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U-Pb zircon geochronology and geological evolution of the Halaban-Al Amar region of the Eastern Arabian Shield, Kingdom of Saudi Arabia

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SUMMARY: U-Pb zircon model ages for eleven major units from the Halaban-Al Amar region of the eastern Arabian Shield indicate three stages of evolution: (1) plate convergence, (2) plate collision, and (3) post-orogenic intracratonic activity.

Convergence occurred between the western Afif and eastern Ar Rayn plates that were separated by oceanic crust. Remnants of oceanic crust now comprise the ophiolitic complexes of the Urd group. The oldest plutonic unit in the study is from one of these complexes and gave an age of 694 ± 8 Ma. Detrital zircons from the sedimentary Abt formation of the Urd group, which is intercalated with the ophiolitic rocks, were derived from source rocks with a mean age of 710 Ma. The Abt formation may be an accretionary wedge on the western margin of the Ar Rayn plate. Plate convergence was terminated by collision of the Afif and Ar Rayn plates during the Al Amar orogeny which began about 670 Ma. During collision, the Urd group rocks were deformed and in part obducted on to one or both plates. Synorogenic leucogranitoid rocks were intruded from 670 to 640 Ma. From about 640 to 630 Ma, widespread unfoliated dioritic plutons were emplaced in the Ar Rayn block, and represent the end of orogenesis related to collision. There is no definitive evidence for a significantly older basement beneath the study region.

The Saudi Arabian Shield is a region for which considerable evidence has accumulated for the operation of late Proterozoic plate tectonics. Western and southern portions of the shield were formed in ensimatic island arc type environments during the period 1000–680 Ma ago (Greenwood *et al.* 1976; Fleck *et al.* 1980; Bokhari & Kramers, 1982; Roobol *et al.* 1983; Stoeser *et al.* 1984). In contrast, an older Proterozoic or Archaean crystalline basement has been reported to underlie parts of the eastern shield (Baubron *et al.* 1976; Delfour, 1979a,b, 1980; Nawab, 1979; Schmidt *et al.* 1979). In these studies, the ages of the basement units were mainly inferred on geological grounds and the few available radiometric age determinations were inconclusive (Baubron *et al.* 1976; Kröner *et al.* 1979).

More recently, Calvez *et al.* (1983) report ~2000 Ma zircons in a trondhjemite associated with the Al Amar fault in the eastern shield (Figs 1 and 2). Further S in the Jabal Khida region (Fig. 1) Stacey & Hedge (1984) report U-Pb zircon, Sm-Nd, Rb-Sr, and common Pb data from a granodiorite, that all indicate an Early Proterozoic (1600–1800 Ma) crustal history for this rock or its protolith. However, in neither of these two areas has the extent of the older rocks been determined.

The present geochronology study is located in the Halaban-Al Amar region of the eastern shield (Fig. 1). It was conducted to determine the ages of the main plutonic rock units, and to place limits on hypotheses to explain evolution of that part of the Saudi Arabian Shield.

Geological setting

On the basis of different lithologies, Delfour (1980) recognized three geological provinces within the eastern Arabian Shield, all of which occur in the Halaban-Al Amar region (Fig. 1). These are: (1) the Afif province in the W, (2) the Ad Dawadimi province in the centre, and (3) the Ar Rayn province in the E. Within the study area, the three provinces are bounded by fault zones. In particular, the boundary between the Ad Dawadimi and Ar Rayn provinces is the Al Amar fault zone which is one of the most prominent features of the region (Moore, 1976; Fig. 2). This zone has been interpreted to be an arc-arc or arc-continent suture (Brown & Coleman, 1972; Al-Shanti & Mitchell, 1976; Nawab, 1979; Schmidt *et al.* 1979).

The Afif province is covered by a thick accumulation of shallow marine to continental type sediments, the Murdama group of Delfour (1979a). Underlying rocks are exposed only locally, and comprise (1) marine type sediments of the Ajal group (2) a few dacitic to andesitic volcanics that may be an early phase of the Murdama, and (3) a large complex of foliated to gneissic dioritic plutonic rocks, the As Sawda domain (Fig. 2) that Delfour (1979a) assigned to an older basement unit. Rocks younger than the

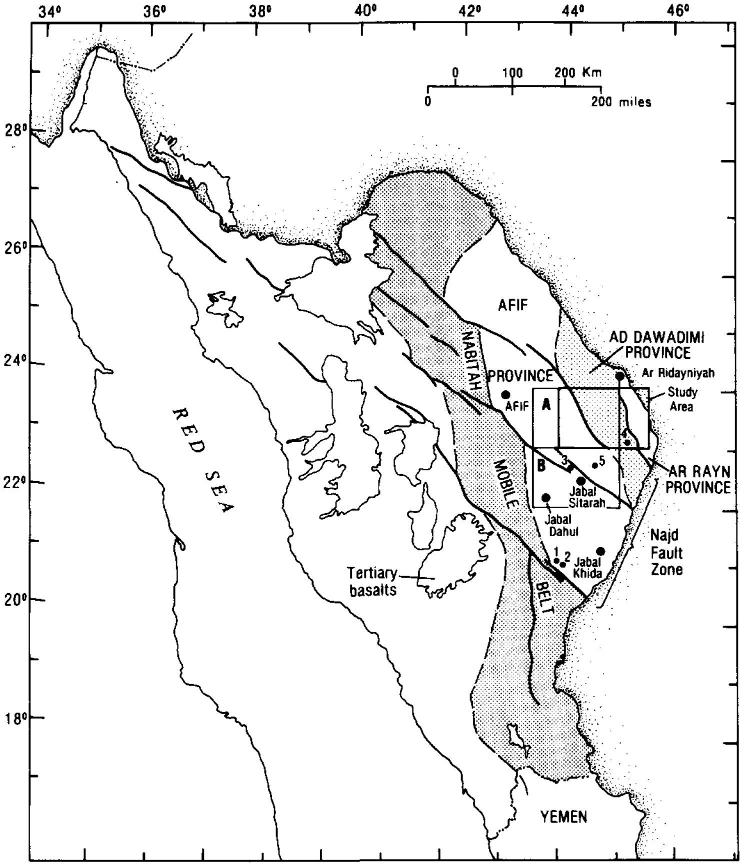

FIG. 1. Index map of the Arabian Shield showing the study area, geological provinces, localities referred to in the text, and the Halaban (A) and Ar Rika (B) 1:250,000 scale quadrangles. Volcanic rocks dated by Darbyshire *et al.* (1983): (1) Arfan 608 ± 9 Ma, (2) Juqjuq 612 ± 22 Ma, (3) Jahhad 616 ± 13 Ma, (4) Hummah 572 ± 23 Ma. Fleck & Hadley (1983) dated the Uyaijah monzogranite (5) at 595 ± 15 Ma.

Murdama include the sedimentary Jibalah group and granites which intrudes the Murdama sediments.

Two main units occur within the Ad Dawadimi province: mafic-ultramafic ophiolitic complexes and clastic sediments of the Abt formation. Together, these constitute the Urd group that forms a broad synclinorium, with the ophiolitic complexes at the base, and the Abt formation at the core. (Delfour, 1979a). Where in contact, the two units are mainly fault bounded.

The ophiolitic complexes are present in several major belts within the study area (Fig. 2). In a recent examination of the ophiolitic zones along the eastern portion of the Abt formation (Fig. 2), Al-Shanti & Gass (1983) conclude that the zones comprise a mélange of dyked gabbro, dolerite, plagiogranite and basic volcanic blocks in a serpentinite matrix. On the basis of the Ti, Zr, Y and Nb chemistry of the blocks, the authors concluded that these rocks formed either in the vicinity of an oceanic transform fault zone and were then deposited in a trench, or that they were the product of fore-arc igneous activity.

The Abt formation, or Abt schist, is a tightly folded and monotonous series of sericite and/or chlorite schists occupying a belt approximately 40 km wide between the Urd mafic belt at Halaban and the Al Amar fault (Delfour, 1979a, 1981). The schists grade to fine-grained graywacke, conglomerate, arkosic sandstone and dolomitic marble (Delfour, 1979a) that are generally metamorphosed to the upper greenschist facies.

In the Ar Rayn province Calvez *et al.* (1983) subdivide the layered rocks of the area into an older Al Amar group and a younger Ahrmer group. The layered rocks, however, are subordinate in area to, and intercalated with, a widespread and complex

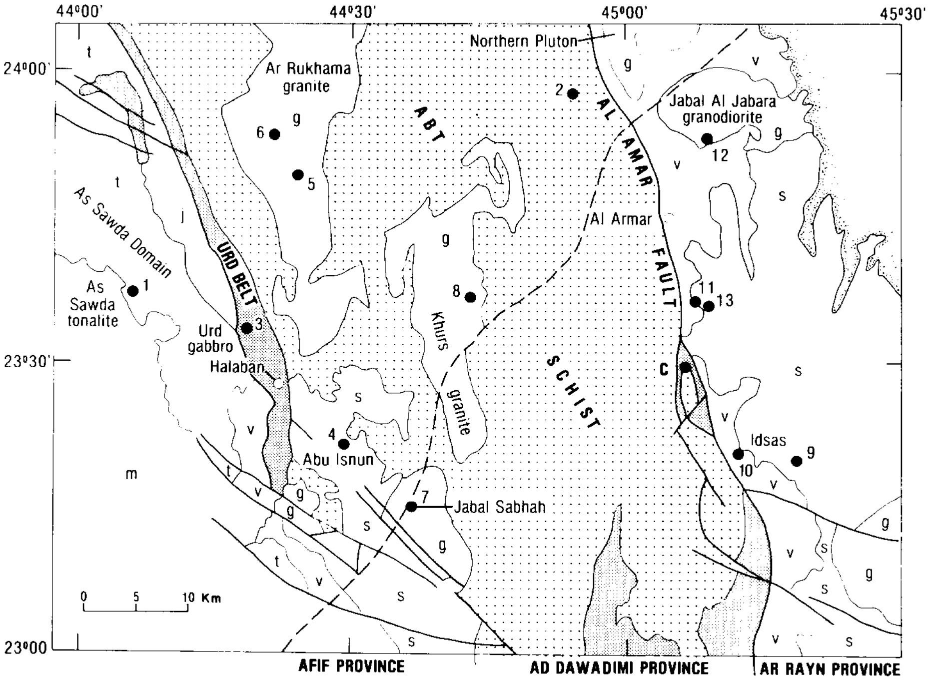

FIG. 2. Simplified geological map of a part of the Halaban-Al Amar region showing sample localities (locality numbers from Table 1). C indicates trondhjemite with 2000 Ma zircons of Calvez *et al.* (1983). The deep seismic line of Healy *et al.* (1982) is shown by the dashed line.

Unit symbols: v, metavolcanic and metasedimentary rocks with hypabyssal diorite; t, tonalite; ▨, Urd group ophiolitic rocks; ▨, Abt schist; a, syntectonic plutonic rocks; m, Murdama group clastic sedimentary rocks; g, post-tectonic granitic plutonic rocks; j, Jibalah group clastic sedimentary rocks; ▨, Phanerozoic sedimentary cover rocks; heavy line, fault.

series of syntectonic gneisses that are tonalitic to granodioritic in composition.

All of the units discussed above, except the Jibalah, are intruded by granitic plutons (Delfour, 1979a). These plutons include hornblende-biotite and biotite monzogranite and granodiorite, as well as two-mica leucogranite. Baubron *et al.* (1976) and Delfour (1979a) report Rb-Sr ages of 640–518 Ma for granites of the Halaban-Al Amar region.

Analytical methods

Chemistry and mass spectrometry of lead and uranium from zircons follow the procedures of Krogh (1973) with minor modifications. Laboratory blank levels for lead were monitored within the range from 0.3 to 2.0 n. Corrections for common lead inherent in the zircons were made by using the composition of lead from feldspar in the same samples, reported by Stacey & Stoeser (1983).

Analytical precisions at the 95% level of confidence are ±1.2% for the concentrations of lead and uranium, and ±0.1% for $^{207}Pb/^{206}Pb$. Uncertainties quoted for the intercepts between regression lines and concordia are 95% confidence limits. They are computed using the method of Ludwig (1982). In all cases where we have computed regression lines for small numbers of data points, four or less, scatter was assumed to be entirely due to analytic error. Correlation coefficients for $^{206}Pb/^{238}U$ and $^{207}Pb/^{230}U$ were determined mainly by the common lead content of the zircons and range from 0.98 to 0.85. Decay constants used for age calculations are those of Jaffey *et al.* (1971).

Results

Samples were selected from major plutonic bodies in the Halaban-Al Amar region, locations are shown in the map of Fig. 2, and the zircon analytical data are listed in Table 1. Concordia plots are in Figs 3 and 4, and a summary of model ages is shown in Table 2. Whole rock Rb-Sr data are listed in Table 3.

The zircon data form two different groups, those from the least evolved rocks that have comparatively low uranium contents (60–600 ppm) and those from the monzogranites of the Ad Dawadimi province that have high uranium contents (1100–5300 ppm). From

TABLE 1: *U-Pb analytical data for zircons from the Halaban-Al Amar region of the eastern Saudi Arabian Shield Zircon fraction: M magnetic, NM, non-magnetic.*

Locality and sample number	*Fraction mesh size*	*Concentrations ppm* U	*Concentrations ppm* Pb*	*Atomic Ratios* $^{206}Pb/^{238}U$	*Atomic Ratios* $^{207}Pb/^{235}U$	*Age Estimate Ma* $^{207}Pb/^{206}Pb$	*Blank corrected* $^{206}Pb/^{204}Pb$
Afif province							
1. 128935	+100 NM	134	14.9	0.10203	0.8709	671	3553
	−325	176	19.5	0.10116	0.8670	680	6868
Ad Dawadimi province							
2. 128955	All sizes	317	22.2	0.06455	0.5578	697	1523
3. 128924	+150	63.2	7.83	0.11192	0.9641	690	4600
	−150	59.6	7.24	0.10847	0.9370	696	2495
4. 128942	+250	2371	170	0.06397	0.5431	659	410
	−200 + 250 NM	1791	132	0.07064	0.6093	693	749
	−250 + 400	2236	173	0.07052	0.6255	753	485
5. 128937	+150 NM	1125	86.5	0.07271	0.6015	604	664
	−150 + 250 M	2312	149	0.05815	0.4737	570	500
	−325	2188	164	0.06620	0.5430	585	489
6. 175607	+200	3962	254	0.05969	0.4821	552	497
	−200	3489	232	0.05892	0.4786	564	357
7. 128941	+100 M	4172	408	0.05525	0.4441	541	110
	−100 + 150 NM	2698	321	0.08754	0.7214	596	255
	+250 M	5267	458	0.06321	0.5101	550	231
	−250 M	4986	402	0.05558	0.4437	526	186
8. 128959	+200 NM	4495	388	0.08409	0.6892	583	1110
	−200 M	3951	335	0.08043	0.6579	579	799
Ar Rayn province							
9. 128921	All sizes NM	304	29.8	0.09564	0.8080	649	1370
10. 128919	+200 NM	177	18.4	0.09812	0.8228	633	7080
	400 NM	164	15.8	0.08881	0.7450	633	5410
11. 128944	+100 NM	491	48.4	0.09557	0.8009	631	6143
	−325 NM	653	65.4	0.09557	0.8020	634	2351
12. 128946	+200 NM	276	26.5	0.08796	0.7368	630	1058
	−325 + 400 NM	272	24.8	0.08718	0.7289	626	3989
13. 175612	+150 NM	322	32.3	0.09752	0.8155	627	2520
	−200 + 325	358	32.2	0.08419	0.7025	622	1182
	−325 M	583	47.4	0.07189	0.6030	633	556

* Radiogenic Pb.

almost all the samples zircon yields were quite small, and in most cases this limited the number of sized fractions that could be prepared.

Data from the low uranium zircons were almost concordant but for most samples the data points were not sufficiently separated for meaningful chords to be drawn. However, the zircons from the dioritic rocks of the Ar Rayn province have very similar $^{207}Pb/^{206}Pb$ ages of ~630 Ma (Table 1, localities 10–13). A single regression line for all nine data points from the four samples has upper and lower intercepts of 631 ± 6 Ma and 2 ± 39 Ma, respectively. We conclude that zircons in all these rocks crystallized at about the same time and all lost lead in a comparatively recent event. Work by Cooper *et al.* (1979) further substantiated by Stoeser *et al.* (1984) shows that zircons from different rock types over a large portion of the southern Arabian Shield all lost lead at the same time. This time was computed for 20 zircon fractions as 15 ± 20 Ma. The loss of lead was attributed to hydrothermal activity during regional uplift prior to opening of the Red Sea. For consistency, we too use a common lower intercept of 15 ± 20 Ma for regression lines of the low uranium samples, localities 1–3 and 9–13. Table 2 shows these as model II ages.

Zircons from the monzogranites (localities 4–8) have considerably higher uranium contents (1100–5300 ppm), their data are generally more discordant and they have higher common lead contents than those from the less evolved rocks (Table 1, Fig. 4). In three cases there is sufficient spread in the data points to establish a line on the concordia diagram and the intercepts are listed as model ages in Table 2. Note that in all three instances elevated lower intercepts of about 110 Ma are obtained. To check the validity of the elevated lower intercept for the pluton from the

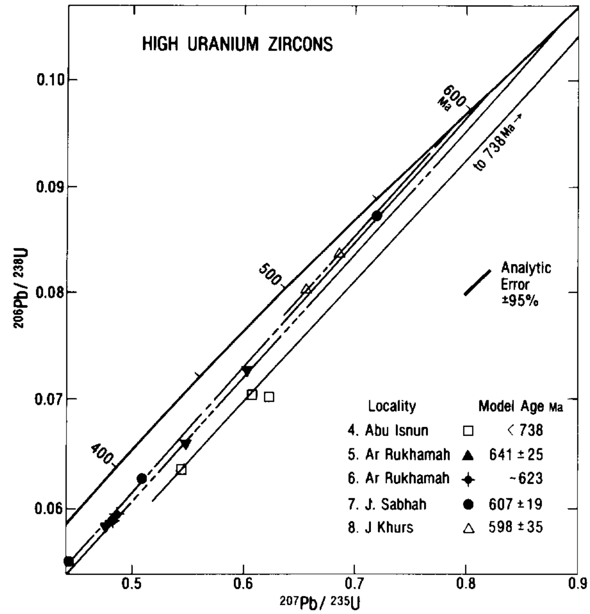

FIG. 3. Concordia plot for the low uranium content zircons in this study. Regression lines are shown for model II that utilizes a common lower intercept of 15 ± 20 Ma, shown to be appropriate for a large region of the southern shield (Cooper *et al.* 1979; Stoeser & Stacey 1983).

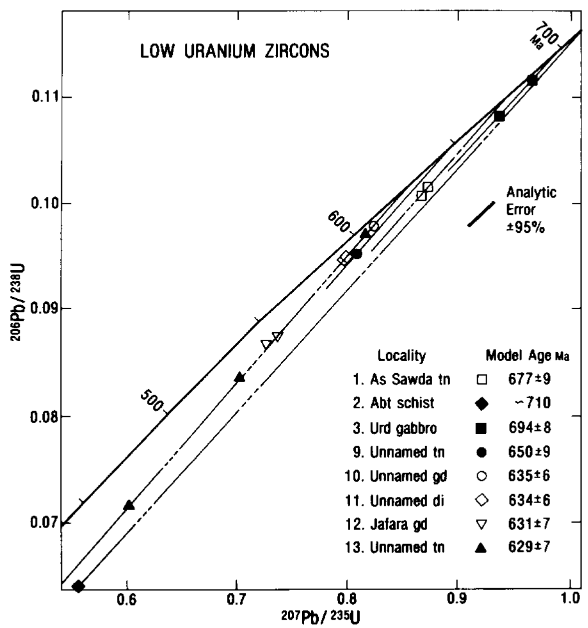

FIG. 4. Concordia plot for high uranium content zircons from granites that intrude the Abt formation. Regression lines through data have lower intercepts of ~110 Ma, Models I and III.

Ar Rukhamah domain, an additional sample was taken (locality 6, 5 km from locality 5). Sufficient zircon was separated for just two sized fractions that unfortunately yielded almost coincident data points (Table 1, Fig. 4). However, these data do apparently confirm an elevated lower intercept as obtained from locality 5. Additional evidence for elevated lower intercepts comes from 100 to 200 km farther S in the shield. Data for granites at Jabal Sitarah and Jabal Dahul (Fig. 1) yield lower intercept ages of approximately 140 and 170 Ma, respectively, (J. S. Stacey and J. D. Aleinikoff, unpublished data). Apparently by Mesozoic time, the high uranium zircons from monzogranites were sufficiently metamict (damaged by radiation) to be particularly susceptible to lead loss. To the E of the study area, episodes of Mesozoic uplift and erosion are indicated by thick sections of upper Triassic and middle Cretaceous sandstone (Powers *et al.* 1963) and the middle to upper Cretaceous Az Zibirah bauxite (Bowden 1981). Moreover, uplift was doubtless accompanied by some thermal activity, both of which mechanisms have been invoked for causing lead loss in metamict zircons (Goldrich & Mudrey 1972; Gebauer & Grünenfelder, 1976). In this study, for the two monzogranite samples where the data did not permit computation of regression lines, approximate upper intercept ages were computed using lower intercepts of ~110 Ma (model III, Table 2).

If significant lead loss occurred in the high uranium zircons during Cretaceous time, it is probable that they were impervious to further loss in Tertiary time. However, the complex thermal history of the region may well account for some of the discrepancies between zircon and Rb-Sr ages in the monzogranites. Nontheless, the zircon model ages should be reliable within the uncertainties quoted, provided that inheritance of older zircon from the sedimentary source rocks has not affected our data.

Samples with zircons of low uranium content

The only rock from the Afif province that we have analysed is a somewhat altered, biotite-hornblende tonalite from the As Sawda domain (Fig. 2, locality 1). Two zircon fractions gave almost identical data points (Fig. 3) and a model II age of 677 ± 9 Ma (Table 2). Therefore, the As Sawda dioritic rocks are a plutonic complex that was emplaced approximately 680 Ma ago. The initial $^{87}Sr/^{86}Sr$ value of 0.7030 (Table 3) does not indicate derivation from sialic basement of significantly older age.

Sufficient zircon for only a single fraction was obtained from approximately 3 kg of the Abt schist in the Ad Dawadimi province, locality 2. These detrital zircons (Table 1) yield a rather discordant data point with a model II age of ~710 Ma (Table 2, Fig. 3).

TABLE 2: *Descriptions and U-Pb model ages for 13 samples discussed. Model I uses intercept ages for regression lines for data; Model II estimates upper intercept ages using a common lower intercept of 15 ± 20 Ma; Model III estimates approximate upper intercept age for a lower intercept of 110 Ma. Uncertainties quoted are model dependent, computed for 95% confidence levels*

Locality number Sample number (N lst, E long)	*Sample description*	*Regression line through data Model I*		*Preferred Model age (Ma)*
		Lower intercept (Ma)	*Upper intercept (Ma)*	
Afif province				
1. 128935 23°36.5′, 44°05.8′	Biotite-hornblende tonalite-As Sawda domain. Plagioclase saussuritized, hornblende and biotite replaced by chlorite.	2/	—	677 ± 9 (II)
Ad Dawadimi province				
2. 128955 23°52′, 44°54′	Abt Schist-Urd group Detrital zircons, low U content.	1/	—	710 (II)
3. 128924 23°32.0′, 44°19.2	Hypersthene gabbro-Urd group ophiolite complex. Foliated rock containing 2 percent quartz, 1% biotite.	2/	—	694 ± 8 (II)
4. 128942 23°21.5′, 44°29.1′	Biotite leuconomzogranite from the Abu Isnun pluton. Weak gneissic, partially recrystallized cataclastic texture.	3/	—	738 (III)
5. 128937 23°48.9′, 44°24.0′	Two-mica monzogranite-Ar Rukhamah domain 6% primary muscovite and biotite. Two generations of plagioclase. Probably partial melting product of Abt sediments.	109 ± 37	641 ± 25	641 ± 25 (I)
6. 175607 23°52.6′, 44°21.3′	Two-mica monzogranite-Ar Rukhamah domain Probably partial melting product of Abt sediments.	2/	—	623 (III)
7. 128941 23°15.3′, 44°36.0′	Two-mica monzogranite from Jabal Sabbah Probably partial melting product of Abt sediments.	115 ± 42	607 ± 19	607 ± 19 (I)
8. 128959 23°35.9′, 44°42.9′	Biotite monzogranite from Jabal Khura Probably partial melting product of Abt sediments.	110 ± 160	598 ± 35	598 ± 35 (I)
Ar Rayn province				
9. 128921 23°17.5′, 45°18.3′	Biotite leucotonalite gneiss (syntectonic) 5% biotite, 1% muscovite, no K-feldspar.	1/	—	650 ± 9 (II)
10. 128919 23°21.3′, 45°11.0′	Biotite-hornblende quartz diorite 7% quartz, 3% biotite, 30% hornblende. Biotite and hornblende extensively replaced by chlorite. Intrudes Al Amar volcanics.	−2 ± 48	633 ± 5	635 ± 6 (II)
11. 128944 23°36.0′, 45°06.8′	Hornblende diorite 2% quartz, no biotite, 30% hornblende. Biotite and hornblende extensively replaced by chlorite. Intrudes Al Amar volcanics.	2/	—	634 ± 6 (II)
12. 128946 23°53.5, 45°07.2′	Biotite leucogranodiorite from Jabal al Jabara weakly foliated syntectonic body intruding Al Amar volcanics.	2/	—	631 ± 7 (II)
13. 175612 23°35.1′, 47°07.1′	Hornblende tonalite 10% hornblende, no biotite. Quartz recrystallized. Intrudes Al Amar volcanics.	−24 ± 23	623 ± 5	629 ± 7 (II)

1/, Only 1 fraction analysed; 2/, virtually coincident data points; 3/, data too scattered to fit meaningful line.

TABLE 3: *Rubidium-strontium data for some of the samples of this study, by kind permission of C. E. Hedge. Data are normalized to $^{86}Sr/^{88}Sr = 0.1194$. Analytical precision for $^{87}Sr/^{86}Sr$ is ± 0.00006 (2σ) between runs*

Locality and sample number	*Preferred model age* Ma (zircon)	*Concentrations ppm* *Rb*	*Sr*	$^{87}Rb/^{86}Sr$	*Atomic Ratios* $^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)i$	*Sample description*
Afif province							
1. 128935	677 ± 9	16.3	1432	0.0329	0.70335	0.70303	Tonalite gneiss–As Sawda domain
Ad Dawadimi province							
2. 128955	710	42.8	292	0.424	0.70746	0.70330	Abt Schist–Urd group
3. 128924	694 ± 8	4.0	915	0.0125	0.70312	0.70300	Hypersthene gabbro–Urd group
Ar Rayn province							
9. 128921	650 ± 9	7.0	564	0.0359	0.70362	0.70329	Tonalite gneiss
10. 128919	635 ± 6	8.8	321	0.0792	0.70393	0.70322	Quartz diorite
11. 128944	634 ± 6	13.8	273	0.1461	0.70453	0.70321	Diorite
12. 128946	631 ± 7	20.4	490	0.1203	0.70433	0.70325	Granodiorite from Jabal Jabara

Analyst K. Futa.

Because of the low uranium content of the zircons (317 ppm) and the whole rock initial $^{87}Sr/^{86}Sr$ value of 0.7033 (Table 3) the most reasonable interpretation of this single analysis is that the zircons were derived from comparatively unevolved rocks with a mean age of 710 Ma.

The oldest rock in this study is apparently from the ophiolitic complex of the Urd group that was sampled NW of the village of Halaban in the Ad Dawadimi province (Fig. 2, locality 3). The rock is a hypersthene gabbro, whose foliation may be of cumulate or tectonic origin. Two fractions are almost concordant and give a model II age of 694 ± 8 Ma, (Table 2, Fig. 3). We interpret this to be the crystallization age for the gabbro and thus for the age of the associated ophiolitic complex. The initial $^{87}Sr/^{86}Sr$ is 0.7030 (Table 3). The time of 694 ± 8 Ma also sets a maximum age for the overlying Abt formation at this locality.

In the Ar Rayn province, the sample from locality 9 is a biotite leucotonalite from a large gneissic massif E of the Al Amar fault. Such gneisses are the dominant rock type E of the fault, and they have been considered to be a remobilized older basement (Kahr *et al.* 1972; Overstreet *et al.* 1972; Coulomb *et al.* 1981; Abdel Monem *et al.* 1982) or younger syntectonic intrusions (Eijkelboom *et al.* 1969, 1971; Nebert, 1970; Al Shanti & Mitchell, 1976). At locality 9, it can be clearly seen that the tonalite was thrust westward over the Al Amar group and the intrusion is interpreted as syntectonic in origin. Sufficient zircon was obtained for only a single analysis, but it gives a model II age of 650 ± 9 Ma (Table 2, Fig. 3). The initial $^{87}Sr/^{86}Sr$ is 0.70329 (Table 3).

The group of dioritic plutons represented by samples from localities 10–13 are only weakly foliated and all intrude the Al Amar volcanic host rocks. As previously discussed, the zircon data are nearly concordant and give similar model II ages between 635 ± 6 and 629 ± 7 as shown in Tables 1 and 2, and Figs 2 and 3. Initial $^{87}Sr/^{86}Sr$ values are in the range 0.70329–0.70321 (Table 3).

Samples with zircons of high U content

Three zircon fractions from the Rukhama granite (locality 5) yield a regression line for which upper and lower intercept ages are 641 ± 25 and 109 ± 37 Ma, respectively (model I, Table 2; Fig. 4). A second sample was collected at locality 6, 5 km to the NW. Sufficient zircon was obtained for only two fractions whose data yield coincident data points. These indicate a slightly younger model III age of ~623 Ma.

South of the village of Halaban we sampled the Jabal Sabhah pluton, a two-mica leucogranite. Figure 4 shows good separation of the four data points, and the chord yields upper and lower intercept ages of 607 ± 19 and 115 ± 42 ma, respectively (model I, Table 2). Although these zircons have the highest common lead content of any in the study, the computed age is not particularly sensitive to the correcting ratios. This is apparently because the most concordant data point is from the fraction with lowest common lead content. The zircon age is, however, appreciably older than the Rb-Sr age obtained by Delfour (1979a) of 556 ± 23 Ma, although the initial $^{87}Sr/^{86}S$ value of 0.7032 is consistent with derivation from the Abt formation.

A biotite monzogranite from the Khurs laccolith of Delfour (1979a) was sampled at locality 8. Data from two zircon fractions have some separation in Fig. 4

and yield a regression line with upper and lower intercepts of 598 ± 35 Ma and 110 ± 35 Ma, respectively. This is considerably older than the Rb-Sr age of 518 ± 12 Ma, initial $^{87}Sr/^{86}Sr$ of 0.7033 ± 0.0008, obtained by Delfour (1979a).

Three zircon fractions from the Abu Isnun monzogranite (locality 4) have comparatively discordant data points (Fig. 4). Consequently, inheritance of older zircon is considered likely. The fraction with the lowest $^{207}Pb/^{206}Pb$ age, has a model III upper intercept age of ~738 Ma. We consider that this monzogranite is primarily a product of partial melting of the Abt formation and that it inherited zircons from that source. It does not appear to be an older basement plutonic unit as proposed by Delfour (1979a), but is probably a post-tectonic intrusive rock, similar in age to the others that intrude the Urd group.

Discussion

Objectives of this study were: (1) to establish the age of the major rock units in the Halaban-Al Amar area, some of which have been identified as older basement, and (2) to examine the overall geological evolution of the region.

Older basement

U-Pb zircon ages have been obtained for four plutonic rock units previously identified as older basement. These are the As Sawda tonalite from the Afif province (locality 1), the Abu Isnun leucomonzogranite (locality 4), the Ar Rukhamah leucomonozogranite from the Ad Dawadimi province (localities 5 and 6) and a leucotonalite gneiss from the Ar Rayn province (locality 9). Three of these units are in the age range 677–643 Ma and, therefore, they are not part of an older basement. The fourth sample, from the Abu Isnun pluton, is probably of similar age, but scatter in the zircon data indicates inheritance of older zircons from another source. This source may be the Abt schist or the Afif crust that may underlie this locality, see Fig. 5.

Discovery of zircons 2000 Ma old in a trondhjemite in the Al Amar fault zone is the only direct evidence for older crust within the study area (location C of Fig. 2, Calvez *et al.* 1983). The trondhjemite is identified as belonging to one of the ophiolitic complexes of the Urd group, but no detailed study of the occurrence has been published. If an older crust does indeed occur in the region of the Al Amar fault, then its effects on the isotopic systems of the rocks of the region that have so far been analysed, seem to be rather subdued. Lead isotope ratios from galenas and from feldspars of intrusive rocks in the Ar Rayn province have somewhat retarded values of $^{206}Pb/^{204}Pb$, and their data consequently plot above the $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ average growth curve (Stacey *et al.* 1980; Stacey & Stoeser, 1983). This we interprete to result from a considerable period of residence in the lower crust (or continental mantle) for at least part of the lead prior to 600 Ma ago. Furthermore, galena data from the Ad Dawadimi and Ar Rayn provinces form a linear array that was interpreted by Stacey *et al.* (1980) to be due to a radiogenic lead component from lower continental crust ~2100 Ma old. Bokhari & Kramers (1982) obtained lead isotope data from massive sulphide deposits in the Al Amar region and their data were similar to some of the galena data of Stacey *et al.* (1980). Bokhari and Kramers did not accept the interpretation of an older lower crustal component in the lead, but they did not offer an alternative explanation for the $^{208}Pb/^{204}Pb$ data. In addition, Duyverman *et al.* (1982) did not observe a significant older crustal signature in their Sm-Nd data from the Ar Ridaniyah gneiss to the north of the study area (Fig. 1). At this time, it has to be admitted that we do not understand the role played by older crust in the Al Amar region of the Shield. Further investigations are clearly needed to resolve this problem.

More definitive evidence for older sialic crust has been found in the Jabal Khida area, 200 km to the S of the present study area (Fig. 1), where a foliated granodiorite contains zircons ~1630 Ma old. In addition, common Pb, Sm-Nd, and Rb-Sr data all confirm an early Proterozoic crustal history for this rock or its protolith (Stacey and Hedge 1984). Common lead isotope studies indicate that some plutonic rocks of the Afif province contain lead derived at least in part from an Early Proterozoic continental crust with isotopic characteristics similar to that found in the Jabal Khida sample (Stacey & Stoeser, 1983; J. S. Stacey, unpublished data). Also initial $^{87}Sr/^{86}Sr$ ratios are somewhat elevated (0.704–0.708) in some late Precambrian plutonic rocks from the Afif province (Baubron *et al.*, 1976; Fleck & Hadley, 1983; Kröner *et al.*, 1979; C. E. Hedge, unpublished data). In contrast to the crust of the southern part of Afif province, lead in feldspars from plutonic rocks of the Ad Dawadimi and Ar Rayn provinces lacks the isotopic signature of an older upper crust.

Geological evolution

The Halaban-Al Amar region of the Arabian Shield has been interpreted to contain a suture zone, in which a sedimentary accretionary wedge and associated ocean floor, represented by the Urd group, was compressed between two plates. Four different plate tectonic models have been proposed:

(1) Al-Shanti & Mitchell (1976) first proposed a plate tectonic model which interpreted the Ar Rayn block as an oceanic island arc, underlain by an eastward dipping subduction zone, with the Abt sediments as an accretionary wedge on the W flank of

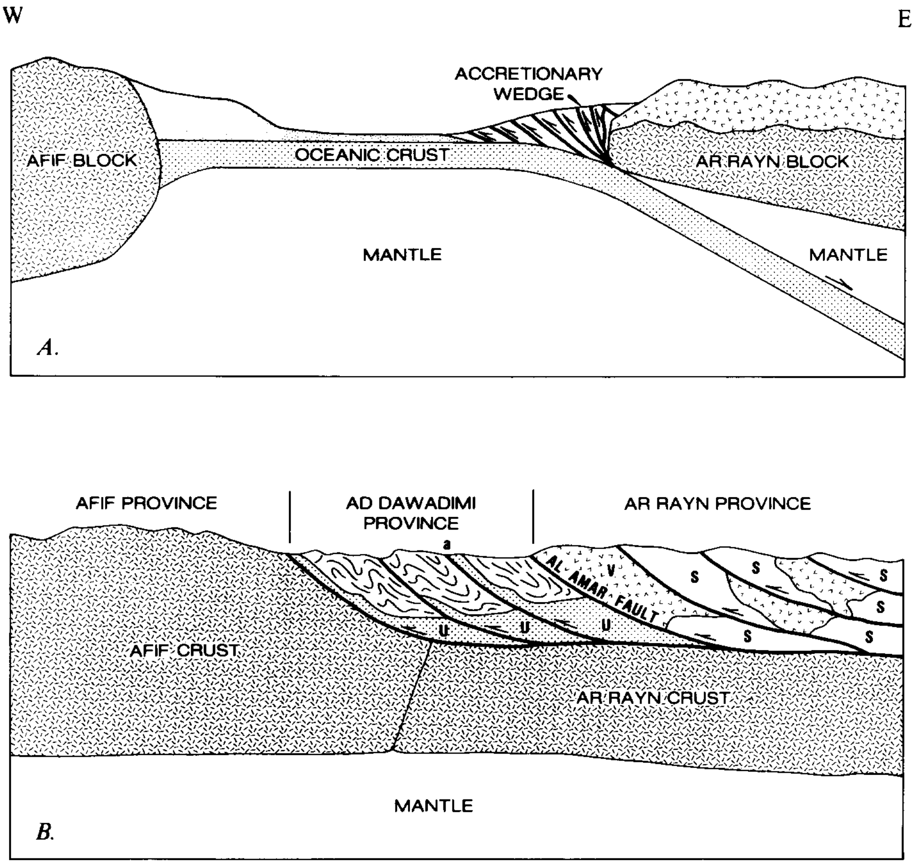

FIG. 5. Generalized geological cross section of the Halaban-Al Amar region. (A) At 680 Ma, shortly before plate collision, and (B) at 640 Ma, the end of collision. Unit symbols: a, Abt schist; u, ophiolitic complexes of the Urd group; v, volcanic and sedimentary rocks of the Al Amar group; s, syntectonic plutonic rocks.

the island arc. Subduction was terminated by collision of the arc with a continental block to the W.

(2) Nawab (1979) interpreted the Ar Rayn block as the site of an island arc located on the eastern margin of a continental block. The Urd group was thought to have developed in a back arc extensional basin, that was subsequently compressed between the arc segment and the continental block.

(3) Schmidt *et al.* (1979) reversed the interpretation of Al-Shanti and Mitchell and called for a westward dipping subduction zone which generated the Hulayfah arc complex in the central Shield. Subduction was terminated by collision with the continental Ar Rayn block from the E.

(4) Al-Shanti & Gass (1983) call for the formation of an ensimatic island arc that was rifted to form a basin floored by oceanic crust between the arc segments. The arc segments then converged with subduction of the back-arc oceanic crust beneath the eastern arc segment. Collision of the segments deformed and tectonically intercalated the Urd group ophiolitic complexes and Abt sediments that were deposited in the back-arc basin.

In addition to the above, Delfour (1981) has proposed without elaboration, that the Ad Dawadimi province is a suture zone between two older basement blocks represented by the Ar Rayn and Afif provinces.

If the Urd group formed by some plate tectonic process, then a fundamental question is whether the crustal blocks on each side of the Urd group rocks are similar. If the blocks are different, then suturing of allocthonous plates, preceded by subduction could be inferred. However, if they are similar then a back arc rift situation is also possible.

Because the pre-Murdama geology of the Afif province immediately W of the Al Amar region is poorly known, and both the Afif and Ar Rayn crusts have been extensively remobilized, it is very difficult to compare their geology. However, results from a deep seismic refraction profile (Healy *et al.* 1982) indicate that the crust in the Halaban-Al Amar region is approximately 43 km thick and that a major crustal discontinuity occurs beneath the Ad Dawadimi province, 25 ± 15 km W along the profile from the Al Amar fault (Fig. 5). Although the geometry of the discontinuity could not be resolved, the crust to the W under the Afif province is seismically distinct from, and less dense than, that to the E (Gettings *et al.* 1983).

The foregoing evidence, together with the more continental character of the Afif province to the SW, supports the concept that the Halaban-Al Amar region contains two distinct crustal blocks that are separated by a zone of highly deformed sediments and ophiolitic rocks. Therefore, we prefer previous interpretations that call for a suture in this region. By this model, the Abt sediments are a clastic wedge associated with a subduction zone and the ophiolitic complexes represent segments of associated ocean floor.

Two of our ages bear directly on the age of the Urd group. The gabbro from the ophiolite complex near Halaban (locality 3) gives a model II age of 694 ± 8 Ma, and detrital zircons from the Abt schist indicate a mean age of 710 Ma for the source rocks of the Abt sediments at locality 2. We conclude therefore, that the Urd group was still forming up to at least 700–690 Ma ago. We note the occurrence of the pre-orogenic Al Amar group of island arc volcanic rocks in the Ar Rayn province and the lack of such rocks in the Afif province. Therefore, if subduction occurred prior to collision, it must have been eastwards directed beneath the Ar Rayn plate. Consequently, of the models listed above, we prefer that of Al-Shanti & Mitchell (1976) which was the first to utilize this idea.

After formation of the Urd group, these rocks were deformed and intruded by a suite of syntectonic leucogranitoids. We have zircon data for two of these monzogranite plutons, the Abu Isnun (locality 4) and the Ar Rukhamah (localities 5 and 6). The Abu Isnun data was scattered, but that for Ar Rukhamah gave a model I age of 641 ± 25 Ma, which places a lower limit on the age of the Abt schist.

Other syntectonic plutonic rocks occur throughout the Ar Rayn province, and one of these, a leucotonalite gneiss (locality 9) gave a model II age of approximately 650 Ma. To the N, in the Ar Ridayniyah area, Baubron *et al.* (1976) have dated by Rb-Sr, a two mica granitic gneiss at 645 ± 35 Ma. In the same region Calvez *et al.* (1983) obtained a U-Pb zircon age of 667 ± 17 Ma for a trondhjemite.

After the formation of the syntectonic plutons, a series of diorites to granodiorites was emplaced within the Ar Rayn province during the period 635 ± 6 to 629 ± 7 Ma (localities 10–13). Calvez *et al.* (1983) have also dated four tonalites and trondhjemites within the Ar Rayn province ranging in age from 644 to 632 Ma.

We conclude that a period of compressional orogenesis, which we will informally refer to as the Al Amar orogeny, and which represents the proposed collision and suturing of the Afif, Ad Dawadimi and Ar Rayn provinces, occurred during the period 670–640 Ma. Previous work, as well as our own field observations, indicates that the direction of tectonic transport and thrusting was westward directed (Al Shanti & Mitchell, 1976; Delfour, 1979a). Given the apparent continuity of the Afif and Ar Rayn crusts beneath the Ad Dawadimi province, and their sharp interface (Gettings *et al.* 1983) we conclude that the Urd group was obducted onto the Afif and Ar Rayn plates, with possible concurrent crustal underthrusting (Fig. 5). Immediately following this deformation, the suite of dioritic and tonalitic plutons was emplaced during the period 640–630 Ma, as a consequence of the crustal heating and remobilization which occurred during active suturing. This episode of orogenesis, plate suturing, and magmatism corresponds closely in time with regional compression and gneiss doming in the southern and central shield, as represented by the Nabitah mobile belt, 680–640 Ma ago (Fig. 1; Schmidt *et al.* 1979; Stoeser *et al.* 1984). The Nabitah mobile belt is interpreted to be a suture zone between the Afif microplate and an island arc terrain to the W.

Following the suturing event, three major geological episodes are recognized. These are: deposition of the Murdama group, emplacement of widespread granitic plutons, and formation of the left-lateral Najd wrench-fault system. The Najd orogeny of Brown (1972) could be reasonably extended to include all these events collectively.

From our data, we can infer only that the Murdama sediments are younger than the 677 Ma As Sawda tonalite. However, to the S in the Wadi Ar Rika quadrangle (Delfour 1980; Fig. 1), Fleck & Hadley (1983) give a 595 ± 15 Ma Rb-Sr age for the Uyaijah monzogranite which intrudes the Murdama group. Also, in the Ar Rika quadrangle, Darbyshire *et al.* (1983) have dated, by Rb-Sr, the underlying Jahhad volcanic rocks at 616 ± 13 Ma. If the Rb-Sr systems in these rhyolitic volcanics have really remained closed, and this age is correct, then it follows that the Murdama group in the study area was deposited during the period 615–595 Ma. Nevertheless, the Rb-Sr isochron age for the Jahhad volcanics should be regarded as a minimum, since such ages for acid volcanic rocks are often too young in spite of their apparently well defined isochrons (e.g., Schleicher *et al.* 1983). Following deposition, the Murdama sediments were deformed into broad open folds. This mild compressional deformation occurred prior to, or contemporaneous with, early Najd faulting.

The granites intruding the Murdama group sediments are similar to granites throughout the eastern Shield which were emplaced during the period 610–570 Ma (Baubron *et al.* 1976; Delfour, 1980; Fleck & Hadley, 1983; Calvez *et al.* 1983). In this paper we have obtained zircon ages for two of these granites, the Jabal Sabhah two-mica leucomonzogranite at 607 ± 19 Ma, and the Jabal Khurs biotite monzogranite at 598 ± 35 Ma. The Jabal Sabhah granite is of particular interest because it belongs to a group of tin-anomalous peraluminous granites which occurs throughout the eastern Shield (du Bray, 1983). Fleck & Hadley (1983) have also dated, the Northern Pluton of Nebert (1970) which lies within the Ar Rayn province (Fig. 2). Their whole rock Rb-Sr isochron age of 604 ± 61 Ma (initial $^{87}Sr/^{86}Sr = 0.7032 \pm 0.0002$), was better defined by a ^{40}Ar-^{39}Ar isochron and plateau ages on hornblende of 609 ± 6 and 609 ± 4 Ma, respectively.

Conclusions

We recognize three orogenic events in the Halaban-Al Amar region.

(1) Convergence of the Afif and Ar Rayn plates, with possible island arc formation, prior to 670 Ma. The Urd and Al Amar groups were emplaced during that period.

(2) The Ad Dawadimi compressional orogeny, 670–630 Ma ago, is attributed to collision and suturing of the Afif and Ar Rayn plates. This collision terminated subduction, deformed the Urd group, and lead to crustal remobilization and the widespread emplacement of synorogenic plutonic rocks.

(3) The Najd orogeny 620–570 Ma ago, was a period of mild compressional orogeny during which the Murdama molasse and associated volcanic rocks were deposited and folded, numerous granitic plutons were emplaced and the Najd left-lateral wrench fault system developed.

Samples from four units, which had been proposed as belonging to a Middle Proterozoic or older sialic basement, have ages in the range 677–643 Ma. There appears to be no definitive evidence to indicate the presence of such a basement beneath the study region. There is Pb and Sr isotopic evidence, however, that a small, older continental component has been added to the crust of the region, but the nature and origin of this component is not understood.

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References

ABDEL-MONEM, A. A., RADAIN, A. A. & GAZZAZ, M. A. 1982. Rb-Sr dating and petrology of Jabal Bitran granite, Idsas Area, Saudi Arabia (abstract). In: TAHOUN, S. A. (ed) *First symposium I.G.C.P. 164, Pan-African crustal evolution in the Arabian-Nubian Shield,* King Abdulaziz University, Faculty of Earth Sciences Research Series, **13,** 4–5.

AL-SHANTI, A. M. S. & GASS, I. G. 1983. The Upper Proterozoic ophiolite melange zones of the easternmost Arabian shield. *J. geol. Soc. London,* **140,** 867–76.

—— & MITCHELL, A. H. G. 1976. Late Pre-Cambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia. *Tectonophysics,* **30,** 41–7.

BAUBRON, J. C., DELFOUR, J. & VIOLETTE, Y. 1976. *Geochronological measurements (Rb/Sr; K/Ar) in rocks of the Arabian Shield, Kingdom of Saudi Arabia.* Rep. Bur. Rech. geol. min. Paris, 76-JED-22, 152pp.

BOKHARI, F. Y. & KRAMERS, J. D. 1982. Lead isotope data from massive sulfide deposits in the Saudi Arabian Shield. *Econ. Geol.* **77,** 1766–9.

BOWDEN, R. A. 1981. *The geology of the Az Zabirah bauxite occurrence.* Deputy Ministry for Min. Res. Rep. RF-OF-21, 34pp.

BROWN, G. F. 1972. *Tectonic map of the Arabian Peninsular.* Map AP-2, Dir. Gen. Min. Res. Kingdom of Saudi Arabia.

—— & COLEMAN, R. G. 1972. The tectonic framework of the Arabian Peninsula. *14th int. geol. Congr.* **3,** 300–5.

CALVEZ, J. Y., ALSAC, C., DELFOUR, J., KEMP J. & PELLATON, C. 1983. *Geologic evolution of western, central, and eastern parts of the northern Precambrian Shield, Kingdom of Saudi Arabia.* Saudi Arabian Deputy ministry for Min. Res. Rep. BRGM-OF-17, 57pp.

COULOMB, J. J., FELENC, J. & TESTARD, J. 1981. Volcanisme et mineralisations a Zn-Cu de la ceinture d'Al Amar (Royaume d'Arabie Saoudite). *Bull. Bur. Rech. geol. Min. Paris (Deuxieme Serie),* **2,** 41–71.

COOPER, J. A., STACEY, J. S., STOESER, D. B. & FLECK, R. J. 1979. An evaluation of the zircon method of isotopic dating in the southern Arabian Craton. *Contrib. Mineral. Petrol.* **68,** 429–39.

DARBYSHIRE, D. P. F., JACKSON, N. J., RAMSAY, C. R. & ROOBOL, M. J. 1983. Rb-Sr isotope study of latest Proterozoic volcano-sedimentary belts in the central

Arabian Shield. *J. geol. Soc. London,* **140,** 203–13.

DELFOUR, J. 1979a. *Geologic map of the Halaban quadrangle, sheet 23G, Kingdom of Saudi Arabia.* Saudi Arabian Dir. Gen. of Min. Res. Map GM-46-A.

—— 1979b. Upper Proterozoic volcanic activity in the northern Arabian Shield, Kingdom of Saudi Arabia. In: TAHOUN, S. A. (ed.) *Evolution and mineralization of the Arabian-Nubian Shield.* Inst. appl. Geol. **2,** Jidda, 59–75.

—— 1980. *Geologic map of the Wadi Ar Rika quadrangle, sheet 22G, Kingdom of Saudi Arabia.* Saudi Arabian Dir. Gen. of Min. Res. Map GM-51-A, 34pp.

—— 1981. Geologic, tectonic and metallogenic evolution of the northern part of the Precambrian Arabian Shield (Kingdom of Saudi Arabia). *Bull. Bur. Rech. geol. Min. Pairs, (deuxieme serie),* **2,** 1–19.

DU BRAY, E. A. 1983. *Mineral potential of selected felsic plutons in the eastern and southeastern Arabian Shield, Kingdom of Saudi Arabia.* US geol. Surv. Saudi Arabian Project Rep. USGS-OF-03-39, 58 pp.

DUYVERMAN, H. J., HARRIS, H. B. W. & HAWKESWORTH, C. J. 1982. Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield. *Earth planet. Sci. Lett.* **59,** 315–26.

EIJKELBOOM, G., GENDI, M., HENDRY, B., LECA, X., SHANTI, M., DELANGE, P. & PFLAM, J. 1969. *Geology and mineral resources of the Al Amar-Ar Rayn quadrangle, Kingdom of Saudi Arabia.* Saudi Arabian Dir. Gen. Min Res. Map MI-18.

——, HENDRY, B., LECA, X., DELANGE, P. & PFLAM, J. 1971. *Geology and mineral resources of the Jabal Khuff quadrangle, Kingdom of Saudi Arabia.* Dir. Gen. for Min. Res. Map Mi-19.

FLECK, R. J., GREENWOOD, W. R., HADLEY, D. G., ANDERSON, R. E. & SCHMIDT, D. L. 1980. *Rubidium-strontium geochronology and plate-tectonic evolution of the southern part of the Arabian Shield.* Prof. Pap. US geol. Surv. Pap. 1131, 38 pp.

—— & HADLEY, D. G. 1983. *Age and strontium initial ratios of plutonic rocks in a transect of the Arabian Shield.* Saudi Arabian Deputy Ministry for Min. Res. Rep. USGS-OF-03-38, 43 pp.

GEBAUER D. & GRÜNENFELDER, M. 1976. U-Pb zircon and Rb-Sr whole-rock dating of low-grade metasediments, Example Montagne Noire (Southern France). *Contrib. Mineral. Petrol.* **59,** 13–32.

GETTINGS, M. E., BLANK, H. R., MOONEY, W. D. & HEALY, J. H. 1983. *Crustal structure of southwestern Saudi Arabia.* Deputy Ministry for Min. Res. Rep. USGS-OF-03-59, 51 pp.

GOLDICH, S. S. & MUDREY, M. G. 1972. Dilitancy model for discordant U-Pb zircon ages. In: INGARINOV, A. I. (ed.) *Recent Contributions to Geochemistry and Analytical Chemistry.* New York, John Wiley & Sons, 466–470.

GREENWOOD, W. R., HADLEY, D. G., ANDERSON, R. E., FLECK, R. J. & SCHMIDT, D. L. 1976. Late Proterozoic cratonization in southwestern Saudi Arabia. *Philos. Trans. R. Soc. London,* **A280,** 517–27.

HEALY, J. H., MOONEY, W. D., BLANK, H. R., GETTINGS, M. E., KOHLER, W. M. LAMSON, R. J. & LEONE, L. E. 1982. *Saudi Arabian Seismic Deep-refraction Profile: final project report.* Saudi Arabian Deputy Ministry for Min. Res. Rep. USGS-OF-02-37, 429 pp.

JAFFEY, A. H., FLYNN, K. F., GLENDENIN, L. E., BENTLEY, W. C. & ESSLING, A. M. 1971. Precision measurements of half-lives and specific activities of ^{235}U and ^{238}U. *Physical Rev.* **4C,** 1889.

KAHR, V. P., OVERSTREET, W. C., WHITLOW, J. W. & ANKARY, H. O. 1972. *Reconnaissance geology of the Jabal Bitran quadrangle.* US geol. Surv. Saudi Arabian Project Rep. 124, 70 pp.

KROGH, T. E. 1973. A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. *Geochim. cosmochim. Acta,* **37,** 485–94.

KRÖNER, A., ROOBOL, M. J., RAMSAY, C. K. & JACKSON, N. J. 1979. Pan African ages of some gneissic rocks in the Saudi Arabian Shield. *J. geol. Soc. London,* **136,** 455–61.

LUDWIG, K. R. 1982. Calculation of uncertainties of U-Pb data. *Earth planet. Sci. Lett.* **46,** 212–20.

MOORE, J. M. 1976. A major lineament in the Arabian Shield and its relationship to mineralization. *Mineralium Deposita,* **11,** 323–8.

NAWAB, Z. A. 1979. Geology of the Al Amar-Idsas region of the Arabian Shield. In: TAHOUN, S. A. (ed.) *Evolution and mineralization of the Arabian-Nubian Shield.* Inst. appl. Geol. Jidda, **2,** 29–39.

NEBERT, K. 1970. Geology of western Al Quway'iyah region, Saudi Arabia. *Neues Jahrb. Geol. Palaeontol. Abhandlungen,* **135,** 150–70.

OVERSTREET, W. C., WHITLOW, J. W. KAHR, V. P. & ANKARY, A. O. 1972. *Reconnaissance geology of the Bir al Badriyah quadrangle, Kingdom of Saudi Arabia (1:100,000 scale).* US geol. Surv. Saudi Arabian Project Rep. 126, 47 pp.

POWERS, R. W., RAMIREZ, L. F., REDMOND, C. D. & ELBERG, E. L., JR. 1963. *Geology of the Arabian Peninsula: sedimentary geology of Saudi Arabia.* Prof. Pap. US geol. Surv. 560-D. 147 pp.

ROOBOL, M. J., JACKSON, N. J. & DARBYSHIRE, D. F. P. 1983. Late Proterozoic lavas of the Central Arabian Shield—evolution of an ancient volcanic arc system. *J. geol. Soc. London,* **140,** 185–202.

SCHLEICHER, H., LIPPOLT, H. J. & RACZEK, I. 1983. Rb-Sr systematics of Permian volcanics in the Schwarzwald (SW-Germany) Part II: Age of eruption and the mechanism of Rb-Sr whole rock age distortions. *Contrib. Mineral. Petrol.* **84,** 281–91.

SCHMIDT, D. L., HADLEY, D. G. & STOESER, D. B. 1979. Late Proterozoic crustal history of the Arabian Shield, southern Najd Province, Kingdom of Saudi Arabia. In: TARHOUN, S. A. (ed.) *Evolution and mineralization of the Arabian-Nubian Shield.* Inst. appl. Geol. Jidda, **2,** 41–58.

STACEY, J. S., DELEVAUX, M. H., GRAMLICH, J. W., DOE, B. R. & ROBERTS, R. J. 1980. A lead isotopic study of mineralization in the Arabian Shield. *Contrib. Mineral. Petrol.* **74,** 175–88.

—— & HEDGE, C. E. (1984). Geochronologic and isotopic evidence for early Proterozoic continental crust in the eastern Arabian Shield. *Geology,* **12,** 310–3.

—— & STOESER, D. B. 1983. Distribution of oceanic versus continental leads in the Arabian-Nubian Shield. *Contrib. Mineral. Petrol.* **84,** 91–105.

STOESER, D. B., STACEY, J. S., GREENWOOD, W. R. & FISCHER, L. B. 1984. *U-Pb zircon geochronology of the Nabitah mobile belt and the Pan African continental collision in the Saudi Arabian Shield.* Saudi Arabian Deputy Ministry for Min. Res. Rep. USGS-TR-04-05.

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