PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1976 **280**, 517-527
doi: 10.1098/rsta.1976.0010

Phil. Trans. R. Soc. Lond. A. **280**, 517–527 (1976) [517]
Printed in Great Britain

Late Proterozoic cratonization in southwestern Saudi Arabia

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Early cratonal development of the Arabian Shield of southwestern Saudi Arabia began with the deposition of calcic to calc-alkalic, basaltic to dacitic volcanic rocks, and immature sedimentary rocks that subsequently were moderately deformed, metamorphosed, and intruded about 960 Ma ago by dioritic batholiths of mantle derivation ($^{87}Sr/^{86}Sr$ = 0.7029).

A thick sequence of calc-alkalic andesitic to rhyodacitic volcanic rocks and volcanoclastic wackes was deposited unconformably on this neocraton. Regional greenschist-facies metamorphism, intensive deformation along north-trending structures, and intrusion of mantle-derived ($^{87}Sr/^{86}Sr$ = 0.7028) dioritic to granodioritic batholiths occurred about 800 Ma. Granodiorite was emplaced as injection gneiss about 785 Ma ($^{87}Sr/^{86}Sr$ = 0.7028–0.7035) in localized areas of gneiss doming and amphibolite to granulite facies metamorphism. Deposition of clastic and volcanic rocks overlapped in time and followed orogeny at 785 Ma. These deposits, together with the older rocks, were deformed, metamorphosed to greenschist facies, and intruded by calc-alkalic plutons ($^{87}Sr/^{86}Sr$ = 0.7035) between 600 and 650 Ma.

Late cratonal development between 570 and 550 Ma involved moderate pulses of volcanism, deformation, metamorphism to greenschist facies, and intrusion of quartz monzonite and granite.

Cratonization appears to have evolved in an intraoceanic, island-arc environment of comagmatic volcanism and intrusion.

Introduction

Reconnaissance geologic maps published by 1963 were compiled at a scale of 1:500000 and were recompiled at a scale of 1:2000000 (USGS-ARAMCO 1963); these provided a framework for unravelling the complex geology of the Arabian Shield. Since 1969, the U.S. Geological Survey Mission in Saudi Arabia has remapped at a scale of 1:100000 most of the southern part of the Precambrian Arabian Shield from latitude 21° 30′ N south to the Yemen border (figure 1).

The Precambrian stratigraphic and tectonic history of the Arabian Shield has been summarized and interpreted by Karpoff (1960), Brown & Jackson (1960), Eijkelboom (1969), Brown (1970, 1972) Brown & Coleman (1972), Schmidt *et al.* (1973), Greenwood, Hadley & Schmidt (1973), and Delfour (1973). Using the results of recent geological mapping, in conjunction with current isotopic data and limited chemical data (Jackaman 1972; Greenwood & Brown 1973), we present here a revised stratigraphy and interpret the orogenic history in terms of the cratonization of the southern part of the Arabian Shield.

This study is part of a geologic and mineral investigation program conducted cooperatively by the Saudi Arabian Directorate General of Mineral Resources and the U.S. Geological Survey.

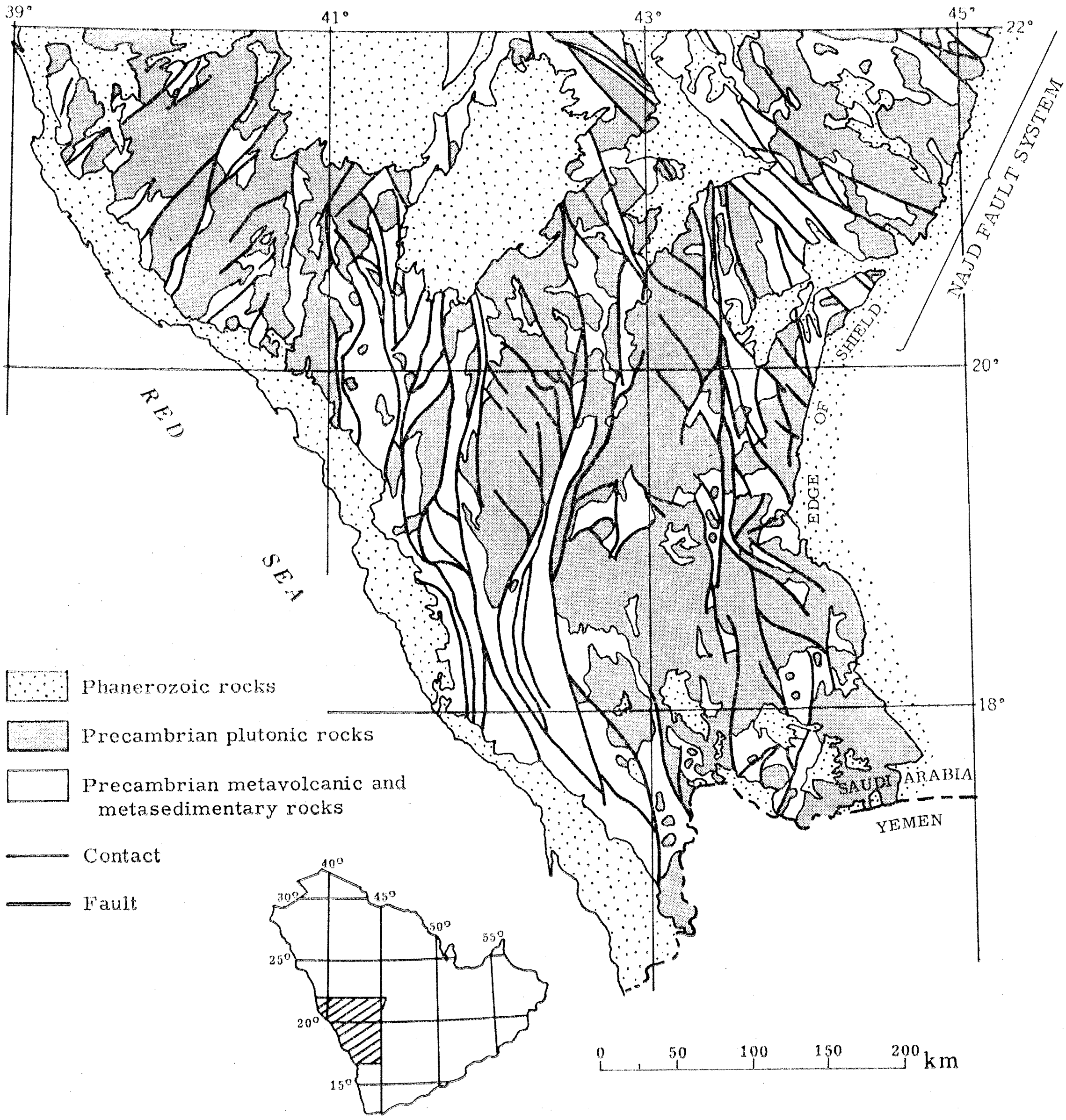

Figure 1. Generalized tectonic map of the southern part of the Arabian Shield.

Hijaz tectonic cycle

Cratonal development of the southern part of the Arabian Shield resulted from volcanic and sedimentary deposition accompanied and interrupted by tectonism, metamorphism, and plutonism from about 1050 to 550 Ma. Mapping and isotopic age data suggest that cratonization occurred in at least three episodes that together constitute the Hijaz tectonic cycle (Greenwood *et al.* 1973) (table 1). The depositional and plutonic products of the three episodes appear to be evolutionary in petrologic and chemical character, and it is the evolutionary character that we wish to emphasize rather than the orogenies. Tectonism and plutonism appear to have been accompanied or overlapped in time by volcanism and sedimentation. Some of the lithologic groups discussed in this report may include the products of two or more periods of volcanism and sedimentation. As a corollary to this, additional orogenic episodes may well be identified by expanded mapping and isotopic dating.

Our usage of Hijaz tectonic cycle follows King (1969) and is preferred over 'Hijaz orogeny' (Brown 1972; Brown & Coleman 1972) because of the progressive and episodic orogenic history of the shield.

TABLE 1. STRATIGRAPHY, OROGENIC EVENTS, AND PLUTONIC ROCKS IN THE SOUTHERN PART OF THE ARABIAN SHIELD

	Units	Principal layered rocks	Orogenic events	Plutonic rocks
Hijaz tectonic cycle: third episode	Murdama Group	conglomerate, graywacke, andesite, rhyolite, marble	Bishah: folds and faults; northerly trends; greenschist metamorphism	granite and quartz monzonite (570–550 Ma)
	unconformity			
Hijaz tectonic cycle: second episode	Halaban Group	conglomerate, graywacke, rhyolite, dacite, andesite, marble	Yafikh: folds and faults; northerly trends; greenschist metamorphism	quartz monzonite (650–600 Ma)
	unconformity?			
	Ablah Group		Ranyah: folds and faults; northerly and northeasterly trends; late transverse shears; greenschist, amphibolite and granulite metamorphism	injection gneiss (785 Ma); second dioritic series (800 Ma)
	unconformity			
Hijaz tectonic cycle: first episode	Jiddah Group, Bahah Group, Baish Group	conglomerate, graywacke, dacite, andesite, basalt	Aqiq: folds and faults; northerly trends; greenschist metamorphism	first dioritic series (960 Ma)

First episode

The first episode started with basalt to basaltic andesite volcanism and associated sedimentation (Baish & Bahah Groups of Schmidt *et al.* 1973), followed or accompanied by andesite and dacite volcanism (Jiddah Group of Schmidt *et al.* 1973), and was terminated by the Aqiq orogeny.

Baish Group

The Baish Group is a thick succession of flow rocks, flow breccia, tuff, intraformational conglomerate and graywacke, with subordinate marble, chert, and thick concordant bodies of quartz porphyry. The flow rocks are microporphyritic and contain relict plagioclase and clinopyroxene phenocrysts. Limited chemical data (Jackaman 1972) indicate that the flow rocks are basalt and basaltic andesite which generally plot in the tholeiitic field defined by Kuno (1968) for aphyric rocks (figure 2*a*). The quartz porphyry (mapped as tuff by Jackaman 1972, and as subvolcanic sills by Greenwood 1975*b*) chemically resembles soda rhyolite. The low Na/Ca ratios of the flow rocks (figure 3) indicate that they are not spilitic. A strong iron differentiation trend is suggested by the AFM diagram (figure 3*a*), and a 'ferric-femic index' of about 90 is estimated for the flow rocks using graphic techniques of Coats (1968). The limited data suggest that the flow rocks have a Peacock 'alkali-lime index' of about 63 and have calcic affinities (Peacock 1931). Marine sedimentary interbeds lack terrigenous detritus, suggesting deposition in a basin isolated from an eroding continental area. From this we infer that the Baish Group was deposited subaqueously as part of a juvenile oceanic island arc, an inference that is supported by chemical resemblance of the flow rocks to the 'island arc tholeiitic series' of Jakeš & Gill (1970).

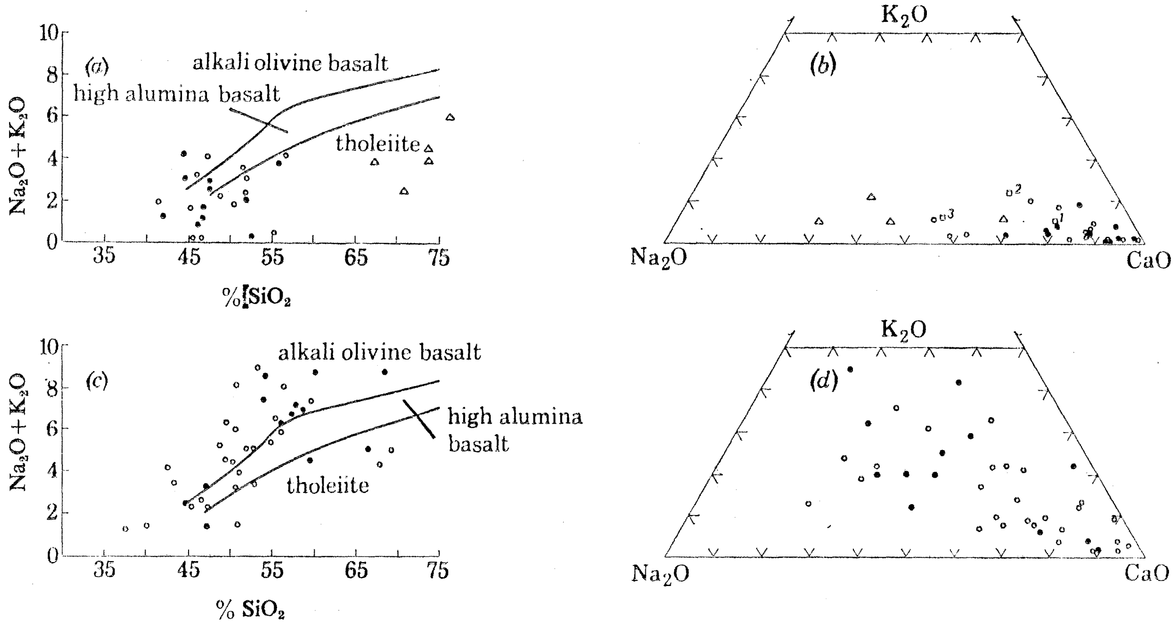

FIGURE 2. Chemical variation diagrams, data from Jackaman (1972): (*a*) total alkali-silica diagram, Baish Group, Wadi Bidah area; (*b*) KCN diagram, Baish Group, Wadi Bidah area; (*c*) Total alkali-silica diagram, Jiddah Group, Wadi Wassat area; (*d*) KCN diagram, Jiddah Group, Wadi Wassat area. ●, Flow rocks; ○, tuff; △, quartz porphyry; □[1] average oceanic tholeiite (Manson 1968); □[2], Troodos, Cyprus (Burke & Dewey 1972); □[3], average spilite (Turner & Verhoogen 1960); —, basalt type field boundaries Kuno (1968).

Bahah Group

Graywacke, conglomerate, chert, and subordinate marble, arkose, and quartzite of the Bahah Group overlie rocks of the Baish Group. Conglomerate clasts include basalt, graphitic chert, graywacke, and quartz and feldspar porphyry probably of hypabyssal origin. Quartz clasts are generally less abundant than plagioclase, and no potassium feldspar clasts have been reported. The Bahah Group appears to have been largely derived by rapid erosion of the Baish Group without significant influx of continental-derived sediments. Sedimentary structures include thin graded bedding, slump structures, minor cut and fill structures, and intraformational sedimentary breccia, all characteristic of turbidite deposits.

Jiddah Group

Rocks of the Jiddah Group include andesite and dacite of pyroclastic and flow origin, associated sedimentary rocks, and minor basalt, and are everywhere mapped in fault contact with rocks of the Baish and Bahah Groups. The Jiddah Group may be younger than the Baish and Bahah Groups (Schmidt *et al.* 1973) or it may be in part a lateral facies variant of them. Volcanic rocks include flow breccia and agglomerate, lava flows, pillow lava, bedded tuff, and welded ash-tuff. Sedimentary rocks include abundant conglomerate containing dacite, basalt, and andesite clasts and finer grained volcanoclastic rocks locally interbedded with chert and marble. Rapid lateral and vertical facies changes are common. The Jiddah Group is the result of extensive intermediate volcanism and concurrent submarine and subaerial erosion and deposition of the associated sedimentary rocks, processes common in island-arc environments (Mitchell & Reading 1971).

Limited chemical data suggest that flow rocks in the Jiddah Group generally plot in the alkali olivine basalt field (figure 2*c*). The AFM diagram (figure 3*b*) suggests a trend intermediate between the trends of the strong iron-fractionated Skaergaard series and the non-iron

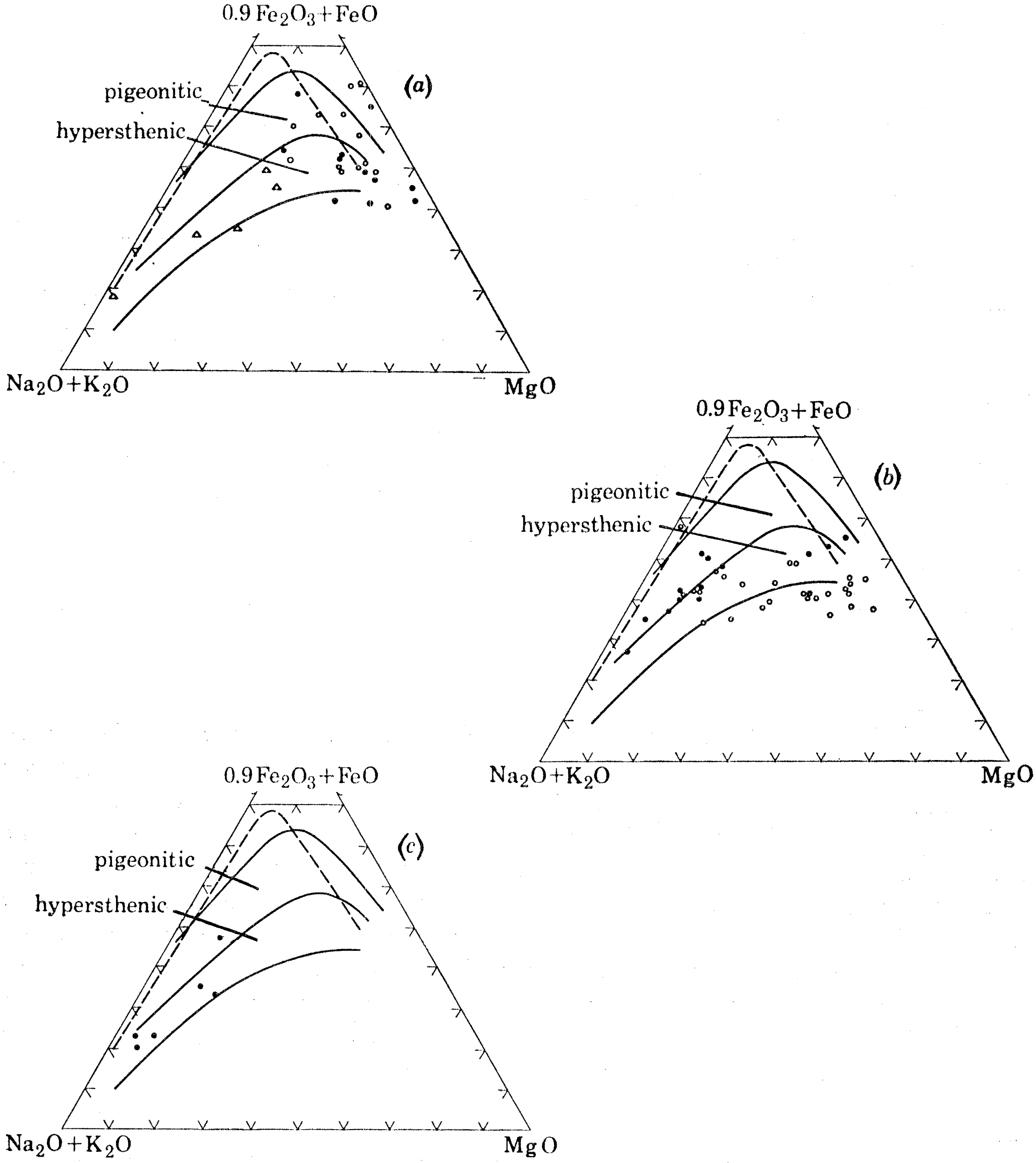

FIGURE 3. AFM diagrams: (*a*) Baish Group, Wadi Bidah area (from Jackaman 1972); (*b*) Jiddah Group, Wadi Wassat area (from Jackaman 1972); (*c*) Halaban Group, central and northern shield (from G. F. Brown, unpublished data). ●, Flow rocks; ○, tuff; △, quartz porphyry; —, rock series boundary (Kuno 1968); ---, Skaergaard trend (Wager & Mitchell 1951).

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fractionated basalt-andesite-dacite series, Cascade province, Oregon and California, shown by Turner & Verhoogen (1960, fig. 43). A 'ferric-femic index' of 76 indicates a 'ferric' differentiation trend (Coats 1968). The variation shown on the KCN diagram (figure 2*d*) is similar to chemical variation in the Cascade province (Turner & Verhoogen 1960, fig. 43). An 'alkali-lime index' of about 55 for the flow rocks falls near the boundary of the alkali-calcic and calc-alkali series of Peacock (1931). The chemical data is compatible with the suggested island arc environment of deposition (Jakeš & Gill 1970).

Aqiq orogeny

The rocks of the Baish, Bahah, and Jiddah Groups were deformed by northerly-trending folds and transcurrent and high-angle reverse faults, metamorphosed to greenschist facies, and intruded by gabbroic to quartz dioritic composite batholiths (first dioritic series) during the Aqiq orogeny, dated at about 960 Ma ago by a Rb-Sr isochron on one of the batholiths (Fleck, Greenwood, Hadley & Prinz 1973). The batholiths generally show evidence of post-tectonic emplacement, and locally consist largely of blocky agmatitic mixtures of layered rocks and early mafic diorite brecciated and intruded by quartz diorite.

The initial $^{87}Sr/^{86}Sr$ ratio of the dioritic rocks is characteristically primitive, about 0.7029 (Fleck *et al.* 1973; Fleck 1975, unpublished data). Limited chemical analysis suggests that these dioritic rocks and a second series of similar rocks described below have calcic affinities (Greenwood & Brown 1973).

Second episode

The second episode started with the unconformable deposition of clastic and volcanic rocks of the Ablah Group on rocks of the Jiddah, Baish, and Bahah Groups and on dioritic rocks. Tectonism, metamorphism, and plutonism involving the Ablah Group during the Ranyah orogeny appears to have been accompanied or overlapped in time by deposition of clastic and volcanic rocks of the Halaban Group. The Halaban Group subsequently underwent tectonism, metamorphism, and plutonism during the Yafikh orogeny.

Ablah Group

The Ablah Group of the southern part of the shield consists of a predominantly clastic basal unit, a middle unit of andesite to rhyodacite, volcanic, and pyroclastic rocks containing minor basalt, and an upper, predominantly clastic unit (Greenwood 1975*a*). The clastic units consist predominantly of conglomerate and coarse graywacke containing clasts of the underlying dioritic and volcanic rocks, as well as sedimentary tuff from contemporaneous volcanism, and locally containing thick clastic to stromatolitic carbonate beds. The group is characterized by rapid lateral and vertical facies variations of the kind that are typical of environments near volcanic sources. Andesite flows are interbedded with andesite-clast conglomerate, suggesting contemporaneous rapid volcanism, subaqueous deposition, and subaerial erosion. These lithologic characteristics are consistent with deposition and volcanism on a partly emergent ridge surmounting an island arc (Mitchell & Reading 1971).

Ranyah orogeny

Rocks of the Ablah and older Groups were folded and offset by transcurrent and high-angle reverse faults of north and northeast trends; the rocks were metamorphosed to greenschist facies and intruded by gabbroic to trondhjemitic batholiths (called the second dioritic series) during the Ranyah orogeny at about 800 Ma (Fleck 1975, unpublished data). Abundant trondhjemite appears to be an exclusive feature of the second dioritic series, but the rocks are otherwise similar to those emplaced during the Aqiq orogeny. The initial $^{87}Sr/^{86}Sr$ ratio of rocks of the second dioritic series is about 0.7028, similar to that of the first series and similarly characteristic of a lower crustal or mantle source. The Ranyah orogeny climaxed with syntectonic intrusion at about 785 Ma (Fleck *et al.* 1973; Fleck 1975, unpublished data) after intrusion of the second dioritic series. Gneissic quartz diorite to quartz monzonite was emplaced in *lit-par-lit* fashion, forming complex phacoidal, domal, and piercement structures, the rocks within and adjacent to which were thermally metamorphosed to amphibolite and granulite facies. The quartz diorite to quartz monzonite gneiss has an initial $^{87}Sr/^{85}Sr$ ratio of 0.7028 in the southwestern part of the southern shield area and 0.7035 to the northeast (Fleck 1975, unpublished data). Vertical tectonic movements and syntectonic intrusions produced nonlinear patterns over broad areas. Related broad, shallow to steeply dipping, transverse shear zones transposed and obscure the early northerly-trending structural grain.

Halaban Group

The Halaban Group of the central and northern parts of the shield consists of a basal, predominantly clastic unit, a middle unit of andesite to dacite volcanic and pyroclastic and associated sedimentary rocks, and an upper unit of rhyolitic to trachytic volcanic, pyroclastic and associated sedimentary rocks. The Halaban Group is estimated to be at least 10000 m thick near Halaban in the central part of the shield (Brown & Jackson 1960). Sedimentary clasts in the Halaban Group include gabbro, diorite, quartz diorite, and volcanic rocks. The group is characterized by rapid lateral and vertical facies variations of the type that are typical of environments near volcanic sources. In places, welded ash flows alternate with water-laid tuff and volcanoclastic rocks. Andesite flows have interbeds of andesite-clast conglomerate, suggesting contemporaneous rapid volcanism, subaqueous deposition, and subaerial erosion such as might exist on a partly emergent ridge of an island arc.

Very limited chemical data (G. F. Brown, unpublished data) suggest that the rocks of the Halaban Group in the central and northern part of the shield resemble rocks of the basalt-andesite-dacite series of the Cascade Mountains in the United States. No iron fractionation is apparent on the AFM diagram (figure 3*c*) and a 'ferric-femic index' of 69 indicates a 'magnesioferric' differentiation trend similar to calc-alkalic rocks of the Cascade Mountains (Coats 1968).

Preliminary unpublished results of Rb-Sr dating suggest that deposition of the lower unit and at least part of the middle unit of the Halaban Group was contemporaneous with deformation, plutonism, and metamorphism of the rocks of the Ablah Group at about 785 Ma ago. The unconformities shown on table 1 appear to have regional but not necessarily shield-wide extent.

Yafikh orogeny

Rocks of the Halaban Group were folded about north-trending axes, offset by transcurrent and high-angle reverse faults of similar trend, metamorphosed to greenschist facies, and intruded by plutons ranging from gabbro to granite during the Yafikh orogeny, from about 650 to 600 Ma (Fleck *et al.* 1975; Fleck 1975, unpublished data). Many of the granodiorite to granite plutons and ring structures of the southern part of the shield appear to have been intruded during the Yafikh orogeny. The granodiorite to granite plutons generally show calc-alkaline chemical trends (Greenwood & Brown 1973); however, a subordinate number of unanalysed plutons show alkalic modal trends and mineralogy (some analysed plutons may be younger than the Yafikh orogeny). The $^{87}Sr/^{86}Sr$ initial ratios are about 0.7035 for the granodiorite to granite plutons (Fleck 1975, unpublished data), and suggest a more evolved source than that of the dioritic rocks.

Third episode

The third episode started with the unconformable deposition of predominantly clastic rocks of the Murdama Group on quartz monzonite, dioritic rocks, and metamorphosed Halaban Group and older layered rocks. The Bishah orogeny terminated this episode.

Murdama Group

The Murdama Group in the Jabal Yafikh quadrangle (Schmidt *et al.* 1973) includes a thick basal unit of conglomerate and conglomeratic graywacke that is overlain by a thin unit of andesitic pyroclastic and clastic rocks, a clastic carbonate unit, and a thick upper unit of graywacke, including siltstone and mudstone. A thin rhyolite in the upper part of the upper graywacke unit as exposed has been dated at about 566 Ma by Rb-Sr methods (Fleck 1975, unpublished data). In the Bishah area, basal Murdama rests unconformably on red granite, older plutonic rocks, and rocks of the Halaban Group (Schmidt *et al.* 1973; Schmidt 1974, unpublished data). Provenance and mode of deposition of the Murdama rocks were similar to those of sedimentary rocks deposited in the earlier two episodes.

Bishah orogeny

The rocks of the Murdama Group and older layered rocks were folded about north-trending axes, metamorphosed to greenschist facies, and intruded by granitic plutons at about 550 Ma (Fleck *et al.* 1975) during the Bishah orogeny of Schmidt *et al.* (1973). Metamorphic mineral boundaries produced during earlier orogenies were offset locally by transcurrent faults. Cratonization of the shield was complete by the end of the Bishah orogeny.

Najd faulting

The southernmost fault zone of the northwest-trending Najd fault system (Brown & Jackson 1960; Delfour 1970) cuts across the southern part of the shield and truncates older north-trending structures produced during the Hijaz tectonic cycle. Najd faulting at about 540–510 Ma (Fleck *et al.* 1975) occurred on a trend distinctly different from that of the structures produced in the orogenies described above. For this reason, and because of the lack of regionally significant volcanic and sedimentary deposits associated with the formation of the Najd fault system the onset of faulting is taken to mark the end of the Hijaz tectonic cycle.

Underlying crust

The nature of the crust upon which rocks of the first episode were deposited has not been determined. Rocks initially proposed as older craton (Hali Group and Khamis Mushayt Gneiss: Schmidt *et al.* 1973; Greenwood *et al.* 1973) have been shown in their type and adjacent areas to be highly metamorphosed equivalents of the layered rocks described above and plutonic rocks which intruded them (Hadley 1975; Greenwood 1975*a*, *b*, *c*, *d*; Greenwood & Anderson 1974, unpublished data).

The rather primitive strontium isotope ratios of the two dioritic series and of the early volcanic rocks and the lack of potassium feldspar or other demonstrably continental-derived detritus in volcanic and sedimentary rocks deposited during the first episode suggest deposition on oceanic crust isolated from eroding continental areas.

Table 2. Comparison of some major element geochemistry of calc-alkaline rocks, island-arc tholeiite, abyssal tholeiite, and continental tholeiite with Arabian Shield metavolcanic rocks

	calc-alkaline series†	island-arc tholeiitic series†	abyssal tholeiitic series†	continental tholeiites†
SiO_2 range (%)	53–70	45–70	47–62	51.5
SiO_2 mode (%)	59	53	49	—
TiO_2 (%)	0.5–1.2	0.5–1.5	1.0–2.5	1.2
Al_2O_3 (%)	16–19	14–19	14–19	16.3
Na_2O/K_2O	2–3	4–6	10–15	2.9

Arabian Shield volcanic rocks

	Baish Group‡		Jiddah Group§		Halaban Group‖	
	range	mode	range	mode	range	mode
SiO_2 (%)	42–56	47	44–68	58	58–75	68
TiO_2 (%)	0.6–0.7	0.6	0.4–1.3	0.9	0.3–1.4	0.5
Al_2O_3 (%)	9–18	15	14–19	17	12–18	14
Na_2O/K_2O	1–23	5	0.2–4.4	1.7	0.2–5.6	1.6
ferric-femic index	90		76		69	

† From Anhaeusser (1973, table 4).
‡ 11 flow rocks from Jackaman (1972).
§ 13 flow rocks from Jackaman (1972).
‖ 6 flow rocks, F. G. Brown, unpublished data.

Cratonization

Cratonal development of the southern part of the Arabian Shield evolved through extensive volcanism and cannibalistic sedimentation accompanied and interrupted by the intrusion of large volumes of plutonic rocks (57 % of exposed rocks on figure 1) and associated tectonism and metamorphism. The volcanism was predominantly of intermediate composition; however, a shift from early tholeiitic to later calc-alkalic rocks and an increase in potassium content is observed from the oldest to youngest deposits (table 2). The plutonic rocks show a parallel shift from early calcic to later calc-alkalic rocks and an increase in potassium content that perhaps parallels a progressive increase in thickness of the neocraton.

Petrographically, the rocks of the shield are similar to rocks deposited in intraoceanic island arcs formed near convergent boundaries of two oceanic plates (Mitchell & Reading 1971). Limited chemical data also show similarity to island-arc deposits, as proposed by Jackaman (1972) especially in the evolutionary trend from early tholeiitic, iron-fractionated volcanic rocks to the later calc-alkaline volcanic rocks (Gill 1970; Jakeš & Gill 1970). The lack of identified older continental crust distinguishes the Arabian deposits from deposits of 'Andeantype' volcanic arcs at continental-oceanic plate boundaries (Mitchell & Reading 1971; Cobbing & Pitcher 1972).

Limited information suggests a northwest trend for the proposed island arc. The trend is suggested by contoured $K_2O/(Na_2O+K_2O)$ ratios for granodiorite to granite in the southern part of the shield (Greenwood & Brown 1973). The northwest trend is also suggested by outcrop patterns in which the oldest (tholeiitic) volcanic rocks are exposed in the southwest and the youngest (calc-alkalic) rocks in the northeast (USGS-ARAMCO 1963) and by an increase in the proportion of granitic to dioritic rocks toward the northeast (Greenwood & Brown 1973; USGS-ARAMCO 1963). The outcrop of older layered rocks to the southwest and progressively younger layered rocks to the northeast may be the result of a northeasterly shift of the axis of the arc during the Hijaz tectonic cycle, an inference that is consistent with the relative abundance of young granitic rocks to the northeast. The increase in potassium content in the granitic rocks (Greenwood & Brown 1973) and the general increase in potassium feldspar in the younger volcanic rocks to the northeast suggest a northeast-dipping Benioff zone under the volcanic arc (Dickinson 1970). The data suggest that oceanic crust existed between the Benioff zone and the continent of Gondwanaland to the southwest and was consumed by subduction during the Hijaz cycle. The apparently episodic character of orogeny in the Arabian Shield suggests that subduction of the oceanic plate also was episodic. Such episodic activity is common in subduction zones associated with modern island arcs, some of which contain arc deposits as old as late Palaeozoic (e.g. Japan: Miyashiro 1961; and Sumatra: Van Bemmelen 1949; Mitchell & Reading 1971). Complete consumption of the oceanic plate and collision of the neocratonic arc and the continent of Gondwanaland may have terminated the Hijaz tectonic cycle and initiated faulting, volcanism, and plutonism in the Najd fault system.

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