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Isotopic studies of postorogenic granites from the northeastern Arabian Shield, Kingdom of Saudi Arabia

by

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1/ U.S. Geological Survey, Denver, CO
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ISOTOPIC STUDIES OF POSTOROGENIC GRANITES FROM THE NORTHEASTERN ARABIAN SHIELD, KINGDOM OF SAUDI ARABIA

by

J. S. Stuckless[1/], C. E. Hedge[2/], D. B. Wenner, and I. T. Nkomo

ABSTRACT

Rubidium-strontium whole-rock isochrons for eight postorogenic plutons of the northeastern Arabian Shield yield ages 630 to 575 Ma. Inclusion of one zircon U-Pb age extends the lower limit to 565 Ma. These ages plus existing data also suggest that the postorogenic granites north of the Nadj fault zone are younger (580 to 565 Ma) than those within the fault zone (630 to 595 Ma). The northern strand of the Nadj fault zone may therefore separate two fundamentally different rocks.

Initial isotopic compositions of lead and strontium indicate that the granites were derived from either unevolved source materials or that the source materials were not much older than the granites (less than 100 Ma). Oxygen-isotope data and chemical data, however, show that at least some of the granites were derived from an evolved pelitic source, and suggest that this component is present in the protolith for several granites. Isotopic and chemical data for the rest of the granites are consistent with derivation from a primitive, island-arc protolith.

Most of the plutons are isotopically homogeneous with respect to both radio- and stable isotopes, and therefore, there is no correlation between isotopic composition and degree of alumina saturation for plutons that vary from peralkaline to peraluminous. This lack of correlation indicates that variations in alumina saturation developed after generation of an isotopically homogeneous magma through a mechanism which is not yet understood.

There are subtle isotopic and trace-element differences between plutons including those that have similar major-element chemistry. These differences define a regional pattern such that the most radiogenic and petrologically evolved granites are generally east of the less evolved granites. This pattern suggests two protoliths: a pelitic source of continental affinity to the east, and an island-arc source to the west. The physical mixing of these two sources as sediments prior to magma generation seems to provide the best model to explain all the data.

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The U-Pb isotope systematics for the postorogenic granites show that both the percentage of uranium loss in recent time and the absolute amount are low relative to other granites that are associated with large, secondary uranium deposits. Therefore, the probability of finding uranium deposits formed by concentration of uranium leached from the postorogenic granites is low.

INTRODUCTION

The Arabian Shield is composed of a complex assemblage of Late Proterozoic metavolcanic, plutonic, and metasedimentary rocks that range in composition from basaltic to rhyolitic, and which have been variably, and in some cases, multiply deformed (Delfour, 1981; Greenwood and others, 1976; Fleck and others, 1980; Stoeser and Elliott, 1980; Fleck and Hadley, 1982; Schmidt and Brown, 1982; Elliott, 1983). These same authors have documented that the charater of magmatism during the time span of approximately 1,100 to 540 Ma changed from unevolved mafic rocks to intermediate rocks to evolved silicic (or bimodal gabbroic-granitic) rocks. Toward the end of this last magmatic period, the Arabian Shield was cut by the northwest-trending Najd Fault system that has a left-lateral displacement of as much as 240 km (Brown, 1972).

In recent years, the youngest granitic rocks (variously referred to as postorogenic, anorogenic, or posttectonic) have received considerable attention because of their tendency to be associated with enrichments in several elements of economic interest (Elliott, 1983). Within the Arabian Shield, occurrences of tungsten (Cole and others, 1981), rare-earth elements and thorium (Harris and Marriner, 1980; Stuckless and others, 1982a), and tin (Elliott, 1980; du Bray, oral commun., 1983) have been reported, and a good potential exists for niobium and tantalum (Elliott, 1983). In addition, these youngest granites have stirred considerable controversy in the debate over the origin of peralkaline granites (Harris, 1981; Radain and others, 1981; Stuckless and others, 1982b) and have been used in the debate concerning the origin of the Arabian Shield (Stacey and others, 1980; Delfour, 1981; Fleck and Hadley, 1982; Schmidt and Brown, 1982; Stacey and Stoeser, 1984).

Isotopic studies of granitic rocks have proved to be useful, not only in the determination of ages, but also in placing constraints on the character of the protolith and conditions of post-intrusive alteration. High delta-18O values and peraluminous compositions are expected with pelitic protoliths regardless of age considerations (for example, Taylor, 1978; Wenner, 1981), and consequently, delta-18O values may correlate well with degree of alumina saturation. Protolithic materials that have a significant crustal history prior to melting can be identified through the use of lead and strontium isotopes, and in some instances, specific inferences about the history of the protolith can be made. Broad-scale isotopic studies of granitic rocks of the United States have documented the existence of regional isotopic patterns which are often correlative with patterns in major and trace-element chemistry of igneous provinces (Kistler and Peterman, 1978; Taylor and Silver, 1978; Masi and others, 1981; Farmer and DePaulo, 1983). These isotopic and chemical variations are attributed to regional variations in the protolith.

The work on which this report is based was performed in accordance with the cooperative agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey. The research is part of a program to study the petrogenesis and mineral potential of granitic rocks of the Arabian Shield. In particular, this report focuses on isotopic results for the postorogenic granites of the northeastern Shield (fig. 1) and will attempt to relate these data to results for other postorogenic granites throughout the Arabian Shield.

The classification of plutonic rocks used in this report is that recommended by the International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Plutonic Rocks (Streckeisen, 1976). Subdivision of te rocks on the basis of aluminia saturation is based on the definitions of Shand (1951) such that rocks with molar $Al/(Na+K)<1$ are peralkaline; $Al/(Na+K+Ca)>1$ are peraluminous; $Al/(Na+K+Ca)<1$ and $Al/(Na+K)>1$ are metaluminous. Decay constants and standard isotopic ratios used are those recommended by the IUGS Subcommission of Geochronology (Steiger and Jager, 1977).

ANALYTICAL PROCEDURES

Rubidium and strontium concentrations (table 1) were determined on separate dissolutions with 87Rb and 84Sr tracers. Replicate analyses of granitic samples indicate an analytical precision of $\pm$1.0 percent, which includes errors due to splitting the rock powders. Replicate analyses of the Eimer and Amend $SrCO_3$ standard yield and average 87Sr/86Sr value of 0.70802$\pm$0.00006 (2 sigma); compositional errors for granitic samples are $\pm$0.02 percent (2 sigma). Reported isotopic data have been normalized to a 88Sr/86Sr value of 0.1194.

Uranium, thorium, and lead concentrations and the isotopic composition of lead were determined on one-half- to 1-g

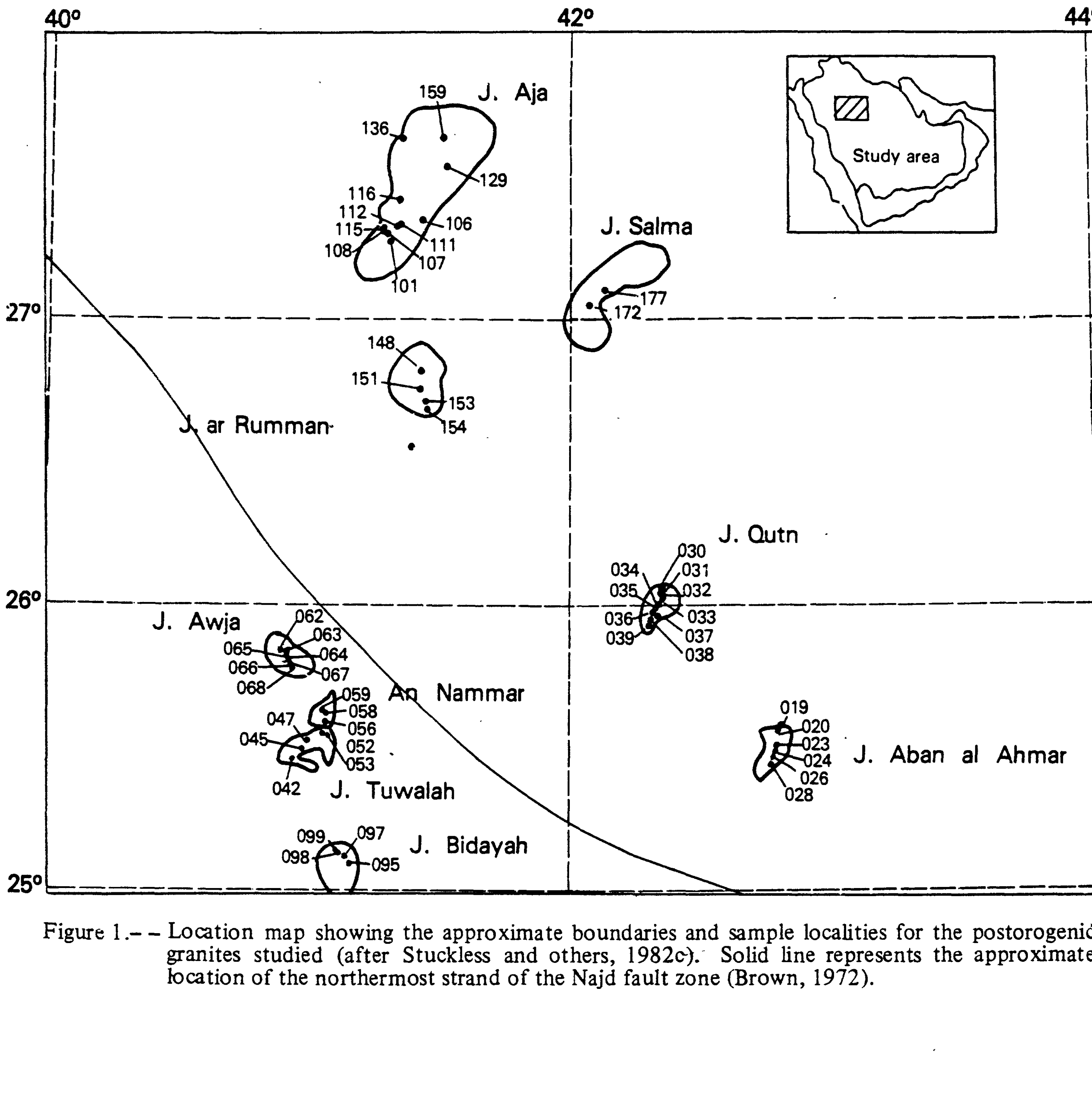


Figure 1.-- Location map showing the approximate boundaries and sample localities for the postorogenic granites studied (after Stuckless and others, 1982c). Solid line represents the approximate location of the northermost strand of the Najd fault zone (Brown, 1972).

Table 1.—Rubidium (Rb) and strontium (Sr) concentrations and isotopic compositions of strontium for granite samples from the northeastern Arabian Shield

Sample no.	Rb (ppm)	Sr (ppm)	87Rb/86Sr	87Sr/86Sr
		Jabal Aban al Ahmar		
155019	166.9	10.7	46.7	1.0860
155020	188.6	15	37.4	1.0062
155023	142.2	99.6	4.15	.7368
155024	150.6	72.4	6.05	.7512
155026	182.2	32.4	16.5	.8410
155028	146.9	95.2	4.48	.7393
		Jabal Qutn		
155030	150.8	15.5	28.9	.9438
155032	358.2	9.6	118	1.6828
155033	322.9	32.1	29.8	.9503
155035	239.5	58.4	12.0	.8047
155037	278.5	51.8	15.8	.8353
155039	428.8	8.2	173	2.1404
		Jabal Tuwalah		
155042	184.9	7.2	79.8	1.4220
155045	248.7	8.4	92.4	1.5285
155047	162	39.6	12.0	.8089
155052	201.2	6.5	97.6	1.5707
155053	268.7	15.8	51.5	1.1644
		An Nammar		
155056	145	17.5	24.5	.9139
155058	147	91.4	4.68	.7439
155059	127.7	115.7	3.20	.7304
		Jabal Awja		
155062	245	8.2	93.1	1.4923
155067	160	46	10.2	.7901
		Jabal Bidayah		
155095	104.9	37.37	8.18	.7736
155097	133	58.9	6.59	.7595
155098	113	68.78	4.77	.7437
155099	99.2	17.4	16.7	.8488
		Jabal ar Rumman		
155148	124	13.5	27.2	.9278
155151	92.6	85	3.16	.7292
155153	98.3	36.1	7.92	.7683
155154	120	12.1	29.3	.9471
		Jabal Salma		
155172	163	63.7	7.46	.7654
155177	225	15.1	44.6	1.0726

splits of finely pulverized whole-rock samples (table 2). Chemical procedures used were essentially those described by Tatsumoto and others (1972) except that final purification of lead was accomplished by electroplating (Barnes and others, 1973). Mass spectrometry was done on an NBS-type 12-inch radius instrument. Lead compositions and concentrations were obtained using a triple-filament mode of ionization with lead loaded with silica gel and phosphoric acid. Mass spectrometric results with an internal precision poorer than $\pm$0.1 percent were rejected. Replicate measurements of the National Bureau of Standards (NBS) Standard Reference Material SRM-981 indicate accuracies of $\pm$0.12 percent of 206Pb/204Pb, $\pm$0.16 percent for 207Pb/204Pb, and $\pm$0.18 percent for 208Pb/204Pb and an error correlation of 0.985 for the 206Pb/204Pb-207Pb/204Pb values (errors stated at the 2 sigma level). Concentration errors are estimated at $\pm$1 percent on the basis of duplicate analyses and include a large component of error as a result of splitting.

Oxygen-isotope data (table 3) were obtained by fluorine extraction (Taylor and Epstein, 1962) and analysis in a VG Micromass mass spectrometer, model 602C, modified with a PSC Data Control System. The 18O/16O values are reported relative to Standard Mean Ocean Water (SMOW), and are calibrated relative to NBS-28 standard that has a defined value of 9.61 per mil (parts per thousand). Accuracy of reported values is $\pm$0.1 per mil (2 sigma).

Regression of best-fit lines was accomplished using the methods of York (1969). Initial 206Pb/204Pb and 207Pb/204Pb values were calculated by projecting the centroid of the data back to a chord on the Stacey and Kramers (1975) lead-evolution model. The chord chosen was the one joining 3700 Ma and the age of intrusion as determined by the Rb-Sr age, except at Jabal Aja for which the Th-Pb age was used.

RESULTS

Geochronology

Six postorogenic plutons of the northeastern Arabian Shield were examined in detail by use of a combination of geochronologic techniques: Jabal Aban al Ahmar (Rb-Sr, Th-Pb, and Pb-Pb), Jabal Qutn (Rb-Sr, Th-Pb, Pb-Pb, ad K-Ar), Jabal Tuwalah (Rb-Sr, Th-Pb, and Pb-Pb), Jabal Bidayah (Rb-Sr), Jabal Aja (Th-Pb and Pb-Pb), and Jabal ar Rumman (Rb-Sr). In addition, three plutons were examined in a cursory fashion for compatibility with results for the better studied plutons: An Nammar (Rb-Sr and Pb-Pb), Jabal Awja (Rb-Sr, Th-Pb, and Pb-Pb), and Jabal Salma (Rb-Sr). A summary of ages obtained is presented in table 4, and initial isotopic ratios are presented in table 5.

Jabal Aban al Ahmar

The pluton at Jabal Aban al Ahmar is a hypersolvus, alkali-feldspar granite. It is roughly zoned with a relatively thin and discontinuous rim of coarse-grained peralkaline granite (samples 155019 and 155020) and a core of fine- to medium-grained metaluminous (samples 155023, 155024, and 155028) to weakly peraluminous (sample 155026) granite (Stuckless and others, 1982c).

The Rb-Sr data are not colinear on an isochron plot (fig. 2) within the limits of analytical precision (MSWD=13.2), and the apparent age of 574±5 Ma and the initial 87Sr/86Sr value of 0.7030±0.0026 are calculated by assuming a normal distribution of the variations in the initial isotopic compositions. Initial Sr isotopic compositions computed for each sample are weakly correlated with the degree of alumina saturation such that the peraluminous sample has the highest initial ratio (0.7060) and one of the peralkaline samples (155020) has the lowest ratio (0.7004); however the second highest initial ratio (0.7038) is for the other peralkaline sample.

The Th-Pb data are colinear on an isochron plot (fig. 3) within the limits of analytical precision (MSWD=2.1). The resulting age of 581±29 Ma is in excellent agreement with that obtained by the Rb-Sr method. The initial 208Pb/204Pb value of 37.405±0.075, like the initial 87Sr/86Sr value, is low.

The Pb-Pb data are also colinear on an isochron plot (fig. 4) within the limits of analytical precision (MSWD= 0.05); however, the limited range of values relative to the percent analytical error results in extremely large errors for the slope and age calculations (table 4). Calculated average values for the initial 206Pb/204Pb and 207Pb/204Pb values of 17.648 and 15.518, respectively, are again low (table 5).

Jabal Qutn

The pluton at Jabal Qutn is different from the other postorogenic plutons examined in this study in that all analyzed samples are peraluminous and that the granite is a subsolvus type (Stuckless and others 1982c). Furthermore, primary muscovite is ubiquitous. Samples used in the current study vary from medium-grained porphyritic to coarse-grained.

The Rb-Sr data fit an isochron (fig. 2) within the limits of analytical precision (MSWD=0.7). The resulting age of 579±4 Ma is not significantly different from that obtained at Jabal Aban al Ahmar, but the initial 87Sr/86Sr

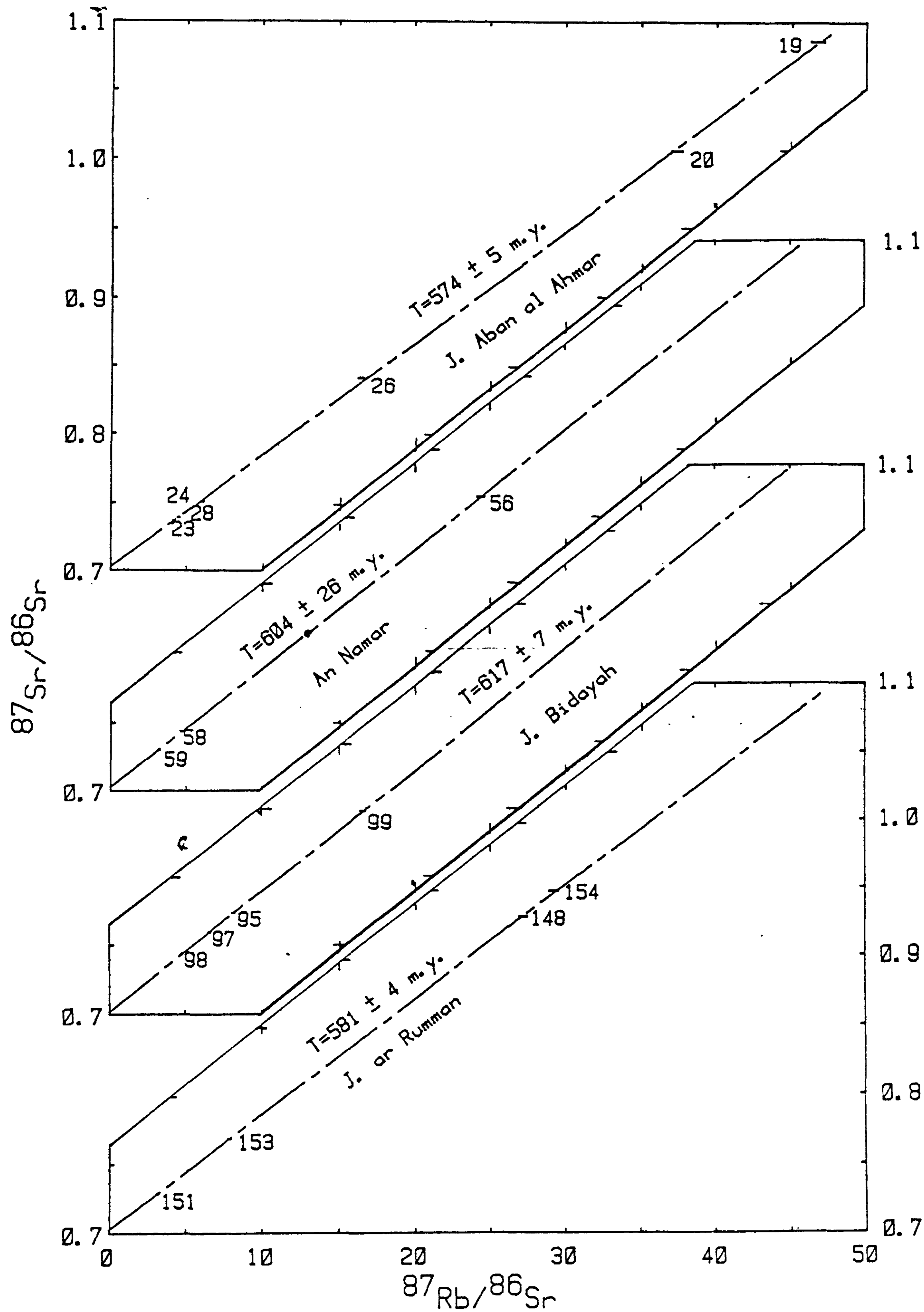
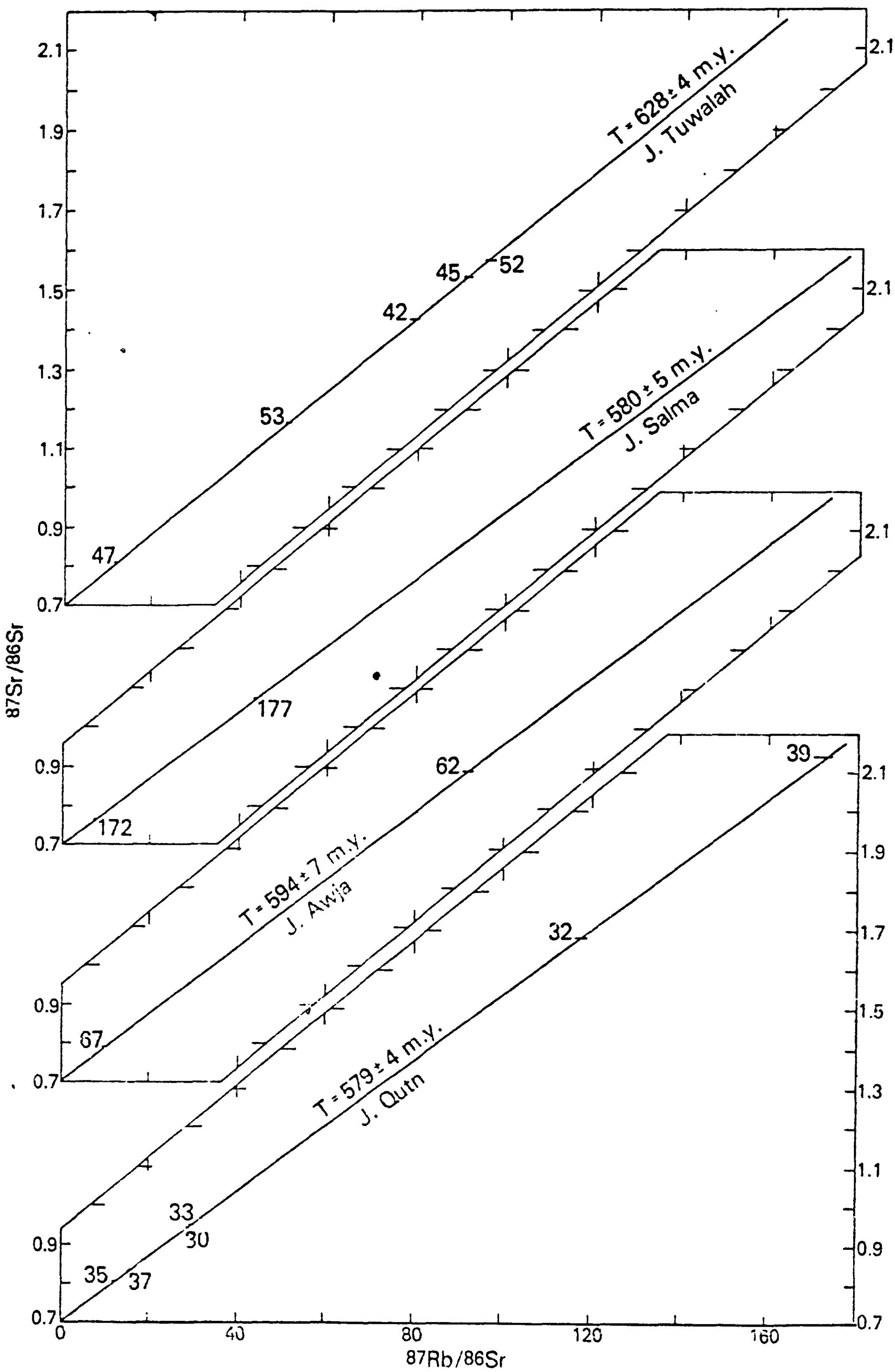


Figure 2.--Rb-Sr isochron diagrams for eight postorogenic plutons of the northeastern Arabian Shield. Samples are labelled with last two or three digits of sample number only.



T = 628 ± 4 m.y.
J. Tuwalah
T = 580 ± 5 m.y.
J. Salma
T = 594 ± 7 m.y.
J. Awja
T = 579 ± 4 m.y.
J. Qutn
47
53
42
45
52
177
172
62
67
39
32
33
30
35
37
87Sr/86Sr
87Rb/86Sr
0
40
80
120
160
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1

Table 2.—Uranium (U), thorium (Th), and lead (Pb) concentrations and isotopic compositions of lead for granite samples from the northeastern Arabian Shield [Leaders (—) indicate no analysis]

Sample no.	U (ppm)	Th (ppm)	Pb (ppm)	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	238U/204Pb	232Th/204Pb
155019	7.22	23.05	54.33	18.573	15.568	38.292		
155019	7.31	23.02	54.14	—	—	—		
155019	7.32	23.03	54.2	—	—	—		
ave	7.28	23.03	54.22	18.573	15.568	38.292	8.52	27.85
155020	6.52	21.09	28.33	19.055	15.595	38.789		
155020	—	—	—	19.075	15.615	38.798		
ave	6.52	21.09	28.33	19.065	15.605	38.794	14.82	49.5
155023	4.15	14.04	21.24	19.153	15.607	38.697		
155023	4.01	13.53	20.53	—	—	—		
ave	4.08	13.78	20.88	19.153	15.607	38.697	12.58	43.87
155024	3.84	13.5	21.09	18.952	15.591	38.689		
155024	3.83	13.4	20.94	—	—	—		
ave	3.84	13.45	21.01	18.952	15.591	38.689	11.75	42.74
155026	6.1	19.46	17.57	19.923	15.655	39.629		
155026	6.16	19.66	17.37	—	—	—		
ave	6.13	19.56	17.47	19.923	15.655	39.629	23.11	76.2
155028	3.41	13.17	19.25	18.994	15.597	38.757		
155028	3.49	13.3	19.46	—	—	—		
ave	3.45	13.24	19.36	18.994	15.597	38.757	11.46	45.43
155030	5.03	14.35	27.37	19.094	15.621	38.407		
155030	4.95	14.19	26.79	19.155	15.627	38.402		
ave	4.99	14.27	27.08	19.105	15.624	38.405	11.82	34.88
155032	13.89	23.49	40.93	19.212	15.63	38.528	21.8	38.1
155033	8.75	19.35	39.54	19.176	15.631	38.355	14.19	32.4
155035	6.87	16.6	30.01	19.682	15.663	38.493		
155035	6.83	16.54	29.75	—	—	—		
ave	6.85	16.57	29.88	19.682	15.663	38.493	14.83	37.06
155037	9.2	20.56	35.07	19.525	15.642	38.477	16.93	39.06
155039	7.84	18.89	47.33	18.795	15.602	38.146		
155039	7.91	18.97	47.42	18.804	15.61	38.138		
ave	7.87	18.93	17.38	18.8	15.606	38.142	10.56	26.24
155042	8.9	33.7	9.17	29.981	16.237	46.626	78.64	308.2
155045	7.07	16.26	19.2	19.869	15.624	38.751		
155045	6.99	16.13	19.14	—	—	—		
ave	7.03	16.2	19.17	19.869	15.624	38.571	23.85	56.78

Table 2.—Continued

Sample no.	U (ppm)	Th (ppm)	Pb (ppm)	206Pb/ 204Pb	207Pb/ 204Pb	208Pb/ 204Pb	238U/ 204Pb	232Th/ 204Pb
155047	6.62	15.89	5.2	25.766	16.004	44.222		
155047	6.47	15.67	5.23	—	—	—		
ave	6.55	15.78	5.22	25.766	16.004	44.222	94.22	234.54
155052	10.25	17.26	31.18	19.584	15.606	38.218	21.14	36.78
155053	7.76	20.92	42.81	18.79	15.566	38.145	11.52	32.07
155059	4.73	11.29	35.54	18.672	15.574	38.128	8.45	20.81
155062	9.77	21.69	42.94	19.294	15.593	38.41		
155062	9.64	21.48	43.42	19.305	15.595	38.416		
155062	—	—	—	19.315	15.605	38.419		
ave	9.7	21.58	43.18	19.305	15.598	38.415	14.42	33.17
155063	7.42	24.19	41.63	19.104	15.589	38.289		
155063	7.42	24.69	41.87	—	—	—		
ave	7.42	24.44	41.75	19.104	15.589	38.289	12.78	38.68
155064	5.86	19.04	25.38	19.15	15.592	38.386		
155064	5.84	18.97	25.21	19.181	15.606	38.417		
ave	5.85	19.01	25.29	19.167	15.599	38.402	14.82	49.76
155066	2.92	6.76	16.59	19.025	15.576	38.302		
155066	—	—	—	19.017	15.576	38.258		
155066	—	—	—	18.994	15.554	38.285		
ave	2.92	6.76	16.59	19.012	15.569	38.282	11.25	26.89
155101	9.52	19.6	72.27	18.525	15.565	37.922	8.31	17.68
155106	4.67	13.47	23.5	18.977	15.594	38.531	12.72	37.93
155107	11.3	27.2	22.88	20.634	15.7	39.746	32.89	81.82
155108	11.11	43.45	78.18	18.742	15.579	38.466	9.06	36.62
155111	2.93	11.53	12.99	19.099	15.586	39.173	14.59	59.33
155112	3.92	7.67	17.98	19.038	15.6	38.22	13.91	28.13
155115	10.38	32.97	42.78	19.138	15.608	38.904	15.65	51.37
155116	6.84	22.42	38.33	18.95	15.599	38.571	11.43	38.71
155129	2.92	9.7	19.9	19.434	15.625	38.342	9.43	32.38
155136	4.12	16.55	27.28	18.859	15.578	38.602	9.66	40.11
155159	9.21	31.89	49.03	19.143	15.611	38.702	12.09	43.24

Table 3.--Delta 18O values for whole-rock samples and quartz separates from granites from the northeastern Arabian Shield [Leaders (--) indicate no analyses]

Sample no.	Whole-rock	Quartz	Sample no.	Whole-rock	Quartz
		Jabal Aban al Ahmar			
155019	8.5	9.7	155024	9.1	--
155020	8.8	--	155026	9.1	9.5
155023	9.7	9.9	155028	9.6	--
		Jabal Qutn			
155030	10.8	--	155035	10.9	--
155031	10.1	--	155036	9.4	--
155032	10.5	--	155037	10.7	10.2
155033	10.8	--	155038	10.6	11.2
155034	10.4	10.8	155039	9.7	--
		Jabal Awja			
155062	3.8	--	155066	7.3	--
155063	7.4	--	155067	7.6	--
155064	8.3	--	155068	7.7	--
155065	8.3	--			
		Jabal Aja			
155106	6.8	--	155115	6.3	--
155107	7.4	7.4	155129	5.7	--
155108	6.6	--	155136	6.7	--
155111	5.3	--	155159	7.9	6.4

value of 0.7055±0.0011 is slightly higher.

The Th-Pb and Pb-Pb data are also colinear on isochron plots (figs. 3 and 4) within the limits of analytical error (MSWD=1.42 and 0.12, respectively). However, the small range in isotopic ratios relative to the size of the analytical errors results in very large errors for the calculated ages (570±106 Ma and 568±1590 Ma, respectively). Unlike the iitial 87Sr/86Sr value, the initial 208Pb/204Pb value of 37.410±0.188 is not elevated relative to that for Jabal Aban 3 and 4) within the limits of analytical error (MSWD=1.42 and 0.12, respectively). However, the small range in isotopic ratios relative to the size of the analytical errors results in very large errors for the calculated ages (570±106 Ma and 568±1590 Ma, respectively). Unlike the iitial 87Sr/86Sr value, the initial 208Pb/204Pb value of 37.410±0.188 is not elevated relative to that for Jabal Aban but the biotite age is slightly young. A similar lowering of K-Ar ages has been noted in the southern Arabian Shield and attributed to thermal pulses which occurred between 610 and 560 Ma and 540 and 510 Ma (Fleck and others, 1976). These events, at least in the northern Shield, were apparently too weak to affect the K-Ar muscovite age which is somewhat more resistant to thermal resetting that the K-Ar biotite age (Dalrymple and Lanphere, 1969).

Jabal Tuwalah

The pluton at Jabal Tuwalah is similar to that at Jabal Aban al Ahmar in that it is a hypersolvus, alkali-feldspar granite, and samples exhibit a wide range of alumina saturations: samples 155042 and 155045 are peralkaline, sample 155047 is metaluminous, and samples 155052 and 155053 are peraluminous. Samples vary from medium-grained porphyritic to coarse-grained with the latter texture most typical of peralkaline varieties.

The Rb-Sr data yield an isochron (fig. 3) within the limits of analytical error (MSWD=1.5). The resulting age is 628±4 Ma and the initial 87Sr/86Sr value is 0.7019±0.0012. This is the oldest age found for any of the postorogenic granites investigated for this report. Baubron and others (1976) report data that yield a model 3 age of 618±30 Ma and an initial 87Sr/86Sr value of 0.7052±0.0163 (age and initial ratio recalculated using the decay constants and regression methods of this report and assuming reported errors are 2 sigma). These results are in general agreement with the more precise values obtained for this report.

The Th-Pb data do not yield an isochron (fig. 5) within the limits of analytical precision (MSWD=6.1), but the calculated age of 613±68 Ma (assuming normal distribution of errors) is in adequate agreement with that obtained by the

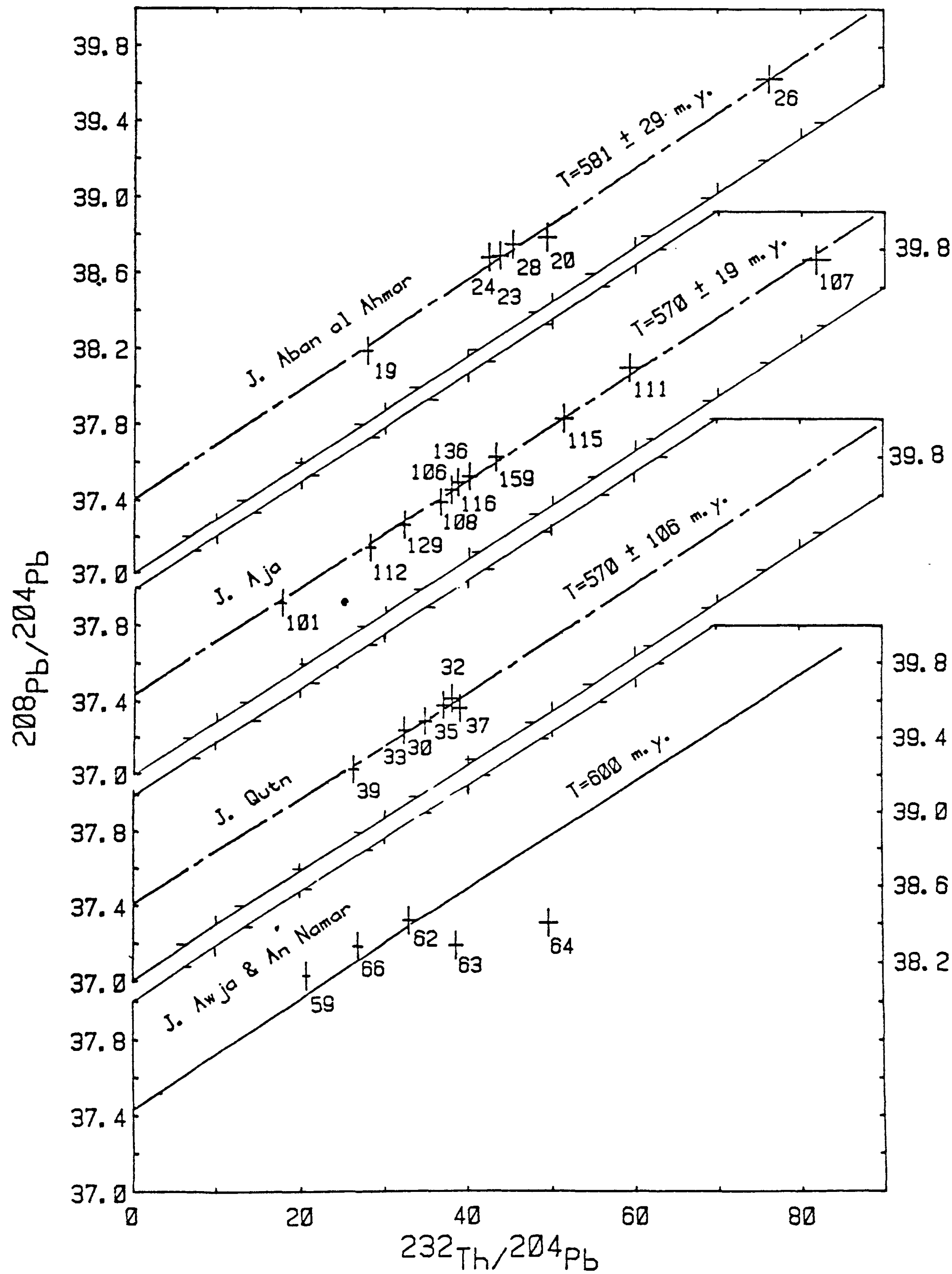


Figure 3.—Th-Pb isochron diagrams for data from five postorogenic plutons from the northeastern Arabian Shield. The line shown for Jabal Awja and An Nammar is a reference isochron only. Samples are labelled with last two or three digits of sample number only.

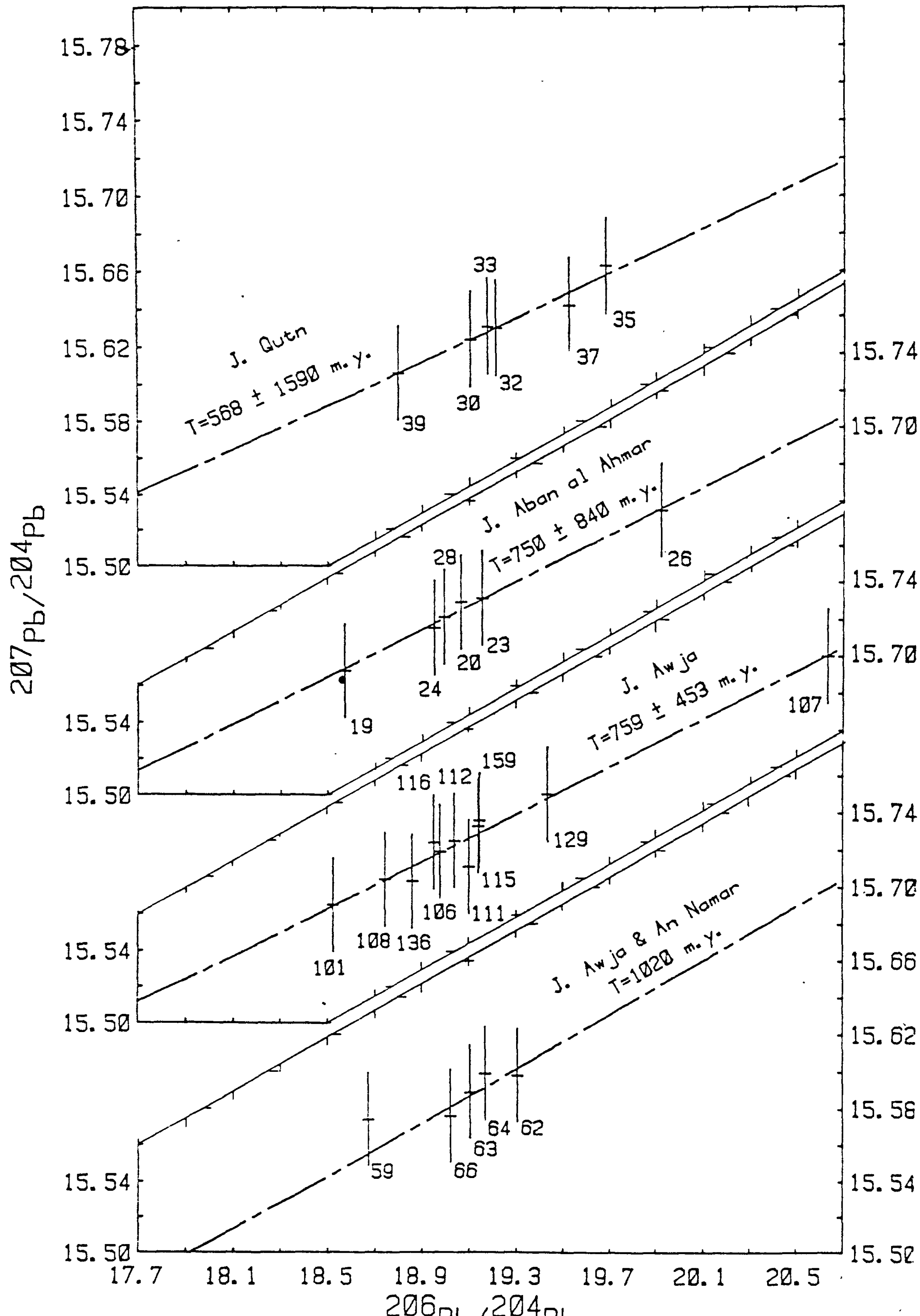
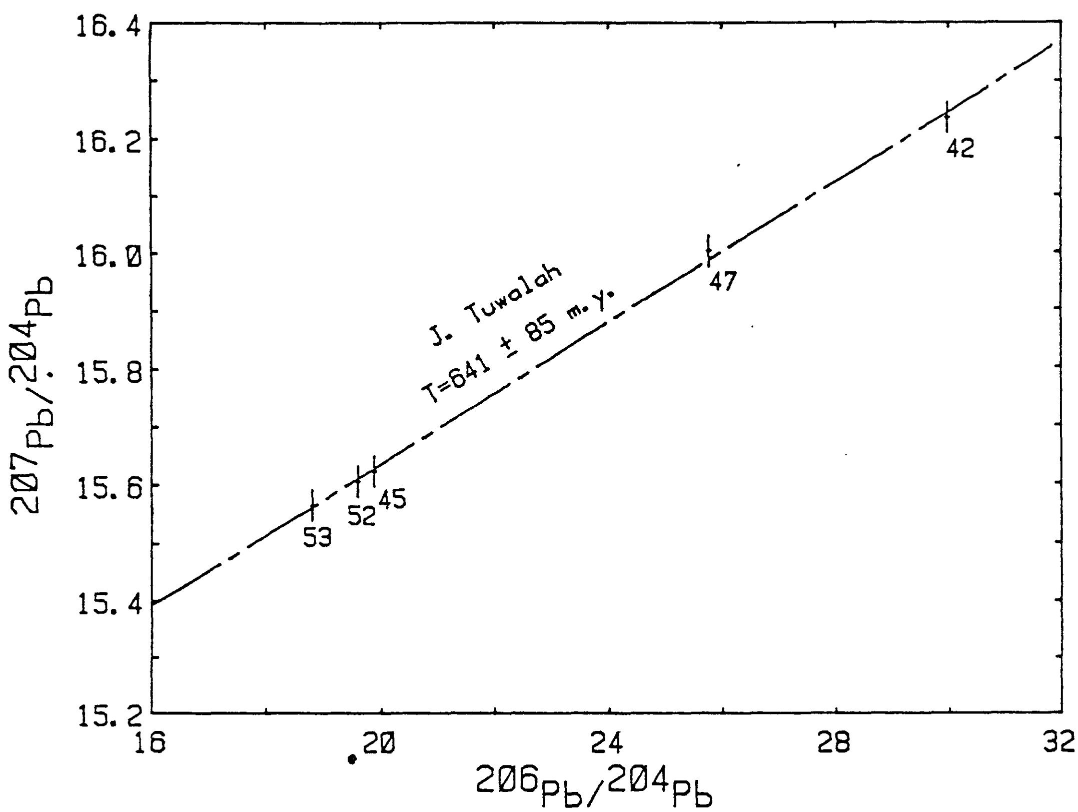


Figure 4.--Pb-Pb isochron diagrams for data from five postorogenic plutons from the northeastern Arabian Shield. The line shown for the Jabal Awja and An Nammar data is regress through the Jabal Awja data only. Samples are labelled with last two or three digits of sample number only.

Table 4.--Summary of ages in millions of years for granitic plutons of the northeastern Arabian Shield [Ages based on whole-rock isochrons except muscovite (M) and biotite (B)]

Pluton	Rb-Sr	Th-Pb	Pb-Pb	K-Ar
J. Aban al Ahmar	574 ± 5	581 ± 29	750 ± 840	--
J. Qutn	579 ± 4	570 ± 106	568 ± 1590	577 ± 11 (M) 552 ± 24 (B)
J. Tuwalah	628 ± 4	613 ± 68	641 ± 85	--
An Nammar	604 ± 26	--	--	--
J. Awja	594 ± 7	--	1020	--
J. Bidayah	617 ± 7	--	--	--
J. Aya	--	570 ± 19	759 ± 453	--
J. ar Rumman	581 ± 4	--	--	--
J. Salma	580 ± 5	--	--	--



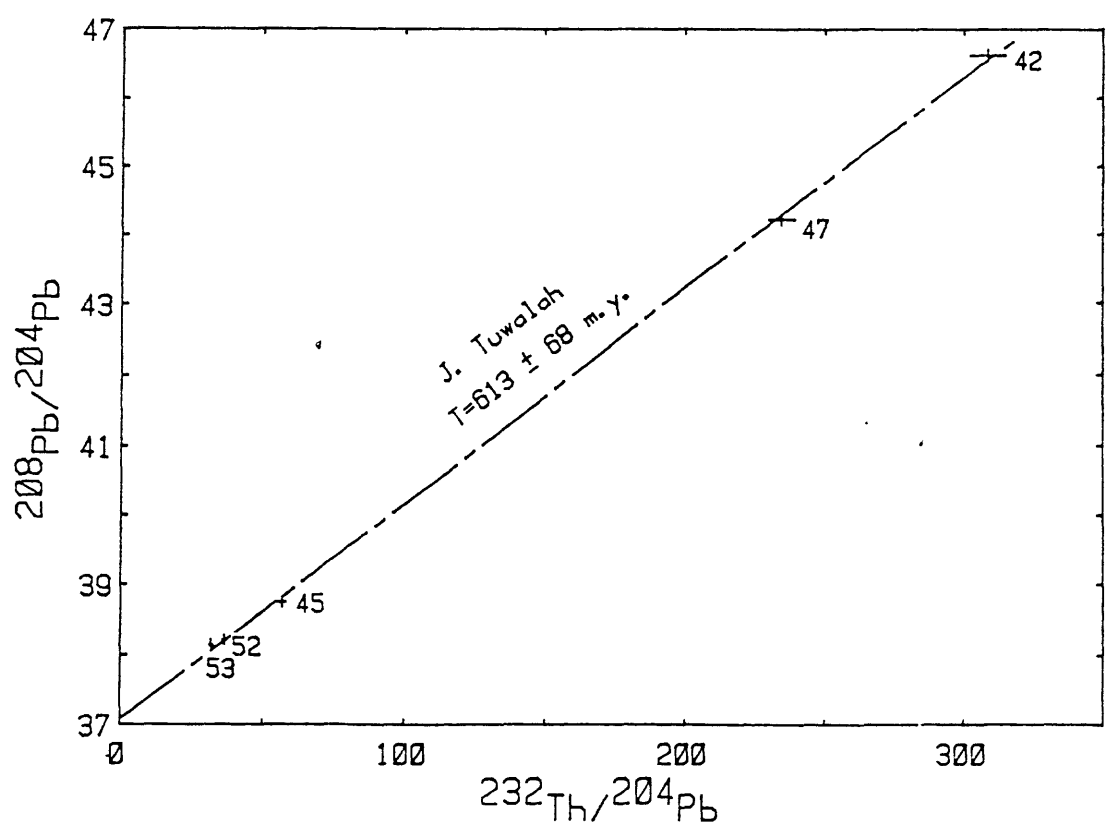


Figure 5.—Th-Pb and Pb-Pb isochron diagrams for samples from Jabal Tuwalah. Samples are labelled with last two digits of sample number only.

Rb-Sr method. The initial 208Pb/204Pb value of 37.077±0.482 is low like the initial 87Sr/86Sr value. Calculated initial 208Pb/204Pb values for each sample do not correlate with the degree of alumina saturation; the highest and lowest values (37.646 and 37.098) correspond to the two peralkaline samples.

The Pb-Pb data are colinear (fig. 5) within the limits of analytical precision (MSWD=0.87) and have the largest range of values found for any of the postorogenic granites in the study area. The resulting age of 641±85 Ma is in good agreement with the Rb-Sr age, and the calculated initial 206Pb/204Pb and 207Pb/204Pb values of 17.496 and 15.486, respectively, are again low.

Jabal Bidayah

The pluton at Jabal Bidayah is a hypersolvus, alkali-feldspar granite which varies from peralkaline (samples 155095, 155097, and 155098) to metaluminous (sample 155099). The peralkaline samples are coarse-grained and the metaluminous smple is a medium-grained porphyry.

The Rb-Sr data are colinear on an isochron plot (fig. 2) within the limits of analytical precision (MSWD=0.15). The calculated age is 617±7 Ma, and the initial 87Sr/86Sr value is 0.7017±0.0007. Data reported by Baubron and others (1976) again yield a model 3 fit with a slightly younger age of 595±21 Ma and a slightly higher initial 87Sr/86Sr value of 0.7051±0.0023.

Jabal ar Rumman

All four of the samples analyzed from Jabal ar Rumman are peralkaline, alkali-feldspar granites. Sample 155148 is a fine-grained porphyry; the other samples are coarse grained and equigranular.

The Rb-Sr data are colinear on an isochron plot (fig. 2) within the limits of analytical precision (MSWD=1.8), the resulting age is 581±4 Ma, and the initial 87Sr/86Sr value is 0.7030±0.0003.

Jabal Aja

The batholith at Jabal Aja appears to be coalesced multiple intrusions. The northern half of the batholith has a discontinuous rim of coarse-grained, peralkaline, alkali-feldspar granite (samples 155106, 155116, 155129, 155136, and 155159). The rest of the batholith is made up of fine- to medium-grained to porphyritic alkali-feldspar granite which varies from metaluminous to weakly peraluminous. The remaining six samples analyzed from Jabal Aja are all weakly peraluminous.

The Th-Pb data fit a straight line on an isochron plot (fig. 3) within the limits of analytical precision (MSWD=0.9). The resulting age is 570 ± 19 Ma that is in excellent agreement with the age obtained by the U-Pb method on zircons (566 ± 4 Ma, J. N. Aleinikoff, oral commun., 1983). The initial 208Pb/204Pb value of 37.473 ± 0.047 is low, and intermediate relative to two values for galena reported for this locality (37.351 and 37.535, Stacey and others, 1980).

The Pb-Pb data are also colinear (fig. 4) within the limits of analytical precision (MSWD=0.27); however, the analytical errors are large relative to the range in values of the data. The resulting age is 759 ± 453 Ma. The calculated initial 206Pb/204Pb and 207Pb/204Pb values of 17.803 and 15.515, respectively, are in fair agreement with those reported for galena from Jabal Aja (17.803, 17.728 and 15.560, 15.510). However, the 207Pb/204Pb ratios for the galenas is slightly lower such that they yield young model ages of 540 and 500 Ma (Stacey and others, 1980).

An Nammar

The pluton at An Nammar varies from peralkaline to weakly peraluminous alkali-feldspar granite. Sample 155056 is peralkaline, and samples 155058 and 155059 are metaluminous. Textures vary from medium-grained equigranular to medium-grained porphyritic.

The Rb-Sr data yield a three-point array (fig. 2) with scatter beyond the limits of analytical precision (MSWD=12). The apparent age is 604 ± 26 Ma, and the initial 87Sr/86Sr value is 0.7031 ± 0.0048. These results are similar to those obtained for other postorogenic, hypersolvus granites, and therefore no other samples for this pluton were analyzed.

Only one sample from An Nammar was analyzed for U-Th-Pb. Data for this sample are plotted with data for Jabal Awja on figures 3 and 4. Calculated initial 206Pb/204Pb and 207Pb/204Pb values of 7.591 and 15.509, respectively, for this single sample are similar to values observed for other postorogenic plutons, but the initial 208Pb/204Pb of 37.518 is slightly high. However, without independent proof of closed-system behavior with respect to Th and Pb, this value is not considered to be significantly different from other initial 208Pb/204Pb values obtained during this study.

Jabal Awja

The pluton at Jabal Awja is the only pluton within the study area (fig. 1) for which all reported chemical analyses are peralkaline (Stuckless and others, 1982c). Textures vary from medium-grained porphyritic to coarse-grained equigranular. All samples are hypersolvus, alkali-feldspar granite.

A line through two Rb-Sr analysis (fig. 2) yields an apparent age of 594±7 Ma and an initial 87Sr/86Sr value of 0.7036±0.0012 (errors based on analytical precision only). These results are similar to those obtained for nearby postorogenic plutons and no further analyses were made.

The Th-Pb analyses do not yield a linear array (fig. 3) which is attributed to open-system behavior of Th or Pb. Lead loss seems the most likely explanation in light of studies elsewhere (Zielinski and others, 1981; Doe and others, in press). An initial 208Pb/204Pb ratio calculated on the basis of the two apparently least-disturbed samples is 37.453, which is similar to values obtained for other postorogenic plutons in this study. We do not have an explanation for the anomalous behavior of Pb in this pluton.

The Pb-Pb data have such a limited range of values that calculation of an isochron age would be meaningless (fig. 4). The slope of the best fit line corresponds to an age of approximately 1,020 Ma. Calculated initial 206Pb/204Pb and 207Pb/204Pb values of 17.539 and 15.494 are similar to those of other postorogenic granites analyzed for this study.

Jabal Salma

The pluton at Jabal Salma is a metaluminous to weakly peraluminous alkali-feldspar granite. Textures are generally fine to medium grained with porphyritic varieties common. Along the northeastern boundary the pluton appears to intrude its own volcanic pile, which in this area appears to be part of the Shammar Group.

A line through two Rb-Sr data points yields an apparent age of 580±5 Ma and an initial 87Sr/86Sr value of 0.7037±0.0007 (based on analytical precision only). These results are similar to those for the other postorogenic plutons, and no other samples were analyzed.

Oxygen isotope studies

Oxygen-isotope analyses were made for whole-rock samples from four postorogenic plutons to check for differences between plutons and to look for systematic variations within plutons as a function of degree of alumina saturation. The results are presented in table 3 and are summarized on figure 6. The results show a fairly large range in values for each pluton relative to the limited range in silica contents of the analyzed samples (Taylor, 1968). This is especially true for the samples from Jabal Awja and Jabal Aja. Nonetheless it appears that the four plutons do have distinctly different mean delta-18O values: Jabal Aban al

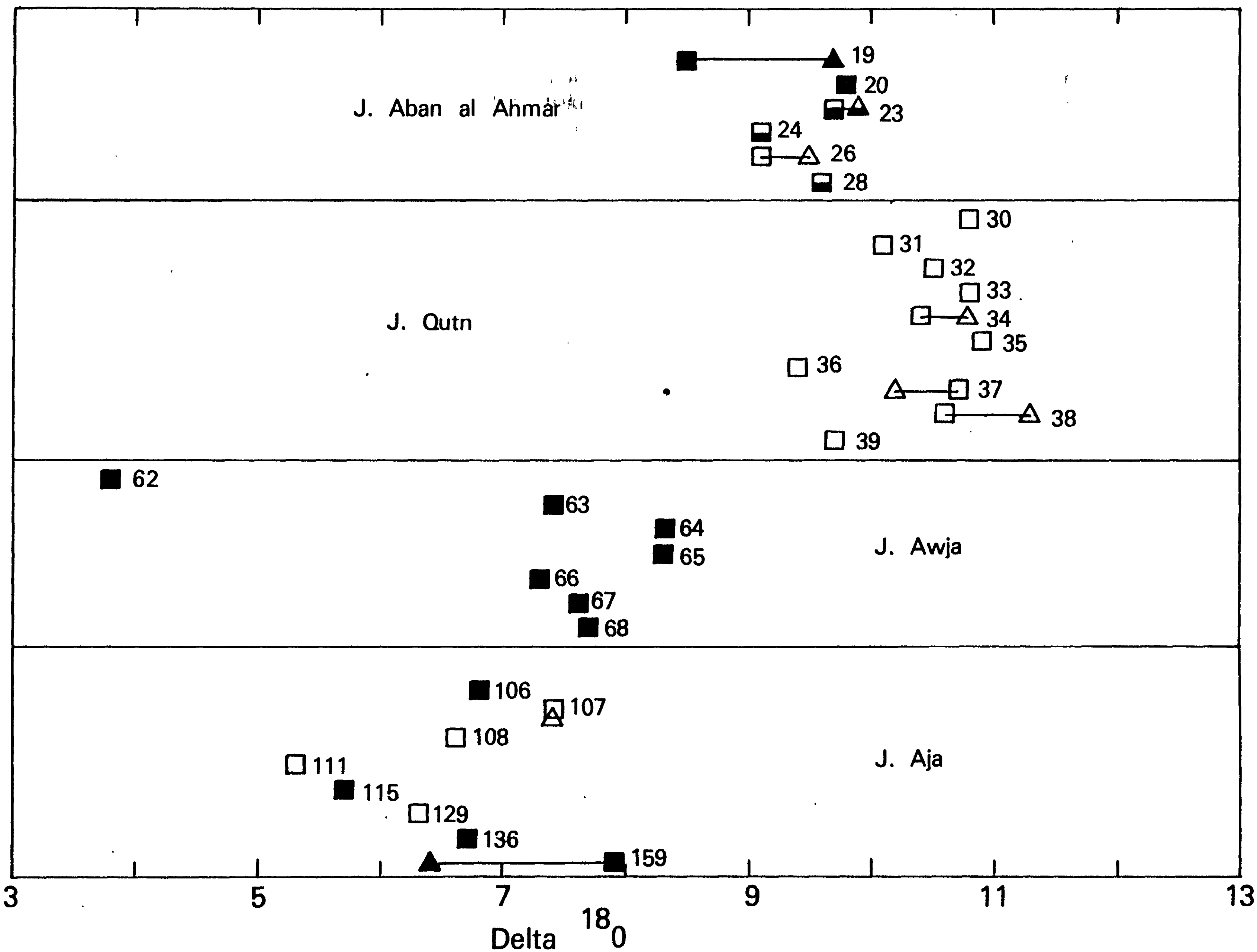


Figure 6.- -Summary diagram of oxygen-isotope results for whole-rock samples (squares) and quartz separates (triangles) from post-orogenic granites of the northeastern Arabian Shield. Filled symbols represent peralkaline samples; open symbols represent peraluminous samples; half-filled symbols represent metaluminous samples. Samples are labeled with last two or three digits of sample number only.

Ahmar=9.3, Jabal Qutn= 10.4, Jabal Awja=7.8, and Jabal Aja=6.6. Alhough there is a weak tendency for oxygen to be heaviest in the peraluminous plutons and lightest in the peralkaline plutons, there is no obvious trend within either Jabal Aja data or Jabal Aban al Ahmar data.

Eight quartz separates were analyzed to see if the spread in oxygen-isotope values was due to primary or secondary e spread in oxygen-isotope values was due to primary or secondary variation is a primary feature because of delta-18O values for quartz do vary within single plutons. Values of delta-18O for quartz separated from granitic rocks are generally 1.5 to 2.0 per mil larger than their corresponding whole-rock values with the difference decreasing with increasing silica (Taylor, 1968). The differences between quartz and whole-rock values within the study area are generally much smaller and in two cases are reversed. Differences in the range of 0.6 to 1.0 could be caused by subsolidus equilibration, and thus, most of the whole-rock data are probably representative at the magmatic oxygen isotopic compositions. The reversal noted from sample 155159 at Jabal Aja is associated with brick-red alteration of feldspar which elsewhere has been shown to be due to low-temperature reaction with meteoric water (Wenner and Taylor, 1976; Wenner, 1981). Brick-red color is common for much of the postorogenic alkali-feldspar granite of the northeastern Arabian Shield. It therefore seems likely that some of the whole-rock values should be somewhat lighter and that the reddened rocks have reacted with meteoric water, probably a low temperature.

DISCUSSION

Uranium mobility

The results for uranium and lead concentrations and the compositions of lead (table 2) can be used to demonstrate recent mobility of uranium if it can be assumed that uranogenic lead has not been gained or lost on the scale of a whole-rock sample since the time of the intrusion (Rosholt and others, 1973; Stuckless and Nkomo, 1978). With the exception of two samples from Jabal Awja, the Th-Pb system appears to have remained closed from the time of intrusion until the present, and therefore the assumption that uranogenic lead has not been gained or lost is probably valid.

The plutons at Jabal Aja, Jabal Qutn, and Jabal Aban al Ahmar all have similar ages and similar initial 206Pb/204Pb ratios. Data for these samples are plotted on an isochron-type plot with reference lines that represent 0, 20, and 50 percent loss of uranium within the last few million years (fig. 7). The results show that few if any samples have behaved as closed systems and that most samples

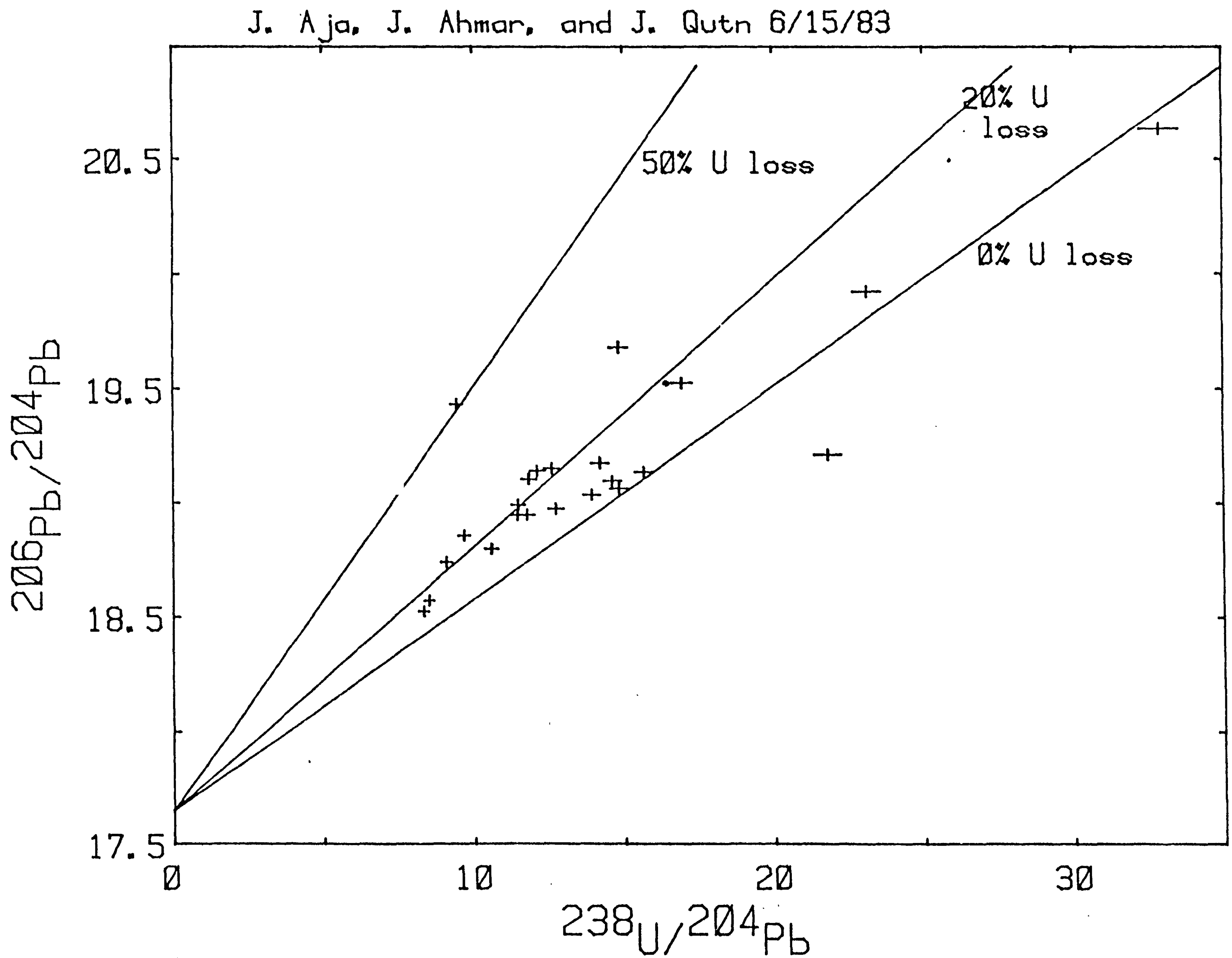


Figure 7.- -U-Pb isochron-type plot for samples from Jabal Aja, Jabal Qutn, and Jabal Aban al Ahmar with reference lines that indicate recent uranium loss, in percent.

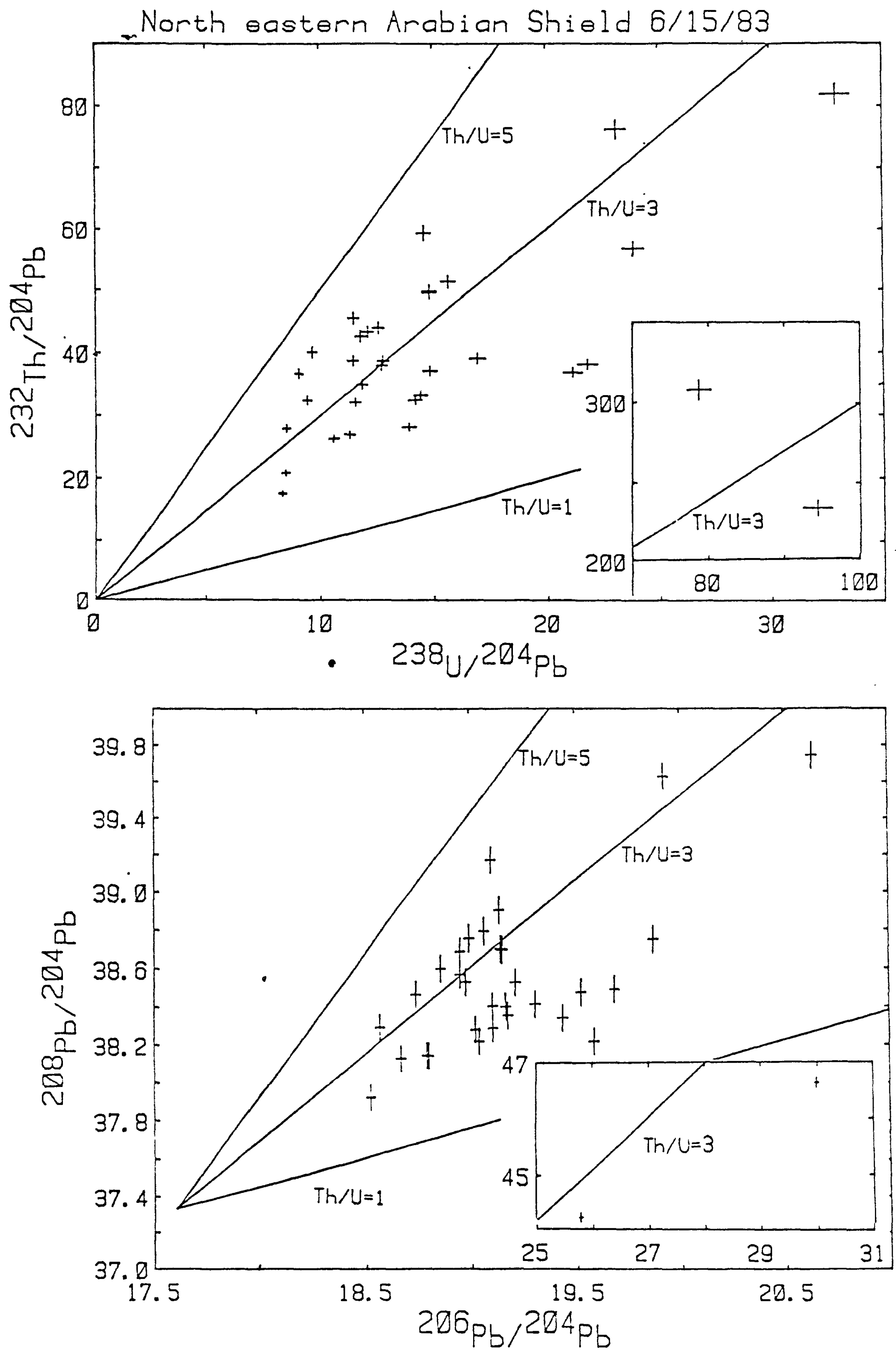


Figure 8.--Plots of 238U versus 232Th and 206Pb versus 208Pb (all axes indexed to 204Pb) for whole-rock samples of postorogenic granites of the northeastern Arabian Shield with reference lines for Th/U values of 1, 3, and 5.

have incurred an apparent loss of uranium of 20 percent or less in recent time. This percentage loss, and the actual amount lost in terms of grams of uranium per gram of rock, are both small relative to that noted for granites near large uranium districts (Stuckless and Nkomo, 1978).

Stuckless and VanTrump (1982) have noted that favorable uranium-source granites have large and variable Th/U values, and that both features can be attributed to uranium mobilization because actual Th/U values and Th/U values based on lead isotopes are markedly different. Figure 8 shows a plot of all the whole-rock lead-isotope data obtained in the curent study. Both patterns yield a tight grouping with a mean value near 3. Thus, none of the data suggest much uranium loss, and therefore the probability for secondary uranium deposits associated with the postorogenic plutons is low.

Geochronology

The Rb-Sr whole-rock method is the most useful geochronologic technique for the postorogenic granites used in this study in terms of both accuracy and cost effectiveness. Both the Pb-Pb and Th-Pb methods are more time consuming, and few samples have accumulated enough radiogenic lead to constrain the slopes of isochrons to a desired level of accuracy for the calculated ages. Conversely the extreme range of Rb/Sr values for the plutons studied results in small errors for the calculated ages.

Results for one pluton dated by the K-Ar technique suggest that there has been a regional heating subsequent to intrusion of the postorogenic plutons and that K-Ar ages may have been lowered. This finding is in accord with the findings of Fleck and others (1976) for the southern part of the Arabian Shield. In the north, this event does not appear to have been of sufficient intensity to have reset K-Ar muscovite ages; however, muscovite is not a common mineral in most plutons. Thus, its use for geochronologic purposes is very limited.

Available ages for the postorogenic granites within the study area (fig. 1) range from approximately 630 to 565 Ma, Thus, plutonism in response to compressive deformation appears to have ended by 630 Ma ago. There is a curious pattern in the data that may be fortuitous; nonetheless, we note that ages for all postorogenic plutons north of the northern strand of the Najd fault zone have ages in the range of 580 to 565 Ma. Postorogenic plutons south of this boundary have ages that are slightly older with a range of 630 to 595 Ma.

This pattern of ages seems to continue to the southeast.

Table 5.--Summary of initial isotopic ratios for granitic plutons of the Arabian Shield [Leaders (--) indicate no analyses]

Pluton	87Sr/86Sr	208Pb/204Pb	206Pb/204Pb	207Pb/204Pb
J. Aban al Ahmar	0.7030 ± 0.0026	37.405 ± 0.075	17.648	15.518
J. Qutn	0.7055 ± 0.0011	37.410 ± 0.188	17.702	15.541
J. Tuwalah	0.7019 ± 0.0012	37.077 0.482	17.496	15.486
An Nammar	0.7031 ± 0.0048	37.518	17.591	15.509
J. Awja	0.7036 ± 0.0012	37.453	17.539	15.494
J. Bidayah	0.7017 ± 0.0007	--	--	--
J. Aya	--	37.437 ± 0.047	17.642	15.515
J. ar Rumman	0.7030 ± 0.0003	--	--	--
J. Salma	0.7037 ± 0.0007	--	--	--

Stacey and Stoeser (1984) report a zircon age of 575 for the pluton at Baid al Jimalah, which is located nearly due south of Jabal Aban al Ahmar and a few kilometers north of the Najd fault (fig. 1). Fleck and Hadley (1982) report a Rb-Sr whole-rock age of 575+7 Ma for the pluton at Jabal Jabalah, which is approximately 100 km east-southeast of Baid al Jimalah and approximately 75 km north of the fault. Other reported data (Baubron and others, 1976; Fleck and Hadley, 1982) are also consistent with the age pattern noted here; however, intralaboratory biases and large reported errors preclude documentation of age differences as small as 15 Ma. If further work substantiates a real age difference for the postorogenic granites north and south of the northern Najd fault, it is possible that this fault separates crustal blocks that are in some way fundamentally different.

Protolith considerations

Knowledge of the characteristics of the protolith from which the postorogenic granites were derived can provide significant constraints on models for the origin of the Arabian Shield as well as constraints on the most likely types of mineralization associated with the postorogenic granites. Two models for the origin of the Arabian Shield have been consistently proposed by several researchers during the past few years. One model calls for accretion of island arc complexes, which in most models is followed by continental collision (Greenwood and others, 1976, 1982; Bokhari and Kramers, 1981; Schmidt and Brown, 1982; Stoeser and others, 1984). The other model calls for rifting at the edge of an older continent and repeated compression of the resulting ocean basins (Kemp and others, 1980; Delfour, 1981; Stern, 1981). Both of these models assume or conclude that the Arabian crust is ensimatic and younger than about 1,100 Ma.

Several lines of reasoning suggest that some parts of the Arabian Shield have a prehistory which significantly predates 1,100 Ma,, and that ensialic material exists at least sporatically. Common lead compositions along the exposed eastern edge of the Arabian Shield exhibit higher 208Pb/206Pb values than those to the west which have been attributed to an older continental component (Stacey and others, 1980; Stacey and Stoeser, 1984). Where compatible data exist, the initial 87Sr/86Sr values are also slightly elevated (Stacey and Stoeser, 1984). The data are somewhat equivocal in that model lead ages are in general agreement with actual ages, and the 207Pb/206Pb values are compatible with an island-arc source (Bokhari and Kramers, 1982). Furthermore, Fleck and Hadley (1982) point out that the initial 87Sr/86Sr values preclude the existence of an Early Proterozoic protolith.

Direct evidence that at least small segments of the

Arabian Shield have a significant pre-1,100 Ma history has been been reported. Calvez and others (1983) report that zircons in a plagiogranite associated with the Al Amar fault have a 2,000 Ma component. Stacey and Hedge (in press) report zircon, Nd-Sm, and Rb-Sr data for a granodiorite from Jabal Khida that document an age of at least 1,600 Ma and for which lead isotopes suggest an even older precursor.

The only direct evidence of ensialic rocks is provided by Al Shanti's (976) description of the Abt Formation (northwest of the northern limit of exposure of the Al Amar fault), which is pelitic and psammopelitic. However, indirect evidence suggests that such rocks exist elsewhere at depth. Radain and others (1981) report delta 18O/16O values for whole-rock samples of the postorogenic granites at Hadb Aldyaheen and Jabal Sayid which range from 7.7 to 11.8 per mil. The high values at Jabal Sayid are apparently primary because quartz values are also elevated, and therefore, a sedimentary precurser such as the Abt Formation is suggested. The wide distribution of strongly peraluminous rocks (Elliott, 1983) also requires a wide distribution of at least a discontinuous ensialic protolith.

Trace element data for the postorogenic granites throughout the Arabian Shield (fig. 9) yield a pattern similar to that of the type I-type II leads first noted by Stacey and others (1980). The extremely high Rb/Sr values (>100) and the extremely low K/Rb values (<125) require either an evolved protolith or an unreasonably high degree of differentiation (Hanson, 1978). Inasmuch as the plotted ratios are averages for several samples, extreme differentiation seems highly unlikely. Furthermore, extreme differentiation would not be expected to yield a regional pattern.

The trace element data suggest a larger area of (or at least more complex distribution of) evolved protolith than that suggested by the distribution of type II leads. In addition to the strongly anomalous values along the east-central margin of the exposed Shield, there are strong anomalies in the southeastern part of the shield near highly metalliferous plutons (Elliott, 1983) but within the area of type I leads (Stacey and Stoeser, 1984). There are also moderate to strong anomalies in the vicinity of Jabal Sayid, Hadb Aldyaheen, and Jabal Qutn all of which have high delta 18O/16O values, but where type II leads are not known. Thus, it seems that oxygen isotopes and trace elements may provide more sensitive indicators than lead isotopes for changes in the protolith for the postorogenic granites. Furthermore, the trace-element data, particularly in the northeastern Shield, suggest a more gradational transition from evolved to unevolved protolith (fig. 9) than that suggested by the lead data. The less well-defined patterns in the southern two-thirds of the Shield may be due to

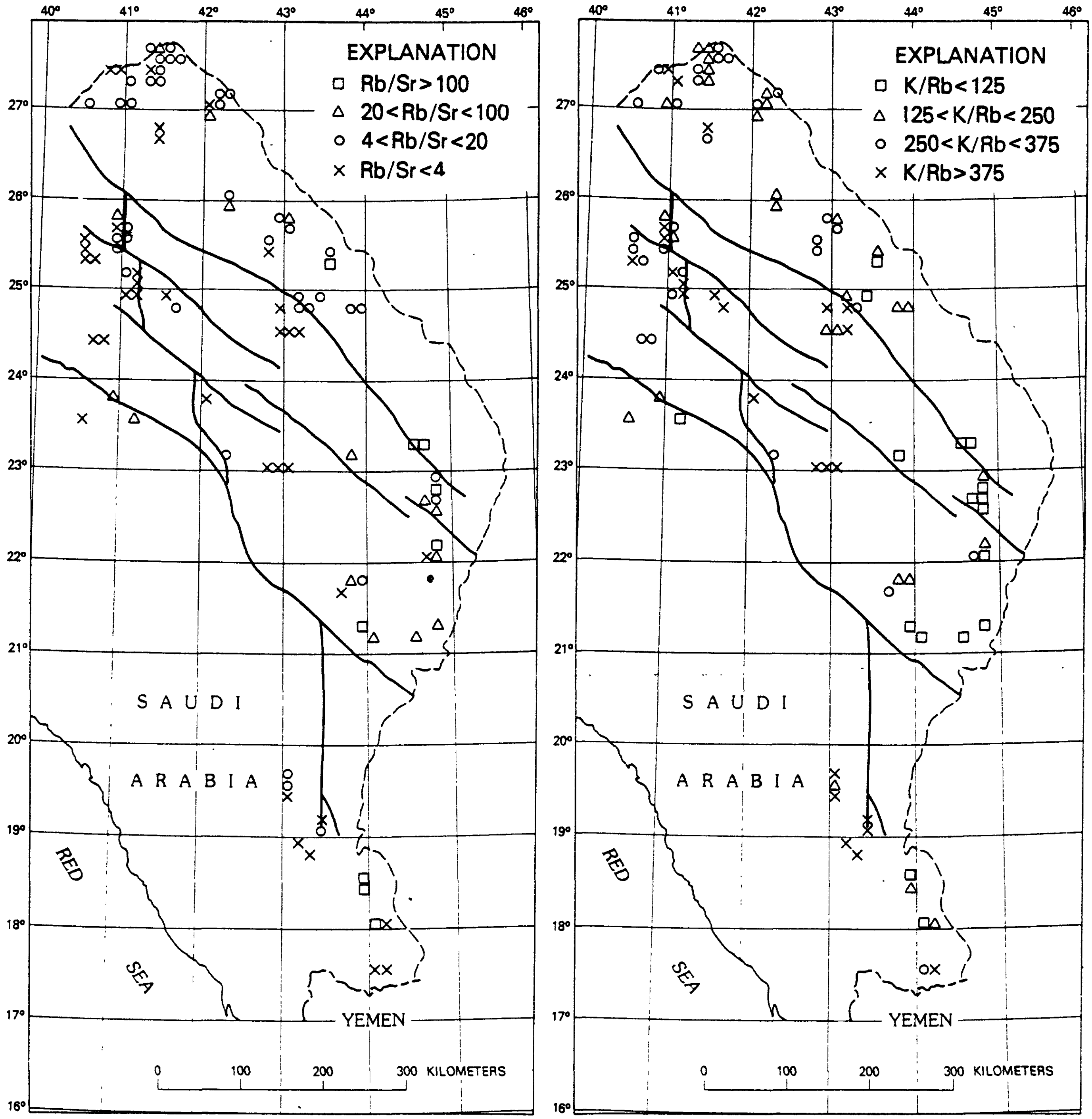


Figure 9.—Maps showing the distribution of average K/Rb and Rb/Sr values for post-orogenic granites of the Arabian Shield. Data are averaged for samples within 15' by 15' areas (Stuckless and others, 1982c; Stuckless and others, in press; and Stuckless and Moore, unpub. data). Also shown are major fault zones (solid lines) and the approximate limit (dashed lines) of exposure of the Arabian Shield (Brown, 1972).

tectonic modifications. Disruption of isotopic patterns in the western United States has been attributed to large-scale movement of crustal blocks both prior to and after emplacement of granites (Kistler and Peterman, 1978; Masi and others, 1981).

The data presented in this paper together with the trace element data summarized in figure 9 suggest a model for the protolith similar to that proposed for the late orogenic granites of the southeastern United States. There, Wenner (1981) noted that delta-18O values have a fairly narrow range within most plutons, but that the average values for the plutons increase in a general east to west fashion. Initial 87Sr/86Sr values and trace element indicators for the degree of magma evolution also increase to the west. The metamorphic country rocks intruded by the granites are largely ensimatic in the east and ensialic in the west, and Wenner (1981) concluded that the late orogenic granites of the southeastern United States were essentially rooted in their protoliths. The Elberton batholith, which was intruded in the zone where the country rocks change from dominantly ensialic to ensimatic, was found to have a wide range of oxygen-isotope compositions and characteristics of both protoliths. A similar but larger-scale pattern of low delta 18O, low initial 87Sr/86Sr, and metaluminous composition within an eugeosynclinal host and a high delta 18O, high initial 87Sr/86Sr, and peraluminous composition has been documented for granites of the western United States (Farmer and DePaulo, 1983).

Field evidence that would indicate the character of the possible protolith near each pluton and a simple regional distribution pattern for available data are not present in the northeastern Arabian Shield. However, the mixing of ensimatic and ensialic protoliths does explain available data. Furthermore, if mixing took place during sedimentation such that the ensialic component was added from a land mass to the east and the ensimatic component was added from the west, then some perturbations in the regional patterns, such as noted near Jabal Sayid, can be interpreted as due to local accumulations of anomalous sediment.

Some of the characteristics of the two end-member protolith can be estimated from available data. The ensialic protolith must be peraluminous and clay-rich to explain the peraluminous and heavy oxygen characteristics of such plutons as Jabal Qutn. The ensialic component must also be enriched in rubidium relative to potassium and depleted in strontium relative to rubidium to account for the extremely evolved plutons along the exposed eastern margin of the Shield (fig. 9). The above features are consistent with a pelitic component for the protolith.

The ensimatic protolith is most likely of island-arc affinity. The low average delta-18O value at Jabal Aja is suggestive of rocks that have come from the mantle with little reaction with oxygen from other sources (Taylor, 1978). Chemical data suggest that one end-member composition of the protolith for the granites is metaluminous (Stuckless and others, 1982a). This same end member must have low Rb/Sr and high K/Rb values. These features are consistent with island-arc sediments.

The age of the protolith cannot be significantly older than the granites (<100 Ma) because the granites derived from the evolved end member (which must have had a high Rb/Sr) such as those at Jabal Qutn do not have strongly elevated initial 87Sr/86Sr values. Furthermore, plutons from the unevolved end member have initial lead isotopic ratios of primitive island-arc material, and hence must have melted shortly after deposition of the sediment.

The protolith cannot have been subjected to a high-grade metamorphism. Such an event would have depleted the protolith in uranium (Moorbath and others, 1969; Gray and Oversby, 1972; Dostal and Capedri, 1978), rubidium, and potassium (Lambert and Heier, 1968). Rubidium would have been lost in preference to potassium (Lewis and Spooner, 1973), such that derived melts would have high K/Rb ratios, and the protolith would have been depleted in delta 18O (Longstaff and Schwarz, 1977; Hoef, 1980). None of these predicted features are observed for the postorogenic granites.

Modern back-arc ocean basins provide an excellent analogue for the type of protolith proposed here. Sediment dynamics described by Gardner and others (1980) for the southern Bering Sea yield a generally gradational mixing of primitive andesitic sediments and mature continental sediments over a distance between the sources of several hundred kilometers. The general pattern has been disturbed by the drastic lowering of sea level during the glacial maximum and by sea-floor topographic features. The latter have caused a basinal concentration of continental pelitic sediments more than 500 km from the present shore line and within a region that is otherwise dominated by arc sediments. Predictably Rb/Sr values are 4 to 10 times greater in the dominantly pelitic sediment than in the nearby dominantly arc sediment, and K/Rb values are lower by a factor of about 0.5 (Gardner and others, 1979).

A protolith made up of marine sediments, metamorphosed to low grade only, is attractive in terms of models proposed for the origin of the peralkaline granites. Harris (1981) has emphasized the importance of halogen complexing in the formation of the peralklaine rocks in the Midian Mountains, and Radain and others (1981) have proposed that underthrusting of salt-rich sediments is fundamental in the genesis of the peralkaline rocks at Jabal Sayid. The protolith proposed here would certainly provide both water and chlorine and might well contain other halogens.

A close match to the hypothetical protolith for the postorogenic granites as proposed above cannot be demonstrated, largely due to lack of chemical and isotopic data for the metamorphic rocks in the study area. Certainly rocks such as those from Jabal Khida can be ruled out because of the highly radiogenic strontium that existed 600 Ma ago (Stacey and Hedge, in press). Rocks such as the Halaban Group and Abt Formation may prove to be at least similar to those proposed for the protolith, but much more data are needed. If the stratified rocks have served as precursors for the mineralized granites, then they may warrant some attention as possible hosts for mineralization.

Finally, we note that the variable degrees of alumina saturation reported for several plutons is most likely due to magmatic processes rather than a mixing of magmas derived from different sources. Although the strongly peraluminous plutons, such as Jabal Qutn, may have acquired their alumina oversaturation from their protolith, there does not appear to be any within-pluton isotopic differences between the peraluminous, metaluminous, and peralkaline varieties at Jabal Aja, Jabal Tuwalah, or Jabal Aban al Ahmar. Furthermore, there appears to be subtle differences between plutons that have similar major element chemistry which suggest that similar magmatic processes acted upon slightly different starting materials with similar results. However, the exact nature of these processes is beyond the scope of this paper.

CONCLUSIONS

Ages obtained for the postorogenic granites from the northeastern Arabian Shield range from 630 to 565 Ma, and therefore, compressive deformation must have ended in the northern Shield by 630 Ma ago. The currently available data suggest that the postorogenic granites within and north of the Najd fault zone are of different ages. Ages within the Najd fault zone range from approximately 630 to 595 Ma, whereas ages to the north range from approximately 580 to 565 Ma.

Comparison of the various dating techniques shows that the Rb-Sr whole-rock method (for the postorogenic granites) yields the most accurate results for the amount of time or funds invested. This technique also yields useful information about the characteristics of the protolith which can be useful in modeling the evolution of the Arabian Shield and any consequent economic implications.

Initial isotopic ratios, oxygen isotopic compositions, and published chemical data all suggest that the postorogenic granites were derived from a protolith that can be described in terms of two end members. Most of the plutons have lead-, strontium-, and oxygen-isotope compositions that are compatible with an island-arc-type source which is not much older than the granites. A few plutons (most notably along the eastern edge of the exposed Shield) have oxygen-isotope and chemical compositions that require a more evolved source; however, the radio-isotope data again require that the source be only slightly older than the granites.

Many of the plutons have chemical or isotopic features that are intermediate to the two extremes. The isotopic features do not seem to be well explained by the mixing of two magmas. We, therefore, suggest a mixed source of island-arc and continental sediments as an explanation. Such a source could explain the regional patterns if the continental material were dominant to the east, and the island-arc material were dominant to the west. Exceptions to the regional pattern (such as the chemically evolved and delta 18 O-rich granite at Jabal Sayid) could then be explained as due to irregularities in the distribution patterns of arc and continental sediment which extended a long way from their provenance. Detailed work will undoubtedly show some tectonic displacement of the pattern.

Evolution of the postorogenic granites is complicated by an as yet poorly understood magmatic process that allows both oversaturation and undersaturation with respect of alumina from a range of starting compositions. This process, which lacks well studied analogues, should be investigated if models for the origin of economic deposits are to be developed as guides for exploration.

Examination of the U-Pb isotope systematics supports conclusions reached on the basis of studies of concentration data (Stuckless and others, 1982c). The probability for uranium deposits associated with the postorogenic granites, especially deposits of a secondary nature, is low.

DATA STORAGE

Data-file USGS-DF-04-21 (Stuckless and others, 1984) has been established for the storage of data used in this report. No entries or updates have been made to the Mineral Occurrence Documentation System (MODS) data bank.

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