DEPARTMENT OF THE INTERIOR
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Stratigraphy of the Miocene Baid formation, southern Red Sea coastal plain, Kingdom of Saudi Arabia

by

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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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SOUTHERN RED SEA COASTAL PLAIN, KINGDOM OF SAUDI ARABIA

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ABSTRACT

The Baid formation, exposed along 700 km of the southern Red Sea coastal plain of Saudi Arabia, is a distinctive lake-bed facies of the volcanic Jizan group. The Jizan group was deposited in a continental rift valley that preceded sea-floor spreading in the Red Sea. The Baid formation consists of thin- to laminar-bedded, tuffaceous siltstone to claystone of silicified rhyolitic composition. The formation is about 250 m thick at its type reference section near Wadi Jizan, where it is confined between felsic and mafic volcanic rocks of the Jizan group. At Ad Darb and Al Qunfudhah, 100 and 300 km northwest respectively, exposed Baid is more than 600 m thick; in these places its upper part is covered by Quaternary alluvium so that most sections are incomplete.

Fossils in the Baid include freshwater fish, mammals, pelecypods, ostracodes, gastropods, and leaves and plant stems. A hippopotamus-like mammal in the Baid may be between 25 and 21 Ma old. The age of the Baid is in the range of 30 to 20 Ma which is the range of penecontemporaneous continental flood basalts on the Precambrian Shield inland of the rift valley. The Baid is older than the Tihamat Asir complex consisting of tholeiitic intrusive rocks that are not older than about 20 Ma.

The Baid sediments were deposited in a series of elongate lakes bounded by explosive, silicic volcanic centers that provided the voluminous air-fall ash that was reworked in the lake environment. The length of the lakes decreased as the volcanic centers became closer spaced and as the crustal heat regime along the continental rift valley increased to the south-southeast, towards the Afar triple junction.

Early during the first stage of sea-floor spreading of the Red Sea (about 20 to 15 Ma), that is, during the intrusion of the tholeiitic Tihamat Asir complex, the continental rift valley containing the Baid formation was extensionally deformed and the rocks of the Baid were tilted about 30° towards the Red Sea. At about this time, the Red Sea escarpment was elevated, and erosion of its resultant rugged

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relief caused the deposition of the Bathan formation, an immature, coarse conglomerate, upon the tilted Baid formation.

The Baid contains no known economic resources, but it is an excellent marker formation in any search for metal deposits in the hydrothermally altered, massive, volcanic rocks of the Jizan group that underlie and overlie the Baid.

INTRODUCTION

The Baid formation is an easily recognized, distinctive sedimentary formation that can be correlated along 700 km of the Red Sea coastal plain from near the Yemen border to east of Jiddah (fig. 1). As such, it is a critical formation in resolving the early history of the Red Sea basin and especially the stratigraphy of a continental rift valley that occupied the early Red Sea basin. The Baid formation consists mostly of silicified, rhyolitic tuffaceous siltstone and claystone. It was deposited during the early Miocene in freshwater lakes between silicic eruptive centers within the rift valley and is described here as a lake-bed facies. Silicic lava and pyroclastic flows of the Layyah formation are about contemporaneous with the Baid formation. The Baid and Layyah formations are underlain and overlain by thick, mafic and felsic volcanic and volcaniclastic rocks of the Ad Darb (lower) and Damad (upper) formations. Together, these volcanic rocks constitute most of the Jizan group which is the product of the continental rift-valley volcanism (Schmidt and others, 1982).

The Baid formation as defined by Schmidt and others (1982) is formally restricted to the lake-bed facies of the Jizan group. Previously, the Baid formation had been identified informally as lake-bed rocks that had volcanic and volcaniclastic rocks above and below (Brown and Jackson, 1958; Gillmann, 1968). However, the relationship of the volcanic rocks to the lake-bed rocks was not clearly defined and made ambiguous the usage of the Baid as a restricted formation with well-defined top and bottom.

This report describes measured sections of the Baid formation between Wadi Jizan and Al Lith (fig. 1) and is preliminary to describing sections of the entire Jizan group. Outcrops of the Jizan group, including the Baid, are confined to a narrow Tertiary outcrop belt, 4-6 km wide, that consists of the easternmost coastal plain and the westernmost foothills. The rocks are well but discontinuously exposed in the easternmost part of the coastal plain in narrow channel bottoms and sides of dissecting wadis at altitudes of about 100 m. These outcrops extend inland and

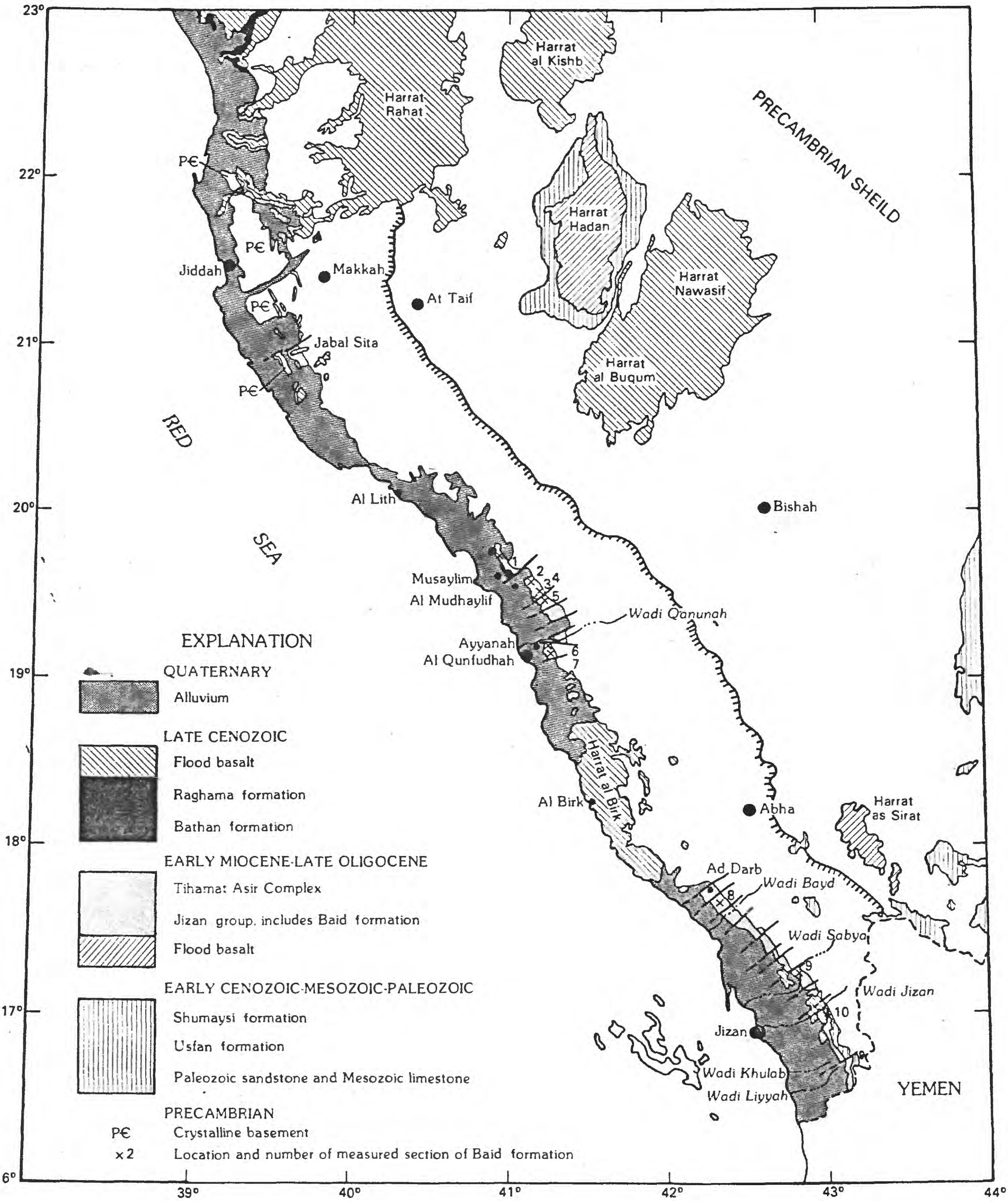


Figure 1.--Index map of southwestern Saudi Arabia showing southern coastal-plain geology and location of measured sections of the Baid formation. For details of geology, see plate 1 in Schmidt and others, 1982.

eastward into the westernmost part of the foothills where the Jizan rocks are more abundantly exposed in hills rising to about 200 m. However, these foothill outcrops are poorly and discontinuously exposed and make continuous detailed section measurement difficult. In general, section measurement of the Jizan-group rocks in the Tertiary outcrop belt is not easy because (1) outcrops are discontinuous in many places; (2) marker horizons, other than the Baid formation as a whole, cannot be followed more than short distances; (3) faults parallel to bedding are difficult to recognize for lack of good marker horizons and cross faults are commonly covered by alluvium; and (4) dikes and sills intrude, alter, and further obscure the rocks.

The coastal plain is commonly 20-40 km wide, in which distance the surface rises from sea level to about 100 m; it consists of Quaternary alluvial fans and pediments that in places are covered by Quaternary eolian sand and silt deposits. From the Tertiary outcrop belt at the head of the coastal plain, the foothills gradually rise in altitude to the Red Sea escarpment. Farther east the escarpment rises steeply to its crest at altitudes of 2,000 and 3,000 m at distances of 75-125 km from the coast. East of the Baid outcrops, most of the foothills and the rugged escarpment are underlain by schists, gneisses, and plutonic rocks of Precambrian age.

Past and present studies

The Baid formation was named and briefly described by Brown and Jackson (1958, 1959) from mapping begun in 1951 on Wadi Bayd, about 80 km north-northwest of Jizan. The 1:500,000-scale geologic maps of the Asir and Tihamat ash Sham quadrangles show in reconnaissance most of the outcrops of the Baid formation from north of Wadi Jizan to south of Wadi Al Lith.

During 1966-67, the French company, Auxiliar Enterprise de Recherches et L'activities (AUXERAP) mapped and measured many sections of the Tertiary volcanic and sedimentary rocks from the Yemen border to Jiddah, but of this work only a summary for the Jizan coastal plain is available (Gillmann, 1968). Gillmann gave two sections from Wadi Jizan and Ad Darb in which the entire volcanic and sedimentary section was called the Baid formation, or what is now defined as the Jizan group (Schmidt and others, 1982).

During the 1970's, quadrangles along the Red Sea coastal plain between the Yemen border and Jiddah were geologically mapped in reconnaissance at 1:100,000 scale by the U.S.

Geological Survey. Tertiary rocks of the Jizan group including the Baid formation underlie the following quadrangles: Jizan (Blank and Gettings, unpub. data); Wadi Khulab (Blank and Gettings, unpub. data); Sabya (Fairer, 1983); Ad Darb (Fairer, in press); Manjamah (Hadley, 1981); Al Qunfudhah (Hadley, 1975); Jabal Shada (Greenwood, 1975); Musaylim (Hadley, 1980); and Harrat Tuffil (Pallister, 1982).

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 Wadi Khulab to Al Birk in March 1974 (Coleman and others, 1979). At this time, a preliminary section of the Baid formation (unrestricted) was measured at Ad Darb. The other sections north of Ad Darb, presented in this report, were measured by Hadley during mapping of the 1:100,000-scale quadrangles reported above.

Between February and May of both 1980 and 1981, Schmidt studied the Baid formation and associated volcanic and intrusive rocks in the southern coastal plain between the Yemen border and Jiddah (Schmidt and others, 1982; Hadley and others, 1982; Madden and others, 1983). The sections of the Baid formation from Wadi Sabya and Wadi Jizan in this report were measured by Schmidt during this field work.

Acknowledgments

Field and office studies for this report were done in accordance with a work agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey (USGS). Support provided by the Saudi Arabian Directorate General of Mineral Resources (DGMR) is greatly appreciated. Discussions with G. F. Brown, H. R. Blank, M. E. Gettings, K. S. Kellogg, J. S. Pallister, R. G. Coleman, and R. T. Gregory have stimulated our overall study of the Red Sea continental margin.

STRATIGRAPHY OF THE COASTAL PLAIN REGION

A schematic stratigraphic column of the rocks of the southern Red Sea coastal plain area is shown on figure 2. A summary of these rocks is given in Hadley and others (1982, table 2). The Precambrian crystalline basement, unconformably underlying the Phanerozoic rocks, consists of late Proterozoic volcanic, volcaniclastic, and plutonic rocks that are highly deformed and metamorphosed to greenstones of greenschist facies or more commonly to schists and gneisses of amphibolite facies; some late plutonic rocks are little deformed or metamorphosed.

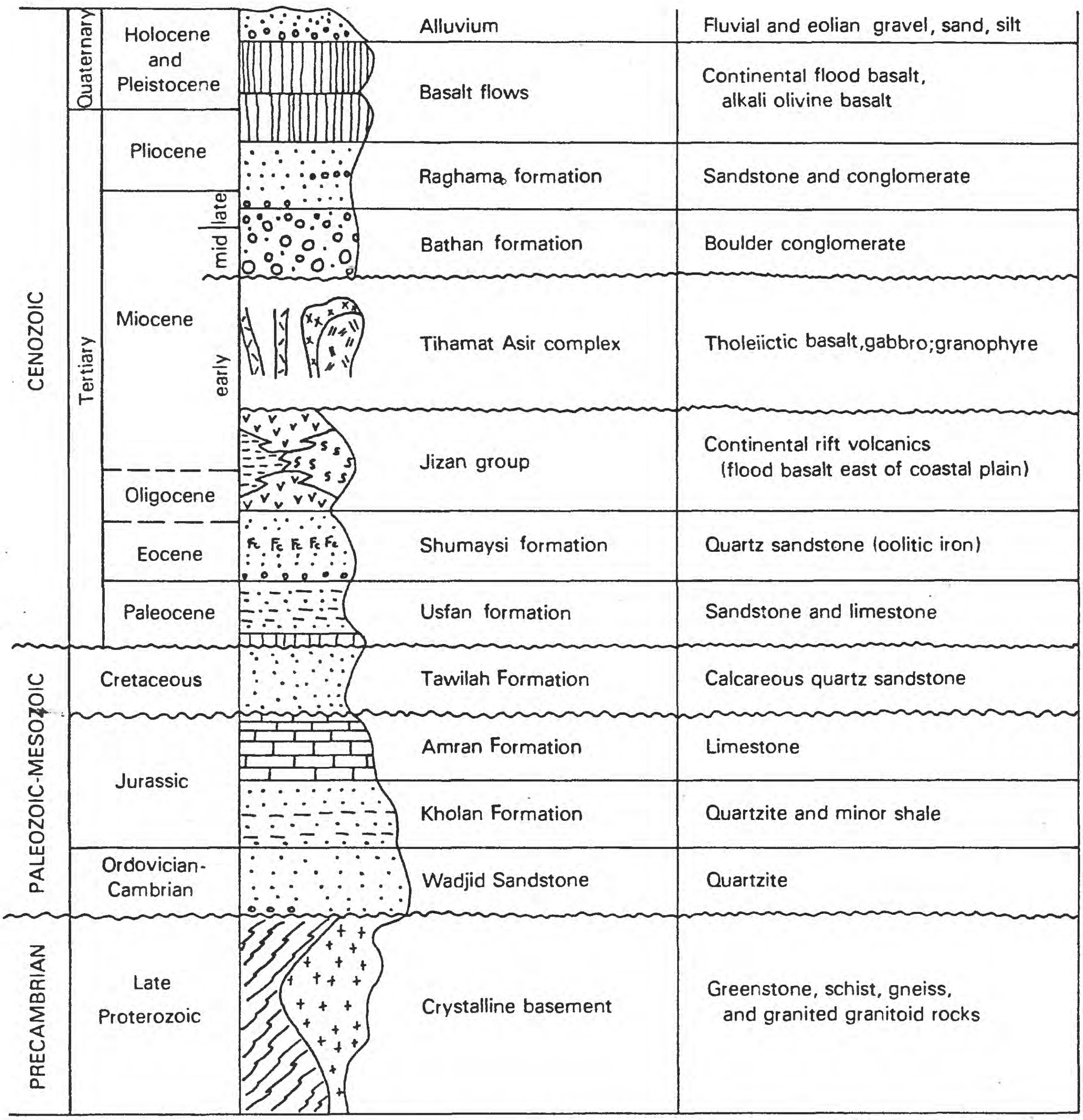


Figure 2.--Composite column of the stratigraphy of the southern Red Sea coastal plain.

The white, coarse- to medium-grained, quartzose sandstone of the Cambrian and Ordovician Wajid Sandstone (Powers and others, 1966) unconformably overlies an Early Cambrian, flat erosion surface cut on the Precambrian rocks. The buff, fine-grained quartzose sandstone with sparse, thin, red shale-siltstone beds and partings is part of the Jurassic Kohlan Formation (Geukens, 1966) that disconformably overlies the Wajid Sandstone. The combined Wajid and Kohlan sandstones previously were named the Khums Formation by Brown and Jackson (1959). The Kohlan conformably grades upward to the fossiliferous, lithographic limestone of the Jurassic Amran Formation (Geukens, 1966). In a few places, the top of the Amran limestone grades upward into a thin, coarse-grained, calcareous quartz sandstone that may either represent a sandstone facies in the upper part of the Amran or more likely represents the disconformable Cretaceous Tawilah Formation as described in the Yemen (Geukens, 1966). These Paleozoic and Mesozoic formations are confined to the eastern edge of the Tertiary outcrop belt in the Jizan area from the Yemen border to Ad Darb (fig. 1).

Early Tertiary deposits older than the Jizan group are confined to the Jiddah coastal plain and foothill area and constitute the Usfan and Shumaysi formations. The Paleocene(?) Usfan formation (Brown, 1970) consists of limestone, sandstone, and conglomerate that rest unconformably on Precambrian rocks. Disconformable above is the Eocene-Oligocene Shumaysi formation (Al-Shanti, 1966; Moltzer and Binda, 1981) consisting of pebble sandstone, sandstone, siltstone, limestone, and several beds of oolitic ironstone. The upper part of the Shumaysi contains several silicic tuff beds that may correlate with the late Oligocene to early Miocene Jizan group and are probably of late Oligocene age (Schmidt and others, 1982). A thick section of basalt flows and sparse intercalated silicic tuff beds of late Oligocene to early Miocene age overlies the Shumaysi formation and probably should be excluded from it.

Throughout the southern Tertiary outcrop belt, the Jizan group (Schmidt and others, 1982) is exposed discontinuously. The Jizan group consists of five formations each of which in different places may or may not be in part intercalated with each other (fig. 3). The basal is the Ayyanah formation. It is composed of fossiliferous conglomerate, sandstone, and limestone and has a maximum known thickness of 42 m. The Ayyanah formation, has been found only in the Al Qunfudhah area, but it is considered correlative with the upper part of the Shumaysi in the Jiddah area.

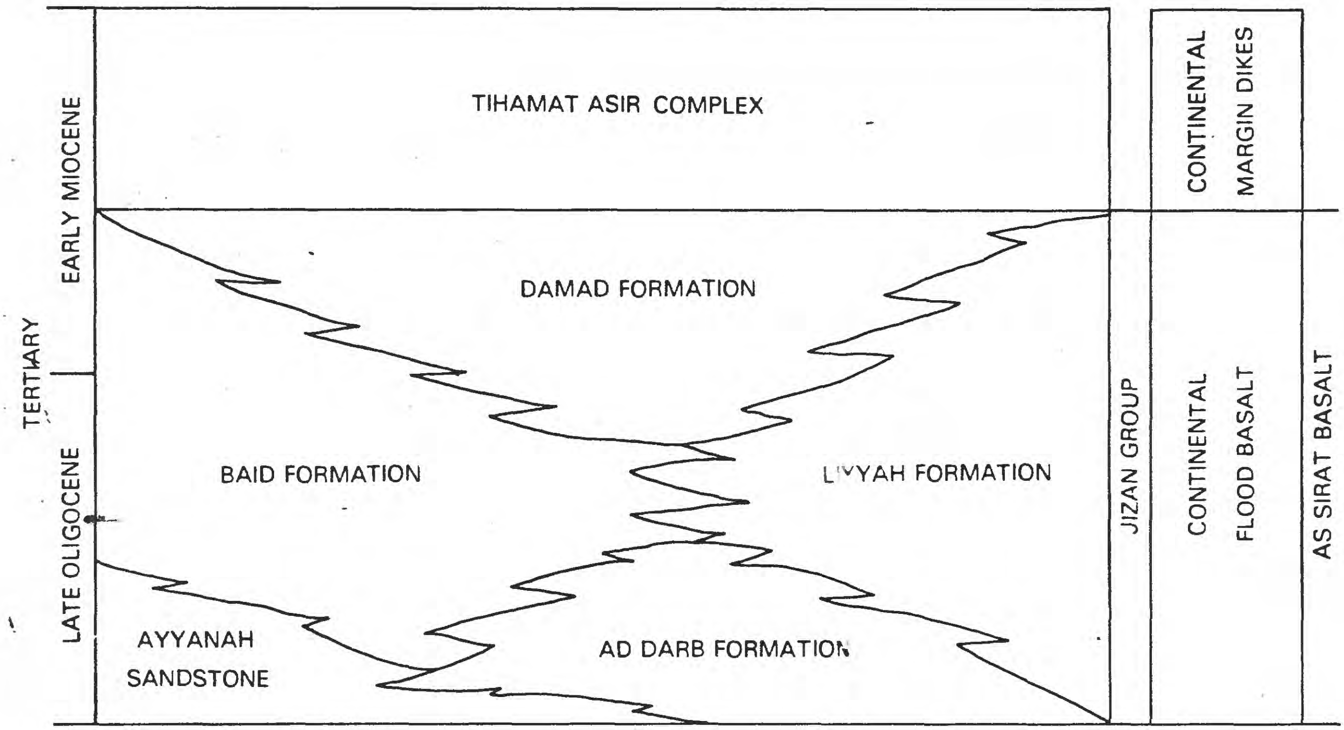


Figure 3.--Diagrammatic stratigraphic section of the Jizan group and intrusive Tihamat Asir complex of the southern Red Sea coastal plain. Diagram also shows relationship of comtemporaneous flood basalt and continental dikes on the Precambrian Shield east of the coastal plain.

The Ad Darb formation is a mafic volcanic and volcaniclastic unit, commonly basaltic in composition, that is the basal volcanic unit in the Jizan coastal plain area. Conformably above it, but in places intercalated with it, is the Liyyah formation of silicic dacitic to rhyolitic lava and ignimbritic flows. The Liyyah volcanoes produced voluminous, explosive ash and tuff that accumulated in lakes between eruptive centers. These lake-bed deposits have been defined as the Baid formation (Schmidt and others, 1982) and consist of silicified tuffaceous siltstone and claystone (figs. 4, 5). The Damad formation, the uppermost volcanic unit of the Jizan group, consists of thick, mafic to felsic breccia flows and volcaniclastic deposits. Wherever exposed, the Damad section is incomplete as it dips beneath the Quaternary alluvium of the coastal plain.

The Tihamat Asir complex of late early Miocene age everywhere intrudes the rocks of the Jizan group as well as the underlying Mesozoic, Paleozoic, and Precambrian rocks. Dikes and sills of basalt and diabase and sparsely of rhyolite are conspicuously abundant in the Jizan to Ad Darb coastal plain region, and especially so where large plutons of gabbro and granophyre intrude the Jizan-group rocks. However, overall the dikes and sills of the Tihamat Asir complex probably constitute only about five percent of the exposed Jizan rocks, but these dikes and sills commonly form resistant outcrops and coarse detritus that tend to obscure the Jizan host rocks.

The Bathan formation (Hadley and Fleck, 1980; Schmidt and others, 1982) of middle Miocene or slightly later age unconformably overlies the Jizan group and consists of immature, coarse, polymictic conglomerate containing sparse discontinuous sandstone lenses. The Bathan is the youngest exposed coherent sedimentary rock unit in the southern coastal plain aside from late Miocene evaporate rocks exposed in the Jizan salt dome at Jizan.

Alkali olivine basalt flows and cinder cones in a large composite volcanic field, Harrat Al Birk at Al Birk, and in isolated volcano centers to the east and north are of Pliocene and Quaternary age and unconformably lie on Precambrian basement (Ghent and others, 1980). A few other isolated basalt volcanoes of Quaternary age are scattered along the southern coastal plain south of Ad Darb where they overlie the Jizan group (Coleman and others, 1979).

Quaternary coastal-plain deposits, consisting of fluvial sand and gravel sheets, fans, and deltas, and of eolian sand dune deposits and water-washed eolian sand and silt de-

Figure 4.--Photograph snowing outcrop of Baid formation on the south tributary of Wadi Sabya. Section is about 20 m thick, bedding dips 30° southwest.

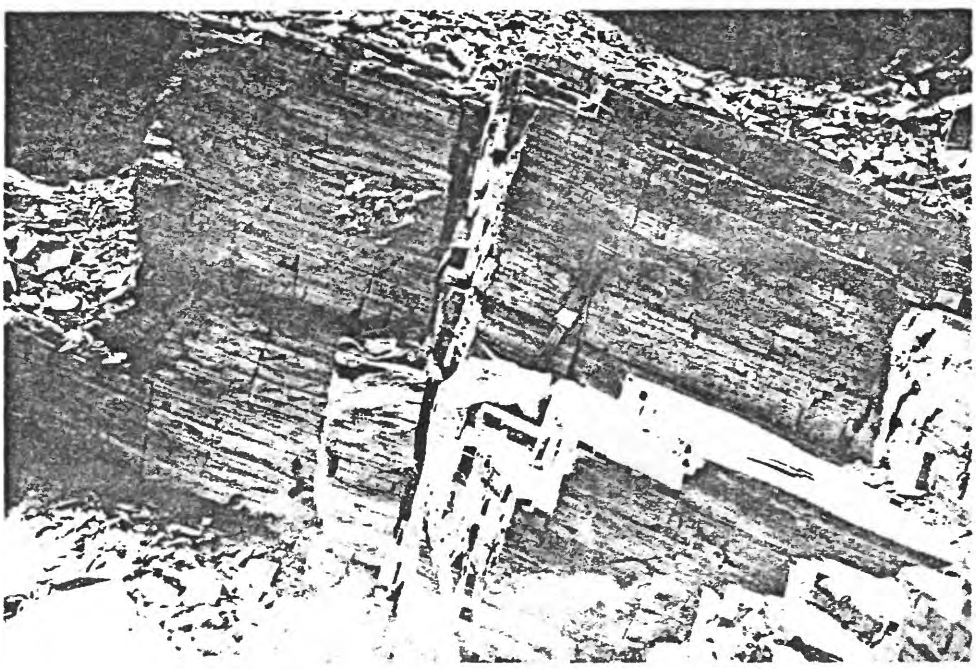


Figure 5.--Photograph showing closeup view of thin-bedded siliceous, tuffaceous siltstone of Baid formation. Attitude is N. 32° W., 28° southwest; photograph taken at outcrop of figure 4.

posits, cover all the older deposits in most of the coastal plain and in much of the adjoining low-relief foothills. Along parts of the coastline itself are narrow exposures of modern and raised, ancient, coral-reef deposits.

The Pliocene Raghama formation, shown on figure 2, is the principal detrital sandstone and conglomerate unit conspicuously exposed in the northern Red Sea coastal plain. It is an undivided composite unit not exposed in the southern coastal plain but probably in part equivalent to the middle and upper Miocene to Quaternary infra-evaporite, evaporite, and continental units (series) recorded by Gillmann (1968) in the 4,000-m-deep Mansiyah drill hole, 40 km north-northwest of Jizan. The abundant exposure of the Raghama north of Jiddah and its lack of exposure south of Jiddah indicate post-Miocene uplift of the formation north of Jiddah and subsidence south of Jiddah.

In the northern coastal plain, other than the Raghama formation and surficial sediments, only the Usfan and Shumaysi formations and Quaternary basaltic rocks are exposed; the Usfan and Shumaysi formations crop out only between Jiddah and less than 200 km north of Jiddah. No volcanic rocks of the Jizan group are exposed north of Jiddah. Although not mapped as a separate unit in the north, the Bathan formation is probably represented by some conglomeratic phases of the Raghama formation.

STRATIGRAPHY OF THE BAID FORMATION

Definition

The Baid formation was restricted to a formation within the Jizan group by Schmidt and others (1982); in that report the Jizan group was newly named and defined in the vicinity of Wadi Jizan. The Baid formation of Brown and Jackson (1958, 1959) was described similarly to the Baid formation of Schmidt and others (1982) (that is, as a lake-bed facies), but it was mapped by Brown and Jackson (1958, 1959) to include volcanic rocks that Schmidt and others (1982) assigned to other formations within the Jizan group. Gillmann (1968) followed Brown and Jackson in unrestricted use of the Baid formation.

Brown and Jackson named the Baid formation for Wadi Bayd, 82 km north-northwest of Jizan and 16 km southeast of Ad Darb, where the Baid-type lake beds are not well exposed beneath the Quaternary alluvial cover. G. F. Brown (written commun., 1981) chose as his stratotype the thick section 2-3 km south of Ad Darb. A generalized stratigraphic column of this type section was published by Gillmann (1968). The base of the Baid formation at Ad Darb is underlain by the Ad Darb formation of the Jizan group, but the upper part is covered by Quaternary alluvium.

A section of the Baid formation near Wadi Jizan is designated in this report as a type reference section. It is located at lat 17° 01.7' N., long 42° 57.3' E. (3.3 km S. 12° E. of the Wadi Jizan dam, 5 km due east of the center of the cutoff meander on Wadi Jizan, and 400-600 m north of the dirt road between Abu Arish and Jabal Fayfa). Here, the base of the Baid is exposed within a few meters of the top of the Ad Darb formation at a distinctive lithologic break between underlying, green, massive, mafic volcanic rocks and the white and buff, well-bedded lake beds. The top of the Baid is exposed within a few meters of the bottom of the Damad formation at a break between underlying, drab-green, well-bedded lake beds and light-green-weathered, massive lithic tuff.

Occurrence

The Baid formation is exposed discontinuously from Wadi Liyyah near the Yemen border to east of Jiddah, a distance of 700 km. It is generally moderately well exposed beneath alluvial terraces in wadi channels and sides where it forms moderately resistant outcrops because of its siliceous composition (figs. 4, 5). In the foothills between wadis, where it has been exposed to longer periods of weathering, its fissile bedding cleavage and close spaced jointing cause it to be highly fractured, weathered, and poorly exposed. Discontinuities of exposure and lack of conspicuous marker beds make it difficult to recognize faults in the relatively homogeneous Baid formation, and hence, a measured section at any locality contains some element of uncertainty.

The best exposures of the Baid are in the sector between Wadi Liyyah and Ad Darb where large and small wadis entrenched into the Baid beneath the coastal-plain alluvial cover are abundant and closely spaced. Also, in this sector, the Baid is slightly better preserved or the Tertiary rocks are slightly less eroded because of the massive resistant outcrops of the Mesozoic and Paleozoic sandstones beneath the Baid and because of the abundant, commonly resistant Tihamat Asir dike swarm within and adjacent to the Baid.

Throughout the sector between Ad Darb and Al Qunfudhah, Precambrian rocks form the westernmost outcrops, implying that the basement here is upfaulted or transform faulted to the west relative to the sectors adjoining to the north and south. Only in the northernmost part of this sector are a few outcrops of Baid rocks exposed.

In the sector between Al Qunfudhah and Al Lith, the Precambrian basement is inland, and more abundant exposures of the Baid formation are found at the head of the coastal plain. Good outcrops are widely discontinuous because dissecting wadis are small and widely spaced. In contrast to the Wadi Liyyah-Ad Darb sector, resistant Mesozoic and Paleozoic rocks are missing as is the wide belt of resistant dikes and sills. Most of the Baid outcrops between the few dissection wadis are protected by two thick, resistant dikes or sills of Tihamat Asir diabase.

In the final sector between Al Lith and Jiddah, the Precambrian rocks extend to near the coast, and Tertiary rocks mostly form only a thin layer on the Precambrian; a thin Baid section occurs at Jabal Sita.

Thickness

Figure 6 shows 10 sections of the Baid formation measured at sites along the southern coastal plain; the locations are on figure 1. These measured sections are summarized in a correlation diagram (fig. 7). Measured thicknesses are highly variable and incomplete because only at Wadi Jizan and Wadi Sabya are the sections confined between other formations of the Jizan group. The three northernmost sections have their upper and lower parts covered by Quaternary alluvium; four others have their upper parts covered by alluvium but have bases that are faulted against the Precambrian basement. At Ad Darb, however, the upper part is covered by alluvium and the base is underlain by the lower volcanic formation, the Ad Darb formation.

The combined thickness of the Tihamat Asir dikes and sills has been subtracted as well as can be estimated. This is relatively easy for the sections from Al Qunfudhah to Musaylim where few dikes are present, but the task is more significant and complex for the Wadi Jizan to Ad Darb sections, where many dikes of the Tihamat Asir dike swarm cut the Baid. However, the total inflation of the section by dikes and sills probably is about 5 percent, and so the measured section is not likely to be too thick by more than 1 or 2 percent.

The Baid is 250 m thick at the type section on Wadi Jizan (fig. 6, section no. 10), and that at Wadi Sabya, 28 km to the northwest, is 220 m thick (fig. 6, section no. 9).

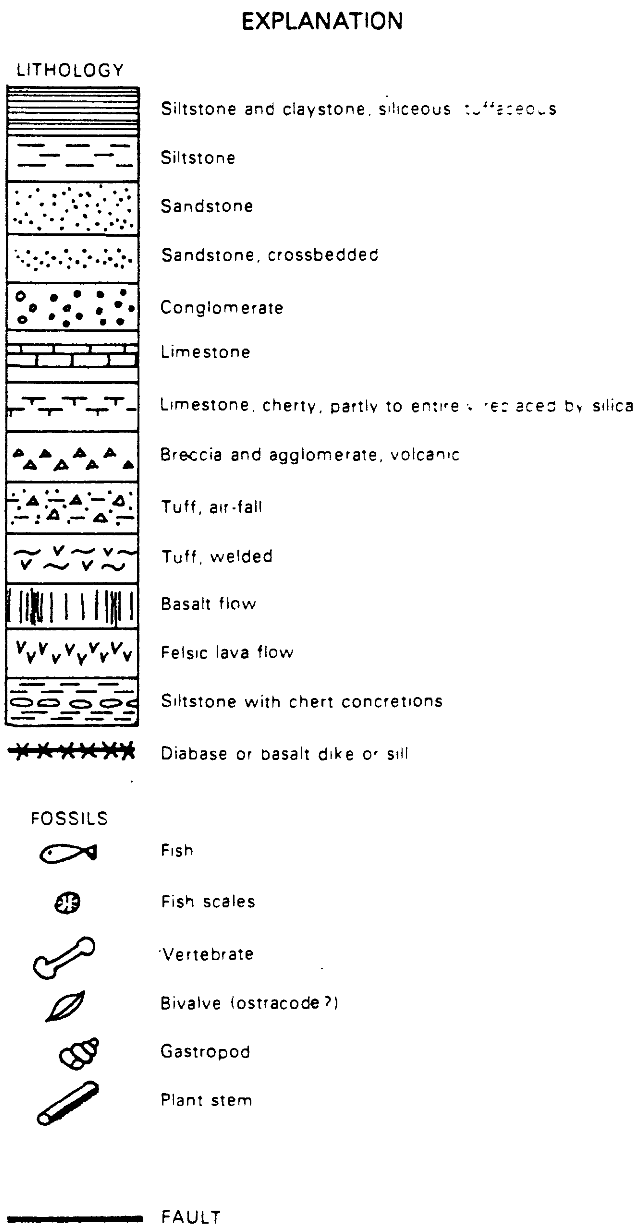
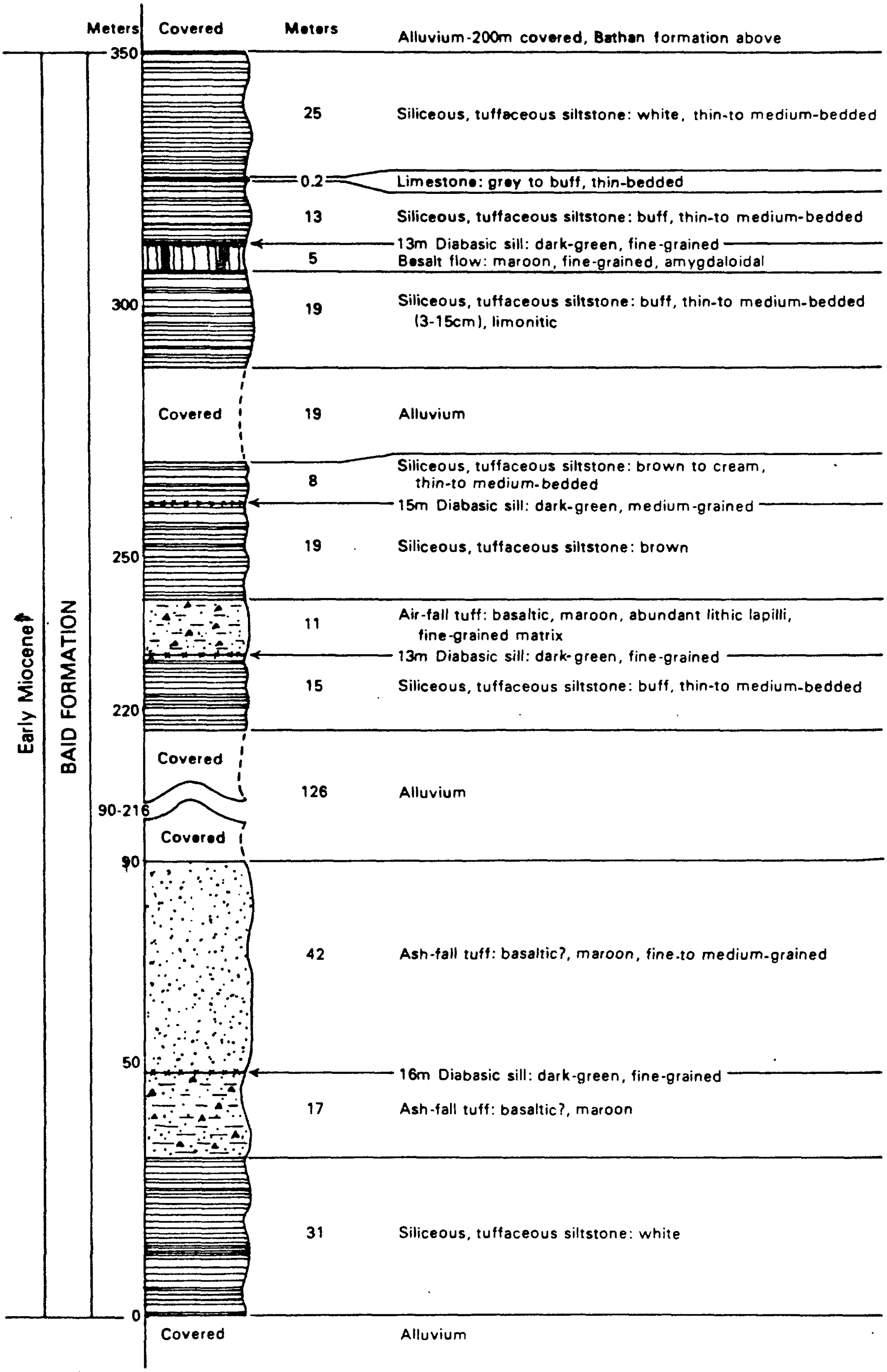


Figure 6.--Stratigraphic columns of the Baid formation (section nos. 1 through 10) measured on the southern coastal plain between Musaylim (NW) and Jizan (SE). The type reference section from near Wadi Jizan is section no. 10.

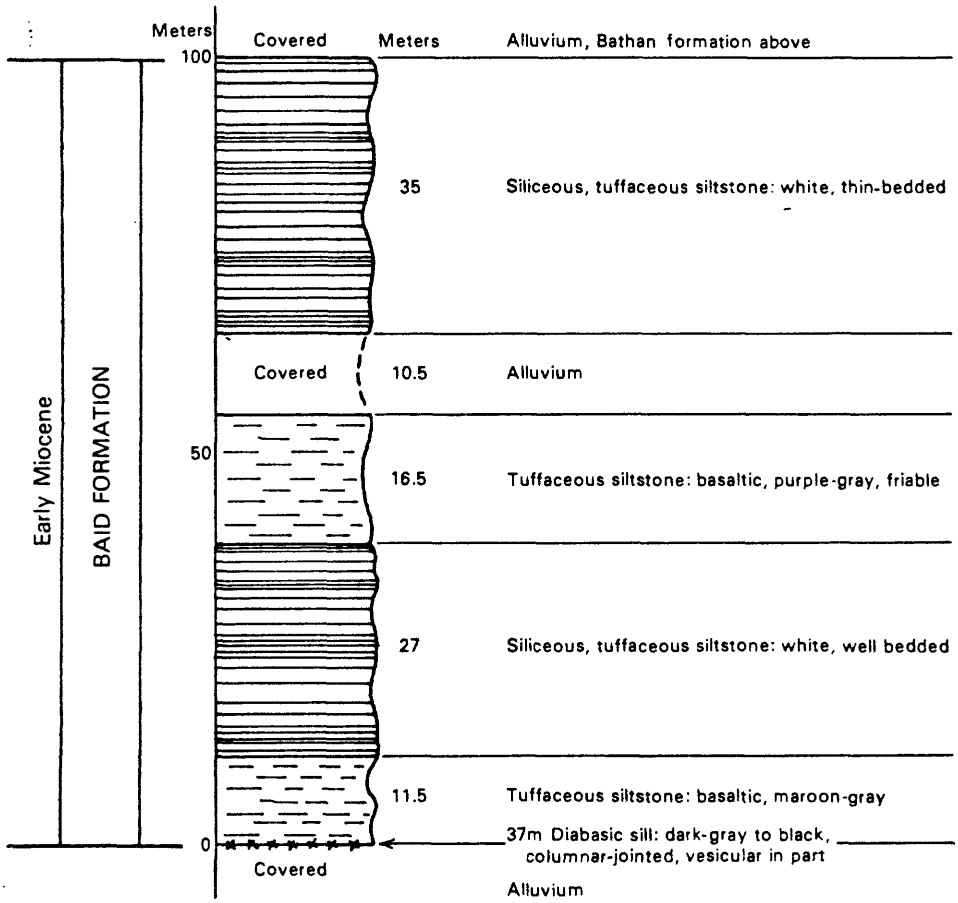
BAID FORMATION-350m exposed
Musaylim Quadrangle
16 km north of Musaylim
Lat 19°47.8'N, Long 40°56.3'E
Average attitude: N60'0W 15°SW

Section No. 1



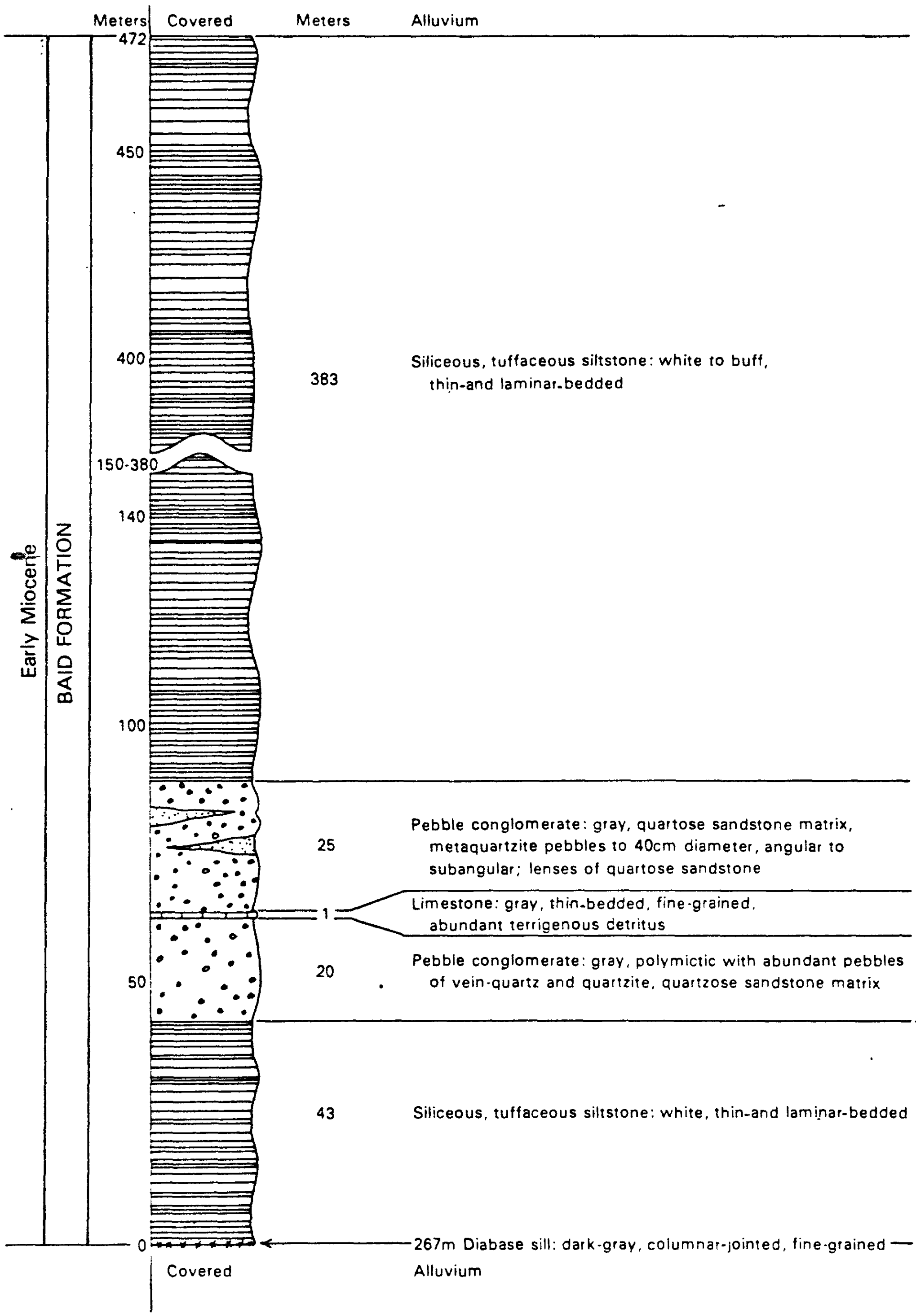
BAID FORMATION-100.5m exposed
Jabal Shada Quadrangle
Wadi Nawan, 13 km east of Mudhaylif
Lat 19°31.9'N, Long 41°10.6'E
Average attitude: N65°W 30°SW

Section No. 2



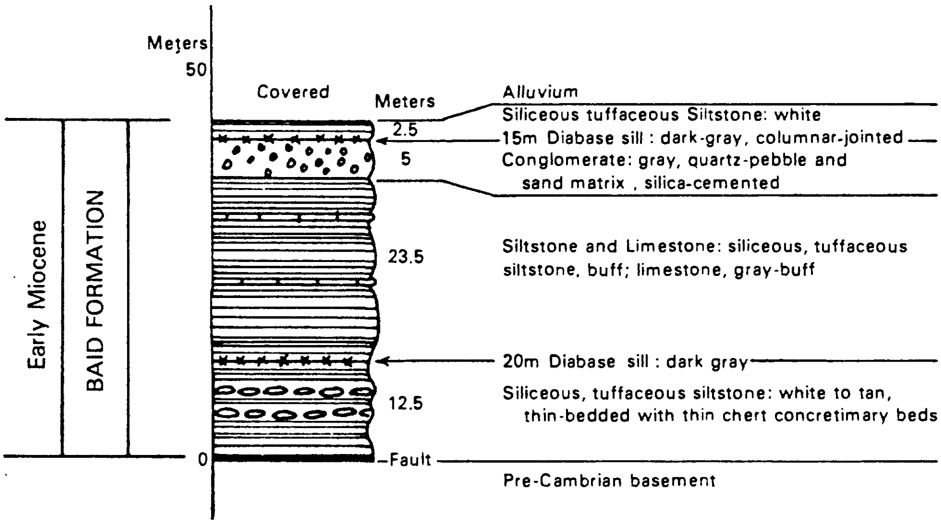
BAID FORMATION-472m exposed
Al Qunfudhah Quadrangle (northern part)
Wadi Ahsibah, 20 km east-southeast of Mudhaylif
Lat 19°27.7'N, Long 41°13.4'E
Average attitude: N15°W 22.5°SW

Section No. 3



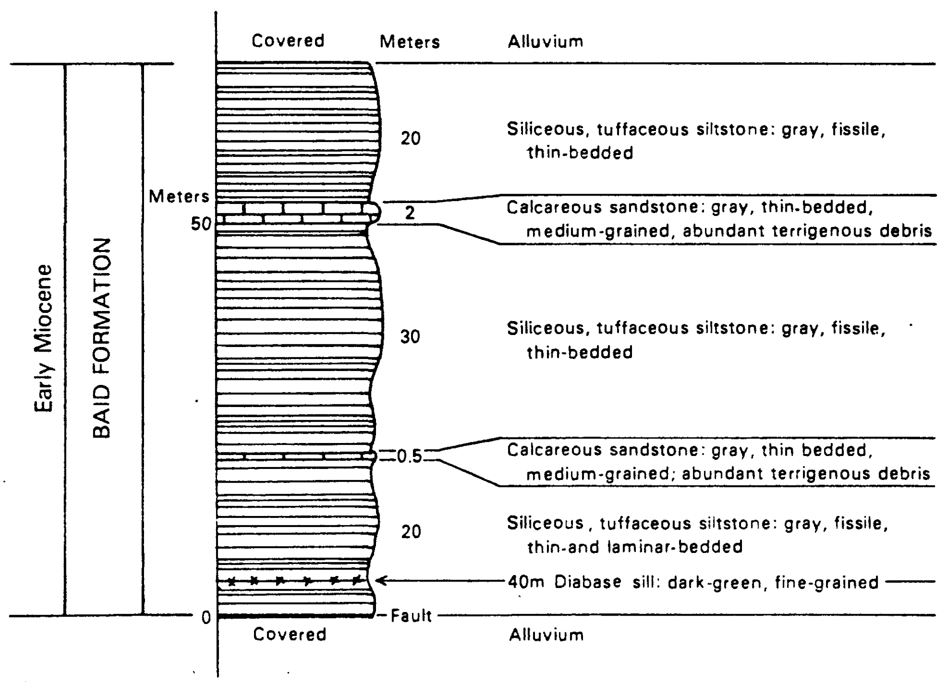
BAID FORMATION-43.5m exposed
Al Qunfudhah Quadrangle (northern part)
Wadi Ahsibah, 22 km east-southeast of Mudhaylif
Lat 19° 29.1'N, Long 41°15.2'E
Average attitude: N30°W 30°SW

Section No. 4



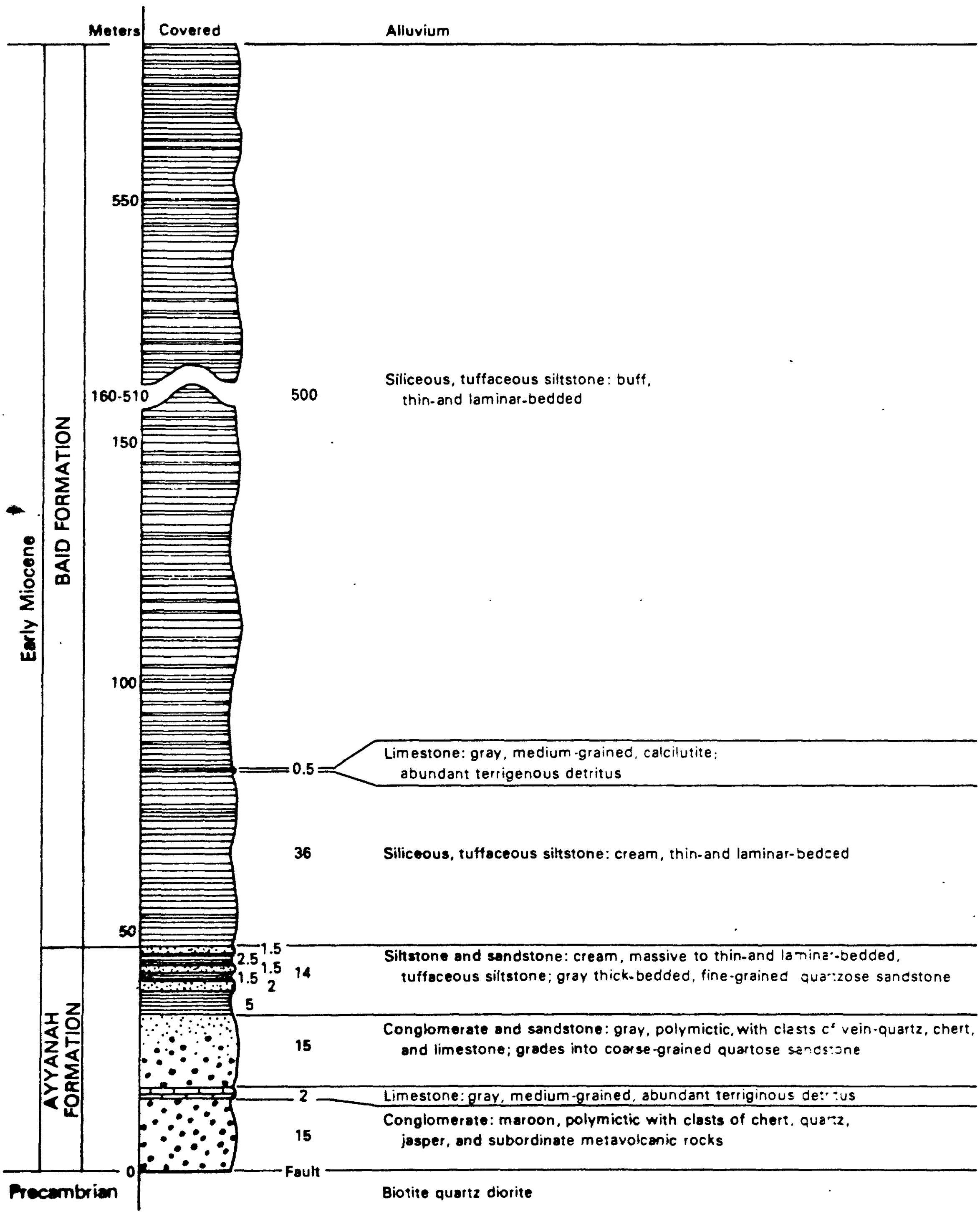
BAID FORMATION-72.5m exposed
Al Qunfudhah Quadrangle (northern area)
Tributary of Wadi Lumah
Lat 19°27.7'N , Long 41°16.9'E
Average attitude: N30°W 25°SW

Section No. 5



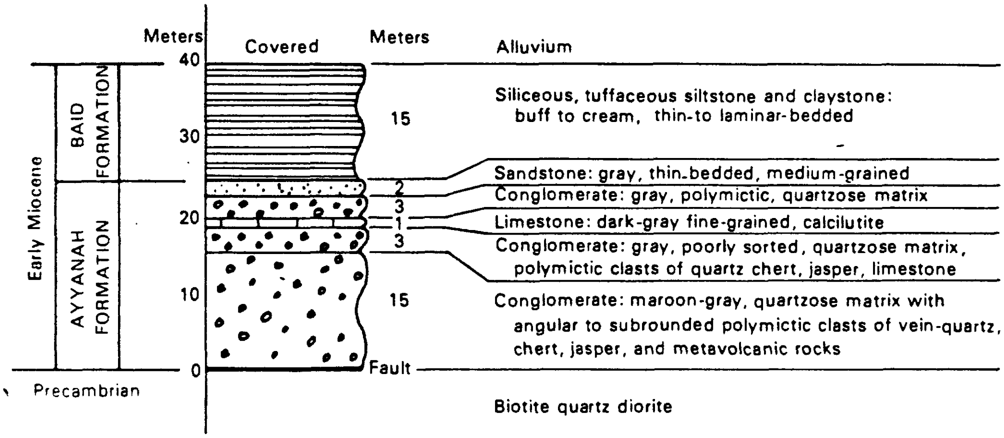
BAID FORMATION-536.5m exposed
AYYANAH FORMATION-46m
Al Qunfudhah Quadrangle
1 km northwest of section 7
Lat 19°11.1'N, Long 41°16.2'E
Average attitude: N30°W 35°SW

Section No. 6



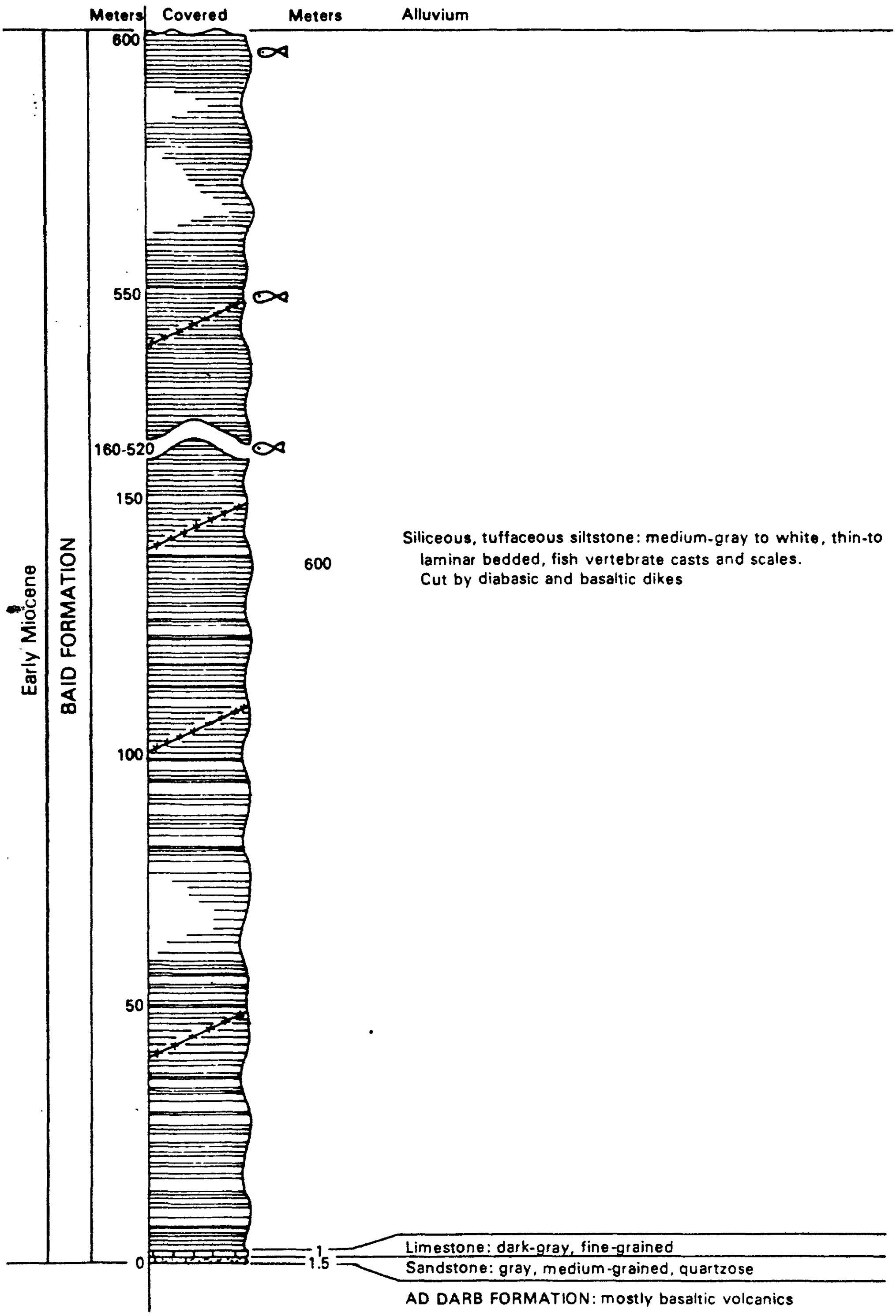
BAID FORMATION-15m exposed
AYYANAH FORMATION-24m
Al Qunfudhah Quadrangle
6 km S78°E of Ayyanah
Lat 19° 11.1'N, Long 41°15.8'E
Average attitude: N 30° W 35°SW

Section No. 7



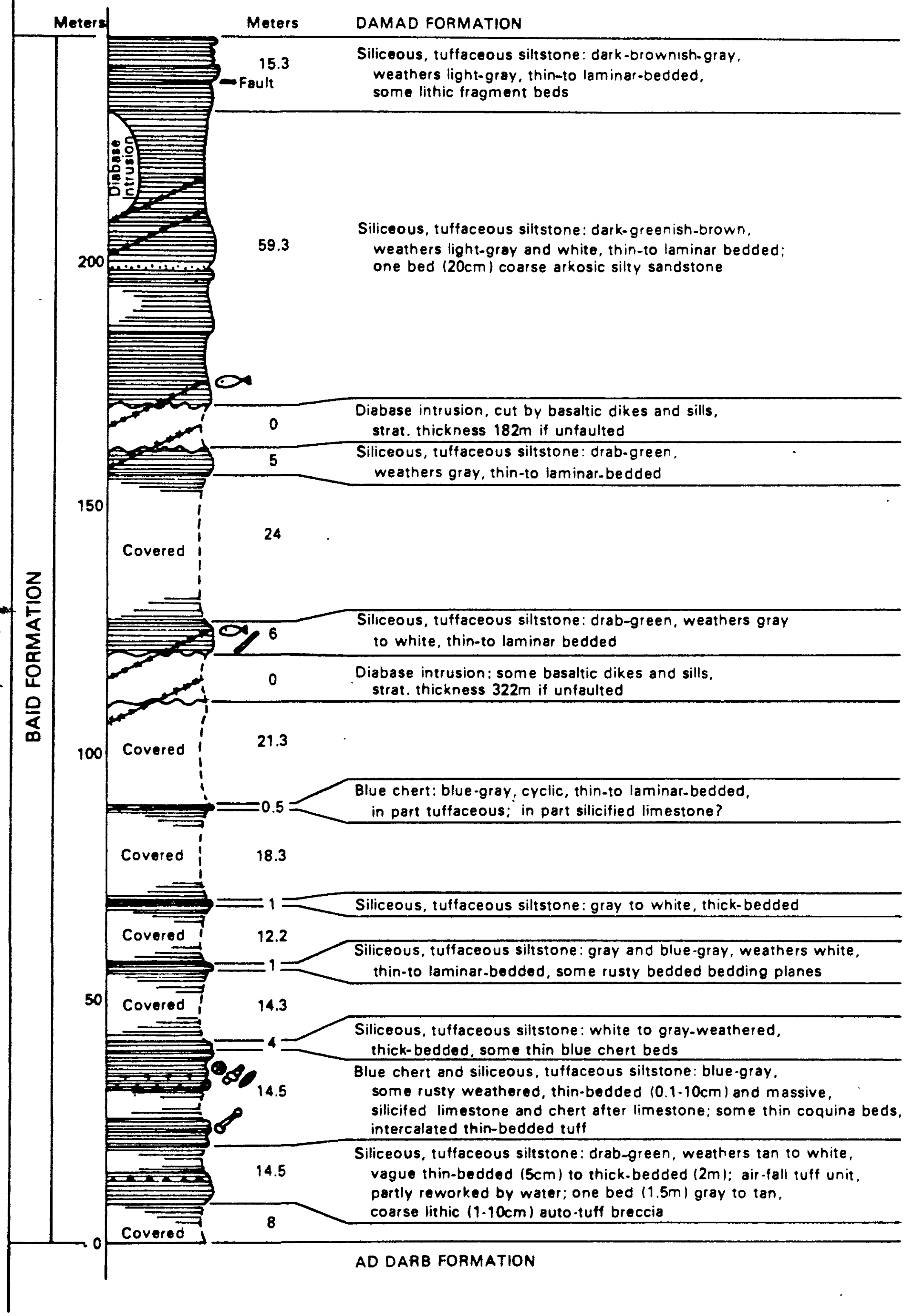
BAID FORMATION-600m exposed
Ad Darb Quadrangle
3 km S62°E of Ad Darb
Lat 17°42.4'N, Long 42°16.3'E
Average attitude: N35°W 30°SW

Section No. 8



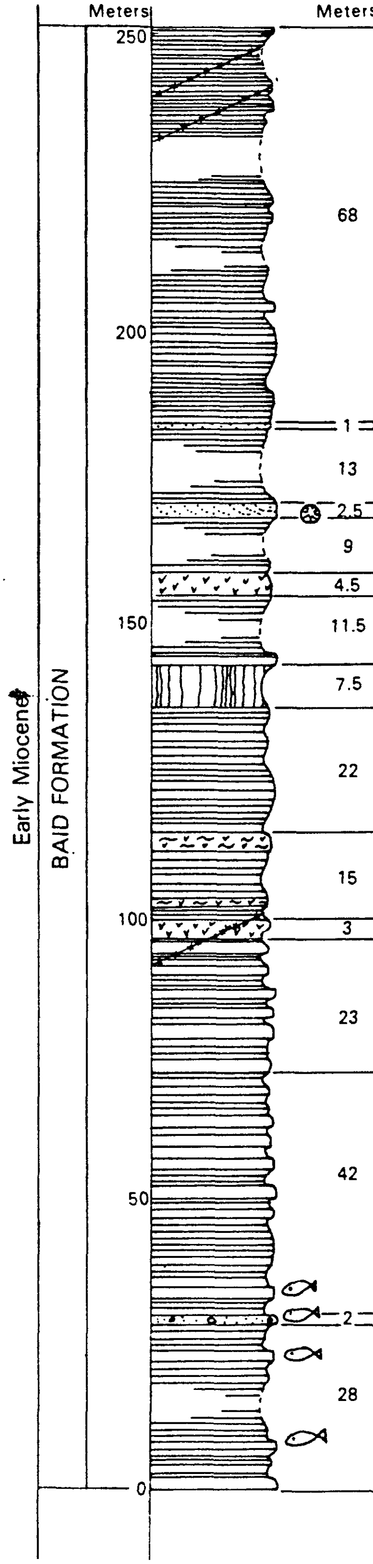
BAID FORMATION-220m
Sabya Quadrangle, Wadi Sabya
Lat 17°13.2'N, Long 42°47.1'E
Average attitude: N50°W 35°SW

Section No. 9



BAID FORMATION-252m
Sabya Quadrangle Wadi Jizan
Lat 17°01.7'N, Long 42°57.3'E
Average attitude: N20°W 30°SW

Section No. 10



Meters	
	DAMAD FORMATION
68	Siliceous, tuffaceous siltstone and claystone: drab-green, gray, white, some fissile-weathered, some cyclic, locally fining up, massive thick-bedded and thin-to laminar-bedded, rhyolitic (cut by several black basaltic dikes, aggregate 9m thick)
1	Siliceous, tuffaceous sandstone: Tan, thin-bedded, medium-to very fine grained
13	Siliceous, tuffaceous siltstone
2.5	Tuffaceous sandstone: medium-green, thin-to laminar-bedded, crossbedded, very fine grained, dolomitic, rhyolitic
9	
4.5	Pyroclastic flow: green-gray, massive, thick-bedded, pumiccous, nonwelded, rhyodacitic
11.5	Siliceous, tuffaceous siltstone: rhyolitic
7.5	Basaltic flow: dark-gray
22	Siliceous, tuffaceous siltstone: gray, cyclic thin-to laminar-bedded, some as coarse as fine sand size
15	Welded tuff: brown, massive, several 2m-thick units, fine compaction foliation, one lithic-crystal, rhyolitic; some in tercalated siliceous, tuffaceous siltstone
3	Porphyritic lava flow: white, massive, fine-grained-rhyodacite (cut by basaltic dike, 2.5m)
23	Siliceous, tuffaceous siltstone: dark gray to tan, cyclic (5cm/10cm upper/lower parts), lower part massive depositionally foliated, upper part laminated
42	Siliceous, tuffaceous sandstone to siltstone: dark-gray to tan and white, some fissile weathered, in part cyclic (5cm/15cm), thin-to laminar-bedded, some fine-and very fine sand sized beds, fining up
2	Tuffaceous sandstone to gritstone: yellowish-tan to gray, local floating volcanic pebbles
28	Siliceous, tuffaceous siltstone: dark-gray, weather light-gray, cyclic, 5 to 20 cm cycles, (3cm/5cm=upper/lower parts), thin-to laminar-bedded
	AD DARB FORMATION

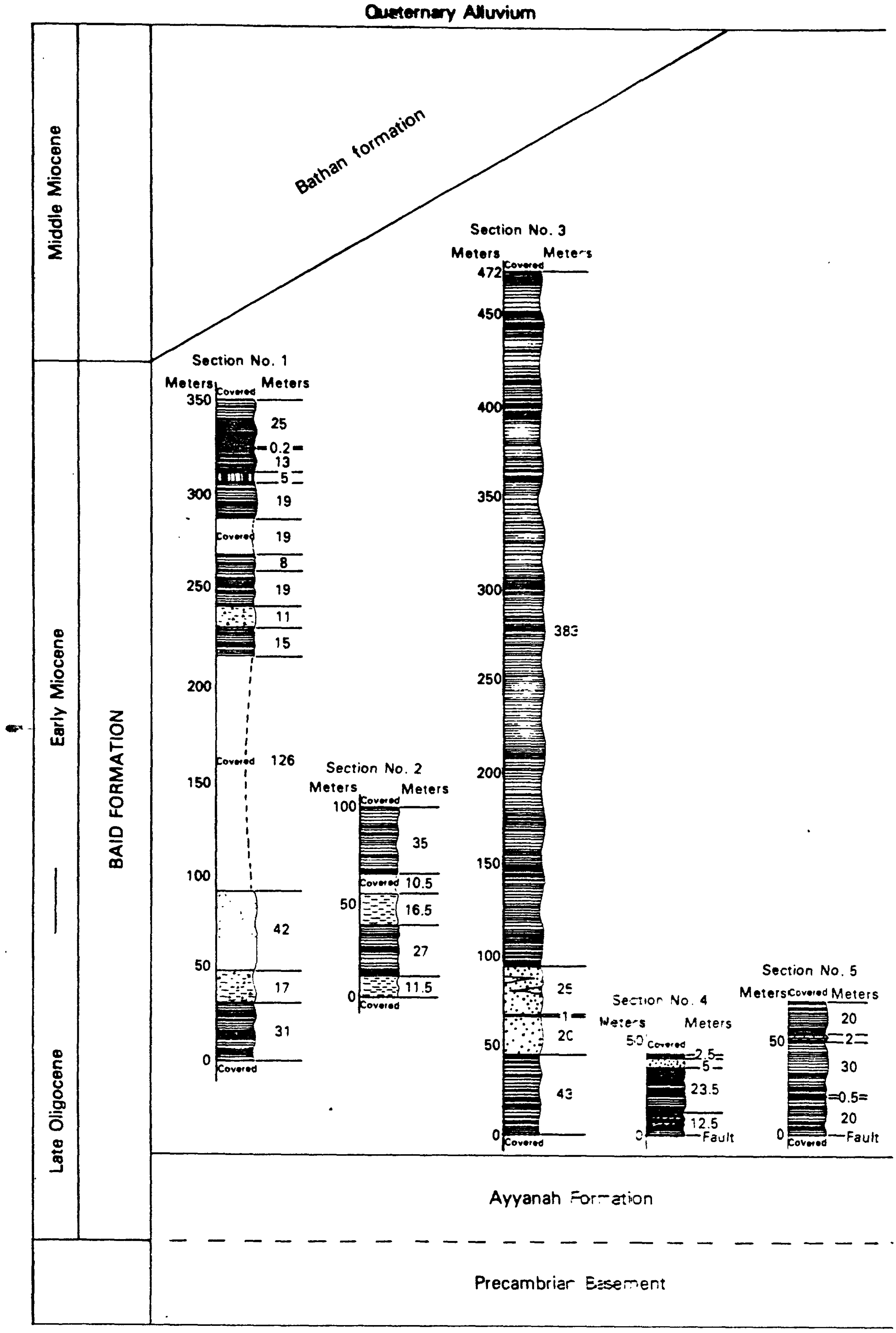


Figure 7.--Correlation diagram of measured sections of the Baid formation from Musaylim to Wadi Jizan. For description of columns and explanation of symbols, see figure 6; for location, see figure 1.

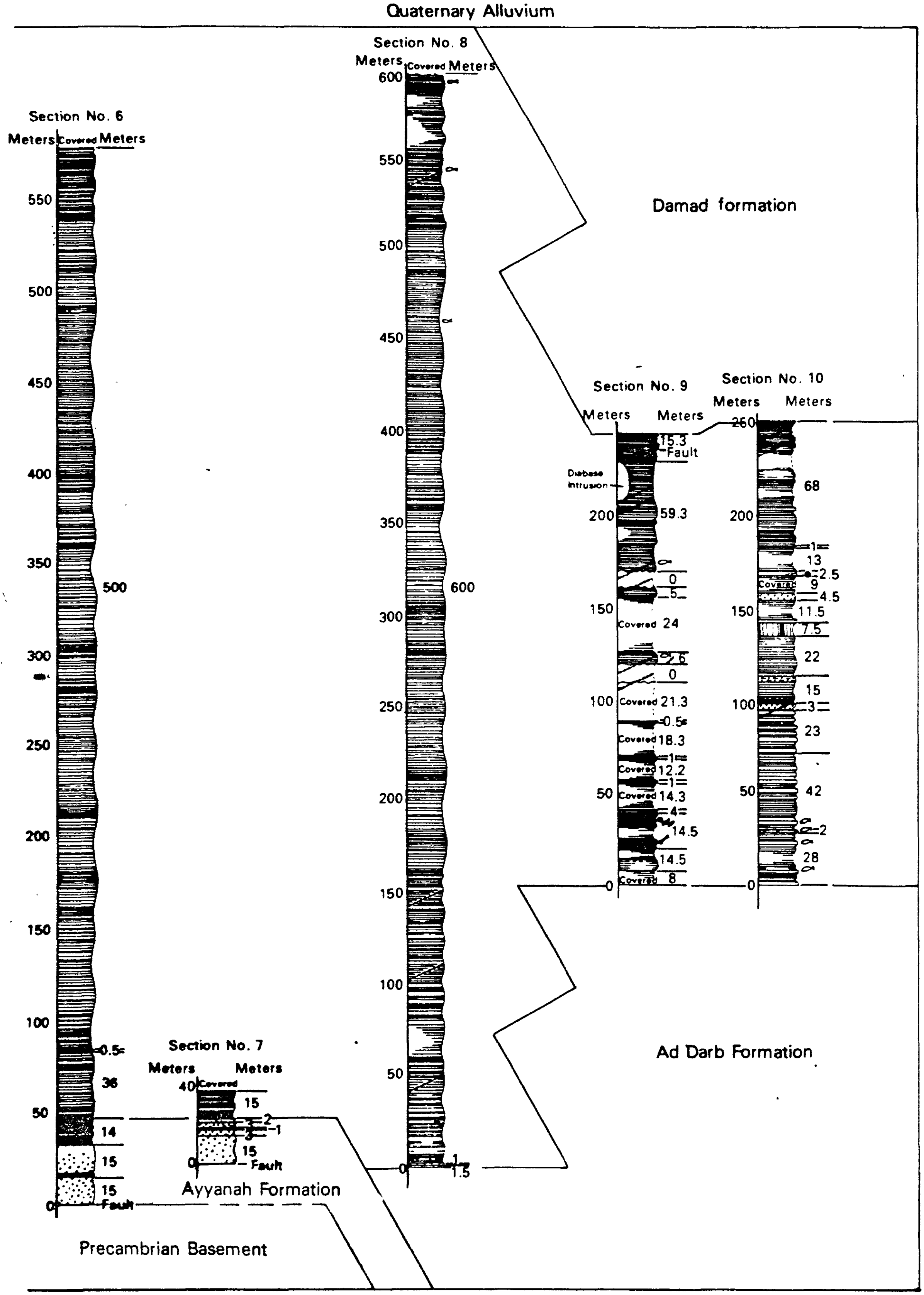


Figure 7.--Continued.

At both sites, the Baid is overlain and underlain by other volcanic rocks of the Jizan group. At Ad Darb, 78 km northwest of Wadi Jizan, a measured section of Baid is more than 600 m thick, with its upper part covered by Quaternary alluvium (fig. 6, section no. 8).

At Wadi Jizan, Gillmann (1968) reported 400 m of Baid-type rock that included other volcanic rocks in the lower part of his section and included dikes and sills of the Tihamat Asir complex. On Gillmannn's (1968) stratigraphic column for Wadi Jizan, Baid lake beds are estimated to be 255 m thick. At Ad Darb, Gillmann reported 1,200 m of Baid probably by including the diabasic dikes and sills and by extrapolation to scattered, possibly faulted outcrops in the presumed upper part of the section.

In the Al Qunfudhah area, the Baid formation is reasonably well exposed both north and south of Wadi Qanunah. South of the wadi near Ayyanah, about 583 m of Baid was measured where the exposed base, although faulted against Precambrian, probably is not missing more than a few meters of section and where the upper part is covered by alluvium (fig. 6, section no. 6). Thirty kilometers north of the wadi on Wadi Ashibah, 20 km east-southeast of Mudhaylif, about 472 m of Baid was measured where both the upper and lower parts of the section are covered by Quaternary alluvium (fig. 6, section no. 3).

On Wadi Nawan, 13 km east of Al Mudhaylif and 35 km northwest of Wadi Qanunah, an incomplete section of Baid is about 100 m thick (fig. 6, section no. 2). Another 40 km northwest, 16 km north of Musaylim, another incomplete section of the Baid measures about 350 m thick (fig. 6, section no. 1). At both exposures, Quaternary alluvium covers the lower part of the Baid, and the Bathan formation unconformably overlies the upper part.

Lithologic character

Throughout the 700 km of southern coastal plain from the Yemen border south of Jizan to Jiddah, the Baid is characterized by freshwater lake beds consisting of well-bedded, siliceous, tuffaceous siltstone and claystone (figs. 4, 5). The consistently monotonous, siliceous, tuffaceous stratigraphy of the Baid is seen in the stratigraphic columns of figure 6, sections no. 1 through 10, which were measured from localities covering 400 km of the total 700 km of coastal plain from which the Baid formation is known. In the explanation to the 1:500,000-scale geologic map of the Asir quadrangle, Brown and Jackson (1959) described the Baid formation as "Miocene?":

> Gray, red, and green siliceous and tuffaceous shale; calcareous layers and lenses; and tuffaceous green sandstone. Locally metamorphosed to novaculite. Contains fresh-water fossils near Darb.

Gillmann (1968) described the Baid formation on Wadi Jizan as "greenish silicite with fish fossils, with layers of greenish shale (chlorite and montmorillonite), rare limestone, volcanic tuff, and at the base, interstratified flows of dacite, dolerite and obsidian" (for 400 m reported). He described the Baid formation in the Ad Darb-Wadi Bayd area as "chiefly grey buff, red or green silicite with fish fossils and intercalated green or violaceous shale (chlorite, illite and montmorillite), volcanic tuffs, and diabase sills."

At the designated type reference section near Wadi Jizan, the Baid formation consists of greenish-gray, thin-bedded and laminated, silicic, tuffaceous siltstone and claystone (fig. 5). A tuffaceous bed may rarely be dolomitic. Weathering colors are light green or tan to white; bedding is commonly laminated to thin bedded (from less than 1 mm to more than 5 cm). Crystal clasts are uncommon and broken, and lithic fragments are rarely seen except in the coarsest debris. In some places the bedding, and especially the laminated bedding, shows soft-sediment deformation.

Cyclical bedding consists of a finely foliated, massive to thin-bedded lower part that grades and fines upward to a well-laminated upper part. Cycles are 10-20 cm thick with 3- to 5-cm-thick upper laminated parts. The lower part uncommonly is as coarse as medium grained (0.25 to 0.5 mm), whereas the upper laminated part is silt to clay size. The typical cycles most probably represent air-fall ash and tuff falling directly on the lake from periodic eruptions of distant volcanoes; the ash and tuff are partly sorted in the air and better sorted in their fall through water to the bottom of the lake where the well-sorted debris is further worked and well layered by gentle water movement.

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

The rocks in thin section are light tan to reddish brown, depending on the small amounts of recrystallized iron oxide minerals dispersed in the rock. Iron oxide has replaced pollen grains in at least one section. All rocks examined are cherty and contain large amounts of silica. No silica-secreting microorganisms such as diatoms were observed, and the excess, secondary-enrichment silica probably was precipitated from the lake water. 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.

Several thin (2-3 m thick) layers of fine-grained lithic-crystal rhyolitic welded tuffs and at least one similarly thin layer of leucocratic, massive, porphyritic rhyodacitic flow have been tentatively recognized. At about 140 m above the base, one 7.5-m-thick basaltic flow has been tentatively recognized.

The total thickness of several basaltic dikes and sills of the Tihamat Asir complex that intrude the Baid section is about 12 m; this expands the thickness of the section only about 6 m. Some dikes and sills noticeably alter the tuffaceous wallrock and locally cause concretionary growth in some tuff beds adjacent to the intrusive rock. The tuffaceous wallrock to one dike shows several centimeters of well-crystallized, coarse, pink zoisite (low-manganese piedmontite?).

The Baid formation at other localities along the coastal plain is very similar to that of the Wadi Jizan reference section. However, rare, thin beds of limestone and pebble conglomerate do occur. At Ad Darb, the base of the Baid consists of 1 m of limestone overlying 1.5 m of medium-grained sandstone. At Ayyanah, 0.5 m of medium-gray, medium-grained, impure sandy limestone occurs 50 m above the base of the Baid. A 1- to 2-m-thick bed of sandy limestone occurs in the basal part of the exposed section, but this lowest limestone is placed within the thin sandstone and conglomerate unit assigned to the Ayyanah formation.

Several 0.5- to 2-m-thick limestone beds occur within the Baid tuffs in the Qunfudhah area north of Wadi Qanunah, and in one section a 1-m-thick, impure, sandy limestone bed is intercalated with pebble conglomerate and sandstone lenses well up in the Baid section. The limestone appears to be unfossiliferous. However, on Wadi Sabya, in 60 m of section, four beds (each 0.5-1 m thick) of dark-bluish-gray chert locally contain remnant calcareous parts. In places, these chert beds consist of silicified oolites that grade into thin siliceous coquinas of very small pelecypod (and ostracode?) and gastropod fossils. Some oolites have centers of fossil shell fragments and rarely of broken quartz crystals. An original, more abundantly calcareous composition may have been entirely replaced by silica in some specific beds of the Baid.

All the sections illustrated on figure 6 contain fine-grained tuffaceous beds that imply voluminous air-fall tuffs and ashes. To the south of Wadi Jizan, the Baid formation thins and contains increasing amounts of coarse washed tuff, silicic lava flows, and silicic welded tuffs as the Baid formation intercalates with the silicic volcanic rocks of the Liyyah formation; thus a silicic volcanic center of Baid age exists between Wadi Jizan and the Yemen border.

At the Wadi Sabya locality between Wadi Jizan and Ad Darb, many white and buff ash-fall tuff beds, 1 to 3 m thick, were deposited directly into the lake environment with little or no water sorting, suggesting the presence of another eruptive center of Baid age. Also, coarse lithic welded-tuff beds occur here in the Baid and signify the proximity of an eruptive center. Eruptive centers can be proposed for the area south of Wadi Qanunah and at Jabal Sita on the basis of coarsening volcanic debris, thinning of the lake-bed section, and thickening of the silicic flow section of the Liyyah.

Where the Baid lake beds are thick and especially where few or no silicic volcanic lava or pyroclastic flows of the Liyyah formation are present, large elongate lakes existed between eruptive centers. Conversely, where the Baid formation is thin, where it contains some coarse volcanic debris and silicic volcanic flows, and where silicic volcanic rocks of the Liyyah formation are thick, a silicic volcanic eruptive center was near.

Paleontology and age

The lowest 35 m of the Baid formation at Wadi Jizan contains many freshwater fish fossils whereas higher in the section only fish scales have been found. In contrast, at Ad Darb, several thin, fossil-fish-bearing horizons are found in the upper part of the exposed section. A 2-m horizon within dark-bluish-gray oolitic chert, 22 m above the base of the Baid at Wadi Sabya, contains thin silicified coquina beds of small pelecypods (and ostracodes?) and gastropods and of more scattered fossil-fish scales and individual fish bones. About 7 m below this bluish-gray chert, a lower jaw fragment of a hippopotamus-like Masritherium was found in a massive tuff bed (Madden and others, 1983).

Brown (1970) briefly discussed the freshwater fish fossils as belonging to two families of the genera Barbus and Tilapia that are widespread in Asia and Africa today. Overall evidence suggested a late Oligocene or Miocene age for the Baid formation (A. H. Dunkle, U.S. National Museum, written commun. to G. F. Brown, 1953). Within the Baid, Gillmann (1968, p. 195) found fish fossils from the Wadi Jizan and Ad Darb areas which he simply classified as "Cretaceous-Tertiary Teleosts." Gillmann also reported some ostracode fossils, but in general considered the Baid "almost unfossiliferous" and only on comparison with the Dogali and Desset series of Erythrea did he suggest a "middle to upper Tertiary age" for the Baid.

Fossil specimens of partly articulated fish vertebrae, fins, and scales were collected in 1974 from silicified, laminated tuffaceous shale of the Baid Formation, 2.9 km south-southwest of the south edge of Ad Darb townsite. From these specimens, Robert L. Meyer (U.S. National Museum, written commun. to Schmidt, 1975) reported:

> cf. Characidae for part of a caudal fin impression on a shale fragment, identification tenuous--Characids having this type of caudal fin are associated with cichlids and cyprinids in Africa.
>
> cf. Barbus for most of a caudal fin impression which appears to be the same species as the Ad Darb specimen identified as cf. Barbus by D. H. Dunkle for G. F. Brown (Dunkle, U. S. National Museum, written commun., 1953). Most of the fish vertebrae submitted, are similar, both in size and centrum, to those of Dunkle's cf. Barbus.
>
> cf. Tilapia for a cast of part of a pectoral and pelvic fin with scale impressions and showing part of a deep-bodied perciform. Dunkle's identification of cf. Tilapia was a smaller individual and does not show either scales or the pectoral fin but has similar pelvic fin.

Van Couvering (1982, p. 95) briefly described Dunkle's cichlid cf. Tilapia as cichlidae indeterminate.

Meyer stated that "these tenuously identified fish fossils belong to groups which are now common elements in most Asiatic and African river and lake systems. The fossil record of these groups is, as yet, too poorly known to provide any definite age assignment even if the identifications could be refined." Meyer further stated that Greenwood (1974) "has reviewed the African fossil occurrences and has found no pattern of definable sequence of events except that the groups identified here are not known from rocks older than Miocene. Consequently, the fishes indicate an age of Miocene or younger but the record is poor enough that an age of Oligocene or younger is not ruled out." Many more fish fossils were collected by Schmidt in 1980 and 1981 and are being studied by Van Couvering.

The lower jaw fragment of a hippopotamus-like fossil collected in 1981 at Wadi Sabya is an anthracothere artiodactyl (even-toed ungulate) identified by C. T. Madden (Madden and others, 1983) as a primitive species of Masritherium. On the basis of East African comparisons, Madden assigned an age of earliest Miocene (from 25 to 21 Ma) to the specimen.

Many isotopic age determinations from the Red Sea Tertiary rocks from North Yemen and Saudi Arabia suggest that the Jizan-group volcanism of the Red Sea continental-rift-valley stage ranges from late Oligocene to early Miocene; that is, from about 30 to 20 Ma (Schmidt and others, 1982, fig. 14). Silicic volcanism tends to be late, between 24 and 20 Ma, in this continental rift volcanism, which agrees well with Madden's vertebrate fossil age.

A few specific K-Ar whole-rock ages are worth reiterating. At Jabal Sita a rhyolitic vent rock, which correlates with the Liyyah formation and silicic tuff volcanism of the Baid formation, is dated at 19.2±0.9 Ma (G. F. Brown, data in Gettings and Stoeser, 1981). In North Yemen, three rhyolitic welded tuffs of the Yemen Volcanics (Grolier and Overstreet, 1978) and two underlying subvolcanic granite plutons range from 21.5 to 20.8 Ma (Civetta and others, 1978) and are believed to correlate with the Liyyah formation and the silicic tuffs of the Baid. North of the Al Qunfudhah area, large diabase dikes of the Tihamat Asir complex, which intrude the Baid formation (Schmidt and others, 1982), are dated at 19.7±1.0 to 18.4±3.1 Ma (Coleman and others, 1979). At Jabal at Tirf a few kilometers south of Wadi Jizan, the Tirf layered gabbro is dated at 23.0±2.0 and 20.0±2.0 Ma and the large Abu Arish granophyre pluton intrusive into the gabbro is dated at 23.3±1.0 and 20.6±0.06 Ma (Coleman and others, 1979); both rocks intrude the Baid formation at the type reference section near Wadi Jizan and both are part of the Tihamat Asir complex that stratigraphically postdates the Baid. The younger age for either of these seems more reasonable (Schmidt and others, 1982).

CHEMICAL COMPOSITION OF THE BAID ROCKS

The predominantly siliceous, tuffaceous composition of the Baid and its stratigraphic association with the rhyolitic rocks of the Liyyah formation strongly suggest that the Baid tuffs are explosive products of ignimbrites and explosive breccias of rhyolitic volcanoes in the continental rift valley.

The chemical composition of the Baid silicic tuffaceous rocks has been examined in Schmidt and others (1982) using 19 chemical analyses from the Ad Darb, Al Qunfudhah, Jabal Shada, Musaylim, and Jiddah areas. All 19 samples were collected as characteristic Baid rocks. Silica ranges from 69.66 to 96.56 percent, but 15 samples have silica contents greater than 80 percent; 6 have contents greater than 90 percent. Obviously, the Baid rocks contain excessive SiO_2 relative to a rhyolitic composition, as shown on figure 8.

The Baid rocks consist of rhyolitic ash that has been replaced in part by silica. Little or no extraneous detrital material is suggested by either petrography or chemistry. The chemical analyses of the Baid rocks (Schmidt and others, 1982) have abnormally high silica contents and low alumina and alkali contents for rhyolite. The FeO* (total iron), MgO, CaO, TiO_2, P_2O_5, and MnO contents are about normal for rhyolite. The rocks in thin section are thoroughly altered and recrystallized to microcrystalline, radial growths of quartz, sericite, and iron oxides--much of this is probably devitrification of initial glass. Rare plagiclase (albite?) phenocrysts are thoroughly recrystallized to microcrystalline quartz, albite, and sericite. In the chemical analyses, most of the alumina and total alkalis have been replaced by silica with essentially no replacement of the other major oxides; for example, FeO* (total iron), MgO, and CaO. All this evidence suggests that albite and orthoclase components, whether initially phenocrysts or glass, have been partly to mostly replaced by silica. Total-iron oxide in the chemical analyses actually shows a slight enrichment relative to silica, and this suggests that about one percent iron oxide was added to the Baid sediments during silica replacement in the lake-bed environment.

The reconstructed chemistry of the Baid rocks indicates that they 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 (and farther south in Yemen), a distance of 700 km. Again, the lateral gradation of lake-bed tuffaceous siltstones and claystones into coarser grained deposits of tuffaceous sand-

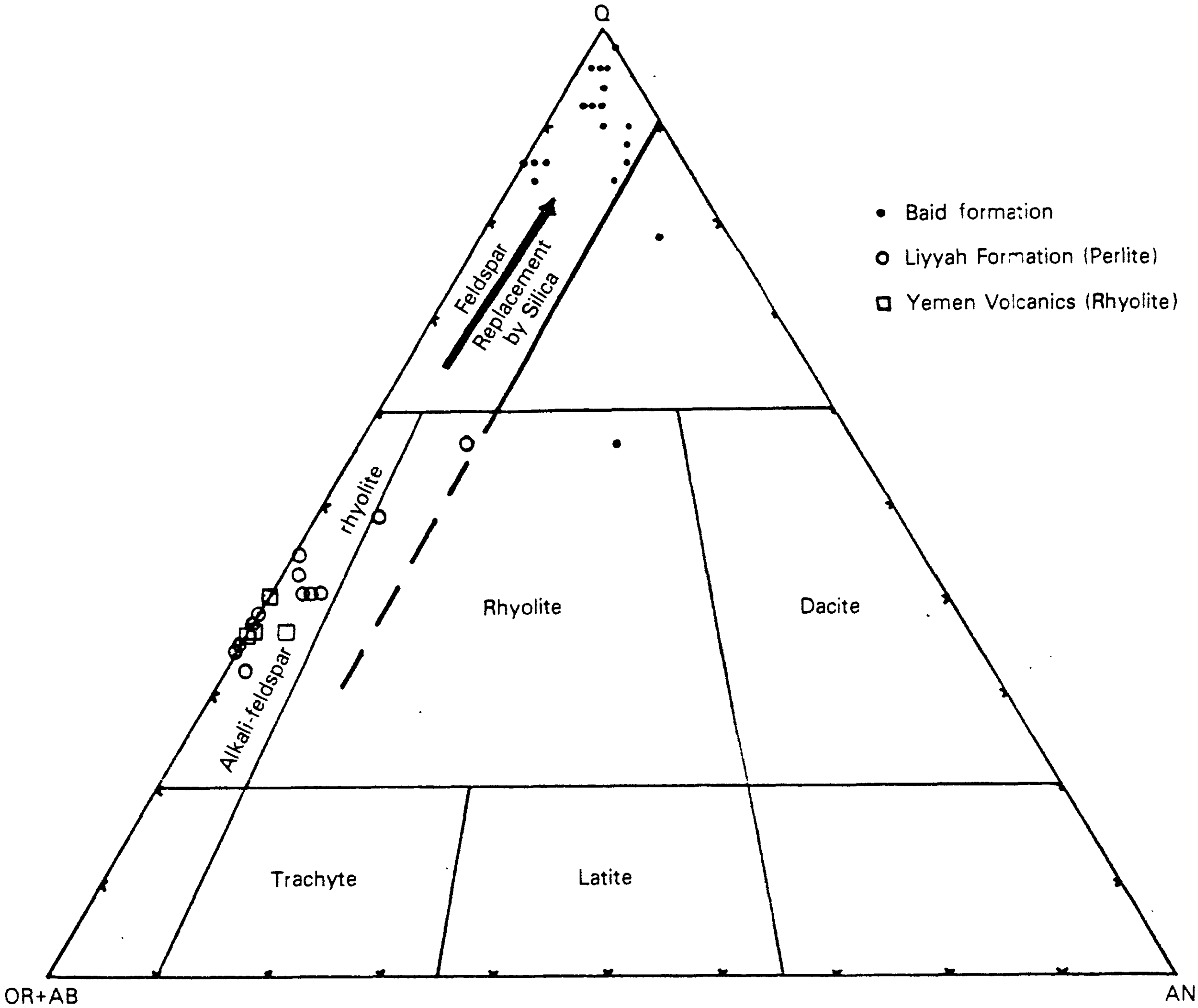


Figure 8.--Ternary diagram showing composition of siliceous, tuffaceous siltstones of the Baid formation in comparison to that of the rhyolites of the Liyyah formation. Diagram shows normative OR+AB (orthoclase+albite), Q (quartz), and AN (anorthite). Rhyolites (perlite) of the Liyyah formation are from Jabal Shama (Jabal Sita area south of Jiddah; Laurent, 1976), and rhyolites from the Yemen Volcanics (equivalent of the Liyyah formation) are from North Yemen (W. C. Overstreet and M. J. Grolier, written commun., 1980). The volcanic tuffs of the Baid formation presumably were compositionally similar to rhyolitic volcanic rocks of the Liyyah formation; however, they were diagenetically partly replaced by silica, as suggested by the trend of the heavy arrow along the compositional zone bounded by the heavy line.

stones and tuff breccias and into Liyyah rhyolitic volcanic rocks in various places between Jiddah and the Yemen border indicates that the rhyolitic volcanic centers were dispersed along the entire southern coastal plain. Because the silicic tuffaceous lake beds are mostly restricted to a single section from tens to hundreds of meters thick and are underlain and overlain by felsic to mafic volcanic rocks, the rhyolitic volcanism seems restricted mostly to a time interval of several million years or less.

The thin limestone beds within the Baid consist of detrital siliceous calcium carbonate. Three analyses of limestone from the Al Qunfudhah area (see analyses in Schmidt and others, 1982) contain only 0.4-4.6 percent MgO and 8-19 percent SiO_2 (fig. 9). Impurities of alumina, iron oxides, alkalis, TiO_2, P_2O_5, and MnO add as much as 3.1-4.9 percent and are most probably volcanic ash contaminants. However, a rhyolitic tuffaceous component cannot be seen directly in the chemical analyses, in that alumina and alkalis probably have been replaced differentially by silica just as in the Baid siltstones and claystones. The very low contents of MgO and P_2O_5 (0.01 to 0.03 percent) reflect the freshwater environment in which the limestones were deposited. Some thin beds of oolitic chert and siliceous coquina were probably originally limestone that was entirely replaced diagenetically by silica.

DEPOSITIONAL ENVIRONMENT

The Baid formation was deposited in freshwater lakes between rhyolitic eruptive centers in the continental rift valley that preceded the first-stage opening of the Red Sea (Schmidt and others, 1982). The rift valley had little relief other than the volcanoes that rose above the elongate lakes. During Baid time extensional block faulting must have been minimal because even local volcanic detrital deposits derived from such block mountains are not known. Also, the Precambrian rocks marginal to the rift had little relief, that is, no Red Sea escarpment existed, because polymictic detritus from Precambrian rocks is rarely found and exceedingly localized in the Baid section. The only significant Precambrian detritus in the Jizan group is that of the volumetrically small, thin (to several tens of meters) Ayyanah formation of the basal Jizan group as mapped in the Al Qunfudhah area. Here, the Ayyanah consists of moderately washed quartz sandstone ranging through immature gritstone to quartz-pebble conglomerate. Such Precambrian detritus, containing little or no feldspar, is assumed to have been eroded from deeply weathered saprolite of Precambrian rocks in which stream dissection did not exceed the

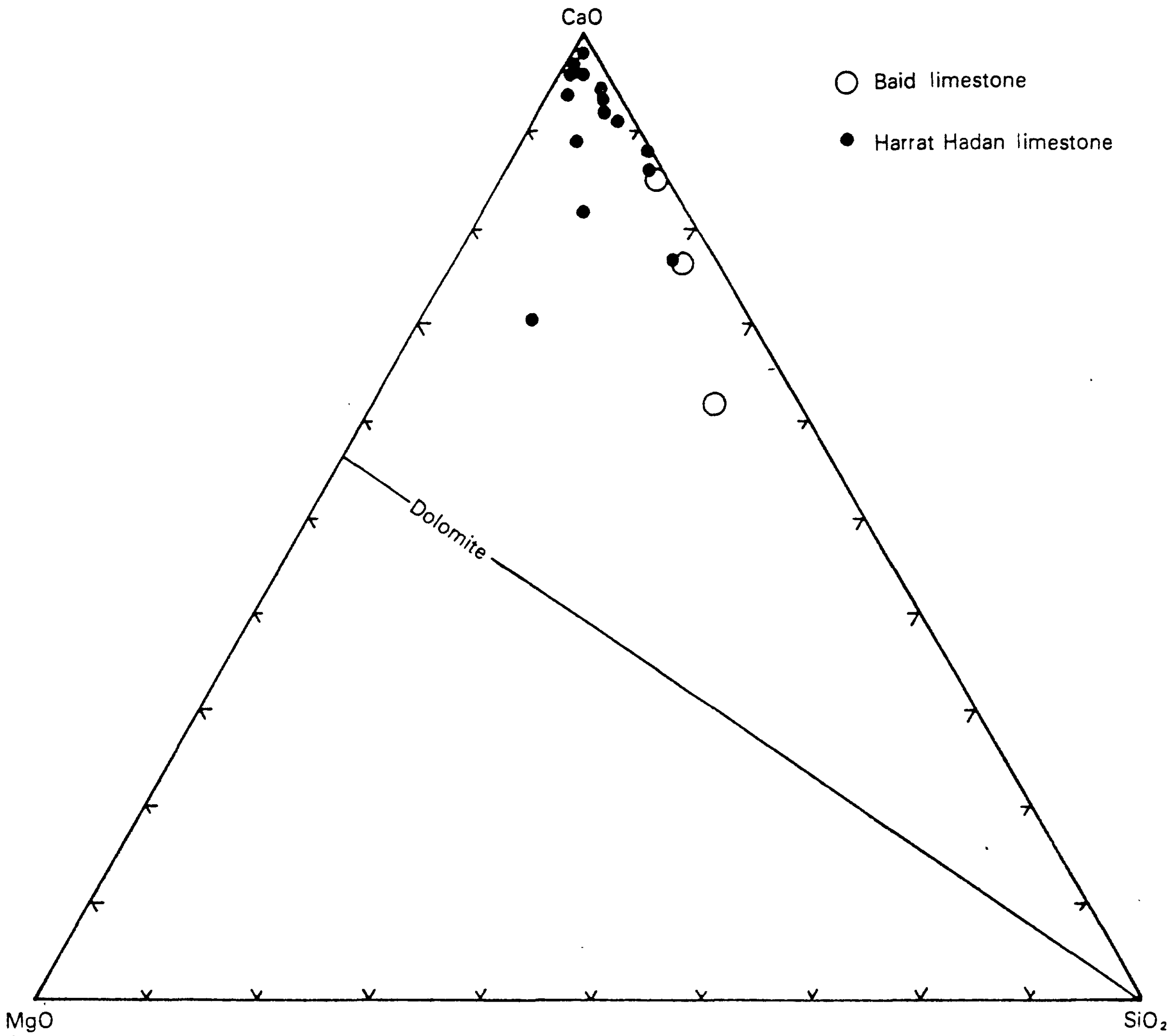


Figure 9.--Ternary diagram (MgO-CaO-SiO_2) showing composition of thin beds of limestone in the Baid formation from the Al Qunfudhah area. For comparison, the composition of limestone of similar age is shown from Harrat Hadan (Martin, 1967; lat 21° 31' N., long 41° 30' E.; see fig. 1), where the freshwater limestone is intercalated with continental flood-basalt flows.

thickness of the saprolite (Schmidt and others, 1982); the detritus could not have been shed from even moderate relief terrane of a rift marginal scarp. A rift marginal scarp could not have existed.

The number and size of lakes is problematical. A large size is suggested by the uniformity, both petrologically and chemically, of the exposed Baid lake beds over distances of nearly 100 km in the Al Qunfudhah area, of 40 km in the Ad Darb area, and perhaps of only 20 km south of Jizan. Lakes widths presumably would be a moderate fraction of a proposed 40-km-wide rift valley. A distinct decrease in lake length to the south corresponds to a distinct increase in volcanism southward; that is, to an appreciable southward thickening of the total section of the volcanic Jizan group. This in turn must correspond to southward increase in the crustal heat regime beneath the continental rift valley toward the triple junction in the Afar.

That the Baid formation in the different areas is the same age is uncertain, even though the available age determinations do suggest that its ages are at least within several million years. It seems reasonable, that, with episodes of felsic and mafic volcanism above and below the rhyolitic Baid and Liyyah formations, the rhyolitic volcanism throughout the rift was largely restricted to a single stage of rift-valley development. This single stage may correspond to (1) a single brief time interval for the whole rift, or (2) a brief time interval in which the rift became progressively younger from south to north as might be suggested by progressive heating with time along the rift. Limited age determinations currently suggest the former; that is, a single brief time interval.

The Baid lakes were fresh, as indicated by widespread freshwater fish. Plant leaves and fragmental plant stems are locally abundant, and at least the plant stems are widespread in the Baid. They probably represent wind and float products carried from adjacent volcanic land masses rather than <u>in situ</u> growths on a periodically dry lake bed, because sedimentary features indicative of periodic drying and of plant root turbation have not been seen. Long-term discontinuities represented by intercalated soil profiles have not been found either.

The sparse occurrence of individual vertebrate fossil fragments as long as 8.5 cm, such as the <u>Masritherium</u> at Wadi Sabya (Madden and others, 1983), suggests that disarticulated mammal bones floated and sank in the lakes; again, in that articulated mammal bones have not been found, greatly fluctuating lake levels caused by drying of the lakes are unlikely. Algal mats on limestone beds in the top part of the fluviatile Ayyanah formation, at the base of the Baid formation, imply very shallow near-shore depth during the initiation of lake-bed formation. Lake depth at any later time was probably shallow but below storm wave base, and in general, the lake bottom was extremely flat because laminar bedding is exceedingly uniform, symmetrical ripples are sparse, and current ripples are rare. On the other hand, the depth was too shallow for turbidite flowage, although enough slope existed in places to produce small-scale, soft-sediment deformation structures.

The silicic airborne ash probably fell directly upon the lake surfaces, producing finely graded depositional cycles. Thickness and character of grading of each cycle were functions of volume of each ash-fall cloud, distance from the erupting volcano, velocity and direction of wind currents, and depth of water in the lakes. In most places, the airborne ash travelled far enough that very fine sand and silt sizes predominate. Yet, silicic explosive volcanoes distributed in places along the entire southern rift valley are required by the presence in places of coarser grained volcanic material in the Baid and by the presence in the nearby areas of silicic volcanic rocks of the Liyyah formation. An alternative hypothesis that all the ash could have been derived from the voluminous ignimbrite eruptions of North Yemen is disproved by the existence of several volcanic centers spaced along the rift; for example, one center as far north as Jabal Sita.

Transport directions of the Baid sediments, measured at various localities, seem noticeably scattered (fig. 10). Measurements were made on trough crossbedding, planar crossbedding, ripple drift, soft-sediment deformation, articulated fish vertebrae, plant-stem orientation, and rock-fragment elongation. Thirty of the fifty-four measurements were made on articulated fish vertebrae. None of these sedimentary data are abundant enough or well enough developed in outcrop to give conclusive results, and the results using many different types of measurements (fig. 10) are not statistically significant. However, inspection of figure 10 does suggest an appreciable transport trend to the southwest, perpendicular to the axis of the rift valley; that is, presumably perpendicular to the elongate shoreline and long axes of the lakes. Another trend to the north-northwest and south-southeast seems parallel to presumed weak, longshore currents. The strongest transport direction on figure 10 is to the north, which might suggest a southerly prevailing wind direction during Baid time.

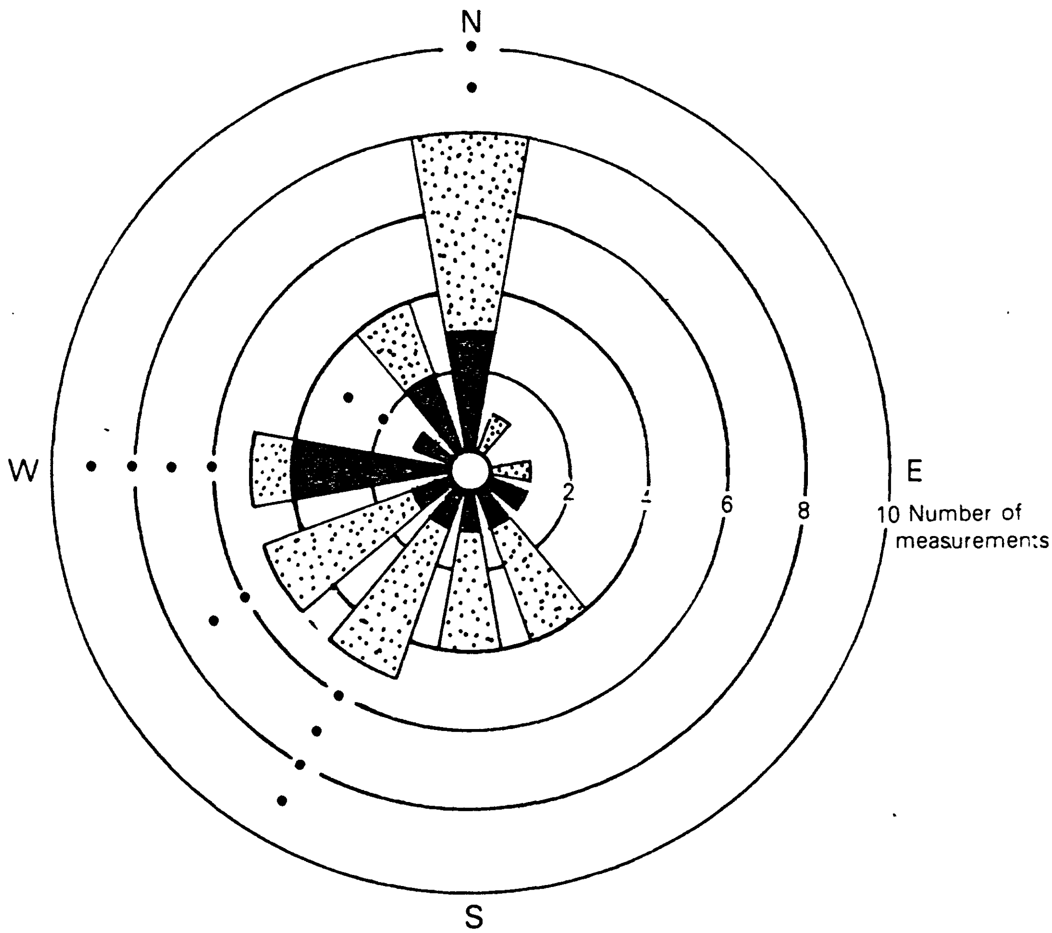


Figure 10.--Rose diagram showing direction of transport of the Baid sediments. Solid area is for indicators at the type reference section of the Baid near Wadi Jizan (15 measurements); stippled area is for indicators at other areas of Baid outcrop (21 measurements). Directional indicators include articulated fish vertebrae (20 measurements), soft-sediment deformation (7), planar crossbedding (6), trough crossbedding (2), and ripple drift (1); orientations without implied unidirections (dots) include oriented plant stems, bones, and rock fragments.

The excess silica in the Baid sedimentary rocks probably was chemically precipitated from dissolved silica in the lake water because evidence for biogenic silica, such as that of diatoms, has not been seen in thin sections of the Baid. The ultimate source of the silica must have been reactive silica dissolved from siliceous volcanic glass. Such reactive silica was most likely dissolved by rainwater from ash covering the landmass surrounding the lakes. Leaching of the silica by groundwater or hydrothermal water from volcanics beneath the Baid lake beds is unlikely because in extensive areas, such as in the Al Qunfudhah area, no volcanic rocks underlie the Baid.

Full understanding of the climate of the volcanic and lake environment of the rift valley during Baid deposition must await further study of the Baid fossils. The region was probably of low relief and near sea level, and the lack of evidence for a Red Sea escarpment during Baid deposition eliminates any possibility of montane influence. The hippopotamus-like fossil Masritherium was certainly a warm-water mammal. The slight iron enrichment of the Baid sediments suggests slight excess iron in the lake waters but not sufficiently excessive to indicate intense tropical weathering. A saprolitic source for the quartzose sandstones in the basal Ayyanah formation, moreover, suggests moderate moisture, warm temperatures, and thick saprolite development rather than the tropical lateritic weathering proposed for the Eocene (Overstreet and others, 1977; Madden and others, 1979). In a study of the paleoenvironments of the East African Miocene, Andrews and Van Couvering (1975) proposed a low bushland climate for the early Miocene of Ethiopia at least as far north as the latitude of the Saudi-Yemen border on the coastal plain.

STRUCTURE

The Baid formation is the depositional product of extensive, explosive rhyolitic volcanism in a continental rift valley that preceded the first-stage opening of the Red Sea. The history of the rift valley and subsequent events leading to the present Red Sea is summarized on figure 11 (Schmidt and others, 1982). The rift valley can be divided into three segments: (1) the Yemen segment, where a wide, hot heat regime caused voluminous crustal magmatism beneath rhyolitic eruptive centers that were sufficiently closely spaced that the constructional volcanic landmass contained few or no large Baid-type lakes; (2) the southern coastal plain segment (from the Yemen border to Jiddah), where a narrow, moderately hot heat regime caused less abundant crustal magmatism beneath rhyolitic eruptive centers that

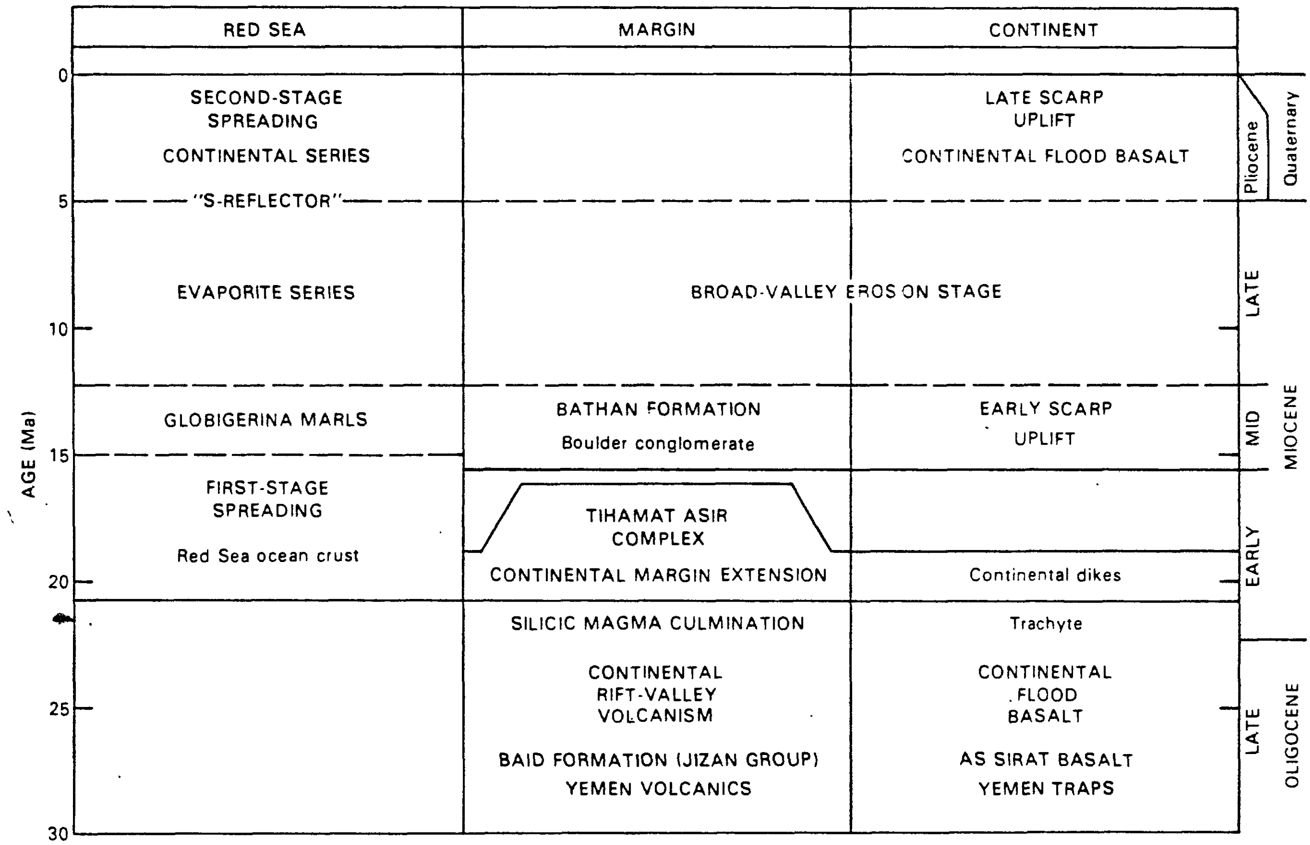


Figure 11.--Diagram showing summary of the geologic history of the southern coastal plain area (continental margin) relative to that of the adjacent Red Sea and the adjacent continental area beginning with the formation of the continental rift valley through the present-day Red Sea.

were spaced adequately for large lakes to form between eruptive centers and for explosive ash and tuff to accumulate and form the Baid lake beds; and (3) the northern coastal plain segment (from Jiddah north to the Gulf of Aqaba), where a narrow, relatively cool heat regime did not cause either lower crustal melting and volcanism or significant formation of basins (fault-block basins) for the accumulation of sediment-fill deposits during the rift-valley stage.

A southeast to northwest decrease in heat regime within the southern coastal plain segment can be seen by the northward decrease in volcanism and by the northward increase in wider spacing between volcanic eruptive centers; hence, individual lake lengths between eruptive centers increase northward.

Lateral crustal extension during the continental rift-valley stage from about 30 to 20 Ma was small, perhaps only that of simple keystone-type fault blocks, and the rift margin remained near sea level. An estimated half width of the rift valley may have been about 20 km or somewhat wider.

Continental-margin extension and accompanying severe crustal thinning occurred during the early part of the first stage of sea-floor spreading of the Red Sea. The continental-margin extension in the uppermost crust was expressed by widespread block faulting, injection of diabase dikes and sills and gabbro and granophyre plutons, and systematic collapse of the rift-valley crust toward the Red Sea axis such that the Jizan-group rocks (including the Baid) dip uniformly about 30° towards the Red Sea. Alternatively, the upper crust may have extended on one or more, low-angle, normal detachment faults dipping towards the rift axis and overlain by shallow crustal fault blocks bounded by curvilinear normal faults (listric) dipping towards the Arabian craton.

Timing of the deformation of the Baid formation (and Jizan-group volcanic rocks as a whole) is restricted to the interval of injection of the Tihamah Asir dikes. Early dikes, presumably intruded about vertically, tend to dip about 60° northeast, whereas late dikes are vertical or nearly so as first observed by Coleman (Coleman and others, 1979). The time of intrusion of these mafic tholeiitic dikes and sills was probably during the first 1-2 million years (20-18? Ma) of sea-floor spreading of the Red Sea.

The Red Sea escarpment rose about the time of--and after--the continental-margin extension and deformation in response to the short-term extensional unloading and to long-term crustal heating caused by a shallow convecting mantle (Gettings, 1982). Erosion of the uplifted escarpment resulted in deposition of the immature, polymictic boulder conglomerate of the Bathan formation (Schmidt and others, 1982). The escarpment rose either as a monocline (Coleman, 1977) on well-distributed, pervasive fractures in the upper part of the Precambrian crust, or as a pseudomonocline in which numerous, inferred, widely spaced, large displacement faults causing uplift are not easily recognized in the Precambrian terrane. Such a pseudomonoclinal type of uplift is required because Mesozoic and Paleozoic rocks, underlying the Jizan-group rocks on the coastal plain, occur within as well as on top of the escarpment. A single, rift-margin, steep-dipping normal fault or narrow fault zone cannot account for the uplift of the escarpment.

ECONOMIC RESOURCES

The lake-bed deposits of the Baid formation have little direct potential for economic resources. No evidence for a metal potential has been found. However, the Baid formation is an important marker within the Jizan group and can be a significant guide in the search for potential resources in those highly altered volcanic rocks above and below the Baid. The resistant, silicic, thin-bedded lake deposits with platy to fissile weathering characteristics may be valuable for crushed rock. They are not desirable for dimension stone for building construction except possibly locally where thick (to about 1 m), massive ash-fall layers may naturally break into ideal sized dimension stone; however, the stone may be too difficult to shape because it is dense, heavy, and excessively resistant. The silica content of the Baid reaches 96 percent, but is still too impure for industrial silica rock.

The sparse thin beds of limestone in the Baid appear to be of satisfactory composition for cement raw material (fig. 9), if sufficiently thick beds of large volume could be found. The limestone is moderately siliceous, and contains low magnesia, alkalis, alumina, and P_2O_5; it has a ratio of SiO_2:(Al_2O_3+FeO*) that is near the ideal of 2.7 for cement raw material. However, large volumes of limestone are not likely to be found in the dominantly volcanic Baid formation.

DATA STORAGE

Data and work materials used in preparation of this report are archived as data-file USGS-DF-04-42, which is stored at the office of the U. S. Geological Survey Mission in Jiddah, Saudi Arabia. No Mineral Occurrence Documentation System (MODS) localities were estabilshed in connection with work on this report.

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