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A Model for Development of Red Sea[1]

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ABSTRACT

Although motion between Arabia and Africa is presently occurring along the entire length of the Red Sea, the morphology and tectonics that result from this motion vary greatly along its length. South of 21°N, the main trough is bisected by a deep axial trough which has formed by sea-floor spreading during the past 4 m.y. and is associated with large-amplitude magnetic anomalies and high heat flow. North of 25°N, an axial trough is not present and the floor of the main trough has an irregular faulted appearance. The magnetic field in the north is characterized by smooth low-amplitude anomalies with a few isolated higher amplitude magnetic anomalies commonly associated with gravity anomalies and in many places probably due to intrusions. Between these regions, the axial trough is discontinuous with a series of deeps characterized by large-amplitude magnetic anomalies alternating with shallower intertrough zones which lack magnetic anomalies.

It is argued that the different regions represent successive phases in the rifting of a continent and the development of a continental margin. An initial period of diffuse extension by rotational faulting and dike injection over an area perhaps 100 km (60 mi) wide is followed by concentration of extension at a single axis and the initiation of sea-floor spreading. The main trough in the southern Red Sea, away from the deep axial trough, formed during the Miocene by the same processes of diffuse extension that are still active in the northern Red Sea. This model explains the available geologic and geophysical data and reconciles previous models for the formation of the Red Sea which emphasize either the evidence for considerable motion between Arabia and Africa or the evidence for downfaulted continental crust beneath much of the Red Sea.

The initial pre-sea-floor spreading stage results in considerable extension (160 km or 100 mi) at 25°N in the Red Sea), can last for several tens of millions of years, and is an important factor in the development of the continental margin. Such an extended phase of rifting and diffuse extension must be taken into account in studies of sedimentation, subsidence, and paleotemperatures.

INTRODUCTION

The Red Sea occupies an elongate escarpment-bounded depression, 250 to 450 km (155 to 280 mi) wide, between the uplifted Arabian and African shields (Fig. 1). Morphologically, the Red Sea consists of shallow continental shelves, a wide "main trough" which extends from about 15°N to the tip of the Sinai Peninsula (28°N) at a depth of 600 to 1,000 m (2,000 to 3,000 ft), and a narrow "axial trough" found from about 15°N to 24°N which is about 2,000 m (6,500 ft) deep, usually less than 50 km (30 mi) wide, and is characterized by steep walls and irregular bottom topography (Drake and Girdler, 1964; Coleman, 1974). South of 18°N, the continental shelves broaden considerably and are underlain by carbonate banks and reefs which effectively fill the main trough. The axial trough is associated with large-amplitude magnetic anomalies (see Fig. 3) (Drake and Girdler, 1964) which have been identified as sea-floor spreading anomalies (Vine, 1966). Later detailed studies (Allan, 1970; Phillips, 1970; Roeser, 1975; Searle and Ross, 1975; Hall, 1977) have confirmed this and, along with the results of seismic refraction studies (Drake et al, 1959; Drake and Girdler, 1964; Tramontini and Davies, 1969) and dredge hauls of fresh tholeiitic basalt (Chase 1969; Schilling, 1969; Young and Ross, 1970), have led to a general acceptance of the fact that the axial trough has been generated by sea-floor spreading over the past 3 to 5 m.y.

The origin and nature of the crust underlying the main trough and shelves are much less certain. Seismic reflection studies (Knott et al, 1966; Phillips and Ross, 1970) showed a strong reflector (reflector S) at about 0.5 sec below the surface of the main trough (see Fig. 13). This reflector was later demonstrated by DSDP drilling (Stoffers and Ross, 1974) to be the top of a thick Miocene evaporite deposit which underlies all of the main trough. Reflector S dates from about the Miocene-Pliocene boundary and appears to mark the time at which a permanent connection between the Red Sea and the Gulf of Aden was established. The great thickness of evaporites (more than 3 km; 10,000 ft) and the strong reflection off their top surface prevent direct observation of the basement rocks by conventional seismic reflection methods.

The first seismic refraction data (Drake et al, 1959; Drake and Girdler, 1964) indicated basement velocities normally associated with continental-type rocks (5.5 to 6.4 km/sec) beneath the main trough. These results have been cited as support of the hypothesis that the main trough is underlain by downfaulted continental rocks (Drake and Girdler, 1964; Girdler, 1969; Coleman, 1974).

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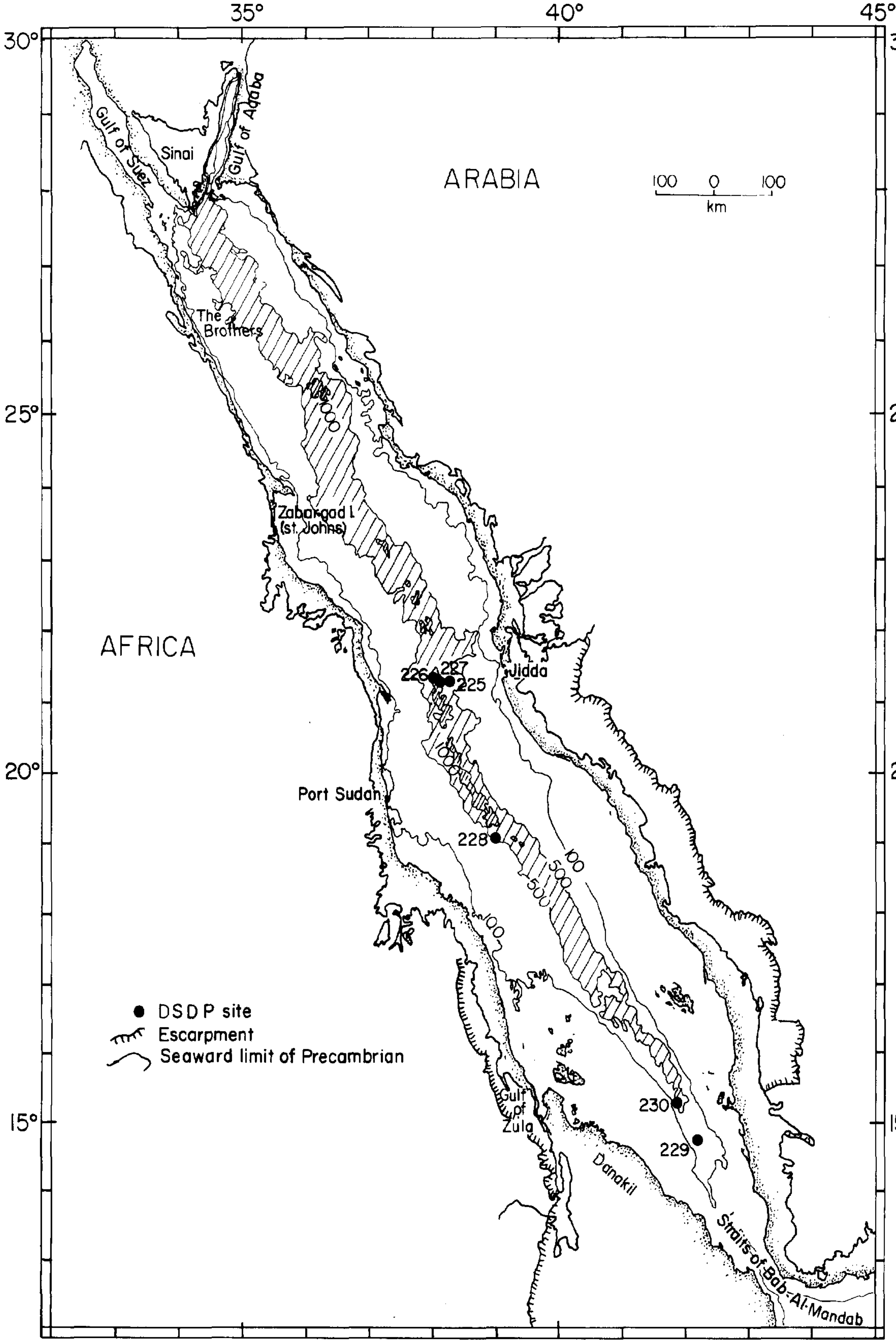


FIG. 1—Location and bathymetry chart of Red Sea. Wide ruling indicates area from 500 to 1,000 fathoms (457 to 914 m) deep and fine ruling areas deeper than 1,000 fathoms (914 m). Bathymetric contours after Coleman (1974).

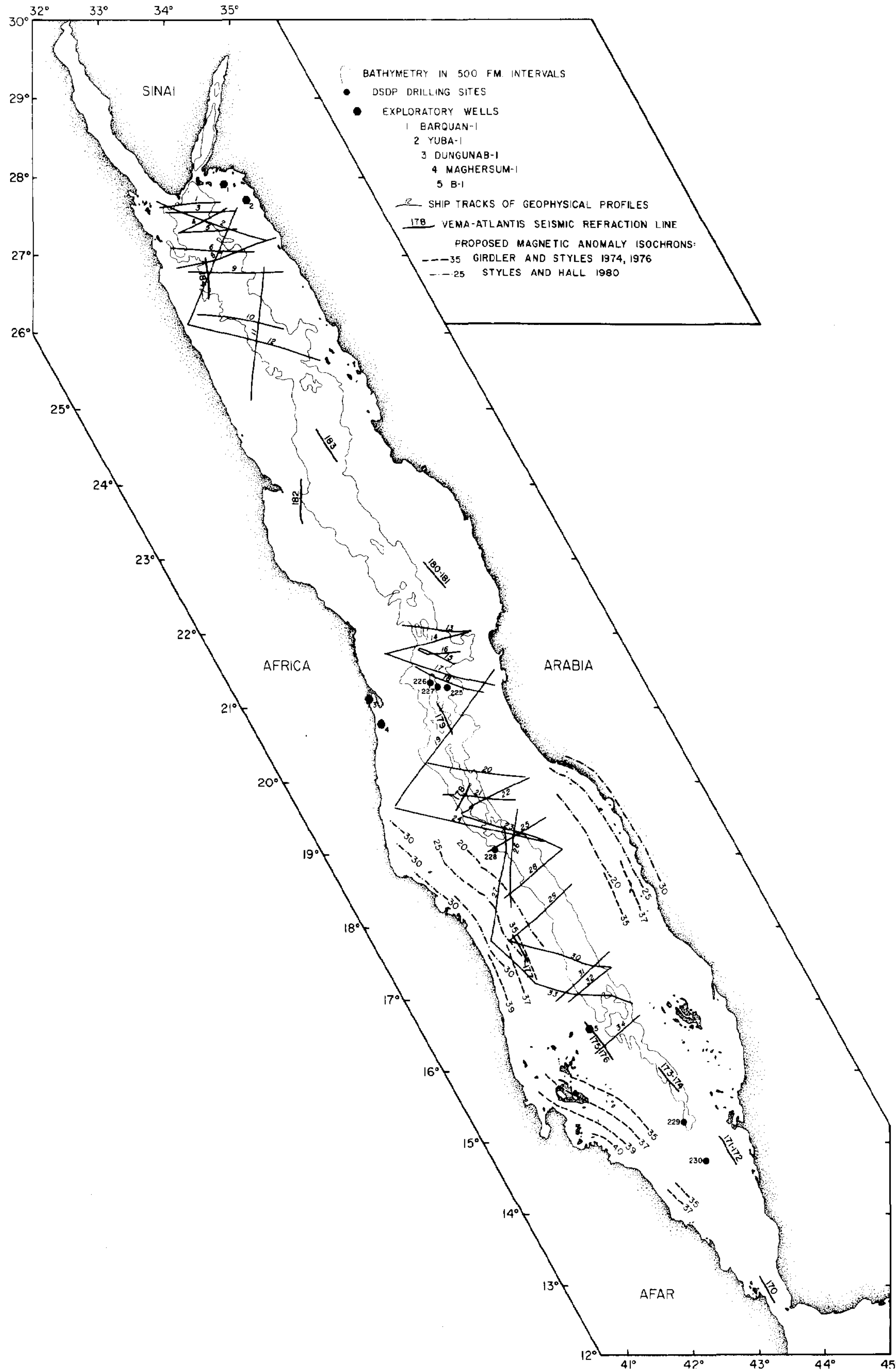


FIG. 2.—Location of ship tracks for profiles in subsequent figures. Track identifications correspond to those on profiles. Also shown are two-ship seismic refraction lines (heavy solid lines), various sets of proposed magnetic anomaly isochrons over main trough and shelves (heavy dashed lines) and location of wells mentioned in text.

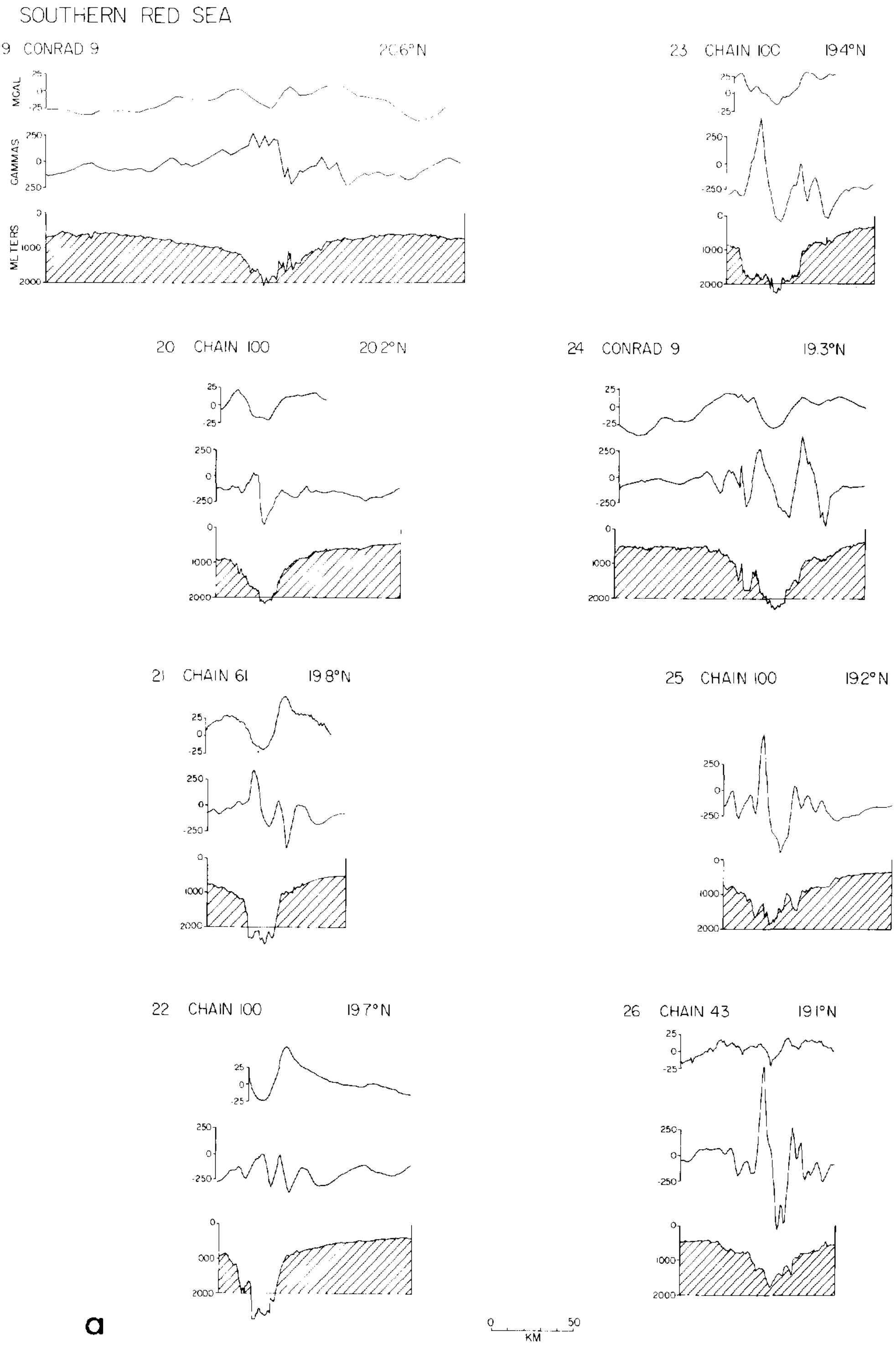
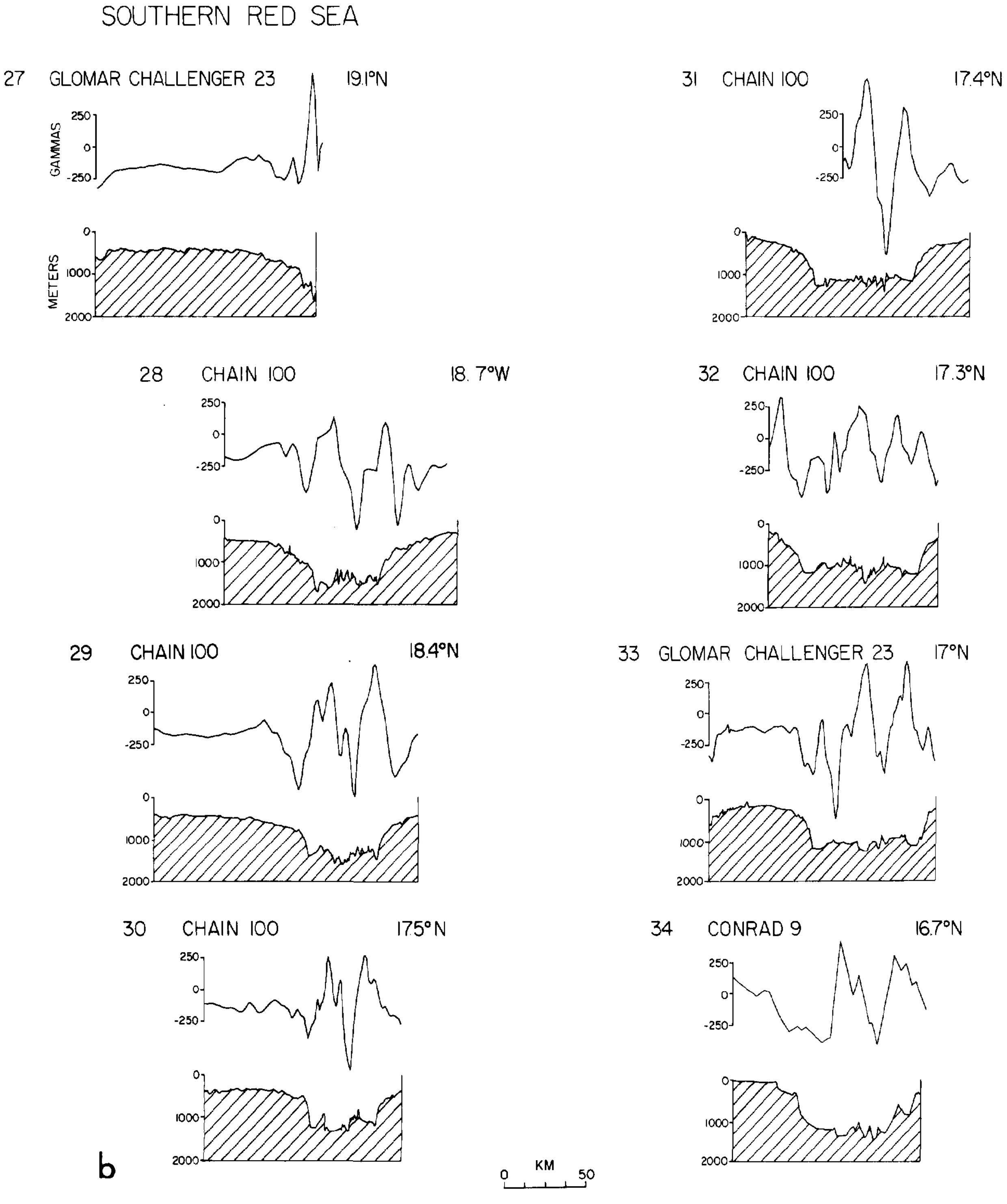


FIG. 3—A. Free-air gravity anomaly, total intensity magnetic anomaly and bathymetry profiles from southern Red Sea. B. Total intensity magnetic anomaly and bathymetry profiles from southern Red Sea. Profiles are aligned along spreading axis. All profiles are projected along N50°E. Positions of profiles are shown in Figure 2.


SOUTHERN RED SEA
27 GLOMAR CHALLENGER 23 19.1°N
31 CHAIN 100 17.4°N
28 CHAIN 100 18. 7°W
32 CHAIN 100 17.3°N
29 CHAIN 100 18.4°N
33 GLOMAR CHALLENGER 23 17°N
30 CHAIN 100 17.5°N
34 CONRAD 9 16.7°N
GAMMAS
250
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(FIG. 3 Cont.)

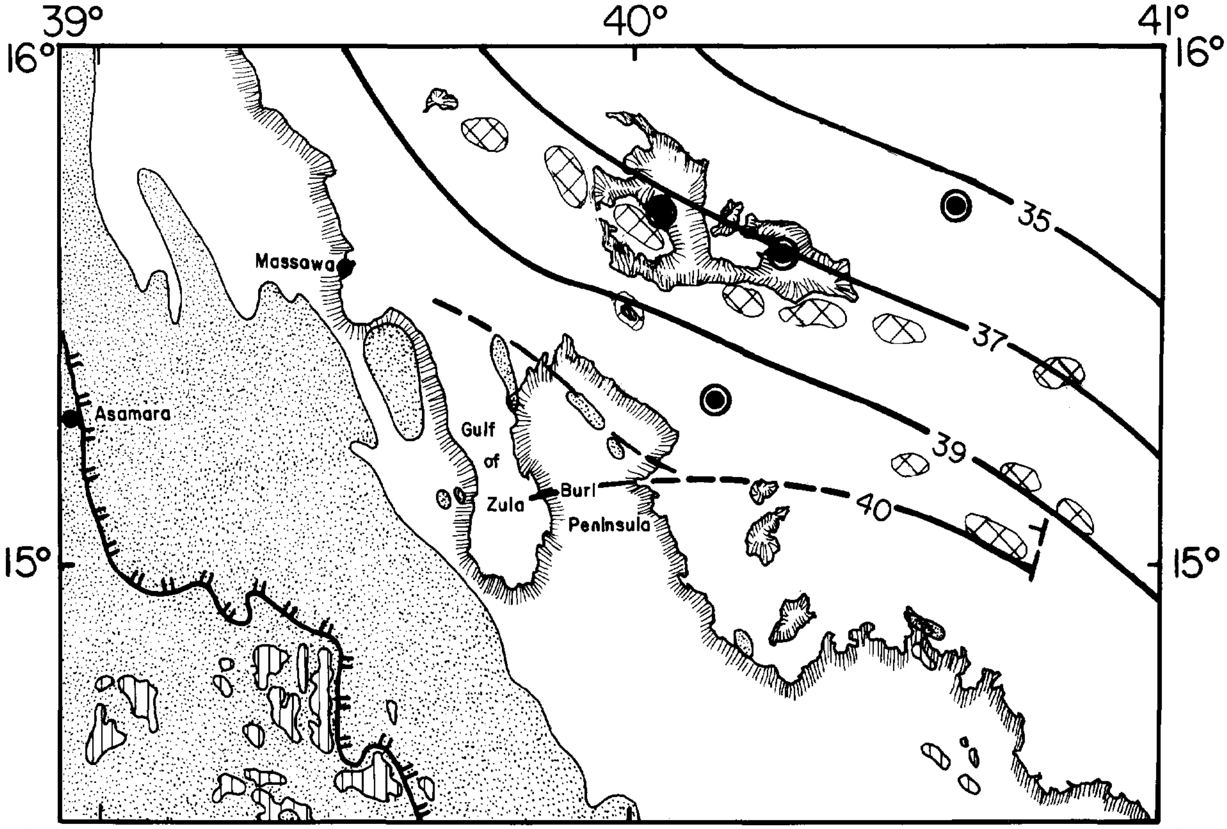

FIG. 4.—Geology and aeromagnetic interpretation of southwestern Red Sea near Gulf of Zulu and northern Afar (after Frazier, 1970). Stippled areas represent exposed Precambrian rocks, vertically ruled areas are Jurassic outcrops, and cross hatched areas are known salt diapirs. Solid lines offshore are magnetic anomaly isochrons proposed by Girdler and Styles (1974). Dashed line shows continuation of magnetic low identified as 40 m.y.b.p. isochron by Girdler and Styles (1974) from aeromagnetic map of Hall et al (1977). Circled dots are exploratory wells and double-barred fault symbol shows rift-boundary escarpment.

This interpretation appeared to be supported by the detailed studies of the structure of the Danakil highlands (often called the Danakil horst) and the margins of the Danakil depression which led to the suggestion that much of Afar is underlain by thinned continental crust (Hutchinson and Engels, 1970, 1972; Black et al, 1972; Morton and Black, 1975). This interpretation also seemed supported by petroleum industry seismic reflection lines in the southern Red Sea just north of Afar that show horst and graben features in what was interpreted to be continental basement (Lowell and Genik, 1972; Lowell et al, 1975) (see Fig. 6).

However, a later detailed seismic refraction study (Tramontini and Davies, 1969; Davies and Tramontini, 1970) of a small area between 22°N and 23°N gave higher velocities of about 6.7 km/sec for at least the inner half of the main trough, which they cited as evidence supporting the hypothesis that the main trough is underlain by oceanic crust. This interpretation is supported by the presence of lineated magnetic anomalies over portions of the main trough and shelf which Girdler and Styles (1974) interpreted as sea-floor spreading anomalies and which have been tied to a number of different positions on the geomagnetic reversal time scale (Girdler and Styles, 1974, 1976b; Styles and Hall, 1980).

A basic dichotomy thus exists in interpretation of the nature of the sea floor under the Red Sea. Studies based on the onshore geology and seismic reflection studies (Hutchinson and Engels, 1972; Lowell and Genik, 1972; Ross and Schlee, 1973; Coleman et al, 1975; Lowell et al, 1975) suggest that oceanic crust is limited to the axial trough and that most of the main trough is underlain by continental crust. This hypothesis is generally interpreted as implying that relatively little motion has occurred between the Arabian and Nubian (Africa west of the East African rift) plates. A second hypothesis, usually based on plate kinematics (McKenzie et al, 1970) or magnetic anomaly evidence (Girdler and Styles, 1974, 1976b; Roeser, 1975; Styles and Hall, 1980) is that the Red Sea is almost entirely underlain by oceanic sea floor.

The purpose of this paper is to reevaluate the available evidence on the basis of recent advances in understanding the structure and development of "passive" continental margins (e.g., Montadert et al, 1979; Steckler and Watts, 1980; Watts, 1981), and to present an alternative model for the development of the Red Sea which allows a large separation between Arabia and Nubia, but limits actual new sea floor to the axial trough. We first discuss the structure and development of the Red Sea in three segments: (1) the southern Red Sea where sea-floor spreading is presently

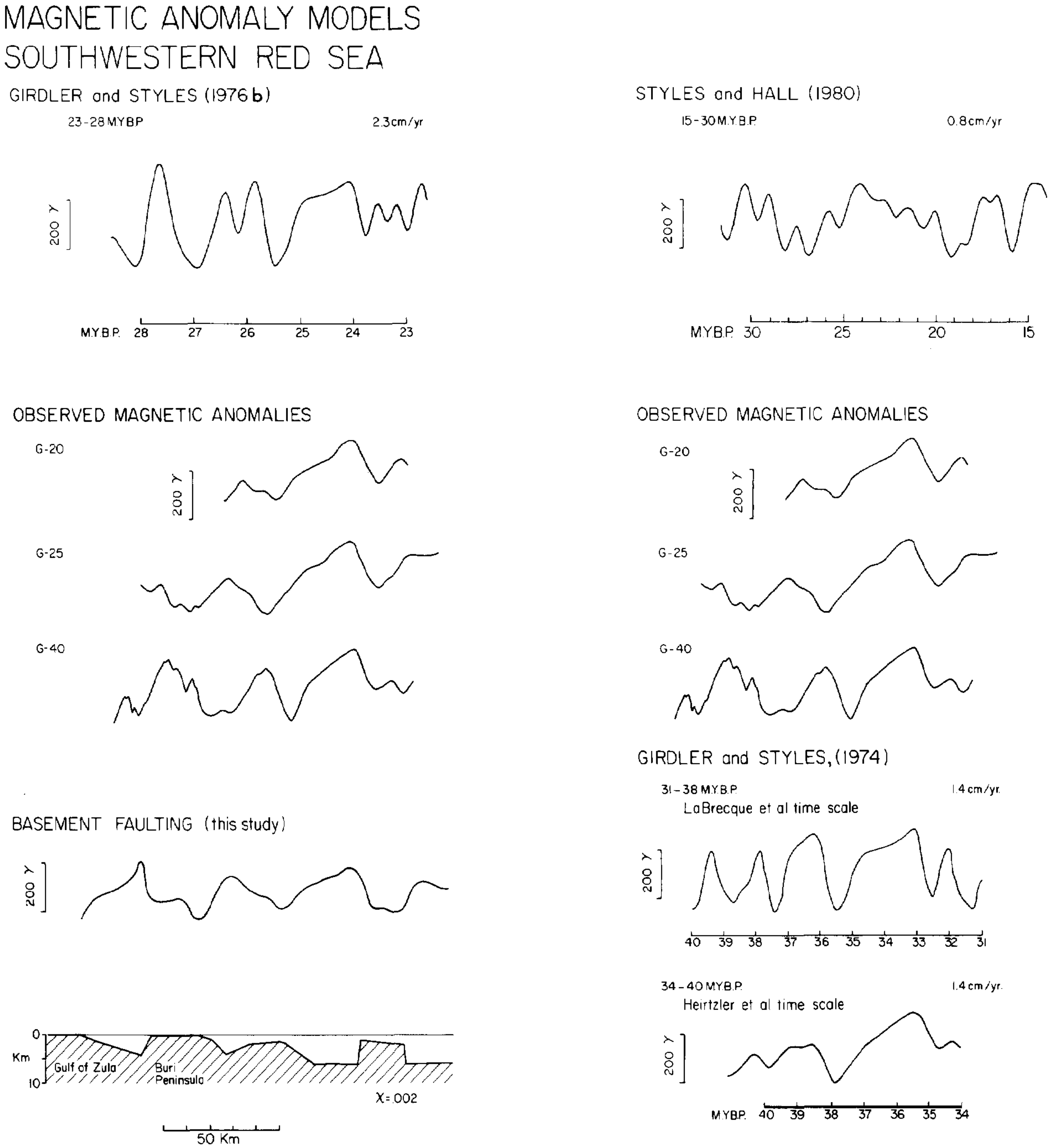

FIG. 5.—Various interpretations of observed aeromagnetic data from region shown in Figure 4. Observed anomalies have been projected onto azimuth N60°E which is also azimuth of all of models. All models were calculated for inclination 19°, declination 0°, field strength 37,500 γ, except for profiles from Girdler and Styles (1974).

occurring, (2) the northern Red Sea where there is no evidence of mid-ocean ridge tectonics, and (3) the transition area between these two zones. We then examine the plate kinematic constraints on the possible amount of motion between Arabia and Nubia and, finally, the implications for the development of continental margins in general.

SOUTHERN RED SEA

Bathymetry, total intensity magnetic anomaly, and, where available, free-air gravity anomaly profiles across the southern Red Sea are shown in Figure 3. Locations of the profiles are shown in Figure 2. The profiles clearly show the differences in morphology between the axial trough with irregular bottom topography and steep walls, and the main trough which is characterized by a smoother more gently sloping bottom.

Magnetic Anomalies Over Main Trough

There is also a marked difference in the nature of the magnetic anomalies over the axial trough and the main trough. As was mentioned, magnetic anomalies in the vicinity of the axial trough are characterized by high amplitudes and short wavelengths and are typical of anomalies found over slowly spreading mid-ocean ridge crests. A detailed study by Roeser (1975) identified these anomalies as a geomagnetic reversal sequence from the present to either 4 or 5 m.y.b.p. between 17 and 18°N and to 2 or 3 m.y.b.p. north and south of there. The magnetic anomalies over the main trough and the wide shelves in the southern Red Sea are of a much lower amplitude (less than 200 γ) and much longer wavelengths (20 to 50 km or 12 to 30 mi) (Allen, 1970) (see Fig. 3).

Girdler and Styles (1974) used aeromagnetic data to demonstrate that lineations which occur in the low-amplitude anomalies over the African shelf between 15°N and 17°N (Figs. 4, 5) can be traced over distances of up to 150 km (95 mi; Fig. 2). They interpreted the anomalies as sea-floor spreading magnetic anomalies 12 to 15, which were generated between 34 and 41 m.y.b.p. on the Heirtzler et al (1968) time scale (32 to 38 m.y.b.p. according to LaBrecque et al, 1977). They have also been identified as anomalies 6C to 8 (23 to 28 m.y.b.p.) by Girdler and Styles, 1976b. A set of magnetic anomalies slightly to the north between 18 and 20°N, on both margins of the Red Sea has been interpreted as anomalies 5C to 10 (15 to 30 m.y.b.p.) by Styles and Hall (1980) who implied that their identification is also valid for anomalies farther south. The western parts of profiles 27, 29, 30, and 33 (Fig. 3B) cross the area in which these anomalies have been reported (Fig. 2).

Probably the major reason for the differing interpretations is that the magnetic anomalies in the marginal areas of the Red Sea are smooth, low-amplitude anomalies without many distinguishing characteristics and are quite unlike the characteristic sea-floor spreading anomalies associated with the axial trough (Fig. 3). There are usually only two anomaly peaks and, as pointed out by Girdler and Styles (1974, 1976b), the main criterion in matching them to the geomagnetic time scale appears to be the presence of a reasonably long reversed interval to reproduce the broader positive anomaly identified as the period between anomalies 12 and 13 by Girdler and Styles (1974) and the period between anomalies 6C and 7 by Girdler and Styles (1976b) and Styles and Hall (1980) (Fig. 5).

Recently J. L. LaBrecque and N. Zitellini (in preparation) have developed a model for the magnetic anomalies in the southern Red Sea in which the anomalies over the marginal areas and over the axial trough both result from a single sea-floor spreading episode beginning about 16 m.y. ago. According to their model, the difference in the magnetic anomaly pattern over the axial trough and the main trough results from a wider zone of dike injection in the older regions combined with a magnetization that decays exponentially with time. The effect of applying those two factors is to attenuate and smooth the anomaly pattern over the shelves and main trough. LaBrecque and Zitellini identify the two prominent anomalies present on a number of profiles (Fig. 5) as anomalies 5 and 5b. In order to cause their model anomalies to correspond spatially to the observed anomalies, LaBrecque and Zitellini assumed a total opening rate of 2 cm/year over the past 16 m.y. This is one third greater than the observed total opening rate (1.5 cm/year over the past 3 to 4 m.y.; Roeser, 1975) which the magnetic anomalies in the Gulf of Aden imply has been constant for about 10 m.y. (Cochran, 1981b).

A different interpretation of the same anomalies was given by Frazier (1970) in terms of tilted fault blocks, a model which carries the structural pattern observed onshore into the water-covered areas. Frazier (1970) argued that a relationship between the magnetic anomalies and basement faulting is suggested by a line of large salt diapirs which exactly follows the magnetic lineations. These can be seen in Figure 4 as the diapiric structures between the 37 and 39 m.y.b.p. isochrons of Girdler and Styles (1974). Frazier (1970) believed that the diapirs are controlled by the basement structure and arose along a large basement fault. Such an association of normal faulting and salt tectonics in the southern Red Sea is demonstrated in Figure 6 which shows a seismic reflection profile across a salt dome in the southwestern Red Sea (Lowell et al, 1975). The interpretation that the lineated anomalies result from basement structure is also supported by the observation that a linear magnetic anomaly with an amplitude of over 200 γ extends for nearly 100 km (62 mi) along the eastern margin of the Gulf of Suez between 28 and 29°N (Folkman and Assael, 1980). This anomaly is directly associated with a rotated fault block which includes Precambrian basement rocks (Garfunkel and Bartov, 1977).

A magnetic anomaly sequence generated by assuming that the magnetic anomalies are the result of normal faulting of the continental basement is shown in Figure 5 along with sea-floor spreading anomalies for the various proposed spreading episodes. The susceptibility used in the modeling (0.002 emu) is at the high end of, but well within, the range of susceptibilities that have been reported for granites by Lindsley et al (1966) and Dobrin (1976) and is the average value reported for granites by Nettleton (1971) and Telford et al (1976). It should also be noted in this regard that the magnetic anomalies shown in Figure 5 are among the largest found in the marginal areas of the Red Sea. This can be seen by comparing the magnetic anomalies shown in Figure 5 with those observed on shipboard profiles over the main trough (Fig. 3, profiles 19, 24, 27, 29, 30, 33). The relationship of the shipboard profiles to the proposed magnetic isochrons (Girdler and Styles, 1974, 1976b; Styles and Hall, 1980) can be seen in Figure 2.

The basement faulting model in Figure 5 matches the observed anomalies at least as well as the various sea-floor spreading anomaly sequences and avoids the problem presented by the fact that the negative anomaly interpreted by Girdler and Styles (1974) as anomaly 15 (their 40 m.y. isochron) continues to the northwest (Hall et al, 1977) over the exposed Precambrian rocks of the Buri Peninsula (see Fig. 4).

The block-faulting model for the magnetic anomalies over the main trough carries the structural pattern observed on the exposed portions of the Red Sea rift into the water-covered area. The Gulf of Zula is a graben feature between the higher standing basement rocks of the Buri Peninsula and the mainland. Just west of the Gulf of Zula is Mt. Ghedem which Frazier (1970, p. 133) referred to as "a separated horst of basement rocks."

Tests of Magnetic Models of Southern Red Sea

All of the two-stage spreading models discussed face problems both with the timing of motion between Arabia and Africa and with the amount of opening which they imply. Bartov et al (1980) observed that offsets of early Miocene (18 to 22 m.y.b.p.) basaltic dikes and of Precambrian markers are identical across a series of anastomosing left-lateral strike-slip faults along the margin of the Gulf of Aqaba in eastern Sinai. These faults appear to be the early manifestation of the Dead Sea transform (Garfunkel, 1981) and thus Bartov et al's (1980) observations imply that motion along the Dead Sea rift began after 18 to 22 m.y.b.p. This timing for the initiation of motion along the Dead Sea transform is in conflict with all of the proposed two-stage sea-floor spreading models for the development of the Red Sea.

Although the LaBrecque and Zitellini model does not conflict with geologic data on the timing of the initiation of separation, as do the two-stage models, it does agree with them in suggesting that essentially the entire width of the Red Sea consists of oceanic crust. A constraint on the reasonableness of this conclusion is provided by examining the implications for the Gulf of Suez. As the amount of motion along the Dead Sea rift is well constrained at about 105 km (65 mi; Freund et al, 1968; 1970) and the structure of the Gulf of Suez is reasonably well known (Robson, 1971; Garfunkel and Bartov, 1977), the effects of any proposed reconstruction of the southern Red Sea on the Gulf of Suez can provide limits on the acceptable amounts of opening.

Basically, two methods have been used to determine Arabia-Nubia poles of opening. McKenzie et al (1970) determined a pole at 36.5°N, 18°E, by fitting the coast lines across the Red Sea, whereas Girdler and Darracott (1977) and Freund (1970) calculated poles at 31.5°N, 23°E, and 32°N, 22°E, respectively, by requiring that motion between Arabia and Nubia be parallel with the Levant shear. The rotation required to close the southern Red Sea to the ocean-continent boundary inferred from considering the magnetic anomalies over the main trough to be oceanic seafloor spreading anomalies is 6.2° about the McKenzie et al (1970) pole or 7.8° about the Freund (1970) pole. Figure 7 shows the resulting reconstruction of the Gulf of Suez region. In these reconstructions, Sinai has been restored to its original position relative to Arabia by a rotation of 1.7° about a pole st 32.5N, 4.4°W determined by Le Pichon and Francheteau (1978).

It can be seen from Figure 7 that there are serious difficulties with the reconstruction using the McKenzie et al (1970) pole. This reconstruction not only totally closes the Gulf of Suez, which is in conflict with the presence of pre-rift rocks within the rift valley (Fig. 8), but it also requires a 10 to 20 km (6 to 12 mi) overlap of the largely unextended basement rocks outside the rift valley.

The reconstruction using the Freund (1970) pole does not result in overlap of the regions outside of the rift valley although it does imply that about 200% extension has occurred within the Gulf of Suez rift and that the crust is about 10 km (6 mi) thick. There are no published data that either directly confirm or prohibit these inferences, although the required amount of extension (70 km or 43 mi in the southern Gulf of Suez) is considerably more than the 15 to 20 km (9 to 12 mi) of opening proposed on the basis of geological mapping by Garfunkel and Bartov (1977).

There is also a philosophical inconsistency since this reconstruction requires a great deal of crustal extension in the Gulf of Suez, but allows none along the margins of the southern Red Sea. This is particularly true because the same pattern of large-scale block faulting observed in the Gulf of Suez can be documented on the exposed portions of the rift along the entire length of the Red Sea and in Afar.

Basement Faulting and Pre-Rift Rocks Beneath Main Trough

The western margin of Afar and the southern Red Sea depression consists of a faulted region roughly 50 km (30 mi) wide characterized by a series of step faults accompanied by block tilting and, in places, by antithetic faulting producing a discontinuous series of "marginal graben" near the foot of the escarpment (Morton and Black, 1975; Mohr, 1978). This pattern continues to the floor of the Danakil depression where the pre-Pliocene structure is buried under the flood basalts of the Afar Stratoid Series. Where older rocks are found again in the Danakil highlands they "are all intensely faulted by normal faults and the blocks between the faults are strongly tilted" (Morton and Black, 1975, p. 56).

Sestini (1965, p. 1466) stated that "faulting is the dominant structural feature of the Sudan coastal region" and pointed out that both the crystalline basement rocks and the Cenozoic sediments of the coastal plain are affected by faulting. The pattern of faulting in the area north of Port Sudan studied by Sestini (1965) consists of a major normal fault with a throw of over 1 km (0.6 mi) separating the Red Sea Mountains proper from the foothills and a series of normally faulted blocks within the rift that are progressively lowered to the east.

Said (1962, p. 111), discussing the Oligocene and Miocene development of the Egyptian Red Sea coast, stated that "the fundamental complex of ancient crystalline rocks with its overlying mantle of Cretaceous and Eocene sediments was subjected then to intense deformation which resulted in a series of highly-tilted fault-blocks running along axes trending north-northwest or northwest."

Brown (1970) and Ahmed (1972) described extensive block faulting accompanied by igneous intrusions in Saudi Arabia along the eastern side of the Red Sea. Ahmed (1972, p. 707) stated, "the Red Sea depression is characterized by rectilinear faults bordering blocks which were rising and sinking concurrent with Neogene deposition."

Subsidence and rotation of blocks of the pre-rift crust and sediments are thus widely observed onshore along the margins of the Red Sea. The important question bearing on the problem of the origin of the Red Sea main trough is whether, and how far, this pattern extends into the water-covered areas. Pre-rift continental rocks were observed in

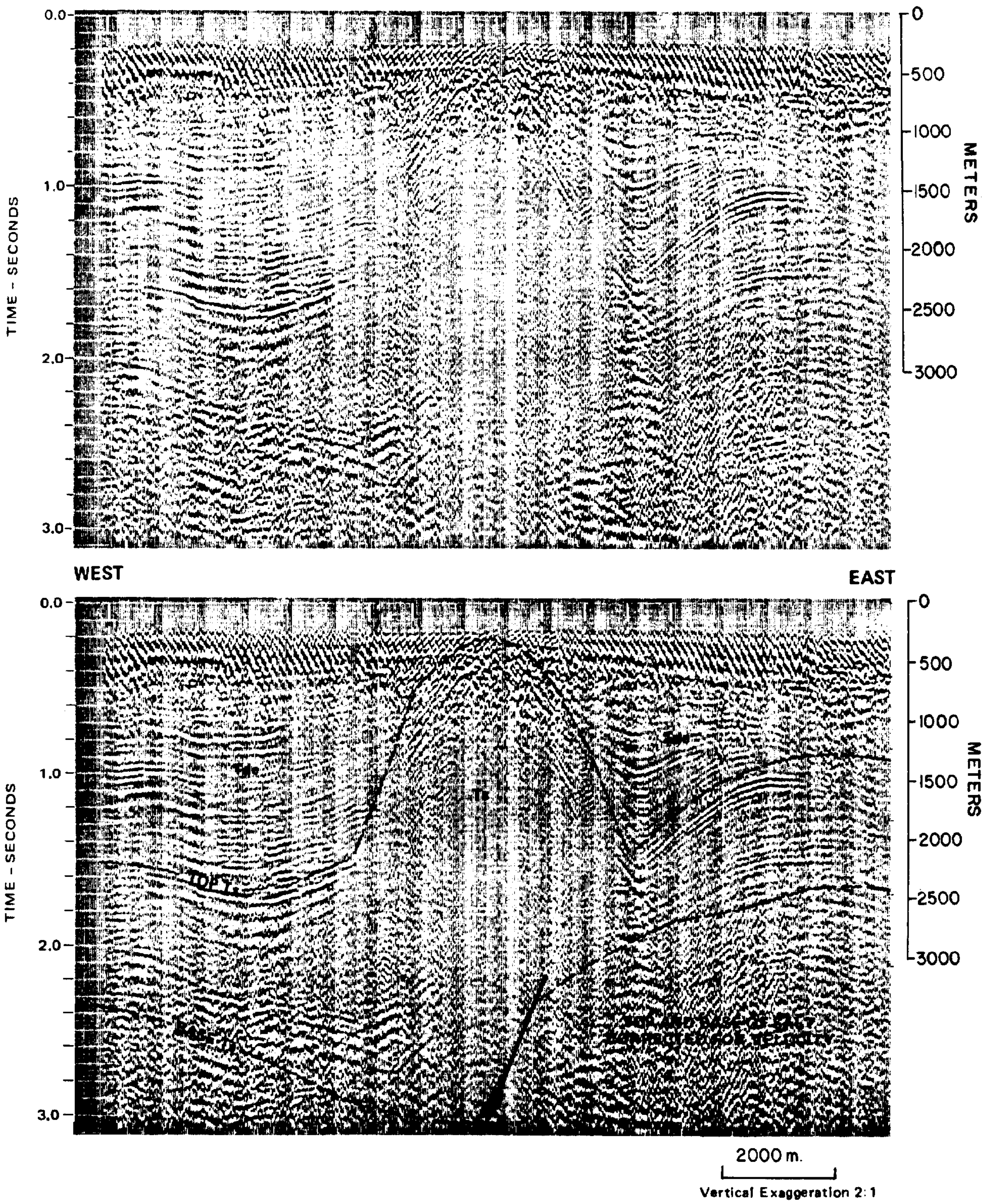

FIG. 6.—Seismic reflection profile from former Esso-Mobil concession in southwestern Red Sea showing piercement salt dome with normal fault below. From Lowell et al (1975).

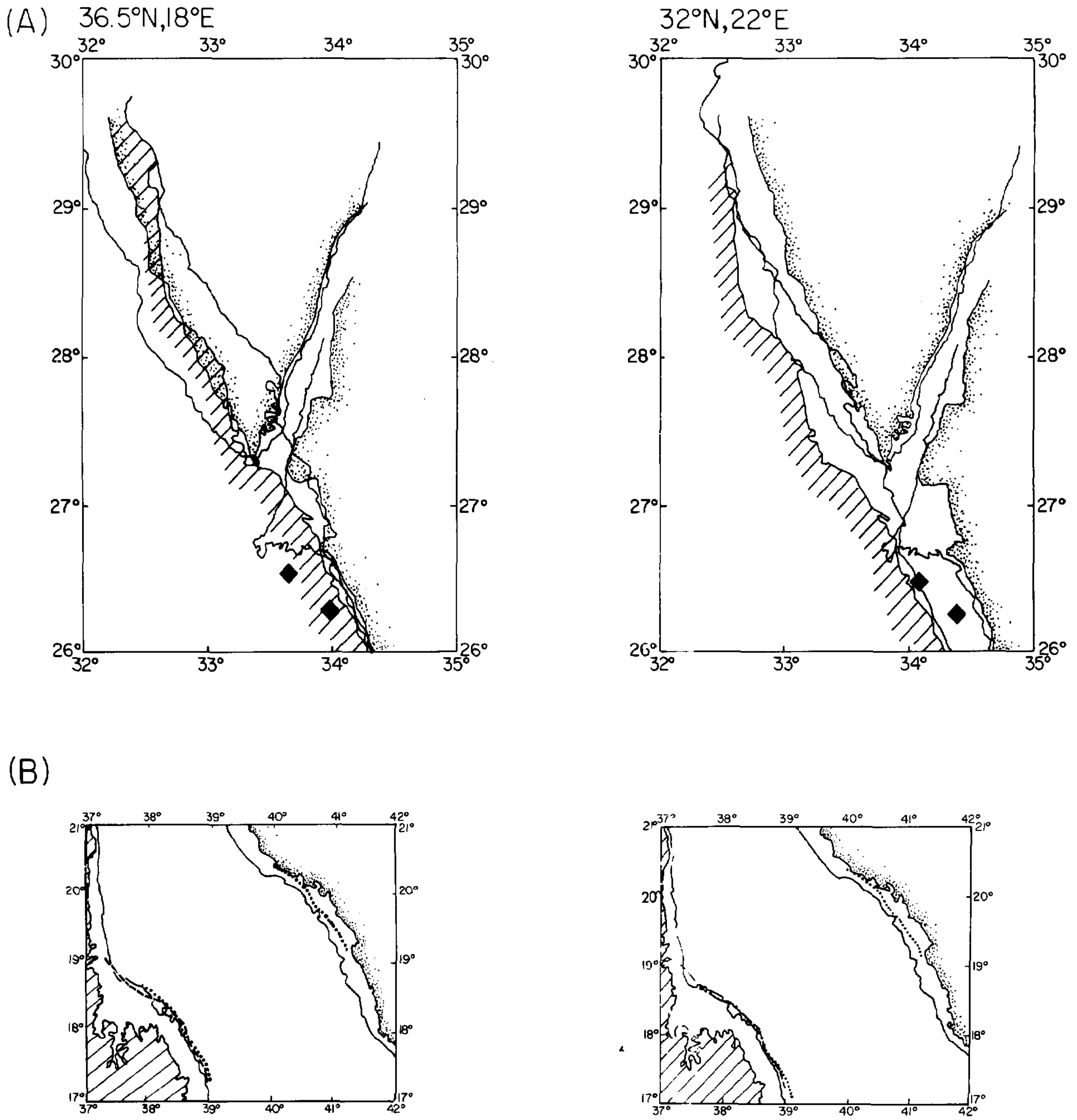

FIG. 7.—A. Reconstructions of Gulf of Suez and northern Red Sea implied by assumption that magnetic anomalies over southern Red Sea main trough are sea-floor spreading anomalies. Shorelines and edge of rift are shown. Pre-rift rocks within Gulf of Suez rift (Fig. 8) are not shown in this figure. Stippling marks edge of rift on Arabian side as does hatching on African side. Black diamonds show rotated positions of Barquan and Yuba wells, which bottomed in granite. Reconstructions were done using two different poles: 36.5 °N, 18°E (McKenzie et al, 1970), and 32°N, 22°E (Freund, 1970). B. Rotation of proposed ocean-continent boundary (B. Styles, personal commun.) determined from aeromagnetic anomalies using same poles and rotation angles as in A.

the Barquan and Yuba wells about 20 km (12 mi) off the coast of Saudi Arabia. These wells bottomed in granite (Mason and Moore, 1970). Cretaceous shales and sandstones were drilled in the Maghersum well (see Fig. 2 for location) on Mukawar Island about 10 km (6 mi) off the Sudan coast near 21°N (Sestini, 1965).

Sestini (1965) showed that Dongunab Bay north of 21°N on the Sudan coast, like the Gulf of Zula, is formed by a graben lying between two horst blocks. He also pointed out that the shelf floor off Sudan consists of several steep-sided platforms separated by troughs, and he suggested that this bathymetry also reflects a horst and graben structure beneath the shelf. *Glomar Challenger* sailed over one of these troughs at the western end of profiles 27 and 33 (Fig. 3) within the area of the main trough that has been suggested to be oceanic crust. Similar troughs are found off the coast of Egypt at distances of up to 40 km (25 mi) offshore (Coleman, 1974).

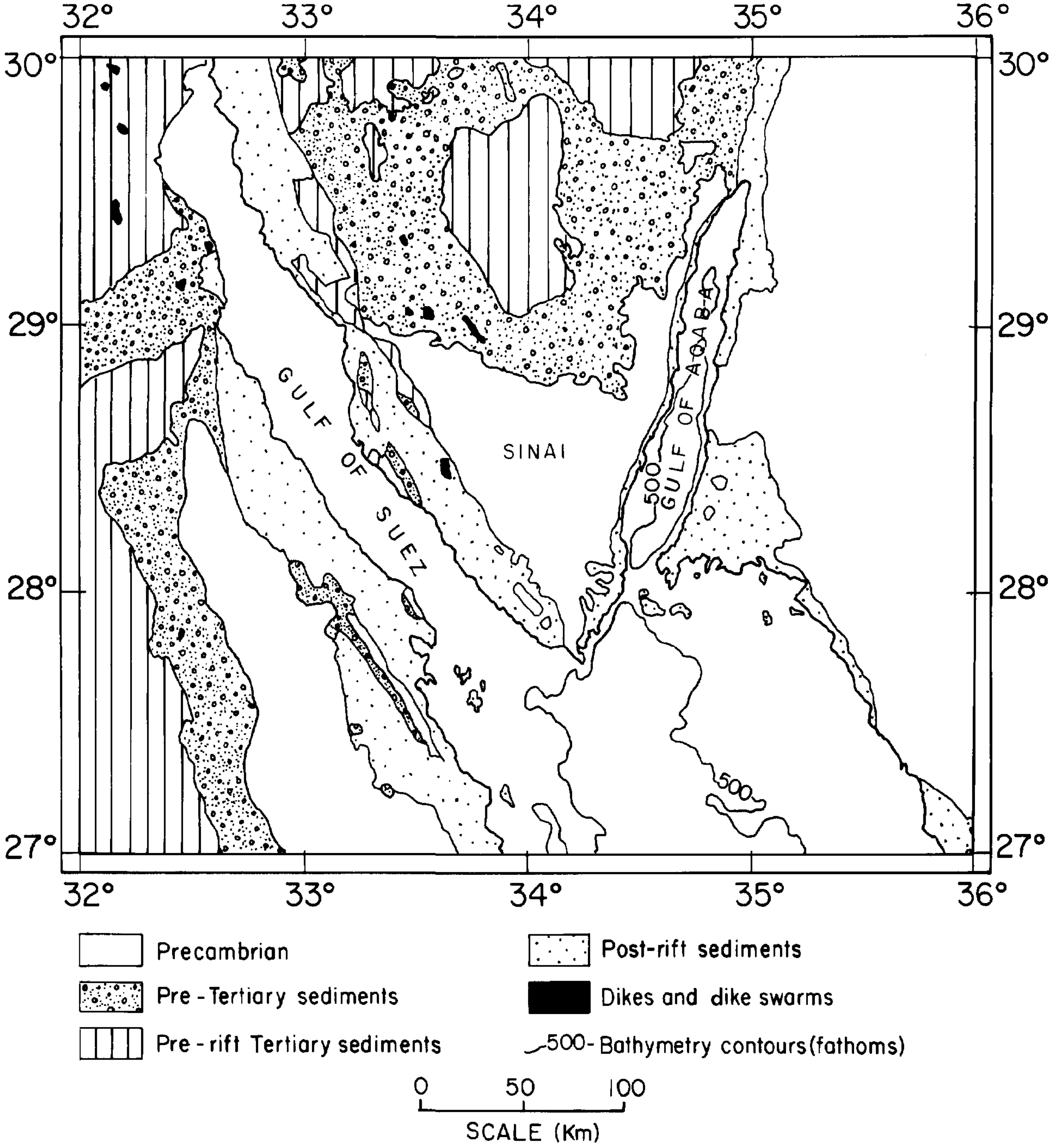

FIG. 8.—Geology of Gulf of Suez area, showing extensive exposed pre-rift rocks within rift. Geology from Coleman (1974) and Garfunkel and Bartov (1977).

Farther offshore, Zabargad (St. John's) Island, 70 km (43 mi) off the coast of Egypt at 23.°5N, is partially made up of metamorphic gneiss similar to Precambrian-early Paleozoic basement rocks of the Eastern Desert of Egypt. This is overlain by a sedimentary sequence (Zabargad formation) which has tentatively been assigned to the Cretaceous on the basis of a pre-Tertiary fossil fish found in it (Bonatti et al, in press). The Brothers, a similar distance offshore at 26°N (Fig. 1), has been described as a fragment of crystalline basement (Moon, 1923, quoted by Gass et al, 1977) although Nesteroff (1955) referred to The Brothers as intrusive gabbroic rocks. At Zabargad, the metamorphic and sedimentary sequence is in tectonic contact with fresh peridotite, and both peridotite and metamorphic rocks are crossed by younger basaltic-doleritic dikes (Bonatti et al, in press). The presence of pre-rift crystalline rocks on Zabargad and possibly on The Brothers, which are the only places where the basement rocks beneath the main trough can be directly observed, suggests the possibility that the entire main trough is underlain by similar rocks.

Lowell and Genik (1972) and Lowell et al (1975) presented a seismic reflection profile extending from nearshore about 50 km (30 mi) seaward near 17°N. They

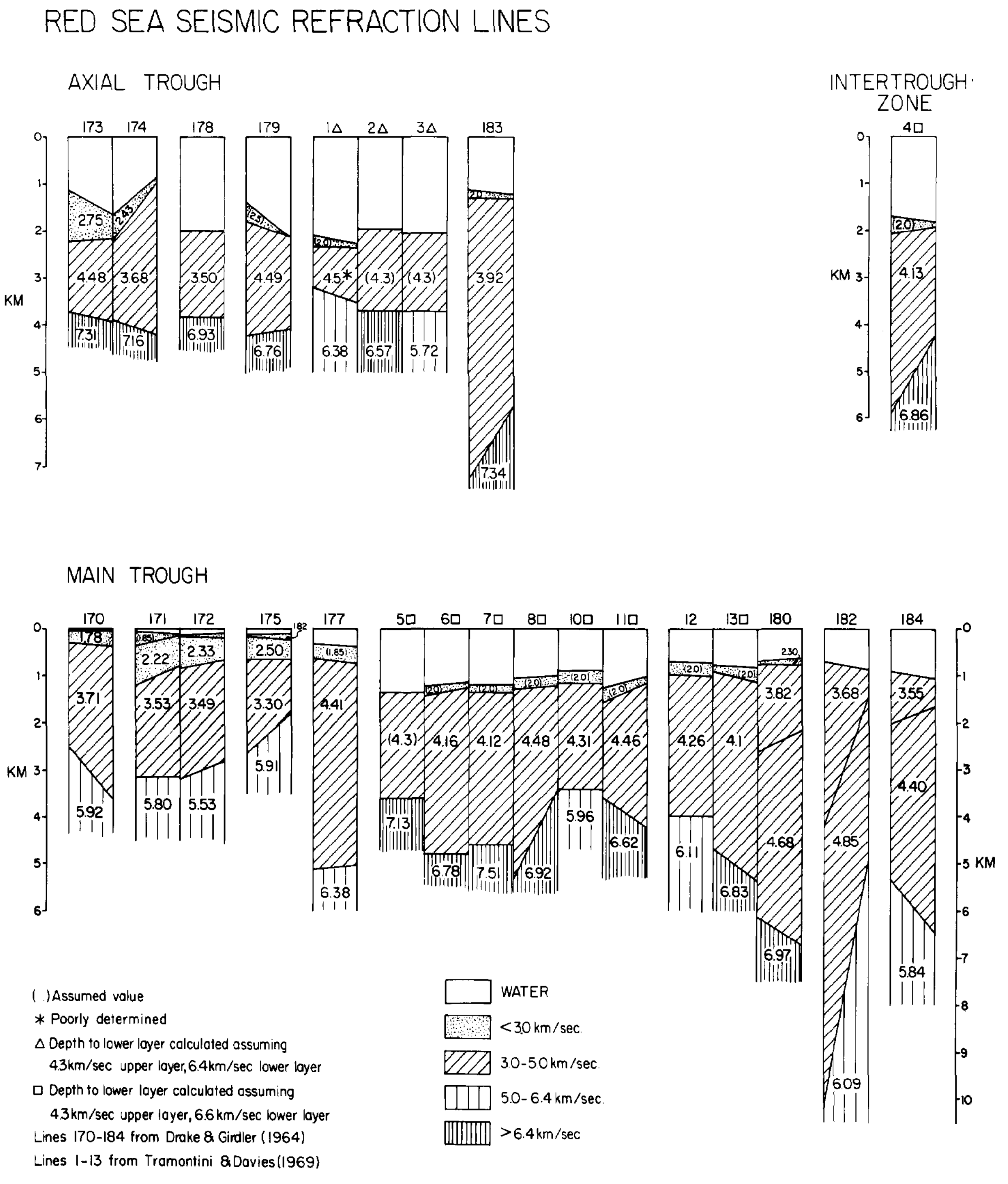

FIG. 9.—Seismic refraction sections obtained from Red Sea (Drake and Girdler, 1964; Tramontini and Davies, 1969). Location of stations is shown on Figure 2. Stations from same immediate vicinity are grouped together.

argued that the basement reflection observed nearshore is continuous with the Precambrian crystalline basement observed onshore and that the basement reflector can be correlated across the western rift (a continuation of the rifting in the Danakil depression and Gulf of Zula northward along the coast), and thus stated that Precambrian basement is present to the eastern end of their seismic line. This is not unreasonable, as the basement reflector is of a similar depth and appearance across the rifted area. However, it is not conclusive because the basement reflector is lost in the 10 km (6 mi) wide rifted area.

The block-faulted nature of the crust is clearer on the seismic line shown in Figure 6, which is located near the B-1 well (J. D. Lowell, personal commun.) 10 km (6 mi) from the edge of the axial trough and just outside the region of high-amplitude magnetic anomalies. The B-1 well is also only about 5 km (3 mi) from Vema-Atlantis seismic reflection line 175 (see Fig. 2) which showed a 5.91

km/sec refractor at a depth of 1.8 to 2.7 km (Fig. 9) corresponding to the basement reflector in Figure 6.

Seismic Refraction Results

Two-ship seismic refraction measurements reported by Drake and Girdler (1964), with one exception, show crustal seismic velocities in the range of 5.53 to 6.38 km/sec (Fig. 9). This velocity range is usually associated with continental type rocks. A separate study of a roughly 1° square area near 22.5°N, 38°E (by Tramontini and Davies, 1969), showed higher velocities, averaging about 6.7 km/sec under the main trough, although with a large amount of scatter (5.96 to 7.51 km/sec). Drake and Girdler's (1964) station 180, which yields a basement velocity of 6.97 km/sec, is in Tramontini and Davies' (1969) study area, confirming the high velocities in that area. The high seismic velocities observed between 22°N and 23°N could result either from Neogene intrusions related to the formation of the Red Sea or from the presence of a Precambrian or early Paleozoic mafic and ultramafic belt, such as has been described in both Arabia and Nubia (Kasmin, 1971; Al-Shanti and Mitchell, 1976; Bakor et al, 1976; Neary et al, 1976; Frisch and Al-Shanti, 1977; Engel et al, 1980).

Thus, crustal seismic velocities characteristic of, and usually considered diagnostic of, "continental" rocks are found at a number of locations under the main trough, although in at least one region higher velocities characteristic of "oceanic" rocks are encountered. The seismic refraction data, therefore, suggest that the main trough of the Red Sea consists of subsided continental crust which has, in places, been massively injected with dense, high-velocity mafic igneous rocks. In particular, the very widespread occurrence of crustal velocities in the range of 5.8 to 6.2 km/sec is difficult to account for if the main trough was generated through sea-floor spreading, particularly when coupled with the direct observation of pre-rift metamorphic and sedimentary rocks on Zabargad Island (Bonatti et al, in press).

Tihama Asir Igneous Complex and Eastern Margin of Red Sea

The conclusion that the basement rocks beneath the southern Red Sea are of continental origin is apparently called into question by the presence of the Tihama Asir igneous complex along the base of the Red Sea escarpment near 17°N in southern Saudi Arabia (Coleman et al, 1975, 1979). This complex, which Coleman et al (1979) described as an ophiolite and which they suggested marks the boundary between oceanic and continental rocks, consists of diabase dike swarms, layered gabbros, and granophyres. Similar assemblages are found along the base of the escarpment at several locations between the Yemen border and Ad Darb at 17°45′N. North of Ad Darb, individual dikes, many 50 km (30 mi) long, with the same compositional range as the Tihama Asir sheeted dikes, are found cutting the Precambrian country rock (Coleman et al, 1975, 1979).

The reason cited by Coleman et al (1979) for concluding that the Tihama Asir sequence represents the edge of oceanic crust extending beneath the Red Sea main trough is a gravity study by Gettings (1977), which attempted to model the Bouguer gravity anomalies across the coastal plain and escarpment with the conclusion that oceanic crust is necessary seaward of the escarpment to match the Bouguer gravity gradient.

A difficulty with this gravity study is that quite unusual crustal models are used. The "oceanic" model consists of a 4 km (2.5 mi) thick sediment layer ($\rho = 2.4$ g/cc), a 10 km (6.2 mi) thick upper crustal layer of density 3.0 g/cc, and a 32.7 km (20 mi) thick lower crustal layer of density 3.173 g/cc, whereas the "continental model" for the crust under the Red Sea is made up of the same sediment layer, a 10 km (6.2 mi) upper crustal layer of density 2.74 g/cc and a 32.7 km (10.5 mi) thick lower layer of density 3.25 g/cc. The relationship between these sections and actual oceanic or continental crustal structure is not immediately apparent. Qureshi (1971) was able to model the Bouguer gravity anomalies across the Sudan margin through thinning of the continental crust. He did this simply by varying the depth to the Moho to fit the regional anomaly left after removing the gravity effect of the sediments by using a geologic cross section given by Carella and Scarpa (1962).

Gettings' (1977) gravity survey delineates three large positive gravity anomalies on the Arabian coastal plain, that are roughly 40 km (25 mi) across and have an amplitude of about 25 mgal. The gravity anomalies are associated with large short-wavelength magnetic anomalies (Gettings, 1977). The outcrops of the Tihama Asir sequence are located on the eastern flank of the gravity anomalies. Neither the gravity nor magnetic anomalies are found between outcrops. These relationships suggest that the positive gravity anomalies are associated with the Tihama Asir sequence and that it consists of a series of large intrusions that extend no farther seaward than the central or western coastal plain.

Offshore magnetic and gravity anomalies are lineated and extend roughly parallel to the axial trough and to the rift-bounding escarpment. The offshore magnetic anomalies are low-amplitude (less than 150 γ) and are spatially related to the gravity anomalies so that magnetic highs and lows are consistently offset slightly to the southwest of the gravity highs and lows. Such a relationship between gravity and magnetic anomalies would not be expected if the magnetic anomalies resulted from sea-floor spreading, but it is what would be expected at this latitude if the gravity and magnetic anomalies were caused by the same, linear, northwest-southeast-trending bodies. This, in turn, suggests that both gravity and magnetic anomalies are due to basement structure. The available data thus appear to support the Coleman et al (1975) conclusion that the Tihama Asir complex (called the Jabal al Tirf volcanic rift zone in that study) represents massive intrusions into the continental crust.

NORTHERN RED SEA

Bathymetry, free-air gravity, and total intensity magnetic anomaly profiles across the northern Red Sea are shown in Figure 10. The location of the profiles are shown in Figure 2. Comparison of Figure 10 with Figure 3 shows a marked

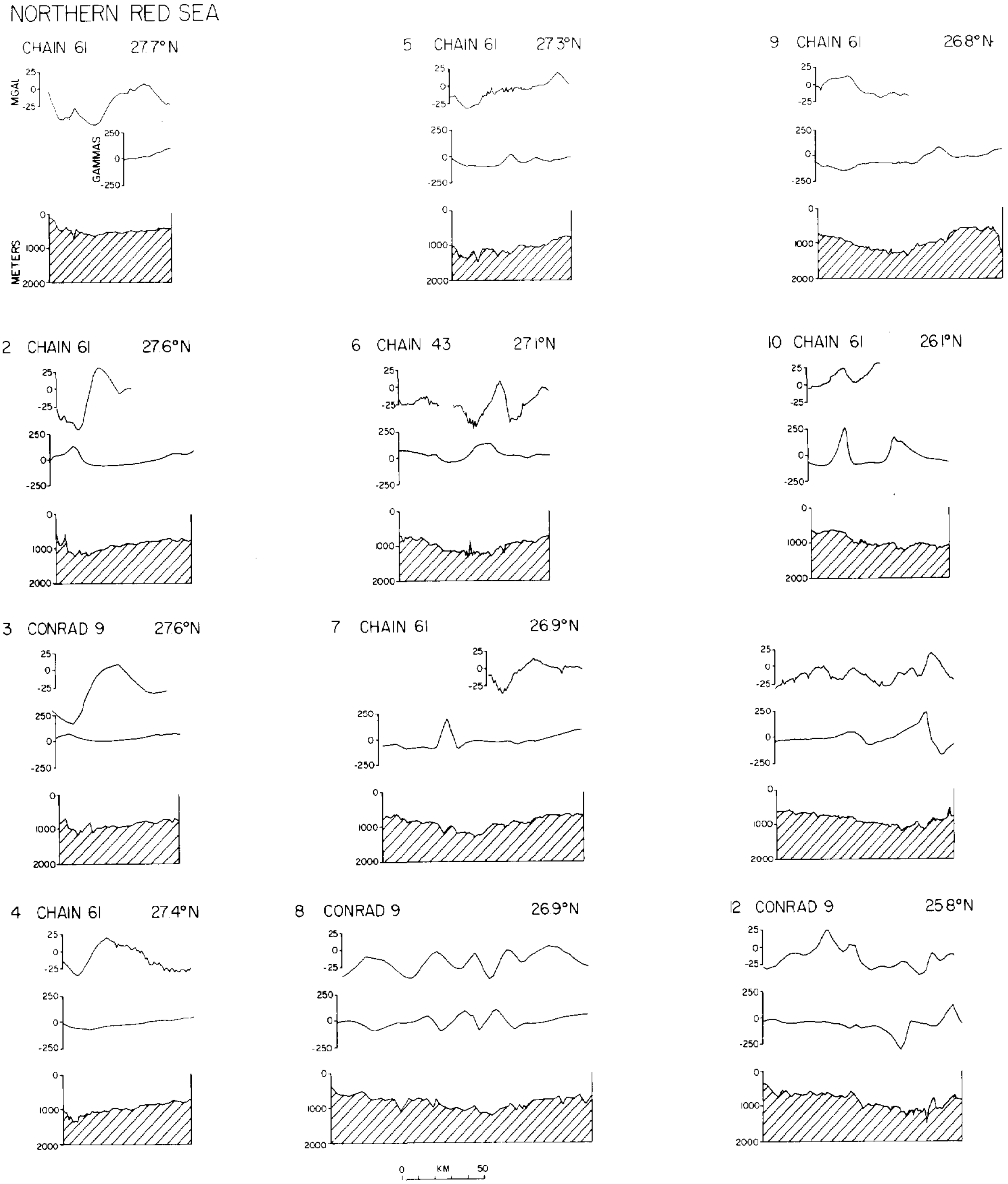

FIG. 10.—Free-air gravity anomaly, total intensity magnetic anomaly and bathymetry profiles from northern Red Sea. All profiles are projected along N50°E. Position of profiles is shown in Figure 2.

difference in structure between the northern and southern Red Sea. An axial trough is not present north of about 25°N (Drake and Girdler, 1964) and the large, lineated magnetic anomalies associated with the axial trough are also not present. The magnetic anomalies in this region are characterized by smooth low-amplitude (less than 100γ) anomalies with a few sharp anomalies of several hundred gammas (Fig. 10).

Many of the magnetic anomalies are associated with gravity anomalies (profiles 6, 8, 10, 11 of Fig. 10) suggesting that they are due to basement structure or to intrusions of dense, highly magnetic rock. The relationship between the gravity and magnetic anomalies in the northern Red Sea is particularly clear in profile 8, which is also shown in Figure 11. When the magnetic anomaly profile is phase-shifted by 124° to remove the skewness introduced by the field inclination and profile azimuth (Schouten and McCamy, 1972), the peaks in the gravity and magnetic

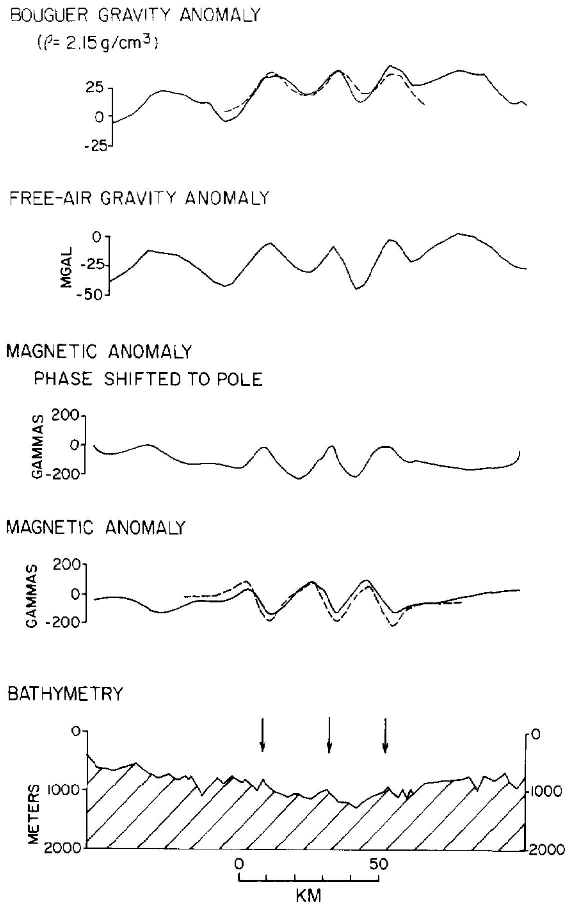

FIG. 11—Free-air and Bouguer gravity anomalies, total intensity magnetic anomalies, and bathymetry along profiles 8 (Fig. 10). Also shown are magnetic anomalies phase shifted to the pole to remove skewness introduced by field inclination and track azimuth. Dashed lines show gravity and magnetic anomalies resulting from three bodies centered under arrows over bathymetry profile. Bodies extending perpendicular to profile are 8 km (5 mi) wide and 3 km (2 mi) thick with their top surface 3 km (2 mi) below sea level. They have a magnetization of 0.003 (cgs) and a density contrast of 0.7 g/cc with evaporites into which they are assumed to be intruded.

anomalies correspond exactly (Fig. 11), suggesting that the same set of bodies produces both. The magnetic and gravity anomalies resulting from an extremely simple model of three intrusive bodies located at the positions marked by arrows on the bathymetry profiles are shown by the dashed lines in Figure 11. The intrusive bodies were assumed to be linear blocks 8 km (5 mi) wide and 3 km (2 mi) thick with their top surface 3 km below sea level. They were assumed to have a magnetization of 0.003 (cgs) and a density of 2.85 g/cc (compared to 2.15 g/cc for the evaporites into which they would be intruded). It can be seen in Figure 11 that this simple model reproduces the shape and amplitude of the magnetic and gravity anomalies. If the bodies are linear, they must be at relatively shallow depth, which would imply intrusion into the evaporite sequence. If they are not linear, as is suggested by the Hall et al (1977) aeromagnetic anomaly map (Fig. 12), then the bodies can be deeper and represent intrusions into basement. For example, vertical cylinders, 7 km (4.3 mi) in radius, extending from 6 to 15 km (3.7 to 9 mi) depth, with a magnetization of 7.5×10^{-4} (cgs) and a density contrast of 0.35 g/cc can also explain the gravity and magnetic anomalies.

The important conclusion for this study is not the exact form of the bodies, but rather that the correspondence between the gravity and magnetic anomalies strongly suggests that they are not sea-floor spreading magnetic anomalies and that they can be modeled by reasonable models for intrusive bodies. This is further supported by the Hall et al (1977) aeromagnetic anomaly map (Fig. 12) which shows anomalies over the central part of the northern Red Sea which are not lineated, but rather are roughly circular. Many of them consist of closed magnetic highs flanked on the north by magnetic lows, which is the form that anomalies over isolated magnetic bodies would take at these latitudes.

Seismic reflection studies in the northern Red Sea (Knott et al, 1966; Phillips and Ross, 1970) show that upper Miocene reflector S is continuous across the main trough, that the upper surface of the evaporites is deformed, and that the deformation is most severe in an area about 100 km (60 mi) wide in the center although extending completely across the main trough (Knott et al, 1966; Phillips and Ross, 1970).

Seismic reflection data from profiles 5 and 7 (Fig. 10) are shown in Figure 13. Clear evidence of extensional faulting on these profiles is shown for example by the elevated horst block between kilometers 18 and 28 of profile 5 and the rotated blocks forming half-graben between kilometers 20 and 45 of profile 7. The Xs over the line drawings in Figure 13 mark narrow open crevasses associated with disturbed subbottom features noted by Phillips and Ross (1970).

Toward the margins of the main trough, the post-Miocene sediments overlying reflector S tend to be much less disturbed than reflector S, implying relative stability since the end of the Miocene, whereas in the central region, the deformation continues up through the overlying sediments, giving the main trough its irregular broken appearance (Figs. 10, 13) and implying continuing tectonic activity. Knott et al (1966) described the central 100 km (60 mi) of the main trough as "intensely fractured". There is no evidence of an axial trough or of any morphologically or geophysically identifiable feature that can be interpreted as a localized spreading center.

It could be argued that an organized spreading center exists, but is obscured by salt flowage. Although some salt flowage into the rift does appear to have occurred in the southern Red Sea (Girdler and Whitmarsh, 1974), the evidence of widespread faulting (Fig. 13), the fact that the post-Miocene sediments have a relatively constant thickness across the main trough, and the gravity and magnetic anomalies implying isolated intrusions suggest that an obscured spreading center is not the case and that extension is occurring diffusely over a broad region. Unpublished GLORIA side-scan sonar data in the northern Red Sea show both rounded lobate features (probably due to salt tectonics) and sharper linear features indicative of faulting (R. Searle, personal commun.).

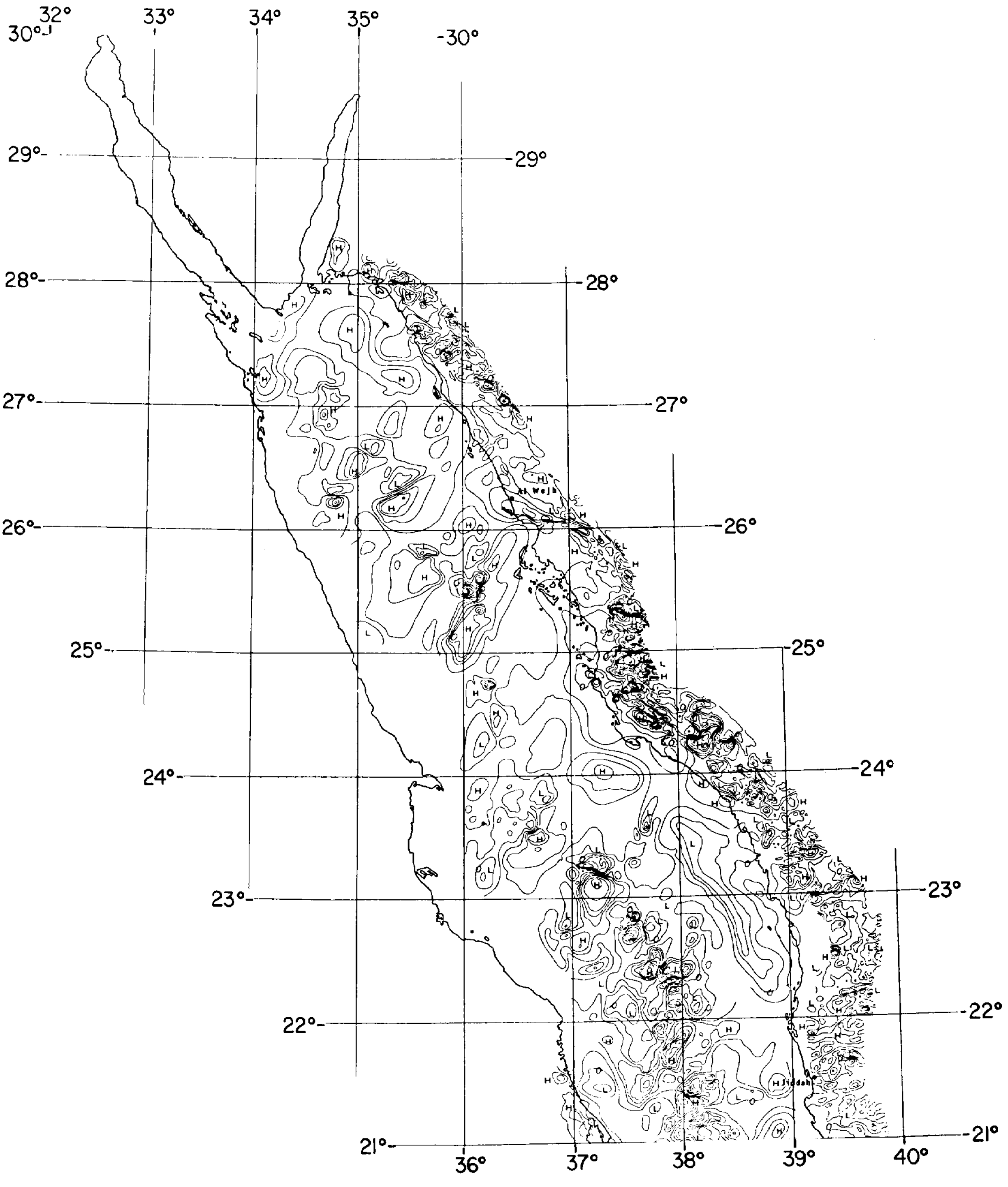

FIG. 12.—Total intensity magnetic anomaly map of northern Red Sea and coastal area of Saudi Arabia. From Hall et al (1977).

CENTRAL RED SEA-TRANSITION AREA

The axial trough, which is a consistent feature of the southern Red Sea (Figs. 1, 3) becomes discontinuous north of about 20°N and from there to about 25°N the central part of the Red Sea consists of a series of deeps, many of which contain hot-brine pools (Bäcker and Schoell, 1972; Bignell et al, 1976) alternating with shallower "intertrough zones" (Tramontini and Davies, 1969; Searle and Ross, 1975). The basins containing the hot brine deeps are very similar to the axial trough in appearance (Fig. 14), with steep sides, a rough bottom, and large magnetic anomalies. In contrast, the intertrough zones are shallower, with gently sloping sides, smoother bottoms, and a lack of significant magnetic anomalies. Figure 14 shows six profiles across this region spaced over a distance of about 70 km (45 mi; see Fig. 2 for locations). The northern two profiles (13 and 14) cross Hatiba Deep and the two southern profiles (17 and 18) cross Atlantis II Deep. The two central profiles are in the intertrough zone between the two deeps.

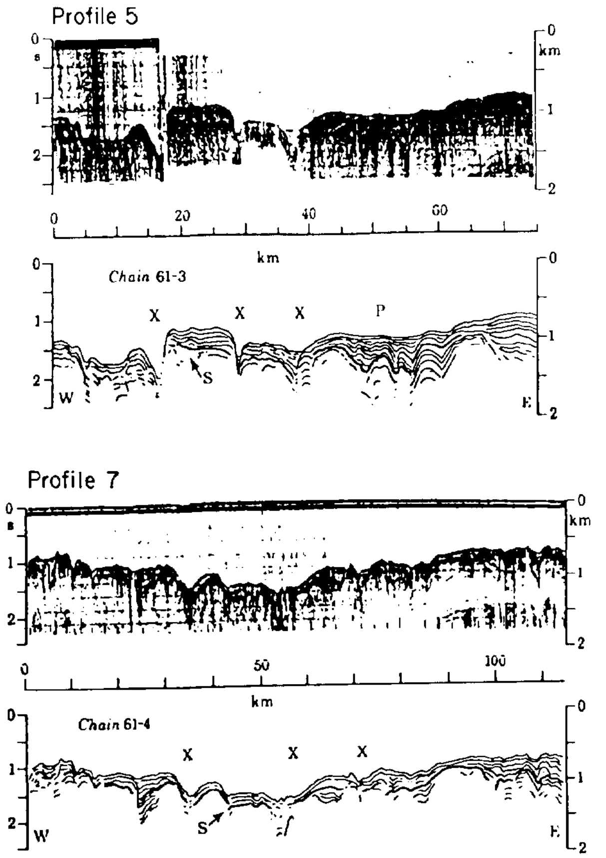

FIG. 13.—Seismic reflection records with line drawing interpretation for profiles 5 and 7 (Figs. 2, 9) across Red Sea near 27°N. Vertical scales are (left hand) one-way travel time in seconds and (right hand) depth in kilometers based on an assumed velocity of 1.5 km/sec for both water and subbottom. Letter symbols refer to disturbed Pliocene layers (P) just above reflector S (S), and narrow crevasses (X) associated with disturbed subbottom features. From Phillips and Ross (1970).

Due to the obliquity of the ship tracks, the western ends of both profiles enter the southern end of Hatiba Deep so that the difference in morphology between the axial trough segments and the intertrough zones can be easily seen by comparing the escarpment at the western end of profiles 15 and 16 with the gentle slopes on the eastern side. Unfortunately, no profile was available which completely crosses the axis of the Red Sea within an intertrough zone.

A peculiarity of the magnetic anomalies associated with the axial deeps is that not only are linear magnetic anomalies found with a strike parallel with the Red Sea axis, but transverse magnetic anomalies are also present cutting perpendicularly across the axis (Phillips et al, 1969; Allan, 1970; Kabbani, 1970). Searle and Ross (1975) successfully modeled the transverse anomalies as edge effects at the ends of northwest-southeast-trending highly magnetized bodies under the hot-brine deeps. The longitudinal magnetic anomalies over the deeps can be identified as sea-floor spreading anomalies and the situation thus implied by the magnetic anomalies is short, highly magnetic mid-ocean ridge segments 10 to 30 km (6 to 20 mi) long, separated by nonmagnetic zones of comparable length. Searle and Ross (1975) interpreted these shallow, nonmagnetic zones as finite-width fracture zones.

However, the intertrough zone is underlain by thick sediments. Seismic reflection lines (Searle and Ross, 1975) clearly show that Miocene reflector S and the overlying sediments continue right up to the axis of the Red Sea in the intertrough zone. Searle and Ross (1975) observed at least 800 m (2,600 ft; 0.9 sec) of sediment near the center of the intertrough zone north of Atlantis II Deep, and stated (p. 599) that "there is thus a strong implication that the sediment and evaporite sequences are continuous across the inter-trough zone." In addition, sea-floor spreading magnetic anomaly 2 (1.8 m.y.b.p.) is not present in the hot-brine region (Searle and Ross, 1975) implying that organized sea-floor spreading has started there only recently compared with the region to the south, where 4 or 5 m.y.b.p. magnetic anomalies are present. This suggests the possibility that the intertrough zones do not represent fracture zones but rather regions in which an organized mid-ocean ridge has not yet become established.

It is thus possible that the region of a discontinuous axial trough between about 21°N and 25°N is an area which is presently changing from the diffuse mode of extension found in the northern Red Sea to an organized mid-ocean ridge spreading center such as is found in the southern Red Sea.

DISCUSSION

Kinematic Problem

The geologic and geophysical data discussed suggest that oceanic crust in the Red Sea is limited to the axial trough and that the main trough is underlain by faulted and intruded continental crust. This, however, does not necessarily mean that only a minimal amount of motion has occurred between Nubia and Arabia. In fact, significant non-sea-floor spreading extension is required by the documented motion on the Dead Sea transform (Quennell, 1956, 1958; Freund et al, 1968, 1970). The actual total amount of motion between Arabia and Nubia is difficult to determine directly because much of it has occurred through diffuse extension and thick Miocene evaporites mask the basement. However, there are plate kinematic constraints that place some limits on it.

The Red Sea is one of a series of plate boundaries surrounding the Arabian plate. Because all these plate boundaries developed in response to the motion of Arabia away from Africa and into southwestern Asia, the motions that have occurred on the plate boundaries are interrelated. Thus, the presence of 10 m.y.b.p. magnetic anomalies in the Gulf of Aden (Laughton et al, 1970; Cochran, 1981b) requires that motion has also occurred between Arabia and Africa in the Red Sea for that length of time. The solid lines parallel with the axis of the Red Sea in Figure 15 show the amount of extension that has occurred in the Red Sea during the past 10 m.y. using the finite rotation pole of McKenzie et al (1970) at 36.5°N, 18°E, which Le Pichon and Francheteau (1978) showed to be compatible with present-day motion, and assuming that the present angular rotation rate of 3.2 × 10^{-7} degrees per year has been constant over the past 10 m.y. The assumption of constant

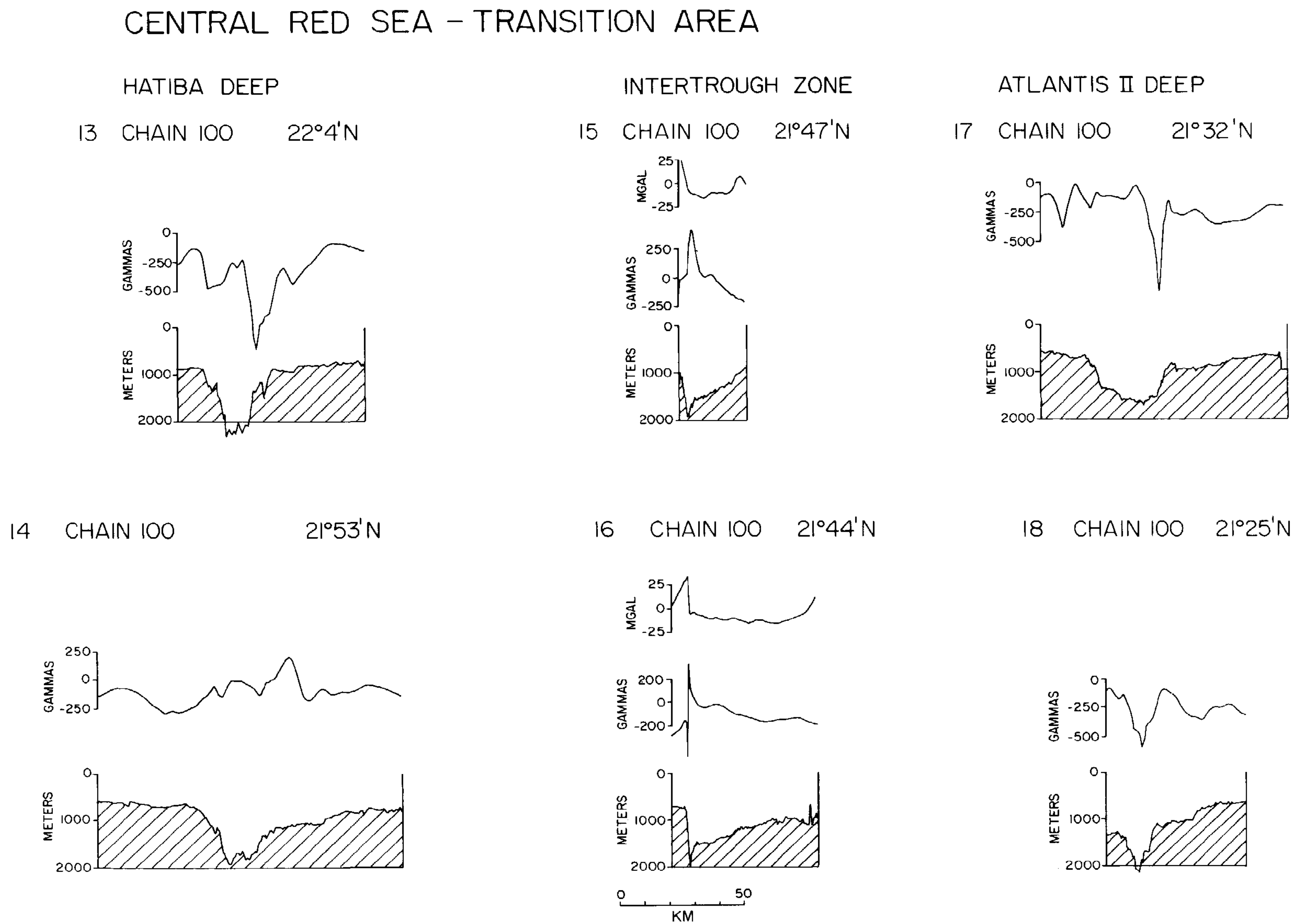

FIG. 14.—Free-air gravity anomaly, total intensity magnetic anomaly and bathymetry profiles across Red Sea in transition area between region of sea-floor spreading to south and diffuse extension to north. Profiles 13 and 14 cross Hatiba Deep, profiles 17 and 18 cross Atlantic II Deep, and profiles 15 and 16 cross intertrough zone between the two deeps. Western end of both profiles 15 and 16 enter Hatiba Deep, so differences between two types of morphology can be seen on those profiles. All profiles projected along N50°E. Profile locations shown in Figure 2.

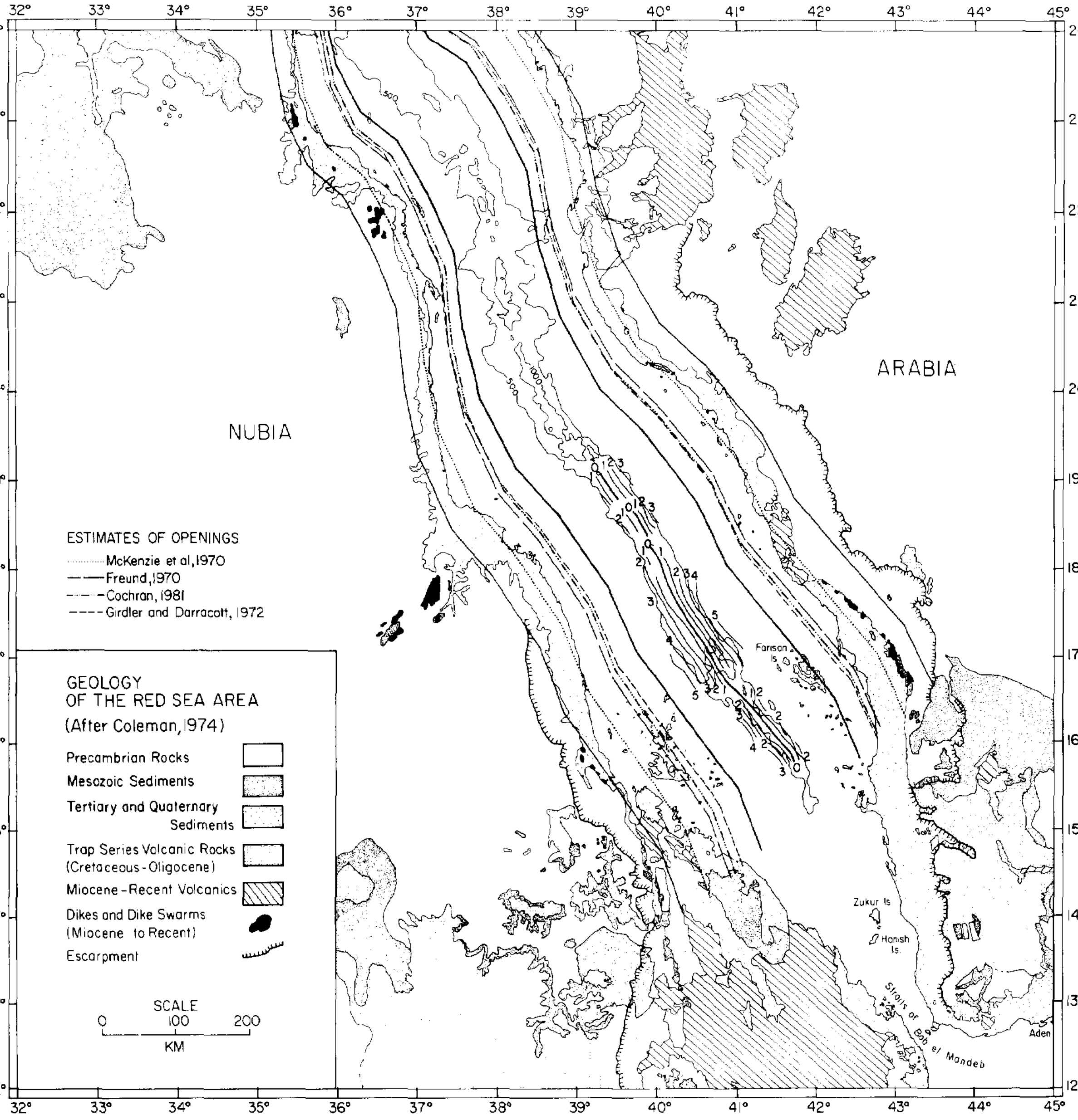

FIG. 15.—Geology of southern Red Sea area and amount of opening implied by various lines of reasoning. Lines over axial trough are magnetic anomaly isochrons (in m.y.b.p.) from Roeser (1975). Solid lines show 3.2° and 8° of opening about McKenzie et al (1970) pole and correspond to opening of Gulf of Aden to 10 m.y. isochron and to rift-bounding faults. Other lines show various estimates (Table 1) discussed in text. Le Pichon and Francheteau's (1978) estimate is indistinguishable from 3.2° (inner solid) line.

rates of opening over this period appears to be valid in the Gulf of Aden (Cochran, 1981b) and thus is valid in the Red Sea up to the uncertainty introduced by the East African rift. This rotation of 3.2° represents an estimate of the minimum amount of extension that must have occurred in the Red Sea. It can easily be seen in Figure 15 that this is significantly more opening than can be accounted for by the sea-floor spreading anomalies over the axial trough.

The dashed lines in Figure 15 show various estimates of the total opening in the Red Sea. As mentioned, two methods have been used to determine Arabia-Nubia poles of opening (Table 1). McKenzie et al (1970) determined a pole at 36.5°N, 18°E, by fitting the coast lines across the Red Sea which was also adopted by Le Pichon and Francheteau (1978) and Cochran (1981b). Girdler and Darracott (1972) and Freund (1970) calculated similar poles at 31.5°N, 23°E, and at 32°N, 22°E, respectively, by requiring that motion between Arabia and Nubia be parallel with the Levant shear. Although the two methods predict quite different directions of opening in the northern Red Sea, the predicted azimuths of present-day plate separation are similar near 20°N where possible fracture-zone traces mapped by Bäcker et al (1975) provide some constraints and the opening directions predicted by either method are consistent with the fracture-zone azimuths (Le Pichon and Francheteau, 1978). It is therefore not possible to choose between them on this basis. The fact that the spreading directions computed for the northern Red Sea with the McKenzie et al (1970) pole are not parallel to the Levant shear requires that Sinai be an independent plate with an active plate boundary extending north through the Gulf of Suez.

Another set of poles has been proposed by Richardson and Harrison (1976), but is not considered here because, as shown by Girdler and Styles, (1976a) and Le Pichon and Francheteau (1978), their solution is inconsistent with the mapped recent fracture zone trends (Bäcker et al, 1975).

Le Pichon and Francheteau (1978) arrived at an estimate of 3.25° about the McKenzie et al (1970) pole for the total amount of opening by assuming that the 45 km (28 mi) of motion on the Levant shear (out of a total of 105 km or 65 mi) that can be dated as post-Miocene (Freund et al, 1968, 1970) represents the same event which created the oceanic crust of the axial trough. They then multiplied the amount of opening required to produce Roeser's (1975) 4 m.y.b.p. magnetic anomaly isochrons by the ratio 105/45 to obtain an estimate for the total opening.

Freund (1970), Girdler and Darracott (1972), and Cochran (1981b) all obtained estimates for the amount of opening in the Red Sea by adding an estimate for the amount of extension in the Gulf of Suez to the documented 105 km (65 mi) of motion along the Levant shear. Freund (1970) and Cochran (1981b) both assumed that 25 to 30 km (15 to 18 mi) of extension has occurred in the southern Gulf of Suez. Girdler and Darracott (1972) assumed that only 13 km (8 mi) of extension has occurred in the Gulf of Suez (Robson, 1970). Neither estimate is well constrained. McKenzie et al (1970) assumed that all of the Red Sea is underlain by oceanic crust and closed it to the shorelines. The amount of opening suggested by McKenzie et al (1970) is almost identical to that assumed in the reconstruction shown in Figure 7A, which uses the same pole and, like that reconstruction, is in conflict with the observed geology in the Gulf of Suez. Reconstructions of the northern Red Sea using the other estimates of the opening given in Table 1 are shown in Figure 16.

The amount of opening predicted by Le Pichon and Francheteau (1978) is very close to the minimum amount that is consistent with the magnetic anomaly data from the Gulf of Aden. Le Pichon and Francheteau's (1978) reconstruction predicts the net effective right-lateral strike-slip motion in the Gulf of Suez (Fig. 16). The field evidence, however (Robson, 1971; Garfunkel and Bartov, 1977), appears to suggest a well-defined component of extensional normal faulting. Garfunkel and Bartov (1977, p. 34) said that "with one known exception (north of Wadi Somar) all the faults are normal" and also stated that the limited evidence they found for a strike-slip component suggests that it is left-lateral.

The method used by Le Pichon and Francheteau (1978) also depends on the existence of a discrete identifiable phase of motion between Arabia and Africa beginning at 4 to 5 m.y.b.p. The identification of magnetic anomalies in the Gulf of Aden implying relatively constant spreading rates over the past 10 m.y. (Cochran, 1981b) suggests that this is not the case. This point will be discussed further.

Girdler and Darracott's (1972) estimate of the opening is based on Robson's (1970, 1971) argument that not more than about 10 km (6 mi) of extension has occurred in the Gulf of Suez. Robson (1971) mapped numerous rotated fault blocks, tilted by as much as 35°, along the eastern margin of the Gulf of Suez. These blocks are bounded by high-angle normal faults and Robson's conclusion that opening is minimal is based on the assumption that these faults remain straight with depth. Garfunkel and Bartov (1977) concluded that 15 to 20 km (9 to 12 mi) of opening could have occurred in the southern Gulf of Suez, but again they assumed that the dip on the faults remains constant with depth "for lack of better information." There is no direct evidence concerning whether the faults remain steep or whether they flatten with depth, as has been observed, for example, along the French continental margin in the Bay of Biscay (de Charpal et al, 1978), in which case considerably more opening could have occurred. The estimate by Girdler and Darracott (1972) of the amount of opening is, however, probably too low because it predicts that a small net compression has occurred in the northern Gulf of Suez (Fig. 16) in conflict with the rift structure and normal faults observed. This conflict can be avoided by slightly increasing the amount of Red Sea opening.

Freund (1970) and Cochran (1981b) both assumed that about 30 km (19 mi) of opening has occurred in the southern Gulf of Suez. This estimate is based on the McKenzie et al (1970) supposition that the crust beneath the Gulf of Suez might be thinned to half of its original thickness. This is neither supported nor ruled out by published seismic refraction data. Cochran (1982) found that the amount of opening in the Gulf of Aden implied by Cochran's (1981b) reconstruction of the Red Sea is near the minimum amount that could have occurred and still satisfy the base-

Table 1. Estimates of Opening in Red Sea

Pole		Angular	
Lat.	Long.	Opening	References
36.5°N	18°E	6.25°	McKenzie et al (1970)
36.5°N	18°E	3.25°	Le Pichon and Francheteau (1978)
36.5°N	18°E	4.34°	Cochran (1981b)
32°N	22°E	6.0 °	Freund (1970)
31.5°N	23°E	5.85°	Girdler and Darracott (1972)
*29.5°N	20.1°E	6.95° (early)	Richardson and Harrison (1976)
15.2°S	32.8°E	1.08° (recent)	

*Richardson and Harrison gave 29.6°N, 20.6°E for early pole. Above position was obtained on redoing their calculation.

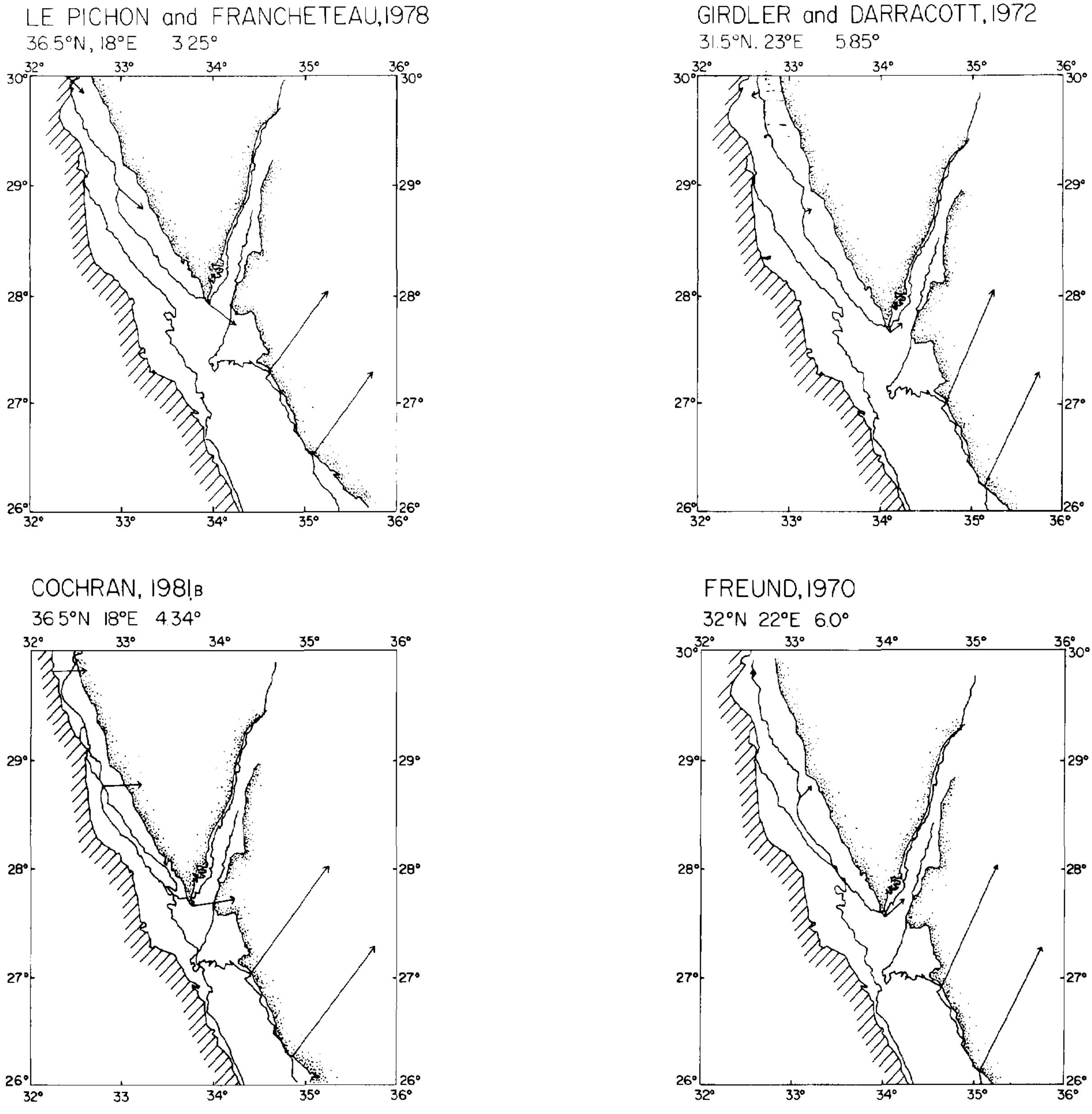

FIG. 16.—Reconstructions of northern Red Sea and Gulf of Suez using poles listed in Table 1. Sinai was first rotated by 1.708° about a pole at 32.5°N, 4.4°W (Le Pichon and Francheteau, 1978) to remove 105 km (65 mi) of left lateral shear along Dead Sea transform and Arabia/Sinai then rotated back toward Africa. Arrows connect restored positions to actual present locations. Shorelines and seaward extent of exposed pre-rift (usually Precambrian) rocks are shown. Pre-rift rocks within Gulf of Suez are omitted for clarity (see Fig. 8).

ment depth and heat flow observed in the Gulf of Aden magnetic quiet zone using variations of either the stretching (McKenzie, 1978; Royden and Keen, 1980) or dike injection (Royden et al, 1980) models for the formation of a continental margin. Because of the different pole position, Freund's (1970) reconstruction produces about 15 km (9 mi) more opening in the eastern Gulf of Aden than that of Cochran (1981b) with the same assumptions concerning the amount of opening in the northern Red Sea. We thus suggest that the total amount of opening in the Red Sea is near or slightly greater than, that suggested by Freund (1970) and Cochran (1981b).

Multiple Phases of Extension

The previous interpretations of magnetic anomalies in the Red Sea (e.g., Girdler and Styles, 1974, 1976b; Styles and Hall, 1980) have suggested that at least two separate, distinct phases of sea-floor spreading have occurred in the Red Sea. The older phase is supposed to have ended at some time between 15 and 34 m.y.b.p. and to have produced the lineated anomalies observed in some places over the shelf. The second phase is assumed to have begun 4 to 5 m.y. ago and to be still continuing. It is assumed in these models that a tectonically quiescent period occurred between these two stages. The model presented in this study suggests that tectonic activity began near the Oligocene-Miocene boundary and has continued without major interruption. The magnetic anomalies interpreted previously as the result of the first phase of sea-floor spreading are here interpreted as resulting from structure within an originally continental basement which was greatly faulted and intruded throughout the Miocene. This interpretation, along with the identification of a sea-floor spreading magnetic anomaly sequence extending over the past 10 m.y. in the Gulf of Aden, implies that the proposed 15 to 5 m.y.b.p. quiescent period probably did not occur.

Certainly a number of tectonic events did occur at about 4 to 5 m.y.b.p. including the extension of Sheba Ridge west of 45°E in the Gulf of Aden, the beginning of sea-floor spreading in the southern Red Sea, and the beginning of the eruption of the Afar Stratoid Series basalts in Afar. However, there is geologic and geophysical evidence of tectonic activity in the Red Sea through the Miocene. This is shown in seismic reflection records (Fig. 13) by the observation that in many places under the main trough the section below reflector S is more highly deformed than the overlying Pliocene and Pleistocene section (Knott et al, 1966; Ross and Schlee, 1973). In some of the profiles, it is clear that this deformation occurred prior to the development of reflector S at the end of the Miocene (Knott et al, 1966). Ahmed (1972) also interpreted seismic data from offshore Saudi Arabia as indicating basement faulting and differential subsidence during deposition of the Miocene evaporites and preevaporite sediments. Along the margins of Sudan, marked differential movement during deposition of the Miocene formations is shown by great changes in thickness and lithology over short distances. An example is the terrestrial and shallow water Maghersum formation which varies in thickness from 66 m (217 ft) in the Dungunab 1 well to 1,435 m (4,708 ft) in the Maghersum 1 well, about 35 km (22 mi) to the southeast (Fig. 2) (Sestini, 1965). Carella and Scarpa (1962) date the Maghersum formation as "Middle Miocene, Helvetian, and ?Lower Miocene." Continuing tectonic activity throughout the Miocene is also clear in the Gulf of Suez where "most of the structural traits were produced by continuing Miocene movements contemporaneous with sedimentation" (Garfunkel and Bartov, 1977, p. 26). In particular, the Langhian and Serravallian (15 to 11 m.y.b.p.) were times of marked motion on the rift bounding master faults resulting in pronounced uplift of the rift shoulders and subsidence of the central trough.

Suggestions that the motion along the Dead Sea rift has been episodic (Freund et al, 1968, 1970) have been cited (Girdler and Styles, 1974; 1976b; Styles and Hall, 1980) as support for the presence of multiple phases of sea-floor spreading in the Red Sea. However, according to Freund et al (1970, p. 124) "there is no conclusive evidence in this matter." What can be definitely established is that all of the pre-Cenozoic markers are offset by about 105 km (65 mi; Quennell, 1956, 1958; Freund et al, 1968, 1970) and that about 45 km (28 mi) of this motion has occurred since the end of the Miocene (Freund et al , 1968). Recently, Bartov et al (1980) were able to demonstrate that motion on the Dead Sea rift began no earlier than about 20 m.y.b.p.

Freund and Garfunkel (1976) and Garfunkel (1981) have pointed out that the present structure of the Dead Sea rift has developed since the early Pliocene as the result of a rearrangement of the pattern of active faults. This rearrangement is most clearly shown by a series of pull-apart rhomb grabens underlying the Gulf of Aqaba and the Dead Sea, each of which has a length of about 35 to 40 km (22 to 25 mi). Garfunkel (1981) has suggested that this rearrangement of the active fault pattern is the result of a slight shift in the pole of motion between the Arabian and Sinai plates. Such a shift in the Arabia-Sinai pole could result from a small change in the rate of extension in the Gulf of Suez.

Although there is evidence for a rearrangement of the fault pattern in the southern part of the Dead Sea rift during the Pliocene, there is no direct evidence of a hiatus accompanying the rearrangement. In fact, the presence of smaller pull-apart basins, such as the Sea of Galilee and the Hula depression which record 10 to 12 km (6 to 7 mi) of opening and were formed in the Pleistocene (Garfunkel, 1981), indicates that a rearrangement of the fault pattern need not be accompanied by a cessation of slip on the plate boundary.

Danakil Plate

Large exposures of pre-rift rocks are found at a number of locations within the Afar rift. The main outcrops are in the Danakil highlands and in the Aisha region where Precambrian basement and overlying Mesozoic sediments are exposed. These regions are quite often referred to as "horsts" and Danakil has been treated as a rigid "platelet" in various applications of small-scale plate tectonics to Afar (e.g., Mohr, 1970; Barberi and Varet, 1977; Le Pichon and Francheteau, 1978). However, as pointed out by Morton and Black (1975, p. 56), "the areas of pre-Miocene rocks exposed within Afar are all intensely faulted by normal faults, and the blocks between the faults are strongly tilted." Thus, these regions have not acted as rigid blocks during the development of Afar. In addition, while Danakil might be considered to have rotated away from the Ethiopian escarpment, it is difficult to account for the Aisha spur in any application of small-scale rigid plate tectonics.

During the diffuse extension stage of rifting, there is no well-defined plate boundary, but rather a perhaps 100 km (60 mi) wide zone of deformation and extension. The Danakil and Aisha highlands could have formed during this period as regions in which, for some reason, the extension and crustal attenuation were less severe, resulting in higher standing areas that were not subsequently buried under flood basalts. The region within 70 km (43 mi) of the Red Sea and Gulf of Aden coasts in northern Afar became tectonically stable by about 8 m.y.b.p. (Barberi et al, 1975) as either the region of diffuse extension became more concentrated or as this area was transported out of it. Northeastern Afar, including much of the Danakil highlands thus is now part of the Arabian plate. There is not now and really never has been a "Danakil plate" in the sense that the term is generally used in plate tectonics.

Implications for Early Development of Passive Continental Margins

Since the mid-1970s, considerable effort has been devoted to studying the structure and development of passive "Atlantic-type" continental margins. Observations of continental margins have delineated several structural features common to most continental margins. Approaching a mature continental margin from landward, coastal-plain sediments are found to thicken gradually toward a feature referred to as the hinge zone, where the continental basement falls away abruptly in a series of faults and flexures (Jansa and Wade, 1975). The hinge zone appears to be a major structural boundary and to be represented at the young ocean basins of the Gulf of Aden and Red Sea by the large escarpment marking the edge of the rift (Fig. 1). The greatest subsidence and sediment accumulation at a mature margin are found seaward of the hinge zone beneath the continental shelf and/or upper continental rise. Gravity and geoid models (Watts and Steckler, 1979) show that at the hinge zone the crust thins from typical continental thicknesses of 30 to 40 km (19 to 25 mi) to about 8 to 20 km (5 to 12 mi).

The crustal structure of a continental margin is probably best known at the sediment-starved margin of the Bay of Biscay (de Charpal et al, 1978; Montadert et al, 1979). There, the margin is broken up into a series of rotated fault blocks 10 to 20 km (6 to 12 mi) wide. Multichannel seismic reflection profiles suggest that the faults are listric, curving at depth to form a plane of decollement (de Charpal et al, 1978). Seaward, the fault blocks become progressively more rotated and deeper, and estimates of the amount of extension implied by this geometry range from 10 to 20% (Montadert et al, 1979) to 150 to 200% (Le Pichon and Sibuet, 1981).

Biostratigraphic data from exploratory wells at mature continental margins show that much of the sediment pile is made up of shallow-water sediments (Jansa and Wade, 1975; Gradstein et al, 1975) which could not be produced by the filling of a preexisting basin. Sleep (1971) corrected the subsidence rates recorded in wells from the United States coastal plain for the effects of sediment loading and found that the remaining subsidence showed an exponential decay in time, with a time constant of about 50 m.y. This result was confirmed by later studies, which took into account such factors as sediment compaction and the finite strength of the lithosphere (Watts and Ryan, 1976; Steckler and Watts, 1978). This is the type of response expected from the cooling of a heated lithosphere (Sclater and Francheteau, 1970). With these models, a mechanism is needed to cause the crust to subside below sea level because if the lithosphere is simply heated, it will expand and then contract back to its original position. Various mechanisms have been suggested for either making the crust denser (Falvey, 1974; Falvey and Middleton, 1981) or thinner (Sleep, 1971; Kinsmen, 1975; McKenzie, 1978; Royden et al, 1980).

The simplest model and the one which appears to best explain the structures observed (e.g., in the Bay of Biscay) is the stretching model of McKenzie (1978). This model starts with a unit length of lithosphere of thickness ℓ with a crust of thickness t_c over an isothermal asthenosphere. A simple linear thermal gradient is assumed in the lithosphere (Fig. 17A). At time T = 0, the lithosphere is instantaneously extended to length β. To conserve mass, the crustal thickness decreases to t_c/β and the lithospheric thickness to ℓ/β, as hot asthenospheric material passively rises in response to the lithospheric thinning (Fig. 17B).

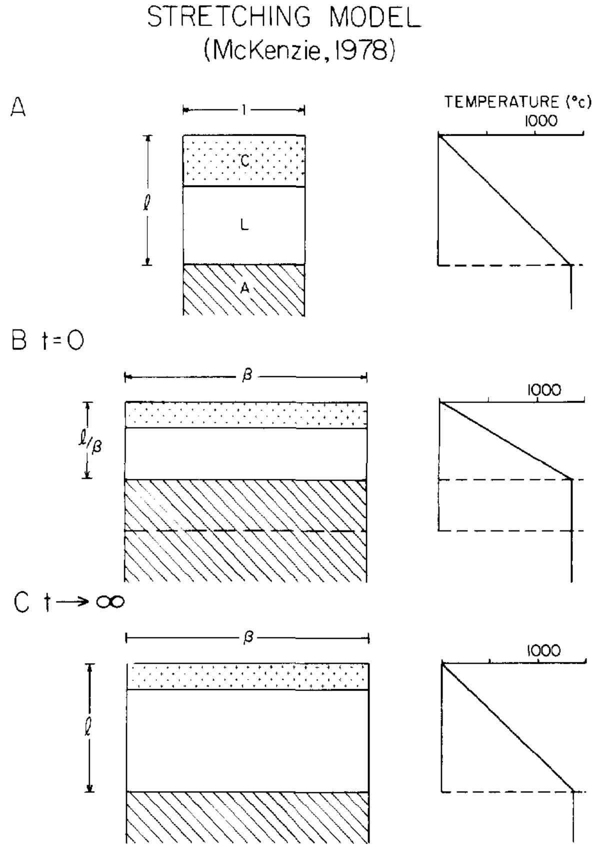

FIG. 17.—Simple model for crustal extension. Unit length of lithosphere (A) is, at time T = 0, instantaneously extended to length β (B), thinning crust and lithosphere to ℓ/β of their original thickness and resulting in a change in temperature structure. With time, lithosphere thickens and thermal gradient returns to its original state (C). Knowledge of initial and final temperature distributions and densities of crustal and lithospheric materials allows surface elevation and heat flow to be calculated as a function of time.

The lithospheric and crustal thinning results in an immediate isostatic adjustment, referred to by Sclater and Christie (1980) as the "fault bounded subsidence," which is due to the fact that the extension results in changing the mass in a vertical column. After the extension has occurred, the lithosphere will start to thicken as heat is conducted through the surface and in time will return to its equilibrium thickness (Fig. 17C) which is determined by a balance between the heat being conducted to the surface and the heat supplied to the base of the lithosphere. With the initial and final thermal states known, the temperature distribution, and thus densities, can be determined as a function of time, allowing the subsidence and heat-flow history to be calculated (McKenzie, 1978; Royden and Keen, 1980).

This model appears to offer an explanation of many of the features observed at continental margins such as tilted extended fault blocks, listric faults, and thinned continental crust seaward of a well-defined hinge zone (de Charpal et al, 1978; Keen and Barrett, 1981; Montadert et al, 1979) and, in the case of the Red Sea, the uniform and high heat-flow values observed over the main trough (Girdler and Evans, 1977). Variations of the stretching model have been applied to the analysis of a number of margins including eastern North America (Watts and Steckler, 1979; Royden and Keen, 1980; Keen et al, 1981), the Atlantic and Mediterranean margins of France (Montadert et al, 1979; Le Pichon and Sibuet, 1981; Steckler and Watts, 1980), and the Gulf of Aden (Cochran, 1981b, 1982). The main trough and shelves of the Red Sea appear to have been produced during the pre-sea-floor spreading "stretching" event. The stretching in the Red Sea appears to have occurred diffusely through a combination of extensional block faulting and dike injection, which has produced large intrusive bodies at some locations.

A period of diffuse extension prior to the beginning of sea-floor spreading appears to be a necessary part of lithospheric rifting leading to the establishment of passive continental margins and an ocean basin. Mid-ocean ridge tectonics require a thermal regime in which basaltic magmas can be continually generated at shallow depths and thus a very thin, hot lithosphere is not only the result of sea-floor spreading, it is a prerequisite for its occurrence. When continental rifting is initiated (e.g., by the beginning of the motion of Arabia away from Africa), the lithosphere is still thick and cold, and thus sea-floor spreading will not be able to begin immediately. The extension therefore appears to be taken up diffusely across an area of the order of 100 km (60 mi) wide (Fig. 18A) rather than at a single spreading center.

The simple model (McKenzie, 1978) (Fig. 17) predicts that the amount of lithospheric thinning is directly related to the amount of diffuse extension. It would therefore be expected that the width of the stretched zone would be similar at all margins and the time that the diffuse extension phase lasts would depend on the opening rate across the developing plate boundary. It is thus reasonable that in both the Gulf of Aden and the Red Sea, the initiation of sea-floor spreading does not represent an isochron, but rather began at the end of the rift farthest from the pole defining the plate motion and has progressed toward the pole.

The McKenzie (1978) stretching model and its variations (Royden et al, 1980; Royden and Keen, 1980; Steckler, 1981) also all assume that the extension happens instantaneously. This assumption greatly simplifies the mathematical treatment by providing simple, well-defined initial conditions, but it does not correspond to what is found in nature. The effect of a finite time of extension is to cause a loss of heat and thus additional subsidence and lithospheric thickening prior to the initiation of sea-floor spreading.

Jarvis and McKenzie (1980) investigated the effects of a finite extension time and concluded (p. 42) that "for most basins the simple model gives reasonably accurate results provided the duration of stretching is less than 20 ma." However, they assumed that heat is only lost in a vertical direction. In fact, significant horizontal temperature gradients can result during an extended rifting event, resulting in horizontal heat flow which will cause additional cooling and subsidence within the rift and heating and uplift of the rift shoulders. Cochran et al (1982) found that, for a rifting event as short as 10 m.y., the instantaneous model results in underestimating the syn-rift subsidence by about 15 to 20%. For a 20 m.y. rifting event, the errors could be as much as 35%.

Because an extended period of rifting serves to transfer a portion of the heat loss and subsidence from the post-rift to the syn-rift stage, it will have a marked effect on the results of model studies of the development of the margin. For example, with a given amount of extension the post-rift subsidence will be less than predicted for the simple instantaneous model and the subsidence rates slower. As a result, studies that use "backstripped" subsidence curves to study the evolution of a continental margin will underestimate the amount of extension that has occurred.

The diffuse extension phase has lasted about 20 to 25 m.y. in the northern Red Sea, so the instantaneous extension model will be subject to significant errors. Extended rifting events also appear to have occurred at other continental margins. For example, Jansa et al (1977, 1980) have identified Carnian to Norian (212 to 200 m.y.b.p.) red beds and evaporites in wells along the Atlantic margin of Canada, where sea-floor spreading is thought to have begun in the Bajocian (about 170 m.y.b.p.) (Jansa and Wade, 1975; Klitgord and Grow, 1980). The effects of an extended rifting event must not be overlooked in analyzing the subsidence and thermal development of a continental margin.

CONCLUSIONS AND SUMMARY

A new model for the evolution and development of the Red Sea explains both data which suggest that only a limited amount of oceanic crust is present and data which suggest that considerable motion has occurred between Africa and Arabia. An initial Red Sea rift about 100 km (60 mi) wide was formed by continental rifting in the late Oligocene or early Miocene. The original rift valley widened through a combination of normal faulting, which by analogy to the French Atlantic margin (de Charpal et al, 1978; Montadert et al, 1979) may be listric in nature, and of dike injection which included emplacement of some sizeable igneous bodies (Coleman et al, 1975, 1979). The northern Red Sea (north of about 25°N) appears to still be in this stage of evolution. The diffuse extension within the rift resulted in a heterogeneous crustal structure which has been found in seismic experiments both in the Red Sea (Fig. 8) and along other continental margins (Talwani et al, 1979; Cochran, 1982). It also served to thin the lithosphere to the point where a mid-ocean ridge type of spreading center could be established near 17°N at 4 to 5 m.y.b.p. The spreading center has gradually extended itself to both the north and south and active sea-floor spreading can presently be documented from about 15°30′N to about 21°N. The deep, rough axial trough represents the sea-floor formed by the new ridge. The area between 21°N and 25°N appears to be presently changing from the dif-

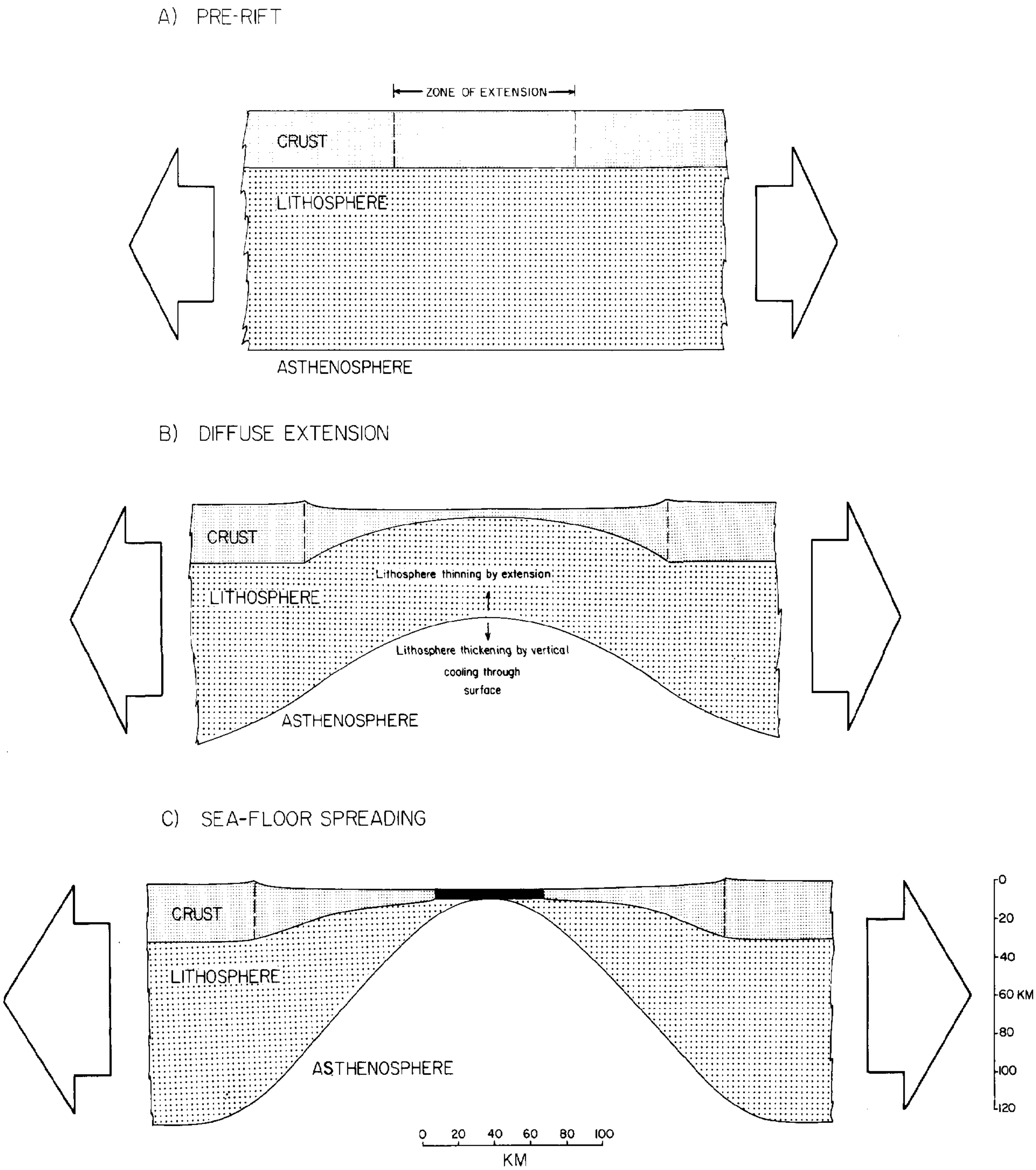

FIG. 18.—Sketch showing development of continental margin and establishment of mid-ocean ridge spreading center. When rifting begins (A), temperatures in upper mantle are too low to support a mid-ocean ridge, and extension occurs diffusely over a wide area. As diffuse extension continues (B), crust and lithosphere are thinned by extension. Lithosphere, which is defined thermally, is also thickening by heat loss through the surface. Finally, if extension continues long enough and fast enough, lithosphere is thinned to point where mid-ocean ridge tectonics can occur and sea-floor spreading commences.

fuse extension to sea-floor spreading mode of plate separation.

The amount of non-sea-floor spreading extension required is large, but not unreasonably so when it is considered that it can be distributed across the entire rift. The amount of opening suggested by Cochran (1981b) implies about 75% extension of the original rift valley prior to the initiation of sea-floor spreading in the southern Red Sea. In the northern Red Sea, near 25°N, about 130% extension is implied. This is consistent with what has been inferred at other well-studied continental margins, such as off Nova Scotia (Keen and Barrett, 1981), the Gulf of Lion (Steckler and Watts, 1980), and the United States eastern margin (Watts and Steckler, 1979; Watts, 1981).

The effects of an extended rifting phase have not been considered in most model studies of the evolution of continental margins. The effect of a finite rifting time is to transfer part of the heat loss (which is all post-rift in the instantaneous mathematical models) to the syn-rift period. As a result, additional subsidence occurs during the rifting phase, with less subsidence and slower subsidence rates in the post-rift period. The maximum temperatures reached are also less than calculated using the various instantaneous rifting models. If the Red Sea is typical of other older continental margins, then the effects of an extended period of rifting and diffuse extension cannot be ignored.

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