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Zircon morphology and U-Pb geochronology of seven metaluminous and peralkaline post-orogenic granite complexes of the Arabian Shield, Kingdom of Saudi Arabia

by

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ZIRCON MORPHOLOGY AND U-Pb GEOCHRONOLOGY OF SEVEN METALUMINOUS AND PERALKALINE POST-OROGENIC GRANITE COMPLEXES OF THE ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

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ABSTRACT

The U-Pb zircon method was used to determine the ages of seven metaluminous-to-peralkaline post-orogenic granites located throughout the Late Proterozoic Arabian Shield of Saudi Arabia. Zircons from the metaluminous rocks are prismatic, with length-to-width ratios of about 2-4:1 and small pyramidal terminations. In contrast, zircons from three of the four peralkaline complexes either lack well developed prismatic faces (are pseudo-octahedral) or are anhedral. Some of the zircons from the peralkaline granites contain inherited radiogenic lead. This complicates interpretation of the isotopic data and, in many cases, may make the U-Pb method unsuitable for determining the age of a peralkaline granite. Zircons in the metaluminous granites do not contain inheritance and thus, best-fit chords calculated through the data have upper concordia intercepts that indicate the age of intrusion, and lower intercepts that indicate simple episodic lead loss. The results show that these granites were emplaced during multiple intrusive episodes from 670 to 510 Ma (Late Proterozoic to Cambrian).

INTRODUCTION

Stoeser and Camp (1985) have divided the Arabian Shield into five terranes that are separated by four suture zones (fig. 1). The three western terranes, the Asir, Hijaz, and Midyan appear to be underlain by rocks of primitive-to-mature island-arc composition (Greenwood and others, 1976; Camp, 1984; Jackson and others, 1984). The three arc terranes are separated by narrow suture zones that contain ophiolitic complexes (Bakor and others, 1976; Claesson and others, 1984; Camp, 1984; Nasseef and others, 1984). The rocks within the western arc terranes were formed approximately 950 to 700 Ma (Fleck and others, 1980; Calvez and others, 1983). The two eastern terranes, the Afif and Ar Rayn, appear to be more evolved and include mature island-arc rocks and older continental crust (Stacey and others, 1980; Calvez and others, 1983; Stacey and Stoeser, 1983; Agar, 1985). The oldest known rocks of the Arabian Shield (1800-1600 Ma) are felsic orthogneisses from the southern Afif terrane (Stacey and Hedge, 1984; Stacey and Agar, 1985). Most of the Afif terrane, however, appears to contain rocks younger than 820 Ma. The Afif terrane is separated from the western arc terranes by the Nabitah orogenic belt. This belt may be interpreted to be the result of continental collision among these terranes during 680-640 Ma (Schmidt and others, 1979; Stoeser and others, 1984). The Afif and Ar Rayn terranes are separated by the Al Amar suture zone that formed between 630-620 Ma (Calvez and others, 1983; Stacey and others, 1984). All of the terranes of the Arabian Shield appear

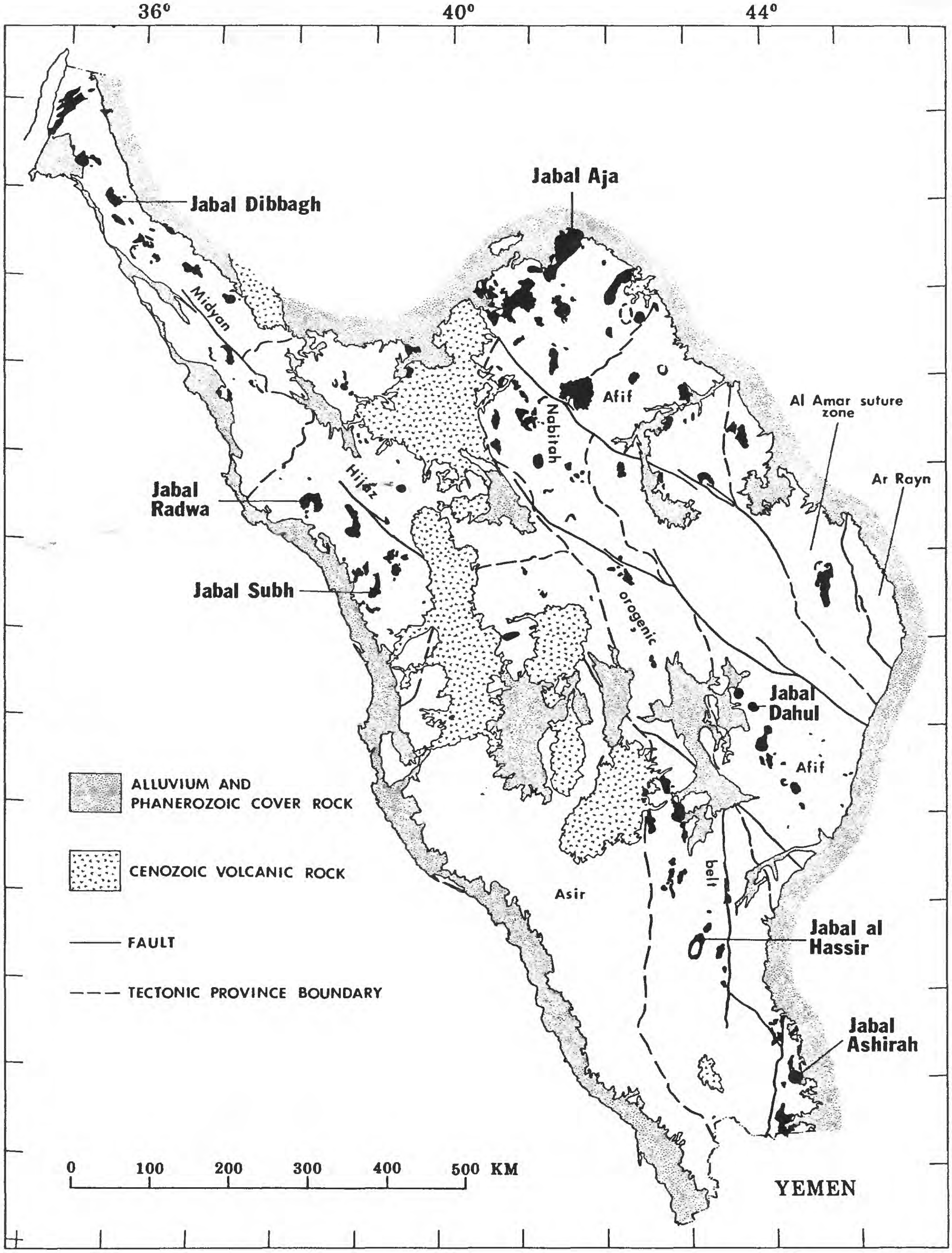


Figure 1.--Map of the Arabian Shield showing the location of granites discussed in this report (bold lettering), the distribution of metaluminous-to-peralkaline alkali-feldspar granites (in black), and tectonic provinces of the Shield (smaller lettering). Northwest-trending faults in the northern half of the Arabian Shield belong to the Najd fault system.

to have been sutured to form an Arabian neocraton during 715-630 Ma (Stoeser and Camp, 1985). Intracratonic tectonic activity continued until about 550 Ma after which the Arabian craton subsided and was buried beneath Paleozoic marine epicontinental sediments.

Most of the granites of the Arabian Shield intruded either late in the suturing episode or as intracratonic intrusions after suturing (between 670-560 Ma). One of the notable features of these granites is the occurrence of peralkaline to peraluminous alkali-feldspar granites throughout much the Arabian Shield (from 680 to 510 Ma, fig. 2) (Stoeser and Elliott, 1980; duBray, 1986; Ramsey, 1986) except in the Asir and Ar Rayn terranes. In most places in the Arabian Shield, these peralkaline granites are the last major intrusive phase prior to cessation of tectonic activity. It was unclear at the beginning of our study, whether most or all of these peralkaline granites were emplaced during a single episode or are the result of multiple intrusive episodes. To help clarify these relationships, the objectives of the present study were to determine U-Pb zircon ages of selected peralkaline granites throughout the Arabian Shield and to examine the U-Pb systematics of zircons from these peralkaline granites.

Partly on the basis of reported occurrences from the literature, seven peralkaline granite plutons distributed throughout the Arabian Shield were selected for study. Samples for the study were collected in 1978 and 1981. Laboratory work showed that three of these granites which had been reported to be peralkaline are, in fact, metaluminous. Four of the plutons studied are ring complexes whose outer rings are either peralkaline or nearly peralkaline hypersolvus granites whereas, the cores are either metaluminous subsolvus granites or granophyre. It appears, however, that these granites are part of the same petrogenetic series. The study of this series has allowed us to compare the morphologies and the U-Pb characteristics of zircons from cogenetic metaluminous and peralkaline granites.

The petrographic nomenclature used in this report follows that of Streckeisen (1976). Thus, the petrographic term "alkali granite" applies to a granite that contains at least one sodiç pyribole (generally katophorite or arfvedsonite amphibole, and (or) aegerine pyroxene). Alkali granites are chemically peralkaline, that is, they have an agpaitic ratio (molecular $(Na_2O+K_2O)/Al_2O_3$) greater than one. The term "metaluminous" refers to igneous rocks that have an agpaitic ratio less than one, but that have a ratio of $(Na_2O+K_2O+CaO)/Al_2O_3$ greater than one.

ANALYTICAL METHODS

Zircons were dissolved in concentrated $HN0_3$ and HF in a teflon bomb assembly (Krogh, 1973) and placed in an oven at about 205^{o} C for three to seven days. Five size fractions were spiked with ^{235}U and ^{230}Th prior to dissolution, whereas the remainder were spiked with only ^{235}U (not analyzed for Th) after dissolution. All solutions were aliquoted and about 25 percent of each was spiked with ^{208}Pb. Lead was extracted using bromide-form anion exchange columns (modified from Krogh, 1973); uranium and thorium were extracted using nitrate-form anion-exchange columns. Lead on a single rhenium filament with H_3P0_4/silica gel and uranium (and thorium) on a triple rhenium filament assembly were analyzed using a 30-cm radius mass spectrometer with digital data

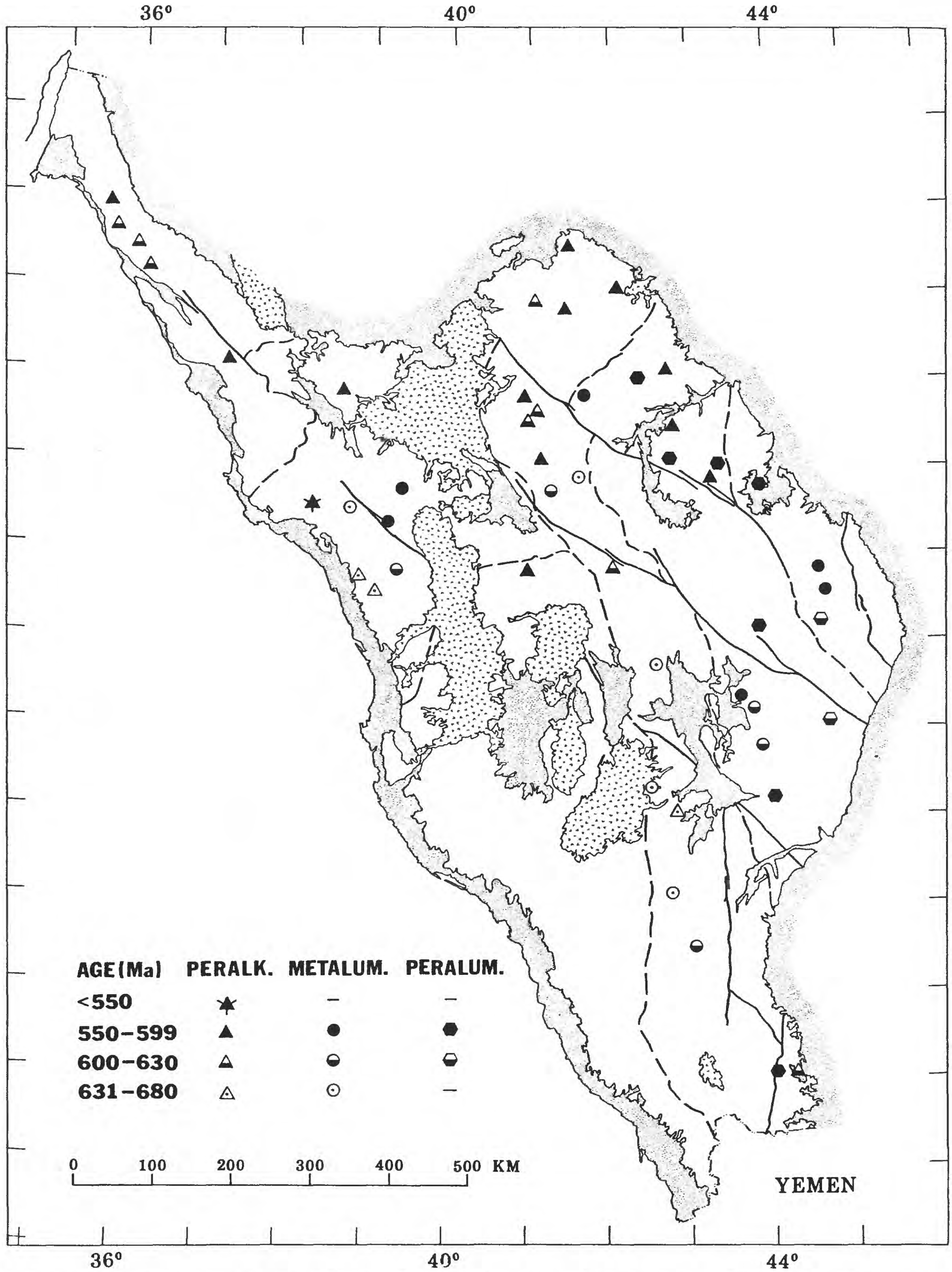


Figure 2.--Map of the Arabian Shield showing the location of alkali-feldspar granites which have been dated by the Rb-Sr whole-rock isochron and U-Pb zircon methods. Data were taken from map and sources presented in Stoeser (1986). Map patterns same as in figure 1. Abbreviations in figure: PERALK. - peralkaline, METALUM. - metaluminous, and PERALUM. - peraluminous.

acquisition and reduction. Lead-composition ratios are accurate to within 0.1 percent except where $^{206}Pb/^{204}Pb$ is greater than 1000, in which case the accuracy is probably about 1 percent. All lead ratios were corrected for 0.1 percent mass fractionation per mass unit and then corrected with the appropriate common lead composition. Pb/U ratios are believed to be accurate to within 1.2 percent. Pb/U isotopic data are discussed below for each complex, from south to north.

Unless otherwise noted, the chemical analyses presented in table 1 were performed by X-Ray Assay Laboratories, Ltd. of Don Mills, Canada. All elements, except FeO, were analyzed by x-ray fluorescence (XRF), with a detection limit of 0.01 weight percent. FeO was analyzed for by wet chemistry methods with a detection limit of 0.10 weight percent.

Table 1. Major and trace element whole rock analyses and CIPW normative calculations for samples discussed in the text. All analyses by X-Ray Laboratories, Ltd. (see text) unless noted otherwise. Sample location coordinates were obtained from geodetically controlled 1:250,000-scale LANDSAT computer mosaics.

Sample no.	111556	111572	111585	111586	111588
unit	Al Hassir rim	J. Subh	J. Dahul inner rim	J. Dahul core	J. Dahul outer rim
N latitude	19°28.0'	23°37.4'	22°11.9'	22°13.6'	22°11.3
E longitude	43°07.2'	39°07.0'	43°47.8'	43°46.1'	43°49.8
lithology	biotite-horn-blende alkali feldspar granite	aegerine alkali granite	hornblende biotite alkali-feldspar granite	biotite monzogranite	biotite-horn-blende alkali feldspar granite
SiO_2	74.9[1]	72.8	75.0	72.5	75.5
TiO_2	0.27	0.29	0.13	0.17	0.14
Al_2O_3	11.6	11.1	11.8	13.3	11.8
Fe_2O_3	3.51*	3.48	0.70	0.75	0.90
FeO	--	0.50	0.80	0.80	0.60
MnO	0.08	0.08	0.03	0.03	0.02
MgO	0.1	0.06	0.03	0.14	0.05
CaO	0.62	0.34	0.54	0.92	0.56
Na_2O	3.5	4.87	3.88	4.23	3.86
K_2O	5.15	4.61	4.92	4.77	4.90
P_2O_5	<.01	0.02	0.01	0.04	0.02
LOI	0.09	0.47	0.77	0.85	0.23
TOTAL	99.5	98.9	98.8	98.7	98.7
Trace elements (ppm):					
F	--	880[2]	2200	1900	1100
Rb	--	110	180	270	170
Sr	--	nd	nd	60	nd
Zr	--	1200	310	190	300
CIPW norms:					
Q	33.26	29.11	33.33	28.19	34.05
C	--	--	--	--	--
OR	30.61	27.75	29.71	28.86	29.44
AB	29.78	32.02	33.55	36.65	33.21
AN	0.74	--	0.26	3.29	0.41
AC	--	8.78	--	--	--
DI	--	0.66	1.57	0.94	0.59
WO	--	0.33	0.26	--	0.66
HY	0.95	--	--	0.52	--
MT	2.05	0.74	1.04	1.11	1.33
IL	0.52	0.56	0.25	0.33	0.27
AP	--	0.05	0.02	0.10	0.05
Agpaitic ratio	0.98	1.17	0.99	0.91	0.99

* All iron as Fe_2O_3

1. U.S. Geological Survey, Analytical Laboratory, Denver, Colo.
2. also Li=16.3 ppm, DGMR/USGS Chemical Laboratory, Jiddah.

Table 1. (Cont'd)

Sample no.	111618A	112991	124085[3]	128913	HSA-11
unit	J. Radwa	J. Aja rim	J. Ashirah rim	J. Ashirah core	J. Dibbagh rim
N latitude	24°33.2'	41°26.2'	18°02.7'	18°15.9'	27°55.3
E longitude	38°13.9'	27°20.3'	44°12.7'	44°03.7'	35°38.5
lithology	aegerine katophorite alkali granite	arfvedsonite aegerine alkali granite	hornblende alkali-feldspar granite	hornblende biotite monzogranite	hornblende alkali-feldspar granite
SiO_2	74.8	74.7[2]	73.5	71.2	73.4
TiO_2	0.23	0.25	0.17	0.27	0.32
Al_2O_3	11.4	10.4	12.9	13.8	11.8
Fe_2O_3	1.77	4.30*	0.92	1.30	1.83
FeO	0.60	--	1.32	1.10	2.1
MnO	0.07	0.07	0.04	0.05	0.10
MgO	0.09	<0.1	0.55	0.24	0.24
CaO	0.32	0.29	0.09	1.14	0.88
Na_2O	4.45	4.0	4.25	4.13	4.66
K_2O	4.76	4.82	5.35	5.33	4.42
P_2O_5	0.02	<0.1	<0.02	0.07	0.06
H_2O+			0.37		--
H_2O-			0.10		--
LOI	0.54	0.08	--	0.85	0.23
TOTAL	99.2	98.6	99.6	99.7	100.0
Trace elements (ppm):					
F	1100[4]	--	--	750	1200
Rb	120	--	--	190	113[5]
Sr	nd	--	--	100	54.8[5]
Zr	650	--	--	320	830
CIPW norms:					
Q	31.64	33.52	26.90	24.64	27.69
QR	28.55	28.89	31.90	31.93	26.17
AB	32.62	27.04	36.29	35.43	36.15
AN	--	--	0.32	3.42	--
NS	--	0.36	--	--	--
AC	4.93	5.05	--	--	2.95
DI	1.27	1.30	0.10	1.53	3.45
WO	--	--	--	--	--
HY	0.36	3.35	2.80	0.45	1.66
MT	0.13	--	1.35	1.91	1.18
IL	0.44	0.48	0.33	0.52	0.61
AP	0.05	--	--	0.17	0.14
Agpaitic ratio	1.09	1.13	0.99	0.91	1.05

3. Taken from J. E. Elliott, unpublished data, 1982.
4. also 250ppm Cl
5. from C. E. Hedge, written communication, 1984.

ZIRCON MORPHOLOGY AND ISOTOPE GEOLOGY

As mentioned above, three of the seven granitic complexes originally mapped as peralkaline are, in fact, metaluminous (see table 2 for agpaitic ratios). Zircon morphology is an excellent indicator of whether the agpaitic ratio of a rock is greater than or less than one. Zirconium saturation in melts is strongly controlled by molar $(Na_2O+K_2O)/Al_2O_3$ (Watson, 1979). Experimental data show that melts with agpaitic ratios of less than 1 are saturated in zirconium at less than 100 ppm whereas the zirconium saturation level is nearly 4 percent Zr when the agpaitic ratio is 2 (Watson, 1979). Watson and Harrison (1983) have shown that the solubility of zirconium in silicate melts is also temperature dependent. This difference in solubility of zirconium in granitic melts results in zircon crystallizing early in metaluminous magmas, but late in the peralkaline magmas. If the melts are strongly peralkaline, little or no zircon forms, but an alkali-zirconosilicate crystallizes instead (Dietrich, 1968; Linthout, 1984). In some peralkaline granites of the Arabian Shield, the late, interstitial mineral elpidite ($Na_2ZrSi_6O_{15}H_2O$) has been found (Stoeser and Elliott, 1980); therefore, as Siedner (1965) suggested, Poldervaart's (1956) generalization that zircon crystallizes early from granitic melts is invalid for peralkaline rocks.

The relative times of crystallization of zircons in our samples, on the basis of morphologic considerations, closely agree with available experimental data. The metaluminous samples contain "normal" (i.e. euhedral, prismatic) zircons (figs. 3, 5, 7a, 7b), whereas the four peralkaline samples, having agapitic ratios ranging from 1.06 to 1.17, contain anhedral or unusual zircons of various shapes and colors (figs. 9, 11, 13). Pupin (1980) has shown that crystal morphology may be a function of the temperature of the melt at the time of zircon crystallization. Zircons obtained from Jabal Radwa (sample 111618) may be an example of this; they range in morphology from "normal" prismatic to bypyramidal to anhedral, and vary in color and trace-element concentrations, and four distinct zircon groups have been identified (Aleinikoff and Stoeser, in prep.).

U-Th-Pb isotopic data are listed in table 2. Both the metaluminous and peralkaline rocks have zircons with wide variations in uranium concentration. Metaluminous-type zircons range from 584 to 5585 ppm uranium, whereas peralkaline-type zircons range from 170 to 1232 ppm uranium. Metaluminous-type zircons from samples 128913 and 111556 have fairly high $^{206}Pb/^{204}Pb$ ratios, whereas the uranium-rich zircons from 11585 and 11586 have much lower $^{206}Pb/^{204}Pb$ ratios. In all of the peralkaline samples, zircons have very low $^{206}Pb/^{204}Pb$ ratios that range from 85.7 to 846.3, with most values being less than 500.

These very low $^{206}Pb/^{204}Pb$ ratios necessitated careful selection of the proper common-lead composition for calculating the radiogenic lead component of the zircons. In general, lead is excluded from the zircon lattice; therefore, much of the lead in zircon is due to *in situ* radiogenic accumulation. Zircons in metaluminous melts almost always have less than 5 ppm common lead and frequently contain less than 1 ppm; however, based on our results, zircons in peralkaline melts can incorporate at least 10 times more common lead than can zircons in metaluminous melts. The (-200) fraction from sample 112991 contained 79.7 ppm, the largest quantity of common lead measured during the course of this study. In all samples, coexisting potassium feldspars were analyzed for their common-lead composition (table 4). Samples 111572, 111618, and HSA-11, which are from the granites near the Red Sea margin, have unrealistically high $^{206}Pb/^{204}Pb$ values (about 19.0). This suggests recent redistribution of lead into feldspar caused by fluid and heat movement during the Tertiary rifting of the Red Sea.

Stacey and others (1980) and Stacey and Stoeser (1983) have subdivided the Arabian Shield into two distinct provinces on the basis of differing common lead compositions. The Jabal Aja and Jabal Dahul granites are located in the eastern part of the Shield, where Stacey and others (1980) and Stacey and Stoeser (1983) have concluded that the Late Proterozoic rocks were derived from an older (approx. 2.0 b.y.) continental source. All other samples in our study were probably derived from oceanic sources. Stacey and Stoeser (1983), however, suggested that Jabal Aja granite belongs in the group that consists of oceanic-source leads. Common lead in zircons from Jabal Aja was corrected for using the Stacey and Kramers (1975) values; common lead in zircons from Jabal Dahul was corrected for using the common-lead ratios in coexisting K-feldspar.

Lead in K-feldspar from Jabal Ashirah granite was used to derive a lead-evolution curve for correction of zircon data from the granitic rocks in the oceanic-source terrane. The $^{207}Pb/^{204}Pb$ ratio was used to calculate a

($^{238}U/^{204}Pb$) value because the $^{207}Pb/^{204}Pb$ ratio is closer to the Stacey and Stoeser (1983) value than the $^{206}Pb/^{204}Pb$ ratio. We explain this choice of ratio by suggesting that the recent redistribution of lead from the rock into the feldspar is more likely to affect the $^{206}Pb/^{204}Pb$ ratio, since there is much more parent ^{238}U (as opposed to ^{235}U) in the rock. Thus, the $^{207}Pb/^{204}Pb$ ratio was probably less disturbed than the $^{206}Pb/^{204}Pb$ ratio and as such was used in the μ calculation. The μ-value derived from the Jabal Ashirah K-feldspar is 9.33; this is in accord with the data and tectonic interpretation of Stacey and others (1980) and Stacey and Stoeser (1983). See Stacey and Stoeser (1983), Stoeser and Camp (1985) and Stacey and Agar (1985) for comprehensive discussions of the possible sources and implications of the common-lead compositions in rocks, feldspars and sulfides throughout the Arabian Shield. In summary, lead compositions in zircons from samples 128913, 111556, 111618 and HSA-11 were corrected for their common lead components using a time-integrated lead evolution with a μ-value of 9.33. In contrast, lead compositions in zircons from samples 112991, 111585, and 111586 were corrected using slightly more radiogenic common-lead values derived from rocks with a μ-value of 9.74.

Table 2. U-Th-Pb Isotopic data of Zircon

		Concentrations (ppm)			Atomic percent				Isotope ratios				
Sample	Fraction	U	Th	Pb	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$^{206}Pb^{1}/^{204}Pb$	$^{206}Pb^{*}/^{238}U$	$^{207}Pb^{*}/^{235}U$	$^{207}Pb^{*}/^{206}Pb$	$^{208}Pb^{*}/^{232}Th$
128913	(+150)	584	--	51.5	0.040	84.9	5.72	9.32	2142	0.0863	0.7220	0.0607	--
	(-150+250)	650	--	59.1	0.062	83.45	5.964	10.52	1355	0.0870	0.7300	0.0608	--
	(-250+325)	668	--	60.9	0.041	84.02	5.693	10.24	2067	0.0883	0.7399	0.0608	--
	(-325)	807	--	66.6	0.059	83.0	5.88	11.11	1418	0.0786	0.6576	0.0607	--
111556	(+100)	885	267	84.3	0.014	86.0	5.41	8.62	6036	0.0949	0.7933	0.0606	0.0287
	(-120+150)	677	208	64.2	0.014	86.0	5.42	8.52	6092	0.0946	0.7907	0.0606	0.0278
	(-150+200)Mag	980	--	75.1	0.013	85.7	5.37	8.93	6443	0.0762	0.6345	0.0604	--
	(-400)	660	--	59.2	0.057	83.7	5.89	10.31	1478	0.0864	0.7216	0.0606	--
111585	(+100)	2277	--	268	0.116	74.2	6.86	18.79	445.7	0.0975	0.8059	0.0599	--
	(-325)	1618	--	182	0.176	75.9	7.09	16.86	431.3	0.0953	0.7860	0.0598	--
111586	(+100)	5585	--	514	0.159	76.0	6.79	17.02	478.7	0.0783	0.6368	0.0590	--
	(-325)	4133	--	419	0.192	73.3	7.13	19.34	382.7	0.0824	0.6727	0.0592	--
111572	(-100+150)NM	743	--	70.2	0.309	73.4	9.08	17.25	237.3	0.0747	0.6515	0.0633	--
	(-150+200)NM	916	--	135	0.475	65.6	10.99	22.90	138.2	0.0982	0.8617	0.0637	--
	(-150+200)VM	1232	--	168	0.383	68.3	9.78	21.52	178.3	0.0976	0.8429	0.0626	--
	(-325)	1094	--	151	0.364	69.8	9.62	20.22	192.0	0.1017	0.8833	0.0630	--
111618	(+100)NM	170	--	15.3	0.089	75.0	5.62	19.32	846.3	0.0766	0.6114	0.0579	--
	(-100+150)NM	189	--	20.6	0.251	63.3	7.27	29.21	252.1	0.0746	0.5910	0.0575	--
	(-325)	202	--	20.3	0.210	64.5	6.69	28.59	320.3	0.0711	0.5749	0.0587	--
112991	(+100)	942	603	148	0.585	58.5	11.94	29.03	99.9	0.0874	0.7099	0.0589	0.0194
	(+100)NM	856	--	122	0.481	63.8	10.74	24.96	132.8	0.0913	0.7424	0.0590	--
	(-100+150)	961	656	154	0.600	57.6	12.11	29.72	96.0	0.0870	0.7071	0.0590	0.0190
	(-200)	1020	815	175	0.643	55.1	12.60	31.68	85.7	0.0865	0.7064	0.0592	0.0182
HSA-11	(+150)NM	697	--	59.6	0.134	75.9	6.45	17.50	565.1	0.0730	0.5981	0.0594	--
	(+150)Mag	970	--	94.8	0.132	60.4	5.49	33.99	456.4	0.0658	0.5380	0.0593	--
	(-250+325)	1026	--	77.9	0.136	75.8	6.46	17.59	559.7	0.0647	0.5300	0.0594	--
	(-325)	1115	--	115	0.150	76.3	6.69	16.91	507.6	0.0881	0.7194	0.0593	--

* Radiogenic lead, corrected for common lead
[1] Blank and fractionation corrected

Table 3. Age data

Sample	Fraction	Ages (m.y.) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$	Concordia Intercepts (m.y.) Lower	Upper	Comments
128913	(+150)	534	552	627	--	35(±36)	637(±7)	Calculated through 4 points.
	(-150+250)	538	557	633	--			
	(-250+325)	545	562	632	--			
	(-325)	488	513	628	--			
111556	(+100)	585	593	625	572	35(±21)	628(±4)	Calculated through 4 points.
	(-100+150)	583	592	626	554			
	(-150+200)Mag	473	499	618	--			
	(-400)	534	552	624	--			
111585	(+100)	600	600	601	--	164 (±21)	601 (±4)	Calculated through 4 points from two samples (111585, 111586).
	(-325)	587	589	597	--			
111586	(+100)	486	500	566	--			
	(-325)	510	552	576	--			
111572	(-100+150)NM	464	509	717	--	Age estimated at approx. 675 (±10)		Based on model Rb-Sr data (C. E. Hedge, pers. comm.) All zircon fractions contain inherited lead, youngest Pb/Pb age is 696 m.y.
	(-150+200)NM	604	631	730	--			
	(-150+200)VM	600	621	696	--			
	(-325)	624	643	708	--			
111618	(+100)NM	476	484	525	--	Age estimated at approx. 510 (±15)		Recalculations of Rb-Sr data of Kemp et. al., (12980) gives 520(±24) m y.; youngest zircon Pb-Pb age is 510 m.y.
	(-100+150)NM	464	472	510	--			
	(-325)	443	461	555	--			
112991	(+100)	540	545	564	389	16 (±118)	566 (±4)	Calculated through 3 points; (-200) excluded.
	(+100)NM	563	564	566	--			
	(-100+150)	538	543	566	380			
	(-200)	535	543	575	364			
HSA-11	(+150)NM	454	476	582	--	-10 (±52)	577 (±13)	Calculated through 4 points.
	(+150)Mag	411	437	577	--			
	(-250+325)	404	432	581	--			
	(-325)	544	550	576	--			

Table 4. Isotopic composition of K-feldspars and galena

Sample	Leach	$^{206}Pb^*/^{204}Pb$	$^{207}Pb^*/^{204}Pb$	$^{208}Pb^*/^{204}Pb$	Pb (ppm)	U (ppm)	Th (ppm)
128913	HF	17.613	15.461	37.219	--	--	--
111556	HNO_3,HCl	17.714	15.460	37.107	5.7	0.1	0.1
111585	HF	17.528	15.556	37.555	--	--	--
111586	HF	17.594	15.554	37.766	--	--	--
111572	HF	18.743	15.517	37.729	--	--	--
111618	HF	18.999	15.544	38.472	--	--	--
112991	HNO_3,HCl	17.807	15.515	37.605	2.0	1.1	4.9
HSA-11	HNO_3,HCl	18.966	15.554	38.506	6.6	0.3	0.4
112991(galena)	H_2O	17.803	15.560	37.535	--	--	--

Pb, U, and Th concentrations determined on feldspars with HNO_3, HCl leach.

* Fractionation corrected.

RESULTS

JABAL ASHIRAH (SAMPLE 128913)

The Jabal Ashirah ring complex (fig. 1), located in the southernmost part of the Saudi Arabian Shield is a poorly exposed circular pluton, 11 km in diameter, (Greenwood, 1980). The pluton consists of a leucocratic monzogranite core and an outer ring of metaluminous-to-peralkaline hypersolvus alkali-feldspar granite. The entire complex was originally mapped as peralkaline by Greenwood (1980), but recent thin section study indicates that only a part of the outer ring is composed of alkali granite. The only available chemical analysis of the outer ring granite shows it to be of transitional metaluminous composition (table 1). Sample 128193 (table 1), which was collected from the central part of the core, consists of a metaluminous fine-grained hornblende-biotite monzogranite that contains about five percent mafic minerals and approximately equal amounts of quartz, oligoclase, and microcline. Accessory minerals are sparse sphene, allanite, opaque minerals and trace amounts of apatite and zircon.

Four size fractions of zircon were analyzed for uranium and lead isotopes (tables 2 and 3). These zircons are euhedral and light brown, with length-to-width ratios of 2-4:1 (with a few acicular needles with ratios of up to 8:1, fig. 3*). Some of the zircons are very finely zoned and nearly all contain acicular inclusions. They contain relatively low concentrations of uranium (between 584 and 807 ppm) and have moderately low $^{206}Pb/^{204}Pb$ ratios. The $^{207}Pb/^{206}Pb$ ages range from 627 to 633 Ma, and the Pb/U ages range from 488 to 562 Ma. A best-fit line calculated through the four points (fig. 4) has concordia intercepts at 35 ± 36 and 637 ± 7 Ma.

JABAL AL HASSIR (SAMPLE 111556)

The Jabal Al Hassir granite complex consists of two main units: an outer ring of coarse-grained, metaluminous hypersolvus alkali-feldspar granite and a complex core of metaluminous granite, granodiorite, and numerous roof pendants (as much as 5 km long) of country rock (Stoeser, unpublished mapping). The two units are separated on their southern and eastern sides by a system of quartz-porphyry dikes. The pluton intrudes a complex synorogenic, granodioritic-to-granitic gneiss terrane that formed during the Nabitah orogeny (680-640 Ma; Stoeser and others, 1984).

Sample 111556 was collected from the central part of the outer ring of the Al Hassir pluton. It is a coarse-grained biotite-hornblende alkali-feldspar hypersolvus granite. The sample is leucocratic, containing about 3 percent hornblende (ferroedenite) and 1 percent biotite. Accessory minerals are opaque minerals, apatite, allanite, abundant zircon, and sparse sphene.

Four size fractions of zircon from sample 111556 were analyzed for uranium and lead isotopes (tables 2 and 3). The zircons are euhedral and medium brown, with length-to-width ratios of 2-4:1 (fig. 5). Many grains are fractured and contain acicular inclusions. A few have very fine zoning. Uranium concentrations decrease with decreasing grain size from 980 ppm in the (-150+200)Mag fraction to 660 ppm U in the (-400) fraction. The (+100) fraction contained about 105 ppm U less than the (-150+200)Mag fraction, probably

* Figures 3-16 are at the end of this section, see page 17.

because the coarser fraction was not subdivided magnetically. Commonly, the more magnetic and finer fractions contain higher uranium concentrations. We cannot explain why the finest fraction contains the lowest uranium concentration.

The $^{207}Pb/^{206}Pb$ ages obtained from the four fractions vary from 618 to 626 Ma; these are similar to the ages obtained from sample 128913. A best-fit line (Ludwig, 1980) calculated through the four points has concordia intercepts of 628 ±4 and 35±21 Ma (fig. 6). The upper intercept is interpreted as the age of intrusion of the complex; the lower intercept represents episodic lead loss probably caused by uplift prior to the opening of the Red Sea approximately 15 Ma by dilatancy lead loss (Goldich and Mudrey, 1972).

JABAL DAHUL (SAMPLES 111585 AND 111586)

The Jabal Dahul granite is a circular pluton, 13 km in diameter, which was emplaced into a complex terrane of synorogenic granitoid rocks consisting primarily of granodiorite and granite (Delfour, 1980). The pluton may be divided into three zones; core, middle and rim. The core consists of a biotite leucomonzogranite, the middle zone is a hornblende-biotite alkali-feldspar granite, and the rim is a biotite-hornblende alkali-feldspar granite. Thin-section study indicates that the textures change from mesosolvus to hypersolvus types going outward from the core, and that the mafic minerals change from only biotite in the central core, to biotite plus hornblende outwards from the outer core to the rim, where hornblende is dominant (D. B. Stoeser, unpublished data). Apparently, the granite also becomes richer in mafic silicates, zircon, and opaque minerals toward the rim. Because of the lack of continuous outcrop, it is not clear whether these changes are gradational or whether the three zones are separate units. Samples were collected from the core and middle zones of the Dahul pluton. Although mapped as peralkaline by Delfour (1980), all of the complex appears to be chemically metaluminous, although the rim is almost peralkaline in composition (agpaitic index of 0.99, table 1) (Ramsay, 1982).

Sample 111585 was collected from the middle zone and consists of a medium-grained alkali feldspar granite. Most of the feldspar is coarse perthite, locally replaced by fine-grained albite. The quartz is mildly strained. The hornblende (ferroedenite) and biotite formed late relative to the quartz and perthite and constitute less than five percent of the rock. The only observed accessory minerals are abundant zircon and trace amounts of opaque minerals.

Sample 111586 was collected from the core zone and consists of medium-grained monzogranite in which the feldspars are sodic oligoclase and perthitic alkali feldspar. Thin-section study indicates a history of early hypersolvus crystallization followed by partial subsolvus recrystallization that occurred during mild deformation. The rock is leucocratic with about 2 percent biotite and a trace of hornblende. The only accessory minerals that were observed are are opaque minerals, abundant zircon, and a trace of hornblende.

Zircons from the core monzogranite are euhedral and brown to dark brown, with length-to-width ratios of 2-4:1 (fig. 7a). About 90 percent of the grains are opaque. The few grains that are translucent have very fine zoning and acicular inclusions. In contrast, zircons from the middle zone are stubby (length-to-width ratio of 1.5-2:1) and light brown (fig. 7b). Many contain rounded cores overgrown by very finely zoned darker zircon. Nearly all grains are highly fractured. The agpaitic ratios of these two rocks are 0.91 (core) and 0.99 (middle zone). The anhedral cores may represent earlier, partially resorbed crystals around which later zircon nucleated. The stubbiness of the crystals, with equally predominant prismatic and pyramidal faces correlates with the whole rock chemistry which is transitional between metaluminous and peralkaline (agpaitic ratio of 0.992). Alternately, if the experimental data of Watson (1979) is applicable, the anhedral cores in zircons from the middle zone may have grown when the melt had an agpaitic ratio greater than one, with subsequent euhedral crystallization as the melt became depleted in Na_2O+K_2O relative to Al_2O_3.

Zircons from the core of the pluton are highly enriched in uranium (tables 2 and 3). The (-325) fraction contains 4133 ppm and the (+150) fraction contains 5585 ppm. Zircons from the middle zone contain about 40 percent less uranium than those from the same size fraction from the core. All four fractions have low $^{206}Pb/^{204}Pb$ ratios, ranging from 383 to 479. The $^{207}Pb/^{206}Pb$ ages have a range from 566 to 601 Ma, a spread uncharacteristic of plutonic rocks of the Arabian Shield (Cooper and others, 1979; Stacey and others, 1984; Stoeser and others, 1984). The Pb/U ages range from 486 to 600 Ma, so that the age of intrusion of these rocks is well-dated by the concordant data from the 111585 (+100) fraction of sample 111585. A best-fit line through the data has concordia intercepts of 601 $\pm$4 Ma and 164$\pm$21 Ma (fig. 8). This age agrees with the whole-rock Rb-Sr age (579$\pm$19 Ma) assigned by Calvez and others (1983) to the nearby (and very similar) Jabal Kursh pluton (Delfour, 1980).

If the isotopic data for each sample in the Jabal Dahul complex are considered alone and best-fit lines are calculated through the two points plus 15 Ma (the procedure of Cooper and others, 1979), then the calculated uncertainties are much larger than when the four data points are considered together without the assumed lower intercept age of 15 Ma. The cause of the lower intercept age of 164$\pm$21 Ma is not known. The high precision and excellent linearity of the data, however, strongly suggest that this lower intercept age of about 165 Ma has geologic significance. Stacey and Hedge (1984) and Stacey and others (1984) report that other rocks of the eastern part of the Arabian Shield have unusually high lower intercept ages. Stacey and others (1984) suggest that such elevated lower intercepts for zircons with high uranium content may be due to lead loss related to unroofing during the Mesozoic. Also of interest are the concordant data from the Dahul core zircons that contain about 2300 ppm uranium. Apparently, uranium content is not the only factor controlling the degree of discordance.

JABAL SUBH (111572)

A sample of Jabal Subh granite (111572) was collected because, unlike all other Pan-African peralkaline granits of the Shield, this granite is cut by diabase dikes and a biotite monzogranite. Thus, field evidence indicates that the Jabal Subh granite is older than some of the post-orogenic rocks in that part of the Arabian Shield.

Sample 111572 is a medium-grained aegerine perthite alkali granite, with an average grain size of approximately 2 mm. The presence of strained quartz and the patchy unmixing and oxidation of the alkali feldspar indicates deformation possibly related to metamorphism. Approximately 7 percent of the pale green aegerine is replaced locally by dark blue arfvedsonite. The only observed accessory minerals are sparse opaque minerals and zircon.

Zircons from sample 111572 are totally anhedral, which correlates with an agpaitic ratio of 1.17, and are either dark brown or pale green (fig. 9). The two color groups were separated according to magnetic susceptibility with the brown zircons being more magnetic than the green zircons. The largest grains analyzed for uranium and lead isotopes (tables 2 and 3) were from the (-100+150) fraction because larger grains are polymineralic. The (-325) fraction (not split magnetically) was also analyzed. Brown, magnetic zircons (in the (-150+200)VM fraction) contain about 1232 ppm uranium, whereas green, relatively nonmagnetic zircons in the same size fraction contain about 916 ppm. The brown zircons have a $^{207}Pb/^{206}Pb$ age of 696 Ma; the green zircons have a $^{207}Pb/^{206}Pb$ age of 730 Ma. Both color groups have Pb/U ages between 600 and 631 Ma. The mixed groups of zircons from the (-325) fraction has an intermediate $^{207}Pb/^{206}Pb$ age of 708 Ma and Pb/U ages of 624 and 643 Ma. Green zircons in the (-100+150)VM fraction have a $^{207}Pb/^{206}Pb$ age of 717 Ma and Pb/U ages of 464 and 509 Ma.

A concordia diagram for the Jabal Subh data is shown in figure 10. Because of the large scatter outside of analytical error, a best-fit line calculated through the data points would have meaningless concordia intercepts. The data can be interpreted in two ways: (1) the rock has a minimum age of 730 Ma, and younger events have caused lead loss and scatter, or, (2) the rock has a maximum age of 696 Ma with scatter being caused by a combination of inheritance and subsequent lead loss. The latter interpretation implies that the green nonmagnetic zircons contain more inheritance than the brown magnetic zircons. This conclusion is contrary to the usual finding that, within a single sample, zircons with inheritance are more magnetic than those not containing inherited material. However, this relationship between isotopic systematics and color can be explained by a model where brown zircons, containing more residual elements, such as Fe, REE, U and Pb (see table 1), formed late in the crystallization history of the peralkaline melt and the green zircons formed relatively earlier. The green zircons may have formed around tiny nuclei of inherited zircon. When the brown zircons began to crystallize, most of the inherited zircon may have already been incorporated in the green zircon. All zircon from sample 111572 formed late, as predicted by the agpaitic ratio of 1.17 and as suggested by the anhedral morphology. If the second interpretation of the U-Pb systematics is correct, then the age of the granite is 696 Ma or less; Rb-Sr data (C. E. Hedge, personal commun., 1983) indicate that the age is 659$\pm$7 Ma (model age based on one sample with a favorable Rb-Sr ratio), confirming the second interpretation. Another granite of the Subh alkali granite suite was dated at 687$\pm$18 Ma (Clark and Duyverman, 1983; Rb-Sr using five data points). In this case, the U-Pb data from the zircons only define a maximum limit for the age but could not date the time of intrusion precisely. Rb-Sr data agree with the field observations and confirm that the granite is older than other peralkaline rocks in the Arabian Shield. In summary, the age of the Jabul Subh granite is about 670 Ma and its zircons contain inheritance from some unknown source.

JABAL RADWA (111618)

Jabal Radwa is located in the northwestern portion of the Arabian Shield. It It is a hypabyssal peralkaline granite, 27 km in diameter, and U-shaped in outcrop (Alabouvette and others, 1975; Petot, 1976; (fig. 1). Kemp and others (1980) analyzed this rock and obtained a 6-point Rb-Sr isochron age of 518$\pm$10 Ma. This age was recalculated to 521$\pm$24 Ma using their data and the best-fit algorithm of Ludwig (1980; 1982). This rock is, therefore, considerably younger than any other dated peralkaline granite in the Arabian Shield.

Although most of the pluton is a fairly homogeneous and fine-grained granophyre, sample 111618 was collected from a coarser-grained large fresh spall block within the core of the granite. Two similar-looking samples labeled A and B were collected from the block about 5 m apart; the whole-rock chemistry for sample A is reported in table 1. Sample A is a seriate, medium-grained, aegerine-arfvedsonite perthite alkali granite. Although the sample has an average grain size of about 2-3 mm, thin sections show the presence of local fine-grained granophyric patches. The sample contains approximately 1 percent aegerine and 3 percent arfvedsonite. Accessory minerals consist of opaque minerals, aenigmatite, and zircon.

Sample 111618 contains four populations of zircon (fig. 11): (1) prismatic, light brown, length-to-width ratio of 2-4:1, (2) pale green to brownish, bipyramidal (having poorly developed to no prism faces), length-to-width ratio of 1, (3) dark brown, bipyramidal, length-to-width ratio of 1, and (4) aquamarine blue, anhedral, adamantine length-to-width ratio of 1. This unusual range in zircon morphology and color may be due to the composition of the melt changing from an agpaitic ratio of less than one to greater than one as crystallization proceeded and temperature decreased. The agpaitic ratio of the rock is 1.07, so that small fluctuations in the amount of alkalis to alumina possibly related to a fluid phase may have had a profound effect on zirconium saturation. The origin of these zircons is now being investigated by Aleinikoff and Stoeser.

Two size fractions of the prismatic zircons, (+100)NM and (-100+150)NM, and a (-325) fraction of mixed prismatic and pale green zircons were analyzed for uranium and lead isotopes (tables 2 and 3). The (-100+150)NM fraction has a $^{207}Pb/^{206}Pb$ age of 510 Ma and Pb/U ages of 464 and 472 Ma. Both the (+100)NM and the (-325)NM fractions have older $^{207}Pb/^{206}Pb$ ages, suggesting inheritance of radiogenic lead in these zircons. The lowest $^{207}Pb/^{206}Pb$ age (510 Ma) is in reasonable agreement with the Rb-Sr data of Kemp and others (1980) and therefore the age of intrusion of the rock is about 510±15 Ma (fig. 12). In accepting the lowest $^{207}Pb/^{206}Pb$ age as the correct intrusive age of the rock, we assume that only recent lead loss (15 Ma or less) has occurred in these zircons that have low uranium content (Stacey and others, 1984). The age (510 Ma) is significantly younger than any other dated peralkaline granite in the Arabian Shield and as such remains enigmatic. The U-Pb zircon age confirms the earlier Rb-Sr age of 521±24 Ma by Kemp and others (1980).

JABAL AJA (112991)

The Jabal Aja peralkaline granite complex lies in the extreme northeastern part of the Arabian Shield. It is one of the largest (35 by 75 km) and most complex of the post-orogenic alkaline granite intrusives (du Bray and Stoeser, 1984; Stoeser and Elliott, 1985; Kellogg and Stoeser, 1985). It consists of two major units (fig. 2): an outer ring complex of coarse equigranular to porphyritic, hypersolvus peralkaline perthite rim granite and comendite porphyry, and a core of complex miarolitic granophyre. The core not only consists of multiple intrusions of granophyre and micrographic granite but also contains roof pendants of country rock and older related granophyres as much as ten kilometers in diameter. There are also sills of metaluminous rhyolite. The Jabal Aja complex is located in a complex terrane of partly gneissic rock that varies from granite to granodiorite that has been extensively injected by dikes and post-orogenic metaluminous and peralkaline granites.

Sample 112991 was collected from a float block in the outer part of the rim granite on the southeastern margin of the pluton (fig. 2). The sample consists of a coarse-grained arfvedsonite-aegerine perthite alkali granite. The pyriboles consist of about 2 percent slate-blue arfvedsonite, about 4 percent aegerine, and a trace of late, red-brown annitic biotite. The aegerine crystallized later than the arfvedsonite and extensively replaced it. Accessory minerals include aenigmatite, ilmenite, fluorite, and zircon.

The sample has an agpaitic ratio of 1.13 and, as would be predicted, nearly all of the zircons are anhedral, with only a few grains having pyramidal and prismatic faces. Zircons are equant and clear-to-pale olive green. Some grains appear to have formed in voids between earlier-formed minerals, and must have crystallized very late (fig. 13).

Four size fractions were analyzed for uranium and lead isotopes (tables 2 and 3). The two coarse fractions, (+100) and (-100+150), initially analyzed have $^{207}Pb/^{206}Pb$ ages of 564 and 566 Ma respectively, and Pb/U ages ranging from 538 to 545 Ma. The finest size fraction, (-200), has a $^{207}Pb/^{206}Pb$ age of 575 Ma and Pb/U ages of 535 and 543 Ma. Because uranium concentration increases and $^{206}Pb/^{204}Pb$ ratios decrease with decreasing grain size (from 942 to 1020 ppm and 99.9 to 85.7), respectively, a non-magnetic fraction was separated from the (+100) population, in order to obtain more nearly concordant isotopic data. The (+100)NM fraction has a $^{207}Pb/^{206}Pb$ age of 566 Ma (analytically identical to the two coarse size fractions) and Pb/U ages of 563 and 564 Ma. The $^{206}Pb/^{204}Pb$ ratio was slightly higher at 132.8. A best-fit line calculated through data from the three coarse fractions has concordia-intercept ages of 566$\pm$4 and 16$\pm$18 Ma (fig. 14). The (-200) fraction was excluded from the calculation because it appears to contain a small amount of inherited lead. Thus, we conclude that the intrusive age of the outer ring is 566$\pm$4 Ma, and that a minor amount of inherited radiogenic lead is present in one of the size fractions.

JABAL DIBBAGH (HSA-11)

The Jabal Dibbagh granite is located in the northwestern most part of the Arabian Shield (fig. 1) and consists of an irregularly shaped pluton, 15 x 25 km, (fig. 2), composed of an outer ring of peralkaline aegerine-amphibole hypersolvus perthite granite and an 8-km diameter core of porphyritic biotite granite and granodiorite (fig. 2) (Harris and Marriner, 1980).

Sample HSA-11 was collected from the outer-rim perthite granite near the contact with the core biotite granite. The sample is a hypersolvus coarse-grained hornblende (ferroedenite) alkali-feldspar granite. Energy dispersive XRF analyses using a scanning electron microscope indicates that the average composition of the perthite feldspar is Ab52.0Or47.8An0.2 and that the amphibole is weakly zoned (from sodic ferroedenite to calcic katophorite) and has an average composition of ferroedenite. The rock also contains minor late, fine-grained red-brown annitic biotite. Accessory minerals include abundant zircon, allanite, apatite, magnetite, and ilmenite, and sparse fluorite and sphene.

The Jabal Dibbagh sample collected for zircons has an agpaitic ratio of 1.06 (table 1). However, unlike other truly peralkaline granites in this study, the zircon morphology does not reflect the peralkaline agpaitic ratio. The grains are light brown, subhedral to euhedral and prismatic, with length-to-width ratios of

2-3:1 (fig. 15). The composition of the HSA-11 amphibole also suggests that the sample is metaluminous in composition but transitional to peralkaline. Because there is no evidence for late stage alkali metasomatism that might have modified a primary metaluminous composition, a slight error in either the soda, potash, or alumina values of the HSA-11 analysis (table 1) is suspected. However, Harris and Mariner (1980) established that the granite of the outer unit of Jabal Dibbagh is generally peralkaline.

Four size fractions were analyzed for uranium and lead isotopes (tables 2 and 3). The $^{207}Pb/^{206}Pb$ ages range from 576 to 586 Ma and Pb/U ages range from 404 to 550 Ma. Uranium concentration increases with decreasing grain size from 697 ppm U in the (+150)NM fraction to 1115 ppm in the (-325) fraction. The (+150)Mag fraction (split from the (+150)NM population by the magnetic separator) contains about 273 ppm uranium more than the (+150)NM fraction. A best-fit line calculated through all four points has concordia-intercept ages of 577 $\pm$13 and 10$\pm$52 Ma (fig. 16). This age compares well with the 586$\pm$11 Ma Rb-Sr whole-rock isochron age of Duyverman and others, 1982. We interpret the upper intercept to be the age of intrusion. The lower intercept age probably represents dilatancy lead loss (Goldich and Mudrey, 1972) caused by the Red Sea rifting event at 15 Ma.

Figure 3.--Photomicrograph of Jabal Ashirah zircons (sample 128913) from the (-150+325) fraction. Note euhedral, prismatic morphology.

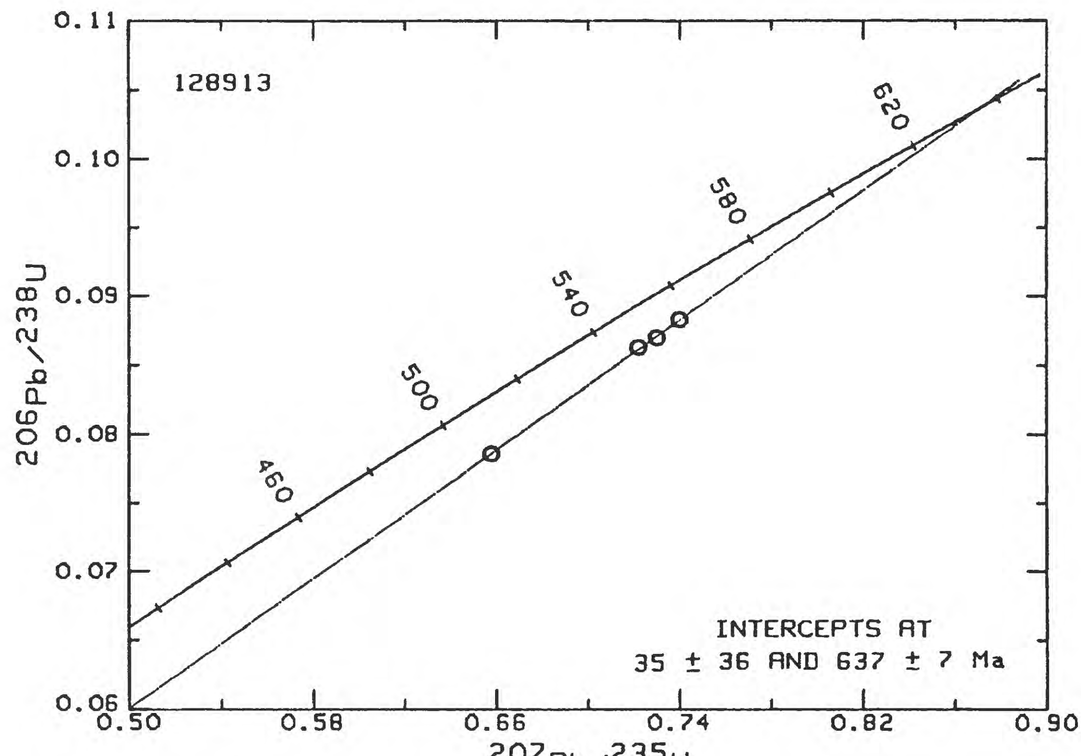


Figure 4.--Concordia plot of Jabul Ashirah isotopic data.

Figure 5.--Photomicrograph of Jabal Al Hassir zircons (sample 111556) from the (-150+200) fraction. Note euhedral, prismatic morphology.

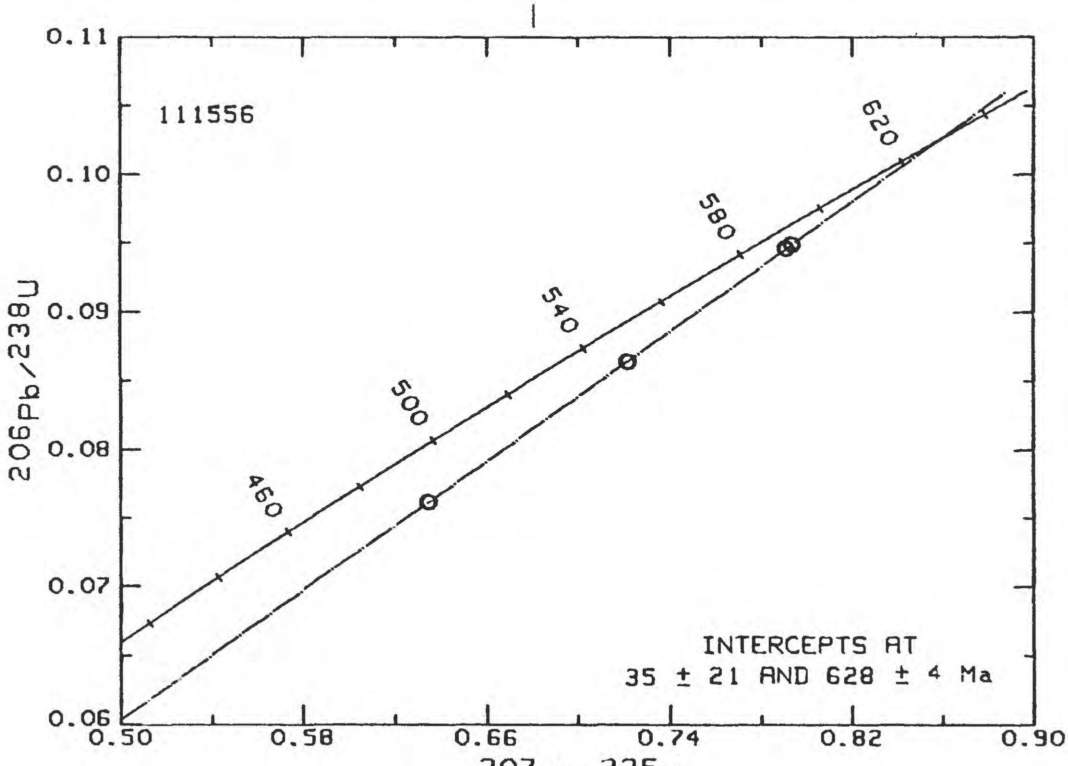
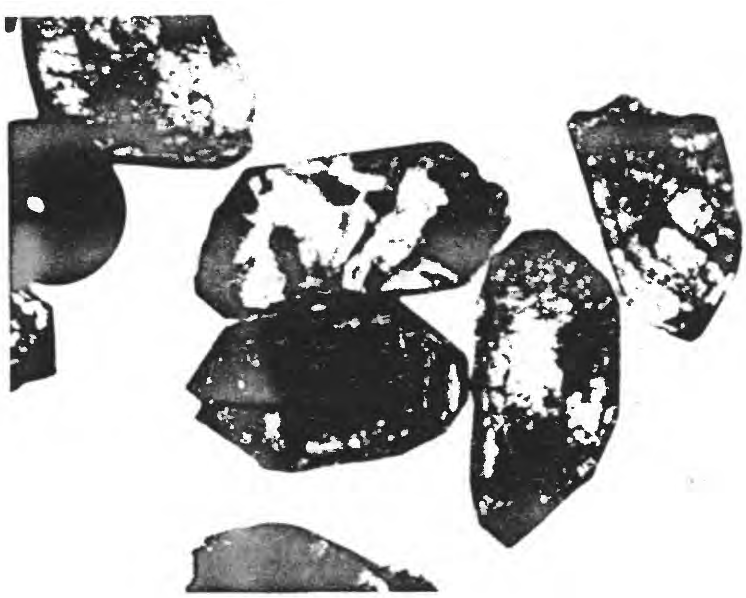


Figure 6.--Concordia plot of Jabal Al Hassir isotopic data.

Figure 7.--(a) Photomicrograph of Jabal Dahul core zircons (sample 111586) from the (-100+150) fraction. Note euhedral morphology and dark color, in contrast to zircons from the Jabal Dahul ring (figure 7b).



(b) Photomicrograph of Jabal Dahul ring zircons (sample 111585) from the (-100+150) fraction. Grains have similar morphology as zircons from the core of the complex (figure 7a) but are somewhat lighter, ranging in clarity from moderate to dark.

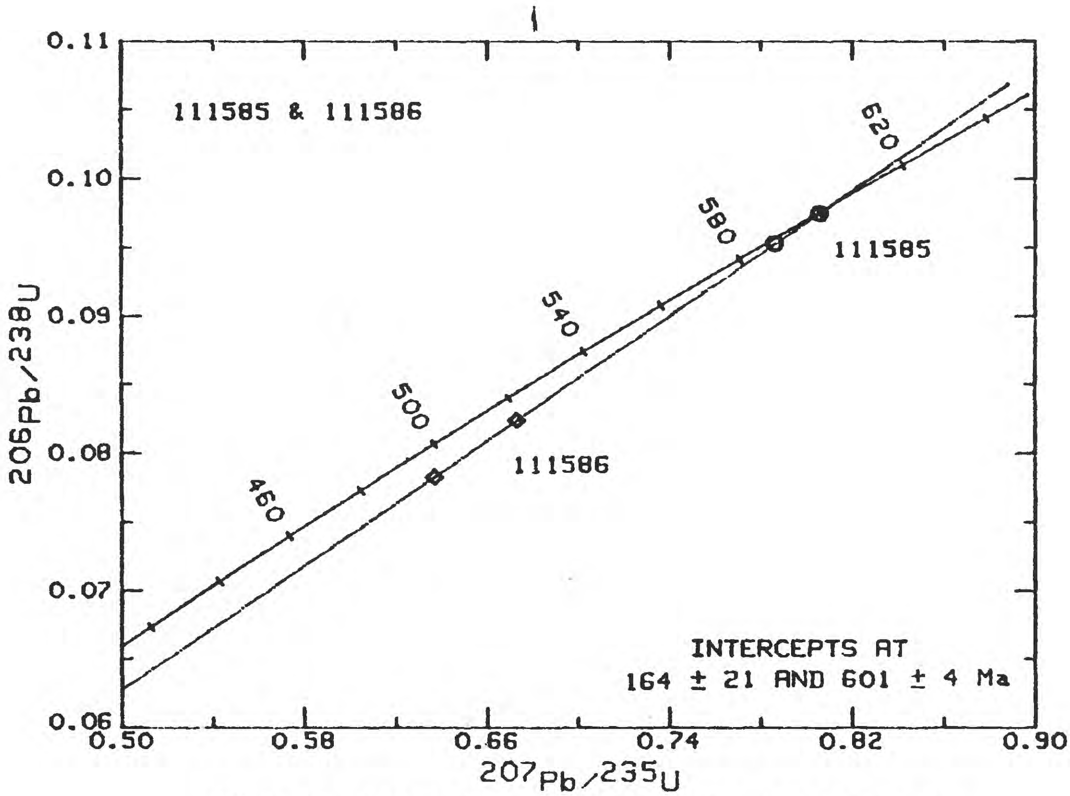


Figure 8.--Concordia plot of Jabal Dahul isotopic data.

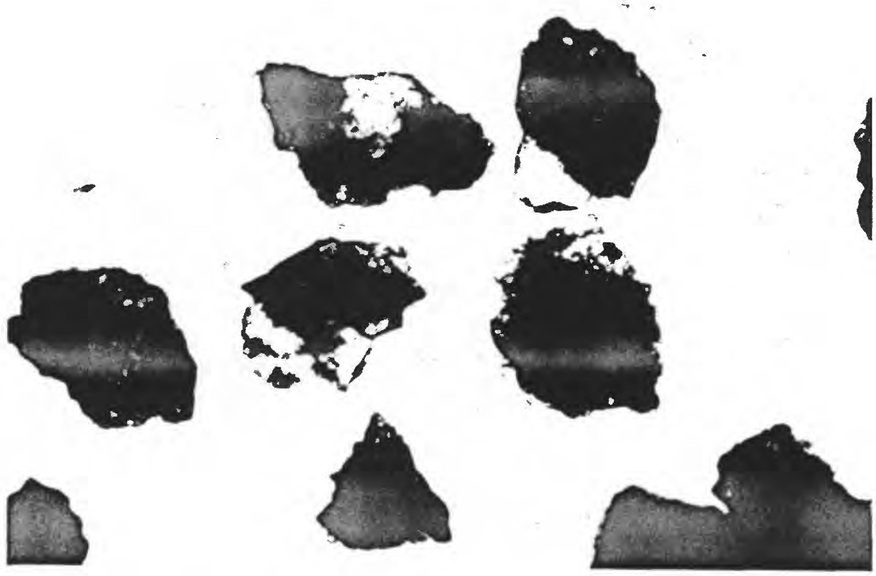


Figure 9.--SEM photomicrograph of Jabal Subh zircons (sample 111572) from the (-100+150) fraction. All zircons are anhedral.

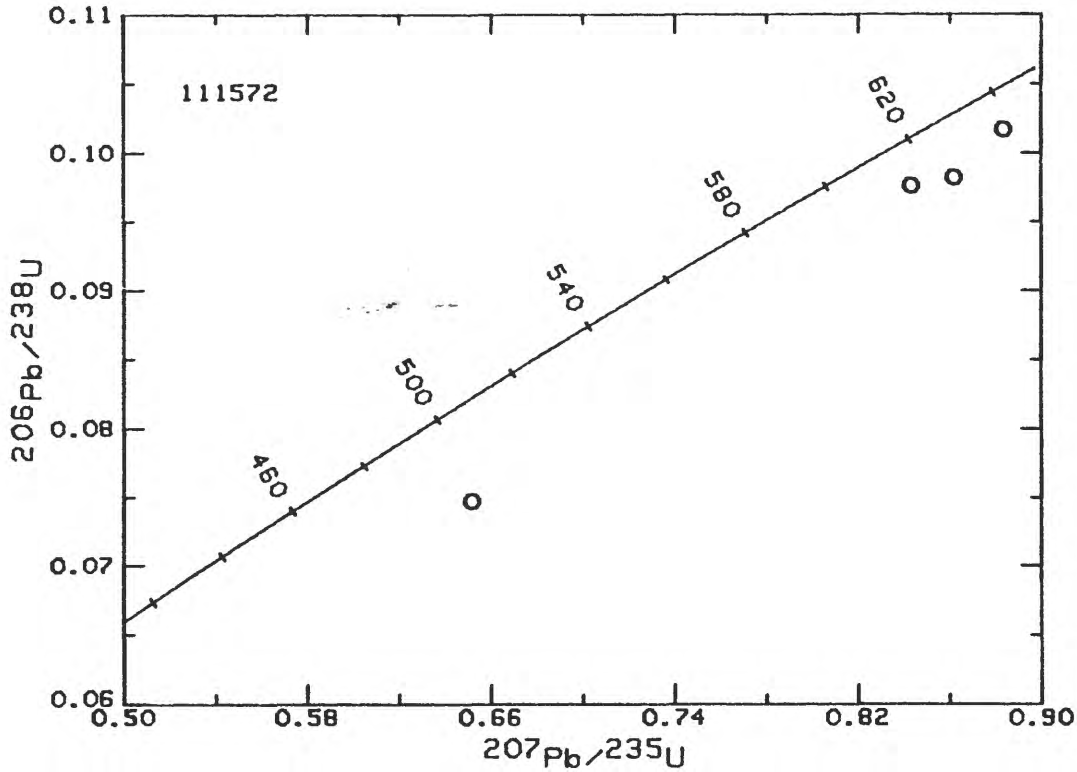


Figure 10.--Concordia plot of Jabal Subh isotopic data. The (-150+200)VM fraction containing brown zircons has the lowest $^{207}Pb/^{206}Pb$ age of 695 Ma. No meaningful age data can be derived from the isotopic results.

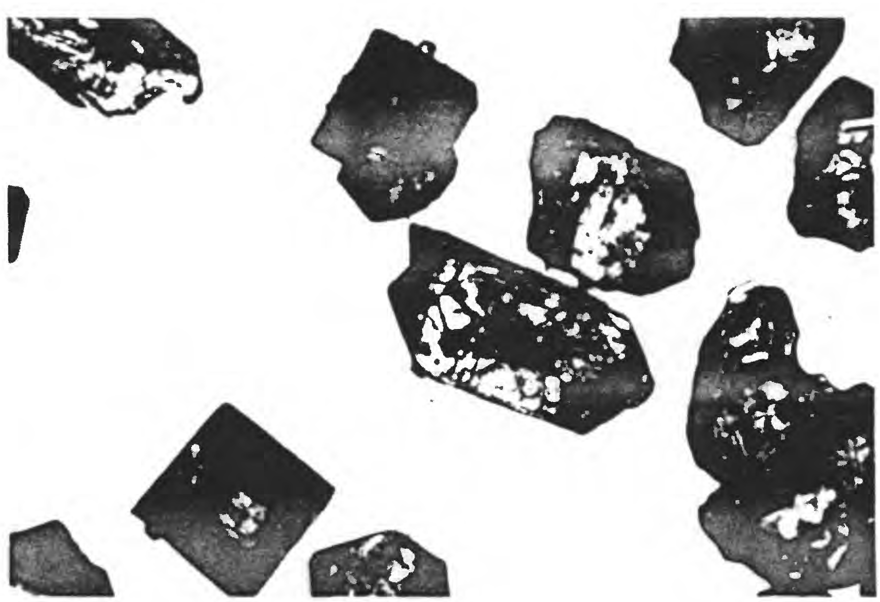


Figure 11.--SEM photomicrograph of Jabal Radwa zircons (sample 111618) from the (+150) fraction. Note large variation in morphology, ranging from prismatic to bipyramidal to, rarely, anhedral. See text for further explanation.

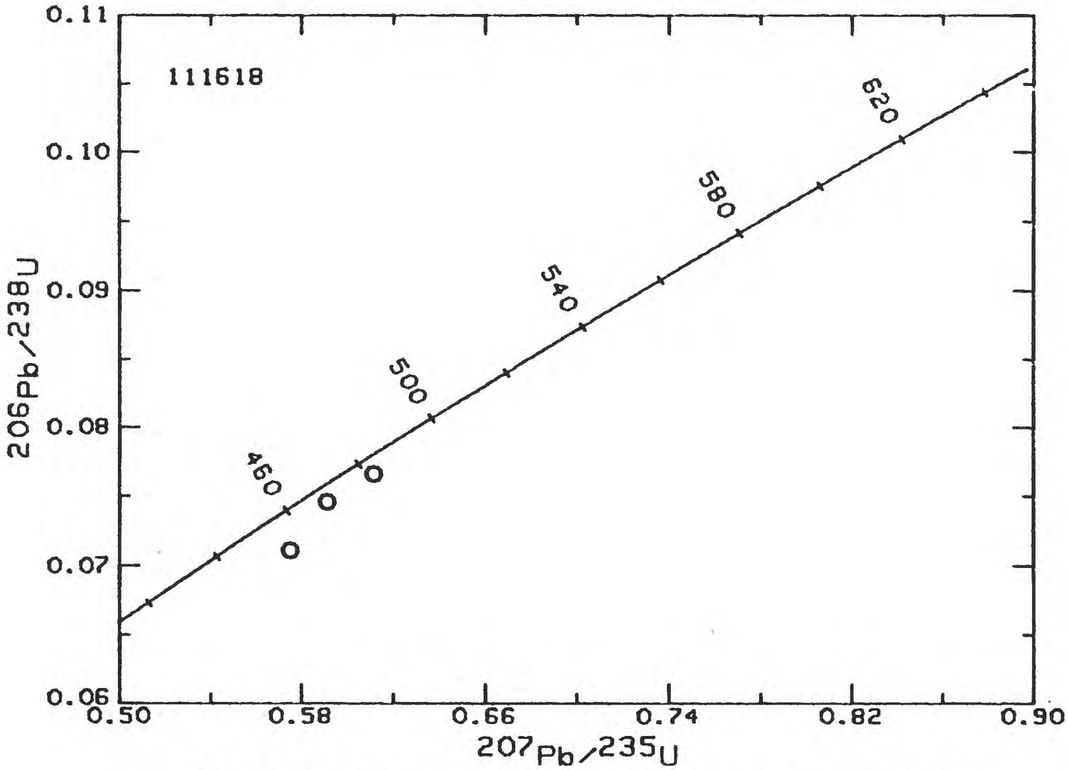


Figure 12.--Concordia plot of Jabal Radwa isotopic data.

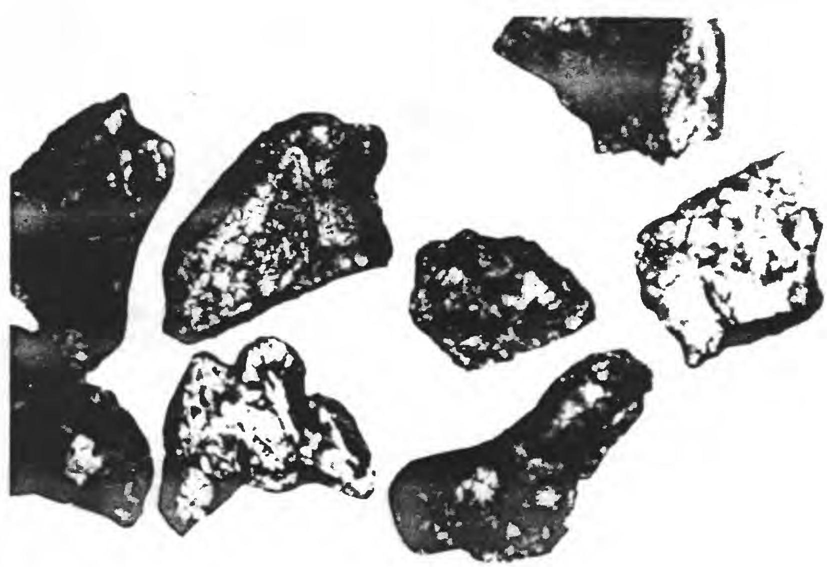


Figure 13.--Photomicrograph of Jabal Aja zircons (sample 112991) from the (+150) fraction.

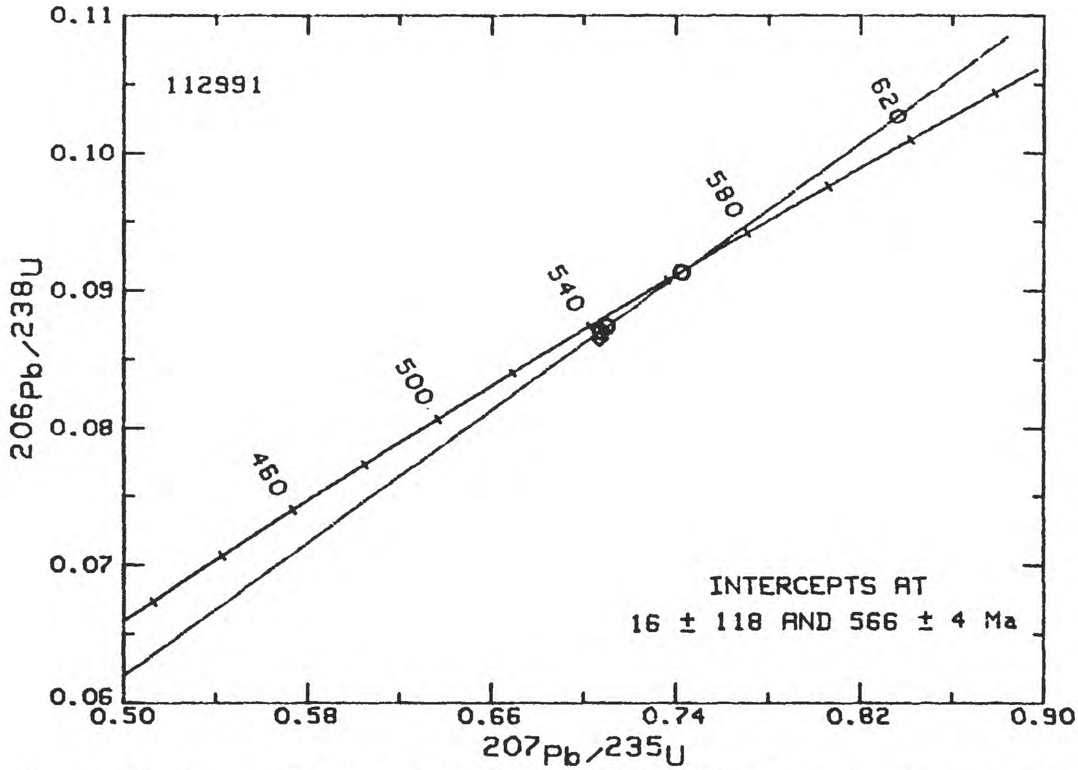


Figure 14.--Concordia plot of Jabal Aja isotopic data. Best-fit line was calculated through only three coarse fractions; the (-200) fraction was excluded.

Figure 15.--Photomicrograph of Jabal Dibbagh zircons (sample HSA-11) from the (+150)NM fraction. Although the agpaitic ratio (1.06) indicates that the rock is peralkaline, the zircons are prismatic, which is more characteristic of metaluminous rocks.

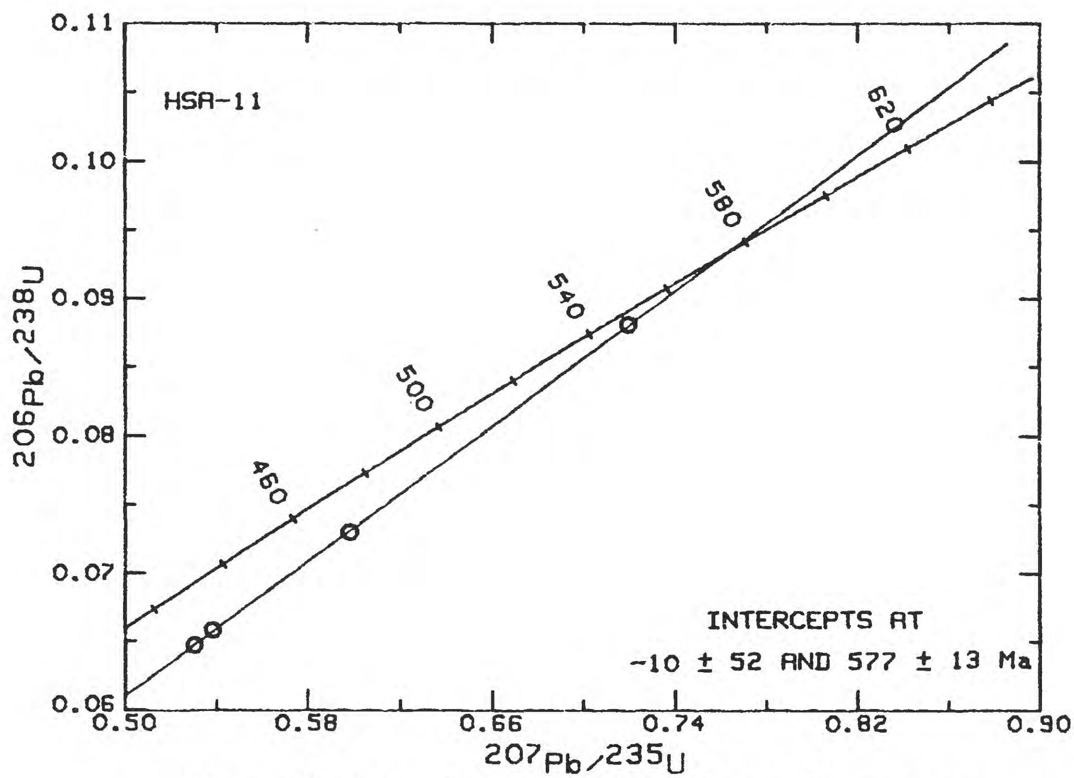


Figure 16.--Concordia plot of Jabal Dibbagh isotopic data.

DISCUSSION

One notable feature of the intracratonic stage of development of the Arabian Shield is the early development of subsolvus calc-alkaline leucocratic biotite granites and granodiorites, which gave way to a final stage of more highly evolved A-type hypersolvus biotite-hornblende or sodic-pyribole bearing alkali-feldspar granite and subsolvus peraluminous alkali-feldspar granite (Stoeser, 1986). Our data are too widely distributed and there is too little to define specific intrusive episodes of the late hypersolvus granites; however, the wide range in ages of these rocks (660 to 510 Ma) suggests that different intrusive episodes occurred although the same general evolutionary sequence appears throughout much of the Arabian Shield.

The oldest granite studied, the Jabal Subh peralkaline granite, belongs to a small suite of granites found in a relatively restricted area within the Hijaz terrane. The 670 Ma age of the Subh granite matches well with the 686±18 Ma Rb-Sr age for another alkali granite of the suite by Clark and Duyverman (1983). The Subh suite was probably emplaced at the end of the tectonic episode that ended with the suturing of the Hijaz and Asir terranes (Camp, 1984; Jackson and others, 1984). The region was tectonically reactivated with additional island arc-type activity and the emplacement of metaluminous subsolvus granites which intrude the Subh suite. The alkali granites of the Subh suite are the only known alkali-granites in the Arabian Shield that do not represent the final major intrusive phase within their local area.

Another province of late hypersolvus granites occur in the southern Arabian Shield within the Nabitah orogenic belt. The Al Hassir complex is located in the central part of the belt, and the Ashirah ring complex occurs on the eastern flank (fig. 1). Orogenic activity associated with the Nabitah belt occurred from 680 to 640 Ma. At the end of the Nabitah orogeny (640-630), postorogenic leucocratic biotite monzogranite plutons were emplaced throughout the southern Arabian Shield (Fleck and others, 1980; Stoeser and others, 1984). The Al Hassir and Ashirah complexes are typical of the last episode of granitic plutonism of the southeastern Shield and were emplaced about 635-625 Ma. It appears that most of the postorogenic emplacement of granites ceased within this region after this time, although J. S. Stuckless (unpublished data) has determined a whole rock Rb-Sr isochron age of 577±19 Ma for the Jabal al Gaharra peraluminous granite located 30 km west of the Jabal Ashirah pluton. There are similar ages for post-orogenic alkali-feldspar granites within the northern part of the Nabitah orogenic belt (fig. 2), and we tentatively suggest that the belt contains a province of such granites that formed soon after the Nabitah orogeny (640-625 Ma).

Post-orogenic granitic activity continued in the northern half of the Arabian Shield during 600-560 Ma (fig. 2) (Baubron and others, 1976; Calvez and others, 1983; Stacey and others, 1984; Stuckless and others, 1984), unlike in the southeastern Arabian Shield, where most of the plutonic activity appears to have ceased by 625 Ma. Three plutons dated in this study lie within the northern half of the Shield: Jabal Dahul (601±4 Ma), Jabal Aja (566±4 Ma), and Jabal Dibbagh (577±13 Ma). These data appear to substantiate earlier work that indicates that most of the subsolvus calc-alkaline metaluminous granites and granodiorites were emplaced in the northern Shield prior to 600 Ma and that most of the plutons emplaced after that time are composed of more evolved hypersolvus metaluminous to peralkaline alkali-feldspar granite, quartz syenite and peraluminous-to-metaluminous subsolvus alkali-feldspar granite.

The youngest granite studied for this report is the Jabal Radwa peralkaline granite which has a U-Pb zircon age of roughly 510 Ma and an Rb-Sr age of 521± 24 Ma (Kemp and others, 1980). This is the youngest known pluton within the Arabian Shield (Jackson and others, in press) and presently stands as a singular anomaly within the evolutionary framework of the Arabian Shield. Although anomalous in age relative to other granites of the Arabian Shield, it is not anomalous relative to the Nubian Shield, where anorogenic alkaline intrusive activity began about 550 Ma and continued throughout the Phanerozoic (Harris and Gass, 1981; Stern and Hedge, 1985; Vail 1985). Additional geochronologic work in the Hijaz and Midyan terranes might uncover other Phanerozoic intrusions.

Several interesting problems were addressed during the course of this study. Firstly, zircon morphology correlates strongly with the alkalinity of the metaluminous and peralkaline host rock. However, initially, it was difficult to identify zircon at all, because in three of the four peralkaline granites, the zircons were anhedral and(or) bipyramidal and occurred in several colors including blue, green and very dark brown. Another problem directly related to zircon morphology involved the very large common-lead component in most of the zircon samples. The ages of four samples were corrected by calculating a lead-evolution curve based on data from the southernmost sample, Jabal Ashirah; the ages of the other two samples were corrected using a co-existing feldspar and the average Stacey and Kramers (1975) values. These methods may not be completely satisfactory but at present we are unable to evaluate our assumptions beyond noting that the calculated ages appear to agree with the geologic field observations and ages obtained using the Rb-Sr method.

The occurrence of both inheritance and lead loss caused nonlinear data arrays on the concordia plots. The lower intercept age (164 Ma) of the Jabal Dahul samples further complicates the isotopic systematics. Non-zero lower intercepts were observed in rocks that occur in the east-central part of the Shield and that have zircons with high uranium contents (Stacey and others, 1984).

Non-zero lower intercepts and inheritance are complicating factors not generally encountered in other U-Pb studies throughout the Arabian Shield (Cooper and others, 1979; Stacey and others, 1984). Peralkaline granites become formidable rocks to date by the U-Pb zircon method when the analysis is complicated by very high common lead contents and unusual zircon morphology. In general, where Rb-Sr whole-rock isochron data were available for the plutons dated by us, the Rb-Sr ages were in good agreement with our U-Pb zircon ages. Therefore, given the problems of dating the peralkaline granites by the U-Pb zircon method, the Rb-Sr method seems preferable for routine geochronology.

CONCLUSIONS

The ages of the seven plutons dated in this study are: (1) Jabal Ashirah (sample 128913), 637±7 Ma, (2) Al Hassir (sample 111556), 628±4 Ma, (3) Jabal Dahul (samples 111585, 111586), 601±4 Ma, (4) Jabal Subh (sample 111572), less than 695 Ma, (about 670 Ma, data of Hedge, personal communication), (5) Jabal Radwa (sample 111618), about 510±15 Ma, (6) Jabal Aja (sample 112991), 556±4 Ma, and (7) Jabal Dibbagh (sample HSA-11), 577±13 Ma.

The primary focus of this study was to determine if the post-orogenic Pan African hypersolvus metaluminous and peralkaline granites throughout the Shield were formed during a single intrusive episode. Our U-Pb zircon data indicate that the granites in the study area range in age from about 670 Ma (Jabal Subh) to 510 Ma (Jabal Radwa), indicating that the metaluminous-to-peralkaline, late post-orogenic granites were emplaced over an interval of a least 150 million years and represent local intrusive episodes. The age data suggest that the tectonic environments responsible for the creation of these metaluminous and peralkaline rocks were not in operation at the same time throughout the Arabian Shield. Four separate episodes appear to have occurred at 670 Ma, 630 Ma, 570 to 560 Ma, and 510 Ma ago. Continuing studies of the geochronology of post-orogenic granites throughout the Shield should refine these age brackets and determine whether the range in ages reflects a continuum with changing geographic location or distinct periods of metaluminous magnetism. Therefore, individual post-orogenic bodies must be dated rather than assigning a single age for all peralkaline and metaluminous rocks of the Shield.

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DATA STORAGE

Data-file USGS-DF-06-4 has been established in the archives of the United States Geological Survey Saudi Arabian Mission, Jeddah, for preliminary data and other work material related to this report. No Mineral Occurrence Documentation System (MODS) localities were established in connection with this report.

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