masse as a response to prolonged uplift of the Arabo-Nubian Shield. This view has often referred for comparison to the Rheingraben, which is also a subsidence in the midst of a regional uplift, although on a far smaller scale. The analogy was first made by Fraas (quoted by Suess, 1875) on the basis of observations in the Gulf of Suez and Aqaba, which he thought were both grabens.

The graben theory was much generalized and extended by Suess, who saw relationships among the various rift subsidences. Unlike many of his successors, Suess saw them as distinct, though related features:

> "At the southern point of the Peninsula of Sinai lies the intersection of two of the greatest sys-

> tems of linear fractures which are known on the face of the earth. The first is that of the Red Sea, which is continued in the direction of Suez; the second which runs almost directly from north to south is that of the Jordan. This...meets the line of the Red Sea at an acute angle and is <u>not continued</u> further."

This distinction between the rifts has been restored in the most recent interpretations (Holmes, 1965, Freund, 1965).

Following Lartet, Suess supposed the Jordan-Aqaba rift was an "asymmetric fault trough". Corresponding rock formations extend much farther north on the east side than they do on the west. The central depression was thought to represent a down-faulted block in the midst of a great normal fault.

The Red Sea, on the other hand, according to Suess was a simple "trough subsidence, perhaps the greatest in the world." Curiously, he thought the Gulf of Suez to be a younger feature than the Gulf of Aqaba, although it has lower and more matured topography.

Gregory(1924) systematized Suess' idea, contending that the entire rift system from Jordan to Lake Nyasa, including the Red Sea, is a continuous series of grabens of like history. He was followed in this opinion by such prominences as Krenkel (1924) and V.V. Beloussov (1962), Cloos (cited by Holmes) has demonstrated through model experiments that such long grabens can be formed by simple uplift on an area overlain by horizontal strata.

Exceptional Opinions

Ball (1911, 1912) suggested that Gulf of Suez is an erosional feature and not the result of faulting activity. He proposed the origin of the Red Sea and Gulf of Suez at a relatively early date as a great land subsidence, possibly during the Upper Cretaceous-Oligocence uplift; the valley was supposed to have been first occupied by a chain of fresh water lakes and a vanished Erythrean river.

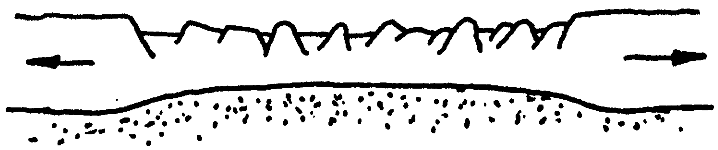
The present paper's thesis is not inconsistent with Ball's Erythrean watershed. His suggestion has otherwise been largely ignored.

A compressional origin was suggested for the Dead Sea as well as for the east African rifts in the papers of Willis (1928, 1936). He did not, however hold that the rift system was contineous or of uniform structure through the Red Sea. Opinions favoring the origin of the Red Sea trough through a succession or alternation of folding and tension were given by Argand and by Lamare.(cited by Owen). This theory has been generally discreditted (Holmes), but only with regard to the Red Sea itself. The Jordan-Dead Sea rift has recently been demonstrated fairly conclusively to result from shear under compression (Freund, 1965).

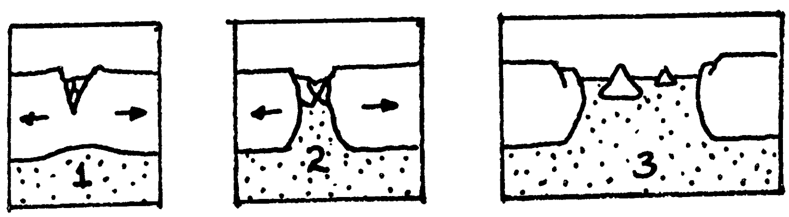
Crustal Separation

The second major trend of Red Sea interpretation is that of continental drift. This theory makes much of the amazing coincidence in shape of the opposite shores as well as their correspondence of topography and geology. It is further supported by observations that the Red Sea and the Gulf of Aden are morphologically and structurally intermediate in character between continental rifts and deep ocean rifts.

According to the drift theory, as described by Wegener (1924), continental rift valleys "form the first steps of a complete separation of the two parts of the (continental) block." (page 168). In the case of the East African rift valleys, "First an opening cleft arises in the more brittle upper strata, whilst the more plastic layers below are stretched." A moderately deep and isostatically uncompensated rift valley is the result. Upon further separation, large areas of land may be submerged.



"In the case of the great rift-valley of the Red Sea, which according to Triulzi and Hecker, is already isostatically compensated, development may have gone so far that at the deeper parts the sima is uncovered. With a further separation of the blocks, the pieces broken from the margins remain behind as islands" floating in pure simatic oceanic crust.



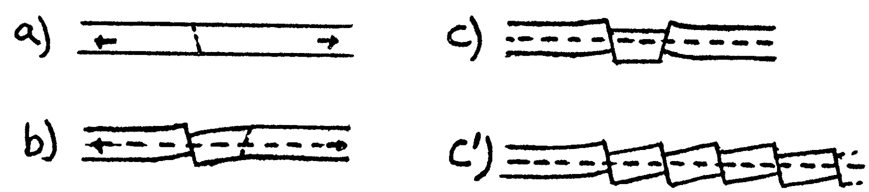
The Red Sea is thus presented as an important example of an intermediate stage of ocean basin formation. Wegener did not develop the examples in any detail, but presented an outline of a theory which was sufficiently advanced to account for major physiographic features of crustal separation basins.

The "necking" and fracture theory of Wegener gives the most satisfactory account of Red Sea evolution of all the theories surveyed. To the detriment of later theoretical development, it appears to have been largely overlooked, perhaps because of its brief treatment (not much more than given in the above paragraph) in the midst of many other proposals.

Elements of the crustal separation theory have further been pursued by many authors, including Carey (1954), Swartz and Arden (1960), Girdler (1958,et seq.) and Holmes(1965).

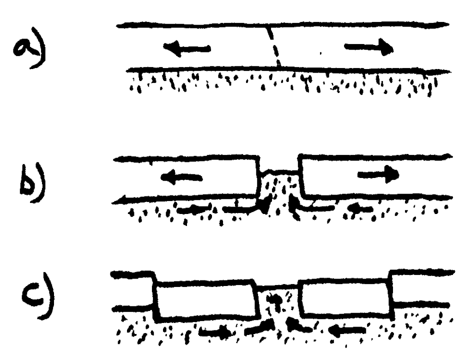
Later Theoretical Developments

A theory of graben formation was developed by Vening Meinesz (Heiskanen and Vening Meinesz,1958) as follows: The first manifestation of uniaxial stress release in the earth's crust is a normal fault with a dip angle of 63 degrees. (stage a)



A slight curvature develops in the crust on both sides of the fault during readjustment toward isostatic equilibrium. On the downward-moving side, this gives rise to an additional tension in the surface of the crust (stage b). A second fracture forms at the point of maximum curvature, which is theoretically at a distance of 65 km. from the first for a crust of 35 km. thickness. If the faults converge downward, the block will subside to form a valley. (stage c). If the faults are parallel or diverge, the block will tilt but will not subside in approaching isostatic equilibrium. (stage c').

R. W. Girdler (1958, '62, '63, '64) has presented a theory based on Red Sea geophysical data which combines elements of crustal drift and block subsidence. He re-emphasized the finding of von Triulzi (1898, 1901) that the central Red Sea is an area of high positive gravity anomaly, whereas the other rift zones are nearly all negative. Girdler deduced that a body of basic intrusive igneous rock 60 km. wide underlies the Red Sea median valley. He suggested that this great dike represents magma extruded from beneath the crust at the time of the rift formation, and that the subsidence of the Red Sea crust is, in fact, due to the displacement of this material. Girdler postulated that forces and motions which formed the Red Sea were similar in kind to those forming other rifts but more intensive (stage a).

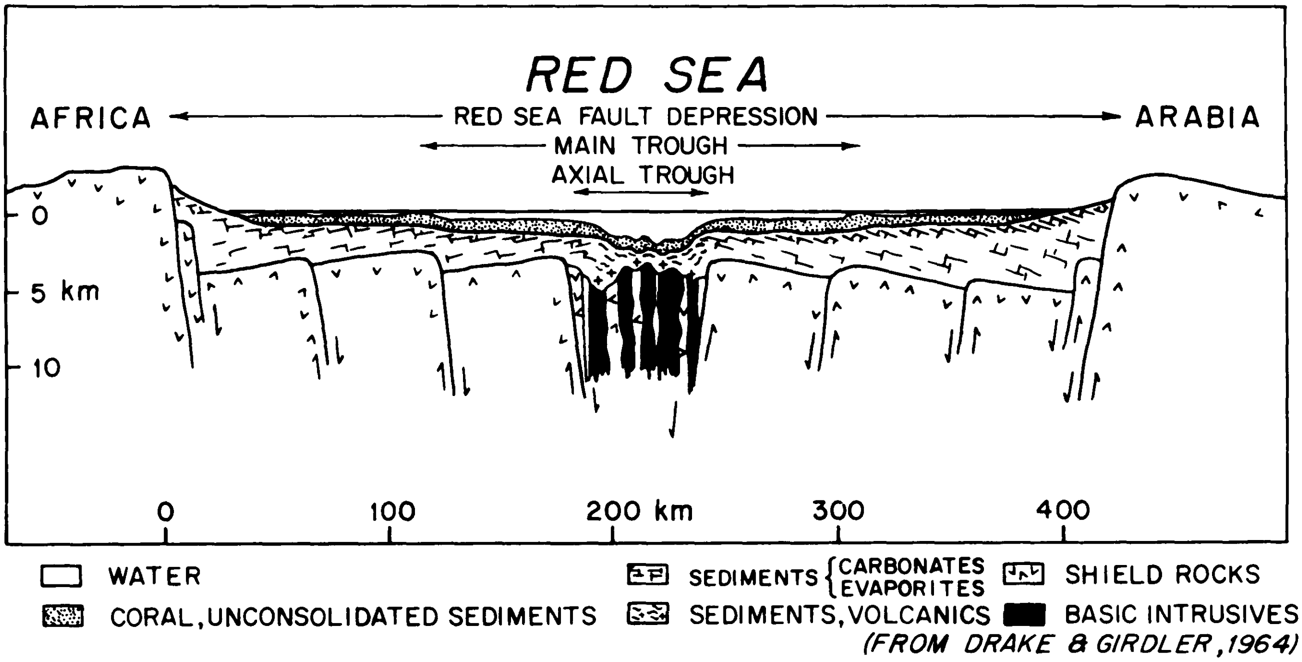


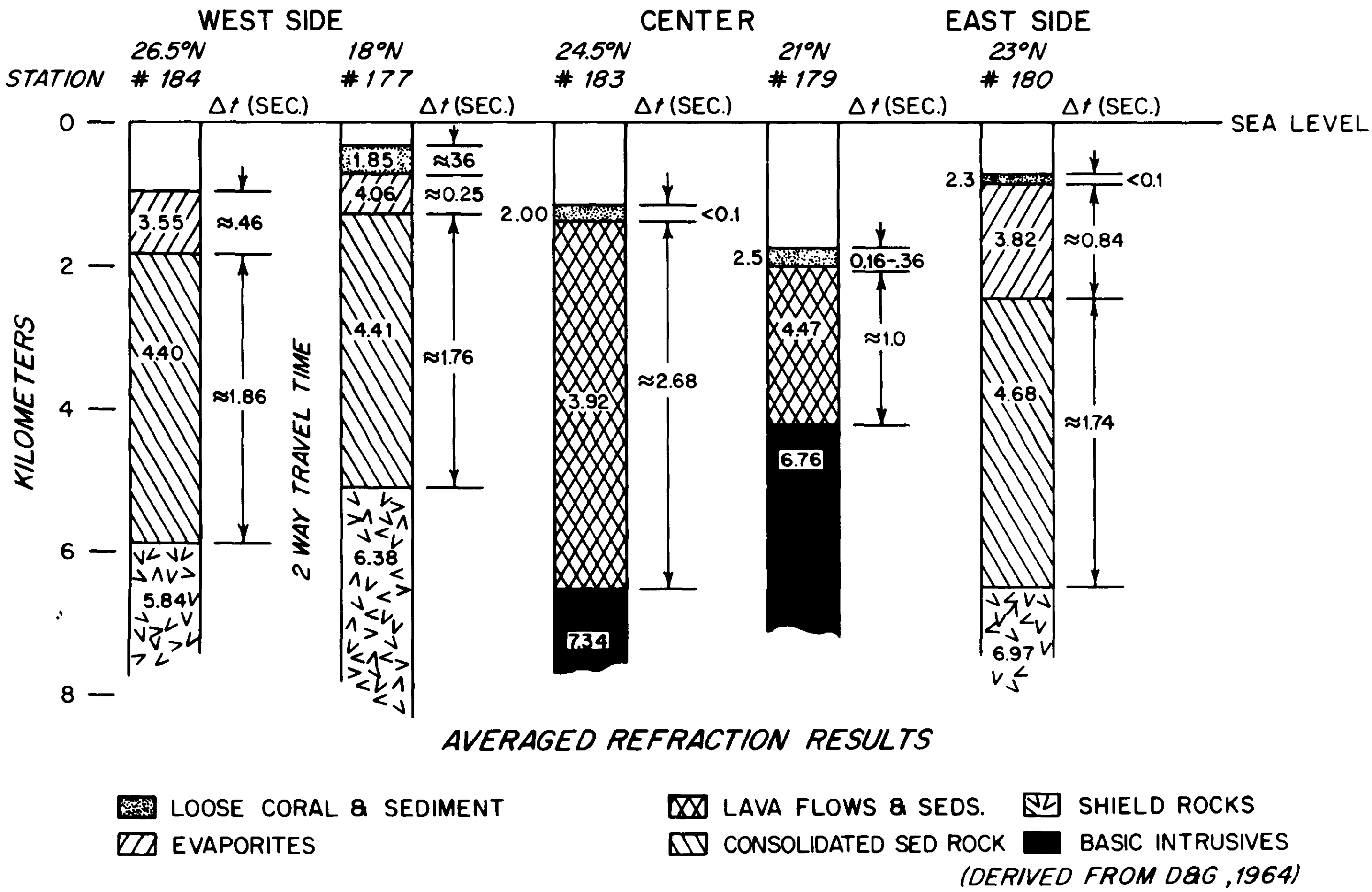
Therefore, instead of a simple normal fault first forming, as in Vening·Meinesz's theory, a complete separation of the crust took place. Sub-crustal magma intruded into the gap subsequently (stage b). The intrusion "caused subsurface movements which originated the rift faulting along the margins of the Sea. The formation of the wide trough is therefore conceived to be a collapse effect due to the movement of igneous material into the fissures of (the) axial fracture zone." (Girdler, 1964) (stage c). Horizontal movement causing the tension and separation was taken to be a rotation of Arabia relative to Africa(second sketch above.)

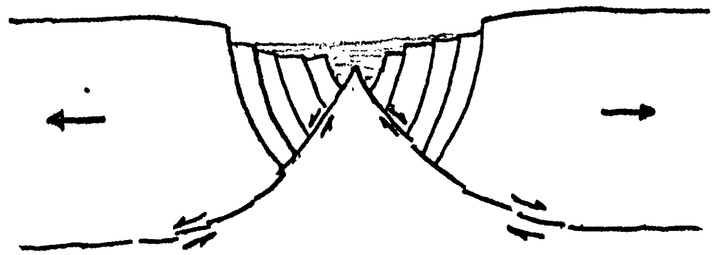
Drake and Girdler (1964) have further developed the details of this model in the light of seismic refraction data. They constructed an idealized cross-section (Figure 3), which is a great improvement over previous suggestions. (Gregory, 1921; Swartz and Arden, 1960; Girdler, 1958).

An alternative theory developed by Carey (1958), concurrently with that of Girdler proposes systematic normal faulting as a mechanism of crustal separation. Carey stated that ductile shear in the lower crust is the most important mechanical factor in crustal block motion. He claimed that the plane of a normal fault changes its slope toward the horizontal at increasing depth in the earth's crust. At its base, the motion of crustal block is resolved into laminar fluid flow.

Figure 3


RED SEA
AFRICA
RED SEA FAULT DEPRESSION
ARABIA
MAIN TROUGH
AXIAL TROUGH
0
5 km
10
0
100
200 km
300
400
WATER
CORAL, UNCONSOLIDATED SEDIMENTS
SEDIMENTS {CARBONATES EVAPORITES
SEDIMENTS, VOLCANICS
SHIELD ROCKS
BASIC INTRUSIVES
(FROM DRAKE & GIRDLER, 1964)


WEST SIDE
CENTER
EAST SIDE
STATION
26.5°N # 184
18°N # 177
24.5°N # 183
21°N # 179
23°N # 180
Δt (SEC.)
SEA LEVEL
KILOMETERS
2 WAY TRAVEL TIME
0
2
4
6
8
3.55
≈.46
4.40
≈1.86
5.84
1.85
≈36
4.06
≈0.25
4.41
≈1.76
6.38
2.00
<0.1
3.92
≈2.68
7.34
2.5
0.16-.36
4.47
≈1.0
6.76
2.3
<0.1
3.82
≈0.84
4.68
≈1.74
6.97
AVERAGED REFRACTION RESULTS
LOOSE CORAL & SEDIMENT
EVAPORITES
LAVA FLOWS & SEDS.
CONSOLIDATED SED ROCK
SHIELD ROCKS
BASIC INTRUSIVES
(DERIVED FROM D&G, 1964)



Thus, in the Red Sea, multiple fracturing of this type has resulted in crustal thinning and the separation of the crustal blocks. The submarine structure accordingly is a series of tabular fault blocks separated by a median ridge of crustal material. This ridge is obscured by sediments in the case of Red Sea. A variation on this theory by Evision (1960) suggested that sliding motions in the upper few kilometers of crust are of primary importance.

The systematic patterns of faulting that he indicated are similar to those of Carey, but secondary faults are shown concave away from the center of motion. His patterns are based on observations of flow in glacial ice.

Carey is an active successor of Wegener in both the the general theory of crustal drift(not discussed here) and in the more specific theory of crustal fracture and horizontal spreading. His treatment of structural detail is more systematic, and supported by theoretical arguments of sub-crustal mechanics. However, his theory is less accomodating to the complexities of topography, morphology, and structure that are observed in the Red Sea. (Figures 2 and 3).

Later Geological Models

Shalem (1952) contributed an interpretation of the basic tectonics of the Red Sea-Near East region. He emphasized the importance of a compressional arc which follows the eastern shore of the Mediterranean, beginning in Sinai and branching toward the east in Syria (see figure). He considered this a basic structural trend of the region which had been overshadowed in interpretations by the more dramatic Jordan trend, which he regarded as an older feature. Folding on the compressional arc, according to Shalem, is intimately associated with volcanic activity in the area; he cited a number of examples of volcanic fissures which are perpendicular to folding trend. He claimed these fissures are parallel to each other, and also to the "Erythrean" trend of the Red Sea; the fissures and the Red Sea thus related, and all were ascribed to the action of "tensional stresses". These stresses, plus the associated compressions, and the volcanic emanations, are seen to occur only on the Arabian side of a supposed Erythrean boundary, the Red Sea-Gulf of Suez line. The African side he interpreted to have been "comparatively stable." Age of the Erythrean faults was taken as Lower Miocene at the latest.

Quennell (1956, reviewed in Quennell, 1958) presented evidence demonstrating that transcurrent motion of the Dead Sea fault is the primary tectonic feature of the structural geology of the area. Motion was indicated to occur in stages, Miocene-Pliocene and Quaternary, with a lapse of time between the periods of activity. Quennell postulated that a rotational motion totaling 6° occurred at the same time as the translation. Thus the Red Sea was suggested to evolve as a consequence of translation-rotation pivoting on the Dead Sea fault beginning in Miocene time.

Swartz and Arden (1960) summarized the stratigraphic succession in the Red Sea region and postulated a sequence of mechanical motions to account for it. As a basic structural model, they assumed a variation on the scheme of Shalem. They postulated the amount of crustal separation to equal the full width of the present Red Sea; by their account, the entire basin is a great fissure, filled by sediments and flows of lava during successive stages of opening.

The tectonic model of Red Sea evolution suggested by Swartz and Arden follows:

" At the end of lower Eocene time the first im-

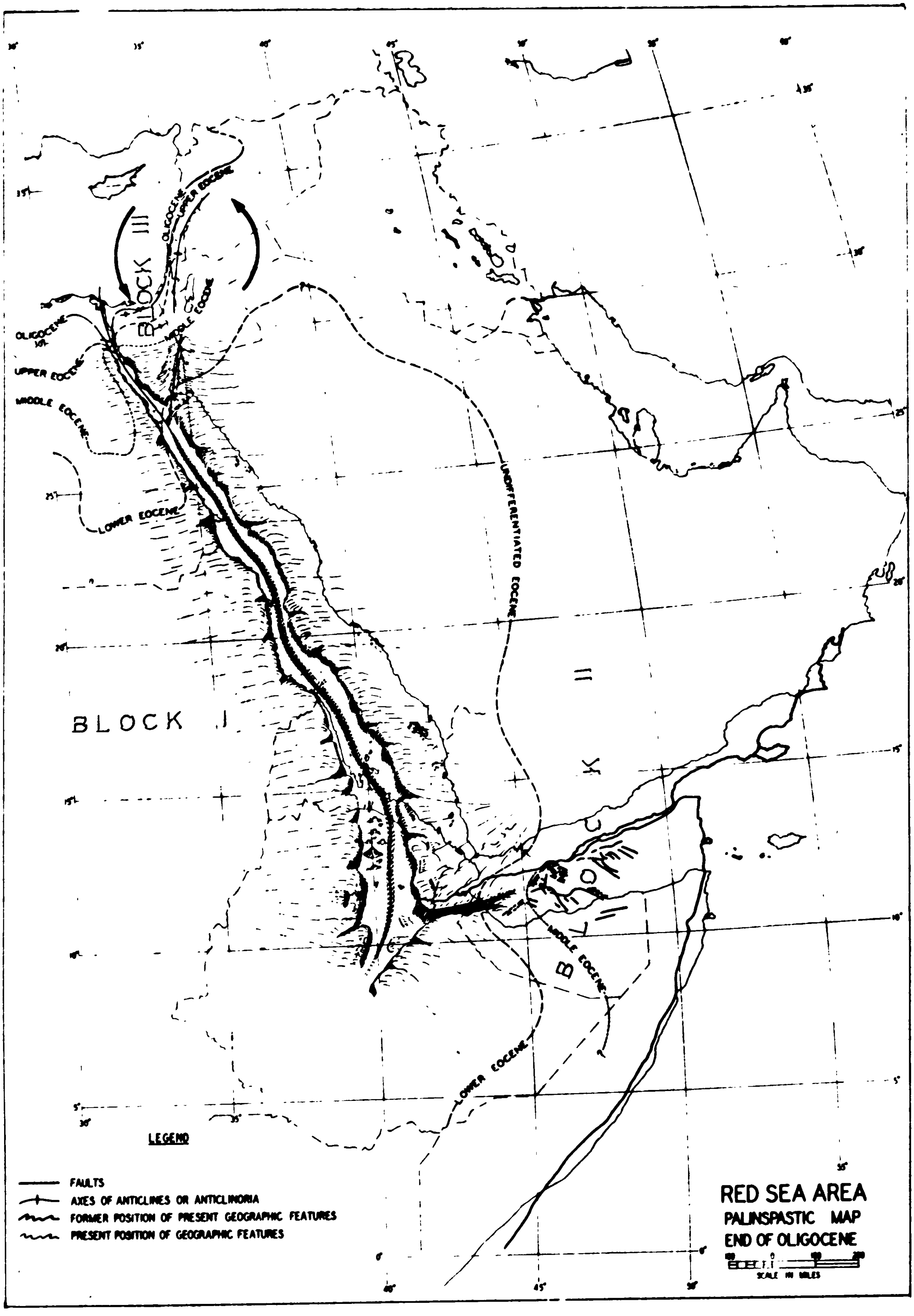


Figure 4 An interpretation of the Erythrean Valley. (after Swartz and Arden.)

> portant folding movements of the northern Red Sea occurred. We believe that at this time a stress couple centering around the southern Hermon Mountains became established, and that energy derived from this couple caused the horizontal shifting of two or more blocks. These movements resulted in concomitant compressional forces developing in the south. (Figure 8)...The Sinai Block (III) moved southeastward along possibly older (Cretaceous) northwest-southeast-trending faults. Concomitantly, the Arabian Block (II) moved first northward against the Sinai Block, and then rotated northeastward from the African Block (I). The lines of separation between Blocks I and II and Blocks I and III united to form a single, jagged separation---the paar. The opening of the paar formed the first stages in the development of the Red Sea and the Gulf of Suez.

In the area of the later Dead Sea, alternating periods of compression and tension allowed the elevation of mountain chains concurrently with the formation of the Dead Sea graben. The paar continued to open, nearly reaching its full width by the end of Miocene time, but still remaining closed in the south. The final major structural development was the separation of the Arabia block from the Somalia block. This began with east-west faulting during late Oligocene or early Miocene time, and culminated with the wrenching open of the straits of Bab el Mandeb in Pliocene time. Figure 4 indicates their interpretation of paleogeography at the critical Oligocene stage. The fissure is shown partly opened, prior to fracturing of the Gulfs of Aqaba and Aden.

The work of Swartz and Arden treated the Red Sea from the point of view of classical stratigraphic land geology. They assumed forces and motions wherever necessary, without being particularly concerned with the structural geology. Thus their deductions are at odds with most of the "structural" theories. Their model is nonetheless accurate in several respects, and has the great advantage of being primarily based on field observations.

Holmes, in his recently revised text (1965) summarized the state of the theory of Red Sea formation as follows :" Like the African rift valleys, the Red Sea and the Gulf of Aden are structural depressions bounded by normal faults, but ...their dimensions are conspicuously different. Until a few years ago this contrast remained unexplained, except by supporters of continental drift who claimed the gap between Arabia and Africa to be a clear manifestation of crustal separation and ocean floor formation, arrested at a relatively early stage compared with, say, the separation of America from Europe and Africa and the formation of the Atlantic floor." The widths of the Red Sea and Gulf of Aden have been explained, according to Holmes, by the discovery (Quennell, 1956, 1958) of the Dead Sea transcurrent fault zone. By Holmes' account, ordinary rifts such as the Rhine graben and the East African Rifts, are the consequence of subcrustal expansion; in the Red Sea case, the additional effect is postulated of a subcrustal current driving the Arabia block in a northeasterly direction. The expansion of the Red Sea thus appears to be a summation of two motions,

a) Uniaxial dilation of the crust and

b) Translation or rotation of one block relative to another.

Freund (1965) gave further details about the translational motion of the Arabia block, deduced from studies of Turonian (Upper Cretaceous) strata on opposite sides of the Dead Sea rift. He stated, following Quennell, that a northward translation has occurred which has the appearance of a counterclockwise rotation of the Arabia block. He locates the center of rotation at about 3000 km. west of the Dead Sea. The amount of displacement is given as 70-80 km., which amounts to 1.5° of rotation around the postulated axis. This is a smaller rotational component than most writers have supposed (5° - 10°). Nonetheless, Freund still follows previous writers in assuming that rotational and translational motion occurred simultaneously. He takes account of evidence for regional tectonic activity beginning in Cretaceous time, and he suggests accordingly that the Dead Sea transcurrent fault may have become active earlier than the Miocene date given by Quennell (op. cit.). He presents additional structural evidence pertinent to the Dead Sea fault motion and further suggests that periods of most active motion along the fault may correlate with periods of folding and uplift of the Tauros and Zagros mountains of Turkey and Iran.

Discussion

Most of the interpretations described have been based on rather few observed geological data or on observations in a limited area. Thus the various suggestions should be considered within the limits imposed by their authors.

Reconnaissance gravity and bottom topography data have been available since the turn of this century (von Triulzi, 1898, 1901). The general patterns of positive anomalies in the Red Sea and negative anomalies in the Gulfs of Suez and Aqaba were known; the structure was considered to be isostatically balanced (Triulzi and Hecker, cited by Wegener, 1924). Nevertheless, two central theoretical ideas have persisted that are inconsistent with these points:

a) The Gulfs and the Sea have commonly been thought to originate in the same way and to have similar structures. However, the differnet patterns of anomaly over large areas indicate that significant differences in submarine density exist. Presumably, differences in submarine structure follow.

b) Theories of block subsidence have implicitly assumed that a detached block will sink to a lower level by displacing underlying plastic material. However, the Red Sea is about ten times as wide as normal crust is thick, so that a block, or a field of that size filled with many blocks, could not bodily subside without changing density or dimensions.

In general, little attention in theoretical discussions has been given to consideration of submarine features. Variations in morphology, though important, have been particularly slighted. Ideal cross-sections have been constructed, nearly always based on the shelf and valley strcuture of the southern end of the Sea, whereas the trough structure has remained a theoretical terra incognita. Recent seismic profiles (discussed later) show the submarine structure to be somewhat more complex than expected, particularly in the north.

Further construction of models for the Red Sea or regional geology should consider the Red Sea submarine geology in its rightful central place. On the other hand, the submarine geology of the Sea should not be isolated from the graben tectonic features of the region, whose motions have formed and are reflected in its submarine structure.

B. New Model

Elements of the various theories surveyed can be combined and correlated with more recently available information to form a more general theory of Red Sea evolution than those described. According to the author's analysis, the Red Sea has developed in two stages, characterized at first by continuous gradual expansion and thinning of the crust; the second stage is characterized by intermittent fracture and block subsidence. Corresponding to these two stages, the Arabian block has moved north and somewhat to the east, first slowly and later rapidly. Development of the northern compressional arc in Turkey and Iran agrees with this sequence. The first period, beginning in the Paleozoic, saw the slow subsidence in compression of the Tethys belt in this area. In the later period, catastrophic compression and orogeny in several stages caused the folding and uplift of the Tauros and Zagros mountains of Turkey and Iran, and the raising of a land bridge between Arabia and this arc.

In the Red Sea itself, the evolution can be postulated and summarized as follows:

1) The Arabian half of the Arabo-Nubian massif began to to recede from Africa during Paleozoic time. Northward strain of the whole massif formed a zone of compression across its northern margin.

2) Motion of the Arabian half of the shield was primarily rotational, with center of rotation in the eastern Mediterranean. In response to the horizontal dilation of the shield, the Erythrean trough formed as a wedge-shaped area of thinning and subsidence.

3) The trough collected continental clastic sediments throughout this first phase of evolution. It was exposed to marine sedimentation at several intervals, probably accompanied by normal faulting.

4) Transgressive intervals corresponded to periods of relative uplift in the Zagros mountains and suggest that the Arabia block moved more actively then .

5) During the long period of slow rotational motion, stresses accumulated most rapidly near the fulcrum in the eastern Mediterranean. Resistance is indicated in the Mesozoic by incipient transcurrent motion in Sinai and in Palestine.

6) In Miocene time, renewed activity resulted in a parting of the crust along the Aqaba-Dead Sea-Jordan line, forming a major left-lateral strike-slip fault. Active normal faulting occured in the Red Sea at this time.

7) Post-Miocene motion of the Arabia block primarily was translational, almost due northward; this direction is at an acute angle to the Red Sea axis, and thus a significant amount of shearing fracture also occured in the Red Sea.

8) Fracturing was largely confined to the axis of the Sea, probably because the crust was thinnest and weakest there. In the southern part of the Sea, the oblique motion parted the crust, allowing intrusion of basic igneous rocks. In the north, complex faulting and general disturbance of the sea bottom resulted.

III. GEOLOGIC EVIDENCE

A. Introduction

The first object of the discussion in this section is to show the pattern of quiescent structural development that existed in the Red Sea prior to the period of rift formation. The second object is to show that the early structural pattern is continuous with that of the later faulting phase.

Most important evidences for the first case are :

a) The presence of a trough on the site of the present Gulf of Suez which subsided almost continuously from its beginning in Paleozoic time until interupted by the first rifting movements in the early Tertiary.

b) Evidence of uniaxial compression throughout northern Egypt, acting in the direction of the Red Sea-Gulf of Suez axis, which existed as early as Paleozoic time, and stopped during the first major period of transcurrent rift motion.

Best evidences for the second case are :

a) The continuity in shape of the Tauros-Zagros arc during several periods of uplift, both before and after the onset of rifting.

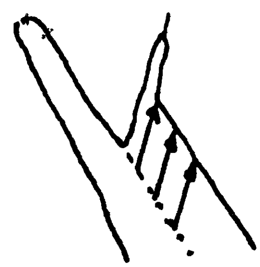
b) Parallel development of tensional and compressional features between the former and the latter structural phases.

The conclusion from these observations is that the Dead

Sea-Jordan transcurrent rift is an internal adjustment of a moving mass somewhat greater than the Arabia Block; and that the greater mass has executed more consistent motion than that of "Arabia Block".

B. Stratigraphic Evidence of Early Red Sea Development

A first postulate to be made is that the sides of the Red Sea were continuous with those of the Gulf of Suez prior to the onset of Jordan rifting. Freund (1965) has demonstrated that Turonian and Cambrian strata are offset nearly the same amount as the inshore Precambrian margin. Quennell (1958) has demonstrated this same motion by several other indicators. Thus upon restoration of the faulted rocks, the eastern boundaries of the basin line up, together with the pre-Tertiary strata. The basement is unbroken on the Egyptian side. It might thus be surmised that pre-rifting tectonic developments in the Gulf of Suez were continuous with those in the Red Sea, and that trough formation in the Gulf of Suez extended south into the Red Sea proper.



Early Trough Development

Conformable Paleozoic and Mesozoic strata lie unconformably upon basement rocks in the Suez depression, and show evidence of basinal deposition. In view of this and the suggested fault restoration, it is evident that a trough existed prior to rift formation.

Stability of the early trough development was dependent upon the tectonic motions of the underlying and surrounding Arabo-Nubian Massif. The most marked characteristic of this Massif is its prolonged and remarkably stable configuration during uplift and erosion. Epeirogenic uplift of the massif has been the dominant feature of the regional geology. Throughout the Paleozoic, clastic sediments were deposited in Egypt which include great thicknesses of greywacke and other pour-in facies (Said, 1962). The topography was ,therefore, probably not low throughout this period, although Picard (1943) described it as an early Paleozoic peneplain.

A corresponding series of continental and marine sediments was deposited around the Arabian rim of the Shield. These generally have the form of off-lapping beds of decreasing age away from the shield (U.S.G.S. map I-270). The location of the northern continental margin is diagramed by Picard (1943), and is seen to occur within quite narrow limits from lower Cambrian to Miocene time.

Precambrian

The currently exposed shield from Jordan to Ethiopia and beyond apparently represents the denuded root zone of a massive Precambrian (and possibly lower Paleozoic--Holmes, 1965) mountain chain (Mohr, 1962; Picard, 1943).

Structural trends of the basement rocks may have been influential to some extent in determining shape and orientation of the original separation. Foliation of the basement is markedly parallel to the basin margins in the south; fracturing has apparently followed old lines of crustal weakness (Mohr, 1962). In the sinuous central section of the Sea, the basement "grain" is oblique to the sea axis (Ruxton, 1956; Brown and Jackson, 1960) and the shores are consequently irregular. Said (1962) mentions a Precambrian structural trend along the Gulf of Suez, but gives no details.

Paleozoic

In view of the distribution of Paleozoic and Mesozoic sediments (U.S.G.S., 1963), it appears likely that the axis of uplift remained fairly constant during those eras. Early parting of the crust may have occurred along the crest of the uplift (Cloos, op. cit.; also Evison, 1960; Rusnak and Fisher, 1964) following pre-existing lines of weakness. No trough sediments are reported prior to Cretaceous time except at the northern end of the basin; thus little direct information about early Red Sea development is available. If the rate of expansion was related to uplift, the trough probably spread outward slowly throughout the span of several geologic periods. Assuming a period of time in the order of 100 million years and a distance of drift less than 100 km., the rate of drift averaged as little as 1 mm. per year.

Earliest trough formation in the Gulf of Suez area is indicated in figures 5 and 6. A lower Carboniferous gulf of the Tethys Sea advanced southward all the way to the present Red Sea. The Umm Bogma formation deposited in this gulf consists of sandstone, marl and crinoidal limestone. Figure 5 indicates the basinal habit both in facies variations and in thickness contours. It is of interest that in an upper member of this formation,black shales predominate in the Gulf concurrent with limestone deposition farther norther. Said (1962) suggested the basin was separated from the open sea by a sill, and further states: "The Gulf must have received great quantities of fresh water to bring about a Black Sea-type of basin where inflow over the sill produced an un-aerated bottom most suitable for the formation of black shales." This interpretation suggests the presence of river drainage, presumably flowing northward into the head of the Umm Bogma gulf. Possibly related conditions existed during fluvio-marine deposition of the early Jurassic period.

Mesozoic

During the Mesozoic era, major marine transgressions occurred in both the south and the north ends of the Red Sea. These were

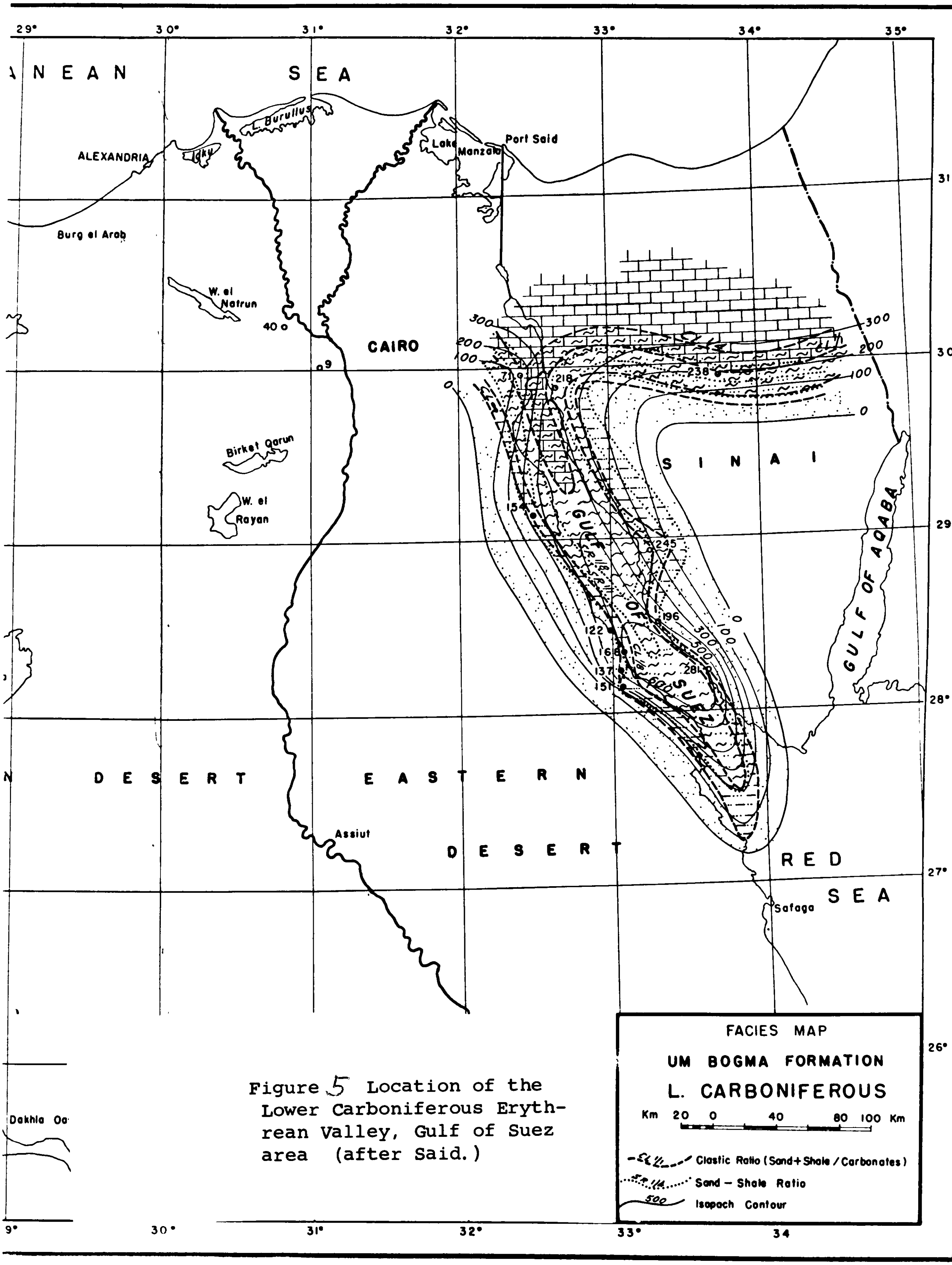


Figure 5 Location of the Lower Carboniferous Erythrean Valley, Gulf of Suez area (after Said.)

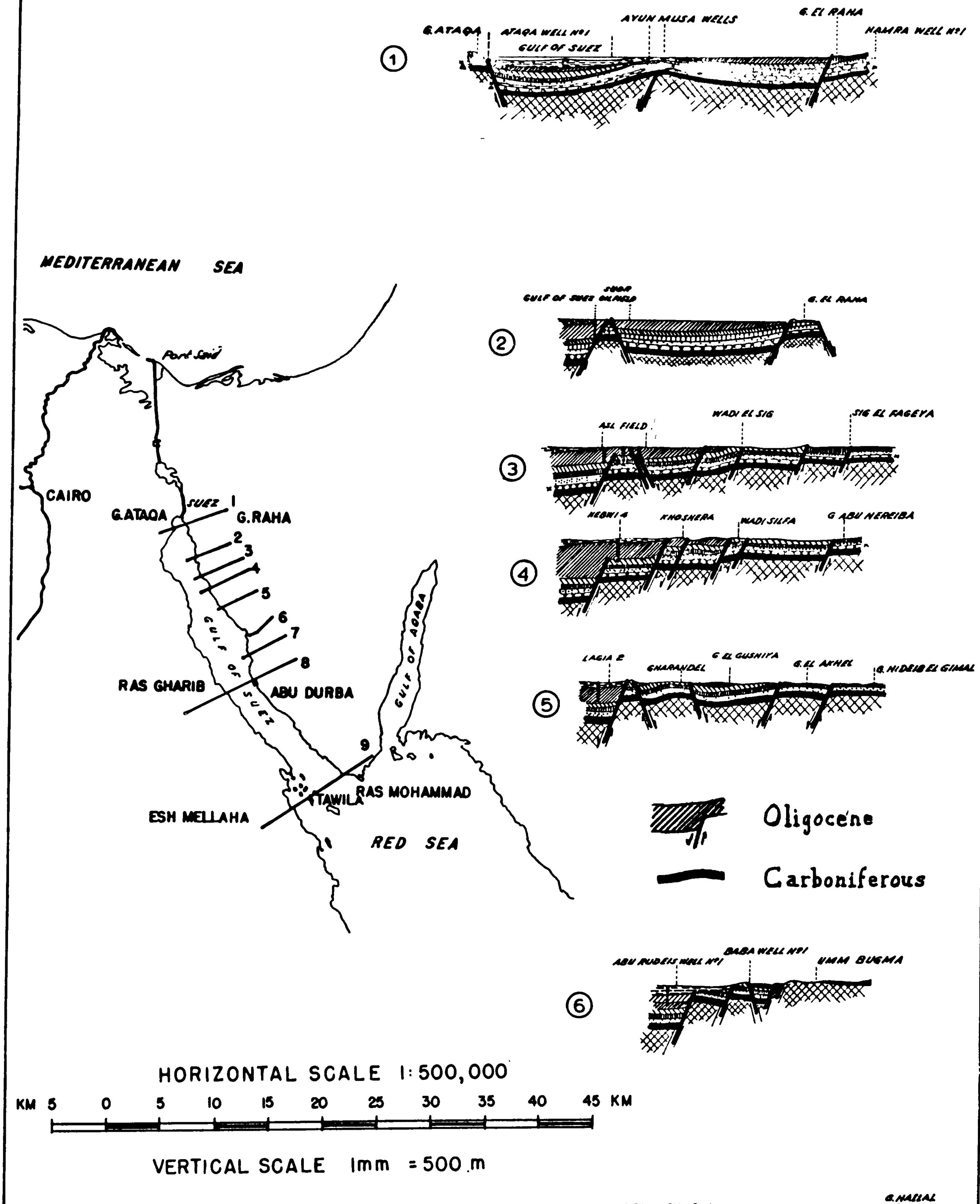


Figure 6 Gulf of Suez sedimentary history. (after Said.)

accompanied by preliminary horizontal tectonic motions. Beginning in Upper Triassic (Mohr, 1962) or Lower Jurassic (Somaliland oil Co.), the sea advanced over Somaliland, South Arabia, and parts of Ethiopia, reaching its maximum extent in Upper Jurrassic. A brief regression occurred in early Cretaceous, allowing elevation and erosion in part of the Jurassic beds. Later renewed transgressions of Mid.-Cretaceous to Mid-Eocene time were somewhat less extensive, stopping short of the head of the Gulf of Aden (Somal. Oil Co.).

Mohr (1962) has suggested on grounds of basalt flow ages that the Afar Plain existed in approximately its present state prior to Tertiary rifting. Thus the southern end of the Red Sea was at its present width during the Upper Mesozoic. The Jurassic transgression which laid marine sediments on the Danakil Horst and the present highlands of Yemen and Ethiopia would therefore have been continuous across the southern end of the Sea (also indicated by Somaliland Oil Co., 1954). There is at present no grounds for estimating how far north into the depression the Jurassic sea may have extended. In the north, transgressions in Palestine and Egypt occurred at approximately the same times (Picard, 1943; Said, 1962) as those in the south. Maxima were reached in the Upper Jurrasic and at several stages from Middle Cretaceous through Lower Eocene. Throughout this period, the basinal character of sedimentation was perserved and the shape of the Gulf remained similar to that illustrated in Figure 5.

Cretaceous-Eocene

Transgressions increased through the early and middle Cretaceous, reaching a climactic series which began in the Campanian epoch of the Upper Cretaceous period. At that time the sea advanced over much of Egypt, and penetrated far south into the Red Sea basin. Beds of the Campanian-Lower Eocene marine series are found lying conformably above basinward-dipping Nubian sandstones as far south as 26 degrees north on the Red Sea shores (Beadnell, 1924; Hume et al., 1920). They are found in faulted outliers away from the shore in Egypt (Beadnell; Said, 1962) and also far to the sough on the Arabian shore near Jidda (Karpoff, 1957). Only the Maestrichtian portion is identified (by Karpoff, 1957) from the latter location; U.S.G.S. (1963) reported Eocene faunas from the same formation. It is interesting to note that Karpoff's stratigraphic description, although scanty, is comparable with the Maestrichtian sequence described in Gebel Duwi by Beadnell (1924). This comprises two layers of white chalk separated by iron-containing beds, the whole followed by a clastic redbed sequence. A possible further occurrence of deposits correlating with this sequence is reported from the Sudan coast at 21 degrees north (Carella and Scarpa, 1962).

It is reasonable to assume on this basis that Cretaceous-Eocene beds underly the whole Red Sea basin, at least north of this latitude.

The main sedimentary facies during Upper Cretaceous in the Red Sea were marls and shales, with chark being the main accessory beds. Meanwhile in the Gulf of Suez, chalk formed almost exclusively. In the Lower Eocene, flinty limestones were deposited in both areas. Deposition in the Red Sea appears to have ended abruptly at the end of Lower Eocene, contenporaneous with marked tectonic movements.

Discussion of Stratigraphic Evidence

The basinal habit of sedimentation in the Gulf of Suez is important to the present discussion in that it is indicative of quiescent trough development in Pre-Tertiary time. Attention is called to Figure 6, which indicates conformable contacts between strata deposited by successive transgressions up until the Oligocene. While faulting is recorded from the Eocene (Tromp, 1950), the major activity in the Gulf of Suez is indicated to begin and end in the Oligo-Miocene (Said, 1962). At that time, graben formation of the type described earlier (Vening Meinesz, P.13) appears to have occurred. Prior to that time, trough subsidence by another mechanism took place. It is here proposed that the Gulf of Suez trough, as well as that of the Red Sea, was isostatically balanced during the early period of formation. Episodic, or possibly continuous lateral expansion of the trough allowed the accumulation and subsidence of a thick sedimentary sequence. This accumulation was compensated by crustal thinning of the type proposed by Wegener (p. 11). In the case at hand, the motion was so slow that surface expressions of the lateral motion were relatively minor. Block motion of the type suggested by Wegener began in the Gulf of Suez during the latter part (Cretaceous-Eocene) of the"quiescent subsidence"phase when the lateral motion was somewhat accelarated. Possible supporting evidences for the above model, in addition to those in the text, should include measurements of crustal thickness below the Gulf of Suez. The crust is expected to be relatively thin, graben subsidence and negative gravity anomalies notwithstanding. It would further be interesting to look for evidence of many minor tensional adjustments in the older sediments of the Gulf of Suez area.

From the model, one might conclude that the entire basin was a shallow and relatively flat feature during the Cretaceous- Eocene marine transgression. In view of this interpretation and the available stratigraphic information, it may be possible to predict the submarine characteristics of this important sequence.

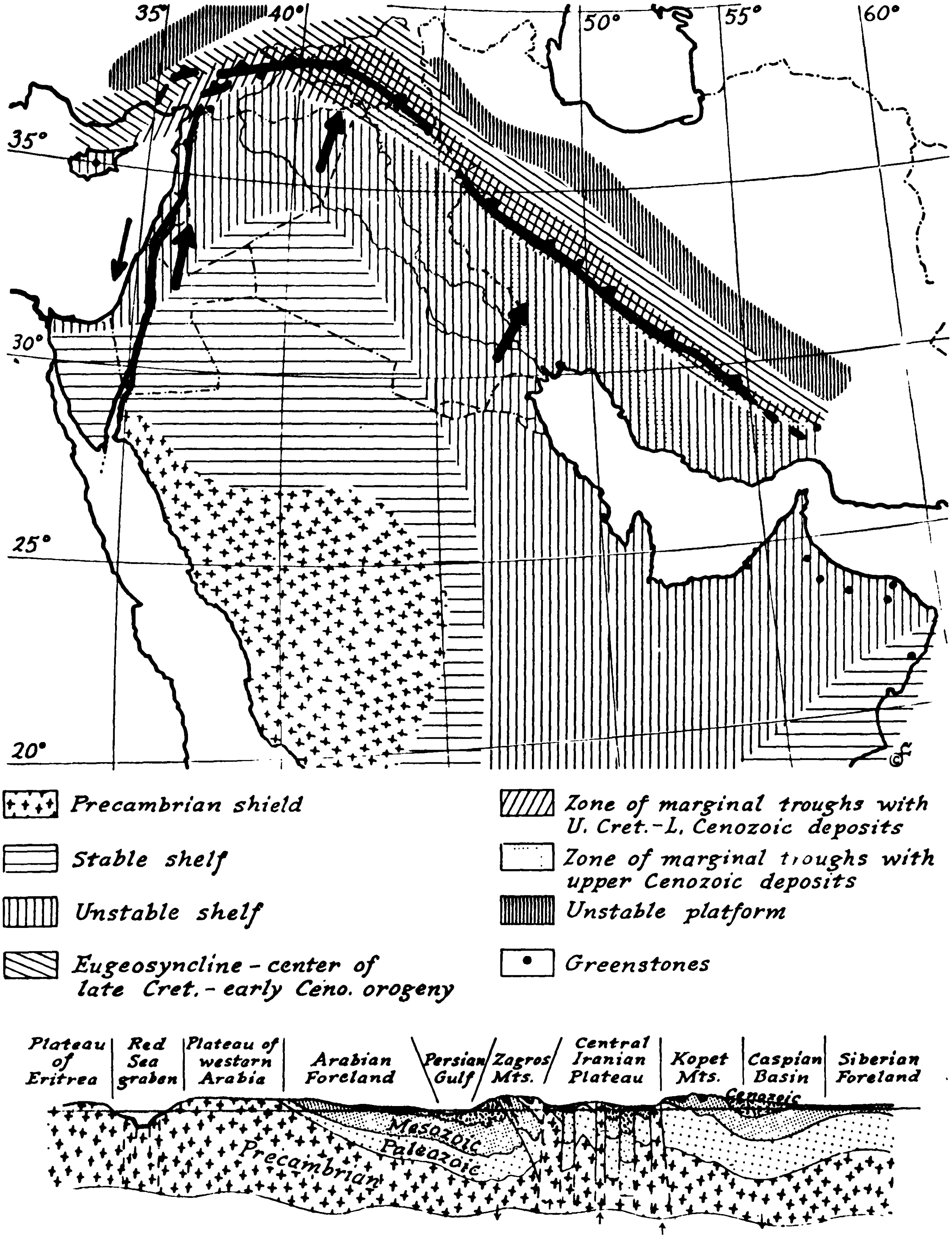


Figure 7 General interpretation of Middle East geology (after Kummel.)

C. Structural Evidence

Several types of episodic structural phenomena occurred in the northern Red Sea region during the pre-Oligocene phase of basin formation. These generally developed with timing and intensity parallel to the marine transgression series, and thus were probably associated with lateral motion of the Arabia block. Taken together, they form a tectonic pattern which supports the postulate of episodic expansion of the Red Sea trough.

During the later period of "rift" formation, a somewhat different tectonic pattern emerged. Elements of it have been correlated by Quennell (1958) and by Freund (1965) and indicate a similar episodic development. In the second period a clear parting of the crust occurred along the Gulf of Aden-Red Sea-Dead Sea lines. The Arabia block was released to move more freely northward, whereas the African side of the Arabo-Nubian Massif ceased its previous motion toward the Mediterranean. Intervals of various structural developments follow:

a) Major transgressions of the Gulf of Suez-Red Sea trough: Lower to Middle Carboniferous; Middle and Upper Jurassic; Upper Cretaceous and Lower Eocene; Mid. Tertiary and later. The last named epoch is exceptional in that boundaries are fault controlled, a thick section of basal clastic developed and deposition is clearly related to the present location of Red Sea shores.

b) Folding and uplift in the unstable shelf areas of

North and West Egypt: Lower to Middle Carboniferous. Compression was active from Paleozoic to Mid-Tertiary, then stopped. Orientation of folds normal to the Red Sea-Suez axis became quite pronounced during the Cretaceous and Eocene stages.

c) Normal faulting of "Erythrean" orientation: Upper Cretaceous (Attia, 1955); Lower Eocene (Tromp, 1950, Said); mid-Tertiary and later (Said). During the last epoch, tensional relief with normal faults of Erythrean orientation developed in place of earlier folding in northern Egypt. Also in that period , major down-faulting of the Gulf of Suez and Red Sea occurred.

d) Vertical block motion, Gulf of Suez region: Increasing through several stages in the Cretaceous-Eocene period (Said, 1961, 1962).

e) Volcanism and hydrothermal activity: Lower Carboniferous (Said, 1962); Upper Jurassic (Picard 1943); Upper Cretaceous; Oligocene (Said); Mid.-Tertiary and later (Quennell).

f) Motion along the Dead Sea fault., incipient strain: Jurassic and Senonian; 62 km. translation; Miocene-Pliocene; 45 km. translation; late Cenozoic (Quennell, 1958).

g) Compression and uplift of the Tauros-Zagros mountains; general uplift, absence of strata in Lower Carboniferous (Kummel); major orogenies: Upper Cretaceous, Eocene, Mio-Pliocene, Quaternary (Freund, 1965; Kummel, 1961).

Items a) and c) appear to both result from a field of uniaxial stress release acting normal to the axis of the Red Sea-Suez trough. Item b) thus seems to result from the conjugate field of uniaxial compression acting in the direction of the trough axis.

An intimate relationship appears to exist between the observed tensional and compressional effects. Maximum activities were generally coincidental, most notably in successive stages of the Upper Cretaceous and at the end of Lower Eocene (Said, 62). Block motion activities (item d) may have resulted from effects of the right angle intersection of folding trend and faulting trend.

Shalem (op. cit.,p.17) presented a diagram showing the continuation of the "Syrian Arc" of folding around the southeast Mediterranean shore and on toward the northeast through Syria. He indicated a pattern throughout the arc of tensional cracks which cross the fold axes and which are oriented parallel to the Red Sea axis. He further cited evidence showing that basalt is characteristically extruded along these cracks. (item e).

Volcanism occurred in the compression zones of Egypt during the pre-Oligocene period of activity (Said, 62), but appears to have ceased after the Mio-Pliocene relaxation of stress in this area. In Arabia and Palestine, fracturing and volcanism appears to have increased in Mid.-Tertiary and later time (Quennell, 1958, Picard, 1949; U.S.G.S., 1963).

Following Quennell, development of the Dead Sea rift was about as follows:

a) First evidences of differential motion along the later fault occurred in Senonian time; drag folds developed during deposition of chalk beds. Earlier evidence of shear occurred probably in Jurassic time.

b) The Sea withdrew northward after Eocene deposition; two uplifts occurred, then a prolonged Oligocene still-stand.

c) Early Miocene time, NW-SE compression gave rise to deep seated thrust faults and the beginning of major shear faults along old zones of weakness.

d) Volcanic activity began and lasted until the second period of transcurrent motion began in Plio-Pleistocene time.

<u>Summary</u>

To summarize the structural pattern indicated above :

a) Episodic compression or motion occurred in the direction of the Red Sea axis in pre-Oligocene time and was expressed by folding of "soft" sediments of the Egyptian shelf and possibly by uplift of mountains in Turkey.

b) Simultaneously, tension perpendicular to the sea axis formed fractures parralel to the axis, some of which served as volcanic and hydrothermal vents.

c) Tensional opening gave a sideways motion to the Arabia block, which apparently put the opposite side of the block into compression, pushing up mountains in Iran.

d) Net motion due to the tensional and compressional effects was approximately northward.

e) Stress accumulated in the Sinai region through successive episodes, eventually causing yield and shearing motion of the Dead Sea fault.

IV. Submarine Structure of Red Sea Sediments

In the light of stratigraphic and structural evidence cited, it has been shown that the Red Sea has a much older history than is commonly thought. The cited age is generally Miocene or at earliest Upper Cretaceous (Freund, 1965; and others), the latter on the basis of reported Maestrichtian strata in the basin (Karpoff, 1952). However, from the forgoing discussion it may be concluded that the Red Sea existed as a continental basin at least as far back as the Carboniferous (figure 5).

It has been further shown that prior to Oligocene time, the basin developed by a different mode than in later time. Such a two-phase evolution appears to have been previously unrecognized. Most authors have suggested different types of simple or compound motion to account for the structure in one stage or one mode of activity.

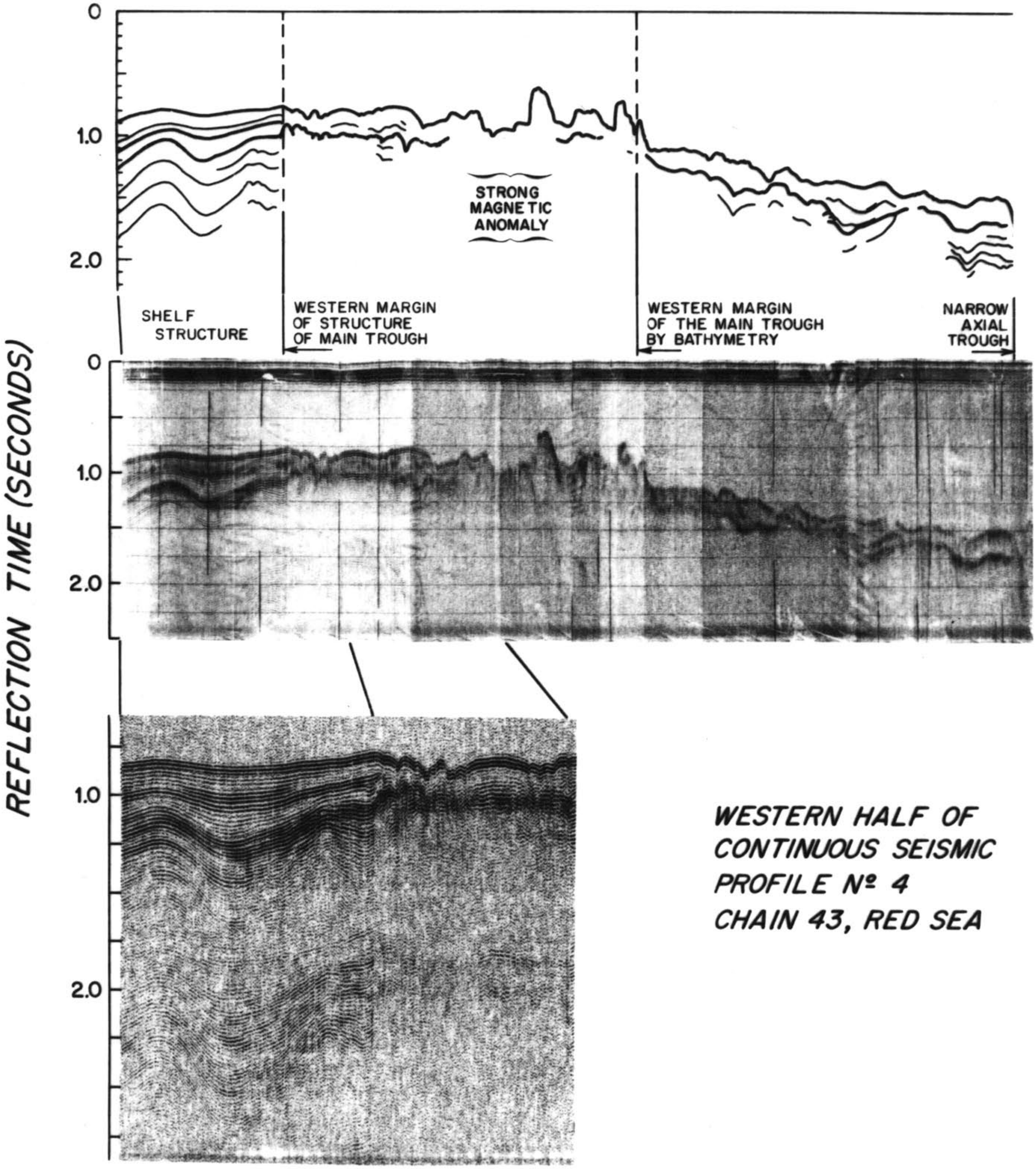
The Gulf of Suez has been discussed at some length and presented as representative of the early phase of Red Sea evolution. This period saw the development of a relatively quiescent subsidence trough. The Gulf of Aqaba, on the other hand, represents the later period of normal faulting and transcurrent rift formation, both of which motions affected the Red Sea. According to the present model, the relative motion of the shores was a) an expansion away from the axis in the first stage and b) a northward translation of Arabia relative to Africa in the second stage. Recent seismic reflection profiles by the Woods Hole Oceanographic Institute (figures 8, 9, 10) may be referred to for further evidence regarding the two phases of motion.

A pattern of deformation may be pointed out in the cross-sections. The shelves at both ends of the Sea have relatively smooth surface topography, and are underlain by gently folded conformable sediments. The median trough, by contrast, is underlain by much-disturbed and irregularly deformed beds. Conformable bedding in this area is largely obscured by the erratic variations in topography and structure.

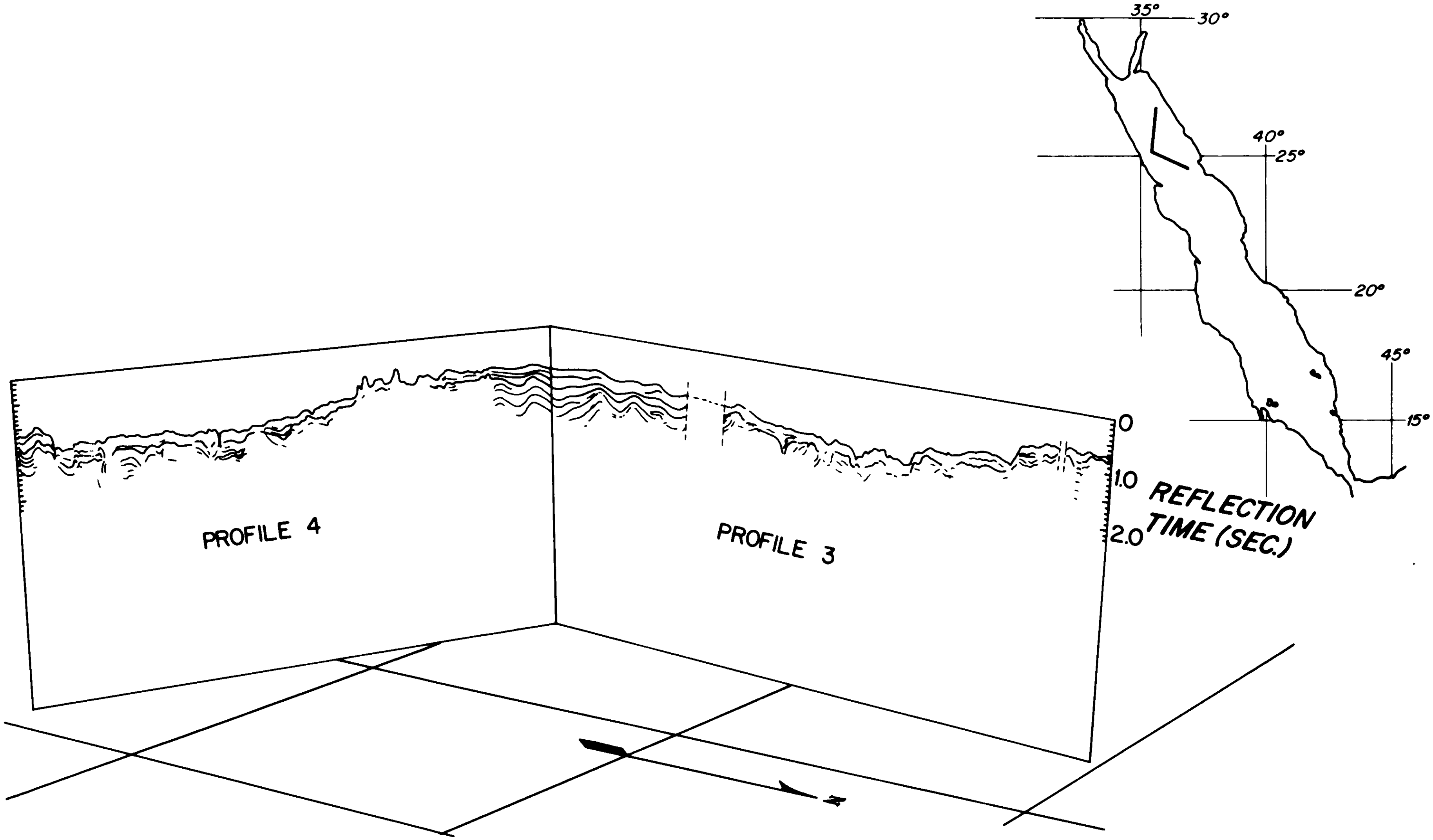
The width of the highly disturbed zone increases markedly from south to north as indicated by the seismic data. It appears to be associated in both areas with the central depression. This depression, the "axial trough", appears to diverge northwards rather than southwards, as supposed by Drake and Girdler (op. cit.) (figure 2).

In the south, the axial trough is associated with strong magnetic anomalies and positive gravity anomalies. These have been interpreted as due to a basic intrusive igneous body underlying the axial trough (Girdler, 1958 et seq.) The width of this

Figure 8



WESTERN HALF OF CONTINUOUS SEISMIC PROFILE Nº 4 CHAIN 43, RED SEA


35°
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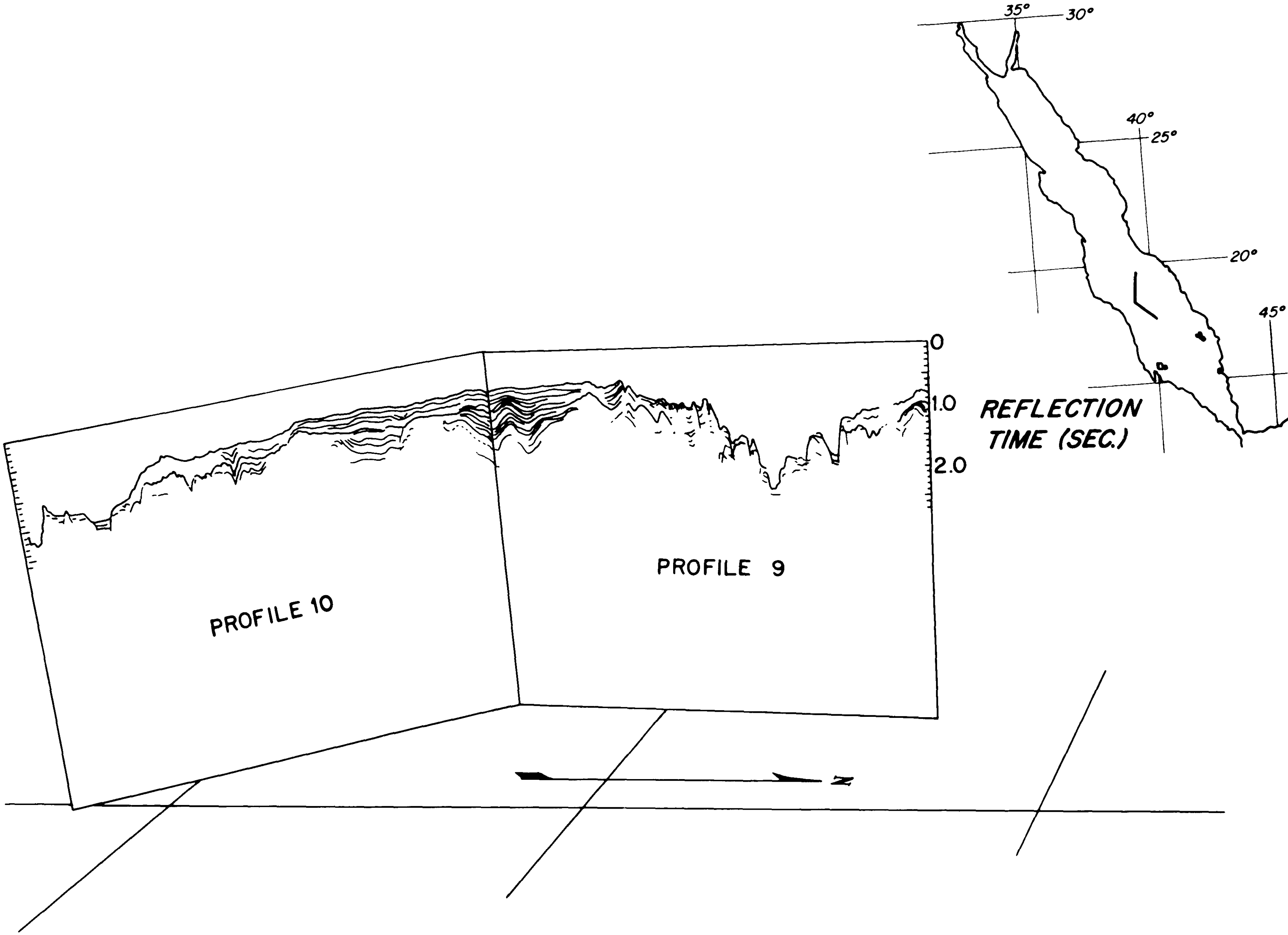
PROFILE 4
PROFILE 3

Figure 9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PROFILE 9
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Figure 10

supposed body is 60 km.; it extends for nearly half the length of the sea. In the central and northern part of the sea, the occurrence of magnetic and gravity anomalies data indicates that igneous bodies are here distributed irregularly. For example, on profile 4 (figure 8) an area of strong magnetic anomaly occurs outside the axial depression. The width of the disturbed zone is on the order of 100 km. in the northern section and thus occupies most of the width of the sea.

It is here suggested that the northern axial trough is an enormous shear zone which has developed as a consequence of Miocene to Recent motion on the Dead Sea fault (Quennell, op. cit.). Assuming a translational motion just east of north, the direction would be about 45° away from the axial direction. During the same motion the southern axial trough parted cleanly to form separated blocks. This might be due to a slight rotation of the block during translation, as suggested by Freund (1965). The southern part of Arabia would move faster than the nortl under such a condition, and might exceed some critical velocity for crustal separation as suggested by Rusnak and Fisher for the Gulf of California (1964). The difference in fracturing behavior could on the other hand be due to a difference in strength of the crust, or lineation of the basement rocks, as pointed out earlier. Or it could be due to the shape of the opposite shore-lines in the central Red Sea. In one area, a northward translation would almost parallel the trough axis; consequently, shearing activity would be greater, at least in that area. It is noteworthy that several deep holes occur in this central part of the Sea (figure 2).

In any case, the amount of disturbance and linear motion of the Arabia block appears to be about constant from the Dead Sea to Bab el Mandab. Motion on the Dead Sea fault was about 80 (Freund) to 100 (Quennell) km. The 60 km. width of the southern median valley is about the same when measured in the direction of supposed translation. The northern trough zone of disturbance could have accomplished the same extension by "necking" down to about half of its pre-rifting thickness. The area is regionally subsided by about 1 km., suggesting that such a change of the crust has taken place.

The likelihood of distension and subsidence of the main trough during rifting is further suggested by the appearance of the disturbed sediments (profile 4). It is most interesting that a reflector of fairly constant depth below the bottom can be recognized. This reflector faithfully follows the bottom topography which latter must, therefore, be a tectonic and not erosional topography. The layer thus appears to be a disturbed sediment layer which was all-ready buried prior to the last major period of rift motion. The appearance of this faulted contact suggests that the right-hand side of the fault moved upwards and its previous upper surface eroded away. This vanished layer would correspond to the second layer of the left-hand side, which ends at the fault. Further deposition occurred contemporaneously with further motion; thus the upper layers in both the disturbed and the stable zones are probably of late-rifting age, or late Pleistocene, according to Quennell's chronology (op. cit.). The second layer is thus probably early Pleistocene; the third may be Pliocene. It is very interesting to note that the three-layered sequence is repeated in a conformably-bedded and subsided section on the right-side of profile 4 (figure 8). The upraised portions contain only two reflecting layers, the late Pleistocene layer, and the postulated pliocene "third" layer. Recent sediments of several meters thickness are found lying unconformably above this sequence as horizontal sediment ponds in low places (S.T. Knott, personal communication based on high resolution bottom sounding records). A similar sequence of disturbed, eroded, and re-deposited sediments might occur at a deeper level. This would correspond to the first period of rifting motion in Miocene time. On the other hand, Miocene motion might have been expressed differently in part, such as in the extensive normal faulting of that period observed in many parts of the Red Sea shores.

A reconstruction of the Red Sea bottom to its condition in the pre-rifting period would apparently re-join and re-thicken the crust to a relatively flat and shallow state, such as is presently observable in the Red Sea shelves. Such a reconstruction would be very much in agreement with the evolutionary model suggested by the present paper, and would correspond to the Cretaceous-Eocene shallow basin whose existence has been postulated in an earlier section. The Red Sea shelves are thus suggested to be remnants of a relatively smooth pre-Oligocene basin whereas the median valley in the south and the deep trough in the north are caused by the post-Oligocene rifting of this basin. From this one may conclude that the ancient clastic sediments and Mesozoic marine deposits of the Red Sea shores may be found below the shelves and furthermore among the fractured and subsided rocks of the main trough of the Sea.

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