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U/PB zircon geochronology of the southern part of the Nabitah mobile belt and Pan-African Continental collision in the Saudi Arabian Shield

by

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U/PB ZIRCON GEOCHRONOLOGY OF THE SOUTHERN PART OF THE NABITAH MOBILE BELT AND PAN-AFRICAN CONTINENTAL COLLISION IN THE SAUDI ARABIAN SHIELD

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ABSTRACT

On the basis of 13 new U/Pb ages for plutonic rocks from the southernmost portion of the Saudi Arabian Shield, the Nabitah mobile belt and orogeny are defined. The Nabitah mobile belt is a 100- to 200-km-wide, 1000-km-long, north-striking belt of intensely deformed rocks that include ophiolitic and synorogenic plutonic complexes. The age data for all but one sample are highly concordant, and it is confirmed that U/Pb systems in zircons from the region remained undisturbed until the late Tertiary.

Three groups of plutonic rocks were studied: (1) tonalitic plutonic rocks of the Wadi Tarib batholith, (2) synorogenic leucogranitoids related to the mobile belt, which range in composition from trondhjemite to leucomonzogranite, and (3) posttectonic monzogranites. The Wadi Tarib batholith was emplaced about 725 to 732 Ma ago and is interpreted to be an intrusive complex related to the Hulayfah island arc. After emplacement of the Wadi Tarib batholith, the southeastern Arabian Shield was subjected to an intense compressional orogeny, the Nabitah orogeny, during which the Nabitah assemblage of synorogenic plutonic rocks was emplaced during the period 680-640 Ma. Immediately following orogenesis, a suite of leucocratic biotite monzogranite plutons were emplaced throughout the region from 640 to 635 Ma.

The Nabitah mobile belt is interpreted to be a suture zone between two allochthonous plates. The western plate, represented by the Hijaz-Asir province, is a composite ensimatic island-arc terrane composed of the Baish, Bahah, Ablah, Halaban, and Hulayfah groups. The eastern plate, or Afif province, consists of a crystalline basement whose geology is poorly understood, but which appears at least in part to have continental affinities. The Nabitah mobile belt is interpreted to have evolved in three stages: (1) pre-collision plate convergence (>680 Ma), during which the Hulayfah

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island arc formed over a west-dipping subduction zone; (2) collision between the Hijaz-Asir and Afif plates (680-640 Ma); and (3) neocratonic intraplate activity after suturing (<640 Ma).

The evolution of the shield is interpreted in terms of a microplate accretion model in which the Nabitah suturing episode is only one of a number of such suturing events that occurred in the Arabian Shield. On this basis, three main stages of evolution are proposed for the shield: (1) pre-accretion, during which the Hijaz-Asir island-arc assemblage was formed by plate-tectonic processes from >950 to 690 Ma; (2) plate accretion during 690-630 Ma to form the Arabian-Nubian neocraton; and (3) intraplate activity from 630 to <550 Ma, during which the Murdama molasse, Pan-African post-tectonic granites, and Najd fault zone formed. The Arabian orogenic belts are discussed relative to the Pan-African Mozambique and Dahomeyan-Pharusian mobile belts of Africa.

Base metals are preferentially associated with the island-arc domains, gold with the Nabitah suture zone, and tin, tungsten, lead, and silver with the Afif province of the eastern shield.

INTRODUCTION

Considerable attention is now being paid by the geologic community to the study of the evolution of the Arabian-Nubian Shield. At the heart of the dialogue are two fundamental issues -- Did at least some of the shield evolve in an environment similar to that of modern plate tectonics, and is there an older continental basement to the shield? We are affirmative on the first issue and although we provide no new data on the second issue, do relate recent discoveries regarding an older basement to the overall evolution of the Arabian Shield.

The main subject of the report is the geochronologic evolution of late Proterozoic plutonic rocks in an area of the southern Arabian Shield (fig. 1). In interpreting the results of the study, we define a major orogeny, the Nabitah orogeny, the effects of which are seen throughout the eastern half of the Shield, and we describe the Nabitah mobile belt, which resulted from the Nabitah orogeny. Although he did not actually use the name, the definitions of both the Nabitah orogeny and mobile belt are in many ways a consequence of the work of D. L. Schmidt, who first mapped and recognized the fundamental aspects of the Nabitah mobile belt (Schmidt and others, 1979; Schmidt, in press), The results and conclusions of the present study are combined with those of our earlier studies in the Arabian Shield (Greenwood and others, 1982; Stoeser and others, in press; Stacey and Stoeser, 1984; Stacey

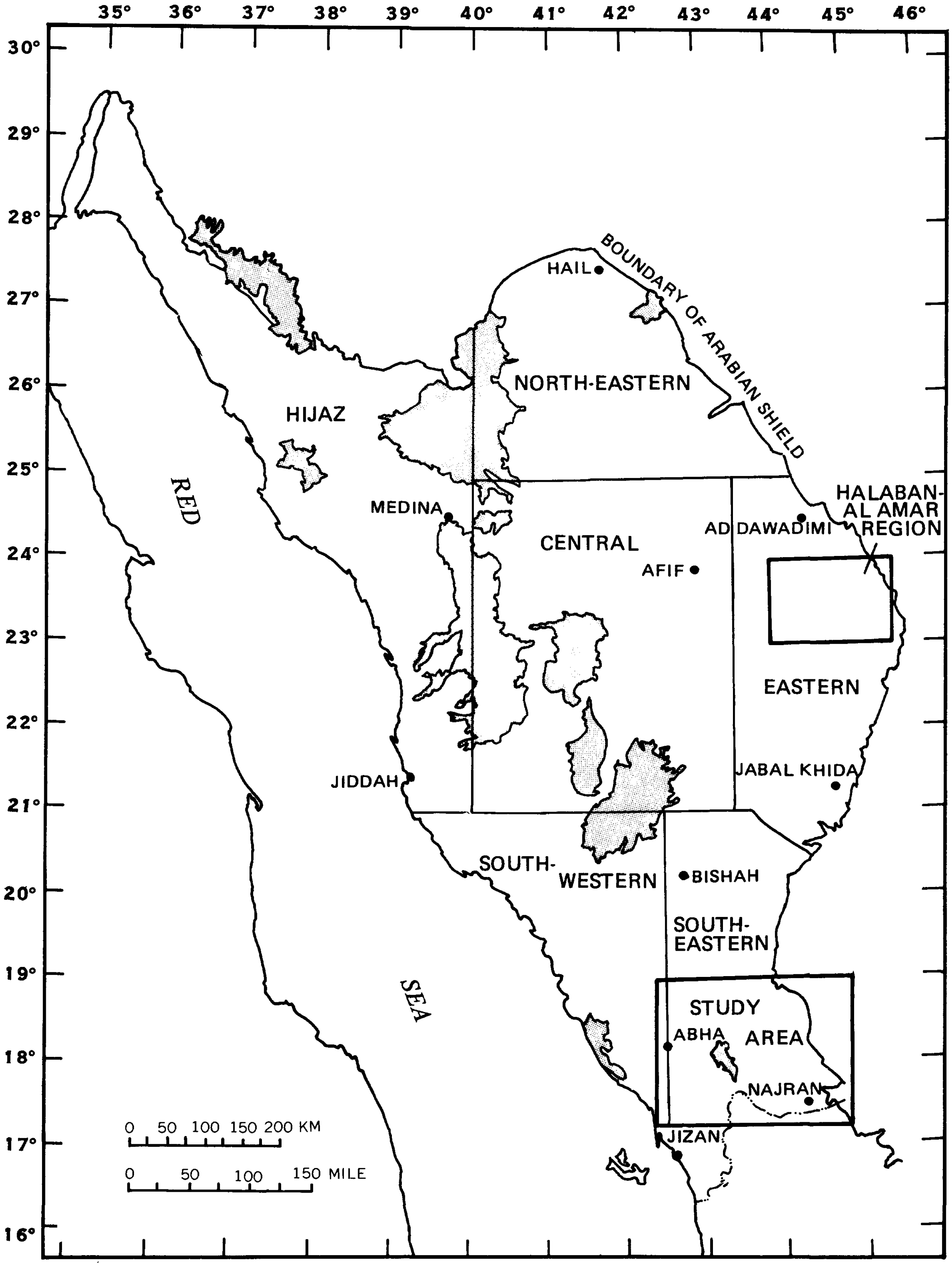

Figure 1.--Index map of the Arabian Peninsula showing the location of the study area, the Halaban-Al Amar region, and other geographic regions referred to in the text. Cenozoic volcanic fields are shown by gray pattern.

and others, in press) and with those of many other workers in order to relate the Nabitah mobile belt to the Pan-African evolution of and mineralization in the eastern two-thirds of the Arabian Shield.

In addition to our work, geochronologic data for the study area are available from two other studies of the southern Arabian Shield. These are a U/Pb zircon study by Cooper and others (1979) and a Rb/Sr whole-rock isochron study by Fleck and others (1980). The samples used in the present study are the same as those used for the southeastern Arabian Shield in the common-lead-isotope study of Stacey and Stoeser (1984).

Many of the rocks included in this study are of Pan-African age. The original definition by Kennedy (1964) referred to a thermotectonic episode within the African craton at about 550+100 Ma. Since that time, the usage of the term "Pan-African" has been broadened by some geologists to refer to orogenesis during the period from approximately 1200 to 500 Ma ago (see, for example, Kroner, 1979a; Gass, 1982). We prefer, however, to stay close to the original definition and will use the term Pan-African to include orogenic events and their products of 600±100 Ma age (Jackson and Ramsay, 1980a).

GEOLOGIC SETTING

The bulk of the Arabian Shield was formed during the period 950 to 550 Ma and is latest Proterozoic to early Cambrian in age (Baubron and others, 1976; Fleck and others, 1980; Calvez and others, 1983). In the study area (fig. 2) the rocks of the shield can be subdivided into four main assemblages: (1) metasedimentary and metavolcanic layered rocks, (2) older tonalitic plutonic rocks, (3) synorogenic plutonic rocks, and (4) postorogenic (or posttectonic) plutonic rocks. The layered rocks were not included in the study, but representatives of all of the plutonic-rock assemblages were sampled and the U/Pb zircon concordia method of age dating applied.

The layered rocks of the study area consist primarily of basic to intermediate metavolcanic rocks and clastic sediments, and most of them are thought to predate all of the plutonic rocks (Anderson, 1979; Greenwood, 1980a,b, in press). Most of the layered rocks of the southern shield show evidence of having formed in an island-arc environment, and they represent at least two main arc complexes that formed during the period 950+ to 680 Ma (Greenwood and others, 1976, 1980; Fleck and others, 1980; Bokhari and Kramers, 1981; Ramsay and others, 1981; Gass, 1982). The older tonalitic plutonic rocks are thought to be arc-intrusive suites formed in

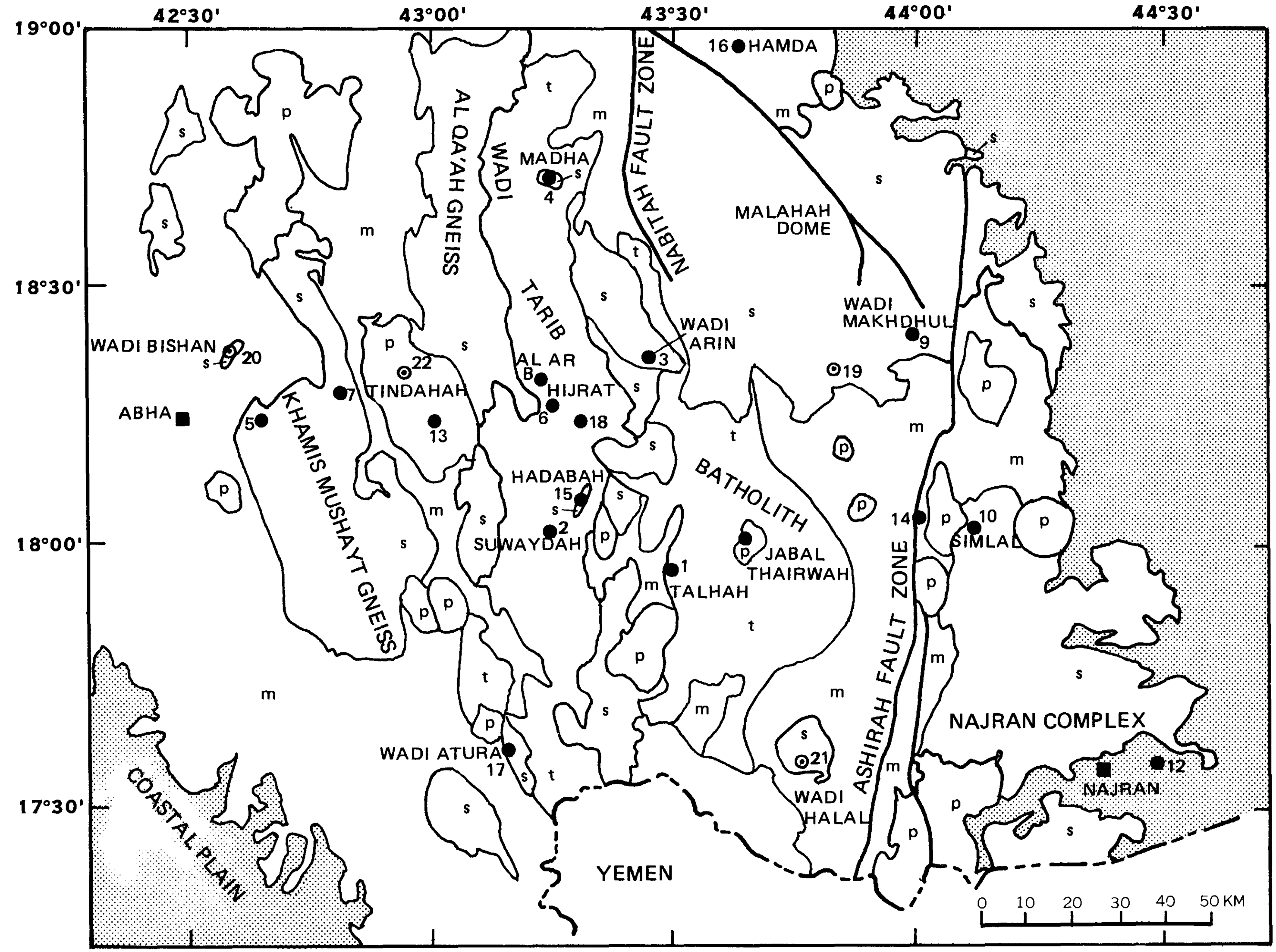

Figure 2.—Simplified geologic map showing location of radiometrically dated samples from the study area (locality numbers from tables 1-4; filled circles, zircon sample localities; circle with dot, Rb/Sr sample localities from Fleck and others, 1980). Unit symbols: M, metavolcanic and metasedimentary rocks; t, Wadi Tarib batholith; s, Nabitah synorogenic plutonic rocks; p, late-orogenic to postorogenic plutonic rocks; stippled pattern, Phanerozoic cover rocks and alluvium; heavy line, fault.

association with the volcanic rocks (Greenwood and others, 1980, 1982; Marzouki and others, 1982). In the study area these are represented by the Wadi Tarib plutonic-rock suite of the Wadi Tarib batholith (Anderson, 1979; Stoeser and others, in press; Stoeser, 1984).

The island-arc assemblage of layered rocks and associated dioritic to tonalitic plutonic rocks occurs throughout the southern and western Arabian Shield as well as most of the Nubian Shield in northeastern Africa. Collectively, these rocks have been referred to as the greenschist assemblage in the Sudan (Vail, 1976), as the Upper Complex in Ethiopia (Kazmin and others, 1978), as Sequence B in the Arabian Shield (Jackson and Ramsay, 1980b), and as the Hijaz magmatic arc for the whole Arabian-Nubian Shield (Kroner, 1979a). To avoid terms with local connotations, we refer collectively to these rocks as the Arabian-Nubian arc assemblage. For the southern Hijaz and southern shield regions of the Arabian Shield (fig. 1), we include in the Arabian-Nubian arc assemblage the Baish, Bahah, Jiddah, Ablah, Halaban, and Hulayfah groups (Greenwood and others, 1976). This assemblage can be further divided into an older arc assemblage (950+ to 800 Ma) that consists of the Baish, Bahah, and Jiddah groups (>800 Ma), and a younger arc assemblage (680 to 800 Ma) that consists of the Ablah, Halaban, and Hulayfah groups (Greenwood and others, 1976, 1980, 1982; Delfour, 1979b; Fleck and others, 1980). We emphasize that, in general, insufficient geologic control is available to recognize individual arc assemblages, and considerably more work is required to define the detailed evolution of the Arabian-Nubian arc assemblage.

The island-arc rocks of the southeastern shield are intruded by widely distributed and voluminous gneissic synorogenic plutonic rocks that are associated with larger areas of intense deformation and metamorphism (Schmidt and others, 1979; Stoeser and others, in press). As will be defined later, these rocks are associated with the Nabitah orogeny and are therefore referred to simply as the Nabitah plutonic-rock assemblage.

The last major group of plutonic rocks that formed in the southern Arabian Shield are those that are usually referred to as the posttectonic or Pan-African granites (Stoeser and Elliott, 1980; Fleck and others, 1980). The posttectonic granites are dominantly metaluminous monzogranites, but range in composition from peraluminous to peralkaline. They typically occur throughout the Arabian Shield as uniform ovoid plutons of pink to red massive-weathering biotite monzogranite. Some, however, are ring structured or in other ways lithologically complex (Stoeser and Elliott, 1980). Some of these granites appear to be cogenetic with a suite of gabbros that occur throughout the shield, but are particularly abundant in the southern shield (Coleman and others, 1972).

ANALYTICAL METHODS

Chemical analyses and mass spectrometry of lead and uranium from zircons used in this study generally follow the procedures outlined by Krogh (1973). Laboratory blank levels for lead were monitored within the range 0.3 to 1.0 nanogram. Corrections for common lead inherent in the zircons were made using the Stacey and Kramers (1975) model modified for lead evolution since 3.7 b.y. ago with $^{238}U/^{204}Pb$=9.22 instead of 9.74, the value used for the average crust. The lower value seems appropriate for galena data from the southern part of the Saudi Arabian Shield (Stacey and others, 1980).

Analytical precisions are ±1.2 percent for concentrations of U and Pb and ±0.1 percent for $^{207}Pb/^{206}Pb$. Uncertainties quoted for the intercepts between regression lines and concordia are computed using the method developed by Ludwig (1982). All uncertainties quoted for our work are 95-percent levels of confidence.

RESULTS

Cooper and others (1979) were the first to report U-Pb zircon age data for the Saudi Arabian Shield. Their study showed that U-Pb systems in zircons from the southern shield remained substantially undisturbed by later metamorphic events that occurred within a few hundred million years of their emplacement. The crystals, being low in uranium content, probably were not sufficiently metamict, that is, damaged by radiation, to lose daughter products during that period. Most of the igneous rocks of the Saudi Arabian Shield were emplaced between 900 and 550 Ma ago, but extensive orogenic and thermal activity in the region occurred between 660 and 570 Ma ago and was responsible for disturbing of the K-Ar and Rb-Sr relations in many of the older units (Baubron and others, 1976; Fleck and others, 1976, 1980). The ability of zircon from the southern Arabian Shield to remain unaffected by that activity has proved to be of great value. Nevertheless, most of the zircon fractions measured had evidently lost lead in a comparatively recent event. This event was probably hydrothermal activity during regional uplift related to the opening of the Red Sea rift. On the basis of the weighted mean of the lower intercepts for the regression lines with concordia, a common lower intercept age of 15$\pm$15 Ma was chosen for all samples by Cooper and others (1979). Anchoring the lower ends of the regression lines in this manner improved the relative precision of the upper intercepts, and differences in age of 15 Ma between samples 800 Ma old could clearly be resolved.

Figure 3 reemphasizes the validity of the 15-Ma lead-loss model for zircons from the southern part of the Saudi Arabian Shield. The supporting U-Pb data are for 20 zircon fractions from six plutonic samples whose zircon model ages range from 657 to 667 Ma. Four of the samples are from Cooper and others (1979) and two from this study. The rocks range in composition from gabbro to monzogranite and are located in all parts of the study region. They are separated by distances of as much as 300 km. In figure 3, the regression line for these twenty data points has an upper intercept with concordia that corresponds to a mean age of 663±4 Ma. The good fit of the data to the line indicates that the only subsequent disturbance for all samples was recent lead loss, shown by the lower intercept to have occurred in the period 15±20 Ma (95-percent confidence limits).

In this study, zircon was recovered from all but one of the samples selected, and the new analytical data for 36 fractions from the remaining 13 samples are shown in table 1. The results are summarized in table 2, where the ages are tabulated according to 3 different models. These models are: (1) average $^{207}Pb/^{206}Pb$ age for the fractions of each sample, (2) ages corresponding to the upper intercepts with concordia of regression lines through the data, and (3) ages corresponding to the upper intercepts with concordia of regression lines through the data anchored to the lower intercept of 15±15 Ma as adopted by Cooper and others (1979).

It can be seen from table 2 that the choice of models makes very little difference to the computed ages, but anchoring the lower intercept for each samples does result in better precision for the data, and fewer zircon fractions need then be analyzed. Therefore, model 3 is preferred, and ages referred to in the text are those of model 3. In table 3, data from this model fall into four age groups of 732 to 729 Ma, 674 to 667 Ma, 657 to 654 Ma, and 644 to 640 Ma. It is convenient to plot all the data together as shown in figures 4 and 5. The four age groups are evident, and the lines drawn through the data are chords joining the 15-Ma lower point on concordia with upper points corresponding to the mean ages of the groups, 730, 670, 655, and 642 Ma, respectively. The chords demonstrate the consistency of the lead loss model for the new data as well as the uniqueness of each age group. In this regard, a regression line through all 16 data points for the five samples in figure 5 yields upper and lower intercepts of 642±4 and 28±18 Ma, respectively.

Rb-Sr data for 10 of the samples discussed in this paper are shown in table 3. These data were obtained by C. E. Hedge and K. Futa, and we are grateful for their permission

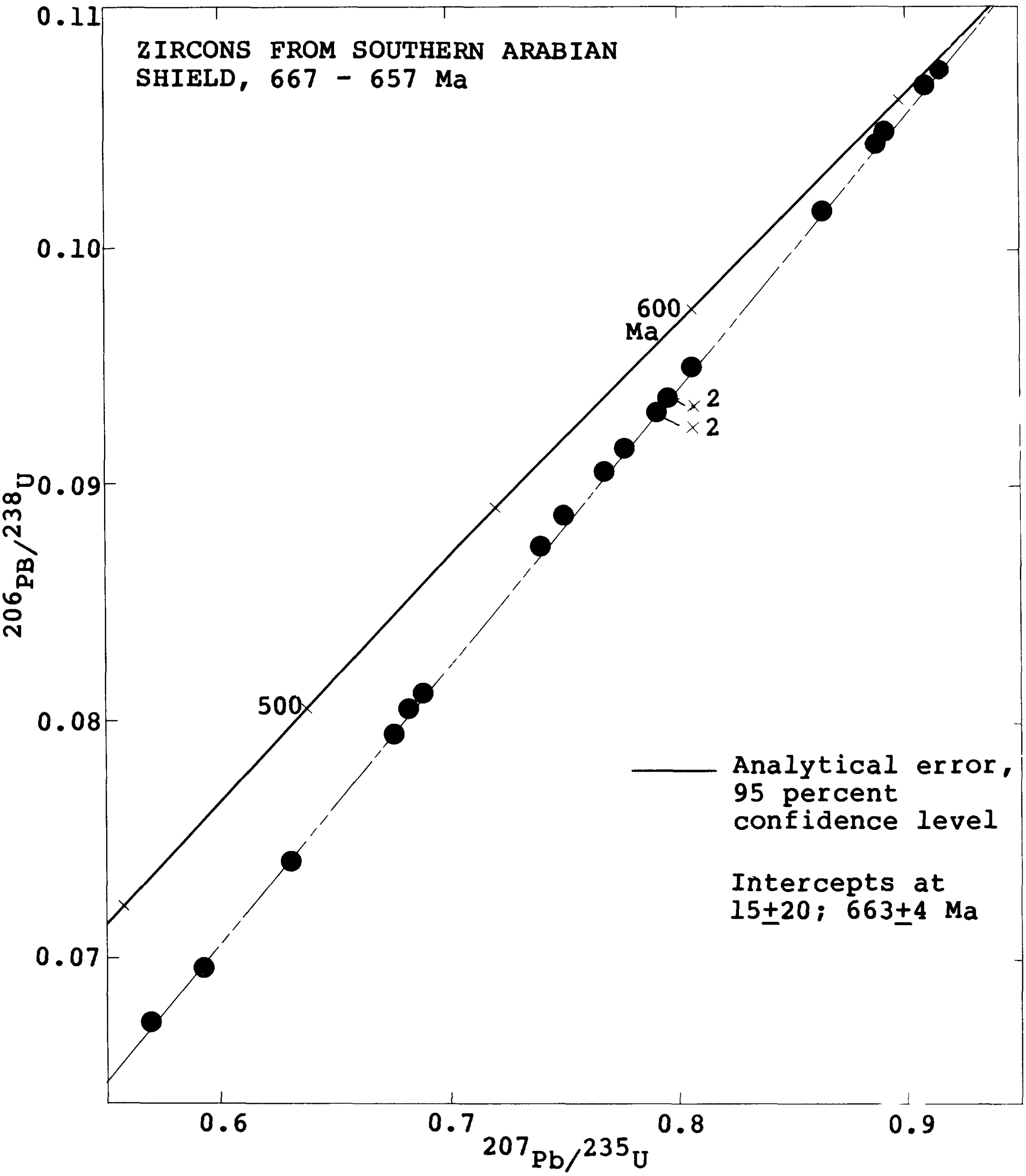

Figure 3.--U-Pb data for 20 fractions of zircon from 6 plutonic rocks from various parts of the southern Arabian Shield. Data from Cooper and others (1979) and this report. Model ages for these rocks range between 657 and 667 Ma. The regression line for all these data gives upper and lower intercept ages of 663±4 Ma and 15±15 Ma, respectively.

Table 1.--U-Pb analytical data for 36 zircon fractions from 14 samples examined for this study

Locality number	Sample number	Mesh size	Concentrations (ppm) U	Concentrations (ppm) Pb	Atomic ratios $\frac{^{206}Pb}{^{238}U}$	Atomic ratios $\frac{^{207}Pb}{^{235}U}$	Atomic ratios $\frac{^{207}Pb}{^{206}Pb}$	Age estimates (Ma) $\frac{^{238}U}{^{206}Pb}$	Age estimates (Ma) $\frac{^{235}U}{^{207}Pb}$	Age estimates (Ma) $\frac{^{207}Pb}{^{206}Pb}$	Blank corrected $\frac{^{206}Pb}{^{204}Pb}$
1.	111552	+100	296	34.3	0.11085	0.9736	0.06371	676	690	732	1222
		-100,+150	304	34.4	.11461	1.0071	.05373	699	707	733	19543
		-200,+250	324	36.1	.11297	.9908	.06361	690	699	728	12782
		-325	355	38.7	.10932	.9597	.06367	699	683	731	6533
2.	112683	-100,+150	114	12.7	.11595	1.0178	.06367	707	713	730	89250
		-250,+325	137	15.4	.11599	1.0174	.06361	707	713	729	12790
		-325	158	17.9	.11727	1.0278	.06357	715	718	727	31125
3.	112805	+100	175	17.4	.10263	.8760	.06199	630	639	674	4527
		-100,+200	265	27.4	.10917	.9318	.06199	668	669	674	9602
		-325	280	25.1	.09399	.8053	.06222	579	600	681	7494
4.	111555	-100,+150	756	62.1	.07813	.6658	.06180	485	518	667	565
		-150,+200	759	65.1	.08469	.7214	.06178	524	562	667	864
		-250NM	859	70.9	.08030	.6835	.06174	498	529	665	695
5.	128918	+100NM	274	29.9	.10665	.90848	.06178	653	656	666	2882
		-250	-	-	.10152	.86483	.06184	623	633	667	-
6.	112806	-200,+250	516	44.6	.08741	.7406	.06153	540	563	658	1275
		-200,+250M	550	46.0	.08868	.7502	.06136	548	568	652	2977
7.	111566	+200	997	85.6	.08575	.7238	.06122	530	553	647	1971
		-200,+250	958	84.1	.08921	.7542	.06132	551	571	650	4483
		-325	865	77.8	.09083	.7687	.06138	560	579	652	3694
8.	111541	+150NM	193	19.2	.09557	.8046	.06106	588	600	641	1605
		+150M	191	22.7	.09546	.8049	.06114	588	600	645	279
		-150,+200NM	221	26.3	.09765	.8222	.06107	600	610	642	2325
9.	128916	+100NM	1550	167	.10073	.84808	.06107	619	624	642	10614
		-325	1375	144	.09930	.8349	.06098	610	616	638	7035

Table 1.—U-Pb analytical data for 36 zircon fractions from 14 samples examined for this study—Continued

Location number	Sample number	Mesh size	Concentrations (ppm) U	Concentrations (ppm) Pb	Atomic ratios 206Pb/238U	Atomic ratios 207Pb/235U	Atomic ratios 207Pb/206Pb	Age estimates (Ma) 238U/206Pb	Age estimates (Ma) 235U/207Pb	Age estimates (Ma) 207Pb/206Pb	Blank corrected 206Pb/204Pb
10.	128917	+100NM	401	39.4	.09336	.7858	.06105	575	589	641	4025
		-200,+250NM	469	48.4	.09968	.8387	.06102	613	618	640	7030
		-400	408	42.6	.10046	.8456	.06105	617	622	641	8079
11.	111554	+100	3097	300.8	.10048	.8438	.06091	617	621	636	11013
		-250,+325	1761	168.6	.09713	.8175	.06104	598	607	641	4846
		-325	1651	153.0	.09323	.7855	.06111	575	589	643	3962
12.	128905	+100NM	134	14.3	.10106	.85065	.06105	621	625	641	2060
		-325NM	202	21.0	.09920	.83512	.06106	610	616	641	2595
13.	(gray)111558	All sizes	1098	92.6	.08216	.6834	.06092	508	532	636	1081
	(pink)111559	+150	1139	68.2	.04664	.3901	.06066	294	334	627	225
	(pink)111559	-150, +200	1030	55.1	.04396	.3640	.06055	277	315	605	285
14.	128912	No zircon recovered									

Table 2.—U-Pb zircon model ages tabulated according to three different models. Also tabulated are the groupings for the common lead from feldspars from the same samples (Stacey and Stoeser, 1983). Group I - oceanic crustal type Pb; Group II contains a Pb component derived from older continental crust. Sample locations shown on figure 2. Uncertainties are 95-percent confidence limits.

Locality number	Sample number	Number of fractions	Range of discordance (percent)	Average $\frac{^{207}Pb}{^{206}Pb}$ age (Ma) (model 1)	Regression through analytical points intercept age lower (Ma) (model 2)	Regression through analytical points intercept age upper (Ma) (model 2)	Regression through 15±15 Ma upper intercept (Ma) (model 3)	Common lead group	Sample description
1.	111552	4	4.7- 9.0	731	21±46	732±9	732±3	I	Talhah tonalite gneiss
2.	112683	3	2.1- 3.1	729	*	*	729±3	I	Suwaydah tonalite gneiss
3.	112805	3	0.3-14.0	676	-70±49	669±4	674±6	I	Wadi Arin tonalite
4.	111555	3	21.6-27.6	666	-1±69	666±19	670±6	I	Mahda two-mica granite
5.	128918	2	2.2- 6.9	666	8±127	667±6	667±4	I	Khamis Mushayt quartz diorite
6.	112806	2	13.0-18.5	657	59±91	664±17	657±3	I	Hijrat trondhjemite gneiss
7.	111566	3	17.1-22.0	650	95±97	668±23	654±7	I	Khamis Mushayt granodiorite gneiss
8.	111541	3	1.0- 9.0	643	-89±325	637±22	644±3	I	Al Ar tonalite gneiss(?)
9.	128916	2	3.8- 5.2	640	*	*	642±5	I	Wadi Makhdhul quartz diorite
10.	128917	3	3.9-10.7	641	1±119	641±9	641±2	I	Wadi Simlal quartz diorite
11.	111554	3	4.0-10.7	640	-119±102	634±5	641±10	I	Jabal Tharwah biotite monzogranite
12.	128905	2	3.2- 5.0	641	*	*	640±3	II	A'ashiba quartz diorite gneiss
13.	111558/9	3	9.5-55.4	624	25±174	642±130	635±15	I	Tindahah biotite monzogranite
14.	128912	No zircon recovered		-	-	-	-	I	Jabal Al Gaharra granite

* Insufficient separation between data points to justify regression line

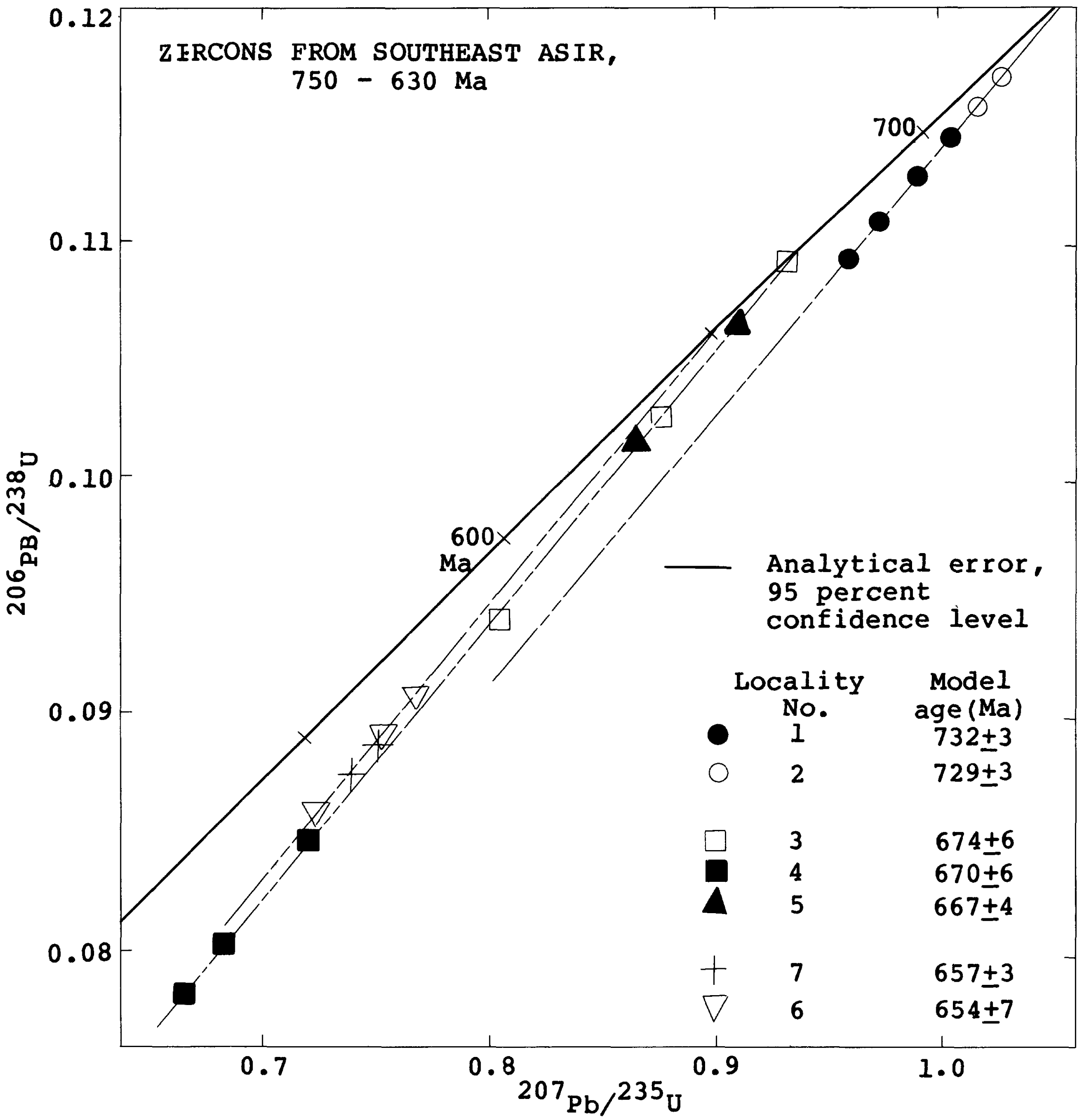

Figure 4.--U-Pb data from seven samples whose ages lie between 730 and 650 Ma. Regression lines are drawn through three groups of data with a common lower intercept of 15±15 Ma (model 3, table 3).

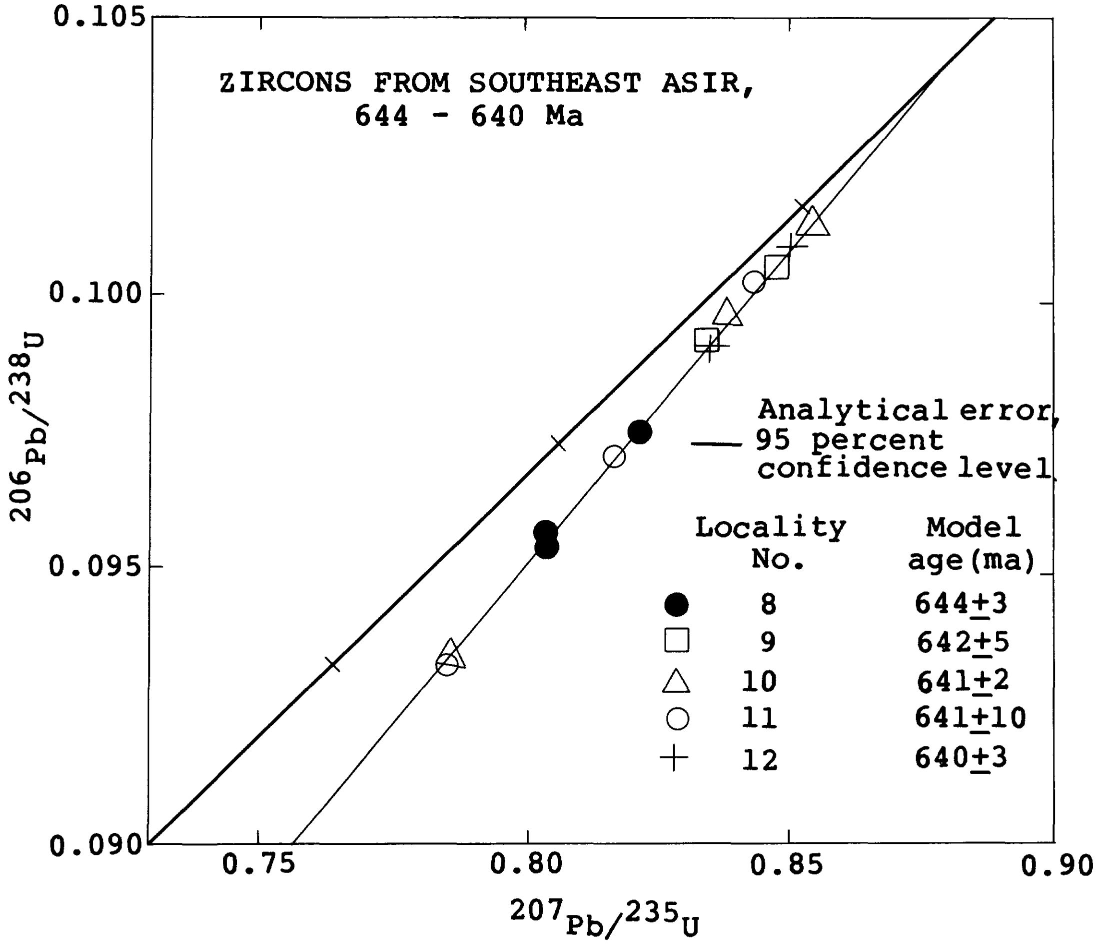

Figure 5.--U-Pb data from four samples whose model ages range between 644 and 640 Ma. A regression line is drawn through the data using a common lower intercept of 15±15 Ma (model 3, table 3).

Table 3.--Rb-Sr data for ten of the samples discussed in this paper. Sample localities shown in figure 2.

Locality number	Sample number	Zircon age (Ma)	Concentrations-ppm		Atomic ratios			Sample description
			Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr_i$	
1.	111552	732	0.8	503	0.0046	0.70290	0.70285	Talhah tonalite gneiss
2.	112683	729	0.9	635	.0452	.70299	.70252	Suwaydah tonalite gneiss
3.	112805	674	33.7	838	.1164	.70355	.70243	Wadi Arin tonalite
4.	111555	670	35.4	561	.1864	.70424	.70249	Mahda biotite-muscovite granite
18.	112680	666	30.3	581	.1510	.70401	.70258	Unnamed granodiorite
7.	111566	654	75.2	358	.6090	.70833	.70265	Khamis Mushayt granodiorite gneiss
8.	111541	644	42.5	806	.1526	.70399	.70258	Al Ar tonalite(?)
11.	111554	641	101	237	1.2386	.71372	.70240	Jabal Thairwah biotite monzogranite
10.	128917	641	38	589	.1906	.70747	.70297	Wadi Simlal quartz diorite gneiss
12.	128905	640	49	954	.1486	.70443	.70307	A'ashiba quartz diorite gneiss

to publish them here. Most of the strontium and lead isotopic data are typical of primitive island-arc rocks like those found in most parts of the southern and western parts of the Arabian Shield (Stacey and others, 1980; Fleck and others, 1980; Stacey and Stoeser, 1984). However, the diorite from Najran (locality 12) has a very slightly elevated $(^{87}Sr/^{86}Sr)_i$ ratio of 0.70307 and is the only sample that contains common-lead isotopes interpreted to contain an older continental crustal component (Stacey and Stoeser, 1984).

The results for each sample locality are presented below and in table 2 and figures 3 to 6. U/Pb zircon data for other localities in the study area are presented in table 4. These results are then synthesized and interpreted in the following discussion and regional interpretation sections. Petrographic, location, and chemical data for the samples are presented in appendices 1 and 2.

Locality 1 - Talhah diorite and tonalite gneiss

The unit sampled was Anderson's (1979) mafic to intermediate rocks unit (map symbol "di"). The informal rock-unit name used here refers to the location of the zircon sample site on Wadi Talhah 4.5 km north-northwest of the village of Talhah. The diorite unit at the sample locality consisted of an agmatite composed of blocks of hornblende diorite (sample 111551) in a matrix of foliated biotite-hornblende tonalite (sample 111552). Although zircon samples of both rocks were taken, zircon was separated only from sample 111552. Anderson (1979) interpreted the diorite unit as being the oldest part of the Wadi Tarib batholith. We obtained a nearly concordant age of 732±3 Ma (fig. 4).

Locality 2 - Suwaydah tonalite gneiss

The Suwaydah tonalite gneiss was sampled in order to date an additional unit of the Wadi Tarib batholith. Preliminary results on our sample (112683) as well as a petrologic study and Rb-Sr whole-rock isochron age for the Suwaydah tonalite gneiss are presented in Stoeser and others (in press). Sample 112683 is a biotite-hornblende tonalite gneiss that was taken from a road cut along the Khamis Mushayt-Najran highway. The very nearly concordant zircon age is 729±3 (fig. 4), as compared to the Rb-Sr age of 725±30. These ages indicate that the Talhah tonalite and Suwaydah tonalite gneiss are essentially of the same age and that the Wadi Tarib suite in this part of the batholith was emplaced about 730 Ma ago.

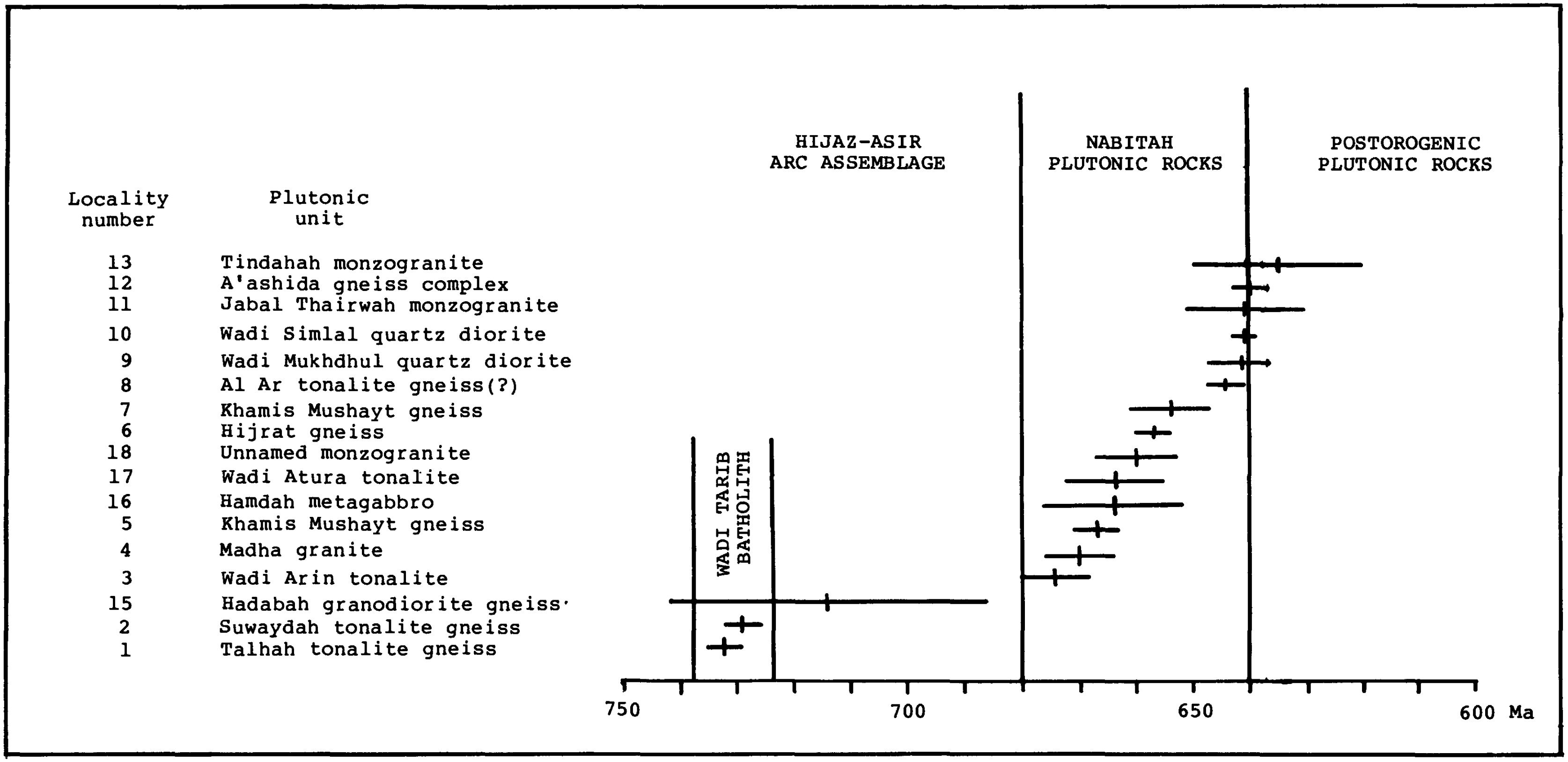

Figure 6.—Age versus sample type for the southeastern Arabian Shield study area. Error limits (95-percent confidence level) shown as bars. Data taken from tables 2 and 4.

Table 4.—Model U-Pb zircon ages from Cooper and others (1979) for localities within the study area. The description of the samples has been changed from the original to correspond to usage in the present study. Sample locations shown on figure 2. Uncertainties are 95-percent confidence limits.

Locality number	Sample number	Range of discordance (percent)	Number of fractions	Average $^{207}Pb/^{206}Pb$ age (Ma)	Regression through analytical points: intercept age upper (Ma)	Regression through analytical points: intercept age lower (Ma)	Regression through 15±15 upper intercept (Ma)	General description
15 2/	112698	31-36 1/	4	711±28	676±?	-106±?	714±28	Hadabah granodiorite
16 3/	112695	26-32	4	661±10	626±19	-149±159	664±12	Hamdah metagabbro
17 4/	112679	15-37	4	662±6	653±9	-21±41	663±8	Wadi Atura tonalite
18 5/	112680	15-39	4	660±5	659±12	7±48	660±7	Unnamed monzogranite

1/ This sample has a short regression line whose error envelopes do not cut concordia twice
2/ 18°06.7' N., 43°19.6' E.
3/ 18°59' N., 43°47' E.
4/ 17°41.7" N., 43°03.3' E.
5/ 18°15.9' N., 43°18.5' E.

Locality 3 - Wadi Arin tonalite

When sampled, the Wadi Arin tonalite was thought to be a younger member of the Wadi Tarib suite, but subsequent mapping indicated that it is part of the Nabitah plutonic-rock assemblage (Stoeser, in press). The pluton is gradationally zoned northward from tonalite to granodiorite. Sample 112805 is a hornblende-biotite tonalite from near the southern margin of the pluton. Its U/Pb zircon age is 674±6 Ma (fig. 4), which places it early in the Nabitah orogenic event.

Locality 4 - Madha granite

The Madha granite is an oval-shaped pluton of garnet-muscovite-biotite leucomonzogranite (Simmons, 1980; du Bray, 1983a), although no garnet was observed in the zircon sample (111555). The pluton was studied in order to date one of several garnet-bearing two-mica granites that occur in the Madha and Wadi Tarib quadrangles (Simmons, 1980; Stoeser, in press). Because the pluton was oval and lacked the complex intrusive style of the synorogenic plutonic rocks, its zircon age of 670+6 Ma appears suprisingly old. The possibility that the Mādha granite may have inherited some zircon from rocks of the Wadi Tarib batholith cannot be ruled out, but because the Madha is petrographically similar to other members of the synorogenic plutonic rocks, we consider it to be part of that group. The Madha granite and other associated two-mica granites were investigated for tin mineralization, but they were found to be barren (du Bray and others, 1982).

Localities 5 and 7 - Khamis Mushayt gneiss

The Khamis Mushayt gneiss of Schmidt and others (1973) is a large complex (25x60 km) of gneissic granodiorite and monzogranite with lesser amounts of migmatite and quartz diorite (Greenwood, in press). The Khamis Mushayt gneiss was originally considered to be intrusive into the surrounding metamorphic rocks (Brown and Jackson, 1959), but later workers interpreted it to be a basement complex older than the layered rocks of the region (that is, early Proterozoic or Archean in age; Schmidt and others, 1973; Coleman, 1973). This interpretation was subsequently discarded by Greenwood and others (1976), who believed that the gneiss was intrusive. We collected two samples from the complex in order to attempt to resolve the conflict. Both samples are from Coleman's (1973) Khamis Mushayt gneiss unit. Sample 111564 (locality 7) is muscovite-biotite granodiorite taken from a large antiformal gneiss body north of the Khamis Mushayt airfield. Sample 128918 (locality 5) is clinopyroxene-biotite-hornblende quartz diorite taken from a road cut of the Abha-Khamis Mushayt highway.

The two-mica granodiorite sample from locality 7 was taken because its lithology is typical of the Khamis Mushayt complex and is similar to other granodiorite-cored antiforms of the study area. Its age of 654±7 Ma (fig. 4) compares well with the whole-rock Rb-Sr isochron age of 664±9 Ma for the granodiorite gneiss of Wadi Bishah of Fleck and others (1980) (locality 20, table 5), which forms the core of a antiformal intrusion near the Khamis Mushayt gneiss. It should be noted that much of the southern part of the Khamis Mushayt gneiss consists of biotite monzogranite gneiss that has not been dated.

The quartz diorite sample (128918) of locality 5 was taken because it appeared that it might represent an older plutonic component entrapped in the granitic gneiss. The zircon age of 667±4 Ma, however, indicates that it is the same age as and cogenetic with the gneissic group.

On the basis of the above results, we conclude that the Khamis Mushayt gneiss is not sialic older basement, but part of the Nabitah plutonic suite. This conclusion is supported by common-lead-isotope studies by Stacey and others (1980) and by Stacey and Stoeser (1984), which show that the Khamis Mushayt gneiss and other plutonic rocks, as well as sulfide minerals of the region, contain lead with characteristics indicating that it was derived from the mantle.

Locality 6 - Hijrat gneiss

Sample 112806 is muscovite-biotite trondhjemite gneiss taken from the Hijrat gneiss of Stoeser (unpub. data, 1984), which consists of a complex of trondhjemite to leucomonzogranite gneiss intercalated with amphibolite and remobilized migmatitic Wadi Tarib tonalite. The sample was taken to determine the age of a typical synorogenic gneiss from the study area. Although there was considerable danger of zircon inheritance by contamination from the Wadi Tarib batholith, the age of 657±3 (fig. 4) indicates that the sample was not contaminated.

Locality 8 - Al Ar tonalite gneiss

Sample 111541 was taken from the Al Ar tonalite gneiss units of the Wadi Tarib suite of Stoeser (unpub. data, 1984) in order to date another major unit of the Wadi Tarib batholith. The zircon age obtained for the Al Ar tonalite gneiss of 644±3 (fig. 5) is in sharp contrast to the 729±3 Ma age obtained for the Suwaydah tonalite gneiss with which the Al Ar tonalite gneiss is correlated (Stoeser, (unpub. data, 1984).

Table 5.--Rb-Sr ages from Fleck and others (1980) for localities within the study area. Sample localities shown on figure 2. Error limits are one sigma.

Locality number	Rock unit	Apparent age (Ma)	Number of points	$(^{87}Sr/^{86}Sr)_i$
19	Wadi Malahah granodiorite	684 ± 43	13	$0.7029 \pm .0001$
20	Wadi Bishah granitic gneiss	664 ± 9	3	$0.7035 \pm .0007$
21	Wadi Halal granodiorite	643 ± 20	7	$0.7028 \pm .0002$
22	Tindahah monzogranite	626 ± 17	3	$0.7037 \pm .0004$

The Al Ar sample is a hornblende-biotite tonalite containing about 5 percent interstitial microcline; its texture indicates deformation and annealing under high temperature. Although the sample was taken from an outcrop that appeared typical of the Al Ar tonalite gneiss, in thin section it was found to contain more potassium feldspar and appeared to be considerably more deformed and recrystallized than is typical.

The unexpectedly young age suggests several possibilities: (1) the Al Ar tonalite gneiss is in fact much younger than expected and part of the Nabitah plutonic suite; (2) the Al Ar tonalite in the vicinity of the sample locality was sufficiently deformed and metamorphosed 640 Ma ago to cause either complete lead loss or recrystallization of the zircon, or (3) the sample does not represent the Al Ar tonalite. We prefer the latter two explanations, and, because the sample is generally similar to the Al Ar tonalite gneiss, we tend to favor the second explanation over the third. With regard to item (3), stratigraphically late mafic tonalite and quartz diorite plutons similar to the Al Ar tonalite do occur in the immediate area of locality 8 (Stoeser, unpub. data, 1984) and a number of such units of similar age have been sampled for zircon age determination in the study area (localities 5, 9, 10 and 12).

Localities 9 and 10 - Wadi Makhdhul and Wadi Simlal quartz diorite

The Wadi Makhdhul and Wadi Simlal quartz diorites were mapped by Greenwood (1980a,b) as early quartz diorite plutons that he correlated with the Wadi Tarib batholith. These plutons were sampled by us on the assumption that if they, as well as their host layered rocks, were all part of an island arc, then the age of the layered rocks and of the arc as a whole could be estimated by dating the associated plutonic rocks. Fleck and others (1980) had estimated the ages of these two plutons by the whole-rock Rb-Sr isochron method. Unfortunately, and as emphasized by Fleck and others, both Rb-Sr age determinations were poorly controlled due to the number of samples and low Rb/Sr ratios. A two-point determination on the Wadi Simlal quartz diorite gave 815 Ma (no error limits) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7027. A three-point isochron for the Wadi Makhdhul quartz diorite yielded 843±273 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7023±0.0006. These ages were significant because they supported the interpretation that the layered rocks of the southeastern shield were of Jiddah-group age (that is, 800 to 850 Ma) as proposed by Anderson (1979) and Greenwood (1980a).

We attempted, therefore, to obtain samples for zircon dating from each pluton. On the basis of Fleck's field notes and sample-location coordinates, we are satisfied that we sampled the Simlal quartz diorite of Fleck and others (1980), but several plutonic rock units were present in the area of his Wadi Makhdhul locality, and we took a sample of a large quartz diorite unit that extends northward from his sample coordinates. However, Greenwood, who was present, indicated his satisfaction that the Wadi Makhdhul sample represents his older quartz diorite unit (Greenwood, 1980a).

The zircon results for the Wadi Makhdhul and Wadi Simlal quartz diorite samples (128916 and 128917) were 642 ± 5 Ma and 641 ± 2 Ma respectively (fig. 5). These nearly concordant ages, if correct, clearly invalidate the correlations with the Wadi Tarib and An Nimas batholiths and indicate that the quartz diorites were emplaced late in the Nabitah orogeny and are not related to the island-arc rocks.

Locality 11 - Jabal Thairwah monzogranite

The exposed part of the Jabal Thairwah monzogranite pluton is 7 by 8 km in area and consists of pink massive-weathering biotite leucomonzogranite that appears typical of the late to posttectonic Pan-African granites of the southern shield (Fleck and others, 1980). The granite is here informally named after Jabal Thairwah, a prominent jabal within the pluton (named on the 1:100,000-scale geologic map of the Wadi Malahah quadrangle; Greenwood, 1980a). The Jabal Thairwah monzogranite was one of two such granites that were sampled for this study in order to obtain ages for typical Pan-African monzogranites of the southeastern shield. Its age of 641 ± 10 Ma (fig. 5) compares well with that of the Tindahah monzogranite (locality 13), which is 635 ± 15 Ma.

Locality 12 - A'ashiba gneiss complex

Sample 128905 is hornblende-biotite granodiorite gneiss from the biotite tonalite to granodiorite gneiss subunit of the A'ashiba gneiss complex of Sable (in press). The sample was taken as part of the general program of dating tonalitic units within the study area. Its zircon age of 640 ± 3 Ma (fig. 5) indicates that it was emplaced at the end of the Nabitah orogeny.

Locality 13 - Tindahah monzogranite

The Tindahah monzogranite pluton, first mapped in the Khamis Mushayt quadrangle and named by Coleman (1973), extends into the Wadi Tarib quadrangle, where it is included in Stoeser's (unpub. data, 1984), monzogranite unit. The Tindahah monzogranite was sampled because, like the Jabal Thairwah monzogranite, it is a typical representative of postorogenic granites of the southern shield.

The Tindahah monzogranite forms a large 17 by 38 km pluton composed of generally homogeneous biotite leucomonzogranite. At the sample locality two phases were found, an older grayish-pink monzogranite (sample 111558) and a younger orangish-pink monzogranite (sample 111559) that locally grades to pegmatite. Zircon samples were taken from both phases and used for the age determination.

The Tindahah monzogranite yielded a model-1 age of 635 ± 15 Ma. This age compares well with the Rb-Sr whole-rock isochron age of 626 ± 17 Ma obtained by Fleck and others (1980). The Tindahah zircons were the only ones found in the study that were significantly discordant (9 to 55 percent), and for that reason they are not plotted on figure 5.

Locality 14 - Jabal al Gaharra granite

The Jabal al Gaharra granite is a small 1.5- by 5-km muscovite-biotite leucogranite pluton. It was reported by Greenwood (1980b) as being the youngest plutonic unit in the region. This granite is tin anomalous, and its economic potential was evaluated by Elliott (in press). Unfortunately, zircons were not found in our sample (128912). Feldspar from this sample was run for common-lead isotopes and found to have an oceanic character indicating no evolved crust in its source region (Stacey and Stoeser, 1984).

DISCUSSION

To summarize in advance, the fundamental conclusions we draw from this study are as follows:

(1) The Wadi Tarib plutonic-rock suite (735-720 Ma) represents an island-arc intrusive complex. This suite is associated with a north-south-trending island arc, the Hulayfah island arc, which existed in the south, central, and northern shield from approximately 785 to 680 Ma.

(2) Formation of the Hulayfah arc may have been terminated by collision of the arc with a plate to the east, represented by the Afif crustal province. This episode of collision, referred to as the Nabitah orogeny, is represented by a linear orogenic belt, the Nabitah mobile belt. The Nabitah orogeny occurred during the period 680 to 640 Ma.

(3) The Nabitah orogeny was immediately followed by the emplacement of postorogenic granite plutons (640-625 Ma).

After discussing the evidence that lead to these conclusions, we used them to construct a model for the evolution of the eastern two-thirds of the Arabian Shield during the period 760 to 625 Ma.

Wadi Tarib batholith

The oldest plutonic rocks identified in the study area are the dioritic and tonalitic plutonic rocks of the Wadi Tarib batholith (fig. 2) (Anderson, 1979). Anderson (1979) first defined and mapped the southern part of the batholith in the Wadi Atf and Mayza quadrangles. He gave the following definition of the batholith:

> "Plutonic rocks that generally lack primary potassium feldspar and range from trondhjemite to gabbro form a large composite batholith that extends into the Mayza' quadrangle from the north. The batholith is herein named the Wadi Tarib batholith because its extension to the north over much of the area mapped by Brown and Jackson (1959) as granite and granodiorite embraces most of the drainage area of Wadi Tarib."

Subsequent to Anderson's mapping, Greenwood (1980a,b) mapped the eastern part of the batholith and correlated a number of dioritic and tonalitic plutons farther east in the Wadi Malahah and Wadi Wassat quadrangles with the batholith. Mapping of the batholith was completed by Simmons (1980) and Stoeser (unpub. data, 1984).

During the early mapping, the layered rocks and older tonalitic plutonic rocks in the region of the Wadi Tarib batholith and to the east were correlated with the Jiddah group and the An Nimas batholith (800 to 850 Ma, Cooper and others, 1979; Fleck and others, 1980) of the Wadi Tarj and An Nimas quadrangles more than 100 km to the northwest (Anderson, 1977, 1979; Greenwood, 1979, 1980a). Later work, however, has interpreted the layered rocks as belonging to the younger Halaban group and the tonalitic rocks of the Wadi Tarib batholith as Halaban-age intrusions (Smith, 1981; Greenwood and others, 1982; Stoeser and others, in press). The Halaban group is part of what has been interpreted as an island-arc assemblage that extends from the southern shield through the central and northern shield (Schmidt and others, 1979; Delfour, 1981; Greenwood and others, 1982).

This arc assemblage is composed of two groups, the Halaban group in the south and the Hulayfah group in the north. These two groups are primarily strike extensions of each other and thought to represent the same stratigraphic assemblage. Because the Halaban group is no longer accepted in its type area (Delfour, 1982), we will refer to these rocks as the Hulayfah group and to the Hulayfah island arc. The Hulayfah group consists chiefly of basic to intermediate volcanics and associated sediments derived from the erosion of these volcanics. The layered rocks and associated plutonic rocks of the hulayfah arc will be referred to collectively as the Hulayfah-arc assemblage.

In the first geochronologic study of the Wadi Tarib batholith (Stoeser and others, 1982), ages for three samples from two plutonic units of the batholith are presented. Two of these ages are given in this report for localities 1 and 2, and the data to support them are given here for the first time. The oldest unit dated was the "diorite" unit of Anderson (1979), which he interpreted to be the earliest phase of the Wadi Tarib batholith; this unit gave a U/Pb zircon age of 732±3 Ma (locality 1). The other unit that was dated is the Suwaydah tonalite gneiss, which gave a 729±3 Ma age by the U/Pb zircon method (locality 2) and 725±30 Ma by the Rb-Sr whole-rock isochron method (10 points); its initial $^{87}Sr/^{86}Sr$ ratio is 0.7025±0.0001 (Stoeser and others, in press).

Ages for the Wadi Tarib plutonic suite match well with limited data for similar intrusive rocks of Hulayfah age further to the north. Fleck and others (1980) report Rb-Sr whole-rock isochron ages of 724±93 and 723±107 Ma on two quartz diorites, and J. S. Stacey (unpub. data) obtained a zircon age of 720±9 Ma on a tonalite gneiss in the Ranyah quadrangle (Greene, 1980). Only two ages are available for Hulayfah-group volcanic rocks from the southern shield. These are 746±16 and 785±96 Ma (Fleck and others, 1980). Therefore, it appears that in the southern shield the Hulayfah-arc assemblage formed at least in part from about 785 to 720 Ma. The isotopic data, however, are too inconclusive to allow us to put definitive age limits on the formation of the Hulayfah assemblage.

Nabitah orogeny and mobile belt

Previous work

As geologic mapping progressed in the southeastern shield, it became obvious that the region contains widespread igneous complexes composed of gneissic plutonic rocks and migmatites surrounded by highly deformed and metamorphosed rocks of the Hulayfah group. These plutonic rocks are interpreted to have formed during a major compressional orogenic event that affected much of the eastern half of the shield (Schmidt and others, 1979; Delfour, 1981; Greenwood and others, 1982; Stoeser and others, in press; Schmidt and Brown, 1982). Schmidt and others (1979) have shown that much of the intrusive activity associated with this period of orogenesis is concentrated in a north-trending belt centered on the Nabitah fault zone, which extends through the central and northern parts of the shield (fig. 7). Schmidt and Brown (1982) referred to this event as the "culminant orogeny" and inferred that it occurred during the period 600 to 660 Ma. They also referred to the Nabitah fault zone as the Nabitah suture.

Definition

In this report we further refine the timing and nature of this orogeny, which we here name the Nabitah orogeny, and we refer to the 150- to 200-km-wide belt of deformation and plutonism associated with it as the Nabitah mobile belt. The name "Nabitah" is taken from Jabal Nabitah (fig. 8), a 5-km-long jabal of serpentinite located in the core of the Nabitah fault zone in the Jabal Ishmas quadrangle of Gonzalez (1974). We chose the term "mobile belt" because it is a nongenetic term that points up the fundamental nature of the belt, which is a linear zone of intense deformation, metamorphism, plutonism, and crustal remobilization. The Jabal al Qarah (Schmidt, in press) and Wadi Tarib (Stoeser, 1983) 30-minute quadrangles are reference areas in the south for the Nabitah orogeny and mobile belt. Our results show that in the southern part of this belt, the Nabitah orogeny occurred during the period 680 to 640 Ma. The age of formation of the Nabitah belt and its proximity to the African craton qualify it as a mobile or orogenic belt of Pan-African age (Clifford, 1970; Kroner, 1979a).

The synorogenic plutonic rocks that formed during the Nabitah orogeny are referred to as the Nabitah plutonic-rock assemblage. The Nabitah orogeny is subdivided into an early phase of active compressional orogenesis and a late passive phase when compression had ceased but active plutonism continued.

The early phase of the Nabitah orogeny (680 to 650 Ma) was marked by the intrusion of gneissic leucogranitoid rocks that appear to have been emplaced in a compressional orogenic environment. We use the term "synorogenic gneiss" for the intrusive plutonic rocks that formed in an active compressional orogenic environment and acquired a foliate or gneissic texture during emplacement and crystallization. The early synorogenic plutonic rocks are characterized by gneissic biotite or two-mica trondhjemite, leucogranodiorite, and leucomonzogranite, with granodiorite being the dominant

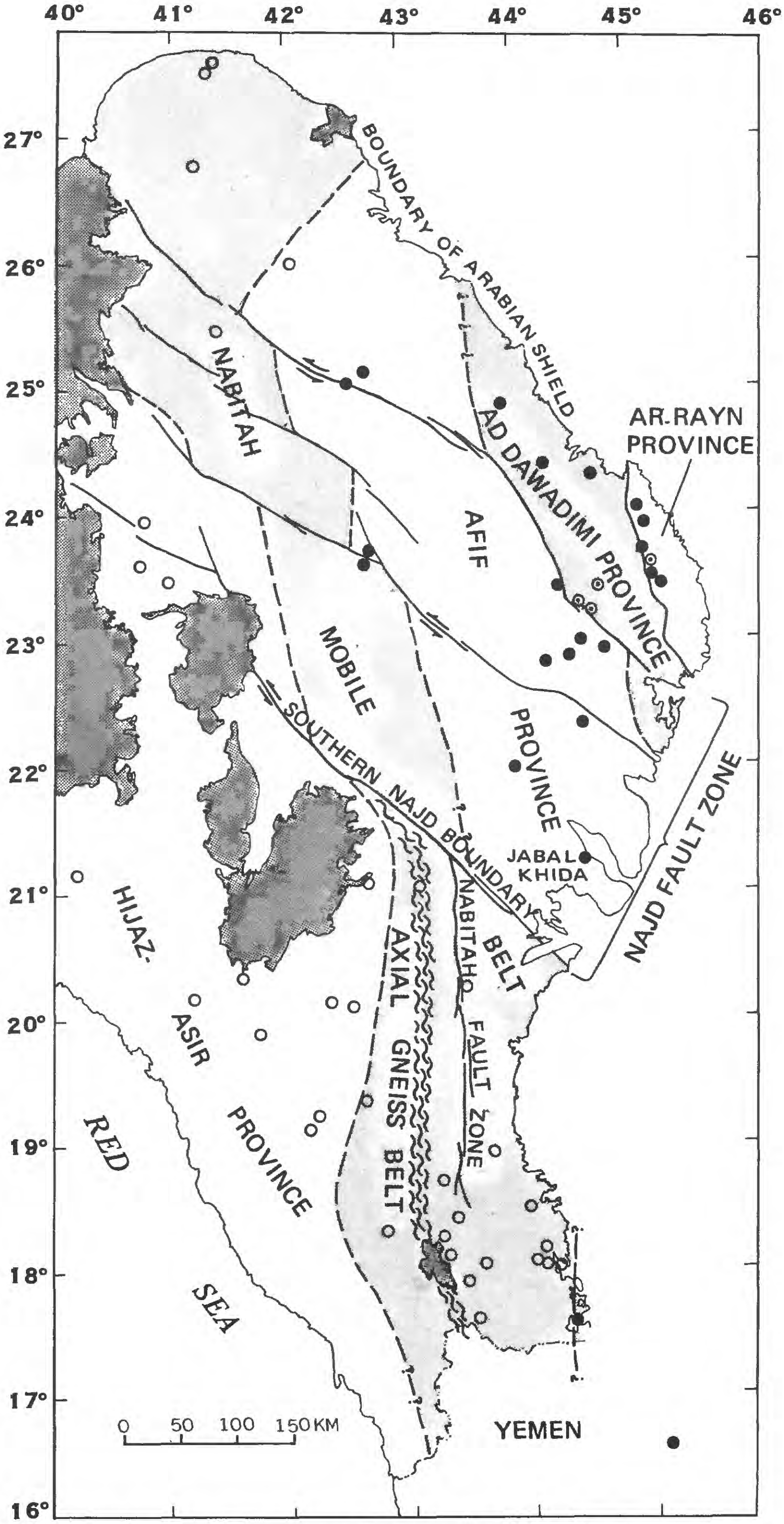

Figure 7.--Map of the Arabian shield east of long 40° E. showing the location of the geologic provinces discussed in the text and common-lead samples taken from Stacey and others (1980) and Stacey and Stoeser (in press). Circles indicate type-I (ensimatic) lead isotopes; large dots, type-II (continental) lead isotopes; circles with dots, transitional lead isotopes. Cenozoic volcanic fields shown with medium-gray pattern, suture zones with light-gray pattern.

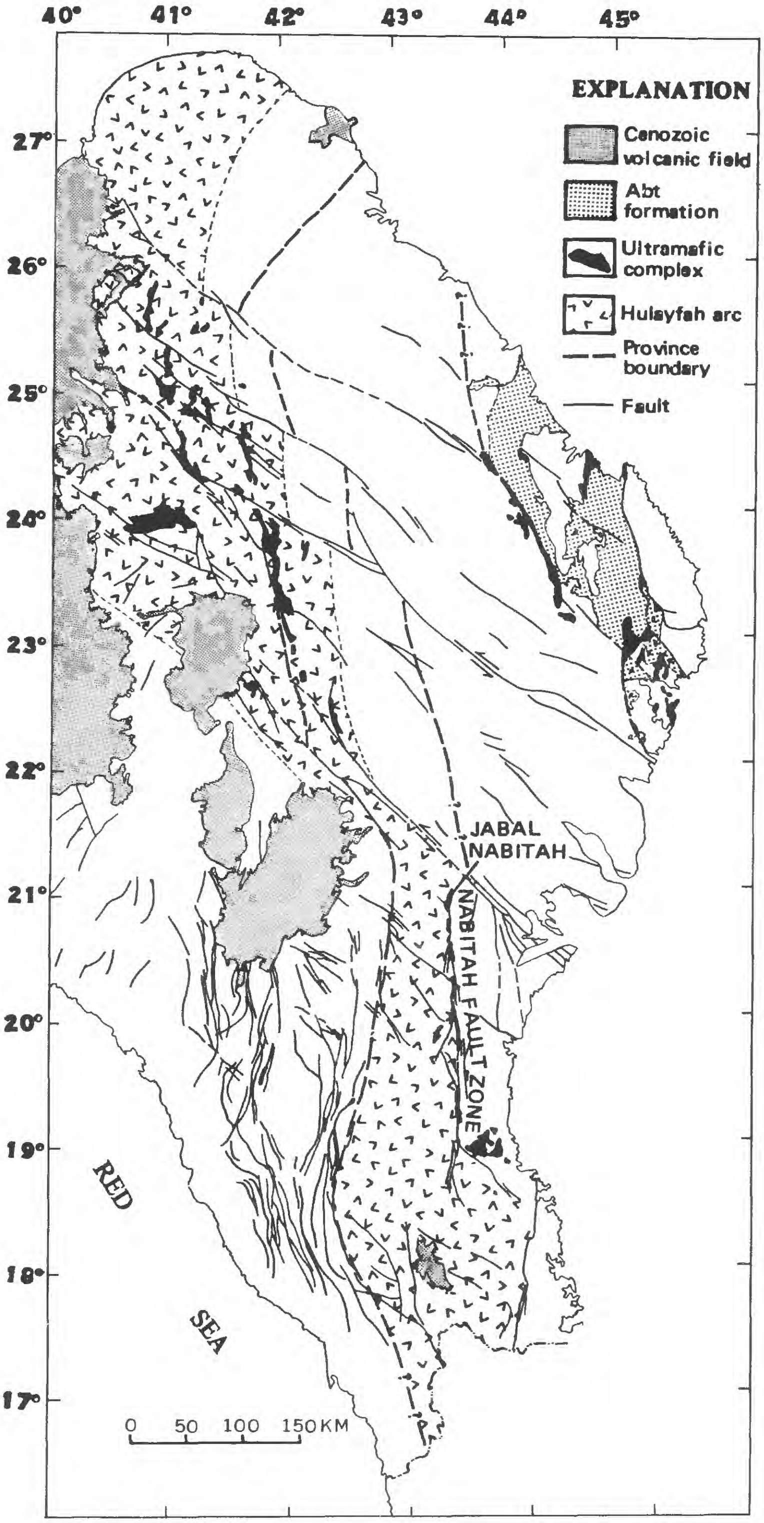

Figure 8.--Simplified geologic map of the Arabian Shield east of long 40° E. showing the approximate distribution of the Hulayfah-arc assemblage, ultramafic (ophiolitic) complexes, the Abt formation, and major faults.

lithology. These rocks are commonly peraluminous and in some plutons are garnet bearing (du Bray, in press). Some of these plutons are simple oval intrusions, but in general they are irregular complex bodies that typically contain large volumes of remobilized older crust in the form of diffuse to sharply defined xenolithic masses of amphibolite and orthogneisses of diorite to tonalite. Some of these plutons have migmatitic envelopes several kilometers wide (Schmidt, 1981; Stoeser, unpub. data, 1984). Unfortunately, detailed structural studies have not been done, but, in general, these plutons appear to have been emplaced in an environment that involved mass transport westward (Schmidt and others, 1979; Stoeser and others, in press). The early part of the Nabitah orogeny is therefore interpreted to represent a period of westward-directed compression accompanied by massive partial melting in the deep crust sufficient to allow wholesale tectonic transport.

The late phase of the Nabitah orogeny (650 to 640 Ma) in the southern shield is characterized by a widespread bimodal suite of diorite to mafic tonalite and foliated monzogranite that appears to have been formed in a more passive environment in which vertical movement was dominant. The late-orogenic plutons presumably were formed by extensive crustal melting during the period after compression had ceased but when temperatures in the crust were still elevated.

In the southern shield, prominent features of the Nabitah mobile belt are, from west to east (figs. 7,8,9): (1) west of the mobilized zone, a broad north-trending belt of intense faulting about 150 km across (fig. 8); (2) a sharp western boundary that marks a change from greenschist-facies metamorphic rocks on the west side to dominantly amphibolite-facies metamorphic rocks to the east; (3) a marked continuous belt of linear gneiss complexes that lie on a well-defined axis (figs. 7 and 9), although gneissic complexes are scattered throughout the mobile belt; and (4) the Nabitah fault zone, which contains a narrow belt of serpentinite bodies strung along its length (fig. 8). The only large area of ophiolitic rocks in the southern shield, the Hamdah serpentinite, occurs at the south end of the Nabitah fault zone (Al-Rehaili and Warden, 1980; Worl, 1981). In the southern shield, the east margin of the Nabitah mobile belt is covered by Phanerozoic sedimentary rocks.

The Nabitah ultramafic or ophiolite belt (Schmidt and others, 1979) (Hulayfah-Hamdah belt of Frisch and Al-Shanti, 1977; or Mawan-As Siham-Wadi Tathlith belt of Delfour, 1981) is particularly interesting and is the longest of a number of such belts within the Arabian-Nubian Shield. The literature contains repeated proposals that these ophiolitic belts are suture zones (for example, Brown and Coleman, 1972; Bakor and others, 1976; Frisch and Al-Shanti, 1977; Schmidt and others, 1979; Shackelton, 1979; Gass, 1982). Little detailed

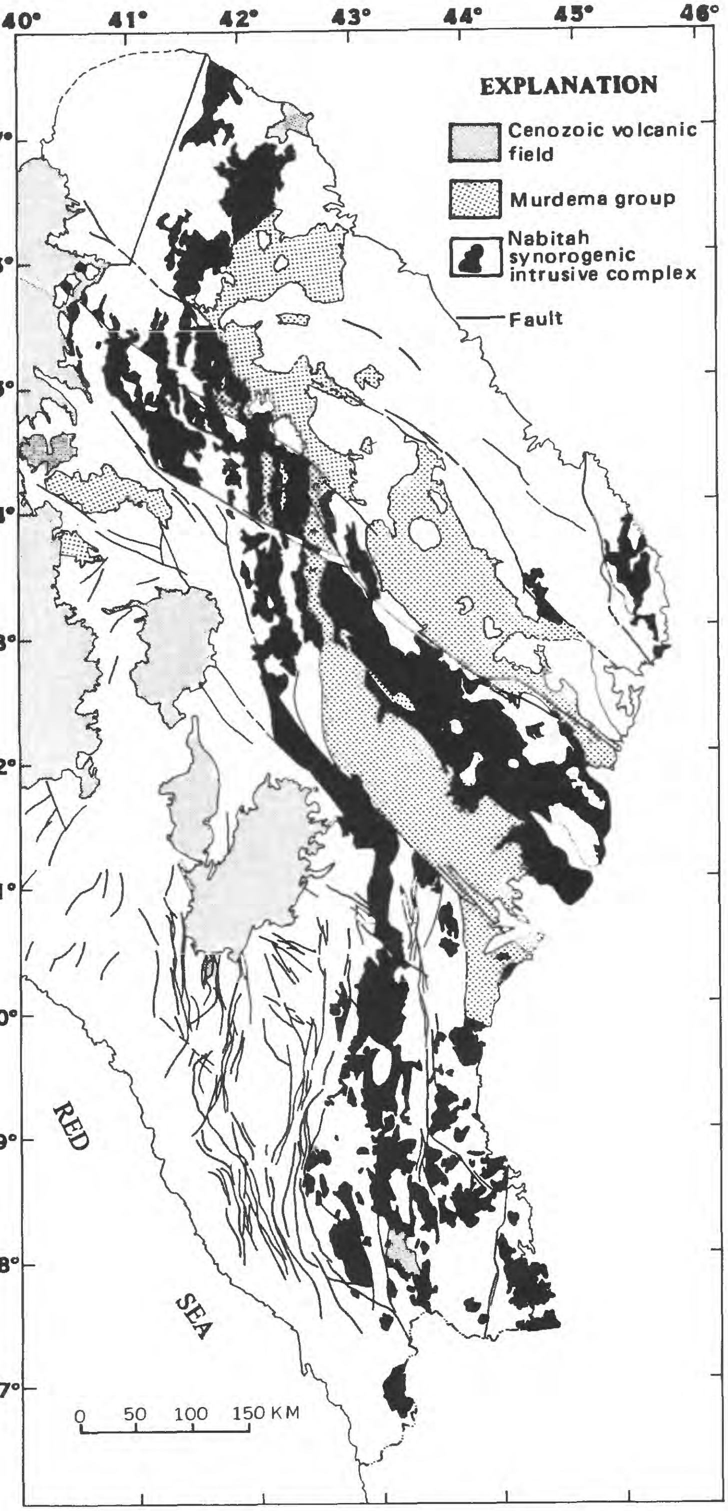

Figure 9.--Simplified geologic map of the Arabian Shield east of long 40° E. showing the distribution of Nabitah synorogenic intrusive complexes and the Murdama group.

information is available on the Nabitah ophiolite belt as a whole, but Frisch and Al-Shanti (1977) have described it in the central shield, and Al-Rehaili and Warden (1980) and Worl (1981) have described the Hamdah serpentinite at the south end of the belt. Few of the ultramafic bodies and complexes along the Nabitah zone appear to qualify as true ophiolites (Frisch and Al-Shanti, 1977). The question of their origin, however, will have to be settled by detailed studies of the larger ultramafic complexes along the belt, particularly those located in the north-central region (fig. 8).

Further to the north, the west boundary of the Nabitah mobile belt is sharply defined. The east margin of the belt, however, is not well defined and is placed where linear north-trending gneissic zones pass into diffuse complexes of gneissic rocks without strongly defined trends. Much of the eastern boundary of the mobile belt is covered by the younger Murdama group. This boundary also approximately correlates with the change from common-lead isotopes of oceanic character in the west to continental in the east (fig. 7; Stacey and Stoeser, 1984 .

The aeromagnetic map of the Arabian Shield (Blank and others, 1980) clearly delineates the Nabitah mobile belt in the central and northern shield. The island-arc terrane to the west has a pronounced east-trending magnetic grain that is sharply truncated by the north-trending magnetic grain of the Nabitah mobile belt. In the southern part of the mobile belt, however, the magnetic grain trends eastward, indicating the relation of the rocks in the southern part of the belt to the island-arc-type rocks of the Hijaz-Asir domain, and only the Nabitah fault zone is clearly delineated as a sharply defined north-striking magnetic zone.

Gneiss domains

A gneiss domain is defined here as a region on the scale of tens of square kilometers or more in area that has been intensely deformed and is dominated by synorogenic plutonic rocks and orthogneisses. These gneiss domains are high-grade plutonic core complexes within broad deformed metamorphic terranes. These terranes also include other small syntectonic plutons and complexes. Within the study area (fig. 2), four main gneiss domains are recognized -- the Khamis Mushayt gneiss (Schmidt and others, 1973), the Al Qa'ah gneiss (Stoeser, unpub. data, 1984) the Malahah domain (or Malahah dome of Greenwood, 1980a), and the Najran domain (or Najran complex of Stoeser and others, in press; Sable, 1983).

The Khamis Mushayt and Al Qa'ah gneiss domains are very similar in that they are dominantly composed of gneissic leucogranodiorite and leucomonzogranite (Coleman, 1973;

Greenwood, 1981; Stoeser, in press) that contain abundant remobilized (migmatitic) elements of older crustal rocks. We obtained two new ages for the Khamis Mushayt domain, one of 654±7 Ma for a weakly foliated antiformal leucogranodiorite body (locality 7), and one of 667±4 Ma for a mafic quartz diorite (locality 5). In addition to these ages, Fleck and others (1980) obtained a 664±9-Ma Rb-Sr whole-rock isochron age for a garnet-bearing leucogranodiorite (locality 20) that occurs as a small antiformal gneiss pluton adjacent to the Khamis Mushayt gneiss, similar to the body at locality 7. No geochronologic data are available for the Al Qa'ah gneiss. It is cut by the Tindahah monzogranite and is therefore older than 635±15 Ma (table 2). The Al Qa'ah gneiss forms part of the axial gneiss belt west of the Nabitah fault zone (figs. 7 and 9).

The Malahah domain (fig. 2) is a very large complex of plutonic rocks that range in composition from gabbro to monzogranite. Structural complexity is shown by intense deformation, very irregular and transitional plutonic boundaries, gneiss domes, and high-grade metamorphism (possibly to the granulite facies) (Greenwood, 1980a; Warden, unpub. data, 1982). Two ages available for plutonic rocks of the Malahah domain are a U-Pb zircon age of 642±5 Ma for the Wadi Makhdhul quartz diorite (locality 9) and a Rb-Sr whole-rock age of 684±43 Ma on a granodiorite gneiss (locality 19).

The Najran domain (fig. 2) is similar to the Malahah domain, although it appears to contain a higher proportion of dioritic and tonalitic plutonic rocks than the other domains. For the Najran domain, two zircon ages are available, the Wadi Simlal quartz diorite (locality 10) at 641±2 Ma and the Wadi Najran A'ashiba gneiss complex (locality 12) at 640±3 Ma.

In addition to ages for the gneiss domains, seven zircon ages are available for other Nabitah plutonic rocks (localities 3,4,6,7,16,17, and 18), most of which intrude the Wadi Tarib batholith. With one exception, the ages obtained for these samples fall in the range from 644 to 674 Ma. The one exception was a gneissic leucogranodiorite from the Hadabah dome (locality 15), which gave an age of 714±28 Ma. This age is significantly older than that of any other syntectonic gneiss unit. Because there is evidence that the Hadabah granodiorite was a direct melt of the Suwaydah tonalite (Stoeser and others, in press), that Hadabah may contain a considerable amount of inherited zircon. In addition, Fleck and others (1980) obtained a whole-rock Rb-Sr age of 643±20 Ma for a granodiorite from the Halal dome (locality 21).

Timing of Nabitah orogeny

From the above data it is clear that, in the southern shield, the Nabitah orogeny began no later than about 675 to 680 Ma and extended until about 640 Ma, when the postorogenic granites began to be emplaced. Owing to the lack of geochronologic data on Nabitah plutonic rocks in the central and northern parts of the Nabitah mobile belt, the timing of the orogeny in these regions is still unresolved. The timing of the end of formation of the Hulayfah-arc assemblage and the start of the Nabitah orogeny remains unclear. No age data for the Hulayfah assemblage demonstrate that any of it is younger than 720 Ma. All of the Nabitah plutonic rocks, except for the Hadabah granodiorite, fall in the span 680 to 640 Ma (fig. 6). There exists, therefore, a gap of about 40 million years between the youngest rocks of the Hulayfah-arc assemblage and the Nabitah plutonic rocks. So few age data are available for the Hulayfah assemblage, however, that the Hulayfah arc may have been in the process of formation as late as 690-680 Ma. We suggest, therefore, that the Nabitah collisional event may have terminated the formation of the Hulayfah arc, but much more geochronologic data will be required to establish this hypothesis.

On this basis, the Nabitah mobile belt can be interpreted in terms of a collision episode involving a hot active arc. Thus, massive crustal remobilization could be expected within the arc due to active magmatism and an elevated geotherm. The axial gneiss zone of the southern shield (fig. 7) may represent the remobilized core zone of the arc. To the west, where the older (cold) island-arc terrane is present, the response to collision was regional lower-greenschist metamorphism, the formation of a pervasive foliation, and mechanical deformation that produced an extensive zone of faulting (fig. 8).

Late to postorogenic events

The most notable geologic events that followed the Nabitah orogeny include the emplacement of numerous granitic plutons, the deposition and deformation of molassic sediments of the Murdama group, and the formation of the left-lateral Najd wrench-fault system and associated Jibalah group (Moore, 1976).

The most intense period of plutonism associated with the Nabitah orogeny appears to have been during the period 645 to 640 Ma, at which time voluminous amounts of diorite to mafic tonalite were emplaced. Although no geochronologic data are available, the extensive gneissic monzogranites of the Khamis Mushayt, Al Qa'ah, and Malahah gneiss domains were probably formed at this time.

The emplacement of oval plutons of unfoliated monzogranite that lack the petrographic and structural characteristics of the synorogenic plutons appears to mark the end of the Nabitah orogeny at 640 to 635 Ma. Although these granites are generally referred to as posttectonic, their emplacement immediately after the last of the synorogenic plutons suggests that they are related to the elevated thermal system present at the end of the Nabitah orogeny. These granites are spatially associated with a series of pyroxene gabbro bodies, many of which are layered and which were probably at least in part cogenetic with the monzogranites. Evidence from previous work indicates that the gabbros were also intruded about 640 Ma (Coleman and others, 1972). Cooper and others (1979) obtained a zircon age of 664 ± 12 Ma on a gabbro (locality 16) that intrudes the Hamdah serpentinite. This age suggests that some of the gabbro of the southern shield may also have been emplaced during the Nabitah orogeny.

Geochronologic studies have shown that voluminous granitoid plutonic rocks, including peraluminous and peralkaline granites, were emplaced in the central and northern shield during the period 620 to 570 Ma (Baubron and others, 1976; Fleck and Hadley, 1982; Calvez and others, 1983; J. N. Aleinikoff and D. B. Stoeser, unpub. data). Interestingly, this group of granites is not known to be represented south of the Najd zone in the southern shield, and significant plutonic activity in this region seems to have terminated by about 625 to 620 Ma (Aleinikoff and Stoeser, unpub. data).

The Murdama group is composed mostly of arkosic clastic sediments that are widely distributed throughout the central, eastern, and northeastern shield. Few geochronologic data are presently available for the Murdama, although a recent study by Darbyshire and others (1983) indicates that the Murdama in the south-central shield is younger than 620 Ma. Their study dealt with volcanic rocks underlying the Murdama sediments, and the ages were obtained by the whole-rock isochron method, which typically gives ages for volcanic rocks that are too young (Schleicher and others, 1983). The lack of deformation of the volcanic rocks suggests that they postdate the Nabitah orogeny and are therefore younger than about 640 Ma. The spatial distribution of the Murdama group within and flanking the Nabitah mobile belt suggests that it is a molasse formed in response to uplift related to the Nabitah orogeny. The age of the Murdama sediments may, therefore, vary widely from place to place within the shield.

The Najd fault system, one of the most prominent structural features of the central and eastern shield, began to form during the latest Proterozoic and continued into the Cambrian (Moore, 1979). Left-lateral offsets of as much as 200 km have been demonstrated for the Najd fault (Brown, 1972; Schmidt and others, 1979). All of these events indicate a significant period of orogenic activity immediately prior to and during the Cambrian Period. Although plate activity is suggested by these events, the specific cause is unidentified. It is perhaps worth noting, however, that regional wrench faulting typically follows plate collisions (Caby and others, 1981).

Orogenic classification

The purpose of this section is to review previous schemes of orogenic classifications that have been presented in the literature and relate them to the present study. These classifications are shown on figure 10, which summarizes the main orogenic events and chief orogenic classification schemes proposed for the Arabian Shield east of long 40° E.

One of the first such classifications was that of Brown (1972; also in Brown and Coleman, 1972), in which three main orogenies were recognized. The earliest, the Kibaran orogeny, which was correlated with the Kibaran of Africa, was based on early K-Ar and Rb-Sr geochronology and the interpretation of an older sialic basement in the southern shield. This interpretation was subsequently rejected (Greenwood and others, 1976). The other two orogenies proposed by Brown and Coleman, the Hijaz and the Najd orogenies, have been retained, but in modified form. It is noteworthy that Brown and Coleman indicated a major culminant orogeny, the Hijaz orogeny, at about 660 Ma and therefore accurately interpreted this aspect of the geochronologic data and mapping then available. Their work was followed by that of Schmidt and others (1973), who proposed a considerably more detailed classification based primarily on 1:100,000-scale mapping.

The two main orogenic schemes presently in use for the Arabian Shield east of 40° E. are those of Greenwood and others (1976, 1980) for the southern and south-central shield and Delfour and others (1982) for the central and eastern shield (fig. 10). Unfortunately, although these classifications have been used in numerous reports, nowhere are they discussed and defined in detail, and their application has tended to be vague.

Greenwood and others (1976, 1980) broadened the Hijaz orogeny of Brown (1972) and Brown and Coleman (1972) into the "Hijaz orogenic cycle" and included within it several specific orogenies (fig. 10). They also rejected the older orogenies defined by Schmidt and others (1973), but retained their Bishah orogeny and Najd wrench-faulting episode.

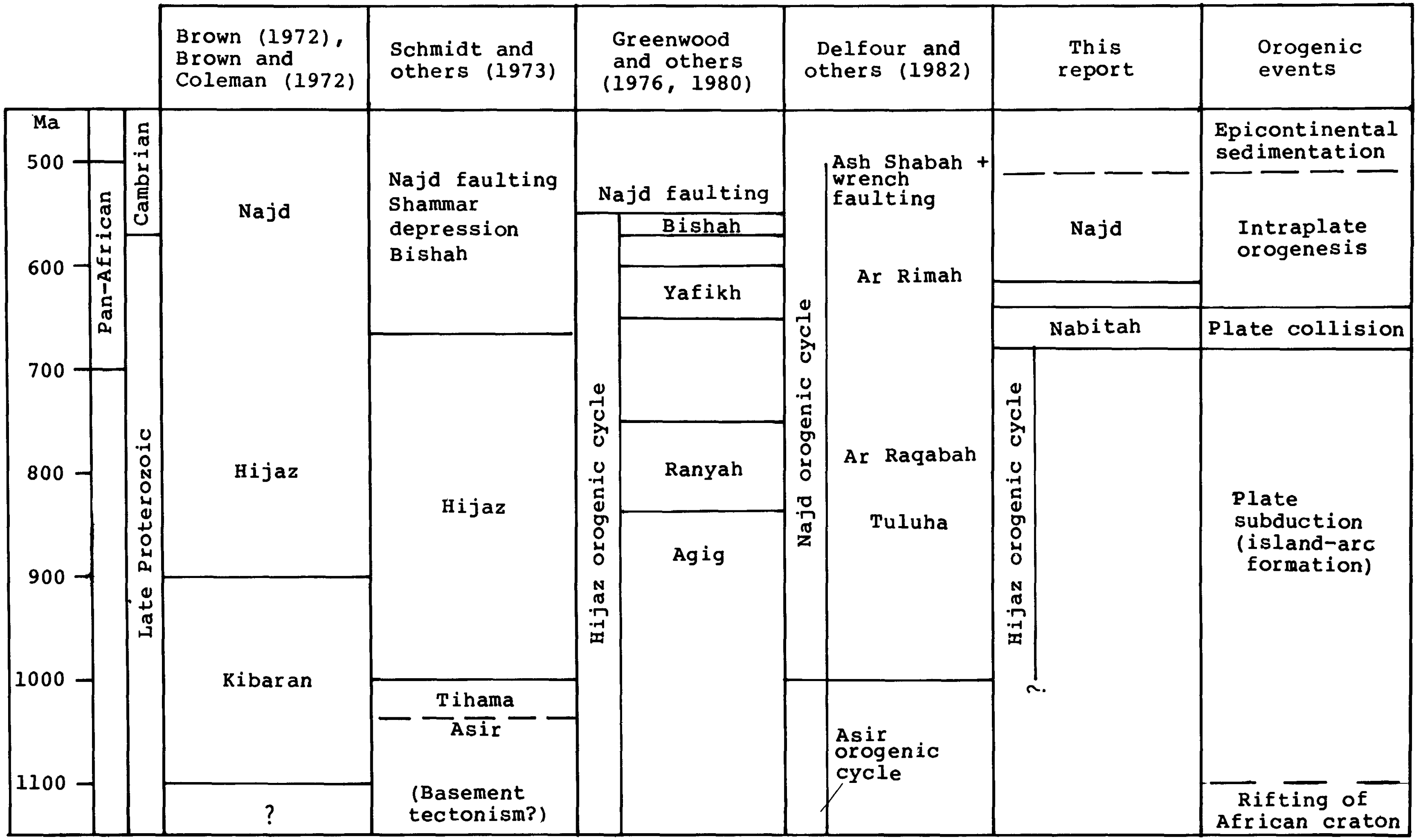

Figure 10.—Summary of major orogenic classification and orogenic events used for the Arabian Shield east of long 40° E. Solid lines bound orogenies that were given specific time limits, otherwise no boundary is shown and the position of the name simply marks the approximate age given in the source reference; dashed lines mark approximate limits.

Delfour (1979a, 1981) and Delfour and others (1982) have developed an orogenic classification for the central and eastern shield which in detail closely parallels that for the southern shield. The chief difference is that Delfour continues to recognize an older sialic basement, which as will be discussed below, appears to have some validity in the eastern shield.

We find none of the current schemes of orogenic classification completely satisfactory. As would be expected in the early work on an area as large and complex as the Arabian Shield, all of these classifications suffer from the same fundamental problems, lack of adequate geochronologic and geologic control. In addition, the definitions of the various orogenies that have been proposed are generally very brief and vague. A contributing problem in defining and correlating regional orogenic events has been a tendency of geologists working on the shield to overextend the application of stratigraphic units, especially at group rank, which has caused considerable difficulty in understanding regional stratigraphic relations and correlations. As more geochronologic research is done and the geology of the shield is synthesized on a regional basis, an integrated system of orogenic classification will have to be established.

We interpret the evolution of the Arabian Shield in terms of three main stages of development: (1) an early island-arc phase, the Hijaz orogenic cycle, from about 950+ to 680 Ma, (2) the Nabitah orogeny, a period of small-plate accretion and suturing (collision) from 680 to 630 Ma, and (3) the Najd orogeny, involving intracratonic and epicontinental activity from 630 to 550 Ma.

Hijaz orogenic cycle

If our interpretation is correct, the collisional events represented by the Nabitah and other suture zones within the Arabian Shield indicate a fundamental change in the geologic evolution of the Arabian Shield. That is, they mark the time at which the ensimatic island-arc development of the various segments of the shield ended and after which the shield was integrated into a single cratonic unit. We recommend, therefore, that the term "Hijaz orogenic cycle" (if it is to be retained at all) be used to refer only to the time during which plate subduction was operating to form the Arabian-Nubian arc assemblage (that is, 950+-680 Ma).

Nabitah orogeny

Several orogenies or orogenic phases have been proposed that may be wholly or partly correlative with the Nabitah orogeny. These are the Bishah orogeny of Schmidt and others

(1973) and Greenwood and others (1976) and the Ar Raqabah and Ar Rimah orogenic phases of Delfour (1979b, 1981).

The Bishah orogeny of Schmidt and others (1973) (fig. 10) presents particular problems in light of the present study. The original definition of Schmidt and others refers to an episode of deformation at about 570 Ma when "the rocks of the Murdama group were folded about north-south axes and slightly metamorphosed". Greenwood and others (1976, 1980) followed this definition and indicated that the Bishah orogeny occurred during the period 570 to 550 Ma. In his later quadrangle work, however, Schmidt (1981) changed the definition of the Bishah orogeny to refer to a period of orogenesis that occurred about 650 to 625 Ma, during which synorogenic gneiss complexes were emplaced into the Halaban group. Unfortunately, Schmidt did not present his reasons for changing the definition of the Bishah orogeny. This oversight presents us with the choice of accepting the revised Bishah orogeny or dropping it in favor of a new name. The problem with accepting the revised definition of the Bishah orogeny is that, although the Bishah area may have served as a reasonable type area for the orogeny as originally defined, it lies outside of and to the west of the Nabitah mobile belt and, therefore, is not a good choice for a reference or type area for the Nabitah orogeny. For this reason, we abandon the use of the term "Bishah orogeny" and propose the new term "Nabitah orogeny".

Delfour (1981) showed two orogenic phases in his Najd orogenic cycle (fig. 10), the Ar Raqabah and Ar Rimah phases, which may relate to the Nabitah orogeny. The Ar Raqabah orogenic phase, placed at about 740 Ma, is considered to postdate the Hulayfah group and predate the Murdama group. The Ar Rimah orogenic phase, placed in the period 690-610 Ma, is considered to postdate the Murdama group and "correlate with the major event of the Pan-African orogeny". Thus, in terms of relative stratigraphic relations, the Nabitah appears to correlate with the Ar Raqabah orogenic phase, whereas, in terms of timing and emphasis it appears to correlate with the Ar Rimah phase. In an earlier work, Delfour (1979b) placed the Ar Raqabah phase at about 640 Ma and the Ar Rimah phase as post 600 Ma. We consider the definition and application of these two orogenic phases to be too vague to be useful.

Najd orogeny

As we have already discussed, there was notable orogenic activity during the interval 615 to 550 Ma. This episode has been referred to as the Najd orogeny by Brown (1972), as the Bishah orogeny in its earlier usages (Schmidt and others, 1973; Greenwood, 1976, 1980), and as the Ar Rimah plus Ash

Shabah orogenic phases of Delfour (1981, 1982) and Delfour and others (1982) (fig. 10). Also, the definition of the term "Bishah orogeny" was modified by Schmidt to refer to what we here call the Nabitah orogeny. Delfour and others (1982) similarly have modified the definition of the Ar Rimah orogenic phase, which originally referred to events around 600 Ma, to mean those around 690 Ma. Although Delfour and others refer to orogenic events during the interval 610 to 535 Ma, they did not name them. For these reasons, we prefer to return to Brown's (1972) term "Najd orogeny" and await more definitive studies which will refine and resolve the orogenic events of the Arabian Shield after 620 Ma.

Two main phases of the Najd orogeny can be recognized. The early phase of the Najd orogeny represents the time during which the Murdama was deformed and metamorphosed and the younger granites of the central and eastern sheild were emplaced (that is, 615-570 Ma). As was noted earlier, there appear to have been two main periods of Pan-African granitic plutonism in the eastern two-thirds of the shield, one associated with the latter part of the Nabitah event during the period 660 to 635 Ma, and one that occurred from about 620 to 570 Ma (Fleck and others, 1980; Fleck and Hadley, 1982; Calvez and others, 1983). Najd plutonism does not appear to be present in the southern shield, with major granitic plutonism having ceased by about 625 to 620 Ma (Aleinikoff and Stoeser, unpub. data).

The later phase of the Najd orogeny represents the time during which the bulk of the displacement occurred on the Najd fault system and the Jibalah group was deposited in depressions related to the faulting (Moore, 1976; Delfour, 1981). It is not yet clear how long the Najd fault system was active, but it clearly began after the bulk of the Najd granites had been emplaced, and therefore, must have been in operation during the period 590 to 550 Ma and may have continued until about 530 Ma (Delfour, 1979b, 1981; Delfour and others, 1982; J. S. Stacey, unpub. data). The Najd orogeny marks the final period of orogenic activity involved in constructing the Arabian Shield, after which the lower Proterozoic Saq and Wajid Sandstones onlapped the subsiding shield from the north and south, respectively (Powers and others, 1966: Anderson, 1979; Greenwood, 1980b).

REGIONAL INTERPRETATION

In this section we integrate the results of this study with several of our recent studies in order to outline the Pan-African evolution of the Arabian Shield east of long 40° E. The chief conclusions and elements of our interpretation are that the Arabian Shield east of 40° can be divided into three distinct and probably fundamentally different crustal terranes or provinces that are separated by two orogenic belts (sutures). The three crustal terranes are the Hijaz-Asir province in the west, the Afif province in the center, and the Ar Rayn province in the east (the last two terms are adapted from Delfour and others, 1982, and Calvez and others, 1983). The Hijaz-Asir and Afif provinces are separated by the Nabitah mobile belt, and the Afif and Ar Rayn provinces are separated by the Ad Dawadimi belt or province (Delfour and others, 1982).

Hijaz-Asir province

The Hijaz-Asir province consists primarily of metavolcanic, metasedimentary, and tonalitic plutonic rocks interpreted as having formed in an oceanic island-arc environment as a result of plate-subduction processes (Greenwood and others, 1976, 1980, 1982; Fleck and others, 1980). In addition to evidence from geologic mapping and, to some extent, from standard geochemical studies, this conclusion is supported by the results of Rb-Sr, U-Th-Pb, and Nd-Sm isotopic studies (Fleck and others, 1980; Stacey and others, 1980; Bokhari and Kramers, 1982; Stacey and Stoeser, 1984). It should be understood, however, that the Hijaz-Asir domain is undoubtedly composed of multiple arc and other assemblages whose origins remain to be resolved.

As was noted earlier, the rocks of the Hijaz-Asir province can be split into two main subdivisions, an older island-arc assemblage that formed during the period 950+ to 800 Ma (Fleck and others, 1980; Greenwood and others, 1980) and a younger island-arc assemblage in the eastern part of the province that formed from 785 to about 680 Ma (Fleck and others, 1980; Greenwood and others, 1982). The older island-arc assemblage consists of the Baish, Bahah, and Jiddah groups in the southern shield (fig. 12). These rocks consist in large part of metabasalt (greenstone), metagraywacke, and minor dacite, andesite, chert, and marble (Greenwood and others, 1976, 1980). In the southwestern part of the shield, the older arc assemblage is underlain by and intercalated with pelitic and quartzofeldspathic sandstone and siltstone that may represent, at least in part, a shelf sequence derived from the African craton or from some other nearby continental source (Fairer, 1981; Ramsay and others, 1981; Pallister, 1984). The younger arc complex consists of the Halaban and Hulayfah groups, which have already been discussed.

Afif province

The Afif province, excluding the Pan-African granites, includes two main lithologic subdivisions -- a younger series

(<640-580 Ma) of intermediate to felsic volcanic rocks and clastic sediments of the Murdama and Shammar groups, and an older crystalline basement complex whose geology is poorly known (Baubron and others, 1976: Delfour, 1981, 1982; Calvez and others, 1983) (fig. 12). The Hulayfah group is reported to occur in extensive areas in the southern half of the Afif province (Schmidt and others, 1979; Letalenet, 1979), but recent work indicates that the volcanic rocks considered to be part of the Hulayfah are approximately the same age as the Murdama group (Darbyshire and others, 1983).

The basement complex consists of voluminous intermediate plutonic rocks, felsic gneisses, and sparse paragneisses and schists (Delfour, 1979b; Letalenet, 1979). Although much of this complex was considered to be of Early Proterozoic or Archean age (Delfour, 1981), this age has not been confirmed by radiometric geochronologic studies, and the bulk of these rocks appear to have formed between 730 to 660 Ma (Baubron and others, 1976; Fleck and Hadley, 1982; Calvez and others, 1983; Stacey and others, unpub. data, 1984). In fact, many of them appear to be related to the Nabitah orogeny.

That older crustal elements of early Proterozoic age are at least locally present in the eastern shield has been shown by Calvez and others (1983), who report finding 2000-Ma-old zircons in a plagiogranite from south of Al Amar, and by Stacey and Hedge (1983), who report U/Pb zircon data for a granodiorite gneiss at Jabal Khida (fig. 7) that give a concordia upper intercept age of 1,630 Ma and a lower intercept age of 660 Ma. Stacey and Hedge also report whole-rock Rb-Sr, U-Pb-Th, and Nd-Sm isotopic data for the Jabal Khida sample that are all consistent with derivation from an evolved continental source of middle to early Proterozoic age with Archean antecedents. This sample may represent a 1,630-Ma-old rock that was remobilized during the Nabitah orogeny, or a Nabitah-age syntectonic plutonic rock that was derived directly from such a crust.

Isotopically the Afif province is distinct from the Hijaz-Asir, Nabitah, Ad Dawadimi, and Ar Rayn provinces in that common-lead isotopes from some feldspar and ores in the Afif province have a continental component that requires an upper crustal early Proterozoic to Archean source (fig. 11; Stacey and Stoeser, 1984). Initial $^{87}Sr/^{86}Sr$ ratios also tend to be slightly elevated in the Afif province (0.7035-0.7070) as compared to the Hijaz-Asir province (0.7020-0.7035) (Baubron and others, 1976; Fleck and Hadley, 1982; Stacey and Hedge, 1983; Calvez and others, 1983; Stacey and Stoeser, in press). It appears, therefore, that the Afif crust is somewhat more continental in character than that of the other provinces and, at least at Jabal Khida, contains an older continental crustal component. Whether the Afif terrane represents a rifted fragment of the African craton or

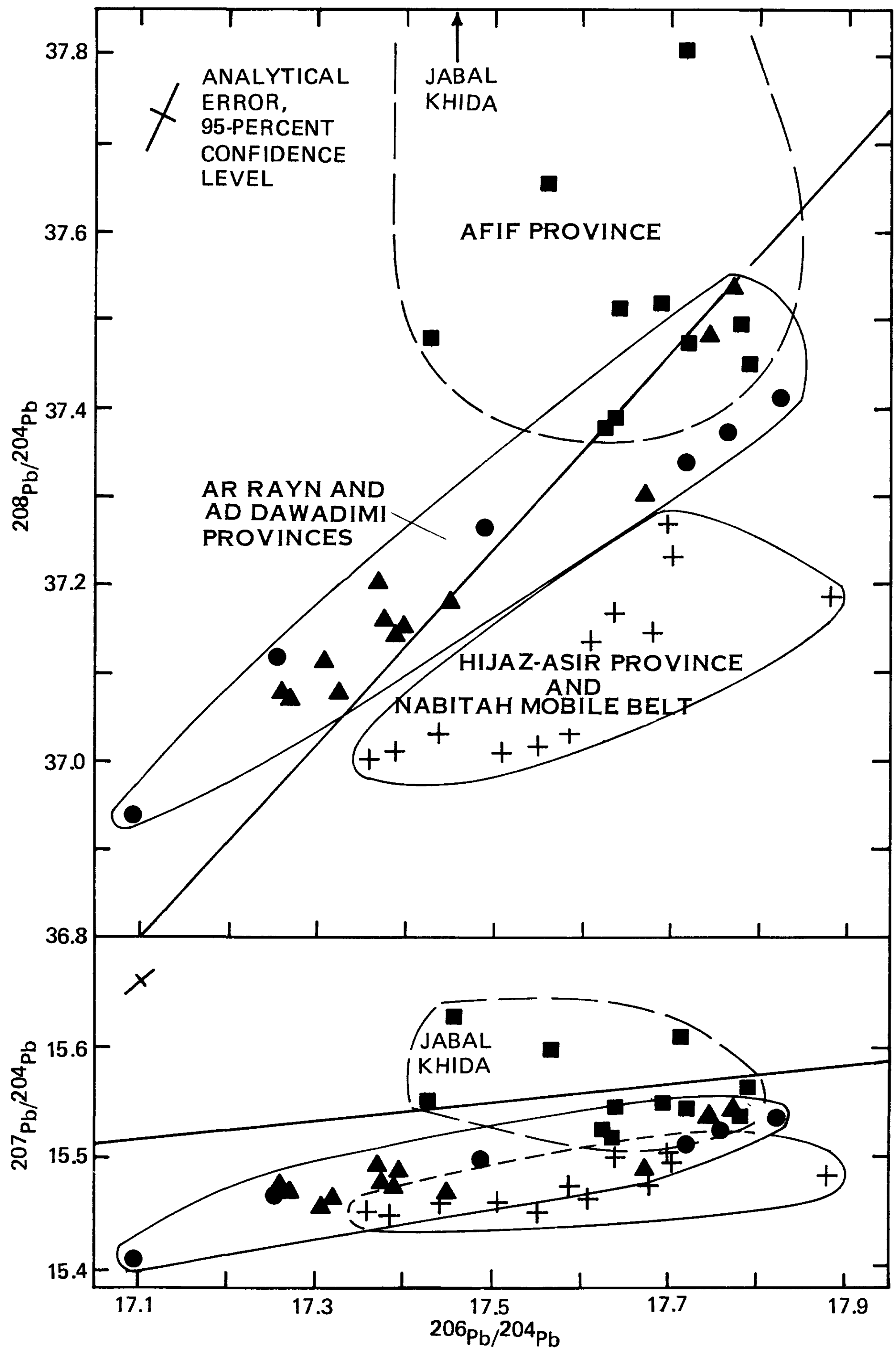

Figure 11.--Common-lead-isotope data for ores and feldspars from the Arabian Shield. Data taken from Stacey and others (1980), Bokhari and Kramers (1982), Stacey and Stoeser 1984), and Stacey and Hedge (1983). Plus signs, Hijaz-Asir domain and Nabitah mobile belt; filled squares, Afif domain; filled circles, Ad Dawadimi domain; and filled triangles, Ar Rayn domain.

is from some other source cannot be determine with available data. As already noted, the Afif crust appears to have been extensively remobilized during the Nabitah orogeny.

Ar Rayn province

The Ar Rayn province is represented by only a small segment in the easternmost Arabian Shield (fig. 7); the rest of it is concealed to the east beneath the Phanerozoic cover rocks. The exposed part is underlain by post-635 Ma volcanic rocks and sediments (Ahrmer group) and granites, abundant 660- to 635-Ma intermediate felsic and plutonic rocks, many of which are gneissic, and some pre-660-Ma volcanic and sedimentary rocks (Al Amar group, fig. 12) (Calvez and others, 1983; Stacey and others, in press). Isotopically the Ar Rayn province is distinct from both other crustal provinces in that the common-lead isotopes exhibit an older lower crustal component (Stacey and others, 1980; Stacey and Stoeser, 1984; Bokhari and Kramers, 1982). Although the Ar Rayn and Ad Dawadimi common-lead-isotope data overlap on figure 11, they lack the highly evolved lead component present in some samples from the Afif domain.

Ad Dawadimi province

The Ar Rayn and Afif provinces are separated by the Ad Dawadimi province, in which the Abt formation, a highly compressed and metamorphosed sequence of metamorphosed sandstone, argillite, and shale, has been tectonically intercalated with an ophiolitic suite of ultramafic rocks, gabbros, and basic volcanic rocks (Delfour, 1979a,b). These rocks, collectively known as the Urd group, have been interpreted to represent either the sedimentary fill of a back-arc basin floored by oceanic crust (Nawab, 1979; Al-Shanti and Gass, 1983) or an accretionary wedge and associated oceanic crust that were compressed during a collisional event (Al-Shanti and Mitchell, 1976; Schmidt and others, 1979; Stacey and others, in press). Radiometric age data suggest that both the Urd group and the Ar Rayn crust were involved in a major period of compressional orogeny, the Al Amar orogeny, during the period 670 to 630 Ma. This compressional episode, caused by plate collision between the Afif and Ar Rayn crustal blocks (Stacey and others, in press), was contemporaneous with the Nabitah orogeny.

TECTONIC EVOLUTION

Thus, for the Arabian Shield east of the Nabitah mobile belt, the effects of the Nabitah and Al Amar orogenies appear to have been pervasive, and much, if not all, of the crust in

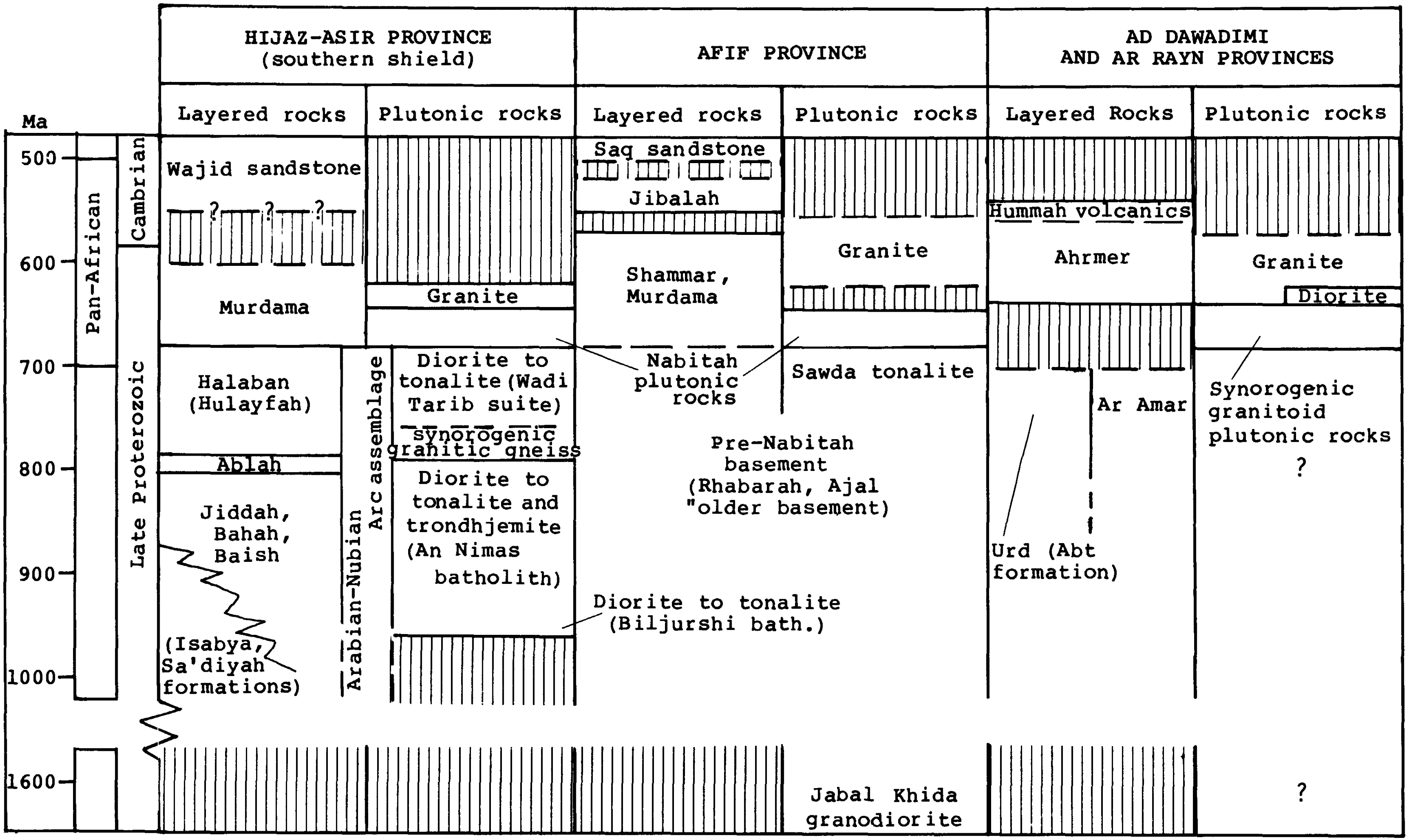

Figure 12.—Simplified stratigraphic columns for the Hijaz-Asir, Afif, Ad Dawadimi, and Ar Rayn provinces. Vertical linex indicate time periods not known to be represented by stratigraphic units; approximate boundaries indicated by dashed lines. Source references: Hijaz-Asir province, Greenwood and others (1976, 1982), Cooper and others (1979), Fleck and others (1980), Stoeser and others in press), Fairer (1982), J. N. Aleinikoff and D. B. Stoeser, (unpub. data); Afif, Ad Dawadimi and Ar Rayn provinces, Baubron and others (1976), Delfour (1979), Letalenet (1979), Fleck and Hadley (1982), Darbyshire and others (1983), Stacey and Hedge (1983), Calvez and others (1983), and Stacey and others (1984).

that region older than 680 Ma was deformed, metamorphosed, and remobilized by these orogenies. Figure 9 shows the distribution of gneissic complexes that appear to be related to the Nabitah and Al Amar orogenies. It is again emphasized that these gneissic complexes represent broad areas of crustal remobilization and, therefore, contain voluminous amounts of older crust, synorogenic leucocratic granitoid plutonic rocks, and some younger granitoid plutonic rocks.

To reconstruct an accurate history of the Nabitah mobile belt, it is critical to resolve the nature of the crust on either side of belt. If the Afif crust can be shown to be similar to that of the Hijaz-Asir province, then the mobile belt could be inferred to have originated by intraplate or back-arc rifting followed by collision. If these two crustal provinces can be shown to be distinctly different, then a plate-tectonic model involving the collision of allochthonous plates can be inferred.

Common-lead-isotope data have proven particularly useful in resolving crustal characteristics within the Arabian Shield. Stacey and others (1980) and Stacey and Stoeser (1984) have recognized two types of common-lead isotopes in rocks, ores, and feldspars from the Arabian-Nubian Shield. Type-I lead is derived strictly from the mantle, whereas type II is more evolved and contains an older crustal component, some of which must have been derived from an evolved continental source. Figure 7 shows the distribution of localities where samples of the two lead types were obtained. The type-I lead is distributed throughout the Hijaz-Asir province and the Nabitah mobile belt, whereas samples from the Afif, Ad Dawadimi, and Ar Rayn provinces contain type-II lead. On figure 11, these data are subdivided into three fields on the basis of similarity and geographic distribution by domain. From the figure, it can be seen that the common-lead isotopes of the Hijaz-Asir, Afif, and Ar Rayn provinces fall into distinct groups, with only a slight overlap between the Afif and Ad-Dawadimi-Al Amar provinces.

A recent deep seismic-refraction profile that crossed all three provinces provided additional evidence that the three crustal provinces are distinct (Mooney and others, 1983; Gettings and others, 1983). The contrast between the Hijaz-Asir and Afif provinces is slight, but the crust in the Afif province appears to be somewhat less dense and therefore more felsic than the crust to the west. The crust of the Afif province, however, is distinctly different from that of the Ar Rayn province. The Ar Rayn crust has different crustal layers than the Afif crust and is considerably more dense (that is, more mafic). In addition, the seismic data require the presence of a major crustal boundary beneath the Ad Dawadimi province (fig. 13B).

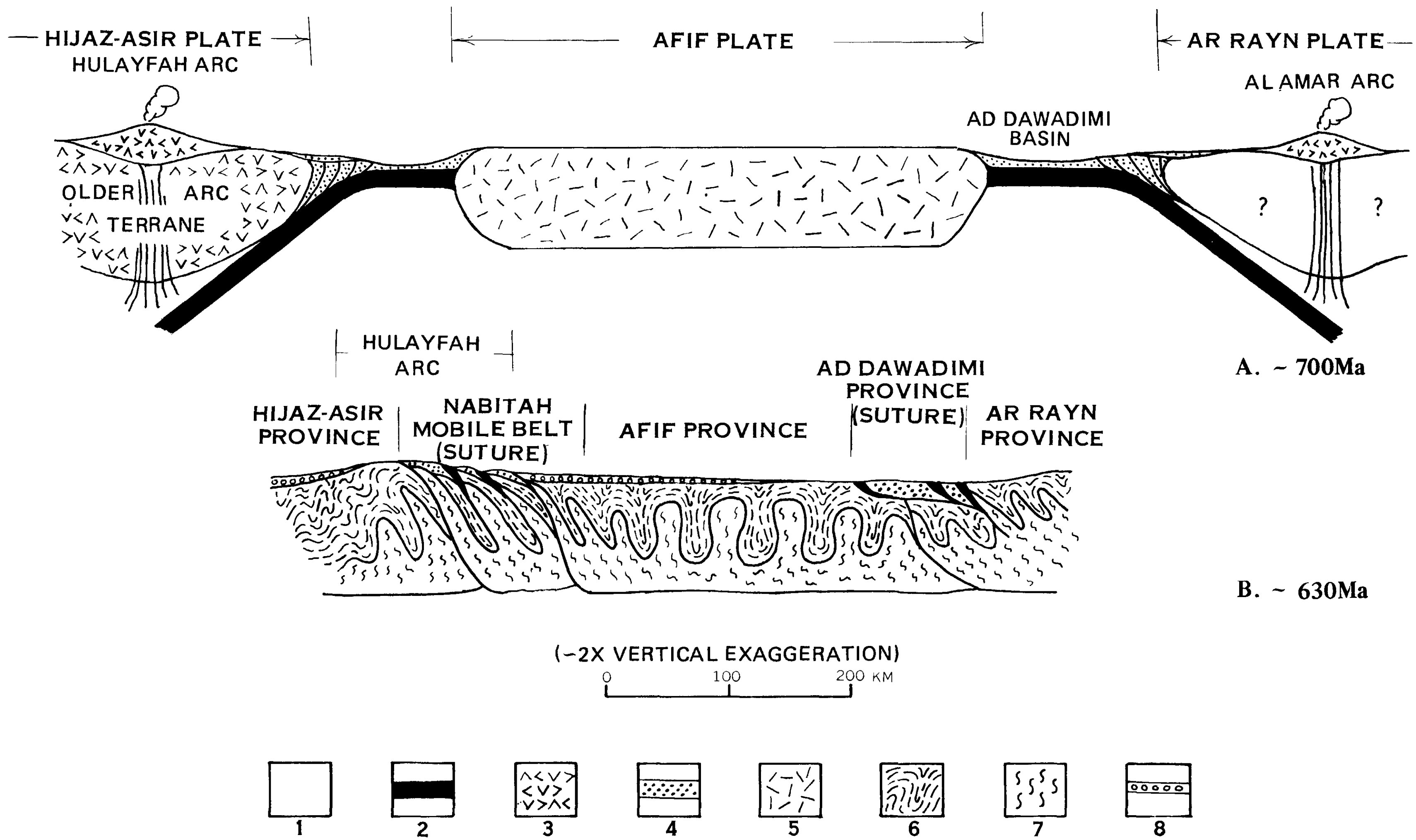

Figure 13.—Hypothetical east-west cross sections through the central and eastern Arabian Shield approximately 700 and 630 Ma ago. See text for explanation. Symbols used: (1) asthenosphere, (2) oceanic crust in A and ophiolitic complex in B, (3) island-arc assemblage, (4) fore-arc, trough, and shelf sediments, (5) continental(?) crust, (6) deformed crust older than 680 Ma, (7) synorogenic plutonic complexes and remobilized lower crust, and, (8) intermontane and shallow-marine molassic sediments (Murdama group).

We propose the following model to explain the tectonic evolution of the Arabian Shield east of long 40° E. during the Pan-African period.

(1) A period of formation and accretion of oceanic island arcs between 950 and 680 Ma, including the formation of the Hulayfah arc between about 780 and 680 Ma in the central and southern shield.

(2) Intense compressional orogeny during the period 680-630 Ma was the result of collision between the Hijaz-Asir and Afif crustal blocks and between the Afif and Ar Rayn crustal blocks (fig. 13B).

(3) A final orogenic phase took place in the northern shield from about 620 to 550 Ma, during which extensive molassic sedimentation, granitic plutonism, and the Najd faulting occurred.

Figure 13 illustrates the situation at about 700 Ma. We suggest that, for the region east of long 40° E., at least two subduction zones were operating, a westward-dipping one beneath the west margin of the Hijaz-Asir crust that generated the Hulayfah arc, and one dipping eastward that generated the Al Amar volcanic rocks of the Ar Rayn province. We are very uncertain, however, about the subduction geometry in the eastern shield (Stacey and others, in press). In the west, a westward-dipping subduction zone appears to be required on the basis of the location of the axis of the Hulayfah arc west of and parallel to the Nabitah mobile belt and associated ophiolitic rocks.

One consequence of this model is that it indicates that the Hulayfah group should not exist east of the Nabitah suture, even though, as discussed earlier, the Hulayfah group has been widely mapped and represented in the eastern shield. An Rb/Sr study by Darbyshire and others (1983) has shown that the bulk of the volcanic rocks that have been assigned to the Hulayfah and Halaban groups in the eastern shield are younger (630-570 Ma) and cannot belong to these units. If these volcanic rocks are not part of the Hulayfah group, then almost no other rocks in the shield east of the Nabitah mobile belt could belong to the Hulayfah group.

We predict, therefore, that the following general lithofacies distribution of layered rocks of Hulayfah age (730+ to 680 Ma) will be found in the central shield. West of the Nabitah ultramafic zone, there should be voluminous volcanic and sedimentary rocks marking the axis of the Hulayfah arc, and, as the Nabitah suture is approached from the west, we should see an increase in the volume of volcanic wackes and flysch, which represent sedimentation on the eastern flank of the arc and in the adjacent trough. The suture zone will be dominated by the ophiolitic suite, accompanied by deep-water finer grained sediments. The age of the oceanic crustal portion (ophiolites) of the Nabitah belt should be within the range from 785 to 680 Ma (that is, it should be contemporaneous with the Hulayfah-arc assemblage). These rocks may be overlain by more shallow-marine sediments formed in the early stages of collision and deposited in small basins along and near the suture zone. The shape and distribution of such basins would be a function of the geometry of collision, including the shapes of the convergent plate margins. In the east part of the suture zone, the rocks should consist mostly of sediments, possibly of a continental-shelf type (White, 1983). Additionally, these Afif-province sediments will flank and overlie a crystalline basement about which little is known.

Even if the predicted sequence is present, it will be difficult to recognize because of structural complications and dismemberment related to the Nabitah orogeny, emplacement of the gneiss complexes, uplift, erosion, and the deposition of molassic (Murdama-type) sediments and possibly volcanic rocks. In addition, the possibility of significant lateral (transform) movement between the Afif and Hijaz-Asir crustal blocks during collision cannot be ruled out. The manner in which the Nabitah zone sharply truncates regional geologic and aeromagnetic trends in the northern part of the Hijaz-Asir province suggests such movement. Another factor that needs to be considered is that the southern shield was much more deeply eroded than the northern shield during late Pan-African and Cambrian time (Stoeser and Elliott, 1980).

The only definitive radiometric ages on the synorogenic plutonic rocks associated with the Nabitah mobile belt are those presented in this report. They indicate that collision began in the southern part of the belt at about 680 Ma and continued until about 640 Ma. Since there is no reason to assume that collision occurred simultaneously along the entire belt, we can say little about the overall timing of the collisional event along its length. Available evidence suggests that, throughout the entire eastern shield, including the Ar Rayn block, the orogenesis was westward directed; this conclusion is reflected in figure 13.

The Nabitah mobile belt is a continuous linear orogenic zone of considerable length and breadth. Many features of the mobile belt are typical of tectonic provinces thought to be collisional suture zones. It contains a belt of ophiolitic complexes, the crust on one side of the belt is distinctly different from that on the other, and a band of island-arc-type volcanic and sedimentary rocks lies parallel to and on one side of the ophiolite line. The geometry of the rock units and tectonic domains clearly favors such an interpretation over one in which the ophiolitic belts represent intraplate rifts that first spread apart enough for oceanic crust to be created, then closed during an episode of compression (Garson and Shalaby, 1976; Delfour, 1981; Kemp and others, 1982).

The interpretation presented in this report rests on reconnaissance-level mapping. The test of the model we have presented must await detailed mapping, structural and lithofacies studies, and isotopic and geochemical studies of the critical lithologies (particularly of the zone containing the ophiolitic rocks and the Hulayfah volcanics and associated plutonic rocks). We also note that regional stratigraphic and other correlations of rock units older than 680 Ma over the entire shield may be invalid.

The occurrence of the Afif province, a relatively small, evolved crustal block intercalated between two other provinces that appear to be of island-arc character and are separated from the Afif province by orogenic zones that appear to be suture zones is very similar to the allochthonous terranes presumed to have accreted to the northwestern margin of the North American craton (Jones and others, 1982; Pavlis, 1982). There, as in the Arabian Shield, it is proposed that elongate allochthonous crustal blocks, possibly including at least one microcontinent of older crust, have been swept together by plate-tectonic processes. In addition to the suturing events described above, Camp (1984) has described and defined the Bir Umq-Port Sudan suture zone in the Hijaz region. Formation of this suture zone between arc terranes is believed to have occurred about 690 Ma. It appears, therefore, that accretion of the Arabian-Nubian Shield onto the African craton proceeded from west to east.

On the basis of major- and trace-element characteristics, Roobol and others (1983) have argued that the volcanic rocks foudn in the Afif and Ad Dawadimi provinces (which have Rb/Sr isochron ages in the range 572 to 616 Ma; Darbyshire and others, 1983) formed in an environment transitional between that of a mature oceanic island arc and a continental-margin island arc (Andean type). If the Nabitah and Ad Dawadimi provinces are sutures, then the Arabian Shield had been welded into a single neocratonic unit by no later than 630 Ma, and these volcanic rocks must have been erupted onto this neocraton. Furthermore, if the volcanics formed above an active subduction zone, it must have been in a continental-margin (Andean) type volcanic arc. If this is correct, then what was the direction of dip of the subduction zone, and where was the associated trench located? Because there is no evidence for a suture zone younger than 600 Ma in the northern, western, or southern parts of the shield, we must assume that the trench was located to the east of the exposed shield and that the subduction zone dipped more or less westward. Assuming plate closure following subduction, there should have been a period of orogenesis during the Cambrian in the region of the central Arabian Peninsula. Thus, the sedimentary record for that region should contain a sequence consisting of deformed older trench flysch-type deposits and arc-marginal clastic sediments overlain by molassic sediments related to uplift. No such sediments are reported to exist in the lower Paleozoic rocks of the region (Powers and others, 1966; Wolfart, 1981), and, therefore, unless a major erosional episode intervened, no such subduction system existed in the region. We suggest that these volcanic rocks are intracratonic in origin and are related to the Najd orogenic activities during the latest Proterozoic and early Cambrian.

An interesting observation is that most of the peralkaline granites of the Arabian Shield (Stoeser and Elliott, 1980) occur within the Nabitah mobile belt or in orogenic zones within the Hijaz region. These granites, as well as associated metaluminous granites, are typical anorogenic or A-type granites (Collins and others, 1982), yet they have a strong spatial association with shield orogenic zones. Their occurrence in these zones contradicts the general association of peralkaline silicic magmas with regions of crustal extension and rifting (Bowden, 1974). On the other hand, it may support the proposal of Collins and others (1982) that A-type granites form by the partial melting of continental crust that has already undergone a previous and major episode of partial melting, such as must have occurred during the formation of the Nabitah mobile belt.

RELATION BETWEEN TO MINERAL OCCURRENCES AND TECTONIC PROVINCES

Although a comprehensive compilation of mineral occurrences in relation to the tectonic and crustal provinces described in this report was not done, a survey of available compilations shows that the occurrence of certain base and precious metals correlates strongly with certain provinces. We have used a recent mineral-occurrence map of the Arabian Shield (van Daalhoff, 1982) to prepare figure 14, which shows only the dominant element present for each mineral occurrence.

The following correlations between mineral distribution and tectonic provinces in the Arabian Shield east of long 40° E. are shown on figure 14: (a) Gold. The distribution of gold mineralization in the Arabian Shield strongly correlates with the Nabitah and Ad Dawadimi suture zones. In particular, gold occurrences are concentrated along the Nabitah fault zone and associated ultramafic complexes (Worl, 1980). (b) Silver and lead. Mineral deposits in which silver and

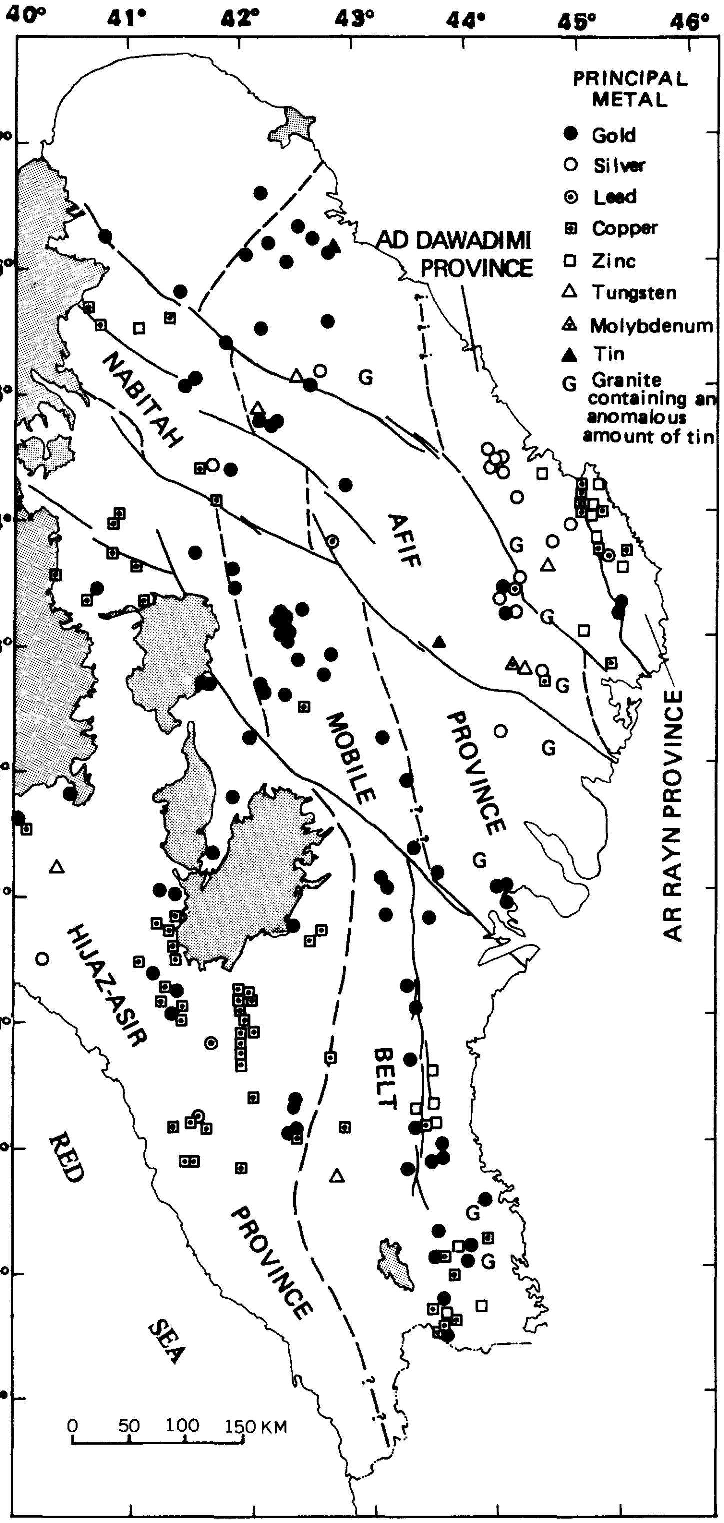

Figure 14.--Map showing the distribution of base- and precious-metal occurrences and tin-anomalous granites in the Arabian Shield east of long 40° E. (modified from van Daalhoff, 1982; du Bray and others, 1982). Heavy dashed lines are province boundaries from figure 7.

lead are the dominant elements are almost completely restricted to the Afif and Ad Dawadimi provinces (Moore, 1976; Al-Shanti and Roobol, 1979). This observation is compatible with the evidence that the Afif crust has more evolved continental characteristics and suggests that at least part of the Ad Dawadimi region is underlain by such crust or that the Afif crust has contributed to the sediments of the Abt formation in the region. (c) Copper and zinc. Deposits rich in these elements are almost completely restricted to the Arabian-Nubian arc assemblage of the Hijaz-Asir province and the volcanic rocks of the Ar Rayn province. The scarcity of such deposits in the Afif domain emphasizes the scarcity of such rocks in that region. Zinc-dominant base-metal deposits appear to be largely restricted to the Hulayfah group of the southern shield and the Ar Rayn volcanic rocks, whereas copper is dominant in the base-metal deposits of the older part of the Arabian-Nubian assemblage. (d) Tin. Although only one significant example of tin mineralization is present in the Arabian Shield, tin-anomalous granites of peraluminous affinity are present in the eastern and southeastern parts of the shield (du Bray, in press ,b). These granites are concentrated in the Afif and Ad Dawadimi provinces, again indicating the continental character of those areas. (e) Tungsten. Small tungsten deposits are scattered throughout the region, but the majority lie within the Afif province (Elliott, 1983). There are few molybdenum occurrences in the eastern shield, but these also occur in the Afif province. It appears, therefore, that the provinces recognized in this and earlier papers, however interpreted, represent fundamental shield crustal units with distinct geologic, isotopic, and metallogenic characteristics (Stacey and others, 1980; Delfour and others, 1982; Stacey and Stoeser, 1984).

RELATION OF THE MABITAH MOBILE BELT TO OTHER PAN-AFRICAN MOBILE BELTS

The identification of a Pan-African-age mobile belt in the Arabian Shield raises the question of the relation of this belt to other Pan-African mobile belts. Recent work is tending to recognize two main types of Pan-African belts -- ensialic intraplate belts that involve orogenic reworking of an older crust, and plate-marginal belts that represent a suture zone formed by plate collision at the end of a "Wilson cycle" (Hurley, 1973; Kroner, 1979a). Clearly, we interpret the Nabitah mobile belt as belonging to the latter type.

Figure 15 shows the position of the Nabitah mobile belt relative to other African mobile belts. The northern extension of the Nabitah belt lies under the Phanerozoic sedimentary cover of northern Saudi Arabia, and nothing is known about the basement in that region. To the south, the Nabitah belt extends into Yemen, where it is largely concealed by

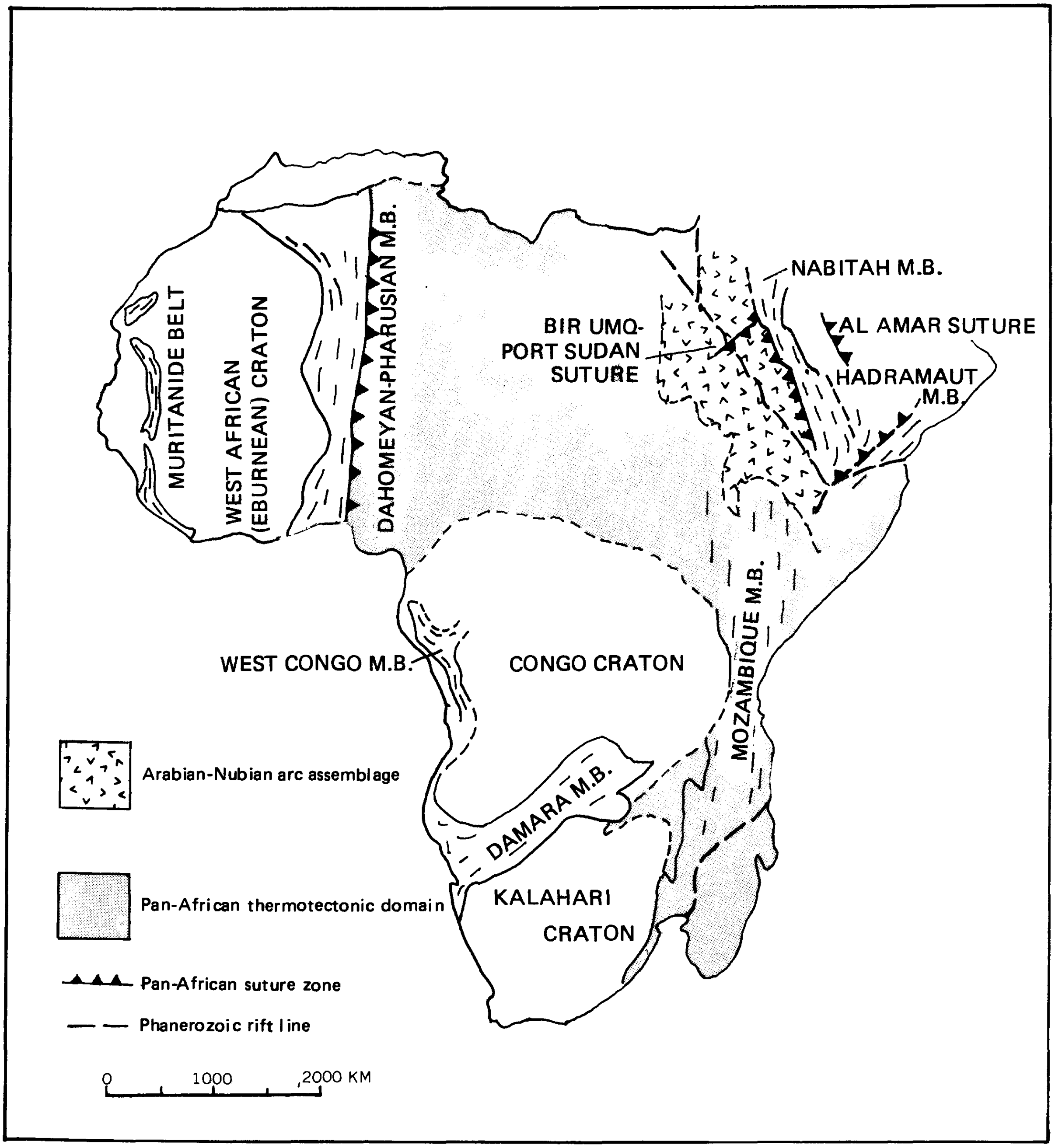

Figure 15.--Simplified geologic map showing the distribution of Pan-African mobile belts (m. b.), thermotectonic domains, the Hijaz-Asir arc assemblage, and Archean cratons in the African Precambrian Shield (after Kroner, 1979a). Triangles on suture zones indicate inferred direction of plate subduction prior to collision.

Tertiary plateau volcanics. There are extensive outcrops of the Precambrian in southern Yemen and the Hadramaut, although little is known about the basement in these areas. Available mapping (Greenwood and Bleackley, 1967; Grolier and Overstreet, 1978) and return-beam videocon satellite imagery of the southern margin of the Arabian Peninsula, which includes southern Yemen and the Hadramaut, clearly show a prominent east-northeast-striking linear belt of intense deformation that has all the earmarks of another mobile belt (fig. 15). The trend of the "Hadramaut belt" is sharply divergent from that of the Nabitah belt. It appears from the above mapping that as the Nabitah belt approaches the Hadramaut belt, the Nabitah belt bends to the southwest and merges with the Hadramaut belt. It is not clear, however, whether the Nabitah belt is truncated by the Hadramaut belt or is in some way related to it.

There has been considerable speculation on the relation of the Mozambique belt to the rocks of the Arabian-Nubian Shield (Vail, 1976; Kazmin and others, 1978; Kroner, 1979a; Hepworth, 1979). It appears however, that the geology of the Arabian-Nubian Shield is so different from that of the Mozambique belt that the Mozambique is considered by most geologists to be a separate geologic terrane. The distinction rests primarily on the island-arc character of the bulk of the Arabian-Nubian Shield as compared to the strongly ensimatic intraplate orogenic nature of the Mozambique belt.

There appears to be growing agreement that the Mozambique mobile belt is older than the Arabian-Nubian arc assemblage (Kazmin and others, 1978; Kroner, 1979a; Almond, 1981). This age difference has led to the question of whether the Arabian-Nubian arc assemblage was deposited over the rocks of the Mozambique belt (Vail, 1976; Hepworth, 1979) or whether the arc assemblage developed in an oceanic environment after oceanic rifting of the Mozambique and therefore has no older continental basement (Greenwood, 1976, 1980; Kazmin and others, 1978; Fleck and others, 1980). As we have stated, isotopic studies appear to leave little doubt that the latter interpretation is correct for the Arabian-Nubian arc assemblage in the southern and western Arabian Shield. Zones of interfingering of Mozambique belt rocks and Arabian-Nubian arc assemblage rocks may represent rifts that formed during the early stages of continental rifting (Kazmin and others, 1978). The western limit of the Arabian-Nubian arc assemblage appears to be well defined as the older Proterozoic and Archean basement of the African craton in northeastern Africa (Vail, 1976; Kazmin and others, 1978). The discovery of older crustal elements to the east of the Nabitah mobile belt (Stacey and others, 1980; Stacey and Hedge, 1983; Calvez and others, 1983; Stacey and Stoeser, 1984) has put an eastern limit on the extent of the island-arc terrane and the amount of oceanic crust that must have been subducted in order to generate the arc volcanics of the Arabian-Nubian Shield (fig. 13). Interestingly, the distribution of arc-type assemblages versus that of apparent continental material is very similar to that predicted by Kazmin and others (1978) on the basis of very limited data.

The main trend of the Mozambique belt is northward from Kenya, such that it strikes directly into the Nubian Shield (Vail, 1976; Kazmin and others, 1978). The eastern limits of the Mozambique belt in northeastern Africa, however, are not clear. Although many maps show the Mozambique belt to be present throughout Somalia (for example, Kroner, 1979a), it is not certain that mid-Proterozoic or older rocks are in fact present in the basement of Somalia (Merla and others, 1979). Thus, we have left the Somalia region with a question mark on figure 15. Further work on the basement of Somalia and southern Ethiopia should prove interesting, for it is in this region that the Mozambique belt, the Arabian-Nubian arc assemblage, the Nabitah belt, and the Hadramaut belt all appear to join.

The Dahomeyan-Pharusian mobile belt of west Africa (fig. 15) appears to be the only other clear example of late Proterozoic plate tectonics among the Pan-African belts (Caby and others, 1981; LeBlanc, 1981; Fabre, 1982). This belt is also interpreted to represent a Wilson-type rifting-subduction-collision cycle, including significant intermediate arc-type volcanism (Caby and others, 1981). Caby and others have in fact noted not only the overall geologic similarity of the Dahomeyan-Pharusian mobile belt and precursors to the Arabian-Nubian Shield, but the timing as well. Both regions appear to have developed during the period 900+ to 550 Ma with a final collisional phase about 600 Ma. If the interpretation of the collisional nature of the Nabitah mobile belt is correct, then the north African craton was caught between two plate collisions during the period 680 to 570 Ma (Caby and others, 1981). Kroner (1979b) has already speculated that the Pan-African overprint of the entire north African craton is due to intraplate stresses resulting from just this situation.

Although a number of researchers have proposed that the Pan-African episode represents the initiation of modern plate tectonics (for example, Burke and others, 1977; Katz, 1974; Kroner, 1979a), it also appears that the latest Proterozoic (680-570 Ma) was the time during which Gondwana was being assembled into its Paleozoic configuration, which had been completed by the Ordovician (McElhinny, 1973; Craddock, 1979; McWilliams, 1981). It now seems safe to indicate that from the time of suturing indicated by the Nabitah and Ad Dawadimi (Al Amar) sutures (that is, after 635 Ma), it can be demonstrated that the Arabian plate remained integrated with the African craton until the early Tertiary, when rifting of the

Red Sea began. This statement rests on the fact that good geologic continuity from 635 to at least 550 Ma has been established for the Arabian Shield and that from approximately middle or late Cambrian time to the present, stratigraphic continuity obtained over most of the Arabian Peninsula (Powers and others, 1966; Wolfart, 1981). That is, after the Najd orogeny had waned, there was no further orogenic activity within the Arabian craton, which became a basement for epicontinental sedimentation throughout most of the Phanerozoic. Thus, those Gondwanaland reconstructions that show the Arabian Peninsula in its present position relative to Africa appear to be correct (Smith and Hallam, 1970; Barron and others, 1978), and those that do not, such as King (1980), are incorrect.

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DATA STORAGE

No base data files were established as a result of this study and no entries or updates were made to the Mineral Occurrence Documentation System data base.

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APPENDIX 1

Sample base data and petrography

This appendix presents base data and short petrographic descriptions of all samples (by sample number) for which U-Pb zircon ages were determined and of other samples presented in Appendix 2. Appendix 1 is divided into two parts: (a) sample mineral modes, and (b) sample base data and petrographic descriptions. Petrographic nomenclature follows Williams, Turner, and Gilbert (1982) except for rock names, which are from Streckeisen (1976). Note that the tables contain data for other samples from the same localities as the zircon samples referred to in tables 1 and 2, and that for these samples the same locality number as the zircon sample is used.

In appendix 1a:

a. Modal abundances were obtained by either the point-count method on thin sections or by visual estimate from thin section. Where applicable, the number of points counted is listed at the bottom of the column.

b. Symbols used: -- indicates mineral not observed in thin section, and n/a indicates "not applicable".

In appendix 1b:

a. Locality number refers to the locality numbers shown in figure 2.

b. Latitudes and longitudes were obtained from the 30-minute photomosaic bases used for the quadrangle mapping, and replotting on these bases is required for accurate relocation of the sample localities.

c. Plutonic unit designates the plutonic assemblage or suite the sample is assigned to (i.e. Wadi Tarib suite, Nabitah plutonic-rock assemblage, or postorogenic plutonic-rock assemblage).

d. Quadrangle name refers to the 30-minute quadrangle from which the sample was obtained.

e. Quadrangle code refers to the standard quadrangle indexing system used by the Saudi Arabian Deputy Ministry for Mineral Resources. The index code refers to the latitude and longitude of the lower left corner of the quadrangle and the specific quarter of the one degree quadrangle by letters A to D, where A refers to upper left, B upper right, C lower left, and D lower right (e.g. 18/43 C).

f. Map unit and symbol refers to the geologic map of the 30-minute quadrangle from which the sample was obtained (except Sable, 1983, which is a 1:250,000-scale quadrangle)

g. Quadrangle reference gives the source geologic map and report for the 30-minute quadrangle referred to above (except Sable, 1983).

h. Average grain sizes are visual estimates from thin section examination.

APPENDIX 1A
SAMPLE MINERAL MODES

Locality no.	15	2	8	1	1	11
Sample no.	108165	111531	111541	111551	111552	111554
quartz	31.8	19.9	15.3	--	25	25
plagioclase	42.6	59.6	51.1	45	54	28
k-feldspar	23.6	59.6	3.8	--	--	32
clinopyroxene	--	--	--	--	--	--
hornblende	--	11.6	10.8	50	7	¼1
biotite	1.4	5.5	16.2	--	1	4
muscovite	--	--	--	--	--	--
sericite	tr.	0.1	0.1	--	--	tr.
chlorite	--	1.1	0.3	--	3	--
epidote	--	1.1	0.4	5	9	tr.
opaque min.	tr.	0.6	--	tr.	1	tr.
apatite	tr.	0.3	0.3	tr.	tr.	tr.
sphene	--	--	1.3	--	--	¼1
allanite	tr.	--	tr.	--	--	tr.
zircon	tr.	tr.	tr.	--	tr.	tr.
calcite	--	0.2	0.1	--	--	--
miscellaneous	0.8	--	0.3	--	--	--
fluorite	--	--	--	--	--	--
points counted	296	1173	2118	n/a	n/a	n/a

locality no.	4	13	13	7	17	18
sample no.	111555	111558	111559	111566	112679	112680
quartz	30	30	29.6	30	35	35
plagioclase	38	32	37.9	50	53	43
k-feldspar	32	32	29.5	12	5	20
clinopyroxene	--	--	--	--	--	--
hornblende	--	--	--	--	--	--
biotite	1	6	0.1	7	7	6
muscovite	¼1	--	0.1	1	--	1
sericite	--	--	--	--	--	--
chlorite	--	tr.	tr.	--	¼1	--
epidote	--	--	tr.	¼1	--	tr.
opaque mineral	tr.	0.1	0.1	tr.	--	tr.
apatite	--	tr.	tr.	tr.	tr.	tr.
sphene	--	tr.	--	tr.	tr.	--
allanite	--	--	--	tr.	--	--
zircon	--	tr.	tr.	tr.	tr.	--
calcite	--	--	--	--	--	¼1
miscellaneous	--	--	--	--	--	--
fluorite	tr.	--	--	--	--	--
points counted	n/a	n/a	601	n/a	n/a	n/a

locality no.	2	3	6	12	n/a	n/a
sample no.	112683	112805	112806	128905	128909	128914
quartz	22.4	25	25.3	20	18	28
plagioclase	58.4	53	64.0	62	40	62
k-feldspar	0.1	¼1	1.4	8	12	--
clinopyroxene	--	--	--	--	tr.	--
hornblende	12.1	8	--	3	20	6
biotite	3.7	9	3.8	7	10	1
muscovite	--	--	2.0	--	--	--
sericite	0.1	--	1.0	--	--	--
chlorite	0.8	tr.	1.2	tr.	tr.	--
epidote	0.9	tr.	0.5	tr.	2	3
opaque mineral	0.5	tr.	tr.	0.1	¼1	0.2
apatite	0.1	tr.	0.1	0.1	tr.	tr.
sphene	--	tr.	--	0.2	tr.	--
allanite	--	--	--	--	--	--
zircon	tr.	--	--	tr.	--	--
calcite	0.1	--	0.4	--	--	--
miscellaneous	--	--	--	--	--	--
fluorite	--	--	0.1	--	--	--
points counted	793	n/a	734	n/a	n/a	n/a

locality no.	9	10	5
sample no.	128916	128917	128918
quartz	8	5	10
plagioclase	42	55	53
k-feldspar	--	--	2
clinopyroxene	--	tr.	5
hornblende	30	28	12
biotite	15	12	18
muscovite	--	--	--
sericite	--	--	--
chlorite	5	--	--
epidote	--	--	--
opaque mineral	tr.	tr.	tr.
apatite	tr.	tr.	tr.
sphene	tr.	tr.	1
allanite	--	--	--
zircon	--	--	--
calcite	--	--	--
miscellaneous	--	--	--
fluorite	--	--	--
points counted	n/a	n/a	n/a

APPENDIX 1B
SAMPLE BASE DATA AND PETROGRAPHIC DESCRIPTIONS

Sample number:108165
Locality number: near 15
Latitude: 18°25'35" N
Longitude: 43°12'24" E
Rock type: muscovite-biotite leucogranodiorite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol): granodiorite gneiss (gg)
Pluton name: Hadabah dome (Stoeser and others, 1983)
Quadrangle reference: Stoeser, 1983
Sample description:

The texture is equigranular anhedral with an approximate average grain size of 1 mm, although the biotite averages only about 0.25 mm. The plagioclase is extensively replaced by microcline and associated myrmekite. Accessory minerals include trace apatite, opaque, zircon and allanite.

Sample number:108701
Locality number: None (not shown on fig. 2)
Latitude: 18°25'35" N
Longitude: 43°12'24" E
Rock type: biotite-hornblende tonalite
Plutonic unit: Wadi Tarib suite
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Al Ar tonalite
Quadrangle reference: Stoeser, 1983
Sample description:

No data, sample lost.

Sample number:111531
Locality number: 2
Latitude: 18°01'52" N
Longitude: 43°19'50" E
Rock type: biotite-hornblende tonalite gneiss
Plutonic unit: Wadi Tarib suite
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Suwaydah tonalite gneiss
Quadrangle reference: Stoeser, 1984
Sample description:

The texture is anhedral inequigranular, with indications of partial cataclasis, and an average grain size of 1.5 mm. Hornblende is bluish-green and mildly poikiloblastic. Biotite is olive-brown and usually less than 1 mm in diameter. Accessory minerals include apatite, magnetite, and trace amounts of ilmenite and zircon.

Sample number:111541
Locality number: 8
Latitude: 18°19'15"N
Longitude: 43°13'25"E
Rock type: hornblende-biotite tonalite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Al Ar? (sample may not represent Al Ar pluton; see text)
Quadrangle reference: Stoeser, 1984
Sample description:

Anhedral inequigranular texture with an average grain size of 2-2.5 mm. The texture is cataclastic with coarser plagioclase (often with deformed lamellae) mortared in a groundmass of fine-grained sutured quartz. Mafics occur as intergranular stringers. Microcline occurs as irregular interstitial patches, with local myrmekite. Accessory minerals are abundant sphene and sparse opaques, allanite, apatite, and zircon.

Sample number:111551
Locality number: 1
Latitude: 17°47'35"N
Longitude: 43°29'15"E
Rock type: hornblende diorite
Plutonic unit: Wadi Tarib suite
Quadrangle name and (code): Wadi Atf (17/43A)
Map unit and (map symbol): Mafic to intermediate plutonic rocks (di)
Pluton name: none (sample taken near village of Talhah)
Quadrangle reference: Anderson, 1979
Sample description:

Texture is anhedral equigranular foliated, with an average grain size of about 0.6 mm. Bimineralic with plagioclase and hornblende as the only two major phases. Grain boundaries ragged and sutured with minor epidote (5%) at boundaries. Accessory minerals are apatite and opaques.

Sample number:111552
Locality number: 1 (same locality as sample 111551)
Latitude: 17°47'35"N
Longitude: 43°29'15"E
Rock type: biotite-hornblende-epidote tonalite gneiss
Plutonic unit: Wadi Tarib suite
Quadrangle name and (code): Wadi Atf (17/43A)
Map unit and (map symbol): Mafic to intermediate plutonic rocks (di)
Pluton name: None (sample taken near village of Talhah)
Quadrangle reference: Anderson, 1979
Sample description:

Strongly foliated with an anhedral inequigranular cataclastic texture consisting of coarser grained (1-3mm) bands of felsic and mafic minerals mortared between fine-grained (¼1/4mm) granulitic felsic domains. Mafic minerals occur as complex clots with epidote cores and hornblende plus biotite rims and abundant opaque mineral inclusions. The mafic clots are locally partially replaced by chlorite and second-generation epidote accompanied by saussuritization of adjacent plagioclase (replacement by sericite, epidote, and calcite). Epidote also occurs in veins cutting the rock. Accessory minerals are opaques, apatite, and rare zircon.

Sample number:111554
Locality number: 11
Latitude: 18°01'15"N
Longitude: 43°38'25"E
Rock type: hornblende-biotite leucomonzogranite
Plutonic unit: post-orogenic
Quadrangle name and (code): Wadi Malahah (18/43D)
Map unit and (map symbol): Biotite-hornblende granodiorite to quartz monzonite (qmb)
Pluton name: Jabal Thairwah monzogranite (informally named in the present paper)
Quadrangle reference: Greenwood, 1980a
Sample description:
The texture is subhedral inequigranular with an average grain size of about 3 1/2 mm. Plagioclase is oscillatory zoned with some zones intensely sericitized. Microcline is partially perthitic, paragenetically late and poikiloblastically replaces the plagioclase. The chief mafic minerals are about 4 percent olive-green biotite and less than one percent hornblende. Accessory minerals include sphene, opaques, and trace allanite and zircon.

Sample number:111555
Locality number: 4
Latitude: 18°40'15"N
Longitude: 43°14'30"E
Rock type: muscovite-biotite leucomonzogranite
Plutonic unit: Nabitah
Quadrangle name and (code): Madha (18/43A)
Map unit and (map symbol): alaskite (ak_3)
Pluton name: Madha granite (du Bray, 1983b)
Quadrangle reference: Simmons, 1980
Sample description:
The sample has a granulitic anhedral inequigranular texture with an average grain size of about 2 to 2 1/2mm. The quartz shows considerable strain and all grain boundaries between the felsic minerals are sutured and complex. Microcline is late intergranular, extensively replaces plagioclase and occurs with minor myrmekite. Muscovite and biotite total to about two percent and are fine-grained (¼0.5mm). The only observed accessory mineral is an opaque.

Sample number:111558
Locality number: 13
Latitude: 18^{0}12'40"N
Longitude: 43^{0}00'15"E
Rock type: biotite monzogranite
Plutonic unit: postorogenic
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Tindahah (Coleman,1973)
Quadrangle reference: Stoeser, 1984
Sample description:

The texture is anhedral equigranular with an average grain size of about 1/2mm. The quartz exhibits considerable strain. Both feldspars appear to be in equilibrium, and the microcline is perthitic. The chief mafic silicate is about 6 percent biotite with a trace of secondary epidote and chlorite. Observed accessory minerals are opaques, apatite, and zircon.

Sample number:111559
Locality number: 13 (same locality as 111558)
Latitude: 18^{0}12'40"N
Longitude: 43^{0}00'15"E
Rock type: biotite leucomonzogranite
Plutonic unit: postorogenic
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Tindahah (Coleman, 1973)
Quadrangle reference: Stoeser, 1984
Sample description:

The texture is anhedral equigranular with an average grain-size of about 1 1/2 mm. Considerable deformation is indicated by heavily strained and recrystallized quartz and deformed plagioclase lamellae. The perthitic microcline appears to be in equilibrium with the plagioclase and does not replace it. The only mafic silicate is less than one percent biotite. A trace of late muscovite and epidote is also found. Accessory minerals are trace opaques, apatite, and zircon.

Sample number:111566
Locality number: 7
Latitude: 18^{0}22'10"N
Longitude: 42^{0}48'15"E
Rock type: muscovite-biotite granodiorite
Plutonic unit: Nabitah
Quadrangle name and (code): Khamis Mushayt (18/42D)
Map unit and (map symbol): Khamis Mushayt gneiss (km)
Pluton name: Khamis Mushayt gneiss (Schmidt and others, 1973)
Quadrangle reference: Coleman, 1973
Sample description:

The texture is anhedral inequigranular with an average grain size of approximately 2mm. The plagioclase is extensively replaced by perthitic poikiloblastic microcline, locally with mrmykitic reaction zones. Quartz exhibits moderate strain. The chief mafic silicates are approximately 7 percent olive-green biotite and less than one percent primary(?) epidote. Less than one percent vermicular muscovite accompanies the biotite. Accessory minerals include sphene, opaques, apatite, allanite, and zircon.

Sample number:112679
Locality number: 17
Latitude: $17^{0}41.7'$N
Longitude: $43^{0}03.3'$E
Rock type: biotite leucotonalite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Atf (17/43A)
Map unit and (map symbol): Wadi Tarib batholith (qd) (note, incorrectly assigned by Anderson (1979) to the Wadi Tarib batholith)
Pluton name: Wadi Atura tonalite (informally named in the present paper) (note, this pluton was referred to in Cooper and others (1979) as the Wadi Atf tonalite gneiss, but this name was selected on the basis of the quadrangle name, not its occurrence in the vicinity of Wadi Atf.)
Quadrangle reference: Anderson, 1979
Sample description:

The texture is anhedral inequigranular seriate, with an average grain size of approximately 1-1.5 mm. Coarser plagioclase (up to 3.5 mm) occurs in a fine-grained matrix of quartz, plagioclase, and sparse microcline. The plagioclase is extensively saussuritized, whereas the microcline is unaltered. The biotite is partially replaced by chlorite and has exsolved microlites of rutile(?). Accessory minerals include trace amounts of apatite, sphene, and zircon (no opaque minerals).

Sample number:112680
Locality number: 18
Latitude: $18^{0}15.9'$N
Longitude: $43^{0}18.5'$E
Rock type: muscovite-biotite granodiorite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: unnamed
Quadrangle reference: Stoeser, 1984
Sample description:

The texture is anhedral inequigranular with an average grain size of approximately 2.5 mm (with feldspar grains up to 5 mm maximum). Microcline is late interstitial and extensively replaces the plagioclase. Quartz exhibits considerable deformation and has partially recrystallized to fine-grained sutured monomineralic domains. Biotite is pleochroic from olive-brown to pale straw-yellow and locally replaced by chlorite. The only abundant accessory mineral is apatite

(0.1%), other accessory minerals include traces of opaque, epidote, and zircon. (also see Cooper and others (1979) for more information on this sample.)

Sample number:112683
Locality number: 2
Latitude: 18°01'52"N
Longitude: 43°19'50"E
Rock type: biotite-hornblende tonalite gneiss
Plutonic unit: Wadi Tarib
Quadrangle name and (code): Wadi Tarib (1843C)
Map unit and (map symbol):
Pluton name: Suwaydah tonalite gneiss (Stoeser and others, 1983)
Quadrangle reference: Stoeser, 1983
Sample description:

The texture is anhedral equigranular with a distinct foliation and an average grain-size of about 1mm. The foliation is chiefly defined by bands and stringers of amphibole and biotite. The hornblende is somewhat poikiloblastic (¼4.5mm) and partially replaced by biotite and epidote. Feldspar is plagioclase with less than one percent microcline. Accessory minerals are apatite, opaques, and rare zircon.

Sample number: 112805
Locality number: 3
Latitude: 18°23'05"N
Longitude: 43°27'38"E
Rock type: hornblende-biotite tonalite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Tarib (18/43C)
Map unit and (map symbol):
Pluton name: Arin tonalite
Quadrangle reference: Stoeser, 1984
Sample description:

The texture is anhedral inequigranular with an average grain size of about 2mm. Partial cataclasis is indicated by a mortar structure in which plagioclase grains, some of which have deformed lamellae, are enclosed in fine granular quartz. Hornblende occurs intergrown with biotite and as poikilitic grains up to 7mm in diameter. Accessory minerals include abundant apatite, sphene, and sparse opaques. A trace amount of secondary epidote and chlorite replace the hornblende and biotite.

Sample number:112806
Locality number: 6
Latitude: 18°14'22"N
Longitude: 43°16'58"E
Rock type: muscovite-biotite trondhjemite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Tarib (18/43C)

Map unit and (map symbol):
Pluton name: Hijrat gneiss
Quadrangle reference: Stoeser, 1983
Sample description:

The rock is fresh with an anhedral inequigranular (granulitic) texture, with an average grain size of about 1.5mm. Quartz is heavily strained, but not recrystallized. Biotite is pleochroic from olive-brown to pale straw-yellow, locally replaced by chlorite, and commonly intergrown with the muscovite. Accessory minerals include apatite and epidote plus trace amounts of opaque and sphene.

Sample number:128905
Locality number: 12
Latitude: $17^{\circ}36'45"$N
Longitude: $44^{\circ}29'40"$E
Rock type: hornblende-biotite granodiorite gneiss
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Habawnah (17/44A)
Map unit and (map symbol): A'ashiba gneiss complex (tg)
Pluton name: A'ashiba gneiss complex
Quadrangle reference: Sable, 1983
Sample description:

The texture is anhedral inequigranular to seriate with a foliation and an average grain size of about 1mm, although plagioclase is coarser with grains up to 6mm. Deformation is indicated by mosaicked quartz and deformed plagioclase lamellae. About 8 percent late interstitial microcline which extensively replaces plagioclase and is accompanied by myrmekite may indicate potassium metasomatism. Hornblende and biotite are fresh and unaltered being replaced by only trace amounts of epidote and chlorite. Accessory minerals are abundant sphene, apatite, and opaques plus a trace amount of zircon.

Sample number:128909
Locality number: none (not shown on fig. 2)
Latitude: $17^{\circ}36'45"$N
Longitude: $44^{\circ}29'40"$E
Rock type: biotite-hornblende granodiorite gneiss
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Habawnah (17/44A)
Map unit and (map symbol): Aashiba gneiss complex (tg)
Pluton name: A'ashiba gneiss complex
Quadrangle reference: Sable, 1983
Sample description:

The texture is anhedral equigranular foliate with an average grain size of about 3/4mm. Hornblende occurs as fine-grained clusters up to 6 or 7mm long parallel to the foliation. Biotite occurs separately from the hornblende in smaller clusters and is typically rimmed by sphene. About 12 percent interstitial microcline tends to be localized in distinct bands within the foliation. Accessory minerals include abundant sphene, opaques, and apatite.

Sample number:128914
Locality number: none (not shown on fig. 2)
Latitude: $18^{0}05'50"$N
Longitude: $43^{0}38'45"$E
Rock type: biotite-hornblende leucotonalite
Plutonic unit: Wadi Tarib suite
Quadrangle name and (code): Malahah (18/43D)
Map unit and (map symbol): Trondhjemite (tj)
Pluton name: unnamed
Quadrangle reference: Greenwood, 1980a
Sample description:

The texture is anhedral inequigranular cataclastic with an average grain-size of about 2 1/2mm. Although the plagioclase has not been significantly deformed and still retains igneous oscillatory zoning, the primary quartz of the rock has been completely granulated to fine-grained monomineralic domains. Approximately half of the hornblende and biotite have been replaced by epidote and chlorite. Accessory minerals include sparse opaques and apatite (with the apatite occurring mainly as inclusions in the opaque minerals).

Sample number:128916
Locality number: 9
Latitude: $18^{0}24'10"$N
Longitude: $43^{0}29'35"$E
Rock type: biotite-hornblende quartz diorite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Malahah (18/43D)
Map unit and (map symbol): gabbro, diorite, and quartz diorite (dgb)
Pluton name: Wadi Mukhdhul quartz diorite(Fleck and others)
Quadrangle reference: Greenwood, 1980a
Sample description:

The texture is anhedral inequigranular with an average grain size of approximately 1mm. Only minor deformation is indicated by weakly strained quartz. Plagioclase is fresh with weak igneous oscillatory zoning. The amphibole is pale green and is either hornblende or actinolite and is extensively replaced by yellowish-brown biotite. Accessory minerals are sparse sphene, apatite, and opaques.

Sample number:128917
Locality number: 10
Latitude: $18^{0}04'15"$N
Longitude: $44^{0}05'35"$E
Rock type: diopside-biotite-hornblende quartz diorite
Plutonic unit: Nabitah
Quadrangle name and (code): Wadi Wassat (18/44C)
Map unit and (map symbol): biotite-hornblende diorite (di)
Pluton name: Wadi Simlal quartz diorite (from Fleck and others, 1980)
Quadrangle reference: Greenwood, 1980b
Sample description:

The texture is anhedral equigranular with an approximate average grain size of 1 mm (and is very similar in texture to sample 128916).

The plagioclase exhibits blotchy normal zoning as well as good oscillatory zoning. The amphibole is weakly pleochroic from very pale green to pale olive-green and is locally replaced by actinolite(?). The biotite is pleochroic pale ochre-yellow to red-brown (titaniferous?) and partially replaced by chlorite. Less than 1 percent diopside or augite occurs both as cores within amphibole and as discrete grains. Accessory minerals include opaques, sphene (as discrete grains and as rims on the opaque minerals), and apatite.

Sample number:128918
Locality number: 5
Latitude: $18^{0}15'45"$N
Longitude: $42^{0}38'40"$E
Rock type: diopside-biotite-hornblende quartz diorite
Plutonic unit: Nabitah
Quadrangle name and (code): Khamis Mushayt (18/42D)
Map unit and (map symbol): Khamis Mushayt gneiss (km) (gneissic hornblende-biotite tonalite (qdn) unit of Greenwood, 1981)
Pluton name: Khamis Mushayt gneiss
Quadrangle reference: Coleman, 1973
Sample description:

The texture is anhedral inequigranular with an average grain size of about 1.5 mm. The texture resembles an annealed mortar structure which consists of coarser domains of plagioclase and quartz in a finer groundmass of granulitic plagioclase, quartz, and minor microcline. It is not clear whether the sample is of a plutonic rock or a granulite-facies metamorphic rock (orthogneiss). The amphibole is pleochroic from pale tannish green to medium green. Biotite is pleochroic from pale straw-yellow to medium olive-brown. A colorless clinopyroxene (diopside?) is paragenetically late and partially replaces the amphibole. Accessory minerals include sphene, apatite, and trace opaques.

APPENDIX 2
CHEMICAL ANALYSES

This appendix presents major-element analyses for all samples for which U/Pb zircon ages are presented in this paper, as well as for a few other samples from the study area for which analyses were available. Base data and petrographic information for all samples are presented in appendix 1. The samples are divided into three plutonic units as defined in appendix 1: Wadi Tarib suite, Nabitah suite, and postorogenic suite. Pluton refers to the pluton or unit name presented in appendix 1b for each sample. (Symbols used: Fe2O3* indicates that all iron is presented as Fe2O3, nd indicates that the element was analyzed for but not detected, and -- indicates an element not analyzed for) (Rock-type abbreviations: qtz. dio. - quartz diorite; granodio.- granodiorite; tonal.- tonalite)

footnotes:

1. Major-element analyses by X-ray Assay Laboratories Ltd., Don Mills, Canada. All elements except FeO done by XRF, with a detection limit of 0.01, FeO by wet chemistry with a detection limit of 0.10.

2. Major-element analyses done by the Rapid Rock method, U.S.G.S. Branch of Analytical Laboratories, Denver, Colorado (analysts: J. S. Wahlberg, J. Taggart, J. Baker).

3. Major-element analyses by the Australian Mineral Development Laboratories, Frewville, South Australia.

4. Trace elements by Kevex XRF, U. S. Geological Survey, Jiddah, Saudi Arabia.

5. Trace elements by X-ray Assay Laboratories Ltd., by XRF

6. Sample for which U/Pb zircon age determinations are presented in this paper.

7. Sample for which U/Pb zircon age determination is presented in Cooper and others, 1979.

8. CIPW normative minerals calculated after oxides recalculated to 100 per cent on a water-free basis. For analyses where all iron was presented as Fe2O3 (indicated by an asterisk *), a Fe2O3/-(Fe2O3+FeO) ratio of 0.3 was used to calculate the norm (i.e. samples 111558, 111559, 111566, 111680, 112679, and 112683)

sample no.	108165	108701	111531	111541[6/]	111551
locality no.	15	none	2	8	1
unit	Nabitah	Wadi Tarib	Wadi Tarib	Nabitah	Wadi Tarib
pluton	Hadabah	Al Ar	Suwaydah	(unnamed)	Talhah
rock type	granodio.	tonalite	tonalite	tonalite	diorite
SiO2	73.0[1/]	53.6[1/]	60.9[1/]	61.90[2/]	46.80[2/]
TiO2	0.18	1.23	0.45	0.83	0.74
Al2O3	15.0	18.1	18.3	16.20	19.50
Fe2O3	0.78	3.10	2.69	1.65	2.22
FeO	0.2	3.9	2.4	3.27	6.60
MnO	0.04	0.09	0.11	0.07	0.17
MgO	1.94	7.50	7.16	2.76	6.80
CaO	0.64	4.00	2.57	4.72	12.80
Na2O	4.19	4.63	3.61	4.62	2.02
K2O	3.44	0.97	0.77	2.20	0.33
P2O5	0.08	0.40	0.16	0.23	0.14
CO2	--	--	--	0.10	0.15
SO3	--	--	--	0.01	0.02
H2O+	--	--	--	--	--
H2O-	--	--	--	--	--
LOI	0.31	1.31	0.31	1.00	1.83
TOTAL	99.80	98.83	99.43	99.56	100.12
Trace elements (ppm):					
Ba	798[4/]	398[4/]	201[4/]	--	--
Nb	nd	6	½2	--	--
Rb	50	30	20	--	--
Sr	760	1230	720	--	--
Y	5	25	11	--	--
Zr	40	200	60	--	--
CIPW norms:					
Q	31.59	3.17	20.66	12.91	--
C	3.43	3.20	7.30	--	--
OR	20.43	5.88	4.59	13.19	1.98
AB	35.63	40.17	30.82	39.60	17.26
AN	2.67	17.67	11.81	17.25	43.99
WO	--	--	--	--	--
DI	--	--	--	3.51	15.20
HY	4.86	21.96	19.65	8.72	7.59
OL	--	--	--	--	8.57
MT	0.25	4.61	3.93	2.43	3.27
HM	0.61	--	--	--	--
PR	--	--	--	0.01	0.02
IL	0.34	2.40	0.86	1.60	1.43
AP	0.19	0.97	0.38	0.55	0.34
CC	--	--	--	0.23	0.35

sample no.	111552[6/]	111554[6/]	111555[6/]	111558[6/]	111559[6/]
locality no.	1	11	4	13	
unit	Wadi Tarib	postorogenic	Nabitah	postorogenic	
pluton	Talhah	Thairwah	Madha	Tindahah	
rock type	tonalite	monzogranite	monzogranite	monzogranite	
SiO_2	61.9[3/]	71.9[3/]	73.4[3/]	68.6[2/]	74.0[2/]
TiO_2	0.59	0.30	0.09	0.49	0.09
Al_2O_3	17.5	14.2	14.9	15.5	14.0
Fe_2O_3	1.61	0.86	0.40	3.15*	1.79*
FeO	3.60	1.35	0.54	--	--
MnO	0.11	0.04	0.02	0.03	0.03
MgO	5.97	2.10	2.41	0.83	0.2
CaO	2.15	0.58	0.25	1.89	0.99
Na_2O	3.75	3.48	4.85	3.9	3.7
K_2O	0.57	3.95	2.03	4.69	5.14
P_2O_5	0.20	0.09	0.03	¼0.1	¼0.1
CO_2	0.05	0.05	0.05	--	--
SO_3	¼0.01	¼0.01	¼0.01	--	--
H_2O+	1.34	0.53	0.47	--	--
H_2O-	0.12	0.07	0.06	--	--
LOI	--	--	--	0.39	0.08
TOTAL	99.46	99.5	99.5	99.47	100.02
Trace elements (ppm):					
Ba	124[4/]	--	--	--	435[4/]
Nb	¼2	--	--	--	15
Rb	13	--	--	--	200
Sr	486	--	--	--	107
Y	4	--	--	--	23
Zr	134	--	--	--	127
CIPW norms:					
Q	23.56	32.35	33.66	21.90	29.71
C	7.56	3.53	4.52	0.58	0.55
OR	3.44	23.60	12.12	28.04	30.43
AB	32.31	29.70	41.39	33.38	31.37
AN	9.23	1.99	0.74	9.48	4.92
WO	--	--	--	--	--
DI	--	--	--	--	--
HY	19.77	6.65	6.62	4.40	2.13
OL	--	--	--	--	--
MT	2.38	1.26	0.59	1.29	0.72
HM	--	--	--	--	--
PR	--	--	--	--	--
IL	1.14	0.58	0.17	0.94	0.17
AP	0.48	0.22	0.07	--	--
CC	0.12	0.11	0.11	--	--

sample no.	111566[6/]	112679[7/]	112680[7/]	112683[6/]	112805[1/]
locality no.	7	17	18	2	3
unit	Nabitah	Nabitah	Nabitah	Wadi Tarib	Nabitah
pluton	Khamis Mushayt	Wadi Atura	(unnamed)	Suwaydah	Arin
rock type	granodiorite	tonalite	granodiorite	tonalite	tonalite
SiO2	71.4[2/]	70.2[2/]	69.8[2/]	61.1[2/]	60.5[1/]
TiO2	0.23	0.29	0.38	0.44	0.60
Al2O3	14.5	15.1	15.3	18.4	17.3
Fe2O3	2.06*	1.97*	3.34*	5.85*	2.29
FeO	--	--	--	--	2.8
MnO	0.02	0.02	0.03	0.11	0.11
MgO	0.67	1.0	0.98	2.5	3.05
CaO	2.19	2.40	2.96	7.33	6.07
Na2O	3.7	4.5	4.0	3.6	4.20
K2O	3.61	2.97	2.58	0.63	1.46
P2O5	<0.1	<0.1	0.1	0.2	0.17
CO2	--	--	--	--	--
SO3	--	--	--	--	--
H2O+	--	--	--	--	--
H2O-	--	--	--	--	--
LOI	0.34	0.71	0.60	0.36	0.39
TOTAL	98.72	99.16	100.07	100.52	98.94
Trace elements (ppm):					
Ba	--	--	--	--	516[4/]
Nb	--	--	--	--	nd
Rb	--	--	--	--	40
Sr	--	--	--	--	801
Y	--	--	--	--	15
Zr	--	--	--	--	76
CIPW norms:					
Q	30.16	25.80	28.16	17.22	13.56
C	0.53	0.12	0.79	--	--
OR	21.72	17.85	15.36	3.73	8.75
AB	31.87	38.73	34.11	30.54	36.06
AN	11.06	12.11	14.14	32.27	24.39
WO	--	--	--	--	--
DI	--	--	--	2.37	4.03
HY	3.37	4.01	5.12	10.20	8.28
OL	--	--	--	--	--
MT	0.85	0.81	1.36	2.37	3.37
HM	--	--	--	--	--
PR	--	--	--	--	--
IL	0.44	0.56	0.73	0.84	1.16
AP	--	--	0.24	0.47	0.41
CC	--	--	--	--	--

sample no.	112806[6/]	128905[6/]	128909[6/]	128914[6/]	128916[6/]
locality no.	6	12	none	none	9
unit	Nabitah	Nabitah	Nabitah	Wadi Tarib	Nabitah
pluton	Hijrat gneiss	A'ashiba	A'ashiba	(unnamed)	Makhdhul
rock type	trondhjemite	granodio.	granodio.	leucotonal.	qtz. dio.
SiO2	70.7[1/]	62.3[1/]	57.2[1/]	67.6[1/]	53.1[1/]
TiO2	0.18	0.88	0.67	0.28	0.93
Al2O3	16.1	16.2	16.0	16.7	16.2
Fe2O3	0.95	1.55	3.16	0.96	1.54
FeO	0.1	2.5	4.4	1.1	7.0
MnO	0.03	0.06	0.13	0.04	0.13
MgO	0.56	2.12	3.71	1.10	5.84
CaO	3.49	4.35	6.54	5.77	7.44
Na2O	5.33	4.67	3.41	4.73	2.98
K2O	1.16	2.71	2.69	0.23	2.12
P2O5	0.04	0.26	0.30	0.11	0.26
CO2	--	--	--	--	--
SO3	--	--	--	--	--
H2O+	--	--	--	--	--
H2O-	--	--	--	--	--
LOI	0.77	0.85	0.85	1.08	1.00
TOTAL	99.41	98.45	99.06	99.70	98.54
Trace elements (ppm):					
Ba	501[4/]	--	--	--	--
F	--	--	380[5/]	280[5/]	--
Nb	nd	--	--	--	--
Rb	28	50[5/]	50	nd	50[6/]
Sr	703	1080	640	1370	420
+	¼4	--	--	--	--
Zr	74	150	90	30	100
CIPW norms:					
Q	27.54	13.45	8.61	26.42	1.39
C	--	--	--	--	--
OR	6.95	16.41	16.19	1.38	12.84
AB	45.72	40.49	29.38	40.58	25.85
AN	16.81	15.61	20.78	23.99	25.18
WO	--	--	--	--	--
DI	0.28	3.82	8.31	3.45	8.93
HY	1.29	5.59	10.07	1.98	21.09
OL	--	--	--	--	--
MT	--	2.30	4.67	1.41	2.29
HM	0.96	--	--	--	--
PR	--	--	--	--	--
IL	0.28	1.71	1.30	0.54	1.81
AP	0.10	0.63	0.72	0.26	0.63
CC	--	--	--	--	--

sample no.	128917[6/]	128918[6/]
locality no.	10	5
unit	Nabitah	Nabitah
pluton	Wadi Simlal	Khamis Mushayt gn.
rock type	qtz. dio.	qtz. dio.
SiO2	54.0[1/]	62.3[1/]
TiO2	1.22	0.83
Al2O3	16.2	15.1
Fe2O3	1.38	1.25
FeO	6.4	3.3
MnO	0.13	0.07
MgO	4.48	3.37
CaO	8.26	4.44
Na2O	3.54	3.89
K2O	1.73	3.36
P2O5	0.37	0.19
CO2	--	--
SO3	--	--
H2O+	--	--
H2O-	--	--
LOI	0.70	0.70
TOTAL	98.41	98.80
Trace elements (ppm):		
Ba	--	--
F	--	--
Nb	--	--
Rb	40[5/]	60[5/]
Sr	570	710
Y	--	--
Zr	120	210
CIPW norms:		
Q	2.81	12.84
C	--	--
OR	10.46	20.24
AB	30.65	33.55
AN	23.75	14.08
WO	--	--
DI	12.90	5.73
HY	14.12	9.65
OL	--	--
MT	2.05	1.85
HM	--	--
PR	--	--
IL	2.37	1.61
AP	0.90	0.46
CC	--	--