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TECTONIC CONFIGURATION OF THE WESTERN ARABIAN CONTINENTAL MARGIN, SOUTHERN RED SEA

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Abstract. The young continental margin of the western Arabian Peninsula is uplifted 3.5 to 4 km and is well exposed. Rift-related extensional deformation is confined to a zone 150 km wide inland of the present coastline at 17 to 18° N and its intensity increases gradually from east to west. Extension is negligible near the crest of the Arabian escarpment, but it reaches a value of 8 to 10% in the western Asir, a highly dissected mountainous region west of the escarpment. There is an abrupt increase in extensional deformation in the foothills and pediment west of the Asir (about 40 km inland of the shoreline) where rocks in the upper plate of a system of low-angle normal faults with west dips are extended by 60 to 110%. The faults were active 23 to 29 Ma ago and the uplift occurred after 25 Ma ago. Tertiary mafic dike swarms and plutons of gabbro and granophyre 20 to 23 Ma old are concentrated in the foothills and pediment as well. The chemistry of the dikes suggests (1) fractionation at 10 to 20 kbar, (2) a rapid rise through the upper mantle and lower crust, and (3) differentiation and cooling at 1 Atm to 5 kbar. Structural relations between dikes, faults and dipping beds indicate that the mechanical extension and intrusional expansion were partly coeval, but that most of the extension preceded the expansion. A tectonic reconstruction of pre-Red Sea Afro/Arabia suggests that the early rift was narrow with intense extension confined to an axial belt 20 to 40 km wide. Steep Moho slopes probably developed during rift formation as indicated by published gravity data, two published seismic interpretations and the surface geology.

INTRODUCTION

The Red Sea and Gulf of Aden are young ocean basins formed in response to divergence of the African, Arabian, and Somalian continental plates. This system began to spread in the Oligocene and continues to evolve today. The western and southern continental margins of the Arabian plate, the eastern margin of the Nubian plate, and the northern margin of the Somalian plate are among the youngest rifted continental margins available for study in the world. These margins are also well exposed due to the great uplifts that flank both ocean basins.

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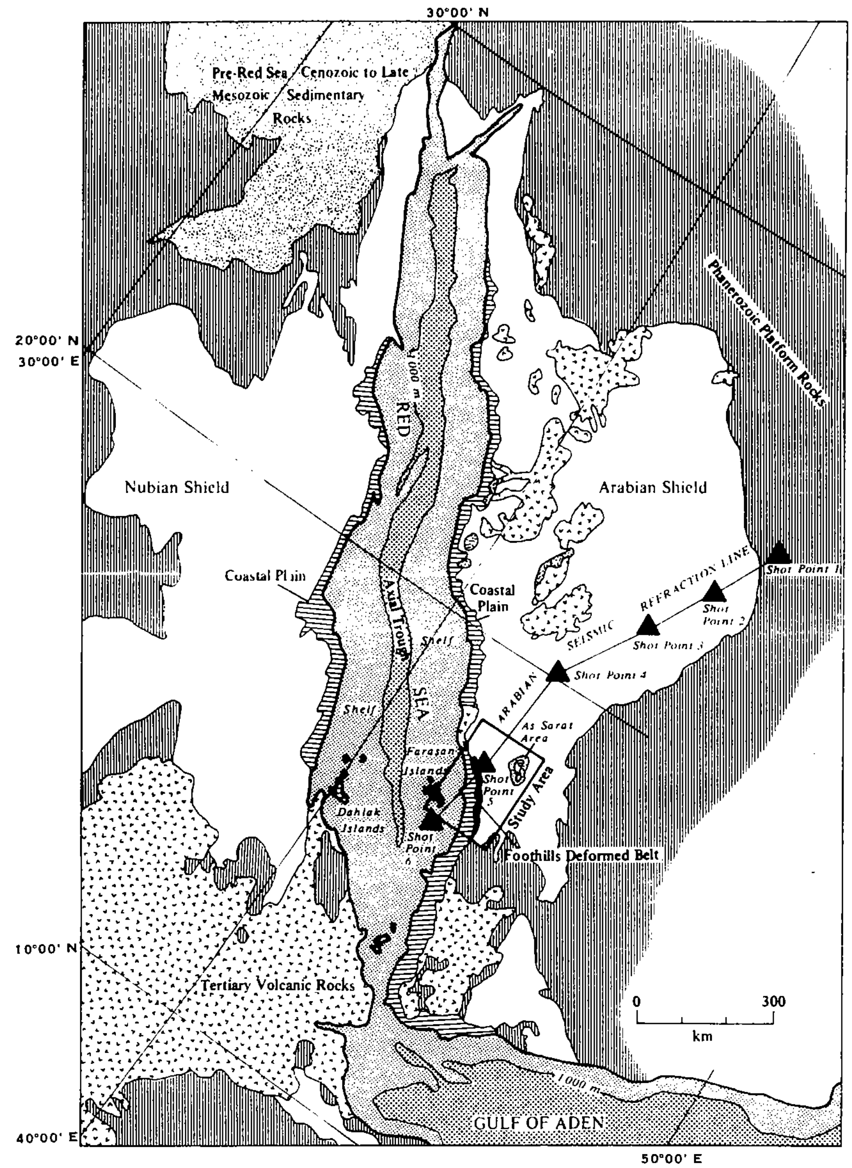


Fig. 1. Batnymetric and geologic features of the Red Sea region. The text discussion centers on the marked study area.

In southwestern Saudi Arabia (Figure 1) escarpment-crest elevations are 2,150 to 2,400 m, and in the deeply incised terrane between that crest and the Red Sea coastal plain the westward increase in Tertiary deformation can be studied in outcrop. This paper integrates published data with my own geologic mapping and regional observations. Reconnaissance geologic mapping is complete from the coastline to the continental interior and petrologic and magnetic studies have been conducted on many of the igneous rocks [Coleman et al., 1977, 1979, 1983; Coleman, 1984a; Kellogg and Blank, 1982]. The Tertiary stratigraphic setting is known in outline [Schmidt et al., 1982; Schmidt and Hadley, 1984]. Drill hole data constrain sediment thickness near the shoreline [Ahmed, 1972] and geophysical data and interpretations constrain crustal dimensions and character [Gettings, 1977; Mooney et al., 1985; Prodehl, 1985; Milkereit and Fluh, 1985].

Some researchers have argued for an abrupt transition from continental to oceanic crust 30 km inland of the Arabian shoreline between 16° 50' and 18° N [Coleman et al., 1977; Mooney et al., 1985; Gettings, 1977; Girdler and Underwood, 1985]. A few [Greenwood and Anderson, 1977; McKenzie et al., 1970; LaBrecque and Zitellini, 1985] call for oceanic crust up to the African and Arabian shores, or they imply its presence there in their tectonic reconstructions of the Red Sea. Cochran [1983] and Coleman [1984b] champion the opposing view that much of the crust offshore of Africa and Arabia is extended continental crust.

Extended continental crust is exposed on the Arabian margin and may be present to an unknown extent beneath coastal plain sediments west of the exposures. However, there is a transition from continental to Tertiary mafic igneous rocks exposed just east of the coastal plain, and mafic igneous rocks are probably abundant beneath the sediment in the thin crust west of that transition. The exposed transition may be the continent-ocean boundary, but the detailed composition of the buried crust between the outcrops and the shore remains uncertain.

PHYSIOGRAPHIC, GEOLOGIC AND GEOPHYSICAL SETTING

Physiography

The Red Sea occupies a long and slightly sinuous basin that trends northwest. Its coastline morphology is similar on either side and it has a narrow, steep-sided axial trough, with an irregular bottom 1.5 to 2.5 km deep. The sinuous shape of the axial trough parallels that of the coastlines. Wide, shallow (0-600 m) shelves flank the axial trough [Coleman, 1974; 1984b; Cochran; 1983]. The shelf is 125 km wide at 17° N, offshore of the study area, and it is dotted with many low islands of the Farasan group (Figure 1).

A coastal plain rises gently landward to maximum elevations of 100 m along most of the Arabian coast and is about 30 km wide at 17° N. The east edge of the coastal plain is marked locally by foothills as high as 650 m, but in other areas the plain gives way eastward to pediment and dissected terrain of slightly steeper slope. The foothills and pediment are 15 km wide, and inland of them the land rises abruptly, in the deeply dissected mountainous terrain known as the Asir, to the west-facing Arabian escarpment. The mountainous terrain is 30 to 60 km wide at 17° N. The land surface slopes gently eastward (Figure 1) in the tablelands east of the escarpment.

Red Sea crust

Oceanic crust is present in the axial trough of the Red Sea [Chase, 1969; Drake and Girdler, 1964; Girdler, 1969], where large-amplitude, marine magnetic anomalies as old as 5 Ma are well documented [Roeser, 1975] and anomaly 5 might be present [LaBrecque and Zitellini, 1985, Figure 4]. Oceanic crust probably extends to at least 70 km from the spreading axis at 21° N. [Yousef, 1982].

The Red Sea shelves and coastal plains are underlain by sediment that well data [Ahmed, 1972; Coleman, 1974, Figure 1], seismic-refraction studies [Drake and Girdler, 1964; Girdler, 1969] and seismic-reflection profiles [Yousef, 1982] show to have a thickness of 4 to 6 km. The character of the subsediment crust is uncertain. Magnetic patterns change from high-amplitude, short-wavelength anomalies in the axial trough to low-amplitude, long-wavelength ones beneath the shelves [Drake and Girdler, 1964]. Some authors [LaBrecque and Zitellini, 1985; Girdler and Underwood, 1985] use magnetic models to infer oceanic crust beneath the shelves and possibly the coastal plain. Gettings [1977] agrees with them on the basis of gravity studies. Yousef [1982], Cochran [1983], and Coleman [1984b] argue that block faults in extended continental crust account for the shelf anomalies and limit oceanic crust to that proven in the axis. They cite limited nearshore drilling data and seismic velocities as consistent with their models.

Pre-extensional Geologic History

The Arabian and Nubian Shields are formed of diverse Proterozoic rocks which underlie a Paleozoic through Paleogene sedimentary platform sequence that surrounds and dips gently away from them (Figure 1). Late Cretaceous and early Tertiary nearshore marine and littoral deposits are thin but widespread in Egypt, recording a southward transgression and regression of a Tethyan seaway [Said, 1962]. Similar correlative strata rest on Shield rocks in west-central Saudi Arabia

[Al Shanti, 1966; Madden et al., 1979], indicating that the marine transgressions and regressions occurred there as well. In Sudan and southern Saudi Arabia, there are scattered remnants of early Tertiary saprolitic and lateritic soils on Proterozoic rocks [Delaney, 1954; Whiteman, 1971; Overstreet et al., 1977]. One such zone is preserved beneath middle Oligocene (25 to 30 Ma: Coleman et al., [1983]) basalt flows in the As Sarat area on the southern Arabian Shield (Figure 1).

The Nubian-Arabian continent was thus near sea level from Cretaceous to middle Oligocene time. It was the site of deposition or of soil development but not of erosion and it had low relief [Mohr, 1971; Stoeser, 1984]. No evidence of uplift, deformation, or erosion is recorded in the As Sarat basalt flows [Kellogg and Reynolds, 1980], indicating that they also formed near sea level and that Red Sea-related uplift postdates the basalts.

Geophysical Configureuration of the Margin

Several interpretations of crustal thickness beneath the Arabian Shield and southern Red Sea have been made from Saudi Arabian seismic refraction line data [Mooney et al., 1985; Milkereit and Fluh, 1985; Prodehl, 1985]. The Moho is subhorizontal 38-45 km beneath the Arabian Shield in these models. There are differences in the interpretations west of the Asir where the Moho rises from its sub-Shield depth to 8 to 15 km beneath the Farasan Islands. Three contrasting interpretations are illustrated (Figure 2).

The interpretation by Mooney et al. [1985] (section A, Figure 2) suggests that the Moho rises abruptly from a continental 38 km beneath the Shield, slightly west of the Asir, to a transitional 18 km beneath the eastern coastal plain. From the coastal plain it gently rises to an "oceanic" 8 km under the Farasan Islands. Prodehl [1985] proposes an alternative interpretation (section B, Figure 2) in which the Moho rises gently from 43 km beneath the Shield, slightly east of the Asir, to about 14 km beneath the Farasan Islands. The transition from continental to oceanic crust is not obvious in his model. The interpretation of Milkereit and Fluh [1985] (section C, Figure 2) is similar to that of Mooney and others [1985] beneath the Asir. They interpret a flat Moho at about a 13 km beneath the shelf of the eastern Red Sea. Milkereit and Fluh [1985] propose a double Moho between the Asir and shelf; one, nearly level, at 13 to 15 km and a deeper one with an east slope. This interpretation requires an inter-crustal layer about 8 km thick with mantle velocities beneath the shelf and western coastal plain [Milkereit and Fluh, 1985, Figure 8].

Bouguer gravity maps [Gettings, 1977; Gettings et al., 1983] depict a steep gradient of 6 mgals/km with a relief of about 80 mgals centered slightly east of the coastal plain. The steep gradient is 25 km southwest of the high-relief topography in the Asir, so is not due to topographic effects. The gradient corresponds to the location of a linear belt of mafic plutonic rocks and to the position where Mooney et al., [1985] place the steep-sloping Moho in their seismic interpretation and is strong evidence in support of profile A (Figure 2).

ARABIAN CONTINENTAL MARGIN

The structure of the margin is described by examining separately the effects of mechanical extension and intrusional expansion. Mechanical extension is defined as any process that produces a constant-volume reorganization of the crust, such as faulting, melting/remobilization, or ductile defomation. Intrusional expansion is defined as any process that results in crustal widening by the addition of crust derived from the mantle. The southwestward effects of each of these processes is analysed and their interaction is described. Figure 3 is a simplified geologic map of part of the Asir and coastal plain near the Saudi Arabian and Yemen border between 16° N and 18° N which provides a reference for the discussion.

Mechanical Extension

Tertiary extensional deformation increases from east to west across the Arabian continental margin. Evidence for extension is minimal in the cratonic rocks east of the escarpment crest, but the value of extension reaches 8-10% between there and the base of the Asir mountains. In the foothills between the Asir and coastal plain extension increases to possibly 110% in a short lateral distance. These areas are examined in the ensuing paragraphs.

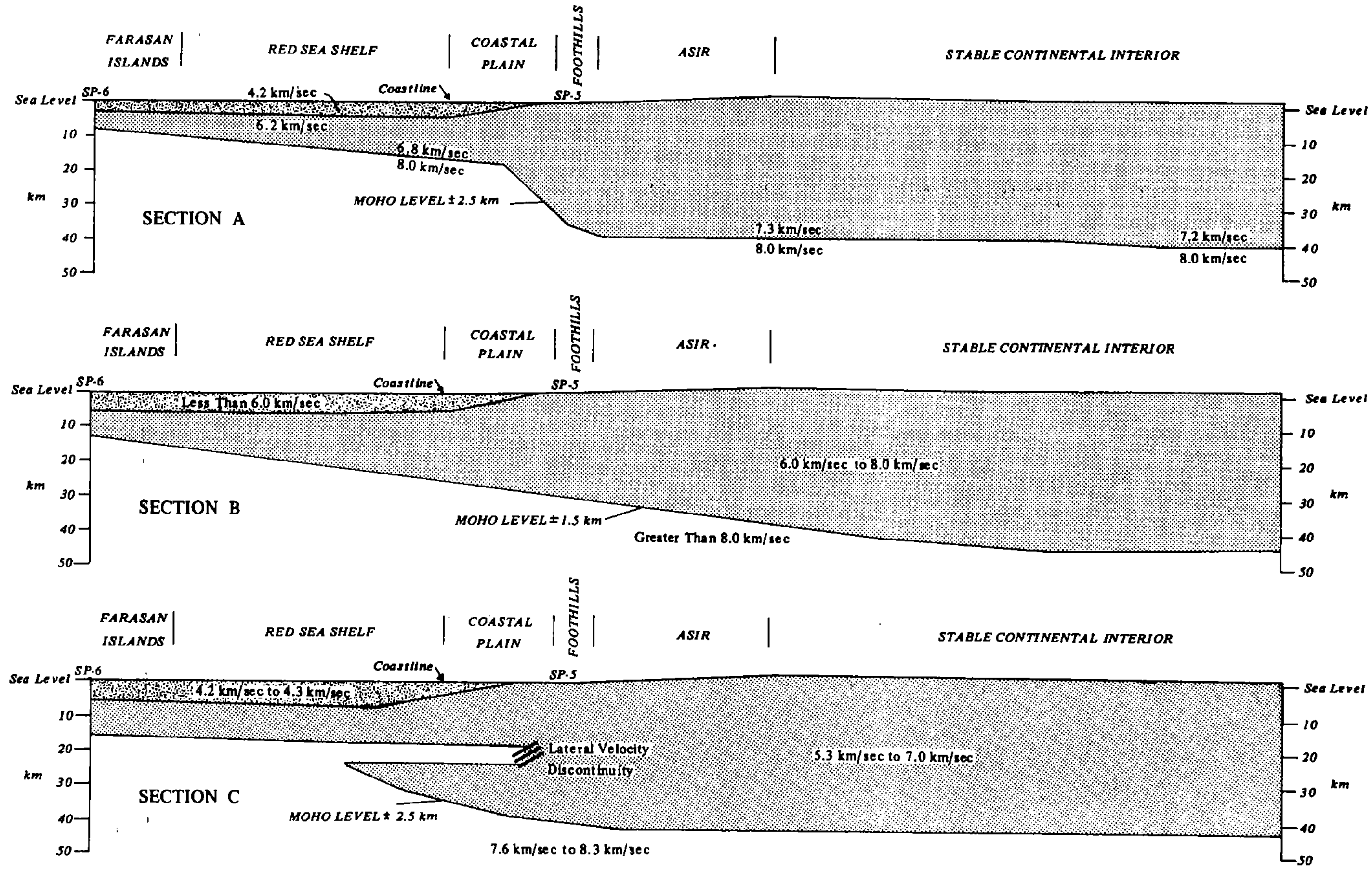


Fig. 2. Crustal structure interpretations of the southwest end of the Saudi Arabian refraction seismic line. Sections are drawn 1:1 between shot point 6 and a point 210 km northeast of shot point 5. Section follows Mooney et al., [1985], section follows Prodehl [1985], and section follows Milkeriet and Fluh [1985].

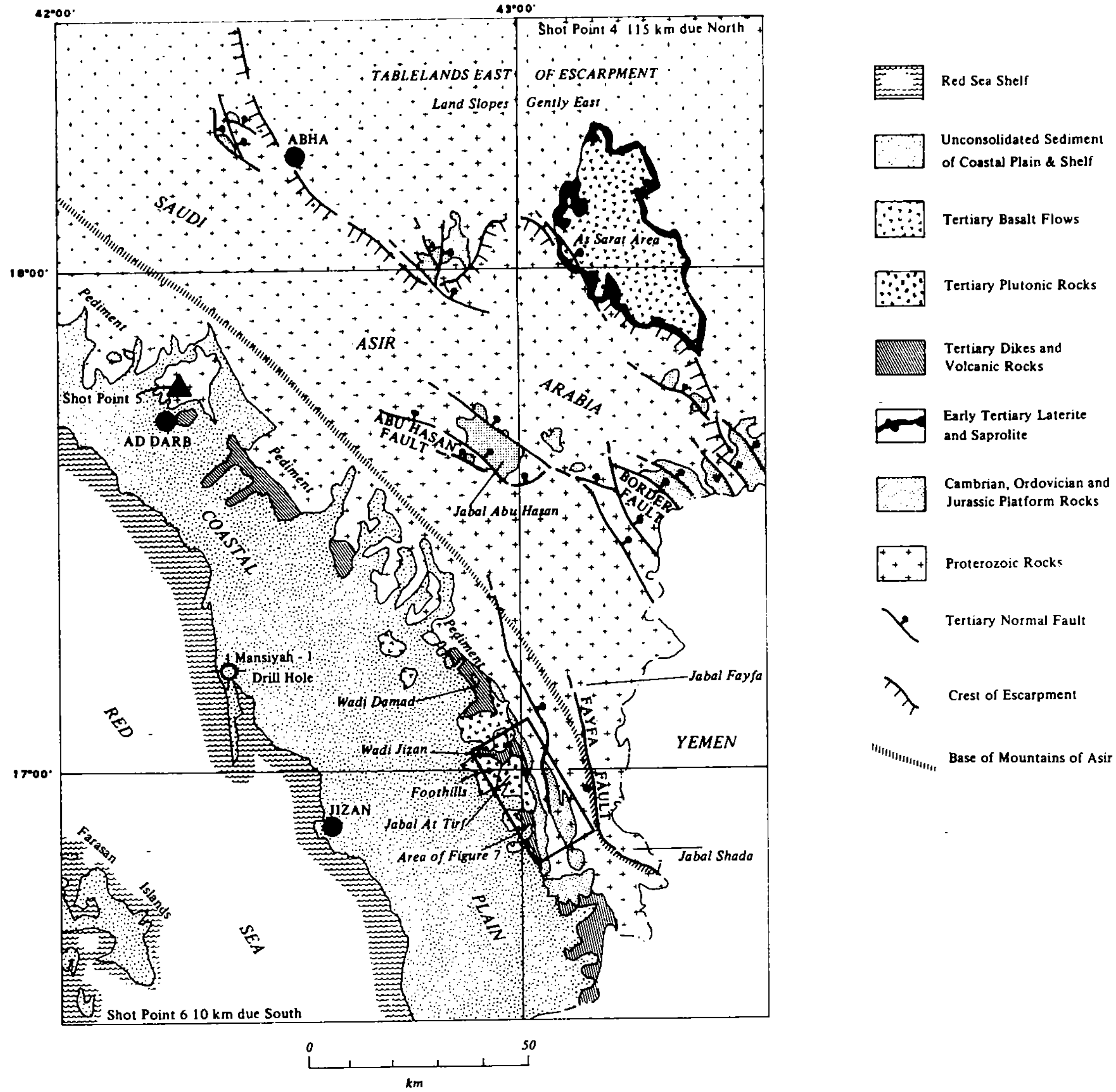


Fig. 3. Generalized geologic map of southwestern Saudi Arabia showing aspects of geology relevant to Tertiary history.

Normal faults with northwest trends cut Ordovician-Cambrian sandstone and Oligocene basalt near the crest of the escarpment and in the As Sarat area [eg., Stoeser, 1984] (Figure 3), but they indicate a negligible amount of extension at a regional scale. These faults are widely spaced, have steep dips and have displacements typically of about 100m. Ordovician and Cambrian sedimentary platform strata are widespread and little deformed near the escarpment and the Saudi-Yemen border. The strata dip 2° to 5° east, and most faults dip steeply southwest creating a step-like, down-to-the-sea pattern, across which there is little net structural relief.

The Abu Hasan and Border faults (Figure 3) are conspicuous normal faults that dip 60 to 80° east, and they are typical of several other major normal faults in the western Asir. These faults strike northwest and each has up-to-the-Red Sea displacement on the order of 1 to 1.5 km. Northeast of these faults, the gentle east dips found in the Ordovician-Cambrian rocks change to 5° to 20° to the southwest and the base of the Cambrian is flexed down to elevations of 900 to 1,400 m. Southwest of the faults, peaks are as high

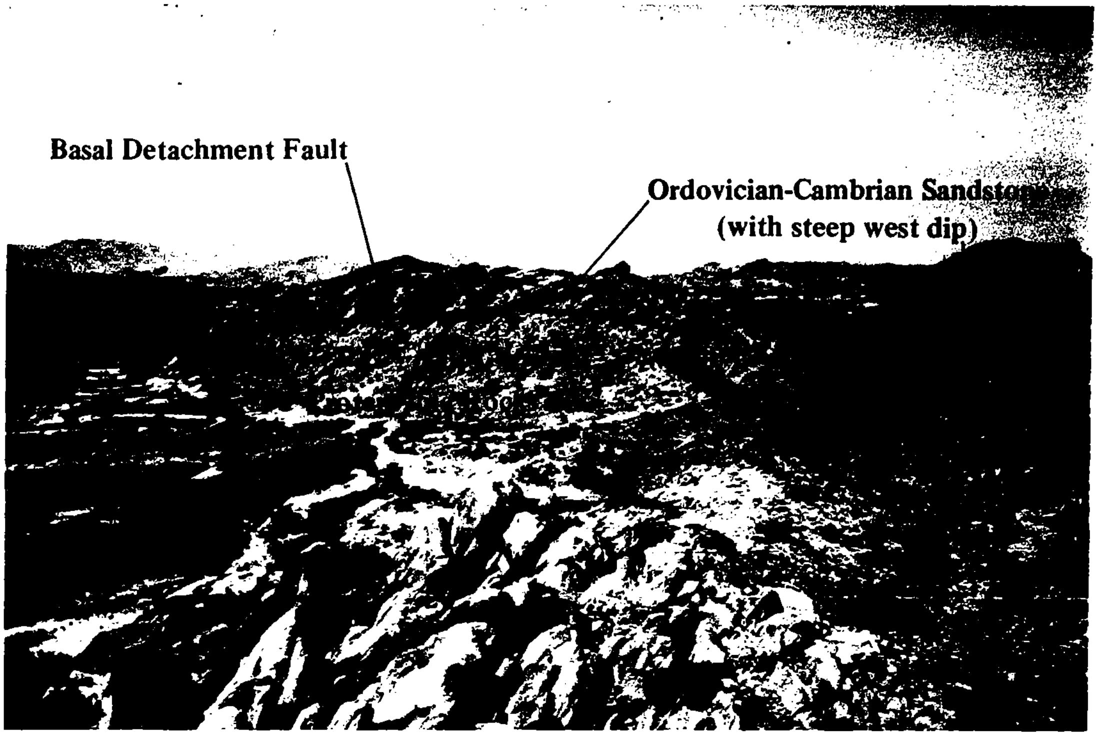


Fig. 4. View to the north-northwest of basal detachment fault. Beds in central part of photograph dip 55° west and are truncated downward at fault with gentle west dip. Proterozoic rocks are below fault. Fault dip steepens slightly to east (right) where it cuts another fault beneath it with an east dip. To west (left) fault assumes an intermediate east dip and it cuts a fault with west dip on ridge. Red Sea is to west.

as 2,400 m, but the sandstone is eroded. High angles (70° to 90°) are maintained between faults and bedding. The large monoclinal flexure associated with these faults suggests reverse drag which may indicate that they flatten downward [Hamblin, 1965].

The break in slope at at the base of the mountains in the Asir is not generally marked by a fault; it trends slightly more westerly than the faults. For 120 km south of Ad Darb (Figure 3), the transition from mountains to coastal plain is gradual, taking place in a zone a few kilometers wide. However, the Fayfa fault crops out along a 20 km stretch between Jabals Fayfa and Shada (Figure 3) at an abrupt change in slope at the base of the mountains. This fault dips west and may have as much as 1.5 km of vertical separation.

Wernicke and Burchfiel [1982] studied extensional tectonism in terms of fault and bedding relations, and concluded that an area with fault dips of 60° and greater, and bedding dips of 20° and less, like the Asir, might be extended by 10%. Asir faults are widely spaced and most have small displacment so regional extension is probably not that great. It may reach 8-10% near the base of the mountains, but it is negligible near the escarpment.

Much more extension is evident in the foothills between the Asir and the coastal plain. Plate 1 is a geologic map of an area between Wadis Damad and Liyyah where fault relations are well displayed. A major normal fault with a west dip of 5 to 20° is evident. The low-angle fault is a detachment between Ordovician-Cambrian sandstone above and undifferentiated Proterozoic crystalline rocks below, except in the southwest part of the map where it is confined to Proterozoic rocks. This is herein called the basal detachment fault (Figure 4). The sandstone above it strikes northwest and dips an average of 55° to the southwest. The sandstone is

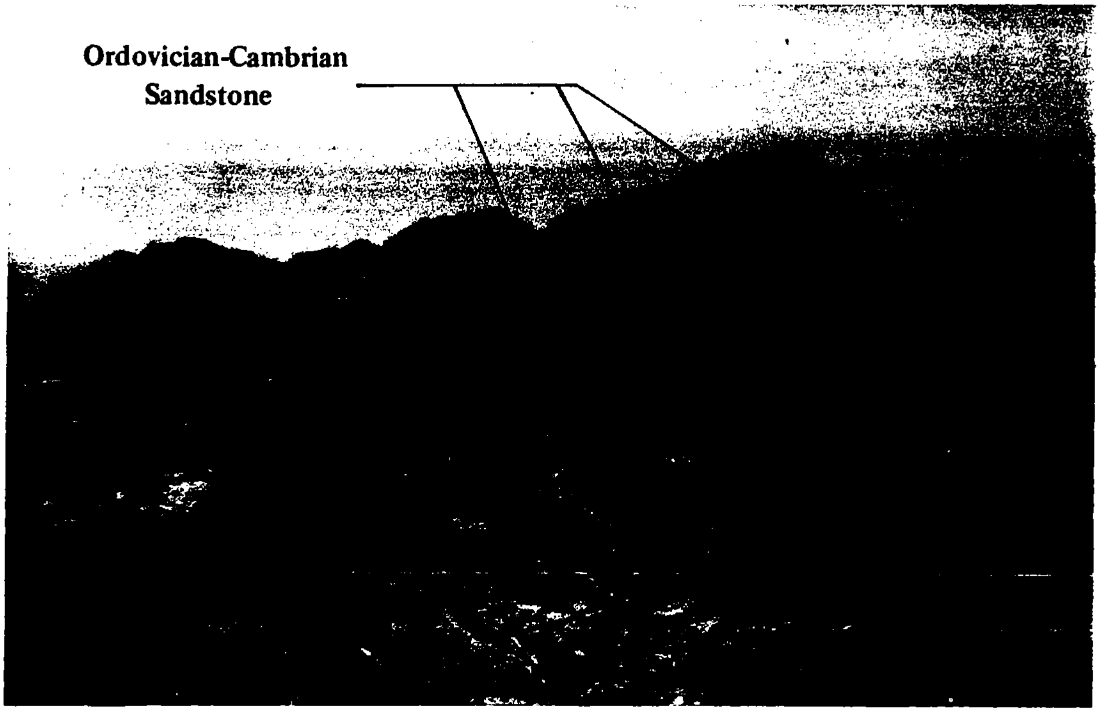


Fig. 5. Faults in upper plate of basal detachment fault. View to south. Faults dip about 30° east and bedding dips 55° west. Light colored rocks in lower half of photo are Proterozoic, darker bedded rocks above are Ordovician-Cambrian sandstone. Displacement is up-to-the-Red Sea (to right in photograph). Faults and beds probably rotated simultaneously.

repeated by numerous normal faults with north-northwest strikes, most of which have east dips of 30 to 40°. These faults have small to moderate displacements and are truncated downward by, or join with, the detachment fault. Several other normal faults that trend generally north and dip east at 60 to 65° repeat the detachment. These are long and continuous structures that have arcuate surface traces (most are concave to the east) and each has up-to-the-Red Sea displacement of 1/2 to 2 km.

The basal detachment fault is the lowest of a stack of normal faults with gentle west dips. Several of these form an anastomosing pattern within the sandstone of the central, north-central and southwest parts of the map (Plate 1). Another one on the west side of the map faults Tertiary volcanic rocks with gentle west dips down against Ordovician-Cambrian sandstone.

The east-dipping normal faults in the upper plate of the basal detachment cause up-to-the-Red Sea displacement (Figure 5) and they are much more numerous and closely spaced (one every 10 to 500 m, averaging one every 50 m) than the map depicts. Fault and bedding strikes are subparallel to the north-northwest, so extension was west-southwest. The faults cut bedding at high angles (60 to 90°), suggesting that they began as steep structures in flat beds and that fault and bedding surfaces rotated simultaneously during the deformation.

The arcuate traces of the steep normal faults that repeat the detachment system suggest downward flattening. In cross section (Figure 6) these faults are interpreted to merge into a deeper detachment with a gentle east dip within the Proterozoic crystalline rocks. This hypothetical detachment, which displaces rocks of the middle crust up to the west, does not crop out and is shown to project beneath the sediment of the coastal plain.

The upper plate of the basal detachment is composed of upper crustal rocks that

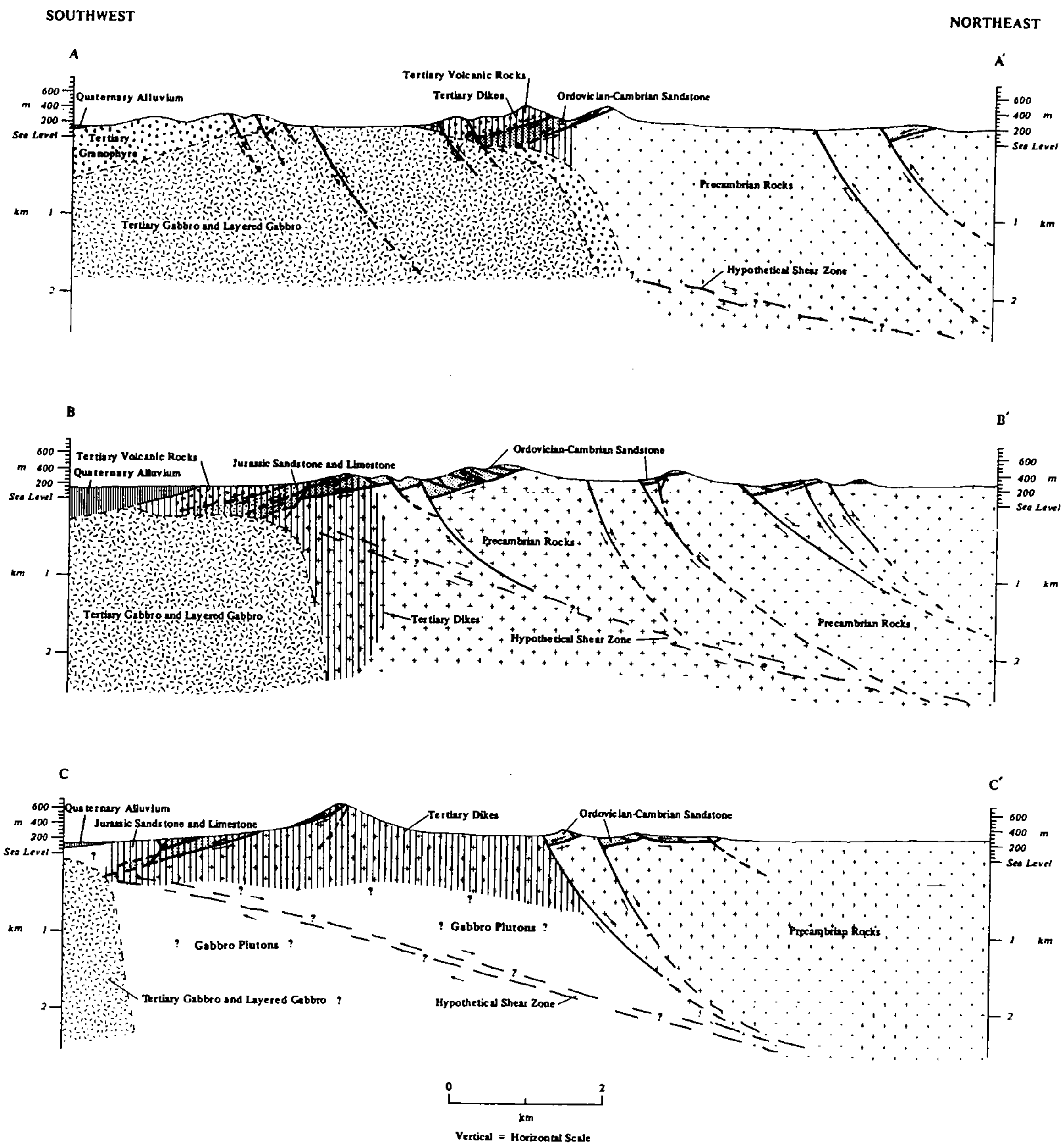


Fig. 6. Structure sections drawn perpendicular to regional strike of foothills deformed zone.

are exposed within a narrow elevation range (100 to 650 m) in a 10-km-wide belt that parallels the Red Sea east of the coastal plain from Ad Darb to south of the Yemen border (Figure 3). The Cambrian and Jurassic platform sequence is in the upper plate along the entire belt; thus, the faulting is confined to the same high crustal levels at all latitudes. The upper plate is faulted against Proterozoic rocks from deeper in the crust.

Fission-track studies (unpublished work by C. W. Naeser and this author) indicate that the Proterozoic rocks in the lower plate were buried to depths of at least 3 to 4 km prior to 25 Ma ago. Most of the apparent apatite ages of samples from low elevations (100 to 600 m) in the Asir between Jeddah and Jizan range from 16.4 to 25.1 Ma old. Two of these ages are from lower plate rocks less that 10 km east of the exposed trace of the detach-

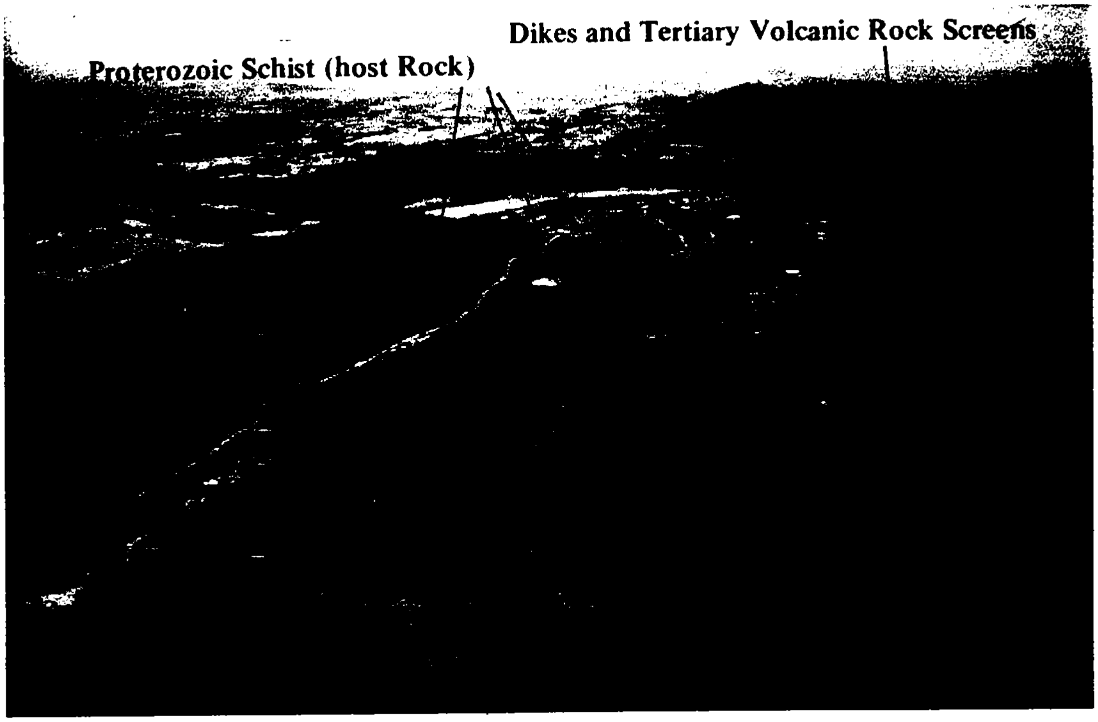


Fig. 7. Transition from Proterozoic rocks without dikes in east (far left side) to dikes intruding dikes and dikes intruding Tertiary volcanic rocks in west (right side). Youngest and least altered dikes form resistant ridges. Light gray Proterozoic schist forms screens between dikes on left side of photo. Darker rocks between resistant dikes on right side of photograph are less resistant dikes and volcanic rocks. Wadi Damad is in middle ground.

ment. Fission tracks in apatite anneal at about 100-150^{o} C, which corresponds to depths of around 3.5 km [e.g., Naeser, 1981]. The apparent ages are interpreted to record cooling due to rapid uplift from depths that correspond to the annealing temperature or deeper. Burial might not have been much deeper than 3.5 km because some of the dates from low elevations are as old as 70 to 144 Ma, indicating incomplete annealing.

Most of the faults probably formed between 23 and 25 Ma ago. Gabbro and granophyre, 20 to 23 Ma old [Coleman et al., 1977], intrudes them, but they deform basalt flows that probably correlate with As Sarat flows (25-29 Ma old). Thus, the faulting and juxtaposition of rocks from two crustal levels probably was accompanied by the uplift.

Intrusional Expansion

There is an abrupt increase in the effects of intrusional expansion from east to west in the foothills and pediment between the Asir and coastal plain. Tertiary dikes, plutons and volcanic rocks increase in abundance from near zero in the rocks east of the foothills to form 100% of the exposures at the east edge of the coastal plain. The transition takes place within 4 km at some places.

There is little evidence for intrusional expansion of the crust in the Asir. East of the escarpment top, the widespread Tertiary basalt flows, such as those in the As Sarat area, appear to have been fed over a long time period by vertical pipes [Coleman et al., 1983. pg. 5]. These pipes, commonly 15 m in diameter, are now preserved as numerous small stocks in areas where the flows have been eroded. They do not appear to offer the potential for intrusional expansion of a measurable amount at any crustal level. Tertiary dikes are uncommon in the eastern Asir.

Proterozoic rocks near the base of the mountains in the Asir are intruded by

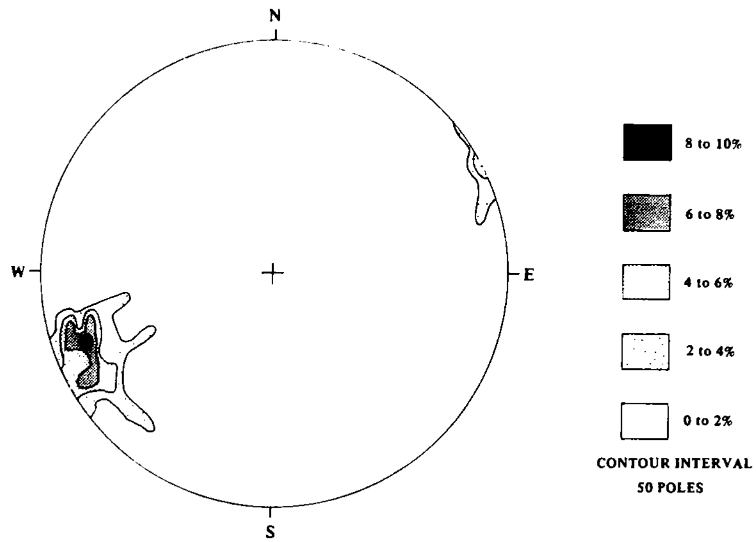


Fig. 8. Lower hemisphere stereo plot of poles of 50 dikes in tributary wadi south of Wadi Damad. Poles to attitudes indicate least principal stress direction to west-southwest, perpendicular to Red Sea axis.

sparse Tertiary diabase dikes. The dikes are 0.25-2 m wide, trend parallel to the Red Sea and cut across all Proterozoic contacts and structures. The crustal expansion indicated by these dikes is negligible.

The number of dikes dramatically increases across a zone only 3 to 4 km wide in the westernmost pediment between the Asir and coastal plain. This zone is well exposed in Wadi Damad and its tributaries (Figure 3), north-northwest of Plate 1, where the detachment faults are mostly eroded. Dike density increases east to west within only 1 or 2 km, from near zero to nearly 50% dikes (Figure 7). Four km southwest of nearly undiked Proterozoic rocks, dikes make up 75 to 100% of the rocks and the screens are mainly altered mafic volcanic rocks. Some rare screens of Ordovician-Cambrian sandstone occur, but no Proterozoic rocks are present. The southwest limit of Proterozoic rock screens is irregular, but is subparallel to the Red Sea.

The Tertiary mafic rocks are exposed for a width of 10 km in the Wadi Damad area southwest of the limit of Proterozoic rocks. The best-developed dike-on-dike intrusion is exposed in the eastern half of the terrane, where screens of Tertiary volcanic rock make up only 10 to 30% of the rock. There is a greater volume of volcanic screen rock in the west. The dikes are 0.5 to 18 m wide, and most of them strike north-northwest and dip steeply east (Figure 8). The consistent north-northwest strike indicates a west-southwest orientation of least principal stress parallel to that indicated by the faults. The youngest 10 to 20% of the dikes are nearly unaltered and form resistant ridges, whereas the remaining older dikes are moderately to highly altered and weather recessively. The screens of volcanic rock are non resistant.

The dikes are basalt, diabase, and gabbro and are composed primarily of calcic plagioclase, clinopyroxene, titanium-iron oxides, and rare iron sulfides. A minor amount of quartz is present in some samples and most contain amphibole, probably replacing pyroxene. Most dikes are equigranular, but there are uncommon inequigranular to porphyritic ones. The rocks are fine to coarse grained, with intergranular, intersertal and subophitic texture. Chlorite is a common alteration product. Plagioclase is variably albitized and pyroxene is uralitized.

Preliminary chemical analyses from dikes, including several in the Wadi Damad swarm, are summarized in Table 1. Coleman et al. [1977, 1979] provide a similar chemical data set for the dikes. The analyzed dikes are rich in aluminum (12 to 19% Al_2O_3) and generally have less than 50% silica. Both quartz-normative and

TABLE 1. Chemical Analyses from Dikes and Volcanic Rocks near Jabal At Tirf and Wadi Damad

	Dike Intruding Schist 1	Dike Wadi Damad 2	Volcanic Rock Wadi Damad 3	Dike Wadi Damad 4	Volcanic Rock Wadi Damad 5	Dike Wadi Damad 6	Dike South of Jabal AT Tirf 7	Dike South of Jabal AT Tirf 8	Dike South of Jabal AT Tirf 9	Dike South of Jabal AT Tirf 10
Sample	222786	222854	222857	222858	222859	222860	222810	222806	222808	222812
Na_2O	3.49	2.94	3.16	2.94	3.31	2.60	3.36	3.31	3.26	3.33
MgO	4.72	6.65	4.18	4.49	3.94	4.84	5.07	5.18	6.19	4.84
Al_2O_3	19.16	14.94	13.05	18.27	13.03	18.93	12.13	11.98	12.21	12.43
SiO_2	48.31	47.63	53.68	48.41	54.05	48.09	49.56	50.39	49.75	52.13
K_2O	0.43	0.11	0.94	0.34	1.40	0.34	0.59	0.44	0.33	0.54
CaO	12.00	13.66	7.95	11.17	7.69	11.27	9.59	9.37	10.42	8.78
TiO_2	1.47	1.77	3.04	2.63	3.16	2.47	2.46	2.65	1.93	2.56
Cr_2O_3	0.04	0.08	0.04	0.05	0.03	0.00	0.03	0.00	0.03	0.00
MnO	0.12	0.30	0.30	0.23	0.22	0.13	0.35	0.23	0.19	0.30
FeO	8.88	11.52	13.73	11.99	13.95	11.16	14.38	14.80	14.24	13.68
Sum	98.64	99.59	100.08	100.53	100.78	99.84	97.60	98.16	98.55	98.58

	Dike Intruding OЄ Sandstone 11	Dike Intruding Dikes 12	Dike Intruding Dikes 13	Dike Intruding Dikes 14	Dike Intruding OЄ Sandstone 15	Dike Intruding OЄ Sandstone 16	Dike Intruding OЄ Sandstone 17	Dike Intruding OЄ Sandstone 18	Dike Intruding OЄ Sandstone 19	Dike Intruding OЄ Sandstone 20
Sample	222793	222794	222796	222797	222802	222806	222800	222798	222792	222790
Na_2O	3.35	3.22	3.69	3.11	3.71	4.07	3.67	3.34	3.96	3.00
MgO	6.02	6.08	6.39	6.90	4.35	3.73	4.53	5.63	2.42	5.52
Al_2O_3	15.99	16.27	15.21	15.48	12.70	17.14	12.16	11.95	14.19	13.43
SiO_2	47.77	48.00	48.58	48.71	49.57	49.15	51.44	49.58	56.68	49.71
K_2O	0.50	0.32	0.43	0.20	1.10	1.44	0.85	0.68	2.04	0.81
CaO	11.73	11.97	11.24	12.48	8.46	9.44	8.58	9.90	6.05	10.14
TiO_2	1.94	1.74	1.81	1.61	3.88	2.34	2.49	2.47	2.36	2.20
Cr_2O_3	0.00	0.02	0.03	0.00	0.00	0.02	0.04	0.02	0.04	0.06
MnO	0.23	0.23	0.34	0.17	0.35	0.19	0.22	0.40	0.31	0.33
FeO	13.02	11.88	11.87	10.60	13.68	11.12	13.65	14.40	11.03	13.88
Sum	100.55	99.73	99.60	99.25	97.80	98.63	97.65	98.37	99.08	99.07

Analyses done on homogeneous glasses made by fusing whole rock powdered samples. Analyses performed on a quantitative JEOL T300 SEM equipped with Tracor Northern energy dispersive detector. Operating conditions: 15 keV accelerating voltage and 10 nanoamps sample current.

nepheline-normative dikes are present. An analysis of volcanic screen rock is also shown on Table 1. Most of the screens range from high-alumina andesite to rhyolite.

The dikes and volcanic rocks are associated with several large plutons of gabbro, layered gabbro, and granophyre. Two large intrusive centers are shown on Plate 1. The gabbro is coarse-grained, olivine-clinopyroxene gabbro with cumulate texture. Euhedral calcic plagioclase occurs in large, oriented laths. Olivine and clinopyroxene fill the interstices. Layers result from differences in abundance of plagioclase relative to mafic minerals. The analyses of Coleman et al., [1979] indicate that the gabbros are chemically similar to the more mafic dike rocks. Granophyre ranges in composition from monzogabbro to granite and it is relatively voluminous. Coleman et al., (1979) emphasize that the dikes, volcanic rocks, and plutons form an elongate, nearly continuous band parallel to the Red Sea axis 20 to 35 km inland of the coast from Ad Darb to north Yemen (Figure 3). Their K/Ar ages indicate that the plutons cooled 20 to 23 Ma ago [Coleman et al., 1979] and they intrude nearly all of the dikes and volcanic rocks.

Plutons of gabbro probably underlie all of the dike swarms at relatively shallow depths. At exposed contacts between gabbro and dikes, the dikes truncate downward at the tops of the plutons. Dikes and plutons appear to have intruded their own volcanic cover. No Proterozoic rocks are preserved in the Wadi Damad dike swarm and the plutons are free of zenoliths. This suggests complete expansion of the older crust and indicates that the Tertiary mafic rocks penetrate the entire thickness of the crust. These terranes are herein called Tertiary mafic crust. The bulk of the Tertiary mafic crust is exposed adjacent to, but west-southwest of outcrops of the Proterozoic rocks and platform sequence sedimentary rocks. The Tertiary mafic crust is overlain by late-Neogene sedimentary rocks of the coastal plain to the west, so its extent in that direction is uncertain. The thickness of the overlying late-Neogene strata increases markedly to the west. They are thicker than 4 km at the coast [Ahmed, 1972], only 30 km from exposed Tertiary mafic crust.

Extension and Expansion

The extensional and expansional events overlapped slightly in space and time. Dikes intrude both plates of the basal detachment fault and there was a complex interaction between dikes and faults.

The most common dike and fault relation is one in which the dikes intrude both the Proterozoic rocks below, and the Cambrian rocks above, the basal detachment fault. The dikes are near vertical in the upper plate, although the sandstone is steeply tilted. The width, spacing, and trend of the dikes is the same above and below the fault. Most of the faulting and tilting thus preceded the injection of dikes and most of the extension occurred before most of the expansion.

Dikes are more numerous in the sandstone beneath some of the structurally higher detachment faults than they are above them. Many of the vertical dikes truncate upward at these faults and the lower-plate sandstone commonly shows a slight thermal metamorphism, not present in sandstone above the fault. In these cases the dikes are not tilted or repeated significantly by the faulting. These relations suggest that tilting and fault repetition of the Ordovician-Cambrian sandstone preceded the intrusion of dikes, but there was sufficient postdike displacement on some of the detachments to move intruded rocks down to the west over the dikes. Late-stage dikes then intruded the rocks above the faults.

Some of the dikes form sills at the soles of detachment faults. The sills are fed by small, near-vertical dikes. Rare vertical dikes emerge from some sills and intrude the tilted rocks above the faults. The sills are composed of basalt with cataclastic or protoclastic texture. The sills indicate that the upward intrusion of some dikes stopped at the faults. Fault activity and intrusion were probably coeval as expansion in the lower plate was alleviated by extension in the upper.

Volcanic rocks containing abundant vertical dikes occur above detachment faults that dip west at several locations near Jabal at Tirf (Plate 1). Dips in the volcanic rocks are westward and commonly less than 20°. I interpret these rocks to be the coeval volcanic cover of the Jabal at Tirf layered gabbro, but the faults that cut them are intruded by the pluton.

EXPLANATION

CORRELATION OF UNITS

Sedimentary and volcanic rocks

QUATERNARY

Qa
Alluvium – Unconsolidated gravel, sand, and silt

Qbf
Basalt flows – Dark colored mafic lavas

Qbc
Basalt cones – Cinders, bombs, ash and flows

TERTIARY

Miocene

Ts
Sedimentary rocks – Non-resistant clastic and chemical rocks

Miocene–Oligocene

Td
Mafic to silicic tuffs and mafic to felsic flow rocks

Tb
Cherty tuffaceous sandstone and mafic flow rocks

Oligocene

Tad
Mafic lava flows

JURASSIC

Jsl
Marine sandstone and limestone, commonly fossiliferous

ORDOVICIAN–CAMBRIAN

O€s
Quartz-rich sandstone, cross-stratified

PRECAMBRIAN

PC
Gneiss, schist and granitic rocks

Intrusive rocks

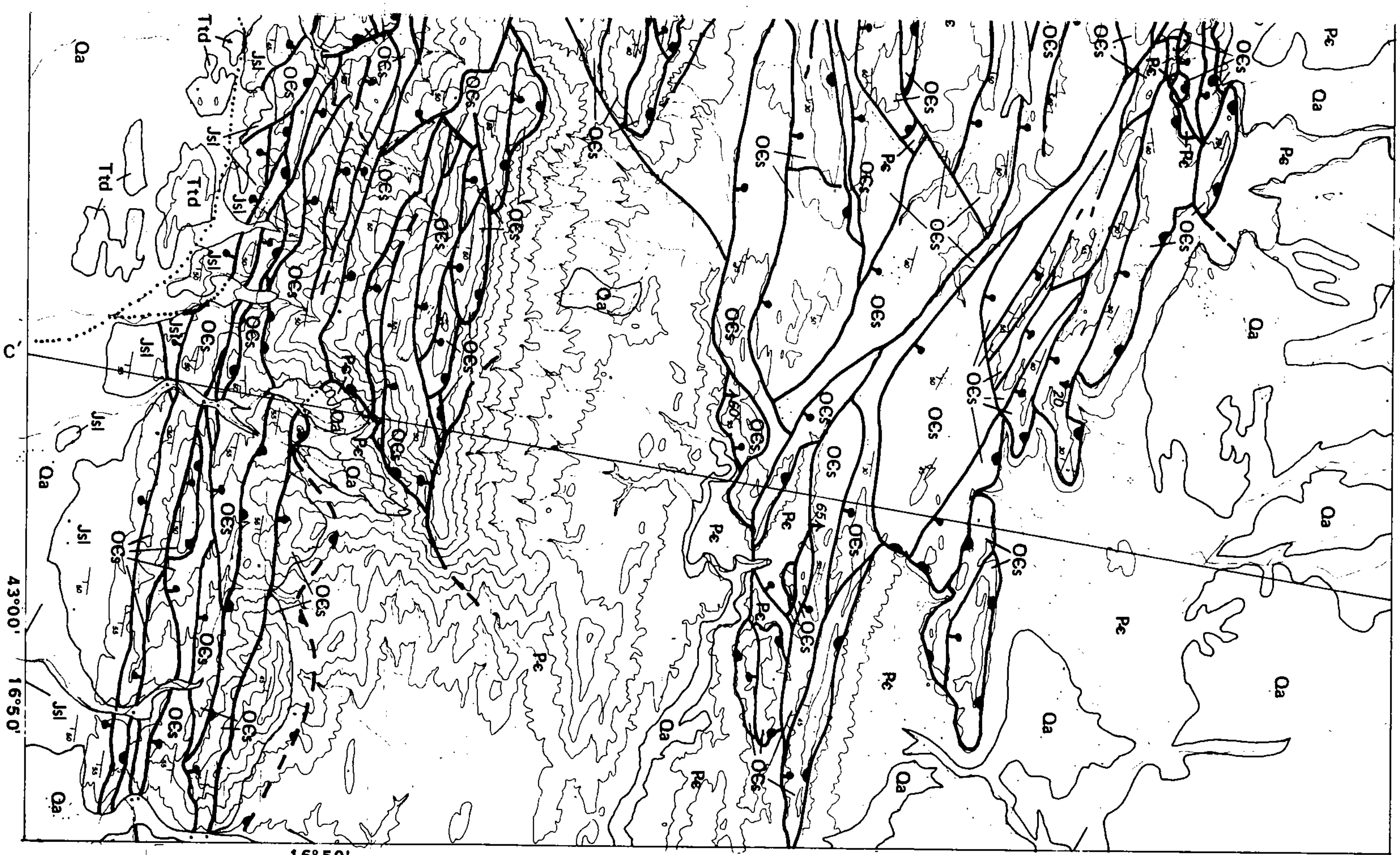
Ttd / Ttgr / Ttgl / Ttg
Tihamat Asir Complex
Ttgr – Coarse to Medium grained granophyre Ttg – Coarse grained gabbro Ttgl – Coarse grained layered gabbro Ttd – dike swarms

SYMBOLS

CONTACT

65 — NORMAL FAULT – Dashed where approximate, dotted where concealed. Ball and bar on downthrown side, arrow shows direction and amount of dip

10 — DETACHMENT FAULT – Dashed where approximate, dotted where concealed. Bumps on upper plate, arrows show direction and amount of dip



Topography from Unpublished USGS data,

Contour interval 10 meters

Geology mapped in Winter

and Spring of 1984

at 1:50,000 scale

1 0 4

Kilometers

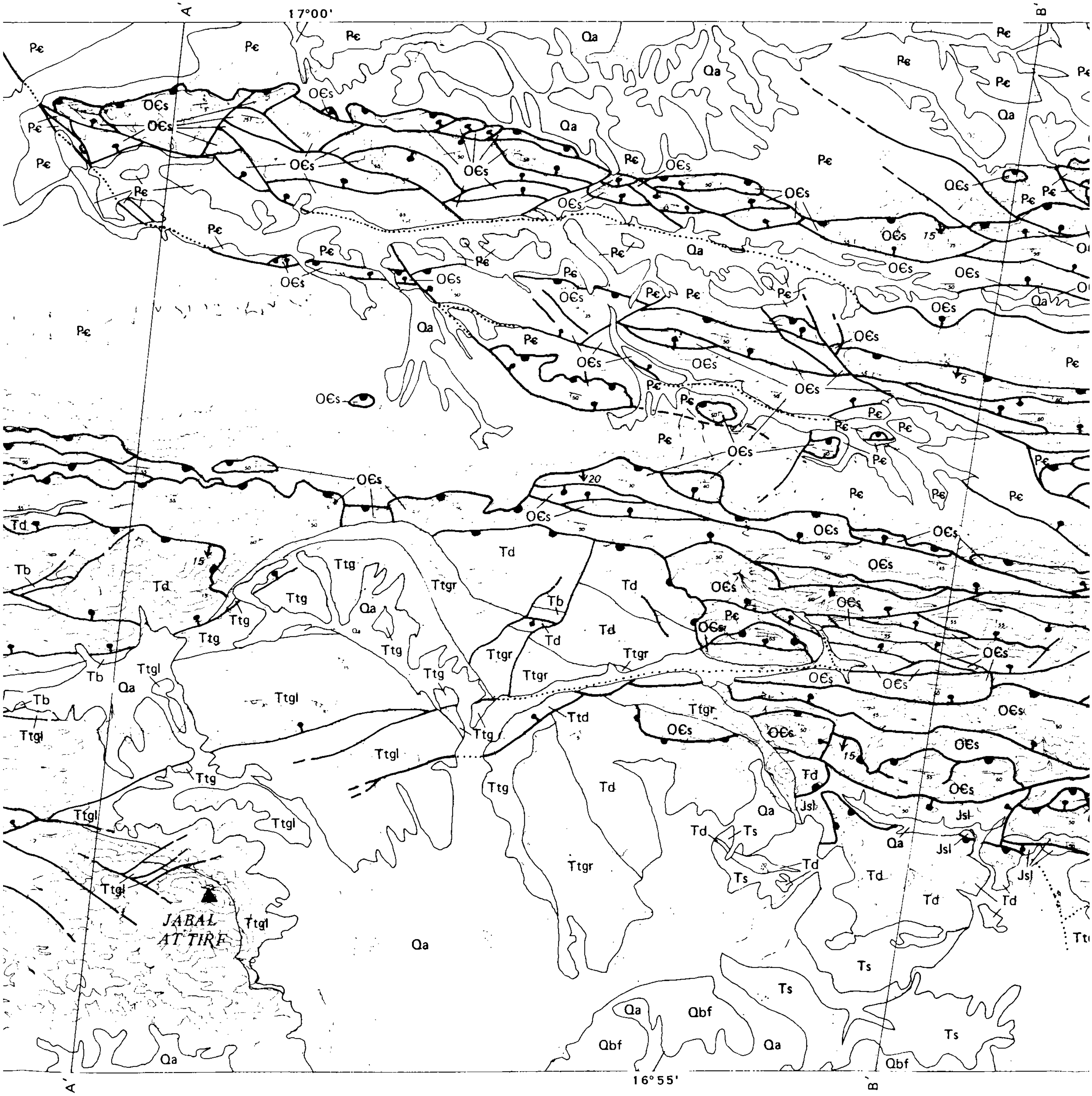
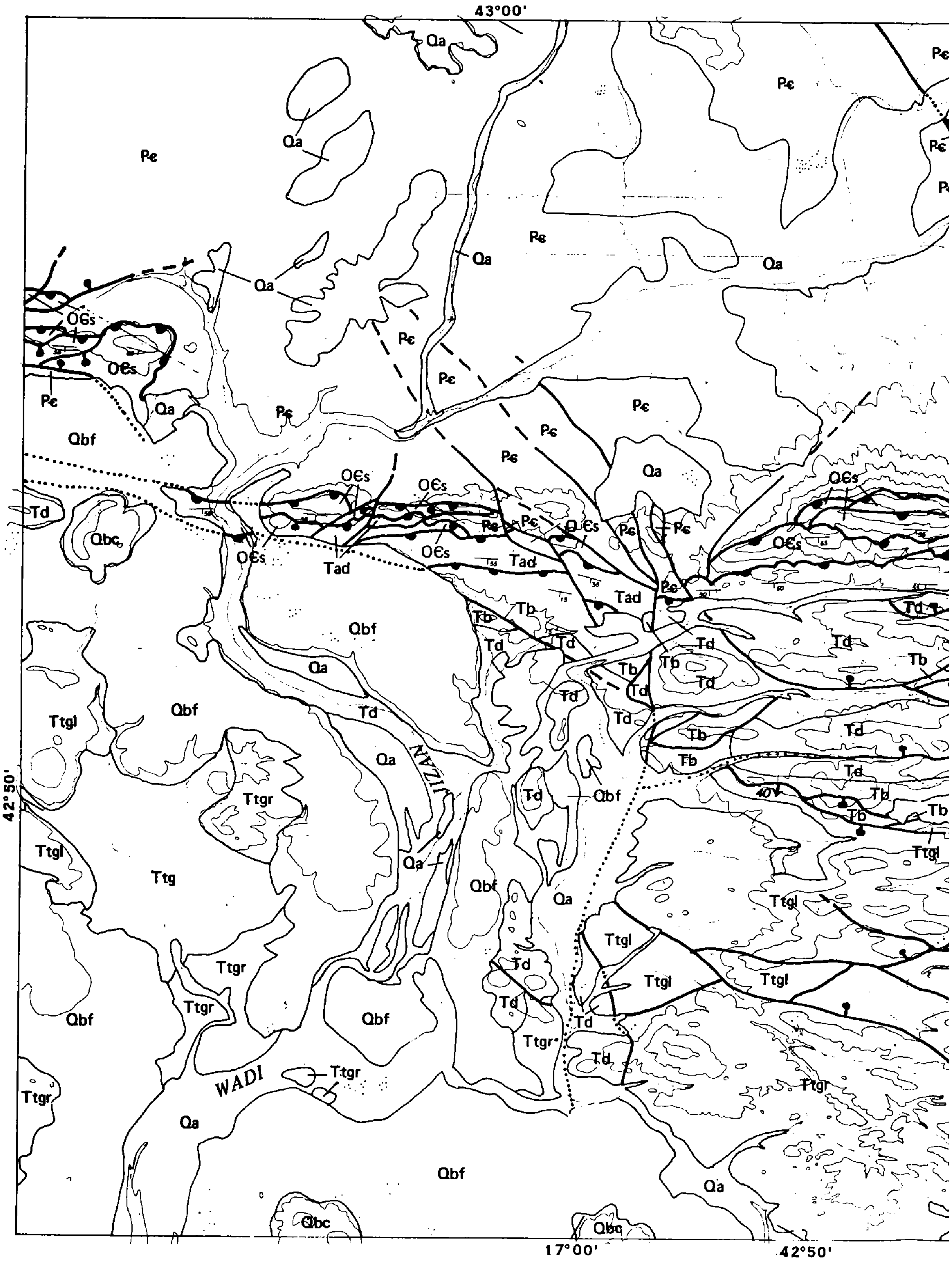


Plate 1. Geologic map of the highly deformed and intruded foothills between the coastal plain and the Asir.


43°00'
42°50'
17°00'
42°50'
WADI
JIZAN
Pє
Qa
Qbf
Qbc
OЄs
Tad
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Tb
Ttgl
Ttgr
Ttg
40

Dike intrusion appears to have followed faulting, because the dikes are neither rotated nor offset from their apparent source. The faulting of the volcanic rocks suggests that the early stages of intusion were accompanied by extension in the overlying rocks. By the late intrusive stages, extension seems to have ceased, and the overlying rocks were expanded by dikes.

DISCUSSION

Tertiary deformation and intrusion on the southwestern Arabian continental margin are confined to a zone 150 km wide inland of the present coastline. The rest of the Arabian Shield forms a uniformly thick continental crust that has not been deformed by Red Sea tectonism. Satellite images of the African margin suggest that Red Sea deformation is similarly confined there. I [Bohannon, 1986] have argued, based on crustal thickness interpretations, that pre-Red Sea tectonic reconstructions of the Afro/Arabian continent should depict nearly coast-to-coast closure or possibly overlaps of the present African and Arabian shorelines of up to 35 km, regardless of the type of crust buried under the shelves and coastal plains. Thus, the early Red Sea rift was only 230 to 300 km wide, and extension did not exceed 10% over most of that area. Intense extension was limited to a zone only 20 to 40 km wide in the axis of the rift. The potential for large amounts of lateral transposition of extension between different crustal layers is limited in a narrow rift. Thus, surface extension can give a rough indication of extension at depth and might even help constrain interpretations of Moho morphology based on seismic data.

The following analysis is an attempt to relate observed surface structure to published models of crustal thickness. One possible tectonic configuration of the Arabian continental margin is modeled.

The vertical displacement across the basal detachment fault indicates a minimum of 3.5 km of crustal thinning beneath the foothills and pediment east of the coastal plain. The Ordovician-Cambrian sandstone in the upper plate was probably near sea level prior to rifting and the Proterozoic rocks of the lower plate were buried to at least 3.5 km. The Proterozoic rocks are not cut by many Tertiary faults and were uplifted more or less as a unit to their present position slightly above sea level, but the sandstone of the upper plate is highly faulted and tilted. The sandstone has also been downdropped 2 km or more relative to correlative strata in the continental interior.

The deformation in the upper plate of the basal detachment fault suggets that the local crust was thinned by more than 3.5 km. Geometric analyses of rotational faults by Wernicke and Burchfiel [1982] indicate that fault and bedding relations like those in the sandstone are consistent with extensional values of around 60%. That value is probably conservative because of the affect of structurally higher, low-angle faults with west dips. An extensional value of 60 to 110% is reasonable for the upper plate.

The figure of 60 to 110% extension suggests an equivalent amount of crustal thinning, but the apparent lack of deformation in the Proterozoic rocks below the basal detachment argues against it. The hypothetical shear zone predicted in the cross sections (Figure 6) offers a possible solution to this discrepancy. The buried shear zone projects to an intersection with the basal detachment beneath the coastal plain sediment. The middle crust beneath the shear zone is displaced up and westward relative to the rocks above it. Hamilton [1981, 1982, 1983] has concluded that intersecting low-angle normal faults are probably present in most extensional crust. He also concluded that deeper faults pass downward into zones of distributed shear below about 20 km and are absorbed in ductile deformation in the lower crust.

The surface geology suggests that the crust beneath the foothills was thinned to 45 to 65% of its original thickness, which would cause a rise in the Moho relative to its position under the Arabian Shield. Most of the shallow extension occurs in a belt less than 10 km wide that parallels the trend of the Red Sea about 35 km inland of the coast. East of that belt there is evidence for no more than 10% extension and the transition between the two areas is abrupt. West of the belt there might not be much continental crust. Thus, the Moho should have a steep east slope beneath the extended rocks. It probably has a gentle east slope beneath the Asir to the east.

The Moho configurations in the seismic interpretations of Mooney et al., [1985] and Milkereit and Fluh [1985] approximately satisfy the predictions made from surface geology. Mooney et al., (1985) depict a 45° east slope on the Moho beneath shot point 5 (Figure 2). The abrupt crustal thinning from 38 to 18 km takes place within a narrow zone directly under the extended belt. Milkereit and Fluh [1985] depict a 15° east slope on the Moho west of shot point 5 (Figure 2) beneath the extended belt. Unfortunately their double Moho interpretation is not possible to evaluate using surface geology. Neither model depicts any crustal thinning east of shot point 5 beneath the Asir. Possibly, the seismic method cannot resolve a change in Moho elevation of only 4 km, the maximum amount predicted by surface extension. The steep Moho slopes proposed by Mooney et al., [1985] and Milkereit and Fluh [1985] explain the steep gravity gradient that is west of the Asir.

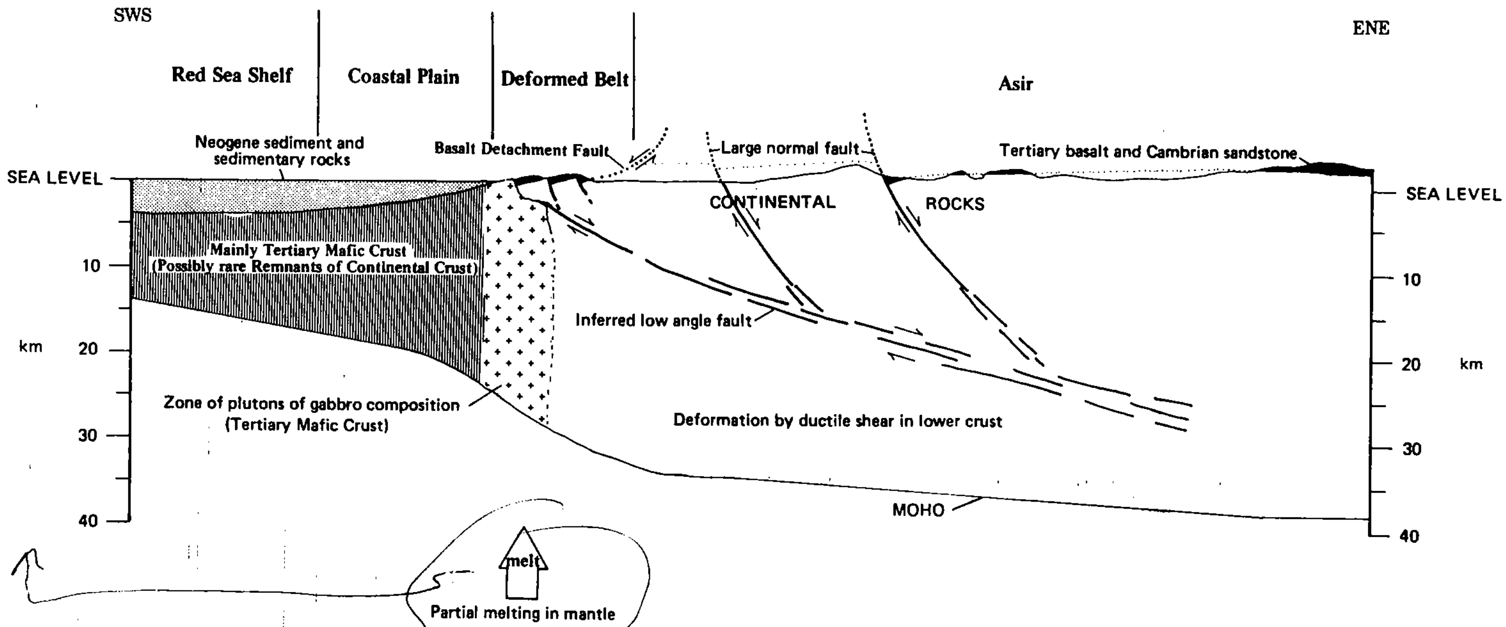
Prodehl's [1985] interpretation is not as consistent with surface geology as the other models are. The gentle east slope that he proposes on the Moho starts east of the top of the escarpment, where surface extension is negligible. He predicts more thinning beneath the Asir than is warranted by surface geology and the Moho slope is uniform beneath the deformed belt. Prodehl's [1985] model requires that the abrupt changes in geology, topography and gravity between the coastline and the continental interior are somehow smoothed out between the top and base of the crust.

The known and inferred structures of the Arabian continental margin are summarized on Figure 9. The Moho is shown 4 km higher beneath the west Asir than it is under the escarpment, and it has a steep east slope beneath the foothills. The middle crust is inferred to be extended by the hypothetical shear zone which intersects the basal detachment beneath the coastal plain and displaces the middle crust up and to the west. It possibly forms a detachment fault beneath the large normal faults and tilted blocks of the Asir. Deformation is assumed to have taken place by ductile shear in the rocks of the lower and middle crust. The plutons of the Tertiary mafic crust are interpreted to penetrate the entire crust west of the extended older rocks. They are exposed in a belt, from which Proterozoic rocks are absent, that is over 180 km long and at least 10 km wide at the surface. The rocks buried beneath the coastal plain and shelf sediment may be Tertiary mafic plutons, extended continental crust, or a mixture of both rock types. I think they may be chiefly Tertiary mafic plutons and dikes because (1) the thin crust there requires unrealistic extensional values if continental rocks are abundant, (2) the exposed mafic plutons intruded through crust that was at least 25 km thick and are thus probable in the thinner crust to the west, and (3) the depth of the subsediment crust (greater than 4 km below sea level) is consistent with an oceanic model. Girdler and Underwood [1985] and LaBreque and Zittilini [1985] call for oceanic crust to at least the shoreline using geophysical arguments.

Regardless of the type of crust beneath the coastal plain, the Tertiary mafic crust was derived from a similar parent to oceanic ridge basalts, but the original magmas possibly fractionated deeper. Preliminary results of a petrochemical investigation by J. E. Quick and R. G. Bohannon (unpublished manuscript, 1986) suggest that the compositions of the dikes in the Tertiary mafic crust can be explained by partial melting of mantle at a pressure of about 20 kb. Figure 10a shows the compositions of 18 basalts projected from plagioclase onto the diopside-olivine-quartz plane using the method of Walker et al., [1979]. Cotectics for 1 atm [Walker et al., 1979] and 10 and 20 kb [Stopler, 1980] are also shown. The data define a field that extends from silica- to nepheline-normative compositions. Plots of TiO_2 and Fe/Fe+Mg against normative silica (Figures 10, #10) suggest that this field is produced by two differentiation trends that proceed from near the olivine-diopside join, one toward silica enrichment and the other toward silica depletion. These observations suggest melting in the upper mantle followed by a rapid rise through the mantle and lower crust with subsequent fractionation of olivine and then olivine + diopside at pressures less that 10 Kb.

CONCLUSION

The important question of crustal character beneath the sediment of the coastal plain and shelf remains unanswered by this study. I am inclined to the more



Fig, 9. Generalized cross section through crust drawn perpendicular to coastline at about 17° N. Vertical equals horizontal scale.

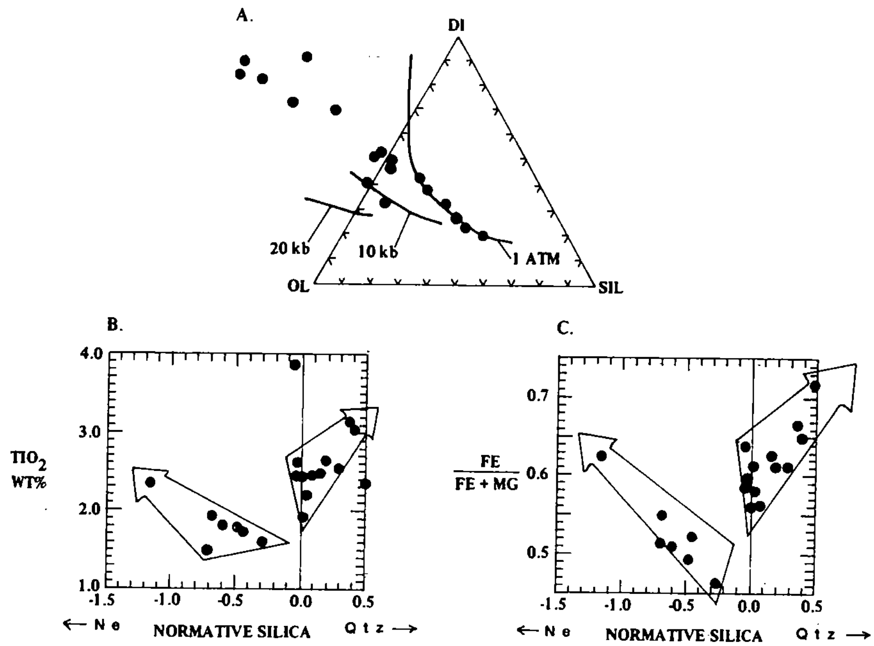


Fig. 10. (a) Compositions of 18 basalt glass analyses compared with deduced phase boundaries [Stopler, 1980; Walker et al., 1979] projected from PLAG onto OL-DI-SIL. (b) Weight percent TiO_2 plotted against normative silica. (c) Iron/iron plus magnesium plotted against normative silica. Plots show a systematic divergence between nepheline- and quartz-normative samples with increasing differentiation.

"oceanic" interpretation, particularly under the shelves where the buried crystalline crust is 4 to 15 km thick. This interpretation requires a shoreline overlap in Red Sea palinspastic reconstructions. The seismic models seem to require a close fit of the shorelines regardless of the crustal character [Bohannon, 1986]. These interpretations are at odds with the shoreline-gap reconstructions from the northern Red Sea [e.g., Cochran, 1983] which rely on extensive continental crust under the Red Sea shelves. A solution to the discrepancy is not obvious and a treatment of the problem is beyond the scope of this paper.

The shore-to-shore and shoreline-overlap reconstructions of the pre-Red Sea Afro/Arabian continent [McKenzie et al., 1970; Greenwood and Anderson, 1977; Girdler and Underwood, 1985; Bohannon, 1986] demand that the early rift was narrow. The Arabian geology shows that most of the rift was extended by 10% or less. Intense extensional deformation and early expansional plutonism were confined to a narrow belt in the rift axis. That belt was only about 20 km wide if there is chiefly Tertiary mafic crust beneath the sediment of the shelf and coastal plain. The belt of extension might be as wide as 50 km if all of the crust beneath the coastal plain and shelf is continental, but that is the upper limit as constrained by crustal thickness. Figure 11a depicts the shape of the continental crust after extension, but prior to intrusion of the Tertiary mafic rocks and it suggests that only 16 km of divergence was necessary to produce the observed extension and crustal thinning. The model is drawn assuming most of the rocks beneath the coastal plain and shelf sediments are Tertiary mafic intrusions.

The Tertiary mafic intrusion interpretation requires a wedge of "oceanic crust" that is 25 km thick adjacent to the continent and less than 10 km thick under the Farasan Islands. The sheeted dikes, layered gabbros, granophyres and volcanic rocks exposed on the Arabian margin are seen as the first of these igneous rocks

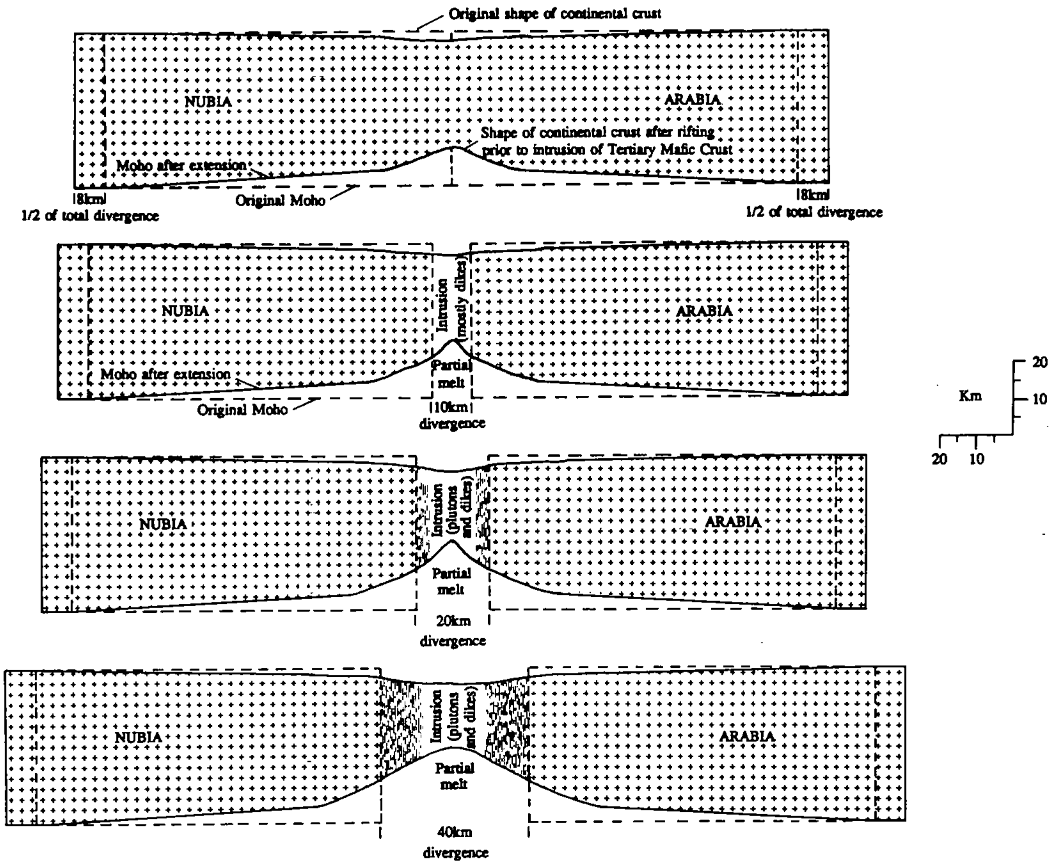


Fig. 11. Model for early history of Red Sea. (a) Possible configuration of Red Sea rift prior to intrusion of Tertiary mafic crust. Rift developed to this approximate configuration by mechanical extension if no extended continental crust occurs beneath coastal plain. Extension causes crust to thin to 65% of original thickness in axis of rift with only 16 km of divergence between Africa and Arabia. (b) Additional divergence was accommodated by intrusion of Tertiary mafic crust into previously thinned continental crust. (c) Further divergence allows a thinner igneous crust to form. (d) Further divergence allows a thinner igneous crust to form.

to have formed. The formation of that crust is explained on Figures 11b,d as a crustal accretion process that began immediately following crustal thinning. Thus, plutons such as the Jabal At Tirf layered gabbro might be "half plutons" intruded on their seaward sides by younger plutons similar to the way sheeted dikes form. The youngest intrusive crust is thick and it contains a large volume of silicic intrusive and volcanic rocks because it intruded thick continental crust when Africa and Arabia were close to one another (Figure 11b). Thinner igneous crust can form with time as the thick continental masses become farther separated and their affect on the lithostatic pressure directly above the partially melted mantle in the axis of the rift lessens. The mafic igneous rocks on the continental margin of Greenland [Brooks and Nielsen, 1982] and the thick oceanic crust off Norway [Mutter et al., 1984] might represent other examples of this process.

This interpretation represents an extreme case and would have to be altered slightly if continental crust occurs beneath the coastal plain. However, I do not regard other models which rely on large amounts of continental crust beneath the Red Sea shelves to be tenable if the seismic models of Mooney et al., [1985], Prodehl [1985], or Milkereit and Fluh [1985] are correct.

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