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NEW CONSTRAINTS ON RED SEA RIFTING FROM CORRELATIONS OF ARABIAN AND NUBIAN NEOPROTEROZOIC OUTCROPS

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Abstract. New constraints on the mechanics of Red Sea opening were obtained by correlating Neoproterozoic outcrops of the Arabian and Nubian Shields along two thirds of the Red Sea coastlines. Using a mosaic of 23 Landsat thematic mapper scenes ($5x10^5$ km^2) together with field, geochemical, and geochronological data, we identified and mapped lithologic units, mobile belts, and terranes within the Arabian and Nubian Shields. Features best align if Arabia is rotated by 6.7° around a pole at latitude 34.6°N, longitude 18.1°E. Implications of our reconstruction include (1) the amount of continental crust underlying the Red Sea is small because the restored Red Sea coasts are typically juxtaposed, (2) only a single pole is needed, implying that the Arabian and Nubian Shields were rigid plates during Red Sea rifting, (3) coastlines reorient to align with preexisting structures, suggesting the rift propagated in part along pre-existing zones of weakness, (4) large sinistral displacements of up to 350 km along the Red Sea are not supported, (5) the pole is inconsistent with the Pliocene-Pleistocene motion along the Dead Sea transform (pole: 32.8°N, 22.6°E +/-0.5° [Joffe and Garfunkel, 1987]), indicating that more than one phase of motion is required to account for the Red Sea opening. However, our pole is similar to that for the total motion along the Dead Sea transform (pole: 32.7°N, 19.8°E +/-2° [Joffe and Garfunkel, 1987]), suggesting that the motion between Arabia and Nubia was parallel to the total motion along the Dead Sea transform.

INTRODUCTION

Despite numerous studies of the Red Sea rift, questions pertaining to mechanics of rifting, onset of seafloor spreading, and interplay between seafloor spreading, crustal extension, and plutonic activity remain unresolved. Crucial to resolving these issues is whether the crust underlying the Red Sea is mostly oceanic or extended continental crust. Magnetic, seismic, and heat flow studies [e.g., Izzeldin, 1987; Le Pichon and Gaulier, 1988; Martinez and Cochran, 1988] convincingly demonstrate the presence of oceanic crust along the narrow axial trough of the rift. However, interpretation of geophysical data over the main trough and shelves is controversial, and hence the nature of the crust in these areas remains unresolved.

A wide range of kinematic models has been proposed to describe the Red Sea rifting. Models differ with respect to separation between the restored Red Sea coastlines, nature of the crust underlying the main trough and shelves, orientation of pole(s) of rotation, amount of angular rotation, amount of extension in the Gulf of Suez, and whether the opening was accomplished by one or more phases of extension. Models that advocate broad extension of the continental crust have the coastlines widely separated [e.g., Girdler and Darracott, 1972; Lowell and Genik, 1972; Le Pichon and Francheteau, 1978; Cochran, 1981, 1983; Voggenreiter et al., 1985; Izzeldin, 1987; Joffe and Garfunkel, 1987]. Other models assume that the Red Sea is almost completely floored by oceanic crust [e.g., McKenzie et al., 1970; Girdler and Underwood, 1985; LaBreque and Zitellini, 1985; Bohannon, 1986,1989; Sultan et al., 1992]. This latter class of models has the coastlines juxtaposed or even overlapping. A third class of reconstructions predict the Red Sea floor to be largely formed of oceanic crust with a small gap (20-40 km) between the restored Red Sea coasts [e.g., Le Pichon and Gaulier, 1988]. These three types of reconstructions will be referred to hereafter as wide-separation, coast-to-coast, and near-coast-to-coast reconstructions, respectively.

Most Red Sea reconstructions use one of two poles of rotation to model the divergence of the Arabian and Nubian plates. The first pole and associated angular rotation was obtained by fitting coastlines (36.5°N, 18°E [McKenzie et al., 1970]) and was later adopted by Cochran [1981] and Le Pichon and Francheteau [1978]. The second pole was determined by requiring that the motion between Arabia and Nubia be parallel to the motion along the Levant shear zone (33°N, 24°E [Quennell, 1959]) (32°N, 22°E [Freund, 1970]) (31.5°N, 23°E [Girdler and Darracott, 1972]). Similar poles were adopted by Joffe and Garfunkel [1987] and Izzeldin [1987]. Joffe and Garfunkel [1987] identified the Dead Sea as a leaky transform and used geometric relations of the structures along the Levant shear zone to define the young (0-5 Ma; pole: 32.8°N, 22.6°E +/-0.5°) and total (0-25 Ma; pole: 32.7°N, 19.8°E +/-2°) motion along the shear zone. They then used their pole parameters to constrain the Red Sea opening pole to 32.5°N, 24.0°E +/-2°. Izzeldin [1987] defined a pole (32.9°N, 23°E) and angular rotation (5.5°) describing the Red Sea opening since anomaly 3 by fitting eastern and western anomaly 3 near 19°N as well as the trend of the best defined transform fault in the area. To compute angular rotations, Freund [1970], Girdler and Darracott [1972], Cochran [1981], and Joffe and Garfunkel [1987] added various estimates of extension in the Gulf of Suez (10 to 35 km) to the well-documented 105 km of sinistral displacement along the Levant shear.

Makris and Rihm [1991] suggested that smaller segments of the Red Sea with similar tectonic regimes and the adjacent crust should be considered separately. They objected to describing the separation between Africa and Arabia by a simple rotational motion around a single pole and modeled the Red Sea as a sinistral, shear-controlled, pull-apart basin. Earlier (640-580 Ma) sinistral displacements of up to 350 km were also inferred [Shimron, 1990]. Finally, whether the Red Sea opening should be described by more than one phase of motion is another subject of debate [e.g., Le Pichon and

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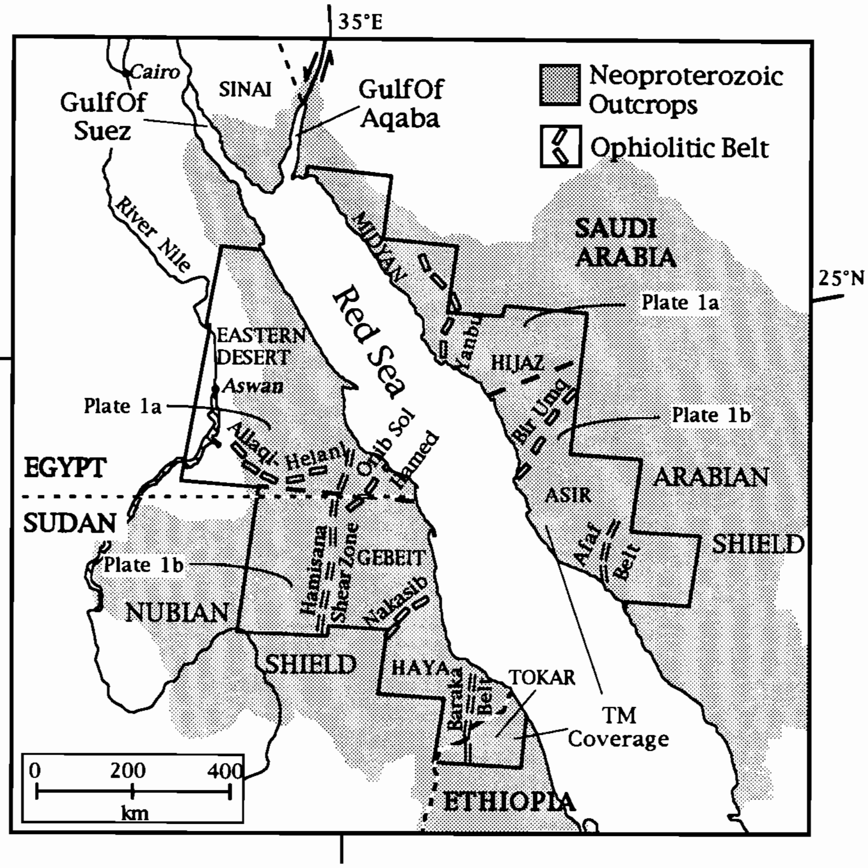

Fig. 1. Location map showing Neoproterozoic outcrops along the Red Sea margins. Also shown are the major volcano-sedimentary arc terranes and interleaving ophiolitic belts. Areas covered by Plates 1a and 1b are outlined.

Francheteau, 1978; Izzeldin, 1987; Le Pichon and Gaulier, 1988].

We argued that because geologic features aligned upon juxtaposing the Red Sea coastlines, the amount of continental crust beneath the Red Sea must be minimal [Sultan et al., 1992]. However, detailed correlations were provided for only two areas in the Eastern Desert of Egypt, NE Sudan, and adjacent areas in the Arabian Shield [Sultan et al., 1992]. These areas cover $2x10^4$ and $5x10^4$ km^2, respectively. In this paper, we consolidate our earlier findings by extending the detailed correlations along two thirds the length (approximately 1200 km) of the Red Sea coastlines (Figure 1). We use new geologic constraints to solve for the pole and amount of angular rotation that best account for the observed geologic correlations. We then address Red Sea rifting kinematics and evaluate published Red Sea reconstructions (Figure 2) and the assumptions on which these models were based.

STUDY AREA

The Arabian and Nubian Shields in NE Africa and in the Arabian Peninsula are relatively recent additions to an older African continent (>1 Ga). The shields were formed by accretion of a complex of ensimatic and ensialic island arcs and interleaving oceanic basins that were later accreted against the African continent 550-950 Ma [Kröner et al., 1987]. The collision-related tectonic fabric is predominantly oriented N-S or NE-SW [Moore, 1979]. The volcano-sedimentary arc terranes are now separated by E-W or N-S trending linear belts of dismembered ophiolitic sequences that presumably mark the suture location along which the arcs collided [Stoeser and Camp, 1985; Vail, 1985; Kröner et al., 1987]. For example, the Gebeit terrane is separated from the arc terranes of the Eastern Desert to the north and the Haya terrane to the south by the Onib-Sol Hamed and Nakasib sutures, respectively (Figure 1). Similarly, the Hijaz is separated from the Midyan and Asir terranes by the Yanbu and Bir Umq sutures, respectively (Figure 1). N-S trending Hamisana, Baraka, and Afaf mobile belts, separate Gebeit from Gabgaba, Tokar from Haya, and northern Asir from southern Asir, respectively (Figure 1).

By 550 m.y. ago the major magmatic (e.g., intraplate rifting, anorogenic magmatism) and tectonic activities (e.g., transcurrent faulting related to the Najd Shear System) ceased. The Arabian and Nubian Shields remained contiguous until about 25 Ma [Bohannon, 1986], when the Red Sea started opening and the shields drifted apart. We traced the continuity of mobile belts (e.g., NE trending suture zones, NW trending Najd shear zones and faults, N-S trending mobile belts), lithologic units (volcano-sedimentary associations, granitoid belts and complexes, dike swarms) to

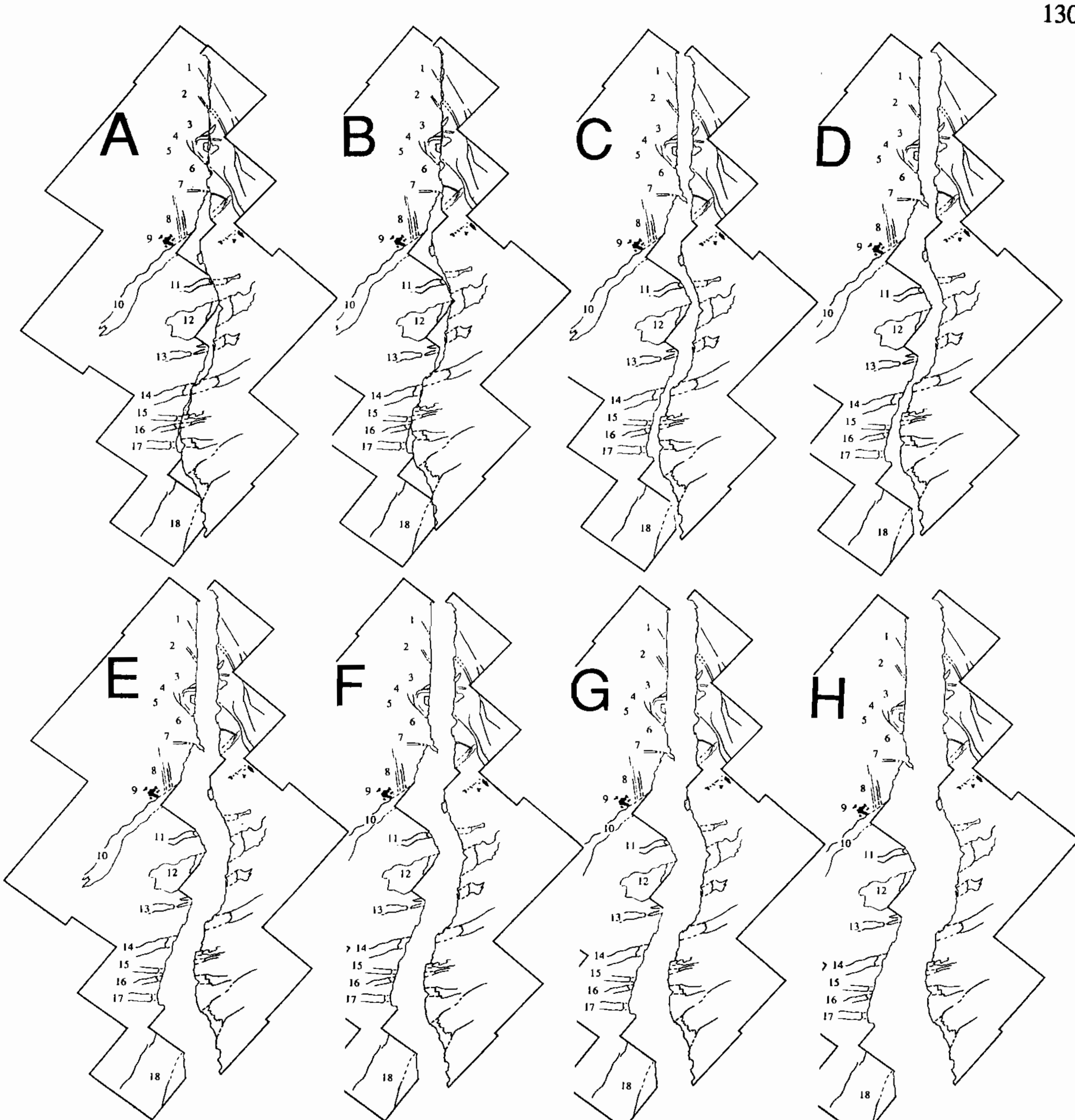

Fig. 2. Sketch map comparing (a) our reconstruction to (b-h) published Red Sea reconstructions. Reconstructions are grouped into three groups: coast-to-coast reconstructions (Figures 2a and 2b), near coast-to-coast (Figures 2c and 2d), and wide-separation models (2e-2h). The Arabian side was rotated using the following poles and angular rotations: (a) Sultan et al. [1992], pole: 34.6°N, 18.1°E; 6.7°; (b) McKenzie et al. [1970], pole: 36°N, 18.°E: 6.25°; (c) Le Pichon and Gaulier [1988], pole: 32.75°N, 22.64°E: 1.89°; 31.82°N, 22.54°E: 3.47°; 32.0°N, 22.5°E; 2°, (d) Joffe and Garfunkel [1987], pole: 32°N, 25°E; 7.75°, (e) Cochran [1981], pole: 36.5°N, 18.0°E: 4.34°, (f) Freund [1970], pole: 32°N, 22°E: 6°, (g) Izzeldin [1987], pole: 31.5°N, 23°E: 5.85°, (h) Le Pichon and Francheteau [1978], pole: 36.5°N, 18.0°E: 3.25°. Selected geologic features in the Nubian Shield and their postulated extensions in the Arabian Shield (shown in parentheses) that were used to constrain our reconstruction (plates 1 and 2; Figure 2a). 1, Hamrawin (Al Muwaylih) shear zone; 2, Sibai (Duba) shear zone; 3, Um Khariga (Wadi Marwah) metavolcanics; 4, dike swarms south of Um Khariga metavolcanics (dike swarms south of Wadi Marwah); 5,Wadi Ghadir (Liban complex); 6, Hafafit (Al Wajh) shear zone; 7, dike swarms north of Wadi Khuda (dike swarms north of Wadi Zaruf); 8, Beitan (Yanbu al Bahr) shear zone; 9, Gebel Gerf nappe (Yanbu suture); 10, Hamisana (Hanabiq) shear zone; 11, 12, and 13, NE trending volcanosedimentary sequences to the south of the Onib-Sol Hamed suture (NE trending volcanosedimentary sequences to the south of the Yanbu suture); 14, Meritri group, Nakasib suture (Shayban formation, Bir Umq suture); 15, 16, and 17, NE trending volcano-sedimentary units to the south of Nakasib (NE trending volcano-sedimentary units to the south of Bir Umq suture); and 18, Baraka (Afaf) belts.

constrain pre-Red Sea relative locations of the Arabian and Nubian Shields.

EXPERIMENTAL APPROACH

Detailed geologic maps and information are needed to identify and correlate geologic features on either side of the Red Sea. Although such maps are available locally, especially on the Arabian side, they are absent on a regional scale, particularly for the Nubian side. Even in areas where maps are available, it is commonly difficult to correlate geologic units across geographical and/or political boundaries since the maps were generated mostly by local institutions that adopt different nomenclature and stratigraphic classifications. Because of the large areal extent of the study region and the difficulty in accessing some areas due to harsh conditions and/or political problems, we were unable to pursue geologic correlations through field work alone. To alleviate some of these problems, we used digital Landsat thematic mapper data, our field observations in the Eastern Desert and Sudan, and published information to pursue correlations along the Red Sea coasts.

Remote sensing observations provide coverage of large areas with quantitative observational parameters (for example, spectral radiance or power received in case of thematic mapper data) and are thus a potentially rich source of information for mapping. The standard Landsat thematic mapper (TM) scene consists of seven images, each 185 km by 185 km; six of which are acquired with broadband passes in the 0.4-2.34 µm wavelength region, and the seventh in the thermal infrared (10.4-12.5 µm). Visible and reflected infrared image elements are 30 m across. For this study, a digital mosaic of 23 Landsat thematic mapper scenes was generated using ratios of Landsat thematic mapper bands (5/4x3/4, 5/1, 5/7) that are sensitive to the content of Fe-bearing aluminosilicates, spectrally opaque, and hydroxyl-bearing or carbonate-bearing minerals, respectively [Sultan et al., 1987; 1988; 1992]. The mosaic covers approximately 5×10^5 km^2 of late Proterozoic outcrops of the Arabian-Nubian Shield and 1200 km of each of the Nubian and Arabian coastlines. Procedures used in generating these mosaics are described by Sultan et al. [1987, 1988, 1992].

The northern half of the TM mosaic and an associated interpretation map are shown in Plate 1a and Figure 3a, respectively, and southern half mosaic and map are shown in Plate 1b and Figure 3b. The mosaic has the Arabian and Nubian Shields placed in their relative pre-Red Sea locations. The Arabian side of the mosaic was rotated until the geologic features on either side of the Red Sea came into optimum alignment (alignment with minimum offset of geologic features). Only the features that were verified by field checks and/or examination of published data were used; features were identified on 1:250,000 scale enlargements of Plate 1.

The position (latitude and longitude) of a "best fit" Euler pole and the amount of rotation about this pole were found by using pairs of locations of geologic features on either side of the Red Sea (Figure 2) using procedures described in Appendix A. These location pairs are assumed to have been coincident before rotation. It is also assumed that deformation can be represented as a single rotational event. We find that features align best upon rotating Arabia by 6.7^0 around a pole located at 34.6^0N, 18.1^0E. In this reconstruction, approximately half the length of the Red Sea coastlines is juxtaposed; the remaining coastlines are either separated or overlap. The gap or overlap between the coastlines, when present, is 5 to 10 km, on average. Features misalign significantly when the location of the pole (latitude or longitude) is changed or when the amount of rotation is changed by more than 0.5^0 to 1.0^0, as is shown by using a variety of published poles to restore the Red Sea coastlines (Figure 2) and empirically varying our pole and checking feature alignments.

GEOLOGIC CORRELATIONS

Geologic features within the Nubian Shield and their postulated extensions into the Arabian Shield are listed in Table 1. A description of these features together with supporting field, geochemical, and geochronological data are listed in Appendix B. Our reconstruction aligns the major mobile belts that intersect the Nubian and Arabian Red Sea coastal plains. The Gebel Gerf nappe aligns with the Yanbu suture, the Nakasib with the Bir Umq suture, the Hamisana shear zone with the Hanabiq, and the Baraka mobile belt with the Afaf belt. Four major shear zones of the Najd System in Arabia project along strike into the Hamrawin, Sibai, Hafafit, and Beitan areas of the Eastern Desert of Egypt.

Unlike the mobile belts, lithologic units within the basement complex do not maintain their strike over long distances. Naturally, the larger the dimensions of a lithologic unit and the smaller the width of the Phanerozoic cover separating it from the coastline, the better the chances for finding an extension for it on the opposing Red Sea margin. Outcrops in the central Eastern Desert and corresponding areas in the Arabian Shield show fine-scale lithologic heterogeneities, whereas those to the south are generally larger in dimensions and lateral extent (Plate 1a). Differences in outcrop patterns between the central Eastern Desert and areas to the south were attributed to brittle deformation associated with the Najd Shear System in the north and its general absence from areas to the south [Sultan et al., 1988]. Thus only a few lithologic units were large enough to be correlated across the Red Sea coastlines. From north to south these are the Dokhan volcanics (near Gebel Nuqrah), Shadli volcanics (mouth of Wadi Um Khariga), and the Wadi Ghadir granitic complex. These units juxtapose the Minaweh formation (near Al Khuraybah), Marrah formation of the Zaam group (mouth of Wadi Marwah), and Liban granitic complexes, respectively. To the north of each of the granitic complexes, a NE trending dike swarm and a trail of serpentinite align.

Further south, the metagabbro-diorite complex of the Eastern Desert aligns with compositionally similar Nabt complex of the Arabian Shield. To the north of each of the complexes, NE trending dike swarms juxtapose. South of both complexes, and as far south as the Baraka (southern Sudan) and Afaf (Saudi Arabia) belts, numerous NE trending volcano-sedimentary and granitoid belts juxtapose. For example, three major volcano-sedimentary belts cropping out to the south of the Onib-Sol Hamed and north of Nakasib and two interleaving granitoid belts align with compositionally similar units on the Arabian side. The Naferdeib, Asoteriba-Gebeit, and Kadaweb juxtapose volcano-sedimentary successions assigned to the Hadiyah and Hamra groups (Plate 1b, Figure 3b, Table 1, Appendix B). Also, granitoids in the Asir terrane are concentrated along three main magmatic

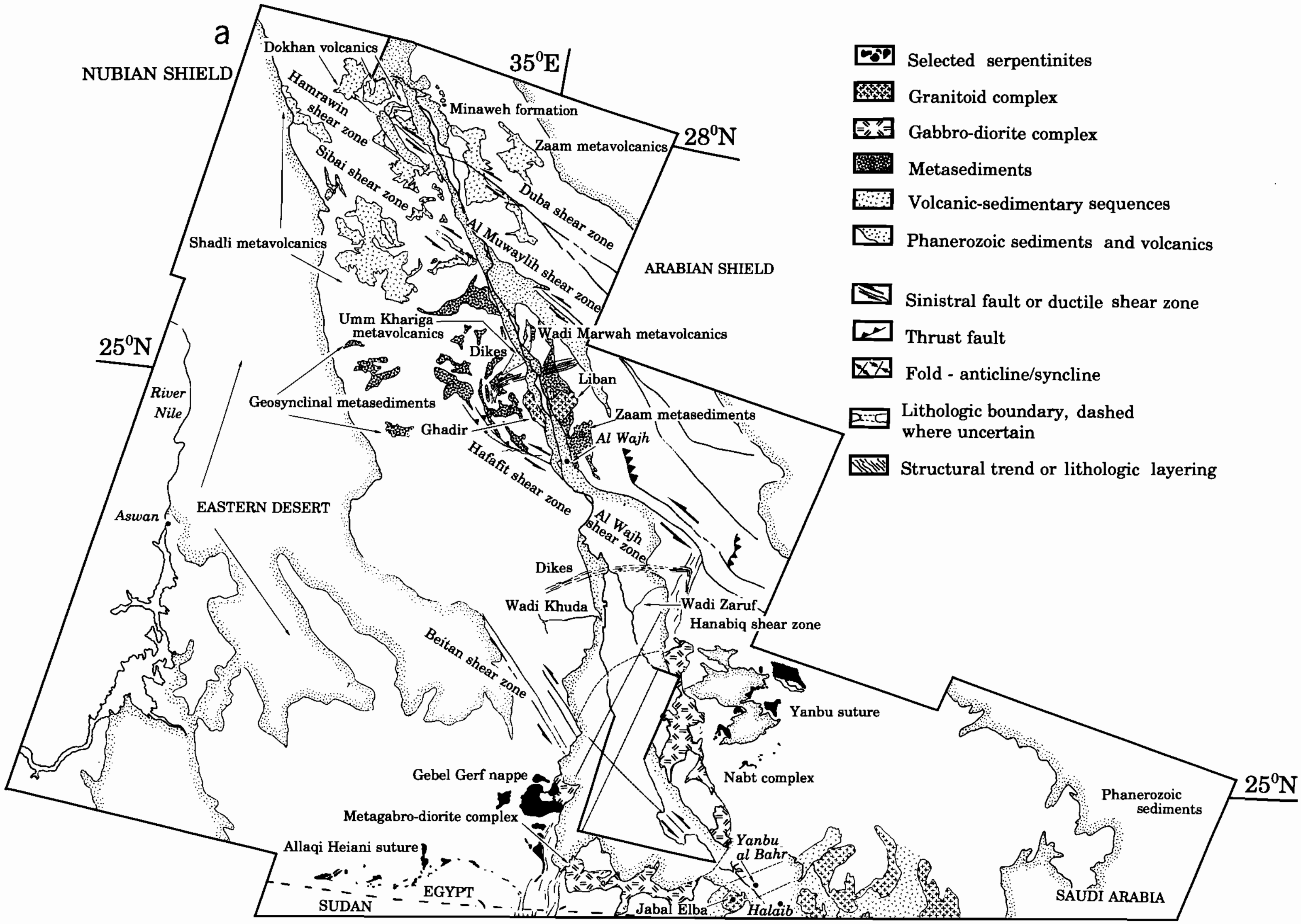

Fig. 3. (a) Interpretation map of Plate 1a. (b) Interpretation map of Plate 1b. Figure 3 shows the distribution of lithologic units and mobile belts in the Nubian Shield and their postulated extensions in the Arabian Shield.

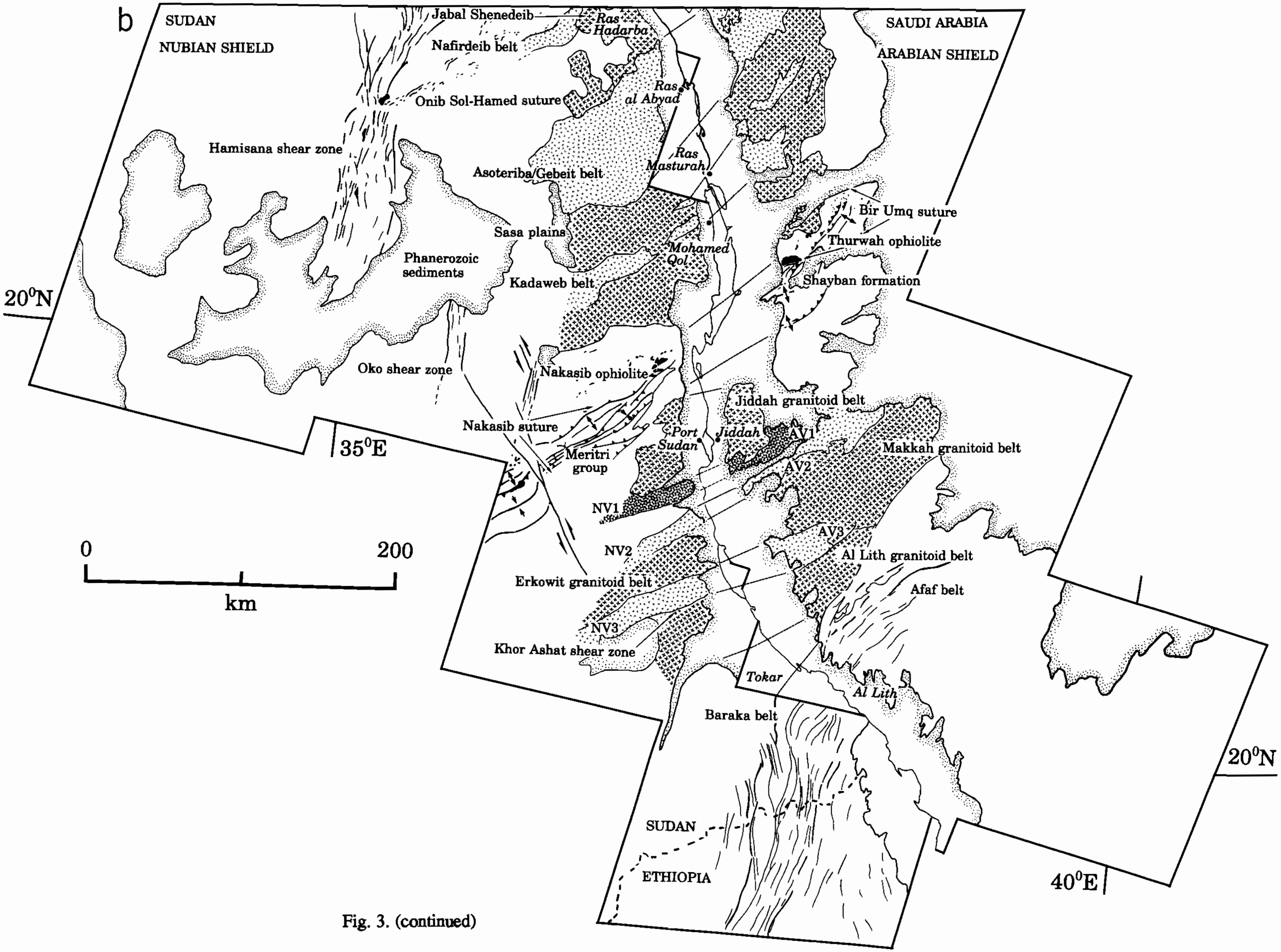

Fig. 3. (continued)

TABLE 1. Geologic Features That Are Correlated Between the Nubian and Arabian Shields

Nubian Shield Feature	Arabian Shield Correlative Feature
Najd faults/shear zones in the Hamrawin, Sibai, Hafafit, and Beitan areas	Najd faults in the vicinity of towns of Muwaylih, Duba, Al Wajh, and Umm Lajj
Dokhan volcanics near Gebel Nuqrah	Minaweh Formation at the vicinity of Al Khuraybah city
Shadli metavolcanics between latitudes 26°30' and 25°45' and at the mouth of Wadi Um Khariga	Metasediments of the Zaam group between latitudes 27°15' and 26°15'
Geosynclinal metasediments between latitudes 25°30' and 24°30'	Metasediments of the Zaam group between latitudes 27°15' and 26°15'
Wadi Ghadir complex	Liban complex
Dike swarms south of the Um Khariga metavolcanics and north of Wadi Khuda	Dike swarms south of Wadi Marwah volcanics and north of Wadi Zaruf
Metagabbro-diorite complex of the South Eastern Desert	Gabbro-diorite of the Nabt complex
Hamisana shear zone	Hanabiq shear zone
Gebel Gerf Nappe	Yanbu suture
NE to NNE trending volcano-sedimentary sequences to the south of the Onib-Sol Hamed suture and to the north of Nakasib suture and interleaving granitic terrains.	NE to NNE trending volcano-sedimentary sequences to the south of Yanbu suture and to the north of Bir Umq sutures and interleaving granitic terrains
Nakasib suture	Bir Umq suture
NE trending granitoid belts and intercalated volcano-sedimentary units to the south of the Nakasib and north of Baraka belt.	NE trending granitoid belts and intercalated volcano-sedimentary units to the south of the Bir Umq suture and north of Afaf belt
Baraka belt	Afaf belt

All geologic features are observable in Plate 1 and are plotted in Figure 3. See Appendix B for descriptions of features.

belts, Jiddah, Makkah, and Al Lith, as are the granitoid belts of the Haya terrane. The Arabian and Nubian magmatic belts align (Plate 1b, Figure 3b).

CONSTRAINTS ON RED SEA RIFTING PROCESSES

We find that wide-separation rifting models fail to align the Arabian and Nubian Neoproterozoic geologic features on a regional scale (Figure 2). For example, E-W to NW trending Hafafit and Sibai shear zones and the N-S trending Hamisana and Baraka belts do not align with their postulated extensions in the Arabian Shield: Al Wajh and Al Muwaylih shear zones and Hanabiq and Afaf belts, respectively (Figures 2e-2h). Because some geologic features strike northeast, the direction of Red Sea opening, they connect on almost all reconstructions without large deflections in their strikes. For example, NE trending volcano-sedimentary and magmatic belts south of the Nakasib suture connect with their Arabian counterparts on almost all reconstructions. Thus E-W, N-S, or NW trending geologic features are more critical in evaluating the validity of various Red Sea reconstructions.

Wide-separation models also predict large dimensions for rock units that are unrealistic. For example, we argue the Wadi Ghadir complex continues in Arabia as the Liban complex (Table 1, Appendix B). Assuming the complex is equant, as is the case with most of the granitoid complexes that are largely formed of massive units, coastal juxtaposition is required. Some granitoid complexes, however, are elongated. The largest in the area is the Hafafit culmination (average length of 40 km; average width of 15 km [El Ramly et al., 1984]). The restored Red Sea coasts will be less than 20 km apart if the Ghadir-Liban complex had the same aspect ratios as the Hafafit culmination. The Umm Khariga metavolcanics of the central Eastern Desert and its continuation in the Midyan region is another example. According to wide-separation models, the unit will strike for distances ranging from 100 up to 200 km in length (Figure 2). Because outcrop patterns in the central Eastern Desert and in the northern part of the Midyan region are characterized by fine-scale lithologic heterogeneity at the outcrop scale (Plate 1a) due to brittle deformation associated with Najd faulting [Sultan et al., 1988], it is unlikely that the metavolcanics could have extended over such large distances. Similar arguments could be made for many of the lithologic units listed in Table 1 and described in Appendix B (e.g., Dokhan volcanics, granitoid complexes). In general, coast-to-coast (e.g., our reconstruction and McKenzie et al. [1970]) or near-coast-to-coast [Le Picheon and Gaulier, 1988] reconstructions produce a better alignment of geologic features compared to the ones that advocate wide separations (Figure 2). Also, in the former models, rock units that extend between the shields maintain reasonable dimensions.

Reconstructions by McKenzie et al. [1970] and Le Pichon and Gaulier [1988] closely resemble ours. Their reconstructions, however, do not align geologic features as well. For example, the Liban complex juxtaposes at least in part the area to the north of the Ghadir complex on the reconstruction of McKenzie et al. [1970](Figure 2b). Similarly, many other geologic features on the Arabian side are displaced northward by approximately 30 km from their postulated extensions on the Nubian side (e.g., Wajh shear zone). Although this problem is not observed on the reconstruction by Le Pichon and Gaulier [1988], NW trending features do not align as well as they do on our reconstruction (e.g., Najd-related Hamrawin-Al Muwaylih, and Sibai-Duba shear zones; Figure 2c).

The separation between the restored Red Sea coasts should approximate the amount of continental crust that was extended and is currently underlying the Red Sea. The continental crust in question will be underestimated if thinning of crust under the coastal plains is not taken in account. Seismic refraction studies in the northeastern and southwestern Red Sea show that the unthinned continental crust is about 35 to 40 km thick and decreases to about 20 km under the coastline over a distance of 30 km [Bohannon, 1986; Gaulier et al., 1988]. The thinning is true of most of the Red Sea margin [Le Pichon and Gaulier, 1988] and could be accounted for by moving each of the coastlines by about 7 km toward the continent [Le Pichon and Gaulier, 1988; Sultan et al., 1992]. The correction, if applied, would have the effect of removing a 7-km-wide strip of each of the coastal plains and would remove most of the observed overlap on our reconstruction between the Red Sea coastal plains (Plate 1, Figure 3). Our reconstruction and seismic data indicate that prior to rifting the continental crust underlying the Red Sea was small (~35 km thick and 14 km wide). Less crust would be predicted if rift-related magmas in the coastal plains were volumetrically important.

The oceanic nature of the crust underlying the Red Sea predicted by our model favors models that advocate Red Sea opening being almost entirely accomplished by seafloor spreading and is inconsistent with models that predict broad extension of continental crust. Only if extension was confined to a narrow (~10-20 km) belt as suggested by Bohannon [1986], could there be small amounts of continental crust under the Red Sea rift as predicted by our model. In his model, Bohannon [1986] predicted an early phase of confined rifting associated with extensive rift-related plutonic activity followed by seafloor spreading.

Our preferred pole for the Red Sea opening differs from published poles that require the motion between Arabia and Nubia to be parallel to the Dead Sea transform (e.g., Figure 2f) and from others obtained by fitting coastlines (Figure 2b)(refer to Introduction), although the latter pole is closer. We believe our pole is more accurate because the total motion along the Dead Sea transform is actually oblique to the transform line and coastlines do not represent lines of actual rifting; matching coastlines will yield only an approximate pole [Joffe and Garfunkel, 1987]. The best estimates for the total motion along the Dead Sea come from detailed structural analysis of the transform. Joffe and Garfunkel [1987] located the Eulerian pole of total and young motions along the Dead Sea transform at 32.7°N, 19.8°E +/- 2°, and 32.8°N, 22.6°E +/-0.5°, respectively. We find that our pole for the Red Sea opening agrees with that of Joffe and Garfunkel [1987] for the total motion if the uncertainty they report on the location of the pole is considered. The correspondence between our pole and theirs suggests the motion between Arabia and Nubia was parallel to the total motion along the Dead Sea transform. Because our pole does not coincide with the young (Pliocene-Pleistocene) motion along the Dead Sea transform (pole: 32.8°N, 22.6°E +/-0.5° [Joffe and Garfunkel, 1987]) more than one phase of motion is required to account for the Red Sea opening.

Our reconstruction is at odds with models that determine the amount of divergence of the Arabian and Nubian plates (angular rotation) by adding an estimate of the extension in the Gulf of Suez to the well-documented 105 km of sinistral displacement along the Levant shear zone (e.g., Figures 2d-2f). These models leave a wide separation between the restored Red Sea coasts. The displacement along the Dead Sea transform is well constrained, whereas that along the Gulf of Suez is not. Earlier estimates [Freund, 1970; Girdler and Darracott, 1972; Cochran, 1981] ranged from 13 to 30 km. Using seismic refraction data from the Gulf of Suez, Le Pichon and Gaulier [1988] showed that the extension in the Gulf of Suez is greater by a factor of 1.5 to 2 times than was originally presumed by these reconstructions. Our results are consistent with the findings of Le Pichon and Gaulier [1988] and with their conclusion that the extension in the Gulf of Suez does not constrain the divergence of the Arabian and Nubian plates to the extent described by earlier models.

Models that suggest the Red Sea opened as a sinistral pull apart basin predict the Arabian and Nubian Shields did not act as rigid plates and that no single pole can describe Red Sea opening [Makris and Rihm, 1991]. Because we matched geologic features of the Arabian and Nubian Shields using a single pole, we see no need to divide the Red Sea and adjacent areas into subareas of different tectonic regimes. Thus we maintain that both shields acted as rigid plates during Red Sea opening. Earlier (640-580 Ma) sinistral displacements of up to 350 km along the Red Sea line [Shimron, 1990] are also unsupported by our reconstruction.

The suggestion that the Red Sea might have propagated along some of the old preexisting lithospheric structures [e.g., Dixon et al., 1987] is supported by our reconstruction. Commonly, we find that as the coastlines intersect large lithologic discontinuities they abruptly reorient and align with these structures. For example, the N-S trending Red Sea coastline to the south of Ras Hadarba (northern Sudan) abruptly reorients into a NW direction as it intersects the postulated extension of the NW trending Beitan, Najd-related, shear zone (Plate 1a, Figure 3a). Similarly, on the Arabian side, as the coastline intersects the Hanabiq shear zone, it reorients from a northwesterly to a N-S direction.

CONCLUSIONS AND IMPLICATIONS

1. Detailed correlations of Neoproterozoic geologic features along two thirds the length of the Red Sea margins were performed on a digital mosaic of 23 Landsat thematic mapper scenes. Geologic features correlated include Najd faults and shear zones, sutures, N-S trending mobile belts, and lithologic units (granitic complexes, volcano-sedimentary

sequences, dikes) that crop out along the length of the Red Sea margins in Egypt, Sudan, and Saudi Arabia. Field observations (Egypt and Sudan) were used to corroborate inferences from Landsat images. Results corroborate earlier findings that geologic features align when Arabia is rotated relative to Africa by 6.7° around a pole at 34.6°N, 18.1°E and that features misalign significantly when the location of the pole (latitude or longitude) is changed or when the amount of rotation is changed by more than 0.5° to 1.0° [Sultan et al., 1992].

2. Generally, coast-to-coast and, to a lesser extent, near-coast-to-coast reconstructions, align geologic features on a regional scale. This implies the amount of continental crust underlying the Red Sea is small. We estimate that prior to rifting, the continental crust underlying the Red Sea was about 35 km thick and 14 km wide.

3. The correspondence between our pole for the Red Sea opening and the pole for the total motion along the Dead Sea transform [Joffe and Garfunkel, 1987] is interpreted to indicate that the motion between Arabia and Nubia was parallel to the total motion along the Dead Sea transform. Because our pole does not coincide with the young (Pliocene-Pleistocene) motion along the Dead Sea transform, more than one phase of motion is required to account for the Red Sea opening.

4. Results are inconsistent with models that determine the amount of divergence of the Arabian and Nubian plates (angular rotation) by adding an estimate (13 to 30 km) of the extension in the Gulf of Suez to the well-documented 105 km of sinistral displacement along the Levant shear zone. Because the displacement along the Dead Sea transform is well constrained, we speculate that the extension in the Gulf of Suez is greater than was originally presumed and that it does not constrain the divergence of the Arabian and Nubian plates to the extent described by earlier models.

5. As far as the correlation of geologic features is concerned, the rotation of the Arabian Shield could be described by a single Eulerian pole. This result is inconsistent with models that suggest the Red Sea opened as a sinistral pull apart basin and predict the Arabian and Nubian Shields did not act as rigid plates [Makris and Rihm, 1991]. Earlier (640-580 Ma) sinistral displacements of up to 350 km along the Red Sea line [Shimron, 1990] are also unsupported by our reconstruction.

6. The Red Sea rift might have propagated along some of the old preexisting lithospheric structures. Often we find that as the coastlines intersect large lithologic discontinuities, they abruptly reorient and align with these structures.

APPENDIX A: PROCEDURES USED TO DETERMINE THE POLE AND AMOUNT OF ROTATION

The position (latitude and longitude) of a "best fit" Euler pole and the amount of rotation about this pole were found by using location pairs. Each pair consisted of the locations of two points on a geologic feature, one on each side of the Red Sea (Figure A1), which are thought to have been coincident before rotation. It was also assumed that deformation can be represented as a single rotational event. The latitude-longitude pairs were transformed to a geocentric cartesian coordinate system, resulting in two vectors for each pair i (i=1 to N), $\underline{p}^a_i$ (the location of the feature on one side of the Red Sea) and $\underline{p}^b_i$ (the vector representing the feature on the other side of the Red Sea). The vector $\underline{n}_i$, normal to the plane $\underline{p}^a_i$ - $\underline{p}^b_i$, and vector $\underline{b}_i$, which lies in this plane and bisects $\underline{p}^a_i$ and $\underline{p}^b_i$ were found (Figure A1a). Thus for each data pair i, a right bisector plane ($\underline{n}_i$ - $\underline{b}_i$) was defined (Figure A1a). The normal to this plane, $\underline{r}_i$, was then found. Data pairs were taken two at a time. The line of intersection between two such right bisector planes (plane i and plane n), using the associated normals $\underline{r}_i$ and $\underline{r}_n$, is an axis of rotation such that a single small-circle rotation maps $\underline{p}^a_i$ to $\underline{p}^b_i$ and $\underline{p}^a_n$ and $\underline{p}^b_n$. This intersection is an estimate of the required rotation pole. All possible combinations of data pairs were used to find N!/(2*(N-2)!) estimates of this pole. The vector mean ($\underline{e}$) of these estimates was then computed [Mardia, 1972] and the average Euler pole was then used to determine the amount of rotation. Two planes were defined for each data pair, ($\underline{e}$ - $\underline{p}^a_i$) and ($\underline{e}$ - $\underline{p}^b_i$), each plane containing the average Euler pole ($\underline{e}$) and one location. The angle between the normals to these planes is the amount of rotation about the average pole necessary to map $\underline{p}^a_i$ to $\underline{p}^b_i$. This angle was calculated for all data pairs, and a Gaussian average is reported.

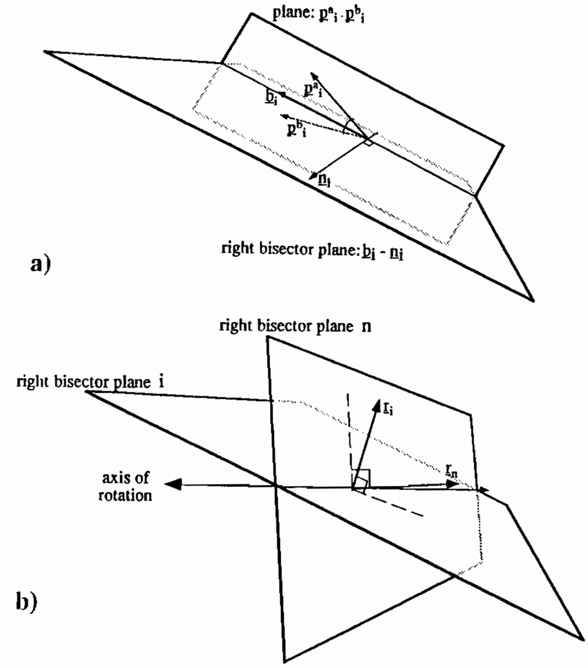

Fig. A1 (a) For each location pair $\underline{p}^a_i$, $\underline{p}^b_i$ a plane with normal $\underline{n}_i$ is defined. The vector $\underline{b}_i$ is defined to lie within this plane and to bisect $\underline{p}^a_i$ and $\underline{p}^b_i$. The plane defined by $\underline{n}_i$ and $\underline{b}_i$ is the right bisector plane. (b) The intersection of two right bisector planes is a single estimate of the required rotation axis. Location pairs are taken two at a time to find N!/(2*(N-2)!) such estimates.

APPENDIX B: DESCRIPTION OF GEOLOGIC FEATURES THAT ARE CORRELATED BETWEEN THE NUBIAN AND ARABIAN SHIELDS

Nubian Shield—Najd faults/shear zones in the Hamrawin, Sibai, Hafafit, and Beitan areas. Four major sinistral faults/shear zones intersect the coastal plains at Hamrawin, Sibai, Hafafit, and Beitan [Abuzied, 1984; Bennett and Mosley, 1987, Sultan et al., 1988]. NW trending sinistral faults and shear zones, subvertical foliations, subhorizontal stretching mineral lineations, tight folds, depositional environments, and igneous activity characteristic of the Najd were documented in these four areas, [Abdel Khalek, 1979; Abuzied, 1984; Stern, 1985; Bennett and Mosley, 1987; El-Gaby et al., 1988; Sultan et al., 1988; E.A. O'Connor, personal communication, 1990]. Najd features were first reported from, and probably best documented in the Hamrawin area [Abuzied, 1984; Greene, 1984]. In the Sibai and Hafafit areas, Najd-related thrusting in a duplex setting was proposed to explain the relationship between the penetrative fabrics of the steeply dipping, sinistral, NW trending ductile shear zones and the flat-lying ramps [Bennett and Mosley, 1987]. El-Gaby et al. [1988] mapped a prominent NW-trending sinistral fault/shear zone in the Beitan area, and Kröner et al. [1987] showed its apparent extension in northern Sudan.

Arabian Shield—Najd faults in the vicinity of towns of Muwaylih, Duba, Al Wajh, and Umm Lajj. The main trends of the Najd Shear System enter the eastern coastal margin of the Red Sea between latitudes 26° and 27°45', where three major NW-SE to E-W trending faults/shear zones [Brown, 1970; Johnson, 1983] were identified as part of the Najd Shear System [Smith, 1979; Davies, 1984, 1985; Davies and Grainger, 1985]. From north to south, these strands intersect the Red Sea margin at latitudes 27°45' (north of Al Muwaylih), 27°20' (around Duba city), and 26°5' (south of Al Wajh). According to our reconstruction, these strands project into the Hamrawin, Sibai, and Hafafit areas, respectively, in the central Eastern Desert (Figure 3a, Plate 1a). Farther south in Arabia, a minor strand subparallel to the Red Sea margin is found northwest of Yanbu al Bahr [Moore, 1979; Pellaton, 1979, 1982a]. According to our reconstruction, this strand aligns with the western Red Sea margin between latitudes 22° and 22°30' (northern Sudan) and projects into the Beitan area in the southern part of the Eastern Desert of Egypt. The Hamrawin-Al Muwaylih, Sibai-Duba, Hafafit-Al Wajh, and Beitan-Yanbu al Bahr shear zones are numbered 1, 2, 6, and 8, respectively, in Figure 2.

Nubian Shield—Dokhan volcanics near Gebel Nuqrah. The Dokhan volcanics are a thick sequence of lava flows with minor pyroclastics. The volcanics are predominantly porphyritic in texture and andesitic to rhyodacitic in composition [El Ramly and Hermina, 1978a; Basta et al., 1979; Stern and Gottfried, 1986]. The flows are intruded by bimodal dike swarms. The volcanics are among the youngest (581-609 Ma) [Stern and Hedge, 1985] dated units in the Eastern Desert basement. Stern and Gottfried [1986] argued on the basis of field, chemical, and geochronologic data that the felsic extrusives are the volcanic equivalent of the 580-595 Ma, posttectonic, Younger granite plutons.

Arabian Shield—Minaweh Formation at the vicinity of Al Khuraybah city. The Dokhan volcanics juxtapose a compositionally [Davies and Grainger, 1985; Clark, 1987] and spectrally (Figure 3a, Plate 1a) similar sequence of andesitic and dacitic flows intercalated with pyroclastic rocks of the Minawah formation. As with the Dokhan volcanics, the flows are commonly intruded by felsic and mafic dykes and rhyolite sills. They are the youngest rock units in the area, and they are the extrusive phase of the posttectonic Tiryam granitic suite [Davies and Grainger, 1985].

Nubian Shield—Shadli metavolcanics between latitudes 26°30' and 25°45' and at the mouth of Wadi Um Khariga. The Shadli volcanics are low grade (greenschist or lower) units cropping out between latitudes 26°30' and 25°45' [El Ramly and Hermina, 1978a, 1978b]. They are lithologically heterogeneous units described as fissure eruptions of subaerial or submarine rhyolite, dacite, andesite, basalt, and pyroclastic lavas [El Ramly and Hermina, 1978a; 1978b]. Pillowed and vesicular andesites and basalts make up most of the volcanic pile, whereas more felsic varieties are subordinate [Hashad, 1979]. The Shadli metavolcanics are among the oldest units in the Eastern Desert [Ries et al., 1983]. Because many of these units have abundant Fe-bearing aluminosilicates, they appear bluish in color on the TM composite. To the north of the Wadi Ghadir complex, a NE-SW trending metavolcanic unit assigned to the Shadli metavolcanics [El Ramly and Hermina, 1978b] crops out at the mouth of Wadi Um Khariga, 20 km to the north of the Ghadir complex . The unit is flanked to the south by metasediments (metagreywackes, tuff sandstone, tuff schists, conglomerates, interbeds of felsic tuffs and siliceous schists). There are no other major outcrops of basalts/andesites cropping out along the Red Sea margin in the vicinity of the Um Khariga metavolcanics.

Arabian Shield—Metavolcanics of the Zaam Group between latitudes 27°15' and 28° and at the mouth of Wadi Marwah. In our reconstruction, the area dominated by the Shadli metavolcanics is continous with a region (latitudes 27°15' to 28°) formed of low grade metavolcanic, metavolcaniclastic, and metasedimentary rocks assigned to the Ghawjah formation of the Zaam group. This unit is composed of massive porphyritic andesite flows and subsidary basalt, vesicular andesite, and andesitic breccia and agglomerate, interbedded with porphyritic dacite and felsic tuffs [Davies and Grainger, 1985]. The Zaam group is the oldest of the exposed stratiform rocks in the area (Al Muwaylih quadrangle) [Davies and Grainger, 1985]. The Um Khariga metavolcanics align along strike with a NE-SW to N-S trending, spectrally and compositionally similar unit at the mouth of Wadi Marwah (Figure 2, feature 3; Figure 3a; Plate 1a). The unit is composed of andesite and basalt with intercalated siltstone, grading upward into andesitic tuff and shale [Davies, 1985]. The unit displays spatial relationships similar to those of the Um Khariga metavolcanics: (1) it is bounded on the east by metasediments composed mainly of litharenite and siltstone that are assigned to the Hawawit formation of the Zaam group [Davies, 1985] and (2) there are no other major outcrops of basalts/andesites in the vicinity along the Red Sea margin [Davies, 1985].

Nubian Shield—Geosynclinal metasediments between latitudes 25°30' and 24°30' In addition to the Shadli metavolcanics, geosynclinal metasediments are important in the area between latitudes 25°30' and 24°30' [El Ramly and Hermina, 1978b]. They exhibit a wide range of lithological types, including biotite and chlorite schists metagreywacke, metamudstone, phyllite, slate, and occasional conglomerate, carbonate, and graphite [Sabet et al., 1973; El Ramly and Hermina, 1978b]. The geosynclinal metasediments and metavolcanics are believed to be components of an extensive ophiolitic melange, the oldest unit exposed in the Eastern Desert [Ries et al., 1983].

Arabian Shield—Metasediments of the Zaam group between latitudes 27°15' and 26°15'. Our reconstruction juxtaposes the geosynclinal metasediments with a domain largely formed of metasediments of the Zaam group (latitude 27°15' to latitude 26°15')(Figure 3a, Plate 1a). In this area, metasediments within the Zaam group become important [Davies, 1985]. In order of decreasing volumes these sediments are: (1) the Kibrah formation (laminated graphitic shale, basalt, andesite, rhyodacite, and limestone), (2) Umm Ashsh formation (litharenite and siltstone), and (3) Hawawit formation (litharenite and siltstone containing partly recrystallized limestone [Davies, 1985]. The Zaam group is the oldest rock unit in the area (Al Wajh quadrangle) [Davies, 1985].

Nubian Shield—Wadi Ghadir complex. Three major intrusive phases were identified in the Ghadir complex in the central Eastern Desert of Egypt: an early dioritic marginal phase, cropping out southwest of the complex; an extensive monzogranitic to granodioritic phase that occupies most of the southern and central [El Maghraby, 1987] Ghadir complex; and a late pink, alkali-feldspar granite in the north. The granodioritic body has numerous partially assimilated xenoliths of different composition and sizes, whereas the late pink granite is devoid of xenoliths. The granite intrudes the two earlier phases and the country rocks [El Maghraby, 1987].

Arabian Shield—Liban complex. The Liban complex juxtaposes the Ghadir complex (Figure 2, feature 5; Figure 3; Plate 1a). It is similar to the Ghadir complex in the relative ages, spatial distribution, and mode of emplacement of the plutonic phases. An early dioritic to quartz dioritic phase forms marginal isolated bodies along the northeastern margin of the pluton [Davies, 1985]. An extensive monzogranitic to granodioritic intrusion occupies the central part of the complex. The intrusion contains abundant xenoliths of the country rocks that are themselves veined by the early diorites and quartz diorites [Davies, 1985]. A late, xenolith-free, pink, coarse-grained syenogranite to alkali-feldspar granite occupies the northern part of the complex and intrudes the country rocks and the earlier granitic phases [Davies, 1985].

Nubian Shield—Dike swarms south of the Um Khariga metavolcanics and north of Wadi Khuda. South of the Um Khariga metavolcanics, the country rocks are pervasively intruded by NE-SW trending dikes. The swarm is 10 km wide; the dikes are mostly felsic to intermediate in composition and porphyritic in texture [Sabet et al., 1973]. Dikes strike N-S as they approach NW-SE trending Najd faults and/or shear zones to the south (proximity of Hafafit and Ghadir areas) and finally align with the faults [Sabet et al., 1973]. The change in orientation of dikes is consistent with a sinistral displacement. Southward, another NE-SW trending dike swarm is found north of Wadi Khuda. The swarm is approximately 25 km long and 5 km wide.

Arabian Shield—Dike swarms south of Wadi Marwah volcanics and north of Wadi Zaruf. Our reconstruction aligns the dikes to the south of Um Khariga with a 13-km-wide, NE trending dike swarm (Figure 2, feature 4; Figure 3a; Plate 1a). The swarm is mostly porphyritic in texture and granitic to andesitic in composition. Margin irregularities and dike offsets indicate sinistral displacements across the margins of many dikes [Davies, 1985]. The dikes cropping out to the north of Wadi Khuda juxtapose an E-W to an E-NE trending dike swarm (Figure 2, feature 7). The swarm is 8 km wide and is truncated to the east by a N-S trending shear zone [Pellaton, 1982b; Duncan et al., 1990]. Individual dikes may extend for up to 17 km [Pellaton, 1982b].

Nubian Shield—Metagabbro-diorite complex of the South Eastern Desert. Arc-related, disconnected gabbroic and dioritic bodies that grade into tonalitic and trondjhemitic compositions are widespread in the South Eastern Desert [El Ramly, 1972; Hashad, 1979]. The intrusives are mapped as the metagabbro-diorite complex on the Egyptian geological survey maps [e.g., El Ramly, 1972]. Single-grain evaporation dating of three grains from a gabbro yielded an average $^{207}Pb/^{206}Pb$ age of 729+/-17 Ma, and a single grain from a diorite from the same area yielded an average $^{207}Pb/^{206}Pb$ age of 736 +/-11 Ma [Kröner et al., 1992].

Arabian Shield—Gabbro-diorite of the Nabt complex. The Egyptian gabbroic to dioritic bodies align with a discontinuous series of intrusives of similar composition and approximate ages that are largely assigned to the Nabt complex of the Umm Lajj, Jabal al Buwanah, and Yanbu al Bahr quadrangles [Pellaton, 1979, 1982a, 1982b] (Figure 3a, Plate 1a). The complex is heterogeneous with gradations from gabbro, through quartz diorite to tonalite and trondhjemite. Similar trondhjemites from the neighboring Wadi al Ays quadrangle were dated at 796 +/- 23 Ma by U-Pb (zircon) [Kemp et al., 1980; Pellaton, 1982b].

Nubian Shield—Hamisana shear zone. The N-S trending Hamisana shear zone crops out in central and northern Sudan and extends for 300 km (length) and 50 km (width) before it is covered by Red Sea coastal plain deposits. On the basis of structural studies of the northern Hamisana shear zone, Stern et al. [1990] concluded that the principal ductile deformation resulted from early coaxial folding about a N-S axis that produced tight, upright to inclined folds, and a N-S trending cleavage on a regional scale. They also documented dextral displacement of the pervasive N-S fabric along coaxial north to northeast shear zones.

Arabian Shield—Hanabiq shear zone. According to our reconstruction, a N-S trending feature, approximately 50 km in length and 20-30 km in width, lies along the projection of the Hamisana shear zone in Arabia (Figure 2, feature 10; Figure 3a; Plate 1a). The fabric is controlled by N-S trending, upright to steeply dipping (60°-80°) folds [Pellaton, 1982b]. A dextral displacement was inferred from the change in orientation of dikes [Duncan et al., 1990] and foliations [Pellaton, 1982b] as they approach the shear zone.

Nubian Shield—Gebel Gerf Nappe. The largest outcrop of ophiolitic rocks in the Eastern Desert is found in the vicinity of Gebel Gerf [El Ramly, 1972]. Kröner et al. [1987] proposed that this is a huge ophiolitic nappe complex that was thrust over low-grade immature metasediments to the north and west and medium to high grade metasediments to the south. This nappe complex contains all diagnostic components of an ophiolite, including pillowed basalts, sheeted dykes, layered and isotropic gabbro, and serpentinized ultramafics [Stern et al., 1990]. Kröner et al. [1992] reported a $^{207}Pb/^{206}Pb$ age of about 740 Ma for four zircons from the ophiolitic gabbro. The nappe is bounded to the north and west by abundant granodiorites dated at 690-710 Ma [Stern et al., 1989]. Thus the emplacement of the Gerf nappe is bracketed between 740 and 710 Ma.

Arabian Shield—Yanbu suture. Our reconstruction shows that the NE trending serpentinite outcrops defining the Yanbu suture juxtapose against the Gebel Gerf ophiolite (Figure 2, feature 9; Figure 3a; Plate 1a). The Yanbu suture is defined by linear belts of dismembered ophiolitic sequences [Bakor et al., 1976; Shanti and Roobol, 1979] and comprise the largest ophiolite occurrences in the Arabian Shield (Jabal al Wask, ~1000 km^2) and the most complete ophiolitic sections in Jabal Ess [Shanti and Roobol, 1979]. Two zircon fractions from Jabal al Wask plagiogranite yield a 740+/-11 Ma [Pallister et al., 1988] model age. This age is significantly younger than the Onib ophiolitic plagiogranite ($^{207}Pb/^{206}Pb$ age of about 810 Ma [Kröner et al., 1992]). Thus the ophiolitic sequences from the Yanbu suture and Gebel Gerf area are young compared to the Onib-Sol Hamed ophiolites, consistent with our Red Sea reconstruction. Because the Hijaz arc magmatism (terrane to the south of the suture) ceased by ~715 Ma [Camp, 1984], emplacement time is bracketed between 740 Ma and 715 Ma. Jabal al Wask ophiolites were probably emplaced around the same time as Gerf nappe.

Nubian Shield—NE to NNE trending volcano-sedimentary sequences to the south of the Onib-Sol Hamed suture and to the north of Nakasib suture and interleaving granitic terrains. Three volcano-sedimentary sequences crop out to the south of and are subparallel to the Onib-Sol Hamed suture and extend for over 100 km in a NE to NNE direction. From north to south, these are the Nafirdeib, Asoteriba and Gebeit volcanics, and Kadaweb volcanics, respectively. The Nafirdeib volcanics extend between Jabals Shenedeib and Elba and project along strike under the coastal plain intersecting the Red Sea shore between Halaib and Abu Ramad (cities within areas of overlap between Red Sea coastal plains on our reconstruction, Plate 2b). The sequence consists of alternating foliated and in part, tightly folded basaltic, andesitic, and dacitic tuffs and lavas, calcareous shales, impure limestones and dolomites, polymict conglomerates, greywackes and quartzites [Fitches et al., 1983; Hussein et al., 1984]. The volcanoclastic series is dated at 712+/-58 Ma [Fitches et al., 1983]. The Asoteriba/Gebeit, and Kadaweb volcano-sedimentary belts are composed mainly of andesite basalt, dacite, and tuff [Hussein, 1985]. The Gebeit and Asoteriba volcano-sedimentary belt extends from the Sasa plain in central Sudan to the south of Ras Hadarba along the Red Sea coastal plain. The Asoteriba group was erupted at 670 +/- 5 Ma [Stern and Kröner, 1993]. The Gebeit volcanics are about 830-872 Ma [Reischmann et al., 1985; Stern and Kröner, 1993]. The Kadaweb belt extends from Jabal Awat and projects to Mohamed Qol area along the Red Sea coastline. Klemenic [1985] reported Rb-Sr isochron ages of 723+/-6 Ma for the Kadaweb calcalkaline volcanics from the Wadi Oko area. The domains between the three volcano-sedimentary terranes are dominated by undifferentiated tonalite, granodiorite, and granite with minor gabbro and diorite [Hussein, 1985].

Arabian Shield—NE to NNE trending volcano-sedimentary sequences to the south of Yanbu suture and to the north of Bir Umq sutures and interleaving granitic terrains. According to our reconstruction, the Nafirdeib volcano-sedimentary succession juxtaposes compositionally similar successions of the Siqam Formation (basalts, andesites, and subordinate tuff) and well bedded sandstone and conglomerate of the Tura'ah formation (Figure 2; feature 11; Figure 3b; Plate 1b). Both formations belong to the Hadiyah group [Pellaton, 1979]. As is the case with the Nafirdeib volcanics, the formations are tightly folded. A major NE trending syncline strikes N30°E and projects along strike under Phanerozoic cover to intersect the Red Sea at Yanbu al Bahr. The Hadiyah group is also similar in age to the Nafirdeib (700-750 Ma [Calvez et al., 1984]). According to our reconstruction, the Asoteriba/Gebeit and Kadaweb volcano-sedimentary belts juxtapose two compositionally similar units that are assigned to the Hamra group [Clark, 1981] (Figure 2, features 12 and 13). The northern unit projects under the Red Sea coastal plain to the north of Ra's Al Abyad, the southern unit to the south of Ra's Mastourah. The Hamra group is composed predominantly of andesite, andesitic tuff, rhyolite, silicic tuff and breccia, and epiclastic volcanic rocks [Clark, 1981]. The age of the Hamra group is not well constrained and could be as old as the Hulayfah group (725-800 Ma) or as young as the Halaban group (650-700 Ma) [Calvez, 1984; Clark, 1981]. The areas between the Arabian volcano-sedimentary belts, like the Nubian belts, are dominated by granites, monzogranite and syenogranite, granodiorite, tonalite, and trondhjemite; diorite, diabase, and gabbro are less common [Stoeser et al., 1985].

Nubian Shield—Nakasib suture. The Nakasib suture has been the subject of recent investigations [Abdelsalam and Stern, 1993] from which we report our description. The Nakasib suture is a NE trending ophiolite-decorated belt of volcanic and sedimentary units metamorphosed to greenschist facies. It separates 870-840 m.y. old Haya terrane in the south from the 830-720 m.y. old Gebeit terrane to the north. Abdelsalam and Stern [1993] mapped five lithologic units within the suture, two of which could be readily traced from TM data into the Arabian Shield because of their lateral extent, large thickness, and characteristic spectral reflectance. These are the Nakasib ophiolite and the Meritri group. The Nakasib ophiolite appears as discontinuous fragments of mafic and ultramafic rocks that show most of the characteristics of ophiolites. The Meritri group is made of conglomerate, greywacke, limestone, sandstone, felsic tuff, and felsic volcanics with an apparent thickness of 4 km. Thrusts, most of which dip to the northwest, separate the main lithologic units including the Nakasib ophiolites and Meritri group. The large apparent thickness of the Meritri and the large areal extent of the Nakasib is related in part to folding along NE trending folds. Folding modified earlier thrust planes and nappes.

Arabian Shield—Bir Umq suture. Our reconstruction juxtaposes the Nakasib suture and the NE trending Bir Umq suture (Figure 2, feature 14; Figure 3b; Plate 1b), confirming earlier suggestions [e.g., Stoeser and Camp, 1985; Kröner et al., 1987] for their lateral continuity from the Nubian into the Arabian Shield. It separates the Hijaz terrane (700-800 Ma) from the Asir arc terrane largely formed of 800-900 m.y. old rocks [Stoeser and Camp, 1985]. The Bir Umq suture, like the Nakasib, is formed of magmatic and epiclastic rocks and dismembered ophiolitic complexes, all metamorphosed to greenschist facies [Nassief et al., 1984; Stoeser and Camp, 1985]. The Nakasib ophiolite juxtaposes the Jabal Thurwah ophiolites (Figure 3b, Plate 1b). All major rock units identified in the 1972 GSA Penrose Conference on ophiolites were described from Jabal Thurwah [Nassief et al., 1984]. The Meritri group juxtaposes the Shayban formation of the Samaran group (Figure 3b, Plate 1b). The Shayban consists of a 4-km-thick sequence of quartzofeldspathic and lithic volcaniclastic and epiclastic rocks with subordinate mafic rocks, felsic lava, and pyroclastic rocks [Ramsey, 1986]. NW dipping low-angle thrusts, imbricate thrusts, recumbent folds, folded nappes, and NE trending tight megafolds (Figure 3b, Plate 1b) [Nebert, 1969; Ramsay, 1986] are common, consistent with findings in the Nakasib area.

Nubian Shield—NE trending granitoid belts and intercalated volcano-sedimentary rock units to the south of the Nakasib suture and to the north of Baraka belt. To the south of the Nakasib suture, the basement complex is dominated by granitoids that crop out along three major belts. The northernmost belt lies just south of Nakasib, whereas the southernmost is bound to the north by the Khor Ashat shear zone. The middle one encompasses the Erkowit pluton and is hereafter referred to as the Erkoit magmatic belt. The magmatic belts consist of tonalitic, trondjhemitic, dioritic, granodioritic, and gabbroic compositions [Hussein, 1985; Kröner et al., 1991]. Geochronologic data are limited; however, the reported dates are among the oldest for plutonic rocks in the Nubian Shield. The Erkoit pluton is dated at 815+/-25 Ma using Rb/Sr systematics [Klemenic and Poole, 1988] and 852+/-30 Ma using U-Pb (zircon) method [Kröner et al., 1991]. Zircons from a weakly foliated granodiorite to tonalite from the Dahand pluton to the northeast of Erkoit yielded a mean $^{207}Pb/^{206}Pb$ age of 870+/-5 Ma using single-zircon evaporation technique [Kröner et al., 1991]. The three granitoid belts are separated by NE trending volcano-sedimentary units, informally lettered NV1, NV2, and NV3 (Figure 3b, Plate 1b). NV1 and NV2 are mapped as a sequence of metamorphosed mafic to intermediate volcanics intercalated with greywacke, sandstone, conglomerate, limestone, and quartzite (Reischmann, 1986). On the TM mosaic, the spectral signatures of these two units are consistent with clastics to the north (NV1) and mafic to intermediate volcanics (NV2) to the south. NV3 is mapped as a volcano-sedimentary sequence of mafic to felsic volcanics, tuffaceous rocks, and clastic sediments [Kröner et al., 1991].

Arabian Shield—NE trending granitoid belts and intercalated volcano-sedimentary units to the south of the Bir Umq suture and north of the Afaf belt. Granitoid belts are widely distributed to the south of the Bir Umq suture [Stoeser et al., 1985]. Our reconstruction shows that the Nubian granitoid belts juxtapose three northernmost magmatic belts of Asir terrane, namely, the Jiddah, Makkah, and Al Lith belts of Stoeser [1986] (Figure 3b, Plate 1b). These belts are largely composed of diorite, gabbro, quartz diorite, tonalite, trondhjemite, granodiorite, and granite [Stoeser et al., 1985]. As with the Nubian belts, the Arabian granitoid belts comprise some of the oldest dated intrusives. Granitoids from the Jiddah belt are 770-820 Ma, and others from the Al Lith are older than 800 Ma [Fleck et al., 1980, 1982; Kröner et al., 1984; Stoeser, 1986]. Among the granitoids are quartz diorites from the Al Lith magmatic belt dated at 853+/-72 Ma using Rb/Sr systematics [Fleck et al., 1980]. The Nubian volcanic belts interleaving with the Nubian granitoid belts juxtapose spectrally and compositionally similar rock units. NV1 aligns with an epiclastic unit [Johnson, 1983], NV2 with an amphibolite, and NV3 with an undifferentiated volcanic unit [Johnson, 1983]. The postulated extensions of the Nubian volcanics into Arabia are mapped as AV1, AV2, and AV3, respectively, in Figure 3b and are features 15, 16, and 17, respectively, in Figure 2. The nature of lithologic contacts is also similar. For example, a NE trending fault separates AV3 from granitoids to the south [Johnson, 1983]. The fault contact lies along the postulated extension of the Khor Ashat shear zone [Kröner et al., 1991] that separates similar lithologies on the Nubian side.

Nubian Shield—Baraka belt. Little is known about the N-S to NNE trending mobile belt in southern Red Sea Hills and in NW Eritrea. V. Kazmin (cited by Mohr [1979]) hypothesized that it might be a suture, on the basis of isolated serpentinite occurrences, and Kröner et al. [1987] speculated that it might continue in Arabia as the Afaf belt (suture?). The terrane is mountainous and consists of volcano-sedimentary successions intruded by foliated, syntectonic granitoids and massive coarse-grained K-feldspar rich granites. Volcanics are bimodal; metabasalt and mafic tuff is intercalated with massive to sheared rhyolite, felsic tuff, and pyroclastics. Deformation across the belt is highly variable; within highly strained areas, tight to isoclinal folds and faults are common [Kröner et al., 1991].

Arabian Shield—Afaf belt. Our reconstruction shows that the Baraka belt juxtaposes the Afaf belt (Figure 2, feature 18; Figure 3b; Plate 1b). The latter marks the boundary between relatively younger (700-800 Ma) terrane to the north and an older (800-900 Ma) terrane to the south within the Asir composite arc terrane [Stoeser and Camp, 1985]. The Afaf is similar to Baraka in gross lithological characteristics and deformation patterns. Volcano-sedimentary successions predominate and are intruded by pretectonic to syntectonic foliated granitoids and post-tectonic coarse-grained, unfoliated, red to pink K-feldspar-rich granites [Prinz, 1983; Kröner et al., 1991]. The volcanics from Al Lith area (northern Afaf) are bimodal (basalts and dacites/rhyolites) and are remarkably similar to the Tokar rhyolites (northern Baraka) in age (Al Lith: 847+/-34 Ma; Tokar: 840-855 Ma) and geochemical affinity [Kröner et al., 1984, 1991; Reischmann et al., 1984]. As with Baraka, the Afaf belt is strongly deformed, with north to northeast trending faults and tight isoclinal folds being the dominant structures [Prinz, 1983; Johnson and Vranas, 1984].

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