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LATE PROTEROZOIC ISLAND-ARC COMPLEXES AND TECTONIC BELTS IN THE SOUTHERN PART OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

by

William R. Greenwood, Douglas B. Stoeser,
Robert J. Fleck, and John S. Stacey

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William R. Greenwood[1], Douglas B. Stoeser, Robert J. Fleck[2], and John S. Stacey[2]

ABSTRACT

Two main subdivisions of layered rocks are recognized in the southern Arabian Shield south of lat 22° N. These are an older ensimatic-arc complex, which formed 1100-800 m.y. ago, and a younger marginal-arc complex, which formed 800-690 m.y. ago. The older ensimatic-arc complex, located in the southwestern part of the Shield, includes graywacke and mafic to intermediate volcanic rocks of the essentially contemporaneous Baish, Bahah, and Jiddah groups. Although the younger arc complex is also dominantly ensimatic in character, it is also partly superimposed over the older ensimatic-arc complex. The superimposed portions of the younger arc complex are represented by the Ablah, Samran, and possibly the Arafat groups. The ensimatic portion of the younger arc group is represented by the Halaban group, which was deposited to the east and northeast of the older ensimatic-arc complex. The Halaban group includes andesitic and dacitic volcanic rocks and associated clastic sedimentary rocks. The layered rocks of both arc complexes are intruded by dioritic (quartz diorite, tonalite, trondhjemite) plutonic rocks.

The southern Shield is also subdivided into a number of structurally bounded, north-trending tectonic belts. Within the older ensimatic complex, three belts are recognized. From west to east, these are the Lith, Bidah, and Tayyah belts. Within these three belts, progressive facies changes indicate a gradation from deep-water facies in the south to shallow-water or terrestrial facies in the north. The distribution of dioritic batholiths, as well as the distribution of layered-rock facies, suggests a northwest-trending axis for the older ensimatic-arc complex. The younger arc complex is present within six belts, the Makkah

1/ U.S. Geological Survey, Reston, VA 22092
2/ U.S. Geological Survey, Menlo Park, CA 94025

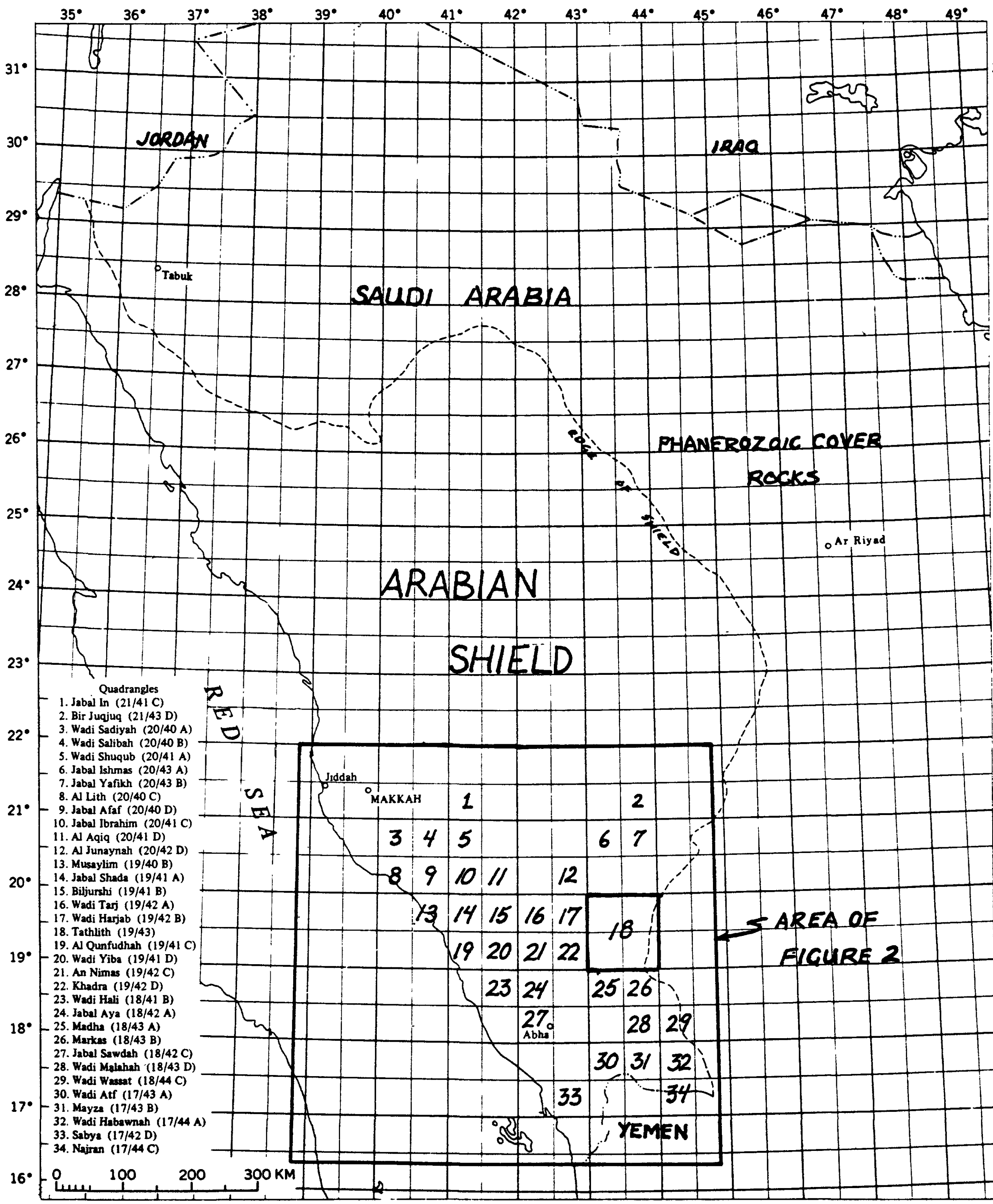

Figure 1.–Index map of the Arabian Shield showing area of figure 2 and location of geologic quadrangles discussed in text.

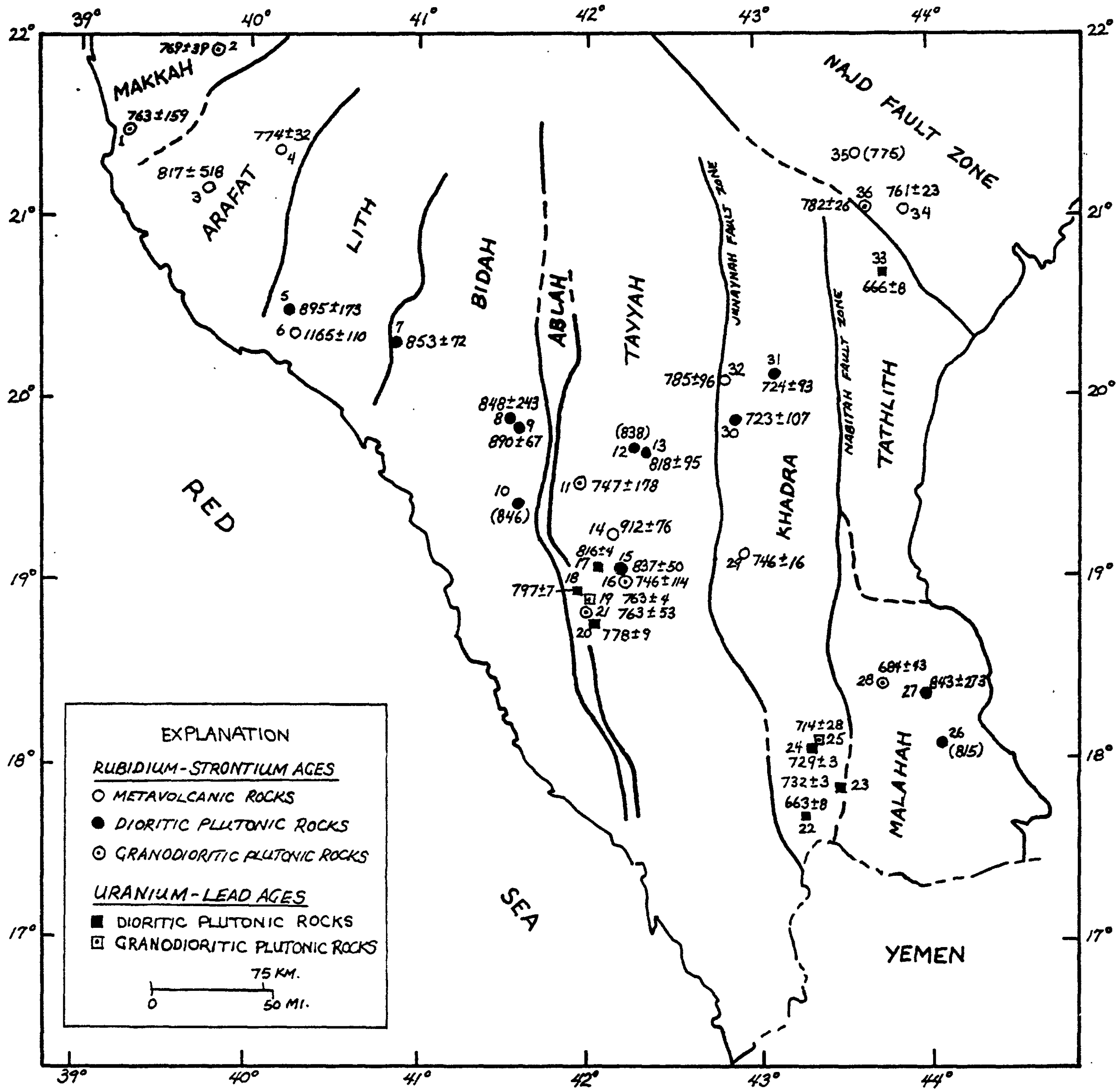

Figure 2.–Map of the southern Arabian Shield showing the location of the proposed tectonic belts and the location of samples used for radiometric age determinations. Each location is marked by an index number and a radiometric age with limits of uncertainty. See appendix for source information for each locality.

source papers. In Fleck and others (1980), the term "quartz diorite" includes both tonalite and quartz diorite as defined in the International Union of Geological Sciences (IUGS) system of plutonic rock classification (Streckeisen, 1973).

Initial $^{87}Sr/^{86}Sr$ ratios are not included in the appendix, but all rocks more than 660 m.y. old have initial ratios in the range 0.7021-0.7035, with only two greater than 0.7030. Thus, nothing in the Rb-Sr data suggests involvement of an older continental crust during the evolution of the southern Shield. A lead isotope study of ore minerals and potassium feldspars of the Arabian Shield by Stacey and others (1980) also suggests that no older (Archean to early Proterozoic) evolved continental-type crust underlies the southern Shield. An early summary of mapping (Schmidt and others, 1973) suggests that older sialic basement underlies the late Proterozoic layered rocks in the southern Shield. However, subsequent mapping and the isotopic studies cited above have established that all of these rocks are of late Proterozoic age and that all rocks of the southern Shield that are more than 660 m.y. old have ensimatic or mantle isotopic characteristics.

Figure 2 shows, with only two exceptions, that rocks more than 800 m.y. old are present west of the boundary separating the Tayyah and Khadra belts. The exceptions are two poorly controlled Rb-Sr ages obtained by Fleck (1980) on two quartz diorite plutons in the Malahah region (appendix 1, localities 26 and 27). Preliminary uranium-thorium zircon data of Stacey now suggest that one of these quartz diorite plutons (locality 26) has an age of approximately 640 m.y. Therefore, we prefer to discount the two dates of Fleck until further information is available.

As noted earlier and as described below, most of the rocks of the southern Arabian Shield have characteristics typical of those formed in the island-arc environment by subduction-related processes. We shall refer to the group of rocks in the western part of the southern Shield, which formed from 1100 to 800 m.y. ago, as the "older ensimatic-arc complex" and those in the eastern and northwestern parts, which formed from 800 to 690 m.y. ago, as the "younger marginal-arc complex". The younger marginal complex is thought to have formed on and adjacent to margins of the older ensimatic complex and thus is partially Andean and partially ensimatic in character.

Tectonic belts

The distribution of layered rock units of different ages and the orientation of superimposed structural elements define a number of north-to northeast-trending belts in the southern part of the Arabian Shield (fig. 2). The boundaries of these belts are defined by major fault zones or extend through intrusive units that appear to intrude major fault zones, and they generally separate layered rocks of different composition and depositional facies and in places metamorphic grade and structural style. Furthermore, many of the belts show significant and similar facies transitions along their strike. Additionally, the large compositional and facies changes that are present locally across some belt boundaries could be the result of major transposition along the boundary faults. Despite these uncertainties, the belt boundaries all represent crustal breaks of major significance, and along each there appears to have been several periods of movement. Because these belts are primarily defined by structural and tectonic features, we shall refer to them as tectonic belts.

Younger, secondary metasedimentary rock units were deposited in tectonic rifts and half grabens along many of these boundary faults. Serpentinized ultramafic rocks also are intruded or protruded into and near some of these faults. Anatectic and remobilized plutonic rocks are intruded as gneiss domes and complex antiformal structures along the margins of several of the blocks.

Most of the boundary faults are north trending and dip steeply. Folds and other lineations in and near these faults commonly plunge both shallowly and steeply down dip. Many of these faults are folded in several places along their strike. The major exception to the general north trend is at the northeast-trending boundaries of the Makkah belt.

Braided patterns and apparent offsets along subsidiary faults within the belts suggest transverse movement along most stretches of the north-trending fault boundaries. Some of these subsidiary faults show both right- and left-lateral movement at different places along strikes. Others show either right- or left-lateral movement. The sense of movement along the northeast-trending faults is not known. Preliminary data suggest that many, if not all, of the boundary and subsidary faults originated as thrusts related to major crustal shortening. Flattening produced by continued compression induced lateral movements controlled by local geometry and rock competency.

On the basis of available geochronologic data, the rocks within the belts fall into two age groups (fig. 2). The older ensimatic-arc complex lies within the Lith, Bidah, and Tayyah belts, which contain layered and dioritic rocks older than 800 m.y. (fig. 3). The younger marginal-arc complex is in the Ablah, Khadra, Malahah, Tathlith, Makkah, and possibly the Arafat belts, which contain layered and dioritic rocks younger than 800 m.y.

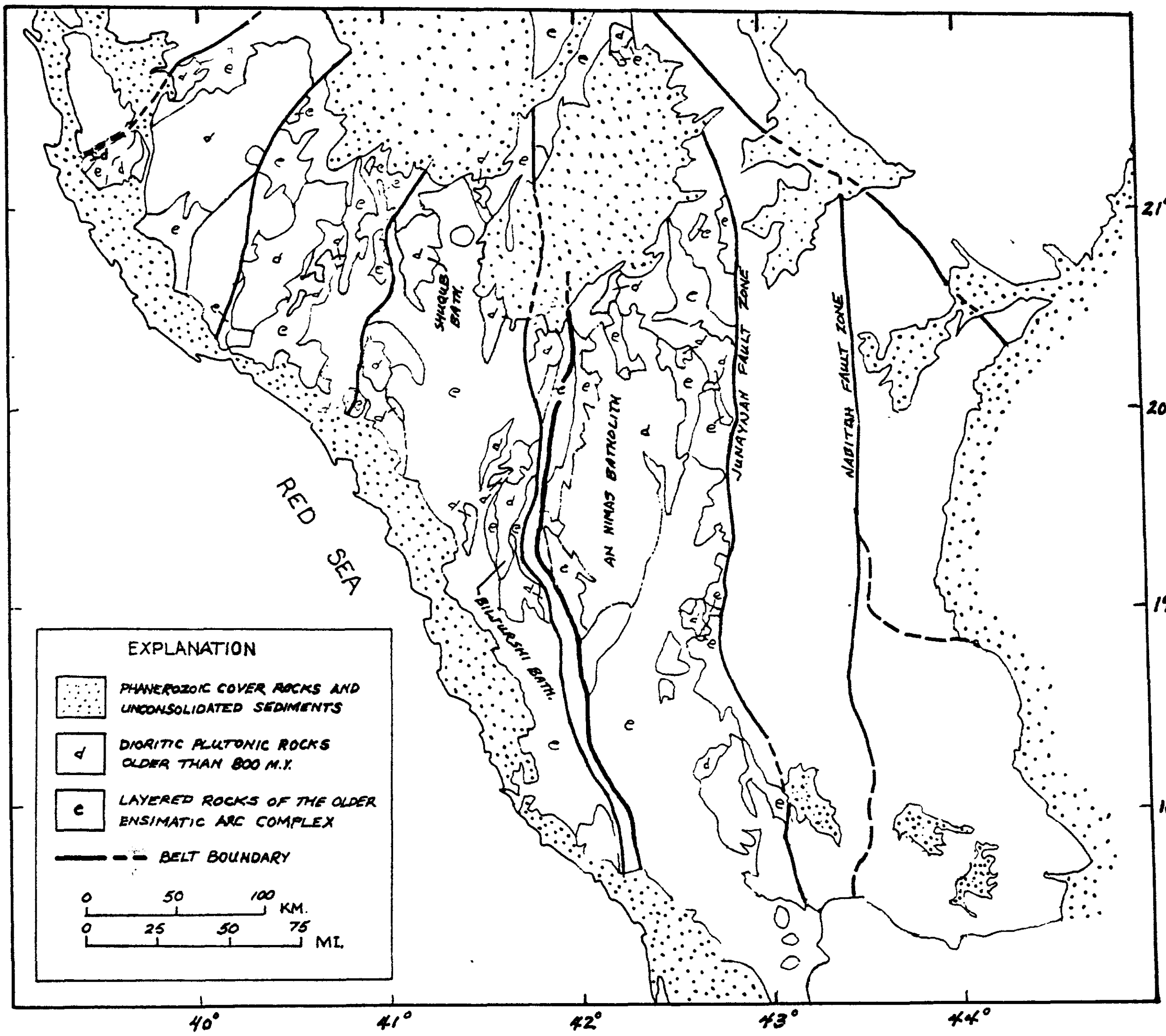

Figure 3.–Geologic sketch map of the southern Arabian Shield showing the distribution of the layered rocks of the older ensimatic-arc complex and dioritic plutonic rocks older than 800 m.y.

OLDER ENSIMATIC-ARC COMPLEX

Lith belt

The Lith belt is named for the Red Sea coastal village of Al Lith, which lies in the Al Lith quadrangle (fig. 3). The belt consists of metamorphosed flow rocks, flow breccia, and generally coarse fragmental rocks of basaltic and andesitic composition and subordinate lithic and crystal dacitic tuff. These rocks are interbedded with and overlain by generally subordinate amounts of volcaniclastic and epiclastic rocks of similar composition accompanied by thin marble beds (Hadley and Fleck, 1979a). The epiclastic sedimentary rocks contain euhedral to subhedral quartz and plagioclase and probably are reworked dacite tuffs. These rocks were originally mapped as the Wadi Lith series and amphibolite by Brown and Jackson (1962) and subsequently as units of the Baish, Bahah, and Jiddah groups by Cater (1977), Hadley (1980), and Hadley and Fleck (1979a,b). Weir and Hadley (1975) also describe rocks of this belt but do not name the units.

The western and eastern boundaries of the Lith belt are defined along part of their strike by infaulted deposits of secondary sedimentary rocks correlated with the Ablah group, as described below. Layered rocks in the Lith belt and the Bidah belt to the east are quite similar in composition and have been considered by most workers to be one unit.

The lowest exposed volcanic rocks in the Lith belt undergo a facies change from northeast to southwest. In the northern and northeastern parts of the belt, amygdaloidal basalt flow rocks are interbedded with thin layers of white marble and chert. In the southwestern part of the belt, amygdaloidal flow rocks, agglomerate (breccia), lithic and crystal tuff of andesitic and basaltic composition, minor volcaniclastic interbeds, and thin marble are found. Dacitic tuff has been described in the lower part of the section from the southeastern part of the Wadi Sadiyah quadrangle (Weir and Hadley, 1975). Volcaniclastic and tuffaceous rocks of andesitic and apparently dacitic composition are predominant throughout the belt in the upper part of the section. Massive amygdaloidal andesite locally overlies the volcaniclastic unit.

The volcanic rocks represent a coalescing group of basaltic to andesitic and minor dacitic composite stratavolcanoes interfingered with shallow-marine basalt flows. Most of the volcanic rocks were deposited in a marine or marine-marginal environment; however, some volcanic rocks were deposited subaerially. Thin marble beds are distributed throughout the Lith group; mudcracks suggest that they probably are of shallow-water algal origin.

The rocks of the Lith belt are broadly folded into a major synclinorium that plunges shallowly to the southwest. Locally small-scale isoclinal folds suggest more intense deformation. The rocks are polymetamorphosed to the greenschist and locally to the amphibolite facies.

Dioritic rocks that intrude the layered rocks of the Lith belt have been dated by the Rb-Sr isochron method at 895 ± 173 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7025 ± 0.0003 (Fleck and others, 1980). These early intrusive rocks comprise a major batholith that ranges in composition from gabbro and hornblende diorite through quartz diorite to tonalite.

Greenschist-facies basalt and andesite in the Al Lith quadrangle (Hadley and Fleck, 1979a) have been dated by Rb-Sr isochron methods at 1165 ± 110 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7029 ± 0.0001 (Fleck and others, 1980). This is the oldest date obtained from layered rocks in the southern part of the Arabian Shield but is interpreted from a three-sample isochron and requires confirmation by additional isotopic studies. The much younger (about 895 m.y.) age of the dioritic batholith in this belt suggests that the volcanic rocks may not be older than 1000 m.y.

Bidah belt

Named for Wadi Bidah in the Wadi Shuqub (Greene and Gonzalez, 1979) and Jabal Ibrahim (Greenwood, 1975b) quadrangles (figs. 1, 2), this belt consists of metamorphosed volcanic and pyroclastic rocks predominantly of basaltic and basaltic andesitic composition, with locally significant dacitic pyroclastic rocks. These volcanic and pyroclastic rocks are interbedded with metamorphosed volcaniclastic and epiclastic rocks of similar composition and locally with marble, chert, impure quartzite, and pelitic rocks. Most of the sedimentary rocks are medium to dark gray, and carbonaceous units are ubiquitous in this belt. Pillow basalts are widely reported, and all sedimentary and volcanic features are compatible with deposition in a marine environment of shallow to moderate depth. No features indicating continental deposition have been reported. Thick units of predominantly volcanic origin have been mapped as Baish group (Greenwood, 1975b). Thick units of predominantly sedimentary origin previously have been assigned to the Bahah group by Greenwood, but they are partially interbedded with volcanic rocks and thus here are included in the Baish group.

The boundary between the Bidah belt and the Tayyah belt to the east is drawn along a major fault zone. Small to large, infaulted secondary sedimentary and volcanic deposits of the Ablah group are present along or near much of this boundary. In the Al Aqiq quadrangle (Greenwood, 1975c), this fault juxtaposes marine-facies rocks of the Bidah belt against continental-facies rocks of the Jiddah group of the Tayyah belt, which are described below.

Volcanic and sedimentary rocks

The volcanic and sedimentary facies in the Bidah belt will be described from south to north. In the southern part of the belt, in the Jabal Sawdah (lower Hali group of Ratte and Andreasen, 1974) and Wadi Hali (Hadley, 1975b) quadrangles, metamorphosed pillow basalts and subordinate basaltic andesite flow and pyroclastic rocks are interbedded with and overlain by metamorphosed dark-gray to carbonaceous shales, quartzite, chert, marble, and graywacke. The feldspathic quartzite in the Wadi Hali quadrangle contains blue quartz clasts (Hadley, 1975b) that probably are of volcanic origin. Andesite increases in abundance relative to basalt in the upper part of this section.

In the northern part of the belt, in the Al Qunfudhah (Hadley, 1975a) and Wadi Yiba (Bayley, 1972) quadrangles, volcanic rocks including pillow basalt and some volcanic breccia are subordinate to pyroclastic rocks and volcaniclastic and epiclastic rocks. Near the western edge of exposed Proterozoic rocks in the Al Qunfudhah quadrangle, pillow basalt and chert are associated with ultramafic rocks (Hadley, 1975a), in what probably is an upfolded section of underlying oceanic crust. The interbedded and overlying sedimentary rocks are predominantly dark slate, carbonaceous schist, quartz schist, dark argillite, and marble. Graywacke is more abundant than in rocks to the south.

Farther north in the Jabal Shada, Jabal Ibrahim, Al Aqiq, Biljurshi (Greenwood 1975a,b,c,d), and Jabal Afaf (Hadley and Fleck, 1979b) quadrangles, abundant flow rocks and flow breccia of basalt to basaltic andesite composition are interbedded with and overlain by coarse- to fine-grained pyroclastic rocks of similar composition, carbonacaeous graywacke, chert, and minor marble. Minor dacitic pyroclastic rocks are present in the eastern part of the Jabal Shada quadrangle, and because of their quartz content they were mapped as Jiddah group (Greenwood, 1975a). However, these rocks lie in the Bidah belt and are now included with the Baish group.

In the northern part of the Jabal Ibrahim quadrangle and north through the Wadi Shugub quadrangle (Greene and Gonzalez, 1979) to the Jabal In quadrangle (Earhart and Mawad, 1970; Gonzalez, 1973; Kiilsgaard and others, 1978), dacitic tuff increases in abundance, and basalt flow rocks and flow breccia decrease in abundance. Sedimentary rocks include subgraywacke to graywacke, interbedded with carbonaceous slate and marble.

Distribution of facies

From south to north, the rocks in the Bidah belt show a shift from deposition of marine pillow basalt, moderately mature sedimentary rocks, and subordinate pyroclastic rocks; through a graywacke basin containing pyroclastic rocks and subordinate submarine flow rocks; to a major volcanic center of basaltic and basaltic andesitic composition; and then to a dacitic volcanic center associated with moderately mature sedimentary rocks. Westward across the belt, the average grain size of sedimentary rocks appears to decrease and the amount of carbonaceous chert to increase. Coarse-grained quartz clasts, probably of volcanic origin, are reported from clastic rocks throughout this belt, but potassium feldspar clasts and terrigenous detritus have not been observed.

The overall sedimentary and volcanic facies changes suggest a transition from an ensimatic, active volcanic arc in the north to a back-arc, small ocean basin formed by extension between the active arc and a continent in the south and west.

Plutonic rocks

Hornblende diorite to quartz diorite and trondhjemite batholiths intrude rocks of the Bidah belt. In the Biljurshi batholith they are dated at 890±67 m.y. (Rb-Sr) (Fleck and others, 1980) and in the Shugub batholith at 838±93 m.y. (Rb-Sr) (Fleck, oral commun., 1981).

Tonalitic to granodioritic gneisses that intrude the layered and older dioritic rocks of this belt have not been dated, but they also intrude rocks of the Ablah group and are correlated with similar gneisses dated in the adjacent Tayyah belt at 763±53 m.y. by the Rb-Sr method (Fleck and others, 1980) and at 763±4 m.y. by the U-Pb (zircon) method (Cooper and others, 1979).

Structure and metamorphism

The layered rocks of the Bidah belt are metamorphosed to greenschist facies and are weakly to strongly cleaved except in and near gneissic domes and antiforms, where they form amphibolite-facies schists and gneisses.

The layered rocks in this belt are tightly to isoclinally folded about north-trending axes. Folds and other lineations plunge moderately to steeply to the south and north. Superimposed folds and lineations are common, and two generations of cleavage are present in several areas. Fault and shear zones were developed parallel with the axial surface of folds, and some shear zones extend as much as 90 km in length.

Tayyah belt

Named for Wadi Tayyah in the Jabal Aya quadrangle (Prinz, 1975) (fig. 1), the Tayyah belt consists of metamorphosed volcanic and pyroclastic rocks of basaltic, andesitic, and dacitic composition and associated volcaniclastic and epiclastic metasedimentary rocks. This belt includes pillow basalts of Wadi Baysh (Baish) in the Sabya quadrangle (George Fairer, written comm., 1980), the type locality for the Baish greenstone of Brown and Jackson (1960) and USGS-ARAMCO (1963). Schmidt and others (1973) designated this unit the Baish group and correlated it with rocks mapped by them as far north as Wadi Bidah following USGS-ARAMCO (1963). As used by them, the Baish group consists primarily of basaltic volcanic rocks, with some interbedded andesitic flow rocks and tuff. Ratte and Andreasen (1974) and Prinz (1975) continued the use of Baish group for predominantly volcanic rocks in the Tayyah belt and applied the term "Bahah group" of Schmidt and others (1973) for predominantly metasedimentary rocks of the belt. Ratte and Andreasen (1974) reported significant amounts of quartz-bearing tuff interbedded with the other volcanic rocks, especially at Jabal Sawdah. Greenwood (1979a,b) reported abundant dacitic pyroclastic rocks in this belt and correlated them with the Jiddah group of Schmidt and others (1973) because of their predominantly andesitic to dacitic composition. Rocks of this belt are included in a general meta-andesitic series on the 1:4,000,000-scale geologic map of the Shield compiled by Greenwood and others (1980).

Isotopic dating of meta-andesite roof pendants in the An Nimas batholith (Greenwood, 1979a) gives a whole-rock Rb-Sr isochron age of 912 ± 76 m.y. (Fleck and others, 1980). This age is only slightly younger than the 932-m.y. K-Ar minimum age on dioritic rocks (Aldrich and others, 1978) that intrude the metabasaltic rocks of the Bidah belt. The metavolcanic and associated metasedimentary rocks of the Tayyah belt can be differentiated from those of the Bidah belt by the contrasting volcanic and sedimentary facies across the northern part of the structural boundary. However, the layered rocks of these belts probably represent broadly contemporaneous deposits.

The eastern boundary of the Tayyah belt separates these rocks from the apparently much younger and locally potassic volcanic and volcaniclastic rocks of the Khadra belt.

Volcanic rocks

Volcanic rocks in the Tayyah belt include a section near the Yemen border of massive metabasalt at least several kilometers thick that contains well-preserved pillow structures (George Fairer, written comm., 1980). Farther north in the Jabal Sawdah area, Ratte and Andreasen (1974) reported pillow structures only at one outcrop but suggested that pillow basalts may be widespread. Amygdaloidal, mafic metavolcanic rocks are also widespread in the Jabal Sawdah area. Ratte and Andreasen also described quartz- and feldspar-bearing volcanic rocks, which they suggested may be silicic tuffs. North of Jabal Sawdah in the Jabal Aya quadrangle, Prinz (1975) observed no pillow structures in the mafic metavolcanic rocks and reports amygdules from only a few outcrops. Fragmental, plagioclase- and hornblende-bearing, porphyritic andesites are found in the Jabal Aya area. In the An Nimas and Khadra quadrangles north of Jabal Aya, Greenwood (1979a,b) described amygdaloidal to scoriaceous, plagioclase-, augite-, and hornblende-phenocrystalline andesitic flow rocks, flow breccia, and tuff, with lesser amounts of plagioclase and quartz crystal tuff, which locally has eutaxitic structure suggesting welded tuff. The quartz diorite schist and diorite schist units of Greenwood (1979a, b) in the An Nimas and Khadra quadrangles appear on reinspection to be massive dacitic units. Finally, in the Biljurshi and Al Aqiq quadrangles (Greenwood, 1975c, d), at the northernmost exposed part of the Tayyah belt, andesitic to basaltic flow rocks and andesitic pyroclastic rocks comprise about two-thirds of the volcanic rocks and dacite flow and pyroclastic rocks comprise the remaining one-third. Thus, it appears that welded andesite and dacite tuff are more widespread and much more abundant in the northernmost part of the Tayyah belt than in the southern part. Volcanic rocks in the northern part of the Tayyah belt are also distinctive in that they contain columnar-jointed basalt flow rocks and welded tuff indicative of subaerial deposition, both of which alternate with shallow-water marine marble and carbonate-cemented rubble. These rocks are interbedded with red andesitic tuff that probably was subaerially erupted but deposited in a marine-marginal environment. The associated sedimentary rocks are coarse grained, of local derivation, and show current-ripple marks and other shallow-water sedimentary structures.

Sedimentary rocks

Starting in the southern part of the belt in the Sabya quadrangle, a basal unit of pelitic rocks, graywacke, quartzite, quartz-pebble conglomerate, marble, and subordinate thin chert is overlain by the thick pillow basalts of Wadi Baysh, which contain only sparse thin interbeds of graywacke, chert, and marble (George Fairer, written commun., 1980). In the Jabal Sawdah quadrangle (Ratte and Andreasen, 1974), chert and slate are interbedded with the volcanic rocks. In addition, a thick sequence of graywacke and carbonaceous, siliceous slate is interbedded with black marble and phyllitic rocks. Contact relationships between the thick metasedimentary sequence and the metavolcanic rocks were not determined in that quadrangle, but the units appear to be contemporaneous. In the Jabal Aya quadrangle (Prinz, 1975), graywacke, which contains rounded clastic quartz and angular to subangular plagioclase, is interbedded with volcanic and pyroclastic rocks. Conglomeratic sections within the graywacke contain pebbles and cobbles of diorite, tonalite, graywacke, quartzite, and red jasper and are as much as 10 m thick. These granitoid clast-bearing graywacke units may also be infaulted slivers of the younger Ablah group. A thick, fine-grained, clastic sequence of dark carbonaceous slate, phyllitic metasiltstone, and subordinate dark marble and buff metasiltstone overlies the metavolcanic graywacke sequence. In the An Nimas and Khadra quadrangles (Greenwood, 1979a,b), the sedimentary rocks are similar to those described by Prinz, except that volcanic-derived quartz appears to be more abundant in the metasedimentary interbeds.

Distribution of facies

Overall, the metavolcanic rocks in the Tayyah belt change from predominantly submarine pillow basalts with minor graywacke-chert interbeds in the southern part of the belt to predominantly submarine basaltic and andesitic pyroclastic rocks with some subaerially deposited silicic welded tuffs in the northern part (fig. 4) (Greenwood, in press). In the southern part, the pillow basalts of Wadi Baysh are reported to overlie mature and probably shallow-water, shelf-deposited sedimentary rocks that contain vein-quartz pebbles and possibly were derived from erosion of Bidah belt rocks to the north or west and possibly the African craton to the south. In the northern part, the base of the volcanic sequence is not observed, and graywacke interbeds increase in overall volume accompanied with an increase in the abundance of pyroclastic rocks. If the diorite and tonalite clast-bearing units are not infaulted Ablah group, the clasts may have been derived by erosion of older diorite rocks in the Bidah belt. If so, the presence of these clasts at several places well above the base of the strata in the Tayyah belt would suggest a nearby and continuously or recurrently eroding source in the Bidah belt during deposition of the Tayyah volcanic graywacke sequence. The overlying carbonaceous and fine-grained clastic rocks and marble were deposited slowly in a low-energy environment after the end of significant volcanic activity and probably were derived by erosion and reworking of emergent parts of the Tayyah volcanic-graywacke sequence. The facies patterns of the Tayyah belt are similar to those in the Bidah belt and suggest that prior to deformation the layered rocks of these belts formed a single, contemporaneous arc complex.

Structure and metamorphism

The rocks of the Tayyah belt show tight to isoclinal folds of meter to kilometer scale throughout most of the

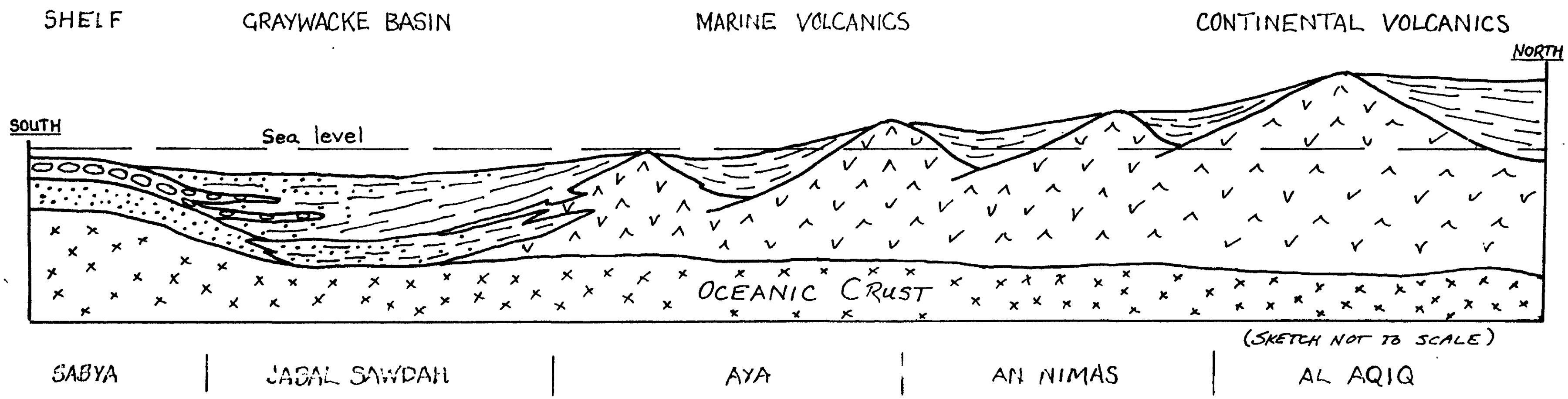

Figure 4.--Generalized cross section showing volcanic and sedimentary facies along strike within the Tayyah belt. Approximate boundaries and names of 30-minute quadrangles discussed in the text shown along the bottom of the sketch. Symbols: x, oceanic crust; dots, shelf pelite and siltite; dots and lines, graywacke basin transition from pelite to graywacke; ellipses, pillow basalt; lines, volcanic sandstone and siltstone and water and airfall tuff; v, andesite and dacite flows, flow breccia, and ash flows.

belt. In areas of tight folding, the rocks are strongly cleaved and locally phyllonitized. Longitudinal faults commonly offset folds and locally break the layered rocks into long, narrow imbricate slices. In these highly deformed areas, folds and other lineations commonly plunge steeply north or south. Less deformed layered rocks of the Tayyah belt are preserved in a broad synform of Baysh pillow basalt in the southern part of the belt and in relatively undeformed roof pendants and caps of volcanic rocks overlying dioritic plutonic rocks of the An Nimas batholith in the Al Aqiq, Biljurshi, An Nimas, and Wadi Tarj quadrangles (Greenwood, 1975c, d, 1979a; Anderson, 1977).

Recent reconnaissance by Greenwood indicates that the Tayyah belt rocks in the Jabal Aya and Jabal Sawdah quadrangles (Prinz, 1975; Ratte and Andreasen, 1974) dip steeply east, are predominantly east facing (sedimentary tops east), and show cleavage dipping more steeply east than does the sedimentary layering. All rock units appear to be fault-bounded blocks stacked up by imbricate listric thrusts that curve to shallow dips at depth. This thrusting appears to have been accompanied by westward-directed folding and followed by continued compression that produced local refolding and transverse and oblique movement on steep faults. Refolding and late transverse faulting appear to be controlled by local geometry and rock competency.

The Tayyah belt rocks are metamorphosed to greenschist facies except in proximity to gneissic intrusions and in mixed terrains with abundant gabbro and granite, where they are metamorphosed to upper amphibolite and granulite facies. Locally depth of metamorphism was in the kyanite stability field during early gneiss-dome development, but generally pressure was no greater than that of the andalusite stability field. Recrystallization is locally complete, but except in areas of intense shearing, many primary volcanic and sedimentary textures are preserved.

Early plutonic rocks

Dioritic rocks of the An Nimas batholith that intrude layered rocks of the Tayyah belt have been isotopically dated by the Rb-Sr isochron method at 837±50 and 818±95 m.y. (Fleck and others, 1980). Rocks of the An Nimas batholith also have been dated by the U-Pb (zircon) method at 816±4 m.y. (Cooper and others, 1979). Although of differing ages, dioritic rocks of the Biljurshi batholith in the Bidah belt and the An Nimas batholith in the Tayyah belt appear similar, both petrographically and in the field. In both, gabbro and hornblende diorite formed early, followed by biotite quartz diorite. However, trondjhemite that cuts the quartz diorite of the An Nimas batholith (Anderson, 1977; Greenwood, 1979a) has not been described in the older Biljurshi batholith.

Locally the trondjhemite contains very minor amounts of interstitial potassium feldspar. The dioritic rocks of these batholiths appear to have been mostly passively emplaced by stoping; the batholiths are steep sided and appear to have shallow-dipping to undulatory roofs. They are elongated north-south parallel with the present belt boundary faults. Much of this elongation appears to be the result of flattening produced by later east-west compression.

YOUNGER MARGINAL-ARC COMPLEX

Ablah belt

Rocks of the Ablah group (Greenwood, 1975c, d; Hadley, 1975b) are found in one large and several smaller structural depressions (grabens?) that formed between the Bidah and Tayyah belts (fig. 5). Lithologically similar deposits are present in depressions along or near the boundaries of the Bidah and Lith belts and possibly the Makkah and Lith belts. Small, downfaulted exposures of similar rocks also are widespread in the Tayyah and Bidah belts.

The Ablah group unconformably overlies older layered rocks of the Bidah and Tayyah belts and dioritic rocks of the Biljurshi and An Nimas batholiths and is intruded by the Baqarah gneiss and similar rocks. This stratigraphic relationship indicates deposition between 814 and 763 m.y. ago (Cooper and others, 1979; Fleck and others, 1980).

Volcanic rocks of the Ablah group crop out only within the Ablah belt in the Al Aqiq, Biljurshi, and Wadi Yiba quadrangles (Bayley, 1972; Greenwood 1975c,d). Sedimentary rocks of the Ablah group are present both within this belt and in smaller structural blocks to the west and east.

Volcanic rocks

Volcanic rocks of the Ablah group crop out in several apparently separate volcanic centers, which will be described from north to south. Near the northern border of the Al Aqiq quadrangle, the lowest exposed unit in the graben includes andesitic, dacitic, and rhyolitic flow, pyroclastic, and volcaniclastic rocks, with minor quartz latite flow rocks, basalt agglomerate, and pillow basalt. Rhyolitic welded tuffs show well-preserved eutaxitic structures. About 70 percent of this unit is of pyroclastic or volcaniclastic origin. Red-weathering flow rocks and welded tuff, which indicate subaerial deposition, alternate with pillow basalt and marble, which indicate marine-marginal conditions. This volcanic unit is overlain to the south by red to brown, coarse-grained volcanic graywacke of fluvial origin. Similar fluvial and deltaic clastic deposits continue to near the southern border of the Al Aqiq quadrangle, where they grade

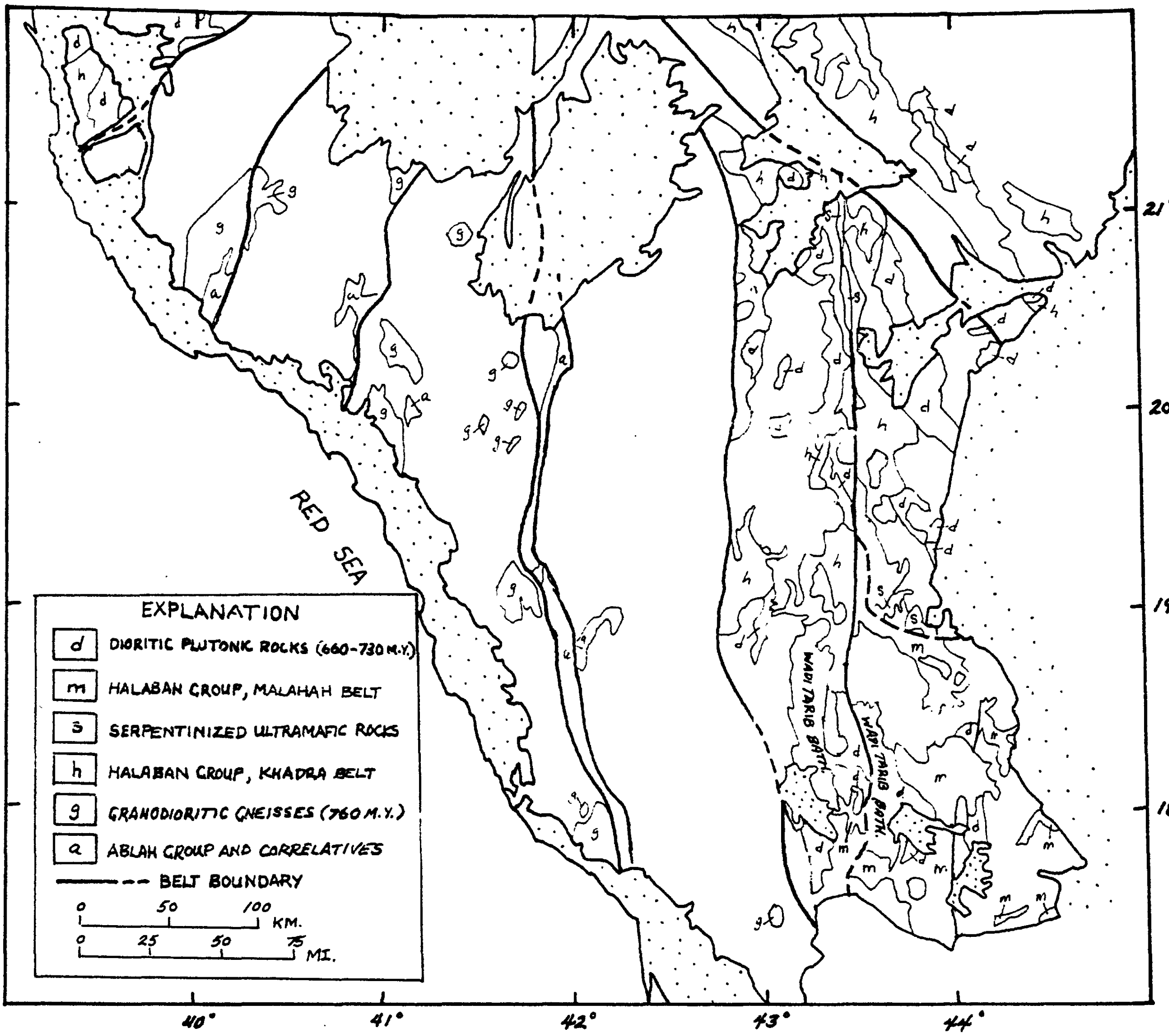

Figure 5.–Geologic sketch map of the southern Arabian Shield showing the distribution of the Ablah group and possible correlatives, granodioritic gneisses of about 760-m.y. age, Halaban group rocks of the Khadra belt, serpentinized ultramafic rocks, Halaban group rocks of the Malahah belt, and dioritic rocks of 660-730-m.y. age. Stipple pattern represents Phanerozoic cover rocks and unconsolidated sediments.

into gray clastic rocks and gray stromatolitic marble of shallow-marine origin. These rocks rest on dacitic tuff and andesite flow rocks, which apparently represent a second, separate volcanic center.

Near the center of the Al Aqiq quadrangle, a third volcanic center higher in the Ablah-group section is indicated by abundant columnar-jointed basalt and andesite flow rocks and welded and unwelded rhyolite flow rocks, which are interbedded with coarse-grained clastic rocks. To the south, several additional volcanic centers are present in the Ablah belt as indicated by abundant volcanic rocks in the Biljurshi (Greenwood, 1975d) and the Wadi Yiba (E. Alan Smith, oral commun., 1980) quadrangles; however, these southern volcanic centers lack rhyolitic rocks.

Sedimentary rocks

Sedimentary rocks in the Ablah group range from red and brown, coarse-grained fluvial and deltaic deposits to gray, finer grained clastic rocks of marine-deltaic origin, which are interbedded with shallow-water stromotolitic and calcarenitic marbles. Marine-continental transitions are present in several places in the Al Aqiq, Biljurshi, and Wadi Yiba quadrangles. In the Wadi Hali quadrangle (Hadley, 1975 b), the Ablah group is highly metamorphosed, appears to be mostly marine, and does not contain large amounts of volcanic rocks. Aluminous shales and quartzite in the Wadi Hali quadrangle and to the south reflect an increase in maturity of the sedimentary rocks compared to the volcanic graywacke common in the Biljurshi and Al Aqiq quadrangles.

Distribution of facies

This highly abbreviated discussion of the sedimentary and volcanic character of the Ablah group is presented to indicate the enormous range of depositional environments within the Ablah belt. Of greatest significance is the association of these rocks with extensional tectonics or rifting of an older basaltic to dacitic and dioritic arc terrain. Rifting appears to have been recurrent during deposition of the Ablah group. Rocks at the southern end of the graben were deposited in marine-basin and open-ocean environments that lack significant volcanic rocks. The central part of the graben is transitional from a marine to a continental-deltaic environment and has basaltic to dacitic volcanic rocks. The northern, predominantly continental environment has significant rhyolitic rocks, as well as basaltic and intermediate volcanic rocks. Thus, there appears to be a progressive change in the volcanic character that accompanies the changing depositional environment in the Ablah depression.

Structure and metamorphism

Rocks of the Ablah group are broadly to tightly and isoclinally folded along the deformed graben. East-dipping thrusts and oblique and transverse faults of right- and left-lateral movement bound and internally break the Ablah group into imbricate fault slices. Crustal shortening, metamorphism, and lateral and upward flowage was much greater in the southern part of the belt than in the north. In the southern part of the graben, gneissic tonalite to granodiorite was emplaced into domical structures along and near the margin of the graben during a major compressional and metamorphic event. This event appears to be the first major compressional tectonic and regional metamorphic event in the southern part of the Arabian Shield. Metamorphism locally reached upper amphibolite facies in kyanite- and sillimanite-bearing metamorphic rocks that were carried up in or on the flanks of the gneiss domes. Elsewhere, the Ablah group and older rocks are metamorphosed to greenschist facies. Isoclinal folding and refolding are common within fault slices that contain these amphibolite-facies rocks. Folds are more open in greenschist-facies rocks in the northern part of the belt. Schistosity is well developed parallel with compositional layering in the marine facies in the southern part, but except near faults, the continental facies in the northern part show little cleavage. The intensity of metamorphic recrystallization decreases rapidly northward in the marine-continental transitional facies.

Infaulted rocks correlated with the Ablah group

Infaulted rocks correlated with the Ablah group are present within the Tayyah and Bidah belts and along the boundaries between the Bidah and Lith belts and the Lith and Arafat belts (fig. 5, appendix). These correlations are made on the basis of conglomerates, which contain granitoid clasts, and mature sedimentary rocks, which include aluminous shales (now metamorphosed to kyanite-bearing assemblages), thick marble, and quartzite. The correlations made on the basis of contained granitoid clasts are probably more reliable.

Clastic rocks correlated with the Ablah group but outside the Ablah belt were mapped in several places within the Al Aqiq quadrangle (Greenwood, 1975c). In each of these places, the rocks contain dioritic clasts but no granitic clasts. In the Jabal Ibrahim and Jabal Shada quadrangles (Greenwood 1975c,d), clastic rocks mapped as Sama formation of the Bahah group contain hypabyssal dioritic rocks and are therefore correlated here with Ablah group.

Kyanite-bearing aluminous metapelite, quartzite, and marble in the Jabal Afaf quadrangle are correlated on the basis of lithologic similarity by Hadley and Fleck (1979b) with the Ablah group of the Wadi Hali quadrangle. That correlation is tentatively continued here and extended to contiguous rocks of similar composition in the Wadi Sadiyah quadrangle mapped as "msq" by Weir and Hadley (1975).

Rhyolite and rhyolite tuff mapped as Baish group in the Al Lith quadrangle (Hadley and Fleck, 1979a) appear to be overlain to the north in the Wadi Sadiyah quadrangle by a metasedimentary unit that contains quartz-feldspar lithic clasts in impure sandstone, graywacke, and volcanic detritus of dacitic composition. The rhyolite and metasedimentary rocks are in fault contact with mafic and intermediate rocks of the Lith belt to the east and are intruded by gneissic granite, herein correlated with the gneiss of Jiddah Airport that is dated by Rb-Sr isochron methods at 763 ± 159 m.y., initial $^{87}Sr/^{86}Sr$ ratio 0.7026 ± 0.0019 (Fleck and others, 1980). This section of rhyolite and conglomeratic clastic rocks may be correlative with the Ablah group and thus mark another rift. On this basis, a boundary is drawn between rocks of the Lith and Arafat belts.

Arafat belt

The Arafat belt is bounded to the northwest by a major northeast-trending fault in Wadi Fatimah, west of the Holy City of Makkah, and to the east by a fault against the Lith belt described below (figs. 1, 2). The northwestern boundary marks the structural contact of the Arafat group of Skiba (1980) with his Samran group to the north in the Makkah belt. Younger volcanic and sedimentary rocks of the Fatimah group (Skiba, 1980) are locally preserved in grabens and half grabens along this northeast-trending fault in Wadi Fatimah. Layered rocks in the Arafat belt include metamorphosed basalt flow rocks and flow breccia, andesite flow and pyroclastic rocks, subordinate dacite flow and pyroclastic rocks, associated sedimentary rocks, and minor marble (Skiba, 1980).

Layered rocks of the Arafat belt have not been radiometrically dated, but Skiba (1980) suggested, on the basis of structural and metamorphic differences, that they are older than the Samran group. Rocks of the Arafat group were intruded by diorite that ranges in age from 820 to 760 m.y. old (Fleck, in press). Of these ages, the one age greater than 800 m.y. is very poorly controlled. If this age is not accepted, the rocks of the Arafat group may be similar in age to rocks of the Samran group in the Makkah belt to the north.

Makkah belt

The Makkah belt is named for the Holy City of Makkah (figs. 1, 2). The belt consists of metamorphosed flow and pyroclastic rocks of predominantly andesitic and dacitic composition, with subordinate basalt and rhyolite and associated epiclastic rocks, all mapped as Samran group

(Liddicoat, 1971; Fujii and others, 1978; Skiba, 1980). These rocks previously were mapped as Jiddah group by Brown and Jackson (1962). Skiba (1980) suggested that the volcanic rocks of the Samran group have continental-marginal, calc-alkaline affinities. Rocks of the Samran group are less intensely deformed and metamorphosed and therefore probably younger than those of the Arafat group of the Arafat belt (Skiba, 1980). Recent Rb-Sr data support the age difference suggested by Skiba by showing that diorite greater than 800 m.y. old may be present in the Arafat belt but not in the Makkah belt (Fleck, in press). However, the age of the diorite in the Arafat belt is highly uncertain. Thus, no age difference between rocks of the Makkah and Arafat belts has yet been established.

The dioritic rocks of the Makkah belt range in age from about 780 to 760 m.y. (Fleck, 1980; in press) and are approximately contemporaneous with tonalitic to granodioritic gneisses emplaced into the Ablah group to the south. These age data suggest that the Samran, Arafat, and Ablah groups, each of which also contains calc-alkaline volcanic rocks, may have been deposited contemporaneously.

The overlying Fatimah group, which is preserved along the southern fault boundary of the Makkah belt, is younger and could be correlative with the Halaban or Murdama groups as used in this report.

Khadra belt

Named for the village of Khadra in the Khadra quadrangle (Greenwood, 1979b) (fig. 1), the Khadra belt consists of metamorphosed flow and pyroclastic rocks of predominantly andesitic to dacitic composition, with associated volcaniclastic and epiclastic rocks. Basalt is abundant locally in the south, and rhyolite is reported in the highest part of the section in the northernmost part of the belt (Hadley, 1976; Schmidt, unpub. data). The volcanic rocks of this belt have been dated by the Rb-Sr isochron method in the range 785±96 to 746±16 m.y. old (Fleck and others, 1980). Throughout this belt, no plutonic rock has been dated that is older than 730 m.y. (Cooper and others, 1979; Fleck and others, 1980; Stacey, written commun., 1980). Most of the rocks of the Khadra belt have been mapped as Halaban group. On its eastern boundary, the Khadra belt is separated from broadly contemporaneous rocks of the Tathlith and Malahah belts by the Nabitah fault zone of Gonzalez (1975).

Distribution of facies

The Khadra belt consists predominantly of andesite and dacite flow and pyroclastic rocks, with subordinate but locally significant amounts of basalt, trachyte, and rhyodacite. The percentage of interbedded clastic rocks varies greatly along the belt according to depositional environment and proximity to contemporaneous volcanic centers.

In the Wadi Atf quadrangle (Anderson, 1978a), near the southern end of the belt, basalt and andesite are the dominant volcanic rocks. Pillow structures are common in this quadrangle, and the interbedded graywacke generally is carbonaceous. Pillow basalt is also common in the Madha quadrangle to the north (Simmons, 1980) and contains non-carbonaceous graywacke and a few thin marble beds.

Farther north, in the Tathlith one-degree quadrangle (Overstreet, 1978), green andesite flow rocks, breccia, and tuff and subordinate associated clastic rocks are present at the base of the section. The clastic layers contain ripple marks, and a few thin marble layers are interbedded with breccia. An overlying section with more abundant clastic rocks contains maroon argillite and hematitic rhyolite agglomerate and flow rocks. The Tathlith rocks appear to record an upward transition from intermediate-composition volcanism in a shallow-water, marine-marginal environment to intermediate and potassic volcanism in a subaerial environment.

In the Khadra quadrangle to the west (Greenwood, 1979b), a predominantly volcanic unit mapped as the Khadra formation consists of flow rocks and flow breccia of andesitic and basaltic composition and pyroclastic rocks of andesitic and dacitic composition. Well-preserved textures indicate welded and unwelded ash-flow tuffs. Interbedded volcaniclastic rocks include conglomerate to siltstone and local ferruginous marble and red and brown chert. Clasts in the conglomerates include marble, chert, and quartz diorite, as well as volcanic lithic clasts. The sedimentary rocks of the Khadra formation appear to represent rapid deposition flanking a major volcanic center. Although sedimentation was dominantly subaerial, it also occurred in marine-marginal embayments.

In the Jabal Ishmas quadrangle (Gonzalez, 1974), a basal unit of graywacke, which has graded bedding and locally contains boulders and cobbles of andesite and some "granitic rocks", grades upward into siltstone and then into gray shale. This unit also contains interbedded andesite flow rocks and dacitic crystal tuff. This lower section, therefore, records an early transition from a marine-marginal environment to a deeper, marine-depositional environment that was adjacent to a moderately active, volcanic center. Overlying the lower mixed clastic and volcanic unit is a volcanic unit consisting of green andesitic flow rocks, tuff, and dacite and basalt flow rocks, with red andesite flow rocks in its upper part. This upper section indicates that the period of marine sedimentation was terminated by volcanism, during which basaltic and andesitic volcanic rocks were deposited under marine-marginal to subaerial conditions.

In the Bir Juqjuq quadrangle (Hadley, 1976), a lower volcanic unit has at its base green andesite and basalt flow rocks, with subordinate andesitic to trachytic welded tuff, breccia, and red unwelded tuff. Higher in the section, this unit consists of dacitic, rhyodacitic, and trachytic flow rocks and red and green pyroclastic rocks, with a few andesitic flow rocks. At the top of the section, this unit consists of green and red andesite, basalt, dacite, trachyte and rhyodacite flow rocks, pyroclastic rocks, and volcanic conglomerate. An overlying mixed sedimentary and volcanic unit contains abundant, well-bedded graywacke and flows and tuffs of andesitic, dacitic, basaltic, and rhyodacitic composition. The graywacke contains boulder beds with volcanic clasts and a few clasts of granite, syenite, and diorite. The Bir Juqjuq rocks appear to record major subaerial volcanism accompanied with and followed by rapid fluvial deposition and varying amounts of intermediate to potassic volcanism.

The diorite clasts in the graywacke of the Khadra belt could have been derived from rocks of the Tayyah belt to the west or from synvolcanic diorite of the Khadra belt exposed by the rapid erosion that produced the graywacke. The granite and syenite clasts in the Bir Juqjuq quadrangle may have been derived by erosion of early synvolcanic granite and syenite or may suggest that this unit is younger than reported.

Overall, the available descriptions in the Khadra belt indicate a transition from marine, mafic and mafic to intermediate volcanism in the south to predominantly subaerial, intermediate to potassic volcanism in the north. It should be noted that the northward transition of volcanic chemistry and depositional environments suggested for the Khadra group is similar to that proposed for the earlier Ablah group.

Structure and metamorphism

Most rocks of the Khadra belt are broadly folded, except near faults or major intrusive centers and gneissic structures. In narrow septa between plutons the rocks dip steeply and most are conformable to plutonic contacts. Most regional folding was about north-trending axes, although such trends are lost in areas of diapiric or hydraulically driven dioritic to granitic plutonism.

Rocks of the Khadra belt are metamorphosed to greenschist facies except near intrusive contacts or in several large intrusive or gneissic centers, where hornfelsic to schistose and gneissic rocks are metamorphosed to pyroxene-hornfels or granulite facies. The presence of andalusite and absence of kyanite indicates that high-temperature and low-pressure metamorphic conditions prevailed in this belt.

Plutonic rocks

Dated intrusive rocks in the Khadra belt include diorite, quartz diorite, tonalite, and trondhjemite, followed by granodiorite, all of which have dates in the period 730 to 660 m.y. ago (Cooper and others, 1979; Fleck and others, 1980; Stacey, written commun., 1980) (fig. 5). Plutonism was essentially continuous in the Khadra belt during the period 660 m.y. to 610 m.y. ago, with the emplacement of large volumes of granite and gabbro (see fig. 6). Younger sodium pyribole-bearing alkali granite was emplaced in the Khadra belt and the eastern margin of the Wassat belt (Stoeser and Elliott, 1980). Much greater volumes of granodiorite and granite were emplaced in this belt than in the Bidah or Tayyah belts to the west (figs. 5, 6).

The concentration of granite and gabbro in and adjacent to the Khadra belt and the associated hornblende- to pyroxene-hornfels facies metamorphism are evidence of greatly elevated heat flow and suggest a major zone of crustal weakness. Smaller volumes of granite and gabbro are present along other lineaments in the southern Shield that may have undergone less extension.

Metasedimentary rocks mapped as Ablah group in the Wadi Atf quadrangle (Anderson, 1978a) rest unconformably on tonalite dated at 663 ± 8 m.y. (Cooper and others, 1979) and contain granite cobbles at the base. This conglomeratic unit is intruded by granite similar to nearby rocks dated at 640 m.y. (Cooper and others, 1979; Stacey, written commun. 1980). Therefore, the metasedimentary rocks of Jabal Atura, as they are herein informally designated, appear to have been deposited during the main magmatic period. They may be correlative with parts of the Halaban group as mapped in the Bir Juqjuq quadrangle, but they appear to be younger than the Halaban group in most of the Khadra belt.

Malahah belt

This belt is named after Wadi Malahah in the Wadi Malahah quadrangle (Greenwood, 1980a) (fig. 1). The western boundary of the Malahah belt is the southern extension of the Nabitah fault zone, which terminates in the southwestern part of the Malahah quadrangle (fig. 6). The southern continuation of this boundary is marked by a belt of syntectonic plutonic rocks. The northern boundary of the Malahah belt is drawn at the southernmost exposures of a major thrust sheet of serpentinite that is overlain by a melange assemblage of the Tathlith belt. The eastern margin of the Malahah belt is covered by the Cambrian-Ordovician Wajid Sandstone. Internally, the rocks of the belt are separated by the north-trending Ashara fault zone (Greenwood, 1980b), which appears to represent a zone of major left-lateral transcurrent movement and, in the

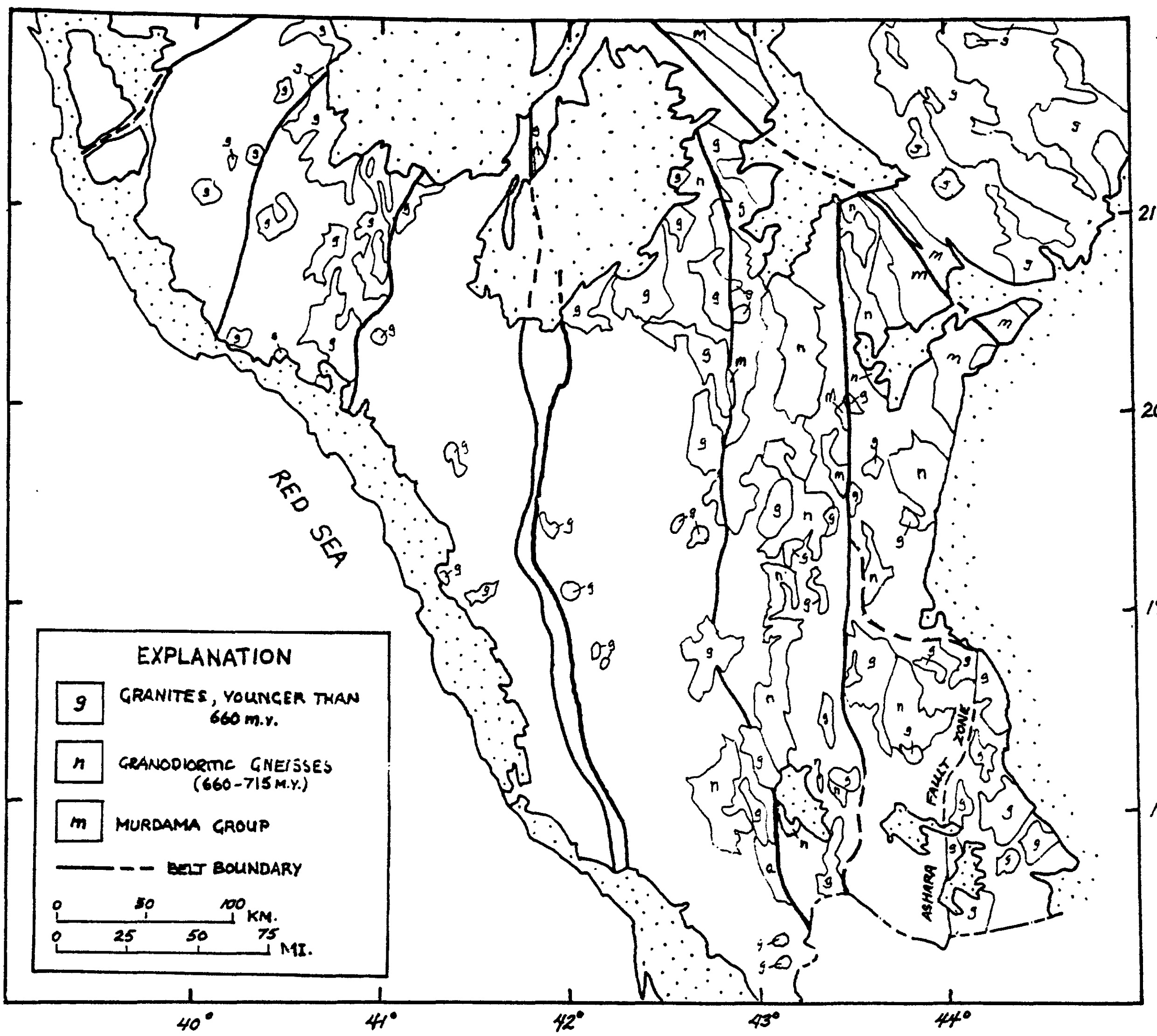

Figure 6.–Geologic sketch map of the southern Arabian Shield showing the distribution of the Murdama group, granodioritic gneisses of 660-715-m.y. age, and granites younger than 660 m.y. Stipple pattern represents Phanerozoic cover rocks and unconsolidated sediments.

southern part of the belt, is the western boundary of a major province of granitic plutons (fig. 6).

The layered rocks of the Malahah belt were originally mapped as Jiddah group by Anderson (1978a, b), Greenwood (1980a,b), and Sable (unpub. data) and as informal lithostratigraphic units by Simmons (1980) and Warden (unpub. data). Subsequent to the mapping, the Jiddah group correlation was supported by two poorly controlled Rb-Sr isochron ages (Fleck and others, 1980) of 815 and 843$\pm$273 m.y. on two quartz diorite plutons (localities 26 and 27: fig. 2, appendix). However, U-Pb (zircon) dating (Stacey, written commun., 1980) and well-controlled Rb-Sr isochron dating (Fleck and others, 1980) have not identified any plutonic rocks in the Malahah or Khadra belts that are older than 730 m.y. Therefore, the layered rocks of the Malahah belt are interpreted to be broadly equivalent in age with the Halaban group of the Khadra belt.

The bulk of the Malahah layered rocks appear to comprise a major arc complex that is subdivided into three major facies assemblages: (1) a mature shelf-type metasedimentary assemblage near the Yemen border; (2) a volcanic-arc assemblage of metavolcanic and metasedimentary rocks; and (3) a fore-arc assemblage of metasedimentary rocks in the northern part of the belt. Minor exposures of an overlying volcanic-arc assemblage also are present in the northwestern part of the belt. This overlying volcanic-arc assemblage appears to be widespread in the northern part of the Tathlith belt and probably also is present in the Khadra belt.

Shelf assemblage

A narrow exposure of east-west striking quartzite, pure marble, and minor metapelite is present near the Yemen border in the Wadi Habawnah and Najran quadrangles at the southern end of the Malahah belt (Sable, unpub. data). No volcanic rocks or volcanic-derived clastic rocks are interbedded with these mature metasedimentary rocks. The transition to the volcanic-arc facies to the north appears abrupt but is badly disrupted by later plutonism and possibly by thrust faulting. This shelf assemblage may represent shallow-water, continental-margin deposition behind the arc, or it may be older and unrelated to the rest of the layered rocks of the Malahah belt. The existence of an older continental block to the south in Yemen and Oman has been suggested by Stacey and others (1980) on the basis of lead isotope determinations on galenas from these areas.

Volcanic-arc assemblage

Volcanic rocks of the arc assemblage in the southern part of the Malahah belt include submarine flow rocks, flow breccia, and crystal and lithic tuff predominantly of andesitic to dacitic composition. The submarine character is suggested by the abundance of hyaloclastic breccia interbedded with calcareous and carbonaceous sedimentary rocks and chert. Pillow structures were also observed in mafic volcanic rocks at one locality in the Mayza quadrangle (Anderson, 1978b). Locally thick, welded and unwelded ash flow tuffs of dacitic composition are apparently younger than these marine volcanic and associated sedimentary rocks. The coarse fragmental character of the tuffs and breccias and the thick welded tuffs suggest the presence of several volcanic centers within the Malahah belt.

The volcaniclastic and epiclastic sedimentary rocks associated with the volcanic-arc assemblage in the southern part of the Malahah belt commonly are gray to black, pyritic, calcareous, and in part carbonaceous, with subordinate chert and thin, discontinuous marble beds. Grain size ranges from boulder conglomerate to slate; pebble-bearing, sand-sized clastic rocks are predominant. Facies changes commonly are rapid along and across strike in the coarser grained units; however, certain disseminated to massive sulfide-bearing layers continue for as much as 18 km along strike in the Wadi Wassat area (Greenwood, 1980b). The sedimentary rocks may represent marine fan deposits that formed from subaerially eroding volcanic centers and that are interfingered with fine-grained, deeper-water slope deposits. In such an environment, the stratigraphic sequence would vary according to relative proximity to volcanic centers of different compositions and times of development.

Fore-arc assemblage

The layered rocks of the northwestern part of the Malahah belt consist of predominant metagraywacke and metapelite and subordinate metamorphosed volcanic sandstone. The pelitic rocks locally are carbonaceous. Flow rocks generally are not interbedded with these rocks, but mafic to intermediate tuffs are present locally in significant amounts. The sedimentary rocks are medium to fine grained. No conglomerate has been reported. The unit is overthrust by serpentinite and mixed serpentinite and metasedimentary rocks of an accretionary melange to the north. The serpentinite and accretionary melange probably were emplaced during or near the end of arc volcanism in the Malahah belt and are overlain by younger arc-facies volcanic rocks in the Tathlith belt to the north. Some of the younger arc-facies volcanic rocks extend south into the Malahah belt.

Plutonic rocks

The eastern part of the Wadi Tarib batholith is included in the western margin of the Malahah belt. Elsewhere in the

Malahah belt, arc-related plutonic rocks are sparse. These arc-related plutonic rocks consist of potassium feldspar-free gabbro, hornblende or hornblende-biotite quartz diorite, and tonalite (Greenwood, 1980a, b). The plutons appear to have been passively emplaced and have steep sides and flat to shallow-dipping tops. As discussed earlier, these rocks probably were emplaced about 730 m.y. ago.

The younger plutonic rocks of the belt consist of tonalitic to granitic syntectonic gneisses and younger monzogranites and peralkaline granites. These rocks are sparse in the western Malahah belt except for the Malahah dome, which consists of a large, complex, uplifted welt of these rocks (Greenwood, 1980a). East of the Ashara fault zone (fig. 6), the Malahah belt is dominated by these rocks, and the southern portion of the Ashara zone marks the western front of intense development of peralkaline and other granites (Stoeser and Elliott, 1980).

Structure and metamorphism

West-dipping, north-trending thrust faults and related shallow-plunging folds are the major structural feature of the Malahah belt. During one or more compressional episodes, these faults were steepened by rotation, and north-trending wrench faults and related steep-plunging folds were developed. The syntectonic granodioritic and granitic gneisses were also emplaced during this period. Regional dynamothermal metamorphism in greeenschist to amphibolite facies was followed by hornblende- to pyroxene-hornfels-facies thermal metamorphism in areas with abundant plutonism. Potassium and sodium metasomatism was widespread and locally modified the composition of the layered rocks.

Tathlith belt

The Tathlith belt is named after the village of Tathlith in the Tathlith one-degree quadrangle (Overstreet, 1978; Worl, 1979) (fig. 1). On the west the belt is bounded by the Nabitah fault zone, on the east it is covered by the Wajid Sandstone, and to the south in the Hamdah area it is covered by the accretionary melange and serpentinite (fig. 5) that form the upper unit of the older arc complex of the Malahah belt (Worl and Elsass, 1980). To the north, this melange is overlain by a younger arc complex composed of metabasalt, meta-andesite, metadacite, and associated sedimentary rocks (Greenwood, unpub. data). In the southern part of the Tathlith belt, the younger arc complexes are preserved only as relatively narrow septa among abundant intrusive rocks in high-grade metamorphic domains. This and the fact that published descriptions of the layered rocks are very limited permits only a sketchy description of the younger arc complex.

Melange facies

The accretionary melange facies of the older arc complex is divided into two main units, a lower serpentinite thrust sheet and an upper, tectonically disrupted metasedimentary-metavolcanic melange unit. The metasedimentary rocks include metamorphosed graywacke, shale, and impure quartzite, Some of the pelitic rocks are carbonaceous and pyritic. Metabasalt flow rocks are present as major tectonic slices and clasts within the metasedimentary rocks. Pillow structures are preserved in some of the larger slices (R.G. Worl, oral commun., 1981). Metamorphosed andesitic and dacitic tuff interbeds also are present in the section. In addition, large plates as much as 1 km long of bedded metasedimentary rocks are present within massive metasedimentary rocks.

This sedimentary and volcanic melange rests with structural discordance on a major serpentinite thrust sheet, which may be as much as 2 km thick. Clasts and slabs of serpentinite as much as 1 km long also are in the overlying melange. The basal serpentinite sheet generally separates the accretionary melange facies in the Tathlith belt from the fore-arc facies in the Malahah belt. In a few places, the serpentinite thins and is missing at the thrust contact between the two belts. This association is similar to fore-arc and accretionary melange of Cretaceous and Tertiary age from the Indonesian region (Hamilton, 1979).

Crude layering and schistosity in the accretionary melange is approximately conformable to nearby contacts with major serpentinite slices. The schistosity probably results from thrusting during formation of the melange. The metamorphic rocks generally are greenschist facies near serpentinite contacts, except in proximity to subsequent intrusive rocks. This relationship indicates that mixing of serpentinite slabs and clasts into the melange resulted predominantly from mass wasting, erosion, and gravity sliding from topographic highs on the underlying serpentinite thrust slice rather than from repeated thrusting of hot serpentinite slabs.

Younger arc complex

The younger arc complex of the Tathlith belt consists predominantly of arc-facies metagraywacke, with interbedded basaltic and andesite flow rocks and pyroclastic rocks of andesitic and dacitic composition (Overstreet, 1978). Most of these rocks are slightly cleaved and are metamorphosed to greenschist facies except near plutonic contacts. The younger arc complex in this belt appears to be correlative with at least part of the Halaban group of the Khadra belt to the west. In addition, it appears that these rocks are present in the northwesternmost part of the Malahah belt in the Madha quadrangle.

MURDAMA GROUP

Rocks of the Murdama group are present in two structural settings in the southern part of the Arabian Shield (fig. 6). The largest exposure of the Murdama group is in the Najd fault zone. In this zone it is fault bounded on the northeast and is in part fault bounded and in part deposited unconformably on older rocks southwest of the main faults of the zone (fig. 6). South of the Najd fault zone, the Murdama group crops out along the Junaynah fault zone in the Al Junaynah (Schmidt, 1981) and Wadi Harjab (Cornwall, 1973) quadrangles. In this north-trending fault zone, the Murdama group rocks are fault bounded on the west side and rest unconformably on red granite and older rocks on the east side. Thus, the Murdama is preserved in grabens to half-grabens both in the northwest-trending Najd fault zone and in the north-trending Junaynah fault zone.

It is not clear that early rifting in the Najd system had a major translational faulting component. In the southern part of the Shield, minor granite plutons were emplaced during Najd faulting. The abundance of Najd-age granite appears to increase to the north (USGS-ARAMCO, 1963). Compression and major left-lateral wrench faulting appear to have followed deposition of the Murdama group. This tectonic event produced gneiss domes and local amphibolite-facies metamorphism in the Najd fault system and shearing and hydrothermal activity throughout the southern part of the Shield. Quartz veins and dikes in the southern part of the Shield may be the products of this event and (or) the earlier rifting in the Najd fault zone.

DISCUSSION

The southern part of the Arabian Shield is formed predominantly of an older (1100-800 m.y.) ensimatic volcanic-arc complex and a younger (800-700 m.y.) marginal volcanic-arc complex. These arc complexes now lie between more ancient continental masses of Africa to the west and Iran to the east. The accretion of the older ensimatic arc to Africa and the subsequent collision of the younger marginal arc with the Iranian(?) craton produced a strong north- to northeast-trending structural grain in rocks of the southern Shield. These structures cut across major depositional facies of the arcs and appear to have been controlled by the orientation and shape of adjacent continental margins during collision. The arcs may have been aligned northwest-southeast and formed above subduction zones that dipped southwest most of the time. The direction of dip of the subduction zones that are related to the formation of the arc complexes is conjectural, but the younging of the layered and dioritic to tonalitic plutonic rocks to the east suggests west-dipping subduction with the zones stepping to the east. Schmidt and others (1978) have previously suggested west-dipping subduction on the basis of lithofacies distribution and structural evidence. However, Greenwood and others (1976, 1980) and Fleck and others (1980) have proposed east-dipping subduction. This and other problems can only be resolved by detailed lithofacies, geochemical, isotopic, and structural studies.

The older ensimatic-arc complex is mapped over an area with a maximum exposed east-west extent of about 300 km and a maximum north-south extent of 450 km in the southern part of the Arabian Shield in Saudi Arabia. Similar rocks probably are present in Africa and may be present at least in parts of northwestern Arabia. The oldest dated, arc-related dioritic rocks intruding the older ensimatic-arc complex are about 900 m.y. old (Fleck and others, 1980). The youngest arc-related dioritic rocks in the complex are about 810 m.y. old (Cooper and others, 1979; Fleck and others, 1980). Therefore, the range of arc-related plutonism in the complex is less than 100 m.y. Volcanic rocks in the complex are dated by a poorly controlled Rb-Sr age as being as old as 1170 m.y. but probably are not much older than the dioritic rocks that intrude them. The complex is composed predominantly of tholeiitic mafic to intermediate volcanic rocks and volcanic-derived sedimentary rocks. No detritus from older sialic terrains has been identified in the complex. The volcanic composition and sedimentary character of the rocks suggest that the arc formed on oceanic crust in isolation from older continental masses. Rb-Sr and lead isotope studies also indicate that the complex formed on oceanic crust (Fleck and others, 1980; Stacey and others, 1980).

Facies changes in the southern part of the Arabian Shield in Saudi Arabia suggest a transition to the south to a back-arc, small ocean basin that may have separated the older ensimatic arc from the African craton. The facies patterns of all the ensimatic rock units are similar and suggest that the units were broadly contemporaneous and formed a single arc complex.

About 800 m.y. ago, tholeiitic volcanism in the ensimatic-arc complex appears to have been replaced at least locally by calc-alkaline volcanism and clastic sedimentation. The earliest phases of the calc-alkaline volcanism and associated sedimentation are now preserved in one major and several minor grabens that comprise units of the Ablah group. The Ablah group rests on and is derived largely from volcanic and dioritic rocks of the ensimatic-arc sequence but also contains mafic, intermediate, and potassic volcanic rocks. The change to calc-alkaline volcanism accompanied by graben deposition indicates a major change in tectonic environment. The Samran group of the Makkah belt and possibly the Arafat group of the Arafat belt were also deposited in the period 800 to 780 m.y. ago and are the products of calc-alkaline magmatism (Skiba, 1980). Deposition of the Ablah, Samran, and Arafat groups was terminated by regional thrusting and folding produced by east-west compression (Greenwood and others, 1976, 1980). This orogeny produced east-dipping thrusts and culminated 800 to 760 m.y. ago in the emplacement of tonalitic to granitic gneisses that appear to have formed by partial melting and mobilization of the older ensimatic-arc rocks (Cooper and others, 1979; Fleck and others, 1980). These gneisses overlap in age volcanic rocks that form part of the younger (Halaban) marginal-arc complex farther to the east and northeast (Fleck and others, 1980).

This period of orogeny affected only the ensimatic and earliest calc-alkaline rocks of western Arabia and appears to represent the accretion of these rocks to Africa. This accretion may have been accomplished by closure of the back-arc basin between the African craton and the ensimatic arc by simple compression and thrusting. However, the closure of this basin was accompanied by calc-alkaline volcanism represented in the Ablah, Samran, and possibly Arafat groups. This volcanism may have arisen from a short-lived, northeast-dipping subduction zone down which most of the original back-arc basin was consumed.

Following the overlapping and closure of the back-arc basin, tholeiitic arc volcanism of the younger marginal-arc complex (Halaban group) to the northeast began about 790 m.y. ago and continued until about 700 or 690 m.y. ago. Facies patterns suggest that this volcanism resulted from an eastern oceanic plate being consumed down an active, southwest-dipping subduction zone that underlay the continental margin formed by the older ensimatic-arc complex. This younger arc complex, which was marginal to the eastern edge of the older ensimatic-arc complex, was probably also mostly ensimatic in character, although it may have developed in part over the older arc complex and could be partly Andean in character. Detailed mapping and considerable isotopic geochronology are required to determine whether rocks of the older ensimatic-arc complex are present east of the Junaynah fault zone, as indicated by Schmidt and others (1978) (fig. 2).

Active arc volcanism of the younger marginal-arc complex terminated in southern Arabia about 700 or 690 m.y. ago, when major compression produced regional thrusting and folding, possibly as a result of collision with the Iranian craton. This orogeny culminated in the emplacement in the southern Shield of gneisses and massive tonalitic to granitic rocks and diorite and gabbro in the period 690 to 640 m.y. ago (Cooper and others, 1979; Fleck and others, 1980; Fleck, in press; Stacey, written commun., 1980). Minor local deposits of granite cobble-bearing conglomerate and rhyolite that were deposited in the waning states of this orogeny are preserved in the southern Shield.

The tectonic belts described in this paper are primarily the net result of the two compressional orogenies that occurred 800-760 and 690-640 m.y. ago. The belts as defined are tectonic features that are superimposed over the two arc complexes. Subsequent to the second orogeny, the Arabian Shield was involved in the Pan-African episode (650-550 m.y. ago), during which extensive terrestrial silicic volcanic and molassic sedimentary rocks were deposited and the Arabian granites emplaced (Fleck and others, 1976, 1980; Delfour, 1977; Stoeser and Elliott, 1980).

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APPENDIX.--*Source data for radiometric age data presented in figure 2*

[Only data obtained by the rubidium-strontium (Rb-Sr) or uranium-lead zircon (U-Pb) methods were used. The number in parentheses after Rb-Sr age gives the number of points used to establish the isochron. Where only two points were used for an isochron, confidence limits could not be calculated]

Locality number	Rock type and locality	Age	Method	Reference
1	Granodiorite and quartz diorite northeast of Jiddah	762±15(13)	Rb-Sr	Fleck (1981)
2	Granodiorite of Wadi Sayyal	769±39(3)	Rb-Sr	Fleck (1981)
3	Diorite south of Makkah	817±518(3)	Rb-Sr	Fleck (1981)
4	Quartz diorite of Makkah-At Taif region	774±32(7)	Rb-Sr	Fleck (1981)
5	Quartz diorite of Wadi Khadrah	895±173(6)	Rb-Sr	Fleck and others (1980)
6	Basalt of Wadi al Faqh	1165±110(3)	Rb-Sr	Fleck and others (1980)
7	Quartz diorite of Wadi ash Shuqah ash Shamiyah	853±72(8)	Rb-Sr	Fleck and others (1980)
8	Quartz diorite of Biljurshi (B)	848±243(3)	Rb-Sr	Fleck and others (1980)
9	Quartz diorite of Biljurshi (A)	890±67(3)	Rb-Sr	Fleck and others (1980)
10	Quartz diorite of Wadi Qanunah	846(2)	Rb-Sr	Fleck and others (1980)
11	Quartz diorite of Al Mushirah	747±178(4)	Rb-Sr	Fleck and others (1980)
14	Trondhjemite of Wadi Asmak	838(2)	Rb-Sr	Fleck and others (1980)
15	Quartz diorite of Wadi Tarj	818±95(4)	Rb-Sr	Fleck and others (1980)
16	Metavolcanic rocks of Wadi bin Dwaynah	912±76(4)	Rb-Sr	Fleck and others (1980)
17	Quartz diorite of An Nimas	837±50(4)	Rb-Sr	Fleck and others (1980)

APPENDIX.--*Source data for radiometric age data presented in figure 2* [continued]

Locality number	Rock type and locality	Age	Method	Reference
16	Granodiorite gneiss of Jabal Mina	746±114(5)	Rb-Sr	Fleck and others (1980)
17	Tonalite gneiss of An Nimas	816±4	U-Pb	Cooper and others (1979)
18	Biotite tonalite gneiss of Wadi Bagarah	797±7	U-Pb	Cooper and others (1979)
19	Leuco-adamellite gneiss of Wadi Bagarah	765±4	U-Pb	Cooper and others (1979)
20	Granodiorite gneiss of Wadi Bagarah	778±9	U-Pb	Cooper and others (1979)
21	Granodiorite gneiss of Wadi Bagarah	763±53(6)	Rb-Sr	Fleck and others (1980)
22	Granodiorite gneiss of Wadi Atura	663±8	U-Pb	Cooper and others (1979)
23	Quartz diorite of Wadi Talhah	732±3	U-Pb	This paper
24	Tonalite of the Suwaydah gneiss	729±3	U-Pb	This paper
25	Granodiorite gneiss of the Wadi Tarib quadrangle	714±28	U-Pb	Cooper and others (1979)
26	Quartz diorite of Wadi Simlal	815(2)	Rb-Sr	Fleck and others (1980)
27	Quartz diorite of Wadi Makhdhul	843±273(3)	Rb-Sr	Fleck and others (1980)
28	Granodiorite of Wadi Malahah	684±43(13)	Rb-Sr	Fleck and others (1980)
29	Metavolcanic rocks of the Khadrah formation	746±16(4)	Rb-Sr	Fleck and others (1980)
30	Quartz diorite of Jabal Umm al Hashiyah	723±107(4)	Rb-Sr	Fleck and others (1980)

APPENDIX.--*Source data for radiometric age data presented in figure 2* [continued]

Locality number	Rock type and locality	Age	Method	Reference
31	Quartz diorite of the Jabal al Qarah quadrangle	724±93(4)	Rb-Sr	Fleck and others (1980)
32	Meta-andesite of the Al Junaynah quadrangle	785±96(3)	Rb-Sr	Fleck and others (1980)
33	Hornblende tonalite gneiss of the Jabal Yafikh quadrangle	666±8	U-Pb	Cooper and others (1979)
34	Metavolcanic rocks of the Arfan formation	761±23(3)	Rb-Sr	Fleck and others (1980)
35	Metavolcanic rocks of the Arfan formation	775(2)	Rb-Sr	Fleck and others (1980)
36	Granodiorite gneiss of the Bir Juqjuq quadrangle	782±26(6)	Rb-Sr	Kroner and others (1979)