UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Middle Tertiary continental rift and evolution of the Red Sea in southwestern Saudi Arabia

by

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Open-File Report 83-641

Prepared for the Ministry of Petroleum and Mineral Resources
Deputy Ministry for Mineral Resources
Jiddah, Kingdom of Saudi Arabia

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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1983

CONTENTS

ILLUSTRATIONS

[Plate is in back pocket]

TABLES

MIDDLE TERTIARY CONTINENTAL RIFT AND EVOLUTION OF THE RED SEA IN SOUTHWESTERN SAUDI ARABIA

by

Dwight L. Schmidt[1], Donald G. Hadley, and Glen F. Brown[2]

ABSTRACT

Middle Tertiary rift volcanism in a continental-rift valley in the Arabian-Nubian Shield was the first surface expression of active mantle convection beneath an axis that was to become the Red Sea. Investigation of the coastal plain of southwestern Saudi Arabia suggests that the rift valley was filled with basaltic and felsic to rhyolitic volcanic rocks (Ad Darb and Damad formations), cherty tuffaceous siltstones (Baid formation), and subordinate Nubian-type quartz sandstone (Ayyanah sandstone) between about 30 and 20 Ma ago. These rocks are named herein the Jizan group. At the same time, alkali-olivine basalt was erupted on the stable Precambrian craton at locations 100 to 200 km east of the rift valley axis.

First-stage spreading of the Red Sea began about 20 Ma ago when diabasic dikes and gabbro and granophyre plutons (Tihamat Asir complex) of oceanic-tholeiitic parentage were intruded into the continental-rift deposits. The new oceanic crust was injected into a region of thinned continental crust. Because of thinning, the continental crust was extended and became fractured into a series of fault blocks. Crustal extension in the attenuated zone was accompanied by mafic and silicic volcanism producing a continental rift-valley tectonic environment. Fault blocks of the rift valley were initially rotated toward the Red Sea during the first-stage spreading episode. Inland from the continental rift, the thick continental crust was distended on long parallel fractures that were intruded by gabbroic to quartz syenitic magma to form continental dikes. This period of continental-margin extension was short lived, lasting perhaps only 1 or 2 Ma. The first-stage sea-floor spreading of the Red Sea continued until about 15 or 14 Ma ago at a half-spreading rate of about 2.2 cm/yr.

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Throughout early Tertiary time, the Arabian Shield erosion surface remained near sea level. First-stage uplift of the Red Sea Escarpment began during middle Miocene time, as evidenced by the coarse polymictic boulder conglomerate of the Bathan formation. Second-stage scarp uplift and second-stage sea-floor spreading followed during Pliocene, Pleistocene, and Holocene time.

INTRODUCTION

Prior to this study, a continental-rift stage had not been recognized as part of the Red Sea evolution. The volcanic deposits of this continental rift are well exposed in low-relief foothills and along incised wadis in the alluviated coastal plain of southwestern Saudi Arabia from Jiddah south to the Yemen border (fig. 1, plate 1). The long-standing contention that the lake-bed deposits of the Baid formation (Brown and Jackson, 1958) were younger than the early basaltic rocks of the Red Sea crust prevented the recognition of the Baid formation as an integral part of a continental rift that predates the formation of oceanic crust in the Red Sea basin. The Baid formation is the central theme of this report.

Previous studies

In 1951 G. F. Brown and R. O. Jackson named the Baid formation for exposures along Wadi Bayd. The formation is described briefly in the explanation to the 1:500,000-scale geologic map of the Asir quadrangle (Brown and Jackson, 1959) as:

> Miocene, gray, red, and green siliceous and tuffaceous shale; calcareous layers and lenses; and tuffaceous green sandstone....Contains freshwater fish fossils near Darb.

Brown (1970) briefly discussed the freshwater fish fossils as belonging to two families of the genera Barbus and Tilapia, which are widespread in Asia and Africa today, and overall evidence suggests a late Oligocene or Miocene age for the Baid formation (A. H. Dunkle, U.S. National Museum, written commun., 1953).

In the Asir quadrangle Brown and Jackson (1959) also mapped an "andesite and diabase" unit, which in many places is in contact with the Baid formation. The andesite and diabase unit consists of:

> hypabyssal igneous complex of glomeroporphyritic andesite, diabase, felsite, aplite, and olivine basalt;

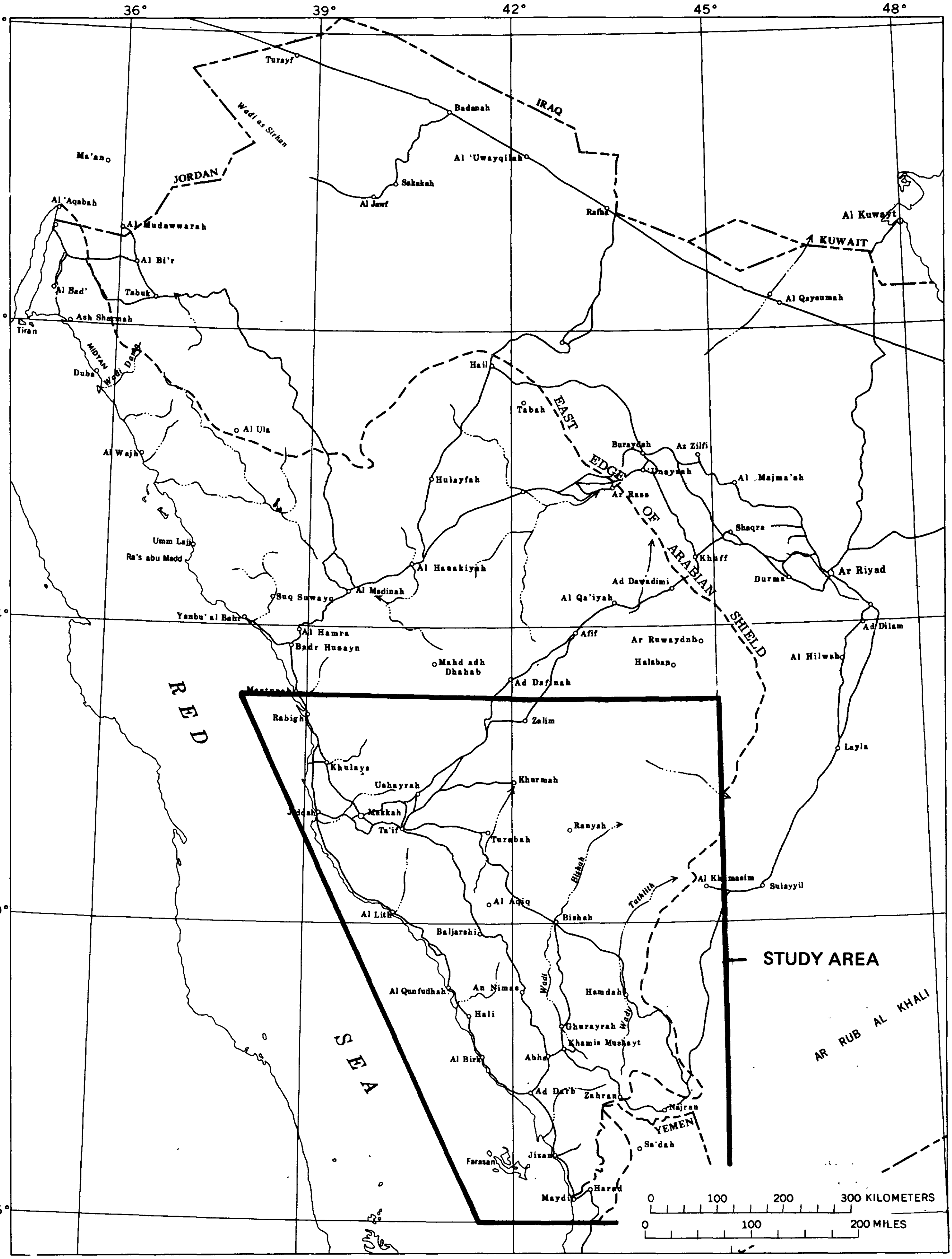

Figure 1.--Index map of western Saudi Arabia showing location of study area.

minor amounts of labradorite, augite gabbro, and fine-grained granite...Also includes shale xenoliths of Miocene age.

Brown and Jackson (1959) rightly recognized these rocks as being essentially a volcanic unit intruded by many diabase dikes, gabbro, and granite. We name the volcanic part of this unit the Jizan group, and the intrusive part already has been named the Tihamat Asir complex. (Coleman and others, 1979).

The Jurassic Hanifa Formation, which consists of limestone, is older stratigraphically than the Tertiary Baid formation (Brown and Jackson, 1959). It is equivalent to the Amran Series in Yemen. Amran Series is used in this report because of geographic proximity as opposed to the type Hanifa Formation of the central Arabian Tuwayq Mountain escarpment. It is underlain by the Jurassic(?) Khums formation and the early Paleozoic Wajid Sandstone, both of which consist of Nubian-type quartz sandstone (Whiteman, 1970). These formations in turn rest on the Precambrian rocks of the Arabian Shield.

Gillmann (1968) of AUXERAP (Auxiliar Enterprise de Recherches et L'activities) published a summary of the geology of the Jizan coastal plain based on geologic mapping, aeromagnetic and seismic surveys, and a deep drill-hole test. He used the stratigraphic terminology of Brown and Jackson (1959) and retained the Baid formation as the youngest exposed deposit associated with the development of the Red Sea.

Within the Baid formation, Gillmann (1968, p. 195) found fish fossils (Cretaceous-Tertiary teleosts), as well as poorly preserved ostracods, in green silicite (siliceous shale) in a section 1,060 m thick east of Jizan. He also records a section 1,200 m thick of Baid formation in the Ad Darb-Wadi Bayd area. Both of these sections include abundant diabasic sills. He suggested a Middle to Late Tertiary age for the Baid formation.

Coleman and others (1979, p. 6, 24) placed the Baid formation unconformably above their Tihamat Asir complex (Blank, 1977), which they interpreted to be the earliest oceanic crust of the Red Sea. The complex consists of sheeted dikes intruded by gabbro and granophyre plutons, and is equivalent to the intrusive part of the andesite and diabase unit of Brown and Jackson (1959).

The Bathan formation, a tilted polymictic boulder conglomerate, overlies the Baid formation and was named for excellent exposures along Wadi Bathan (Hadley and Fleck, 1980). Nebert and others (1974) mapped and described a similar deposit east of Jiddah that they considered to be Neogene(?) in age. Brown and others (1963) first described these deposits and included them in a "terrace sand and gravel" unit that is "dissected and not obviously related to the present drainage." Hadley and Fleck (1980) assigned a Pliocene age to the Bathan formation and associated its deposition and deformation to Pliocene uplift and faulting of the Red Sea Escarpment. The Pliocene age assignment of the Bathan Formation was suggested on the basis that the Bathan "bears no relationship to the Holocene drainage system; it is strongly indurated, it is moderately tilted, and it dips toward the Red Sea escarpment" (Hadley and Fleck, 1980, p. 7).

Quaternary to middle Miocene sedimentary deposits are recorded from a deep drill hole, Mansiyah Well No. 1, located 1.5 km inland from the coast and 40 km north of Jizan (Gillmann, 1968, p. 196-198). This drill hole intersected (unit terminology from Gillmann):

171 m of Pliocene and Pleistocene sandy limestone

2,059 m of a Continental Series, divided into an upper member of red shale with metamorphic and volcanic rock pebbles, a middle member of red shale with thin dolomite and anhydrite beds, and a lower member of red shale with sandstone and conglomerate

1,242 m of Evaporite Series of middle to upper Miocene salt with rare anhydrite layers

460 m of Infra-evaporitic Series of lower Miocene gray shale containing silt, fine-grained sandstone, and conglomerate

The drill hole was terminated at 3,931.6 m, and Gillmann interpreted the Infra-evaporitic Series to be laterally equivalent to the Baid formation, despite the fact that no volcanic debris is reported. His correlation across the Red Sea to the Sudan well Durwara No. 2 suggests that the Infra-evaporitic series, in which presumably no fossils were found, may be equivalent in part to the middle Miocene and lower-middle Miocene Globigerina Marls.

Present studies

In March 1974, D. G. Hadley, R. G. Coleman, and D. L. Schmidt briefly studied the Tertiary intrusive, volcanic, and sedimentary rocks of the southern coastal plain from Harrat al Birk to Wadi Khulab (Coleman and others, 1977; Ghent and others, 1979). Subsequently Hadley and Greenwood extended the study of the Baid formation from Al Birk to south of Jiddah. Their mapping of the Baid formation is recorded on four 1:100,000-scale quadrangle maps: Al Qunfudhah (19/41 C), Musaylim (19/40 B), Manjamah (18/41 A), and Jabal Shada (19/41 A) (Hadley, 1975, 1980, and 1981 and Greenwood, 1975a, respectively).

More recent regional mapping of 1:100,000-scale quadrangles that contain the Baid formation has been done in the Ad Darb area (Fairer, both in press), in the Jizan area (Blank and Gettings, unpub. data), and in the area south of Jiddah (Pallister, 1983). Between January and May of both 1980 and 1981, Schmidt studied the Baid formation and associated volcanic and intrusive rocks in the coastal plain between Jiddah and the Yemen border (fig. 1, plate 1).

In the present study, we show that the Baid formation is an integral part of a volcanic sequence deposited in a continental-rift valley that predates sea-floor spreading of the Red Sea and intrusion of the Tihamat Asir complex. We show that the Quaternary to middle Miocene coastal deposits of Gillmann (1968) overlie Red Sea oceanic crust and cannot be correlated with the Baid formation. The middle Miocene Bathan formation records the initial uplift of the Red Sea Escarpment.

Acknowledgments

This research is part of a continuing program of investigations of the Arabian Shield and contiguous parts of the Red Sea coastal plain. The work on which this report was based was performed in accordance with a work agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey (USGS). The support provided by the Saudi Arabian Directorate General of Mineral Resources (DGMR) is greatly appreciated. Chemical analyses were computed and plotted on the USGS Multics computer system by George VanTrump, Jr., Denver, using the Graphic Normative Analysis Program (GNAP) (Bowen, 1971), as modified by Stuckless and VanTrump (1979). We are particularly grateful to C. T. Madden (USGS, Denver) for preliminary vertebrate fossil identifications that corroborate our age assignment of the Baid formation. Extensive discussions with H. R. Blank, Jr., M. E. Gettings, J. S. Pallister, and R. G. Coleman have greatly stimulated our study of the Red Sea continental margin.

STRATIGRAPHY

Jizan group

Aside from the prior informal designation of the Baid formation (Brown and Jackson, 1959), a stratigraphy for the rocks of the continental rift, the Jizan group, is established for the first time in this report (fig. 2). Stratigraphic names as used in this report are informal pending completion of the compilation of detailed sections and additional study of thin sections. Numerous sections (plate 1) show the stratigraphic position of the Jizan group rocks relative to

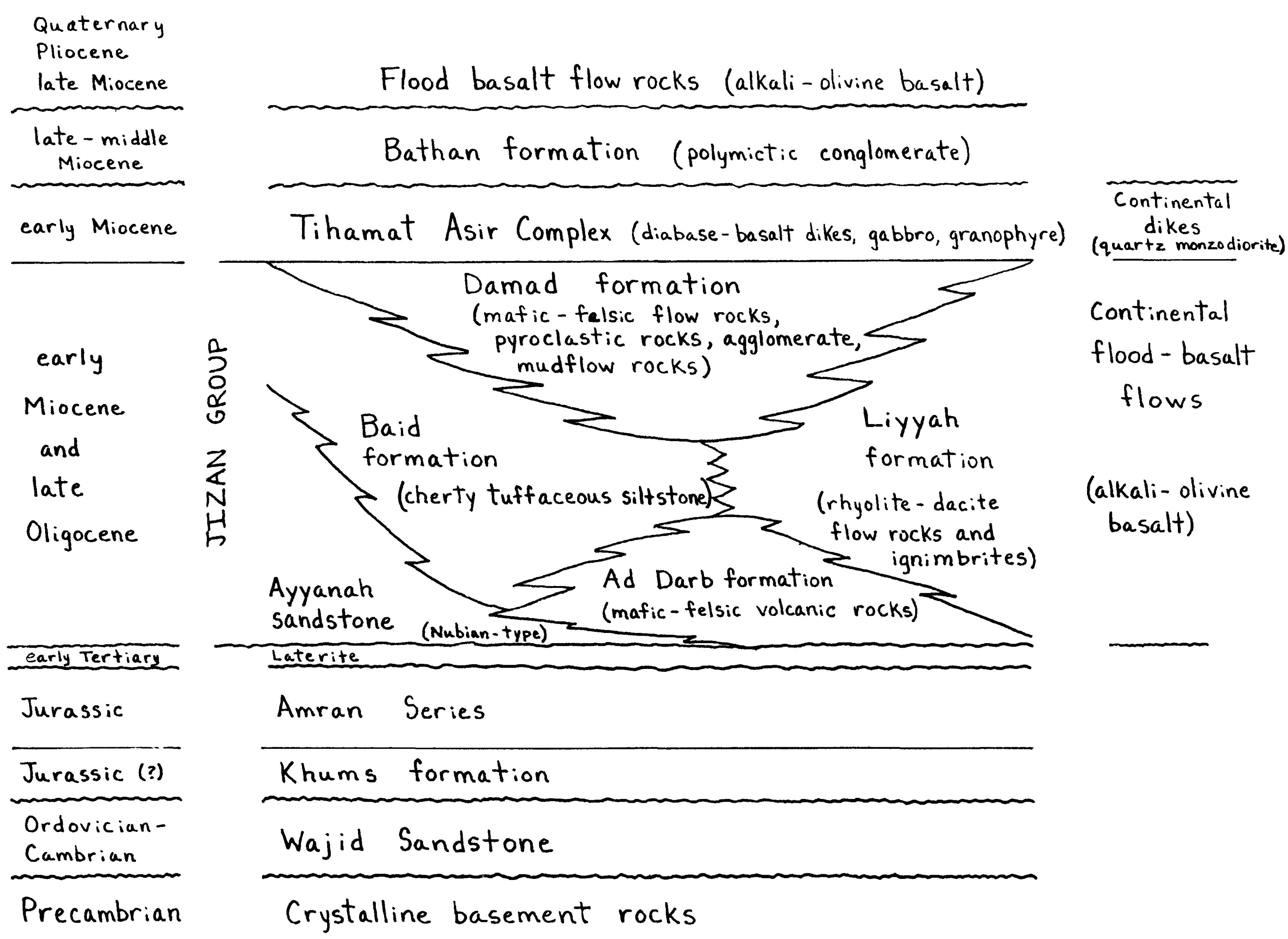

Figure 2.--Schematic stratigraphic diagram showing the middle Tertiary Jizan group and rock units above and below it within the continental rift of the Red Sea coastal plain, southwestern Saudi Arabia. Dikes and flows (right side) are inland of the continental rift.

older and younger rocks at various localities along the coastal plain from Khulays to the Yemen border.

The rocks of the continental rift are designated herein the Jizan group for the well-exposed partial section in Wadi Jizan east of Abu Arish. For the most part these rocks are exposed along the foothill belt, which is from 4 to 6 km wide and located on the east side of the Jizan coastal plain from Ad Darb to the Yemen border. The Jizan group consists of a local basal sandstone unit, a thick sequence of mafic and felsic volcanic rocks, and the widely recognized Baid formation (Brown and Jackson, 1959) that consists of cherty tuffaceous siltstones. The lower mafic to felsic volcanic rocks are herein designated the Ad Darb formation; compositionally restricted felsic volcanic rocks (largely time equivalent to the Baid formation) are designated the Liyyah formation; and the upper mafic to felsic volcanic and volcaniclastic rocks are designated the Damad formation. The volcanic and volcaniclastic rocks of the Ad Darb and Damad formations are highly altered deuterically and hydrothermally and are thermally metamorphosed where intruded by dikes and plutons. The rocks of the Liyyah formation are likewise altered, but because of their silicic composition, they are altered less intensely. Aside from the Brown and Jackson (1959; Gillmann, 1968) reference to andesite in their andesite and diabase unit, the Jizan volcanic rocks have not been previously recognized or mapped. The volcanic rocks increase in thickness from Ad Darb south to the Yemen border as the thickness of the Baid lakebed facies decreases. From Al Qunfudhah northward, a basal quartz sandstone and quartz-pebble conglomerate unit, herein named the Ayyanah sandstone, underlies the Baid formation and the volcanic rocks of the Damad formation.

The exposed thickness of the Jizan group varies greatly from less than 100 m between eruptive centers to more than 2,000 m at eruptive centers. However, commonly the base is not exposed and the top is always deeply eroded. In addition, the rocks are intensely faulted, and structural complications require detailed mapping to resolve the stratigraphy.

Ayyanah sandstone

A clastic facies of thin beds of well-bedded quartz sandstone and quartz-pebble conglomerate (fig. 3) derived from weathered Precambrian terrane comprises the base of the Jizan group in the coastal plain of Al Qunfudhah. One or two thin sandy limestone beds (fig. 4) are interbedded with quartz sandstone beds in the upper part of the formation. These quartzose sedimentary rocks are named the Ayyanah sandstone for the village of Ayyanah, 15 km east-northeast of Al Qunfudhah. About 17.5 km east-northeast of Ayyanah, on the north side of Wadi Qanunah, there is a reference section in

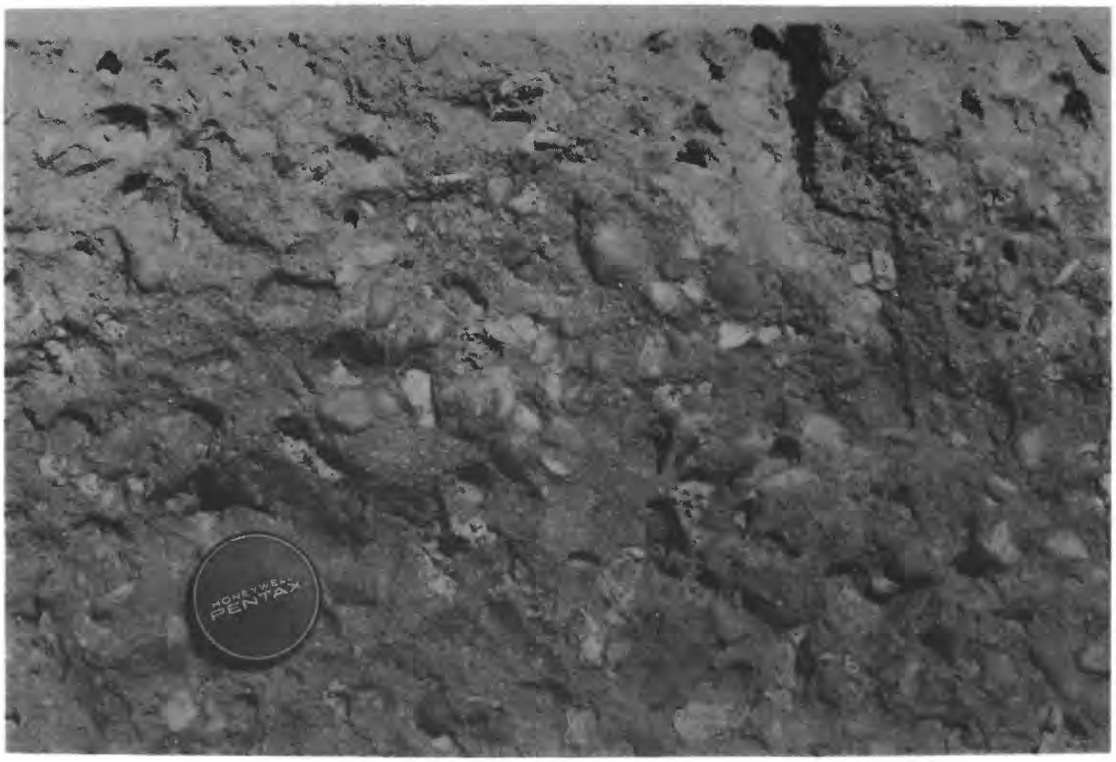

Figure 3.--Photograph showing outcrop of basal, red, quartz-pebble, very coarse grained sandstone; Ayyanah sandstone, Al Qunfudhah quadrangle, 6· km S. 78° E. from Ayyanah.

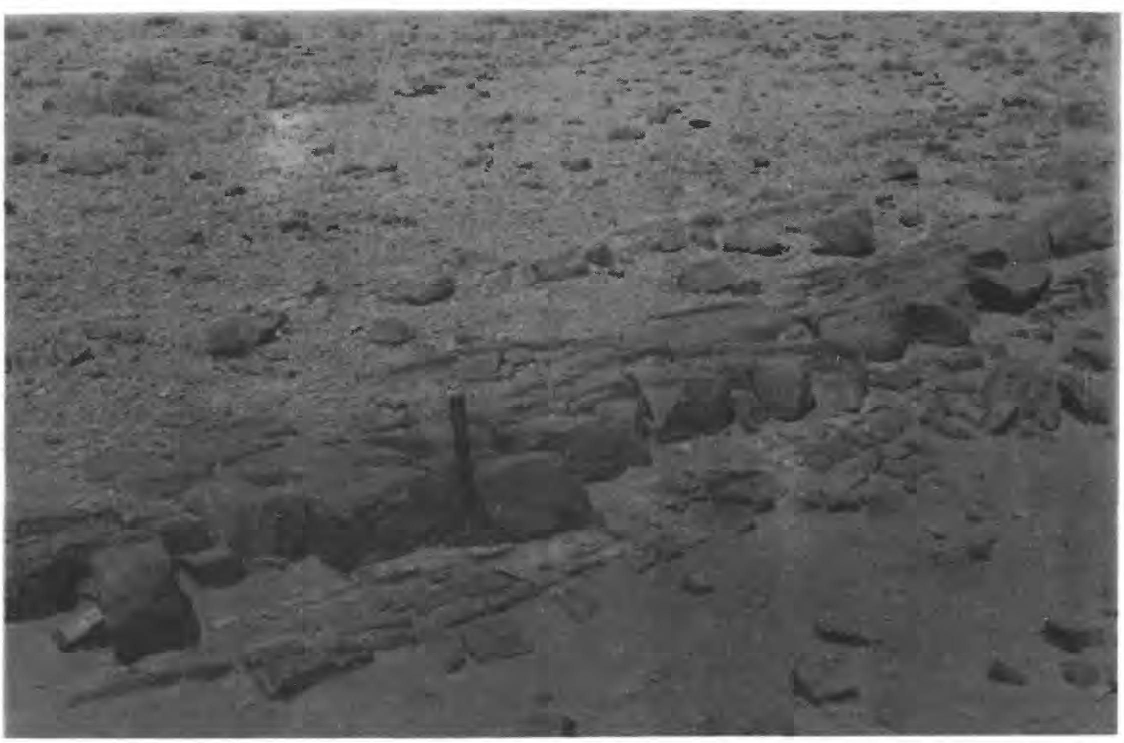

Figure 4.--Photograph showing outcrop of dense, gray limestone bed, 10 cm thick, which overlies quartz sandstone; Ayyanah sandstone, near locality of figure 3.

which the submature quartzose sedimentary rocks are 42 m thick. These rocks unconformably rest on saprolitic Precambrian schists and are overlain conformably by Baid formation siltstones. On the south side of Wadi Qanunah, the Ayyanah sandstone is 22 m thick between the overlying Baid formation siltstones and a fault against the Precambrian rocks (Hadley, 1975).

The Ayyanah sandstone was derived from deeply weathered Precambrian crystalline rocks on a low-altitude, low-relief surface; no Red Sea Escarpment could have existed at this time. Southward from Al Qunfudhah to the Yemen border, very little of this continental sedimentary facies is found because the exposed basal part of the Jizan group consists of volcanic deposits.

East of Jiddah, the Shumaysi formation, as much as 180 m thick, consists of a quartz sandstone facies that is similar to the Ayyanah sandstone. In contrast, the middle member of the Shumaysi formation contains a distinctive oolitic iron facies, and pollen from this member suggests a lower Eocene (Cuisian) age (Moltzer and Binda, 1981, p. 70). However, the upper member contains a layer of siliceous ash that probably correlates with the Baid formation. Mollusk fossils from the upper member were identified to be not older than Oligocene (L.R. Cox, in Al Shanti, 1966, p. 23). The upper Shumaysi formation is overlain by a basaltic flow sequence containing several more siliceous ash beds similar in composition to those of the siliceous siltstones of the Baid formation (see chemistry discussion, below).

Therefore, at least some part of the upper member of the Shumaysi formation may correlate with the Ayyanah sandstone. The volcanic rocks, as much as 100 m thick overlying the Shuymaysi formation east of Jiddah, probably correlate with some part of the Jizan group.

Baid formation

The cherty tuffaceous Baid formation (Brown and Jackson, 1959) is a lake-bed facies of the Jizan group and is present in most outcrops of the rift volcanic rocks from the Yemen border to Jabal Sita, south of Jiddah, a distance of almost 600 km. The lake-bed facies is thin or even missing in areas where silicic volcanic eruptive centers can be identified, such as at Jabal Sita and Wadi Liyyah. The lake-bed deposits consist of water-worked silicic ash and tuff produced by explosive volcanism within a continental rift that evolved into the Red Sea basin.

In the area between Ad Darb and the Yemen border, the Baid formation is well confined between the Ad Darb and Damad formations. It is as thick as several hundred meters, but near eruptive centers, such as in Wadi Liyyah, it thins to less than a meter. A good reference section on the south side of Wadi Jizan is about 300 m thick. To the north, near Al Qunfudhah, more than 150 m of the Baid formation are exposed, but in most places both its top and bottom are covered by Quaternary alluvium. The base of the Baid formation is only in direct contact with the Ayyanah sandstone in a few places, and in these cases, several thin quartzose sandstone beds are interbedded with the lowest 10 to 20 m of the Baid formation. Farther north at Jabal Sita, the Baid formation siltstones are thin where they are overlain and underlain by thick volcanic sections from a local eruptive center (Pallister, 1983).

The Baid formation lake-bed deposits (figs. 5, 6) consist of cherty and tuffaceous siltstone, claystone, and shale. Individual beds are cyclic (varvelike); they are commonly graded and consist of a more massive, coarser grained, lower part that passes upward through an increasingly finer grained, more laminated middle part to a thin, finely laminated, very fine grained upper part. Some cyclic beds grade upward from a sand-sized tuffaceous lower part; other beds contain lapilli and rare breccia-sized volcanic debris. Some cycles may represent the direct deposition of air-fall ash and tuff from periodic eruptions of distant volcanoes; however, most probably represent cyclical erosion and deposition by intermittent rains of erupted ash from the surrounding landmass.

As observed in thin section, representative samples of the Baid formation rocks are highly siliceous and sericitic, and, under high-power magnification, the silica appears as microcrystalline to cryptocrystalline radial growths. Grading is commonly obscured by very fine grained deuteric sericite and microcrystalline iron oxides. In many sections a strong foliation parallel to layering was observed that may mimic an original depositional fabric formed from devitrified glass shards.

In thin section the rocks are light tan to red brown, depending on the amount of recrystallized iron oxide minerals dispersed in the rock. In at least one section iron oxide had replaced pollen grains. All rocks examined are cherty and contain large amounts of silica. No silica-secreting microorganisms such as diatoms were observed, and therefore the excess silica probably accumulated by secondary enrichment from solution of the primary tuffaceous siltstones. Identifiable volcanic phenocrysts of quartz or feldspar are rare in the thin sections studied. Detritus from the Precambrian terrane has not been identified, and if it exists, such detritus is extremely sparse and fine grained.

Figure 5.--Photograph showing outcrop of Baid formation, Jabal Shada quadrangle; section is 3 m thick, bedding dips 30° SW.

Figure 6.--Photograph showing closeup view of thin-bedded and laminated cherty tuffaceous Baid formation; from outcrop of figure 5.

Liyyah formation

The Liyyah formation is named for Wadi Liyyah near the Yemen border, and a reference section is located 2.5-3 km northwest of Wadi Liyyah in a south fork of Wadi Khulab. Abundant silicic volcanic flow rocks, ignimbrites, tuffs, and breccias of rhyolitic and dacitic(?) composition and of tan to red-brown and dark-gray color have been observed within the mafic to felsic volcanic sections south of Wadi Khulab. Thick sections are also exposed in the vicinity of Jabal Sita and Harrat Tuffil. These thick Liyyah sections were probably deposited at silicic volcanic centers within the continental rift (fig. 2). Thinner sections and individual flow units of silicic flow rocks, ignimbrites, and tuffs are above, below, and within the Baid formation, but overall, silicic volcanic rocks are sparse in areas where the Baid formation is thick, as in the Wadi Jizan to Ad Darb area and in the Al Qunfudhah area. The silicic volcanic rocks were deposited mostly at and near eruptive centers, and the Baid formation was deposited between these centers from airborne ash and tuff. Therefore, the Liyyah formation is considered to be mostly contemporaneous with the Baid formation, and the respective thicknesses of the two formations are inversely related to one another. South of the Yemen border, the abundant silicic volcanic rocks (mostly ignimbrites) in the extensive and thick Yemen Volcanics (Grolier and Overstreet, 1978) are believed to be equivalent to the Liyyah formation.

Ad Darb and Damad formations

In the Jizan group, massive, intensely altered volcanic deposits are both above and below the Baid and Liyyah formations. The lower volcanic unit is named the Ad Darb formation for the town of Ad Darb, and a reference section is located 3-4 km southeast of Ad Darb and 2 km south of Wadi Itwad. The upper volcanic unit is named the Damad formation for Wadi Damad, and a reference section is located along a north fork of Wadi Jizan, 3-4 km south of Wadi Damad.

These formations consist commonly of light-green tuff, agglomerate, pyroclastic flow rock, and lava. Some thick, mafic volcanic-breccia deposits are thoroughly altered and oxidized bright red brown. Field observations suggest that the volcanic rocks vary from basalt and andesite to trachyte, although no chemical analyses are presently available. In some massive sections, detrital layers, beds, and mudflows were found, but these units are difficult to identify, except locally where faint sedimentary structures and volcanic clasts can be recognized. These detrital layers are entirely volcaniclastic and are similar in composition and alteration to the interlayered eruptive rocks.

The Ad Darb formation ranges from zero to several hundreds of meters thick depending on the distance from eruptive centers. At distal areas little or no rock of the Ad Darb formation is found beneath the Baid formation. In places near eruptive centers, the silicic volcanic rocks of the Liyyah formation separate the volcanic rocks of the Ad Darb formation from the volcanic rocks of the Damad formation.

The Damad formation is cut everywhere by an erosional unconformity such that its true thickness is not known, but in places, hundreds to perhaps several thousands of meters of the Damad formation can be measured. The Damad formation more commonly contains many thick massive layers of mudflow and volcaniclastic deposits.

Tihamat Asir complex

Throughout the Tihamat Asir area between Ad Darb and the Yemen border, the Jizan group has been intruded by many diabasic dikes and gabbro and granophyre plutons. Blank (1977, p. G3) named the dikes the "Tihamat Asir dike swarm"; Coleman and others (1979, p. 3) broadened the term to "Tihamat Asir complex" to include the plutonic rocks; we similarly use Tihamat Asir complex for the unit. These intrusive rocks are of oceanic-tholeiitic parentage (Coleman and others, 1979), and they were intruded into the continental margin during the initiation of sea-floor spreading.

Diabasic dikes form long black ridges in the foothill belt west of the outcrop of Precambrian rocks. Along the incised wadis that cut the foothill belt and adjacent coastal plain, young dikes, commonly from a meter to several tens of meters wide, intrude older, more altered diabasic dikes. Taken to the extreme, the intensely altered matrix rock between identifiable dikes formerly was presumed to consist entirely of a dike-on-dike complex that represented the edge of the Red Sea oceanic crust exposed on land (Coleman and others, 1979). However, the altered matrix rock is volcanic rock belonging to the Jizan group. The Jizan group volcanic rocks and Tihamat Asir complex intrusive rocks are considered to be underlain by thinned continental crust and not by oceanic crust.

From our measured sections in the Tihamat Asir, the diabasic dikes account for 10 percent or less of the exposure width of the rift volcanic rocks; this is affirmed in studies by H. R. Blank, Jr., M. E. Gettings, and K. S. Kellogg (written commun., 1981). In places the dikes are closely spaced, but in adjacent areas the dikes are widely spaced.

Bathan formation

The Bathan formation is a coarse polymictic boulder conglomerate that unconformably overlies the Jizan group as exposed in places from Harrat al Birk northwest to Jiddah. The conglomerate is exposed on the north side of Wadi Hali (Hadley, 1981), on the north side of Wadi ad Duqah near Musaylim (Hadley, 1980), northeast of Al Lith on Wadi Bathan where the reference section is defined by Hadley and Fleck (1980), beneath Harrat Tuffil, and east of Jiddah near Wadi Fatimah (Nebert and others, 1974). At all five localities the Bathan formation overlies rocks of the Jizan group and is not known to be cut by diabasic or basaltic dikes of the Tihamat Asir complex. The boulder conglomerate was first described by Brown and others (1963) for the out-crops at Wadi Bathan and east of Jiddah.

The Bathan formation is a terrigenous clastic sequence that consists mostly of boulder-cobble conglomerate, pebble conglomerate, and sparse beds of coarse-grained sandstone (figs. 7, 8). Boulders, as long as 2.5 m, are composed mostly of Precambrian rocks, but local volcanic clasts of Jizan group rocks are found. At Wadi Bathan the conglomerate is deformed along faults parallel to the Red Sea axis, and it dips about 15° NE., opposite to the common westward dip of the Baid formation in the coastal plain. The Bathan is at least 100 m thick but may be several times as thick. East of Jiddah the formation dips from 20° to 30° SW. and is from 150 to 200 m thick (Nebert and others, 1974, p. 24). The conglomerate is deeply eroded everywhere, and its original thickness in places may have been as much as 200 to 300 m.

The Bathan formation is younger than the Tihamat Asir complex because Tihamat Asir dikes are not known to cut the formation. More specifically, the Bathan formation is younger than the Jizan group because it contains clasts of the Baid and Liyyah formations in Wadi al Lith and at Harrat Tuffil. The angular unconformity beneath the Bathan formation suggests that it is considerably younger than the Jizan group, and it is probably middle or late Miocene in age. The Bathan formation records the first erosion of a high-relief Precambrian terrain to the east of the continental rift, and its composition contrasts sharply with the lack of coarse, nonvolcanic clastic rocks in the Jizan group. The Bathan formation records the first major, rapid uplift of the Red Sea Escarpment.

Figure 7.--Photograph showing outcrop of Bathan formation, about 30 m thick, as exposed from near type section in the Al Lith quadrangle. Large boulder in right foreground is 2 m across.

Figure 8.--Photograph showing closeup view of Bathan formation near the confluence of Wadi Bathan and Wadi al Lith, 2.5 km north of the outcrop shown in figure 7; a coarse-grained sandstone bed, 10 cm thick, is seen above hammer.

CHEMISTRY OF LIYYAH AND BAID FORMATION ROCKS

Available chemical analyses of volcanic rocks from the Jizan group are limited to silicic rocks, the most fractionated products of the continental-rift volcanism. The cherty tuffaceous siltstones of the Baid formation were sampled at Jabal Sita, Musaylim, Al Qunfudhah, and Ad Darb; these and one sample of bedded tuff from near Wadi Fatimah (east of Jiddah) have a geographical distribution of 500 km along the southern coastal plain. The analyses of 22 rocks including 3 limestones are given in table 1. Thirteen analyses of perlite (table 2) underlying Jabal Shama, just north of Harrat Tuffil, are from Laurent's (1976) investigation of the perlite as an industrial raw-materials product. The perlite probably correlates with the Liyyah formation. In addition, four analyses (W. C. Overstreet and M. J. Grolier, written commun., 1980), representative of the rhyolitic welded tuffs from the Yemen Volcanics of North Yemen (Grolier and Overstreet, 1978), are also included in table 2. As mentioned above, the silicic volcanic rocks of the Yemen Volcanics probably correlate with the Liyyah formation.

Rhyolites of the rift volcanic rocks

Plots showing the normative compositions of the perlites from Jabal Shama (Liyyah formation), the tuff from Wadi Fatimah, and the ignimbrites (welded tuffs) from North Yemen (fig. 9) indicate that using the modal classification of Streckeisen (1979) they are all rhyolite and mostly alkali-feldspar rhyolite. These three suites of rhyolite are similar in major-element composition; the average SiO_2 contents are 76.5 and 75.7 percent (water free) for the Jabal Shama suite and Yemen Volcanics suite, respectively. Four of thirteen of the Jabal Shama rhyolites are peralkalic (as defined by Shand, 1951) and three are alkalic, whereas one of four of the Yemen Volcanics is alkalic; all other rhyolites are peraluminous (fig. 10).

The normative compositions of the rhyolites plot in the projection of the low-temperature trough on the Ab-Q-Or face (fig. 11) of the Ab-Q-Or-H_2O tetrahedron (Wyllie, 1977, p. 44). The magma equilibrated at a shallow crustal depth (1 to 2 kilobars, 4 to 7 km, fig. 11) in sialic crust beneath the continental rift. The rhyolites crystallized from water-saturated partial melts derived from the hot, underlying continental crust. (On figure 11, we rely mostly on the Yemen analyses because they are good-quality rapid-rock analyses, whereas, we have no information about the quality of the analyses on the perlite samples.)

Table 1.--*Chemical and normative analyses of middle Tertiary cherty tuffaceous siltstones and limestone of the Baid formation from the Red Sea continental rift, southern coastal plain, Saudi Arabia*

[All values in weight percent. Analyses by DGMR-USGS laboratory, Jiddah; K. J. Curry, supervisor. Leaders indicate either not analyzed (chemical analysis) or calculated as zero (normative minerals)]

Sample	81956	81959	93040	93086	93091	93093	93157	93225	93226	93227	93255
Lat(north)	19°42.2'		19°47.6'	19°47.1'			19°47.6'	19°28.9'			19°16.4'
Long(east)	41°00.8'		40°55.7'	40°55.6'			40°55.9'	41°15.3'			41°18.8'
Rock type	Tuffaceous siltstone						Cherty tuff	Tuffaceous siltstone			
SIO2	90.64	84.94	72.34	90.46	84.80	85.12	92.58	73.98	77.28	93.36	69.66
AL2O3	2.71	4.25	17.67	2.73	3.71	3.54	1.67	5.30	6.50	1.61	10.82
FE2O3	2.11	3.82	0.62	1.55	4.26	2.59	2.07	3.26	3.30	1.03	2.46
FEO	0.11	0.29	0.14	0.32	0.18	0.25	0.14	0.07	0.04	0.49	0.07
MGO	0.61	0.60	0.37	0.43	1.32	1.06	0.40	1.80	2.20	0.21	0.67
CAO	0.36	0.41	0.50	0.35	0.52	1.47	0.44	4.80	1.45	0.35	4.00
NA2O	0.20	0.27	0.03	0.34	0.37	0.17	0.05	0.15	0.20	0.13	1.94
K2O	0.56	1.85	0.38	1.60	1.25	0.18	0.26	0.60	0.70	0.07	0.16
H2O	3.18	3.00	8.27	1.41	3.18	4.69	1.84	9.31	7.73	2.12	9.31
TIO2	0.23	0.45	0.22	0.26	0.43	0.25	0.19	0.31	0.43	0.09	0.19
P2O5	0.01	—	0.01	—	0.02	0.07	0.01	0.05	0.06	—	0.01
MNO	0.04	0.10	0.03	0.06	0.12	0.03	0.03	0.14	0.26	0.03	0.06
CO2	—	—	—	—	—	—	—	—	—	—	—
TOTAL	100.76	99.98	100.58	99.51	100.16	99.42	99.68	99.77	100.15	99.49	99.35
NORMATIVE MINERALS[1]											
Q	87.806	76.837	74.874	82.655	77.169	83.300	91.765	66.837	72.734	93.738	83.556
C	1.173	1.091	17.684	—	0.877	0.592	0.542	—	3.160	0.702	0.230
OR	3.391	11.273	2.433	9.638	7.617	1.123	1.570	3.919	4.476	0.425	1.050
AB	1.734	2.356	0.275	2.933	3.228	1.519	0.432	1.403	1.831	1.130	8.232
AN	1.763	2.097	2.616	1.221	2.525	7.216	2.164	13.283	7.359	1.783	1.967
AC	—	—	—	—	—	—	—	—	—	—	—
WO	—	—	—	0.229	—	—	—	5.175	—	—	—
EN	1.55	1.541	0.998	1.092	3.390	2.787	1.018	4.956	5.929	0.537	1.853
FS	—	—	—	—	—	—	—	—	—	—	—
MT	—	—	—	0.483	—	0.189	—	—	—	1.454	—
HM	2.162	3.939	0.672	1.247	4.393	2.604	2.116	3.604	3.571	0.055	2.732
IL	0.326	0.852	0.390	0.503	0.657	0.501	0.368	0.494	0.693	0.176	0.307
TN	—	—	—	—	—	—	—	0.202	—	—	—
RU	0.064	0.015	0.033	—	0.098	—	0.001	—	0.100	—	0.050
AP	0.024	—	0.026	—	0.049	0.175	0.024	0.131	0.154	—	0.026

Table 1.--*Chemical and normative analyses of middle Tertiary cherty tuffaceous siltstones and limestone of the Baid formation from the Red Sea continental rift, southern coastal plain, Saudi Arabia* --Continued

Sample	93276	93478	93479	93638	93639	93640	93642	93769	93244	93248	93264
Lat(north)	19°10.7'	17°44.1'		17°43.5'				21°34.6'	19°28.9'	19°27.5'	19°15.1'
Long(east)	41°16.6'	42°13.7'		42°14.5'				39°34.9'	41°15.3'	41°16.8'	41°19.1'
Rock type	Cherty siltstone	Siltstone	Chert	Laminated mudstone				Tuffaceous siltstone	Limestone		
SIO2	88.14	88.06	96.56	84.90	83.64	86.04	87.82	90.50	12.40	19.00	7.94
AL2O3	2.30	4.46	0.90	4.85	5.78	5.18	4.84	2.91	1.11	2.20	1.88
FE2O3	4.10	1.95	0.26	4.05	3.02	2.94	2.19	2.11	1.23	1.26	2.15
FEO	0.04	0.25	0.32	0.50	0.43	0.50	0.61	0.11	0.61	0.29	0.07
MGO	0.67	0.28	0.11	0.44	0.56	0.35	0.39	0.37	1.80	4.60	0.43
CAO	0.72	0.81	0.42	1.57	1.63	0.52	0.57	0.40	46.40	37.52	48.46
NA2O	2.50	0.20	0.03	0.04	0.04	0.03	0.05	0.15	0.01	0.09	0.03
K2O	0.04	0.47	0.01	0.60	0.70	0.73	0.65	0.09	0.03	0.29	0.10
H2O	1.09	2.76	0.95	2.61	3.53	3.27	2.62	3.02	4.69	6.13	6.32
TIO2	0.19	0.17	0.07	0.31	0.33	0.30	0.28	0.16	0.12	0.11	0.23
P2O5	—	0.01	—	0.01	0.03	0.03	0.03	0.01	0.01	0.01	0.03
MNO	0.05	0.05	0.03	0.06	0.10	0.06	0.05	0.01	0.99	0.51	0.06
CO2	—	—	—	—	—	—	—	—	31.60	27.87	32.03
TOTAL	99.84	99.47	99.66	99.94	99.79	99.95	100.10	99.84	101.00	99.88	99.73
NORMATIVE MINERALS[1]											
Q	74.798	85.796	96.384	80.529	79.457	84.320	85.478	90.790	—	—	—
C	—	2.247	0.077	1.340	2.145	3.586	3.170	1.924	—	—	—
OR	0.239	2.872	0.060	3.643	4.297	4.462	3.940	0.549	—	—	—
AB	11.755	1.750	0.257	0.348	0.352	0.263	0.434	1.311	—	—	—
AN	—	4.088	2.111	7.935	8.197	2.466	2.700	1.982	—	—	—
AC	8.517	—	—	—	—	—	—	—	—	—	—
WO	1.379	—	—	—	—	—	—	—	—	—	—
EN	1.690	0.721	0.278	1.126	1.449	0.902	0.996	0.952	—	—	—
FS	—	—	0.317	—	—	—	—	—	—	—	—
MT	—	0.492	0.382	0.934	0.785	0.970	1.352	—	—	—	—
HM	1.208	1.677	—	3.517	2.596	2.372	1.314	2.179	—	—	—
IL	0.194	0.334	0.135	0.605	0.651	0.589	0.546	0.262	—	—	—
TN	0.222	—	—	—	—	—	—	—	—	—	—
RU	—	—	—	—	—	—	—	0.027	—	—	—
AP	—	0.024	—	0.024	0.074	0.073	0.073	0.024	—	—	—

1/ Normative minerals: Q, quartz; C, corundum; OR, orthoclase; AB, albite; AN, anorthite; AC, acmite; WO, wollastonite; EN, enstatite; FS, ferrosilite; MT, magnetite; HM, hematite; IL, ilmenite; TN, titanite; RU, rutile; AP, apatite. Total sums to 100.000 ± 0.005.

Table 2.-- *Chemical and normative analyses of perlite of the Liyyah formation from the Red Sea continental rift*

[All values in weight percent. Rhyolites (perlites) from Jabal Shama, for which total iron was reported as Fe_2O_3, are reproduced from Laurent (1976); rhyolitic welded tuffs from the Yemen Arab Republic (W. C. Overstreet and M. J. Grolier, USGS, written commun., 1980) were analyzed by USGS laboratories, Reston, Virginia, USA. Leaders indicate either not analyzed (chemical analysis) or calculated as zero (normative minerals)]

Sample	DL579	DL621	DL586-2	DL589	DL586-1	DL571	DL620	DL566	DL561	DL562	DL587
Lat(north)	20°44.3'?	20°39.7'	20°44.9'	20°44.5'	20°44.9'	20°44.6'	20°44.5'	20°39.7'			20°44.9'
Long(east)	39°38.1'?	39°40.5'	39°37.9'	39°37.6'	39°37.9'			39°40.5'			39°37.9'
Rock Type	Rhyolite	Perlite									
SIO2	76.60	72.50	72.50	72.40	72.30	72.10	72.00	71.70	70.10	69.90	69.80
AL2O3	10.50	10.40	0.50	10.60	12.60	11.20	10.60	12.70	11.80	11.50	12.80
FE2O3	1.10	1.60	0.70	2.60	1.20	1.30	0.90	0.70	1.60	3.00	1.50
FEO	—	—	—	—	—	—	—	—	—	—	—
MGO	0.15	1.30	0.20	0.10	0.10	0.20	2.40	0.40	0.40	0.50	0.10
CAO	0.40	1.30	0.60	0.30	0.30	0.30	0.80	0.40	0.20	0.90	0.70
NA2O	2.20	4.00	3.40	3.60	3.30	2.80	2.90	4.70	3.80	3.10	3.10
K2O	6.40	4.60	4.80	5.30	3.70	4.30	4.10	3.60	4.10	3.70	3.80
H2O	0.50	5.00	4.20	5.10	4.50	6.70	5.90	4.30	5.80	7.20	6.50
TIO2	0.20	0.20	0.20	0.10	0.10	0.10	0.20	0.10	0.10	0.10	0.10
P2O5	—	—	—	—	—	—	—	—	—	—	—
MNO	—	—	—	—	—	—	—	—	—	—	—
CO2	—	—	—	—	—	—	—	—	—	—	—
TOTAL	98.05	100.90	97.10	100.10	98.10	99.00	99.80	98.60	97.90	99.90	98.40
NORMATIVE MINERALS[1]											
Q	39.686	31.187	36.333	33.637	40.762	41.622	36.408	30.892	33.965	37.794	38.713
C	—	—	—	—	2.800	1.510	—	0.365	0.811	0.819	2.519
OR	38.769	28.345	30.532	32.968	23.359	27.530	25.802	22.559	26.306	23.586	24.434
AB	18.839	29.077	29.371	26.333	29.833	25.669	26.133	42.174	34.913	28.297	28.543
AN	—	—	—	—	1.590	1.612	4.044	2.104	1.077	4.817	3.779
AC	0.215	4.827	1.408	5.050	—	—	—	—	—	—	—
NS	—	0.172	—		—	—	—	—	—	—	—
WO	0.551	2.505	1.025	0.501	—	—	—	—	—	—	—
EN	0.383	3.376	0.536	0.262	0.266	0.540	6.366	1.056	1.082	1.343	0.271
MT	—	—	—	—	—	—	—	—	—	—	—
HM	1.053	—	0.267	0.991	1.282	1.408	0.958	0.742	1.737	3.236	1.632
IL	—	—	—	—	—	—	—	—	—	—	—
TN	0.503	0.512	0.528	0.258	—	—	0.129	—	—	—	—
RU	—	—	—	—	0.107	0.108	0.160	0.106	0.109	0.108	0.109
AP	—	—	—	—	—	—	—	—	—	—	—
CC	—	—	—	—	—	—	—	—	—	—	—
MG	—	—	—	—	—	—	—	—	—	—	—

Table 2.--*Chemical and normative analyses of perlite of the Liyyah formation from the Red Sea continental rift*--Continued

Sample	DL572	DL580	50-T-26	G-761-A	G-761-B	MG-766
Lat(north)	20°44.6'		13°54.7'	15°07.8'		
Long(east)	39°37.9'		44°19.7'	43°55.7'		44°34.6'
Rock Type	Perlite			Welded tuff		
SIO2	68.90	68.90	70.50	69.35	72.15	75.05
AL2O3	11.60	11.70	12.37	12.45	13.43	11.48
FE2O3	1.00	1.00	2.55	1.90	2.81	3.00
FEO	—	—	1.13	1.03	0.20	0.04
MGO	0.40	0.70	0.50	0.37	0.12	0.13
CAO	0.90	1.80	1.38	0.69	0.23	0.46
NA2O	2.50	1.70	4.04	3.13	3.45	3.64
K2O	2.90	2.30	3.57	4.43	4.05	5.01
H2O	8.60	8.80	1.22	5.64	2.49	1.13
TIO2	0.10	0.10	0.80	0.52	0.36	0.25
P2O5	—	—	0.12	0.06	0.03	0.03
MNO	—	—	0.11	0.14	0.13	0.07
CO2	—	—	0.90	0.05	0.28	0.27
TOTAL	96.90	97.00	99.19	99.76	99.93	100.56
NORMATIVE MINERALS[1]						
Q	46.133	51.371	33.104	34.495	37.544	34.585
C	3.071	3.562	1.759	1.605	3.459	—
OR	19.408	15.410	21.533	27.814	24.561	29.775
AB	23.957	16.309	34.894	28.140	29.960	30.977
AN	5.057	10.125	0.381	2.885	—	0.190
AC	—	—	—	—	—	—
NS	—	—	—	—	—	—
WO	—	—	—	—	—	—
EN	1.128	1.977	1.271	0.979	0.001	0.326
MT	—	—	1.717	2.411	—	—
HM	1.133	1.134	1.418	0.356	2.884	3.017
IL	—	—	1.551	1.049	0.719	0.236
TN	—	—	—	—	—	0.135
RU	0.113	0.113	—	—	0.196	0.072
AP	—	—	0.290	0.151	0.073	0.071
CC	—	—	2.089	0.121	0.349	0.618
MG	—	—	—	—	0.257	—

1/ Normative minerals: Q, quartz; C, corundum; OR, orthoclase; AB, albite; AN, anorthite; AC, acmite; NS, sodium metasilicate; WO, wollastonite; EN, enstatite; MT, magnetite; HM, hematite; IL, ilmenite; TN, titanite; RU, rutile; AP, apatite; CC, calcite; MG, magnesite. Total sums to 100.000 ± 0.005.

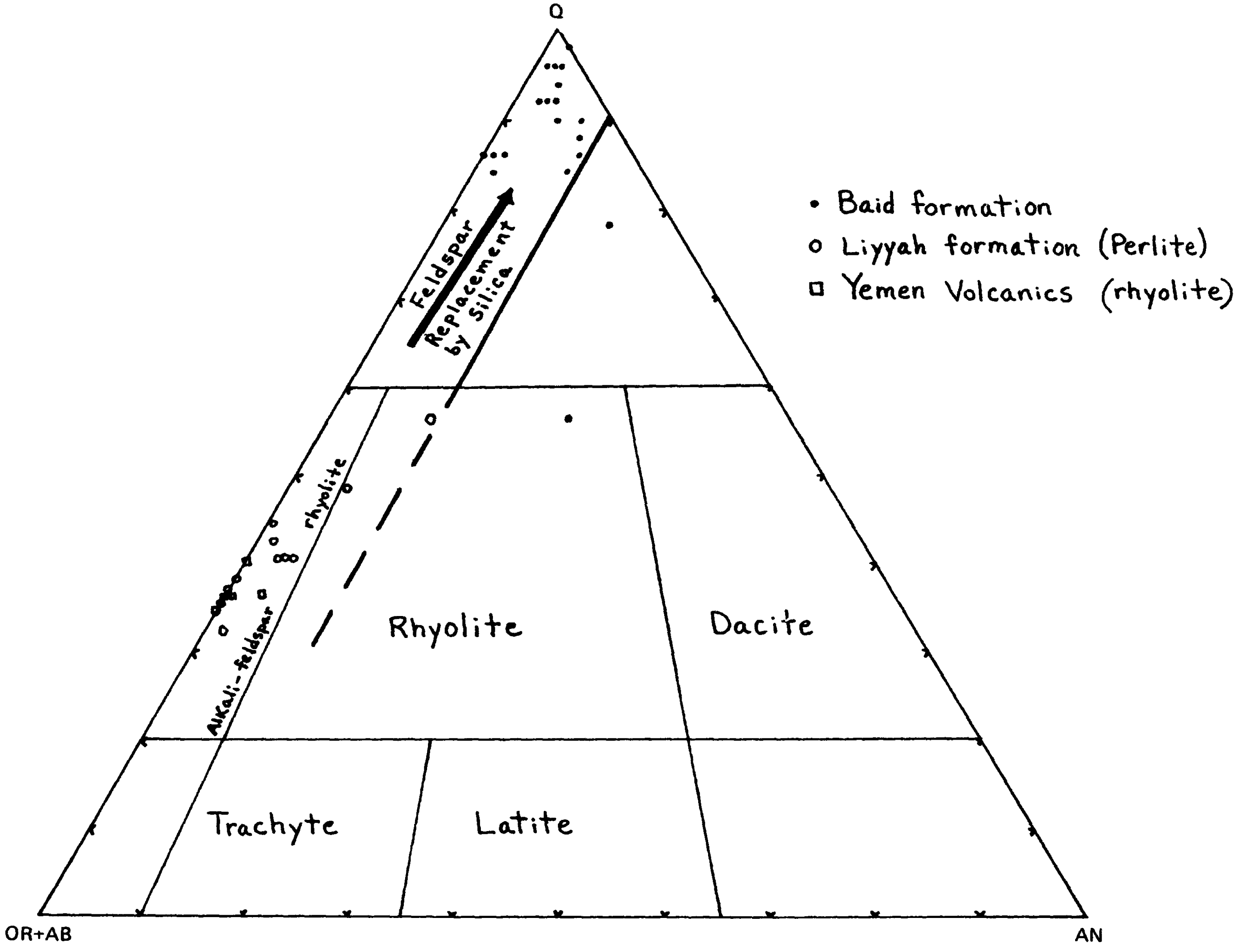

Figure 9.--Ternary diagram showing distribution of normative (orthoclase+albite) (OR+AB)-quartz(Q)-anorthite(AN) in rhyolites of the Liyyah formation from Jabal Shama, Saudi Arabia, in rhyolites from North Yemen, and in cherty tuffaceous siltstones of the Baid formation from the coastal plain of southwestern Saudi Arabia. Modal classification from Streckeisen (1979) is shown only for comparison; heavy line and arrow discussed in text.

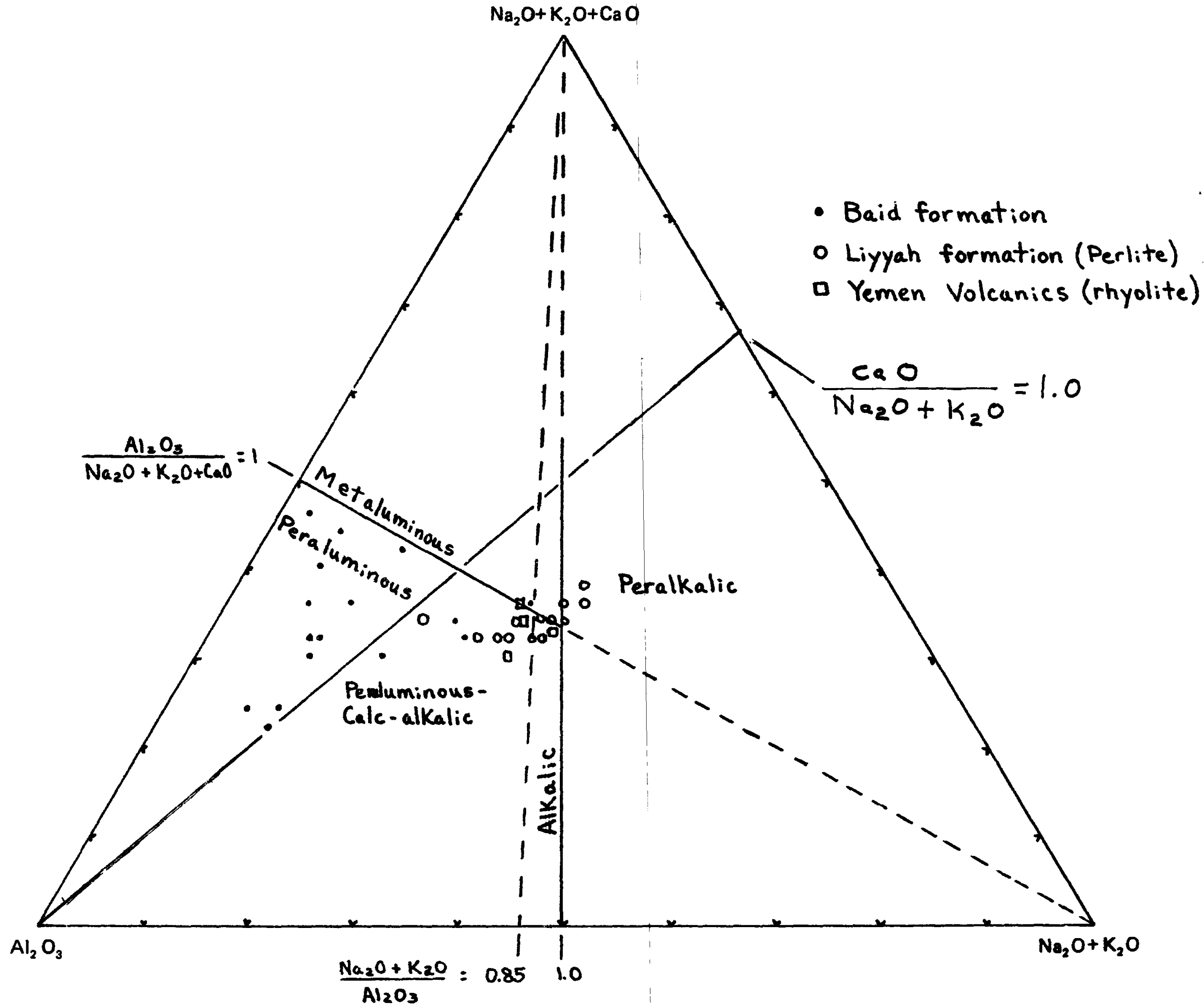

Figure 10.--Ternary diagram showing distribution of molar Al_2O_3-(Na_2O+K_2O+CaO)-(Na_2O+K_2O) in rhyolites and in Baid formation siltstones of figure 9 and showing their division into peralkalic, alkalic, and peraluminous fields. Left boundary of alkalic field (at 0.85) is arbitrary.

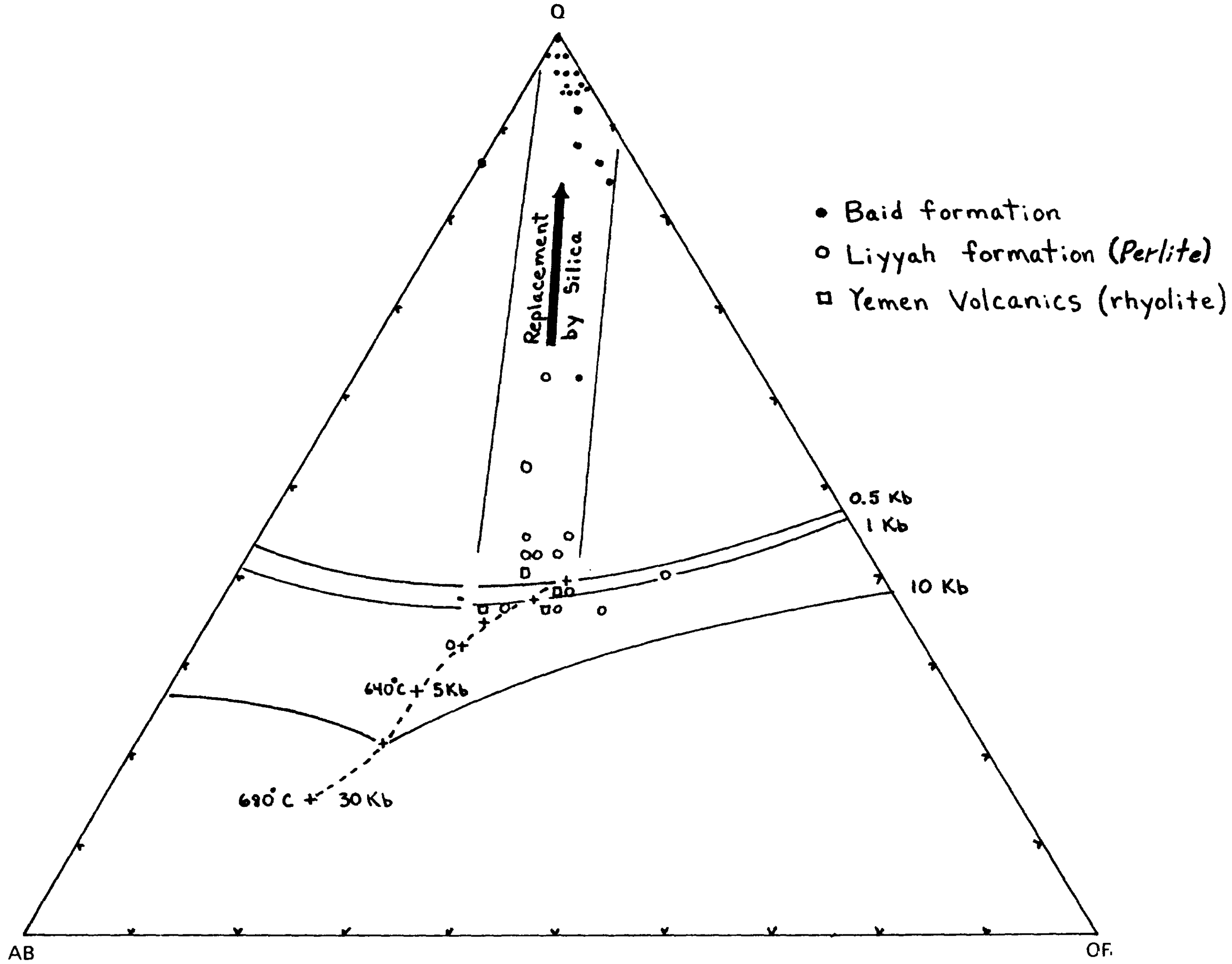

Figure 11.--Ternary diagram showing distribution of normative albite(AB)-quartz(Q)-orthoclase(OR) in rhyolites and in Baid formation siltstones of figure 9 in relation to experimental, water-saturated, liquidus field boundaries (solid lines) and low-temperature trough (dashed line, as controlled by data points, +) for system Ab-Or-Q-H_2O (Wyllie, 1977, fig. 1A). Arrow and parallel guidelines indicate apparent replacement by silica at constant Ab/Or.

Silica replacement of Baid formation tuffs

The cherty tuffaceous siltstones of the Baid formation consist of rhyolitic ash that was replaced in part by silica; as observed in thin section they appear to contain little or no extraneous detrital material. The chemical analyses of 19 of these cherty tuffaceous lake-bed rocks (table 2) have abnormally high silica contents and low alumina and alkali contents for rhyolite (fig. 12). The FeO (total iron), MgO, CaO (fig. 13), TiO_2, P_2O_5, and MnO contents are about normal for rhyolite. In thin section, the cherty tuffaceous siltstones of the Baid formation are thoroughly altered and recrystallized to microcrystalline, radial growths of quartz, plus sericite and iron oxides. Rare plagioclase (albite?) phenocrysts are thoroughly recrystallized to microcrystalline quartz, albite, and sericite. All this evidence suggests that albite and potassium feldspar have been partly to mostly replaced by silica.

Silica variation diagrams clearly demonstrate a linear replacement of alumina and total alkalis by silica (fig. 12) but essentially no replacement of other major oxides, for example, FeO (total iron), MgO, and CaO (fig. 13). Total iron oxide shows a slight enrichment relative to silica, which suggests that about 1 percent iron oxide was added to the Baid formation siltstones during silica replacement in the lake-bed environment. These diagrams indicate selective replacement of albite and potassium feldspar by silica. This replacement of alkali feldspar by silica is also noted on the normative ternary diagrams of figures 9 and 11.

The rhyolites from Jabal Shama and North Yemen have mostly peraluminous compositions that grade into alkalic and peralkalic compositions. Most of the rhyolites of North Yemen were extruded explosively as ignimbrites (Civetta and others, 1978, p. 308), as were many of rocks of the Liyyah formation. The reconstructed chemistry of the Baid formation siltstones indicates that they too were derived from rhyolites that were necessarily of explosive origin; air-fall ash and tuff were deposited in lake environments from Jiddah to the Yemen border, a distance of 600 km. The wide extent and thickness of the Yemen Volcanics indicate a great volume of explosive rhyolite all the way to the Gulf of Aden, 400 km south of the Yemen border. Because the cherty tuffaceous siltstones are restricted to a single sequence from tens to hundreds of meters thick that is underlain and overlain by felsic to mafic volcanic rocks, the rhyolitic volcanism seems to have been restricted to a time interval of several million years or less.

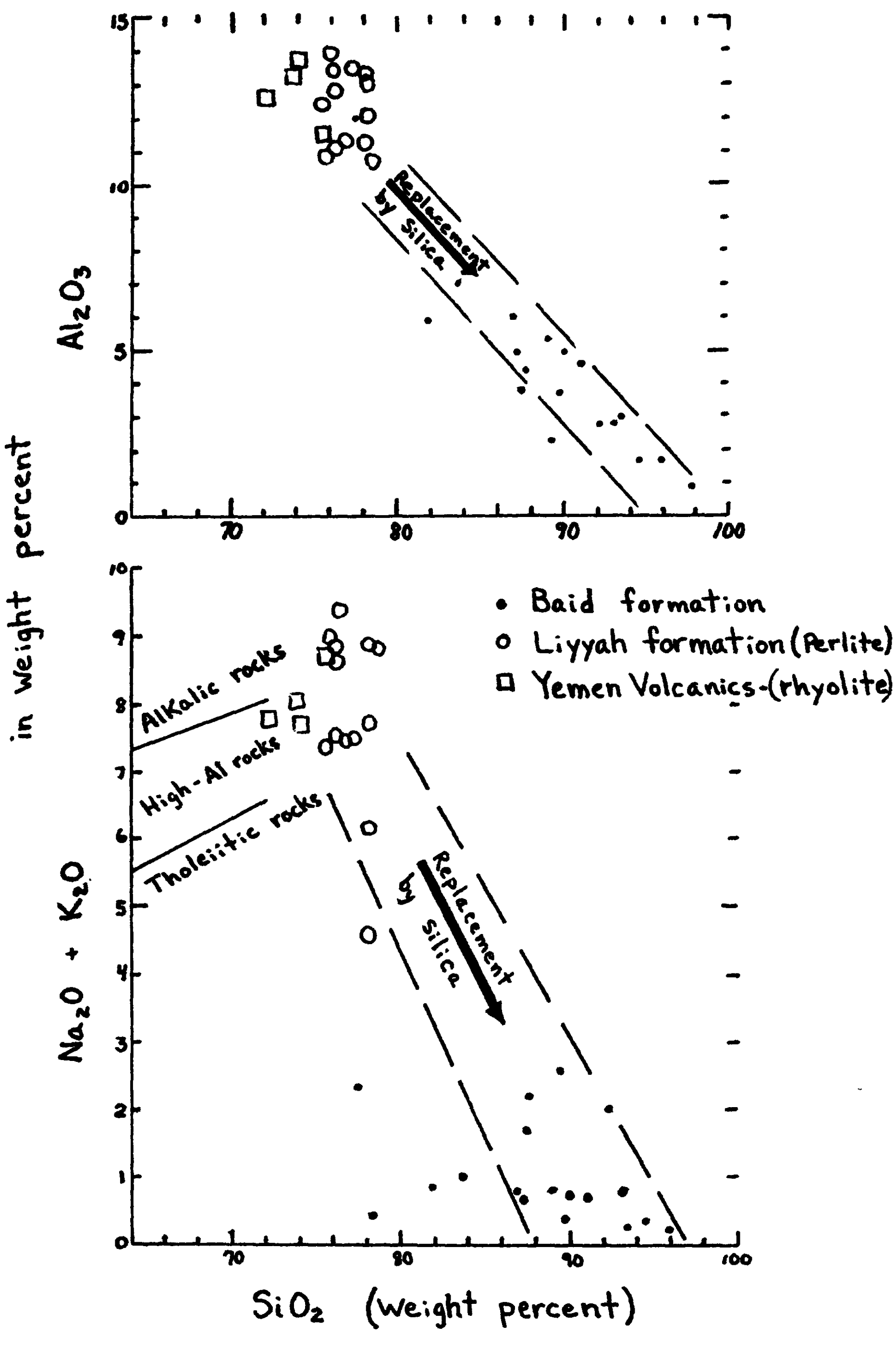

Figure 12.--Silica variation diagrams showing distribution of Al_2O_3 and Na_2O+K_2O in rhyolites and in Baid formation siltstones of figure 9. Arrows and dashed parallel guide lines indicate apparent replacement by silica. Solid lines on left side of $(Na_2O+K_2O)-SiO_2$ diagram subdivide calc-alkalic rocks of Japan according to Kuno (1966).

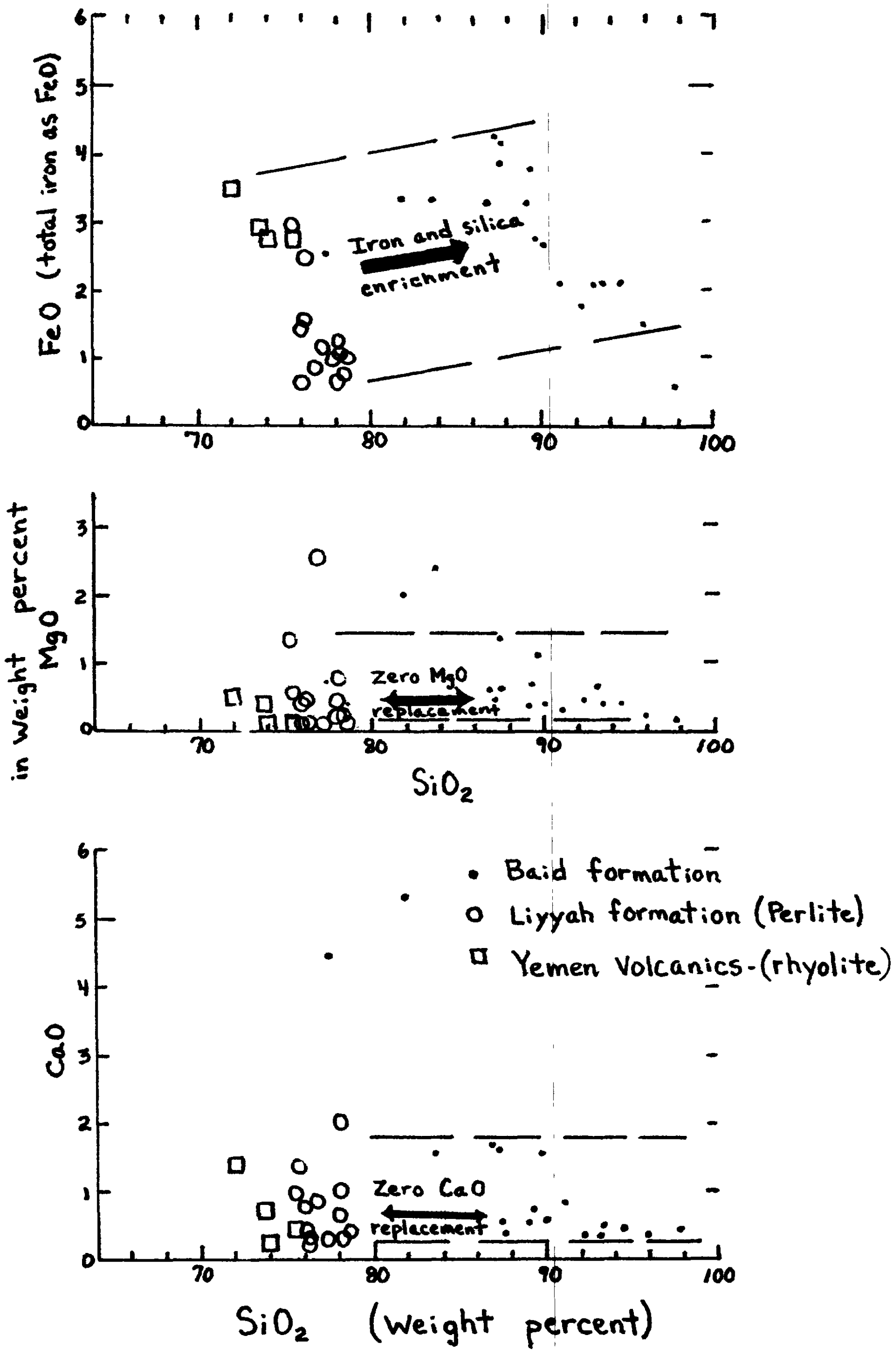

Figure 13.--Silica variation diagrams showing distribution of total iron as FeO, MgO, and CaO in rhyolites and in Baid formation siltstones of figure 9. Arrows and dashed parallel guide lines show enrichment trends as indicated.

AGE AND K_2O CONTENT OF THE RIFT VOLCANIC ROCKS

A precise age for the rift volcanic rocks (Jizan group) in southwestern Saudi Arabia cannot be given with certainty at this stage of the study. All age determinations discussed below were determined by the K-Ar whole-rock method unless noted as otherwise. No systematic age determinations have been made of either the Jizan group or the diabasic dikes of the Tihamat Asir complex in the Ad Darb-Jizan coastal plain area. However, the ages of the Jabal at Tirf gabbro and associated Abu Arish granophyre have been dated as being between 23 and 20 Ma old (four K-Ar dates, Coleman and others, 1979, p. 25). The gabbro and granophyre directly intrude the rift volcanic rocks (Jizan group, including the Baid siltstones) and are considered to be about equivalent in age to the diabasic dikes of the Tihamat Asir complex. If the Tihamat Asir complex actually represents the initiation of sea-floor spreading, as seems likely, then the rift volcanic rocks are somewhat older.

Figure 14 shows the relationships between K_2O content and age for units from the southern coastal plain. The Yemen Volcanics, a thick sequence of interlayered basaltic and rhyolitic volcanic rocks (of which at least the silicic volcanic rocks probably correlate with the Liyyah formation) are estimated to be locally more than 2,000 m thick in North Yemen (Grolier and Overstreet, 1978), although an average thickness of less than 1,000 m seems likely (450 m thick in some sections of Civetta and others, 1978). The basaltic and rhyolitic rocks of the sequence range from 29.0 to 20.3 Ma old (17 determinations, Civetta and others, 1978, p. 312). The fact that the ages become younger stratigraphically upward in all sections (Civetta and others, 1978, p. 312) shows consistency and suggests the data are reliable. Because the top of the Yemen Volcanics is everywhere eroded and the base has not been dated, the age range may be slightly greater. The rhyolitic layers are more abundant in the upper part of the section (Grolier and Overstreet, 1978; Civetta and others, 1978, p. 312), and five of the six rhyolite samples range from 24.1 to 21.0 Ma in age.

The Yemen volcanism undoubtedly was synchronous with the continental rifting of the Red Sea, and the age of the Yemen volcanism suggests that continental rifting began about 30 Ma ago (fig. 14). The Ethiopian Trap Series in the southern Afar (Aisha horst area, Chessex and others, 1975; Black and others, 1975) and west of the Afar (Blue Nile Gorge, McDougall and others, 1975; Jones, 1976) has an age range similar to that of the Yemen Volcanics; however, silicic volcanic layers are reportedly much less abundant.

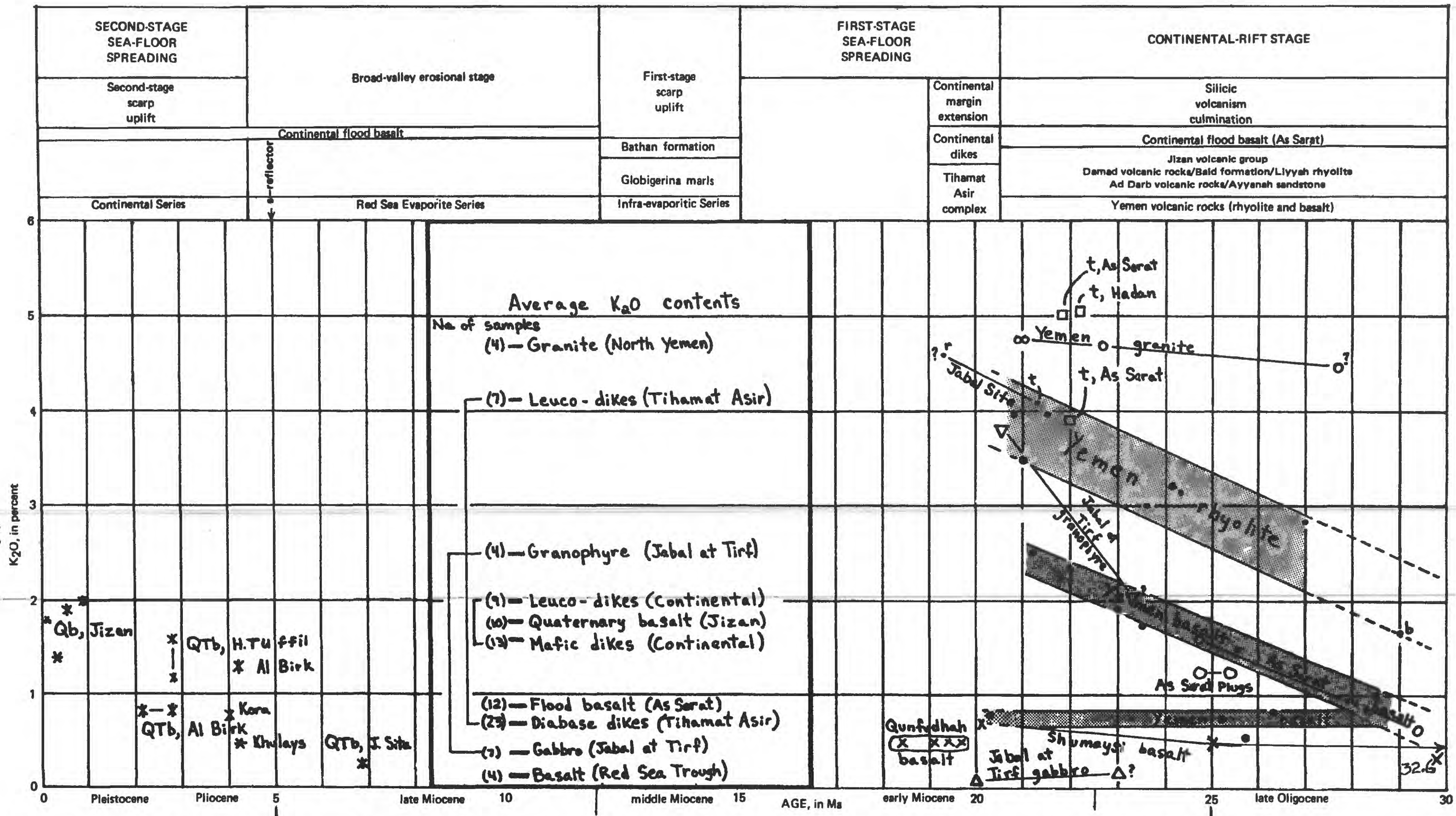

Figure 14.--Diagram showing K-Ar (whole-rock) ages and K_2O contents of volcanic and plutonic rocks associated with the evolution of the Red Sea. Rocks are from the southwestern coastal plain and inland basalt fields of Saudi Arabia and from North Yemen. Top part of diagram summarizes the evolutionary history of the Red Sea. Rhyolite (r), basalt (b), trachyte (t), and granite belong to the continental-rift stage (Jizan group). Gabbro and granophyre of Jabal at Tirf and diabase of Al Qunfudhah and Wadi Shumaysi belong to the continental-margin-extension stage of the initial sea-floor spreading of the Red Sea. Flood basalts of Quaternary (Qb) and Quaternary-Tertiary (QTb) age shown on the left side of diagram are associated with second-stage sea-floor spreading of the Red Sea. Some age determinations are suspect and are queried. Insert in the center of diagram shows average K_2O contents (short horizontal lines) of some representative rocks (mostly from Coleman and others, 1979); vertical lines connect pairs of leucocratic and melanocratic rocks of similar age.

Four dates on basalt flows (more than 580 m thick) and feeder pipes from the As Sarat area range from 29.4 to 24.7 Ma old (fig. 14). One trachyte stock that intrudes the As Sarat flood basalts is dated as being 22.1 Ma old (Coleman and others, 1977). These dates and the K_2O contents agree well with those of basalts from the Yemen Volcanics (fig. 14). The only uncertainty in making As Sarat basalts synchronous with the Yemen Volcanics is that As Sarat basaltic sequence does not contain silicic tuff layers. Such tuff layers might be expected if atmospheric circulation allowed northward transport of silicic ash from Yemen, even though As Sarat is between 250 and 300 km north of the nearest explosive eruption centers in North Yemen. In North Yemen, Civetta and others (1978, p. 312) showed only one ignimbrite and one granite as old as 27.0 and 27.7 Ma, respectively; in contrast, three other rhyolites and two other granites range from 21.5 to 20.8 Ma. Thus, most explosive volcanism in North Yemen may be younger than the uppermost preserved basalt flow in As Sarat.

The age of the Baid formation in the Al Qunfudhah area has been reported as being from 19.7 to 18.4 Ma old (Coleman and others, 1979; G. F. Brown, unpublished data, 1980); this age has led to the erroneous assumption that the Baid formation is younger than the Tihamat Asir complex. These dates are reportedly on basalt flows within the Baid, individually as thick as 280 m. A thin section of the rock from the site of one dated sample shows a coarsely holocrystalline diabasic texture that is more characteristic of a sill than a flow. Our more recent fieldwork suggests that most of these relatively fresh basaltic layers are sills, and it is likely that these younger sills were dated because, in contrast, the nearby basaltic flows within the Jizan group are highly altered. Furthermore, the K_2O contents of the four dated basalts from the Al Qunfudhah area are extemely similar (0.493 to 0.513 percent), even though the dated specimens were collected along a strike length of about 100 km. Also, the K_2O contents are consistently similar to those of the tholeiitic diabase dikes (average 0.7 percent) of the Tihamat Asir complex of the Jizan area rather than to the generally higher K_2O contents (0.572 to 1.77 percent) of the continental flood basalts of the Yemen Volcanics and As Sarat (fig. 8).

Farther north, in Wadi Shumaysi east of Jiddah, a sequence of basalt flows more than 300 m thick (Al-Shanti, 1966, p. 14; possibly from 500 to 700 m thick) lies conformably above the Shumaysi formation, which dips 20° to 25°. R. J. Fleck (Coleman and others, 1979, p. 25) has obtained a date on the basal basalt flow of 20.1 Ma; its K_2O content (0.714 percent) is again similar to those of the diabasic sills (reportedly basalts) from Al Qunfudhah (fig. 14).

Again, as at Al Qunfudhah, we suggest that the Wadi Shumaysi sample represents a sill of the Tihamat Asir complex rather than a basalt flow as reported. The similarity of the K-Ar data for these five dated samples from Al Qunfudhah and Wadi Shumaysi can hardly be coincidental; the dated rocks are considered herein to be tholeiite sills of the sea-floor-spreading episode. In addition, G. F. Brown (unpublished data, 1980) obtained dates for the basalt from the Wadi Shumaysi area (north of Wadi Fatimah) of 25.0 Ma (drill-hole sample) and 32.6 Ma (surface sample). These dates suggest that mafic volcanic rocks of the continental-rift stage also exist in the volcanic pile above the Shumaysi formation.

Peralkalic granite and rhyolite were the ultimate magmatic products of continental rifting, and their production must indicate optimum high-temperature, low-pressure, and perhaps source-depletion conditions in the crust beneath the continental rift. Furthermore, both the rhyolites and basalts systematically evolve with time, that is, K_2O increases as age decreases (fig. 14); thus production of the ultimate peralkalic magma would suggest an approaching end of the continental-rift stage. The estimated modal age of the continental-rift granite, rhyolite, and trachyte is about 21.5 Ma, and this age should correspond likewise to the average age of the silicic tuffs of the Baid formation. In figure 14, the K_2O content of the Yemen rhyolites systematically increases from 3 to 4 percent as the age decreases. The Yemen granites do likewise at overall higher K_2O contents; the Yemen granite at Jabal Sabir, south of Taiz, contains 4.7 percent K_2O and has been dated at 21.0, 20.9 (Civetta and others, 1978), and 22.7 Ma (K-Ar date on hornblende, Grolier and Overstreet, 1978; Richard Marvin, written commun., 1974) (fig. 14). Civetta and others (1978) also have dated a granite (4.46 percent K_2O) 18 km northeast of Al Hudaydah at 27.7 Ma.

The Yemen and As Sarat flood basalts systematically evolved from about 0.7 percent K_2O 30 Ma ago to 2.5 percent K_2O 21 Ma ago, although some primitive types containing 0.7 percent K_2O persisted throughout this age range. In the As Sarat basalt sequence, small volumes of trachytic intrusive rock (5.02 percent K_2O) are dated at 21.8 (Coleman and others, 1977) and 22.0 Ma (3.87 K_2O; Grolier and Overstreet, 1978; Richard Marvin, written commun., 1974). At Harrat Hadan, 200 km east of Jiddah, a plug of trachyte or hornblende latite containing 5.04 percent K_2O is dated at 22.2 Ma. As at As Sarat, the trachyte of Harrat Hadan represents differentiated magma of very small volume relative to the thick pile of flood basalt of the harrat.

Within the continental rift, 70 km southeast of Jiddah at Jabal Sita, plugs of rhyolite (4.59 percent K_2O) and trachyte(?) (4.08 percent K_2O) are dated at 19.3 and 21.3 Ma, respectively (G. F. Brown, unpublished data, 1980), which agrees well enough with age of the culmination of potassic volcanism within the rift.

The Jabal at Tirf layered gabbro is dated at 23.0 and 20.0 Ma and is intruded by a large volume of granophyre that is dated at 23.3 and 20.6 Ma (2.05 and 3.80 percent K_2O, respectively; Coleman and others, 1977). The gabbro pluton intruded cold rift volcanic rocks of the Damad formation and has a wide chilled border, whereas the granophyre probably intruded the gabbro shortly after the emplacement of the gabbro. The gabbro and the granophyre as separate intrusions should have similar cooling ages that must actually be younger than the latest rift volcanic-granite ages, which from figure 14 would be younger than 21 Ma and certainly younger than the rhyolite-granite modal age of 21.5 Ma. The older ages on the granophyre and gabbro, 23.3 and 23.0 Ma, respectively, are probably in error.

In conclusion, the above ages suggest that continental-rift volcanism coincided with alkali-olivine basalt volcanism occurring 100 to 200 km east of the rift (for example, As Sarat and Harrat Hadan) between 30 to 21 Ma ago. Rhyolitic volcanism originated within the continental rift. Silicic volcanism and plutonism culminated about 21 to 22 Ma ago, a date which probably corresponds to the average age of deposition of the cherty tuffaceous siltstones of the Baid formation. Sea-floor spreading began about 20 Ma ago shortly after this culmination of silicic rift volcanism. Oceanic-crust magma is represented within the continental rift by the tholeiitic diabase dikes and gabbro plutons of the Tihamat Asir complex.

STRUCTURE

The structural history of the continental rift is divided into two distinct structural events. An early rift-valley deformation accompanied by continental-rift volcanism produced extension and local rotation of fault blocks of the Arabian-Nubian Shield. Later deformation along a newly formed continental margin caused major extension and fault-block rotation toward the Red Sea during the initiation of sea-floor spreading. The deformational effects of the late continental-margin extension have obscured most of the lesser deformation of the rift-valley structure.

Rift-valley structure

The rift-valley structure in the Arabian-Nubian Shield prior to the initiation of sea-floor spreading has not been deciphered but was probably relatively simple and similar to that of other, youthful continental rifts of the world. For the most part, the rift volcanic rocks were deposited conformably on previously eroded, but essentially flat lying, Mesozoic and Paleozoic sedimentary rocks in a multiple horst-and-graben structure (fig. 15). Most commonly, the contact between the rift volcanic rocks (Jizan group) and the Mesozoic-Paleozoic rocks is conformable and only locally is this contact an angular unconformity. The rift volcanic rocks presumably remained essentially horizontal within the rift valley during the continental-rifting stage, except for possible deformation in the vicinity of the active horst-and-graben faults.

The half-width of the continental rift can be defined only along the coastal plain between Ad Darb and the Yemen border where the rift belt is well exposed and where gravity and aeromagnetic data (Gettings, 1977) and a seismic deep-refraction profile (Healy and others, 1982/1983) are available. The gravity profile in particular restricts the location of the contact between oceanic and continental crust to an area about 3 km east of Abu Arish. The exposed rift belt is from 4 to 6 km wide and is as wide as 10 km at Jabal at Tirf. The continental rift by definition is underlain by continental crust, and, in fact, a few xenoliths of metaquartzite from the underlying Wajid Sandstone are found in the rocks of the Tihamat Asir complex. For example, a granulite-hornfels, metaquartzite xenolith containing coexisting metamorphic orthopyroxene and potassium feldspar occurs in a small granophyre stock that intrudes the rift volcanic rocks in Wadi Jizan.

Xenoliths of quartzite from the Wajid Sandstone or Khums formation are found in the six Quaternary basalt cinder cones that were erupted as much as 3 km west of the exposed rift belt. The xenoliths are of two types. One type possesses rinds of chilled basaltic glass and is believed to represent fluviatile cobbles brought up from ancestral wadi channels beneath the erupting volcanoes. In contrast, xenoliths of the second type have no rinds, are uniformly metamorphosed throughout, and are considered to have been derived from sandstone of the Wajid or Khums buried at depth. The first type was in disequilibrium with the erupting host basaltic lava, and the second type of xenolith source rock was more in equilibrium with the host basalt. If the origin of these contrasting quartzite xenoliths is interpreted correctly, then continental crust must underlie the Jizan area coastal plain volcanoes to a distance of from at least 3 to 5 km west of the exposed western edge of the rift belt.

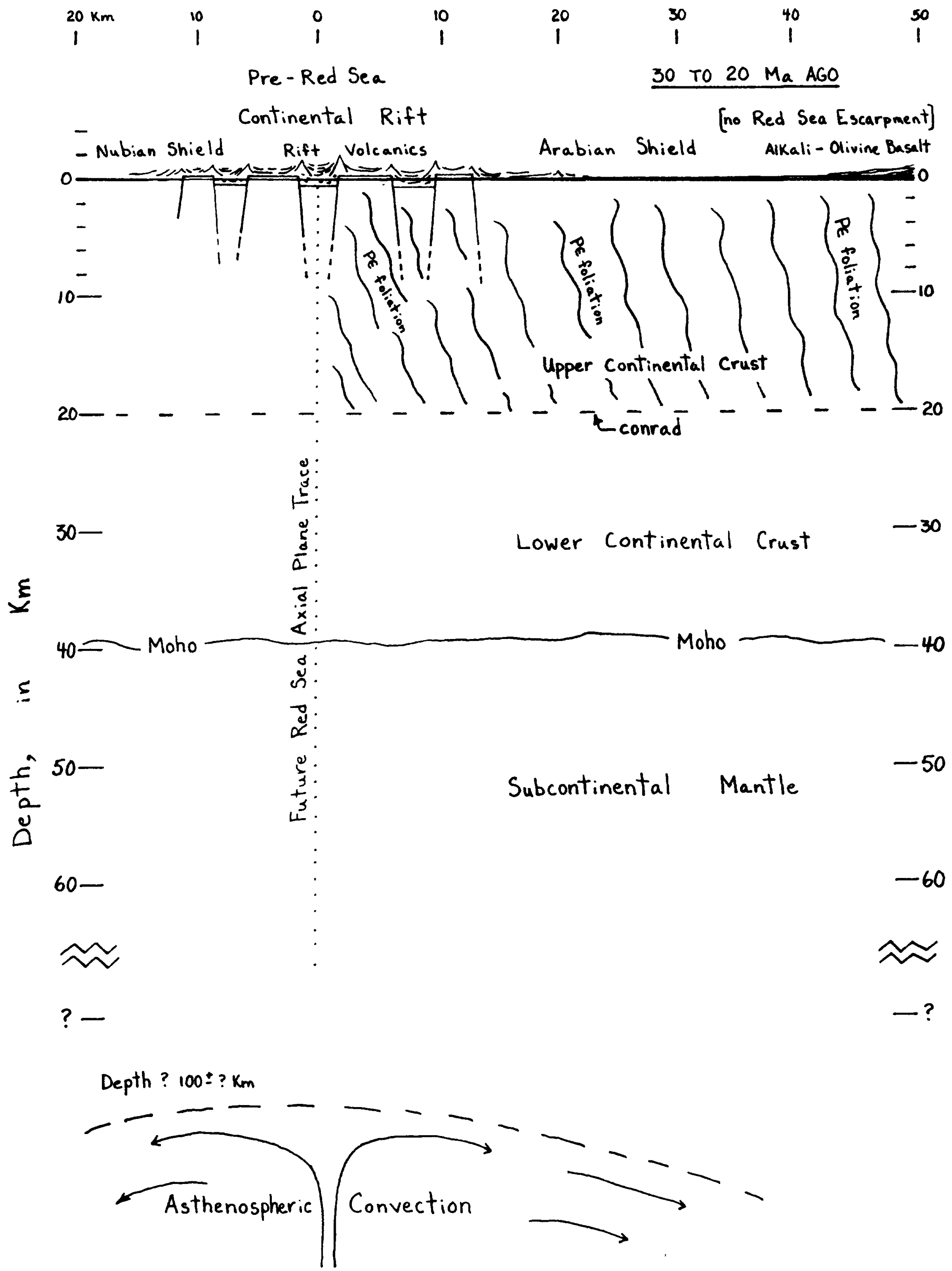

Figure 15.--Schematic structural cross section of continental-rift valley and Arabian-Nubian lithosphere between 30 and 20 Ma ago. Inland, continental flood basalt, such as the As Sarat basalt, is shown on the right. The convecting asthenospheric ridge is shown at some unknown depth beneath the future Red Sea axis. Vertical and horizontal scales same.

For the purpose of drawing the coastal cross sections of figures 15 to 17, we propose a contact between oceanic and continental crust about 3 km east of Abu Arish and 5 km west of the westernmost granophyre outcrops of Jabal at Tirf. It remains to be seen whether or not such a configuration can be precisely modeled to fit the gravity profile (Gettings, 1977, 1982). The resulting half-width for the continental rift is then about 12 km or a maximum of 15 km, which seems unusually narrow by comparison to half-widths of about 25 km for most world rifts. If the continental dikes (Blank, 1977) that intrude Precambrian rock along the entire length of the Red Sea continental margin are considered to be deeply eroded rift-margin fractures of the original horst-and-graben faults, then the half-width of the horst-and-graben structure may have been from 30 to 50 km wide or even a maximum of 70 km wide.

Continental-margin extension

Mapping within the exposed rift belt of the coastal plain shows that the belt is intricately broken along two orthogonal sets of faults that trend north-northwest and east-northeast. Most fault structure is inferred using discontinuities of stratigraphy along strike and abrupt lateral changes of dip of bedding. Only a few faults are exposed. Bedding in the Jizan group dips an average of 30° consistently toward the Red Sea; the range of dips is from 0° to 50°. These dips are measured most easily in the Baid lake-bed deposits. The rift volcanic rocks have similar dips, but these are generally difficult to measure because of the massive character and intense alteration of the rocks. A similar range of dips toward the Red Sea is seen in the underlying Wajid Sandstone, Khums formation, and Amran Series and indicates that no significant angular unconformity separates the rift volcanic rocks (Jizan group) and the underlying Mesozoic-Paleozoic rocks. Most of the deformation occurred after deposition of the Jizan group rocks and was associated with the initiation of sea-floor spreading.

Faults bounding the various fault blocks are commonly spaced from a few hundred meters to several kilometers apart and imply intensive large-scale breakage of the upper crust of the continental margin. On the small-scale map of plate 1, major faults that strike perpendicular to the Red Sea offset the rift belt at intervals of about 5 km. Where locally mapped in detail, these faults consist of an array of small-scale parallel faults. The faults parallel to the Red Sea that are within the Precambrian schists and gneisses tend to follow the strong Precambrian structure that is more northerly than the rift trend. The <u>en echelon</u> character of these faults in places maintains the gross structure parallel to the northwestern rift trend.

Layering in the Jabal at Tirf gabbro (Coleman and others, 1977) dips about 60° toward the Red Sea. We assume that the gabbro pluton, as a single block, has been rotated about 30° SSW. toward the Red Sea and that its primary stratification was about 30° SSW. The diabase, basalt, and leucocratic dikes of the Tihamat Asir complex (Coleman and others, 1977), which lie within and parallel to the exposed rift belt, have dips of from 60° E. to vertical. Commonly the more altered and presumably older dikes dip eastward, whereas the least altered and youngest dikes are vertical. Therefore, the intrusion of the dikes spanned the period of block rotation, that is, the episode of the continental-margin extension (Kellogg and Blank, 1982).

We conclude that extensional tectonic processes, which occurred after deposition of the rift volcanic rocks, broke the continental margin within the continental rift into an orthogonal maze of fault blocks that on average dip about 30° toward the Red Sea. The extensional faults parallel to the Red Sea were filled progressively with tholeiitic magma (dikes) during the initiation of sea-floor spreading of the Red Sea. Faults perpendicular to the Red Sea most probably are parallel to, and locally a few correspond to, transform faults within the newly formed oceanic crust. Within the continental rift, these perpendicular faults have mostly vertical displacements, and left-lateral displacement seems to have occurred only where the lateral extension on either side of a given fault differed across the fault. These perpendicular faults are more difficult to document in the Precambrian rocks east of the exposed rift belt.

The mechanism of the extensional faulting appears to be a collapse of the thinned continental crust beneath the continental rift (fig. 16). Rigid surface blocks of the competent Phanerozoic rocks were rotated about 30° toward the Red Sea, which accounts for about 15 percent expansion, whereas the dikes of the Tihamat Asir complex injected into these rocks account overall for another 5 percent of extension. Therefore, the total extension was about 20 percent within the extended continental margin. The base of these rigid blocks was the Wajid Sandstone, which lay on the top of the Precambrian schists. The Precambrian rocks beneath the rigid cover blocks must have extended an equal amount by pervasive fracture cleavage or pervasive fracture jointing. Where north or northwest-trending Precambrian-age schistosity existed, the Precambrian rocks were pervasively rotated by reactivation of this old schistosity about 30° toward the Red Sea. Where the Precambrian structure was not nearly parallel to the Red Sea, a new pervasive fracture jointing developed trending approximately parallel to the Red Sea axis. This fracture jointing accommodated the required extension. At depth, the Precambrian crust extended by ductile and plastic flow (fig. 16).

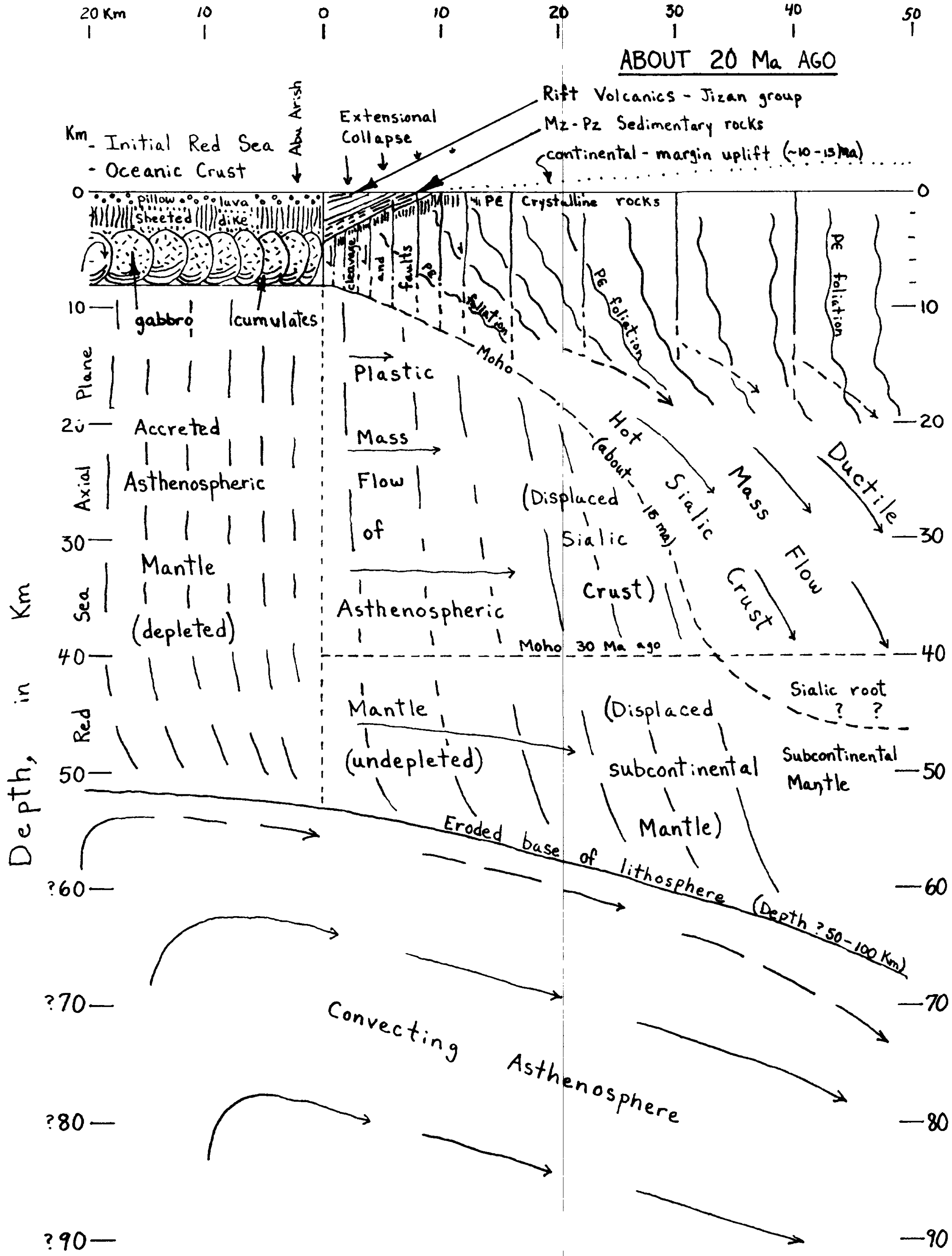

Figure 16.--Schematic structural cross section of the initial part of the first-stage sea-floor-spreading and continental-margin-extension episode about 20 Ma ago. Model for individual gabbroic magma cells in newly forming oceanic crust is according to data from Pallister and Hopson (1981). Vertical and horizontal scales same.

East of the rift belt, the Precambrian schistosity and foliation commonly dips about 45° ENE. or less, whereas elsewhere throughout the Arabian Shield Precambrian foliations are commonly steep. This gently dipping Precambrian foliation is observable in the vicinity of Ad Darb, Al Qunfudhah, and Al Lith. We suggest that a near-vertical Precambrian foliation in the continental margin has been rotated toward the Red Sea during the continental-margin extension.

If the Moho position is shown correctly in figure 17 (Healy and others, 1982/1983) then the continental crust has been thinned to 30 percent of its presumed original thickness of 40 km beneath the exposed rift belt in the Jizan area. This would require continental crust extension at this locality of 70 percent, which is 3.5 times the 20 percent extension suggested above for the Phanerozoic rocks at the surface. Hence, a mechanism of simply stretching the continental lithosphere above vertically mobile mantle or asthenosphere is not correct. As shown on figure 16, we suggest that a large part of the continental crust in the continental-margin zone has been horizontally displaced by asthenospheric mantle originating in the axial-spreading zone. The geometry of the cross section (fig. 16) requires that 480 km^3 (600 km^3 -20 percent allowable expansion) of continental crust be displaced subhorizontally for each kilometer of axial length. Whether this mechanism is feasible, possible, or even realistic, we do not pursue.

Continental faults

Continental dikes (Coleman and others, 1979) fill tensional faults in the Precambrian terrane as much as 50 km east of the continental rift. The dike set extends along the coastal mountain belt below the Red Sea Escarpment from Ad Darb to the Gulf of Aqaba (Blank, 1977, plate G3). The continental dikes chiefly consist of low-quartz rocks that range from gabbro to quartz syenite but most of which are quartz monzodiorite (Blank, 1977, p. G6; Coleman and others, 1979, p. 12). Chemically the continental dikes represent an evolved mafic magma. Both spatially and compositionally they represent a suite of hypabyssal rocks of different rock type and structural setting than those of either the rift volcanic rocks (Jizan group) or the Tihamat Asir complex rocks. The magma probably originated as a subalkaline tholeiitic melt (Coleman and others, 1979) in the shallow asthenosphere (fig. 16) and was differentiated and contaminated during emplacement through thick continental crust. This genetic model contrasts with the tholeiitic magma that formed the Tihamat Asir complex in thin sialic crust of the continental rift.

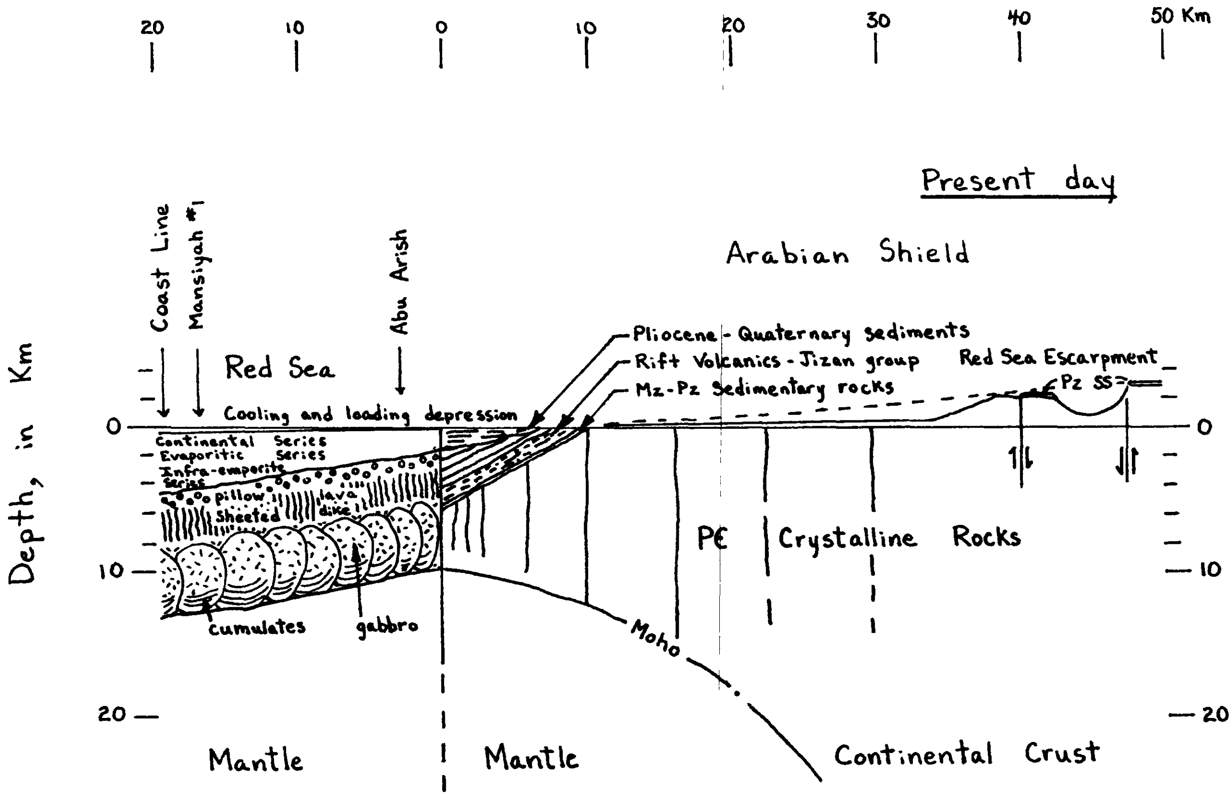

Figure 17.--Schematic structural cross section of the present-day Red Sea margin of southwestern Saudi Arabia. Vertical and horizontal scales same.

Faulting in Precambrian rocks parallel to and east of the continental rift can be assessed by the distribution and spacing of the continental dikes (Blank, 1977, plate G3). Individual dikes tend to be shorter, more abundant, and more closely spaced (from 1 to 5 km apart) near the continental rift. With increasing distance away from the rift (about 50 km inland), the dikes are longer, more distinctly singular, less abundant, and more widely spaced (about 20 km apart). Hence, the spacing of faults and presumably the intensity of tensional faulting decreased away from the continental rift. From 10 to 30 km east of the exposed rift belt between Ad Darb and Jizan, only a few continental dikes have been mapped. Clastic dikes that consist of quartz sandstone derived from the Wajid Sandstone are prominent in the area (Fairer, in press); however, presumably the clastic dikes originated initially as distentional continental-margin faults. Deeper in the crust, they are most probably filled by magma of composition similar to continental dikes.

The mean age of the continental dikes is 22 Ma (9 dates, ranging from 25 to 18 Ma: Blank, 1977; Brown, 1972). Similar continental dikes extend across the southern Sinai and range from 22 to 18 Ma old; however, they are left-laterally displaced, probably about 107 km across the Aqaba transform fault (Bartov and others, 1980; Eyal and others, 1981), with respect to the continental dikes in northernmost Saudi Arabia. This amount of transform faulting is about equal to the required displacement assuming full-width sea-floor spreading of the Red Sea (Quennell, 1956; Freund and others, 1970; Hatcher and others 1981).

We conclude that the continental dikes filled distensional faults in thick continental crust inland from the continental rift during the continental-margin extension and the coincident initiation of sea-floor spreading (fig. 14).

Scarp uplift

Prior to, during, and after continental rifting, the surface of the Precambrian Shield was deeply weathered, was near sea level, and had little vertical relief, contrary to the concept that uplift and doming preceded rifting and sea-floor spreading (Gass, 1970). A Red Sea Escarpment did not exist, as evidenced by the following. 1) No regional angular unconformity exists between the rift volcanic rocks (Jizan group) and the underlying Wajid Sandstone, Khums formation, and Amran Series; in fact, this lack of noticeable structural relief indicates long stability of the Arabian Shield until the time of continental rifting. 2) Coarse, or even fine, polymictic conglomerates are not found at the base of or within the rift volcanic rocks. The nonvolcanic, submature

Nubian-type quartz sandstone and sparse quartz-pebble conglomerates (Ayyanah sandstone) at the base of the rift volcanic group indicate erosion of a low-relief, thoroughly weathered Precambrian terrane in which the depth of erosion did not exceed the thickness of saprolite, which is 20 to 30 m thick where well preserved beneath the As Sarat basalt field (Overstreet and others, 1977). 3) The ignimbrites of continental-rift extend 150 km east across the Precambrian shield of Yemen without noticeable thinning (Shukri and Basta, 1955, p. 132).

The initial and rapid uplift of the Red Sea scarp is recorded by the Bathan formation from Jiddah south to Al Birk. This thick, coarse, polymictic conglomerate indicates erosion of the first rapidly emerging steep topography along the Red Sea during the Tertiary, namely the Red Sea Escarpment. The Bathan formation is considerably younger than the Jizan group, and the initial uplift of the scarp was most probably after the first-stage spreading of the Red Sea. Some block faulting was associated with the scarp uplift because the Bathan formation is tilted 15° NE. in the Wadi Lith area Hadley and Fleck, 1980) and from 15° to 20° SW. in the Wadi Fatimah area east of Jiddah (Nebert and others, 1974, p. 24). Given these sparse data, we do not attempt to further evaluate the nature of fault-block structure of the scarp-uplift stage.

EVOLUTION OF THE RED SEA

Early Tertiary setting

Structural elements in the Red Sea area are not evident prior to development of the continental-rift valley beginning in late Oligocene to early Miocene time. Early Tertiary events in the Red Sea region were presumably independent of later Red Sea evolution. Slight epeirogenic downwarping during Paleocene time resulted in a shallow marine sea extending from the Mediterranean through Egypt and Jordan south to the vicinity of Jiddah, where about 100 m of limestone and fine-grained sandstone were deposited as the Usfan formation (Brown, 1970, p. 80-81), and 200 km to the east in the vicinity of Harrat Hadan, where more than 22 m of mudstone, shale, and limestone were deposited as the Umm Himar formation (Madden and others, 1979/1980). The last vestiges of this sea (the dying Tethys Sea) probably lasted through middle Eocene time in northern Saudi Arabia (Kluyver and others, 1981) and is represented in the Jiddah area possibly by part of the Shumaysi formation (Moltzer and Binda, 1981, p. 70). In North Yemen, more than 200 m of marine sandstone of the Paleocene Midj-zir Series was deposited (Geukens, 1966).

Cratonic stability during early Tertiary time is indicated by the thick lateritic soil (a ferruginous cap, from 1 to 2 m thick, underlain by from 20 to 30 m of saprolite; Overstreet and others, 1977, p. 6) that developed across the low-relief, low-altitude, crystalline rocks of the Precambrian Shield.

Continental-rift stage

Continental rifting along the proto-Red Sea began about 30 Ma ago (figs. 14 and 15) as a mantle plume rose beneath the Afar triple junction and as mantle convection progressively extended along three axes: that of the proto-Red Sea, the Gulf of Aden, and the East African rift. The continental rift progressively developed until about 20 Ma ago. The heat regime at and near the triple junction in Ethiopia, Somalia, and especially Yemen was much greater than farther north along the Red Sea axis. Near the triple junction, abundant silicic and mafic volcanic rocks were deposited in a wide continental rift as well as inland from the rift. Farther north along the continental rift (the proto-Red Sea axis), the volume of volcanic rocks decreased, the rift narrowed, and silicic volcanism was restricted to within the rift. Silicic volcanism within the rift extended as far north as Jiddah, 1,100 km north-northwest of the triple junction. The distinct northward decrease in size of the continental rift and in the intensity of volcanic activity seems directly related to a decreasing heat flow away from the triple junction and to the progressive northward development with time of mantle convection along the proto-Red Sea axis. North of Jiddah, volcanic rocks of the continental-rift stage have not been found. During the approximately 10 Ma of the continental-rift stage, both the mafic and silicic volcanic rocks seem to have evolved with time, that is, their K_2O content increased with decreasing age (fig. 14), as the heat flow increased beneath the continental rift.

In southern Arabia, the oldest Tertiary volcanic rocks indicative of an active and rising mantle are dated at about 30 Ma old. Inland from the Red Sea area, flows of alkali-olivine basalt are well preserved in the deeply eroded fields of As Sarat (about 600 m thick, 100 km inland) and Harrat Hadan (about 200 m thick, 200 km inland). In both places, early Tertiary lateritic deposits are well preserved beneath the basalt flows (Overstreet and others, 1977; Madden and others, The As Sarat basalts and underlying laterite extend southward into the Yemen to the latitude of Sadah. South of Sadah, the volcanic pile is about 1,000 m thick and consists of peralkaline rhyolite (comendite and pantellerite), trachyte, trachyandesite, olivine basalt, and ankaramite (Shukri and Basta, 1955, p. 160). Laterite beneath the volcanic rocks south of Sadah has not been recorded, and its lack suggests some slight erosion that is represented by a few thin beds of Nubian-type sandstone reportedly at the base of and intercalated within the volcanic rocks. Some slight upwarping over a broad region may be suggested by the erosion of the laterite beneath the Yemen Volcanics and by the related thin intercalated quartz sandstones, but there is no evidence for erosion deeper than the thickness of the saprolite. A topographically high regional dome, as implied by Gass (1970), did not exist.

The distribution of middle Tertiary volcanic rocks clearly indicates increased continental heat flow as the Afar triple junction is approached. North of Sadah (about 450 km north of the triple junction) mantle-derived alkali-olivine basalt and subordinate trachyte (Coleman and others, 1977) was extruded through a full continental thickness (Healy and others, 1982/1983) South of Sadah, similar basaltic rocks are interlayered in a one-to-one ratio with rhyolitic ignimbrites that were derived from thinned, hot, continental crust beneath the continental rift. The ignimbrites of the Yemen Volcanics probably originated from abundant explosive volcanoes, now eroded down to their granite roots, in a highly active continental rift that had a half-width of 50 km or more. On eruption these ignimbrites traveled more than 100 km east of their rift vents. The conspicuous increase in K_2O with decreasing age (from 30 to 20 Ma) for both the basaltic and rhyolitic volcanic rocks in the Yemen sequence (fig. 14) implies an increase in crustal heat with time within the continental rift crust and marginal to it for distances of as much as 200 km.

Tertiary granite plutons in the wide continental rift of North Yemen are exposed as far as 350 km north of the triple junction (Grolier and Overstreet, 1978). Silicic volcanic rocks (without exposed granite plutons) within the narrow rift on the southernmost coastal plain of Saudi Arabia, from 450 to 600 km north-northwest of the triple junction, are subordinate to felsic and mafic rocks and imply that silicic magma production in the continental crust in this area was much less than in Yemen. Again, the heat flow from the convecting mantle ridge beneath the continental rift in southern Saudi Arabia was less than to the south, that is, crustal heat decreasing with distance.

The Baid formation is the key and unifying feature to the identification of the continental rift in Saudi Arabia. Its composition (figs. 9, 10) and distribution (plate 1) indicates that explosive volcanism produced siliceous ash throughout the rift to as far north as Jiddah. We have only two age determinations of 21.3 and 19.3 Ma on rhyolite and trachyte(?) from the Jabal Sita area (G. F. Brown, unpublished data, 1980) and the major-element chemisty from the Jabal

Shama perlite (table 2) to suggest that the age and chemistry of silicic magmatism did not change significantly along the continental rift in spite of the apparent northward decreased heat flow. Even though rift volcanism probably did not extend northwest of Jiddah, rift structural elements continued northwest along the proto-Red Sea axis.

First-stage sea-floor spreading

Sea-floor spreading of the Red Sea began about 20 Ma ago; this is deduced from all the age and K_2O data shown on figure 14, as well as from the geologic arguments presented above. About this time the Tihamat Asir complex of tholeiitic diabase and basalt dikes and gabbro and granophyre plutons was intruded into the rift volcanic rocks (Jizan group) within the continental rift of the coastal plain of Saudi Arabia. The Tihamat Asir complex is inferred to be restricted to a narrow zone, probably about 12 km wide, at the thinned continental margin of the Arabian Shield.

The chemistry of the Tihamat Asir dikes and the layered gabbro of Jabal at Tirf suggest an origin from tholeiitic magma similar to that of modern Red Sea oceanic basalt (Coleman and others, 1979). The origin of the voluminous granophyre of the same age is less certain, and it could in fact be derived from the lower crust. However, the mafic-rock chemistry (including the rare-earth-element contents and Rb-Sr ratios) has been modified considerably, probably by contamination with older continental crust as well as by differentiation at shallow crustal depths (Coleman and others, 1979). Both contamination and shallow differentiation are likely if these rocks intruded a complexly faulted and thinned continental crust in a continental rift, as we propose. A continental-rift environment, involving circulating nonmarine water, also helps to explain the large depletion in ^{18}O values in the Jabal at Tirf layered gabbro (Taylor and Coleman, 1977). As further evidence that at least a thin continental crust underlies the exposed rift belt, xenoliths of metamorphosed Wajid Sandstone and rare Precambrian gneisses are found in the basalts of Quaternary volcanoes located from 2 to 3 km west (seaward) of the Jabal at Tirf layered gabbro.

Once sea-floor spreading began, the Arabian-Nubian Shield parted along the full length of the Red Sea and the formation of oceanic crust was synchronous along this entire length as predicted by rigid-plate tectonic theory and as shown by the magnetic-stripe anomalies of Hall (1979). In the Jizan area, Blank and others (1981) showed that the easternmost magnetic-stripe anomalies of the Red Sea (Hall and others, 1977) are produced by the Tihamat Asir complex, that is, the oldest magnetic stripe actually is produced by the dikes that intrude continental crust. The easternmost anomaly is positive, and the reversed second anomaly appears on the western edge of the complex.

Modeling of magnetic-stripe anomalies of the Red Sea, exclusive of those of the axial trough, using synthetic anomalies generated from the Tertiary geomagnetic polarity time scale, shows a good match for the interval from 21 to 15 or 14 Ma ago (M. E. Gettings, written commun., 1981). This model evidence, though not decisive, agrees with the age assignments of figure 14.

A brief continental-margin extensional episode accompanied the initiation of sea-floor spreading. Most deformation of the rift volcanic rocks (Jizan group), the underlying Paleozoic and Mesozoic sedimentary rocks, and the underlying Precambrian crystalline rocks occurred at this time. The continental extension had the character of collapsing toward the new ocean crust (fig. 16). The relative age of this extension is well recorded by the geology. The Jizan group as a whole was rotated about 30° seaward, and the earliest, most intensely altered Tihamat Asir dikes were similarly rotated, whereas the younger, less altered Tihamat Asir dikes are typically vertical. This episode of initial spreading and crustal extension lasted perhaps 1 to 2 Ma during the interval of time that the first ocean crust was emplaced, consolidated, and cooled.

The thicker continental crust, from 50 to 100 km inland of the continental rift, was distended on vertical fractures that were filled with magma originating in the deep, underlying convecting mantle. The average age of these continental dikes is about 20 Ma (Eyal and others, 1981) or 22 Ma (Blank, 1977), which at least roughly agrees with the initiation of sea-floor spreading. Hence, the continental crust marginal to the continental rift was distended at the same time that the continental rift was extended.

Initially the continental margin extended and the sea floor spread while the world rigid-plate configuration and dynamics were such that the Arabian plate could rotate away from Africa, that is, the continental margin extended briefly until the linear rate of formation of new lithosphere equalled the rate of plate movement. When these two parameters were balanced, continental-margin extension ceased.

The present-day crustal structure across the extended continental rift at Ad Darb, from the Arabian Shield on the northeast to the oceanic crust at the Farasan Islands, has been determined using a seismic deep-refraction profile (Mooney, 1980; H. R. Blank and M. E. Gettings, written commun., 1981; Healy and others, ~~1982~~/1983 and a gravity study in the Jizan area (Gettings, 1977). The crust of the Arabian Shield is about 40 km thick, and the oceanic crust beneath the Farasan Islands is about 8 km thick. Several kilometers east of the exposed rift belt at Ad Darb, the continental crust thins to about 18 km; hence, across the continental rift itself, a thinned continental crust from 10 to 15 km thick is reasonable (fig. 16). The gravity study east of Jizan suggests an oceanic-continental crust boundary east of Abu Arish within a steep 150-mgal step (4-5 mgal/km) in the gravity data. Our field studies indicate that the entire exposed rift belt is underlain by continental crust; hence the ocean-crust boundary actually lies a few kilometers west of the exposed rift belt but east of Abu Arish and entirely beneath the Quaternary cover.

Subsequent events

The first-stage opening of the Red Sea (Girdler and Styles, 1974) possibly extended from 20 to 15 or 14 Ma ago (figs. 14, 16), a time span that suggests a half-spreading rate of about 2.2 cm per year. From 4 to 6 km of clastic and evaporitic sedimentary rocks were deposited upon the newly formed oceanic crust. These include the middle Miocene Infra-evaporitic Series, the upper Miocene Evaporite Series, and the Continental Series of Gillmann (1968), as recorded in the Mansiyah drill hole (3,931.6 m deep) north of Jizan (fig. 17). The Infra-evaporitic Series is correlated with the lower and upper Globigerina Marls of the Gulf of Suez (Tromp, 1950; Said, 1962, p. 19, 180, 313; Souaya, 1966) by way of comparable rocks in the Sudan coastal area (Sestini, 1965; Gillmann, 1968, p. 204; Whiteman, 1971, p. 205-211), as well as with reef limestone in the Jiddah area where Vindobonian (middle Miocene) foraminifera have been reported (B. Steenstra and H. A. McClure, written commun., 1975). The Infra-evaporitic Series constrains a minimum age of Middle Miocene for the end of the first-stage opening of the Red Sea. The top of the Evaporite series is well dated by the "S" anhydrite reflector throughout the Red Sea and presumably corresponds to the "M" reflector of the Mediterranian Sea at about 5 Ma ago (Ross and Schlee, 1977, p. E13).

Gillmann (1968) suggested that the Baid formation may correlate with his Infra-evaporitic Series, located at a depth of 4,000 m in the Mansiyah drill hole. By our interpretation, the Oligocene-lower Miocene tuffaceous Baid formation will not be found in any of the Red Sea sedimentary rocks that overlie oceanic crust and also not, as suggested by Gillmann, on top of the Evaporite Series in the Jizan salt dome. The Baid formation is restricted to the continental margin east of Abu Arish, and a sequence correlative with the Baid formation should be found on the Sudan coastal plain in the western half of the continental rift.

One of the enigmas of the Red Sea history is the age of the Red Sea Escarpment. It has been postulated that an early large dome rose over the mantle plume at the triple junction and above the convecting mantle ridges beneath the triple arms of the Red Sea, Gulf of Aden, and East African rift (Gass, 1970). No polymictic sands or gravels are found beneath or within the Jizan group, and no Precambrian detritus is found in the extensive Baid formation, which contains only volcanic ash and erosional volcanic debris. Additionally, the early Tertiary lateritic paleosol is only preserved today beneath the Jizan volcanic rocks near sea level in the Al Lith and Ad Darb areas and beneath the flood-basalt flows on the inland plateau in the As Sarat, Harrat Hadan, and Sadah (North Yemen) areas. This implies that the laterite was widespread and erosionally stable through the continental-rifting stage and that it was thoroughly eroded only upon uplift of the Red Sea Escarpment.

The Nubian-type basal sandstone (Ayyanah sandstone) of the Jizan group and Yemen Volcanics represents erosion of a thin saprolitic surface of low relief on stable Precambrian crystalline rocks near sea level. In contrast, the chaotic coarse conglomerate of the Bathan formation is the first clue of the uplift of a Red Sea Escarpment (fig. 14) at some time considerably after deposition of the Jizan group. Possibly correlative terrigenous conglomerates and sandstones in the Infra-evaporite Series suggest a middle Miocene age for the Bathan.

During a long nontectonic interlude, a broad-valley erosional stage (fig. 14) developed on the early escarpment and the initial rugged relief of the scarp was greatly subdued. Two broad erosional valleys, transecting the escarpment west of Harrat Rahat northeast of Jiddah, are preserved beneath upper Miocene basalt flows from Harrat Rahat. In contrast, the present-day streams flow in steep canyons incised below the broad-valley level.

In the Biljurshi area, Greenwood (1975b) suggested a two-stage uplift of the escarpment and identified an ancient elevated erosion surface that cuts across steeply dipping Precambrian structures and that probably represents the broad-valley erosional stage. These highly eroded, relict surfaces are vaguely recognizable in other places such as south of Khamis al Bahr (40 km north-northeast of Al Birk).

Most significantly, the broad-valley erosional stage (or the nontectonic interlude) is well documented by the late Miocene pause in shear movement on the Dead Sea Rift when Jordanian drainages flowed across the rift to the Mediterranean Sea (Zak and Freund, 1981).

During and since Pliocene time, the Red Sea Escarpment was rejuvenated in a second-stage scarp uplift. This late uplift is likely still in progress today as witnessed by the very rugged and steep topography of the modern scarp, by deeply incised wadis, and by the commonly reversed topographic relief of 100 m or more on Pliocene basalt flows in the coastal plain north and south of Jiddah.

Approximate timing of the cyclic Red Sea Escarpment uplifts is suggested by the stratigraphy (fig. 14) in the Mansiyah drill hole. Gillmann (1968, p. 199, 205) notes "some conglomerate" as a "regressive facies" in the middle Miocene(?) upper Infra-evaporite Series, and we suggest that this conglomerate facies correlates with the Bathan formation. The apparent lack of clastic detritus in the thick upper Miocene Evaporite Series may correspond inland to the broad-valley erosional stage. The thick, post-Miocene Continental Series consists of clastic debris including "sandstone and conglomerates" and "50 m of graywacke and polygenic conglomerate" (Gillmann, 1968, p. 196) that we suggest may correspond to the rejuvenated, second-stage scarp uplift.

During Pliocene-Pleistocene-Holocene time, that is, the last 5 Ma, a second stage of sea-floor spreading produced the 60-km-wide axial trough of the Red Sea and suggests a spreading half-rate of about 0.6 cm per year. At the same time and earlier, abundant alkali-olivine basalt flows were extruded on the Red Sea coastal plain (150 km from the Red Sea axis), in the Hijaz mountains (300 km from the axis), and on the upland plateau of the Najd (400-500 km inland from the axis). Some of these youthful volcanic fields may be as old as middle Miocene.

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