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Rb-Sr isotopic studies of postorogenic granites from the Eastern Arabian Shield, Kingdom of Saudi Arabia

by

J. S. Stuckless[1] and K. Futa

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This report is preliminary and has not been reviewed for conformity
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[1] USGS, Denver, CO

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ABSTRACT

Thirteen Rb-Sr whole-rock isochrons for postorogenic granites of the eastern Arabian Shield yield ages that range from 567 to 617 Ma, a similar range to that previously determined ages for leucocratic, evolved granites in that region. The dated plutons range widely in terms of degree of petrologic evolution from primitive (at Najran) to highly evolved (at Jabal al Gaharra) and include several plutons that are anomalously enriched in tin and tungsten (Jabal Tarban, Jabal al Gaharra, Jabal Khinzir, and Jabal Minya). Although no uniform relationship was established between age or initial $^{87}Sr/^{86}Sr$ *and degree of petrologic evolution, the more evolved plutons tend to be younger and to have slightly higher initial* $^{87}Sr/^{86}Sr$ *values. There is a tendency for metalliferous plutons to have elevated initial* $^{87}Sr/^{86}Sr$ *values, but not all plutons with elevated* $^{87}Sr/^{86}Sr$ *values are known to be metalliferous. Several of the dated plutons are situated within the Najd fault zone, and thus, some of the ages are useful in determining times of strike-slip fault activity. The youngest pluton cut by Najd faulting is at Jabal Tukhfah (573±13 Ma). Displacement at this locality is about 2 km, and if normal rates of strike-slip movement are assumed, this displacement suggests that movement for one strand of the Najd faults ceased by about 560 Ma.*

Available data indicate that postorogenic granites tend to be older in the southern part of the Arabian Shield. This suggests that plutonism started in the south and progressed to the north. Initial $^{87}Sr/^{86}Sr$ *values also form a regional pattern. These ratios tend to be higher in the eastern part of the Arabian Shield, and suggest one source of continental affinity to the east and one of oceanic affinity to the west. The distribution of initial strontium isotope ratios does not clearly discriminate between the various models for Shield evolution; however, a sedimentary source region of mixed end members seems more compatible with the data pattern than models based on discrete boundaries between unrelated accreted blocks.*

INTRODUCTION

The Late Precambrian shield of Saudi Arabia is composed of several major volcanic-plutonic assemblages and related sedimentary rocks that have been regionally metamorphosed to low to intermediate greenschist facies and that have been variably, and in some cases, multiply deformed (Greenwood and others, 1976; Delfour, 1977; Fleck and others, 1980; Stoeser and Elliott, 1980; Fleck and Hadley, 1982; Schmidt and Brown, 1982; Elliott, 1983). These authors have noted that rocks of the earlier volcanic-plutonic assemblages were produced by unevolved mafic magmas, whereas progressively younger assemblages were produced by intermediate to evolved silicic (or bimodal gabbroic-granitic) magmas. The evolution of the Arabian Shield took place during the approximate time span of 900 to 540 Ma. The main orogenic activity, which ceased about 640 Ma, created dominately north-trending structures (Fleck and others, 1980; Greenwood and others, 1982; Stacey and Agar, 1985; Cole and Hedge, 1986). These structures were truncated by the northwest trending features of the Najd fault system. Faulting along the southern strand of this system commenced in a right lateral sense at about 640 Ma and changed to left lateral about 620 Ma (Stacey and Agar, 1985). Cole and Hedge (1986) have shown that left-lateral movement along the northern strand began about 670 Ma and ended about 625 Ma. Net left lateral displacement of the oldest structural elements across the whole Najd zone has been estimated to be as much as 240 km (Brown, 1972).

Postorogenic intrusions, which in this report include all plutons that post-date regional folding and metamorphism, commenced sometime between 640 and 630 Ma (Fleck and others, 1980; Stacey and Agar, 1985) and continued until about 510 Ma (Aleinikoff and Stoeser, 1987). Previous research suggests a younging of intrusive ages from south to north or southwest to northeast (Fleck and Hadley, 1982; Stuckless, Hedge, and others, 1984). In the southern part of the shield, K-Ar mineral ages have been disturbed by regional thermal pulses that occurred between 540 and 510 Ma (Fleck and others, 1976). In the north, however, these events were apparently too weak to be recorded by the K-Ar system in muscovite, but may have been strong enough to partly reset the K-Ar system in biotite (Stuckless, Hedge, and others, 1984).

The postorogenic plutons (also referred to as posttectonic or anorogenic plutons) have been subdivided within the northeastern Arabian Shield into an older (approximately 620 Ma), unevolved group of plutons and a younger (570-585 Ma) set of evolved granites (Cole and Hedge, 1986). A similar subdivision may be possible for the entire eastern and central Arabian Shield, but such a subdivision is not currently recognized.

The highly evolved, and possibly youngest, postorogenic plutons have received considerable attention because of their geochemical similarity to economically important granites as defined by Tischendorf (1977), and because these granites tend 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, Knight, and others, 1982; Drysdall and others, 1984), and tin (Elliott, 1985; du Bray, 1985) have been reported, and the potential for concentrations of niobium and tantalum is estimated to be high (Elliott, 1983). Many of the young granites in Arabia contain sodium pyroboles.

Studies of several of these postorogenic intrusions have contributed significant data to the debate on the origin of peralkaline granites (Radain and others, 1981; Harris, 1981; Stuckless, Nkomo, and others, 1984). Chemical and isotopic features of these granites have also been used in suport of several models concerning the origin and evolution of the Arabian Shield (Stacey and others, 1980; Delfour, 1981; Schmidt and Brown, 1982; Fleck and Hadley, 1982; Stacey and Stoeser, 1984; Stuckless, Hedge, and others, 1984; Stacey and Agar, 1985).

The present report contains the results of age determinations by the rubidium-strontium whole-rock isochron method for samples from 13 bodies of postorogenic granite in the eastern Arabian Shield (fig. 1). Samples from the southern (Stuckless and others, 1983) and central (Stuckless and others, 1985) parts of this area were previously collected and analyzed for major, minor, and trace elements. The age and strontium isotope results in the current study are discussed in terms of their regional patterns in relation to data for similar granites throughout the eastern Arabian Shield.

The work is based on project studies according to a work 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. 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 the rocks on the basis of alumina 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 on Geochronology (Steiger and Jager, 1977).

ANALYTICAL PROCEDURES

Samples used in this study were taken from collections made by Stuckless and others (1983) and Stuckless and others (1985). The original sample numbers were retained for the current study. Each sample was judged to be representative of the freshest material at the sample locality. Most samples were collected from recent spall blocks. Original samples weighed between 2 and 5 Kg and were ground to minus-32 mesh. Splits of approximately 30 g were ground to minus-200 mesh, and approximately one-half gram aliquots were used for analysis.

Rubidium and strontium concentrations (table 1) were determined on separate dissolutions with ^{87}Rb and ^{84}Sr tracers. Replicate analyses of granitic samples indicate an analytical accuracy of ±1.75 percent for rubidium and strontium concentrations which includes errors due to splitting the rock powders. Replicate analyses of the Eimer and Amend $SrCO^3$ standard yield an average $^{87}Sr/^{86}Sr$ value of 0.70802 ± 0.00006 (2 sigma); strontium isotopic compositional errors for granitic samples are ±0.035 percent (2 sigma). Reported isotopic data (table 1) have been normalized to a $^{86}Sr/^{88}Sr$ value of 0.1194.

Regression of best fit lines was accomplished using one of two models (I and III) proposed by York (1969). A model I regression is used if the mean square of the weighted deviates (MSWD) is small enough (generally <1.6) such that the observed scatter about the isochron can be accounted for by analytical error alone. A model III regression is used if the observed scatter of data is large relative to analytical error. For this regression the excess scatter is attributed to a variable initial $^{87}Sr/^{86}Sr$. Regression is accomplished by an iterative process in which the error in $^{87}Sr/^{86}Sr$ is progressively increased until all data points fit a regressed line within the limits of analytical error plus variability in the initial $^{87}Sr/^{86}Sr$. Results of isochron regressions are summarized in table 2.

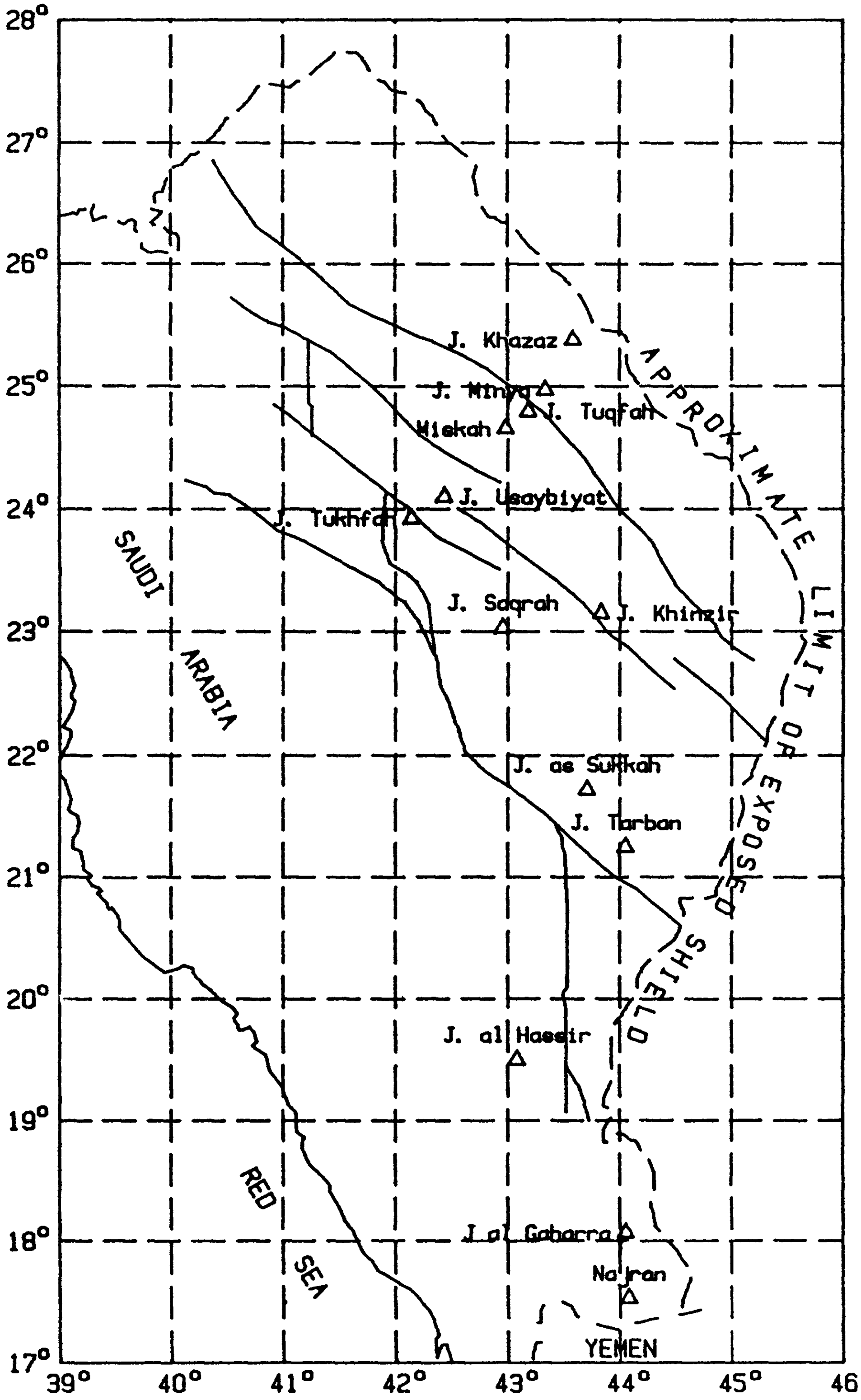

Figure 1.--Map of western Saudi Arabia showing the location of plutons dated in this study, the approximate eastern edge of the exposed Arabian Shield, and generalized Nabitah and Najd faults.

Table 1.- Rubidium and strontium concentrations and the isotopic composition of strontium for samples of postorogenic granite from the eastern Arabian Shield, Kingdom of Saudi Arabia

Sample number	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
		Jabal Tarban		
155500	682.2	12.74	177.86	2.2063
155501	697.2	5.19	567.62	5.4029
155502	780.7	10.27	268.47	2.9538
155504	251.4	87.46	8.3804	.77379
		Jabal as Sukkah		
155507	97.16	49.32	5.7311	.75268
155508	131	184	2.0647	.72146
155509	98.18	65.8	4.336	.74148
155510	120.5	324.4	1.0762	.71271
		Najran		
155540	129.3	55.94	6.7274	.76127
155541	122.6	59.7	5.9738	.75585
155542	105.9	61.21	5.031	.74771
155543	74.73	80.33	2.699	.72636
		Jabal al Gaharra		
155546	587	3.94	659.77	6.1212
155547	602.8	5.96	384.47	3.9064
155549	912	5.49	790.25	7.2823
		Jabal al Hassir		
155567	78.49	13.99	16.466	.84185
155568	68.73	18.68	10.749	.79488
155570	168.9	57.85	8.5607	.77724
155572	108.2	55.04	5.7202	.75211
		Jabal Khinzir		
184080	288.8	114.4	7.349	.7634
184130	269.5	175.7	4.457	.7401
184420	543.4	7.79	240.5	2.6518
184421	266.7	176	4.403	.7399
184422	92.25	320.4	.8341	.7103

Table 1.- Rubidium and strontium concentrations and the isotopic composition of strontium for samples of postorogenic granite from the eastern Arabian Shield, Kingdom of Saudi Arabia -- continued

Sample number	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr
Jabal Minya				
184117	519.3	54.28	28.32	.9353
184359	446.9	52.38	25.21	.9135
184424	509.7	55.82	27.03	.9305
184425	653.5	190.3	10.02	.7854
Miskah				
184149	182.3	63.26	8.4	.7733
184242	258.5	70.41	10.72	.7933
184368	95.31	77.22	3.584	.7339
184426	219.5	181.7	3.507	.7328
184427	216.3	160.3	3.919	.7361
184429	95.46	202.6	1.365	.7149
184430	76.24	98.11	2.254	.7226
184442	114.3	214.2	1.547	.71664
Jabal Saqrah				
184402	121.3	39.05	9.069	.78593
184403	185.1	101.9	5.282	.74846
184404	223.3	6.788	103.54	1.5946
184405	139.2	184.8	2.185	.72179
184406	116.1	50.24	6.732	.76446
Jabal Tuqfah				
184241	113	8.02	42.2	1.05579
184431	177.5	140.8	3.661	.73435
184432	165.2	40.35	11.97	.80161
Jabal Khazaz				
184433	290.5	11.53	77.57	1.35058
184434	254.4	60.75	12.25	.80647
184435	513.7	3.125	778.2	7.1911
Jabal Usaybiyat				
184439	266	10.25	80.06	1.3739
184440	343.7	8.02	138.3	1.8763
184440A	348.4	38.67	26.68	.93636
184441	104.8	107.6	2.827	.72738
Jabal Tukhfah				
184392	357.1	26.03	41.02	1.03638
184393	227.3	69.04	9.602	.78019
184394	222.4	64.61	10.045	.78274

Table 2.- Summary of Rb-Sr results for postorogenic plutons of the eastern Arabian Shield, Kingdom of Saudi Arabia

Pluton	Location		Age	Initial	MSWD
	Lat.	Long.	(Ma)	^{87}Rb/^{86}Sr	
J. Tarban	21° 15'N	44° 0'E	587	0.7037	1.35
4 samples			±6	±.0015	
J. as Sukkah	21° 43'N	43° 42'E	609	0.7034	1.59
4 samples			±11	±.0004	
Najran	17° 32'N	44° 5'E	617	0.7029	2.75
4 samples			±19	±.0052	
J. al Gaharra	18° 4'N	44° 0'E	575	0.7377	1.49
3 samples			±19	±.1405	
J. al Hassir	19° 30'N	43° 5'E	590	0.7043	1.61
4 samples			±15	±.0018	
J. Khinzir	23° 9'N	43° 50'E	567	0.7041	.197
4 samples			±9	±.0008	
J. Minya	24° 58'N	43° 20'E	587	0.7072	2.29
4 samples			±15	±.0171	
Miskah	24° 40'N	42° 59'E	585	0.7037	.706
8 samples			±8	±.0003	
J. Saqrah	23° 2'N	42° 57'E	604	0.7050	16
5 samples			±9	±.0045	
J. Tuqfah	24° 48'N	43° 11'E	584	0.7032	3.33
3 samples			±37	±.0173	
J. Khazaz	25° 23'N	43° 35'E	584	0.7044	.002
3 samples			±8	±.0023	
J. Usaybiyat	24° 6'N	42° 26'E	591	0.7061	6.1
4 samples			±8	±.0194	
J. Tukhfah	23° 55'N	42° 8'E	573	0.7013	1.11
3 samples			±13	±.0022	

RESULTS AND DISCUSSION

JABAL TARBAN

The plutonic rock at Jabal Tarban is a biotite monzogranite that crops out over a 5 km^2 area (du Bray, 1983). The outcrop pattern suggests a nearly circular intrusion, but exposures form a series of nearly east-west elongated hills. Petrographic observations show that the monzogranite consists of quartz, microcline, albite, minor biotite, and trace amounts of zircon, opaque oxides, and fluorite. Chemical data show that the pluton is weakly peraluminous and highly evolved. Differentiation indices are all greater than 90 (Stuckless and others, 1983); Rb/Sr values are generally high (>50), and K/Rb values are generally low (<100 Stuckless and others, 1983; du Bray, 1983). The pluton is cut by many quartz veins and is enriched in several trace elements (Ag, Be, Bi, Pb, Sn, W, Li, F, Rb, Zn, and Nb) that are typically associated with hydrothermal alteration (du Bray, 1983). Samples chosen for dating, however, appeared to be free of such alteration.

The four samples chosen for dating exhibited an extremely large range of Rb/Sr values (table 1). The analyses fit a straight line within the limits of experimental error (fig. 2) and yield an age of 587±6 Ma. The initial $^{87}Sr/^{86}Sr$ is 0.7037±0.0015 (table 2). The pluton at Jabal Tarban is anomalously enriched in tin, tungsten, and related elements and is one of the most evolved plutons analyzed during the current study; however, neither its age nor initial ratio are markedly distinct from less evolved or non-mineralized postorogenic granites from elsewhere within the Arabian Shield.

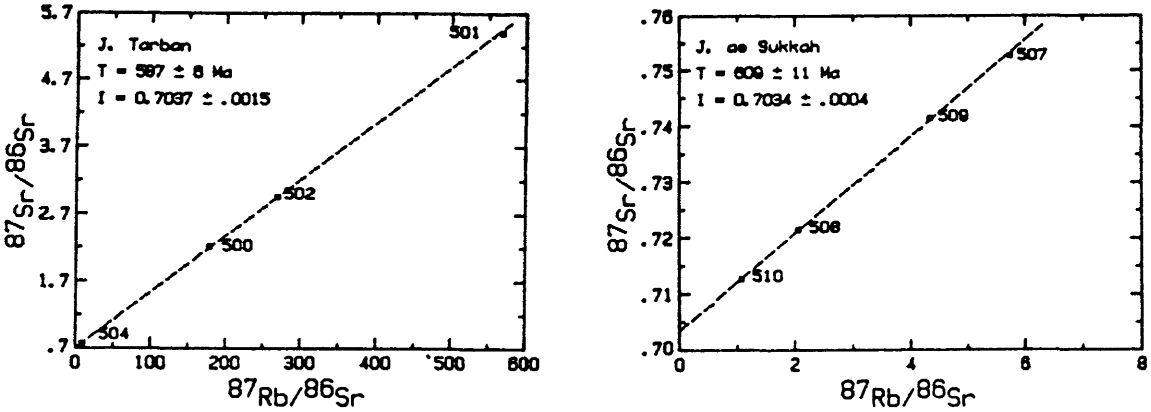

Figure 2.--Rb-Sr isochron diagrams for plutons dated for this study. Data points are labeled with the last three digits of the sample numbers (table 1).

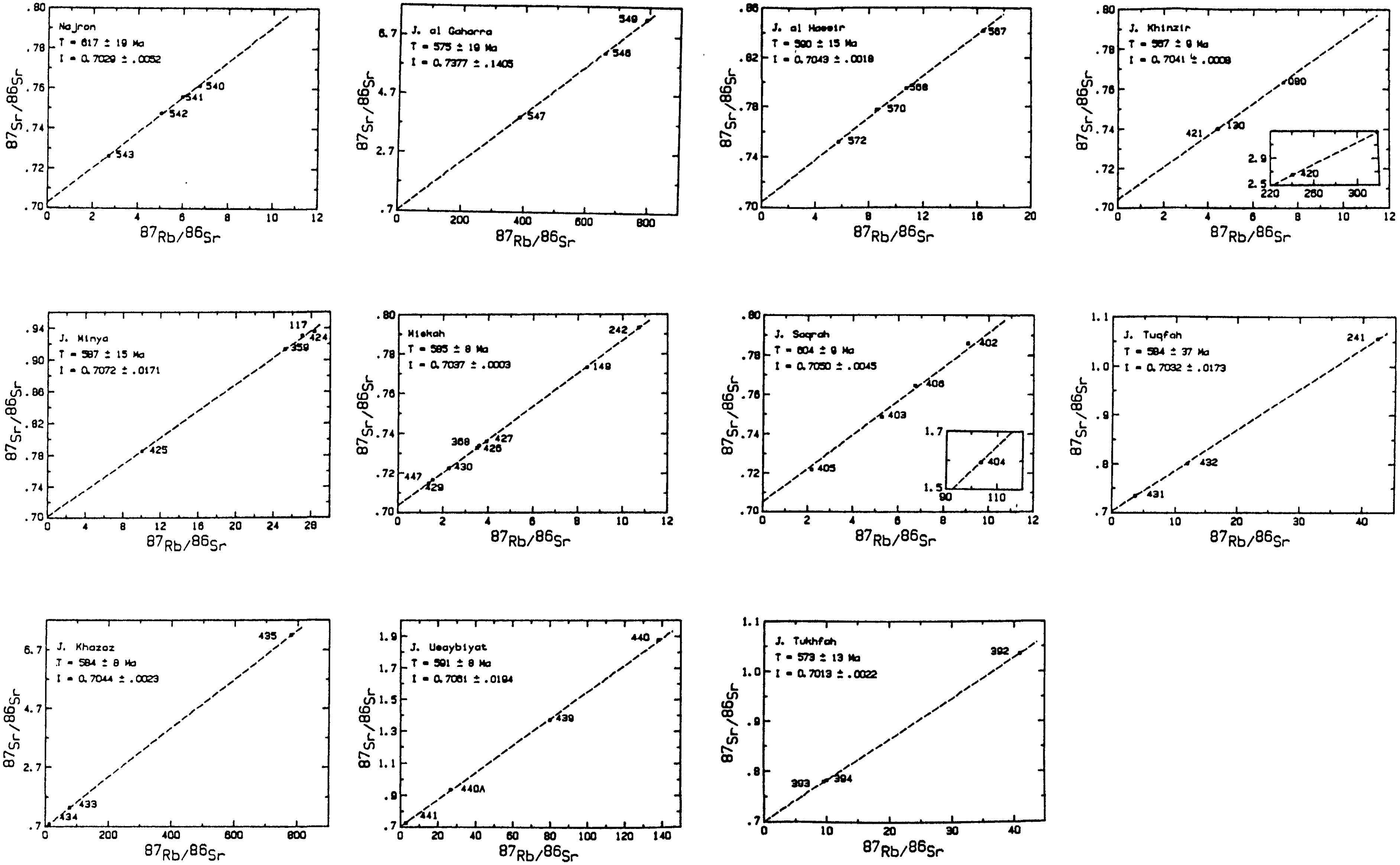

Figure 2.--Rb-Sr isochron diagrams for plutons dated for this study--Continued.

JABAL AS SUKKAH

The pluton at Jabal as Sukkah is a subcircular granite stock that is about 12 km in diameter (Brock, 1982). The rock lacks chloritic biotite and strain textures that are common in the older granites of the region, except near a north-trending shear zone which is interpreted to be a left-lateral fault of Najd system (Brock, 1982). The granite is subsolvus and contains subequal amounts of quartz, microcline, and oligoclase. Biotite, the only mafic mineral, is generally less than 3 percent of the mode. Accessory minerals include zircon, opaque oxides, apatite, and sphene. Major-element data show that the rock is weakly peraluminous and petrologically evolved (average differentiation index for 5 samples is 92.6); however, trace-element data show a high average K/Rb value (314) and a low Rb/Sr value (1.24) (Stuckless and others, 1983). These values are more typical of unevolved granites.

The four samples chosen for dating have a moderate range of Rb/Sr values (table 1) and are colinear within the limits of analytical error (table 2 and fig. 2). The resulting age is 609±11 Ma, and the initial $^{87}Sr/^{86}Sr$ is 0.7034±0.0004. Left-lateral movement along the southern Najd faults started about 620 Ma (Stacey and Agar, 1985), and thus the age relationships at Jabal as Sukkah show that shearing along the Najd system continued for at least 10 m.y.

NAJRAN

The Najran batholith is described by Sable (1986) as a coarse-grained biotite alkali feldspar granite that locally contains subcalcic amphibole (ferrohastingsite), particularly near its fine-grained, granophyric margin. It is unlike other postorogenic plutons in that its margin is more irregular and embayed than the typical smoothly circular or elliptical bodies. Limited chemical data indicate that the granite is metaluminous and one of the least evolved of the postorogenic plutons in the eastern Arabian Shield (Stuckless and others, 1983; Stuckless and others, 1985). Differentiation indices average 89.8; the average K/Rb is high (419), and the average Rb/Sr is low (1.39).

The four samples analyzed from Najran have a moderate range in Rb/Sr values (table 1) and are not colinear within the limits of analytical error (table 2 and fig. 2). A model III fit to the data (which assumes variation in the initial $^{87}Sr/^{86}Sr$ among samples at the time of crystallization) yields an age of 617±19 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7029±0.0052. Compared to other postorogenic granites of the southern Arabian Shield (Fleck and others, 1980), both the age and initial ratio are reasonable and thus a variable initial ratio is a reasonable explanation for the poor fit of the data to a straight line. A variable initial ratio would be consistent with derivation of the batholith from an inhomogeneous source region; Sable (1986) and Greenwood and others (1982) have noted that the Najran batholith was emplaced along the Ashara fault, which joins two dissimilar terranes.

JABAL AL GAHARRA

The intrusion at Jabal al Gaharra is an alkali-feldspar granite emplaced along the north-south Ashara fault zone such that the pluton is now exposed as a 4.5 by 1.5 km elliptical pluton 25 km north of Najran (Elliott, 1985). Albite, quartz, and microcline (in decreasing order of abundance) comprise more than 90 percent of the rock; the rest of the rock consists of muscovite, phlogopite, and trace amounts of fluorite, topaz, apatite, and rare cassiterite (Elliott, 1985). Attempts to date the granite by U-Pb showed that at least one sample contained no zircon (Stoeser and others, 1984) which is atypical of the Arabian postorogenic granites. The granite is moderately peraluminous and very highly evolved as indicated by an average differentiation index of almost 95, an extremely high average Rb/Sr of 182, and a very low K/Rb of 47.3 (Stuckless and others, 1983). Elliott (1985) noted that Jabal al Gaharra has a strongly anomalous tin content, but that quartz veining and other signs of post-magmatic hydrothermal activity (such as alteration textures seen in thin section) are rare. In spite of the anomaly, no notable tin concentration has been discovered.

The three samples chosen for dating have extremely high ^{87}Rb/^{86}Sr values, and although the analyses are colinear within the limits of experimental error (fig. 2), the calculated initial ^{87}Sr/^{86}Sr (0.7377±0.1405) is very imprecise (table 2). The error in calculated ages is not affected by the extremely high ^{87}Rb/^{86}Sr values, and thus the calculated age of 575±19 Ma is of better precision. This age is the youngest determined for postorogenic granites of the southern Arabian Shield (Fleck and others, 1980; Stoeser and others, 1984; Aleinikoff and Stoeser, 1987).

JABAL AL HASSIR

The pluton at Jabal al Hassir is a large (17 by 35 km), zoned ring complex that varies from hypersolvus alkali-feldspar granite near its outer edge to subsolvus granodiorite in its core (Stoeser and Elliott, 1980). The pluton is unique relative to most of the other postorogenic plutons in that it contains abundant xenoliths of unaltered country rock, especially in the southern half of the intrusion. The differentiation index for six samples is uniformly high and averages 94.0 (Stuckless and others, 1983). The K/Rb varies from 220 to 681 and suggests an unevolved pluton. The Rb/Sr varies from 1.9 to 5.5. Stoeser and Elliott (1980) report that the outer ring of the pluton is peralkaline, but data reported by Stuckless and others (1983) show that samples from the pluton, including 3 from the northern and southern rim, vary from metaluminous to weakly peraluminous.

The four samples chosen for dating exhibit a large range in ^{87}Rb/^{86}Sr (table 1), and analyses are colinear within the limits of experimental error (fig. 2), but only marginally so (MSWD=1.61, table 2). The age and initial ^{87}Sr/^{86}Sr for a model I regression are 590±15 Ma and 0.7043±0.0018 respectively. A model III regression yields 588±8 Ma and 0.7046±0.0051. Four zircon fractions yield a distinctly older upper intercept age of 628±4 Ma (Aleinikoff and Stoeser, 1987). The zircon data are nearly perfectly colinear; two of the fractions are fairly concordant, and the lower intercept (35±21 Ma) is not anomalous. Thus, there is no evidence for zircons inherited from the blocks of country rock or other obvious reason for the disagreement in the ages obtained by the two methods. In view of the somewhat large MSWD for the Rb-Sr data and the generally greater reliability for U-Pb zircon ages, the 628±4 Ma is tentatively accepted as the better estimated of the age of intrusion at al Hassir.

JABAL KHINZIR

The Jabal Khinzir body is a small (5 by 4 km), well exposed, elliptical pluton near the south end of the larger, circular Ad Darah granite (Moore, 1984). The granite at Jabal Khinzir is similar to that at Jabal al Gaharra in that it is a leucocratic, two-mica, monzogranite to alkali-feldspar granite, and Jabal Khinzir is anomalously enriched in tin (Moore, 1984). The granite has associated aplites and pegmatites, but lacks abundant quartz veins or strong evidence of hydrothermal alteration. Chemical analyses for the pluton show a range in differentiation indices of 89.0 to 95.1; K/Rb values are low (average for 7 samples is 106), and Rb/Sr values (range of 1.5 to 57.1 and average of 22.4), although elevated, are not as high as those at Jabal al Gaharra (Stuckless and others, 1985). The pluton is not as strongly peraluminous as Jabal al Gaharra; the molar ratio of Al/(Na+K+Ca) ranges from 1.03 to 1.10 and averages 1.06. Sample 184422 is from an aplite dike that cuts the margin of the pluton and is much less evolved than the granite (differentiation index=81.1, K/Rb=329, and Rb/Sr=0.26). The aplite is therefore, of doubtful magmatic relationship to the pluton.

Four samples of the granite and one sample of spatially associated aplite were analyzed as part of the current study (table 1). The four granite samples have a large range in ^{87}Rb/^{86}Sr and exhibit an excellent fit to an isochron (table 2 and fig. 2). The resulting age is 567±9 Ma, and the initial ^{87}Sr/^{86}Sr is 0.7041±0.0008. The data for the aplite do not lie on the same isochron within the limits of experimental error, and thus confirm the suspicion that the granite and aplite are not genetically related. Baubron and others (1976) report a distinctly younger Rb-Sr whole-rock age for Jabal Khinzir of 552±5 Ma. The reason for the disagreement is not obvious, but the earlier work may have included some samples, such as the aplite, that are not cogenetic with the tin-bearing pluton.

JABAL MINYA

The pluton at Jabal Minya is also identified by Moore (1984) as a tin-bearing granite. Like the previously described tin-bearing granites it is leucocratic, contains two micas and fluorite, and is a microcline to microcline-albite granite in composition. It occurs as a small elliptical body (1.5 by 2.0 km) along the southern border of a larger granodiorite pluton (Beurrier and Villey, 1983; Cole, 1986), which is similar to the occurrence at Jabal Khinzir. The granite has a subsolvus texture, and most samples are weakly peraluminous (average molar Al/(Na+K+Ca) is 1.05 for 5 of 6 samples and 1.27 for the sixth sample). Differentiation indices for six samples range from 90.4 to 91.7 and average 91.1; K/Rb values are consistently low (44 to 88), and Rb/Sr values are moderately high (3.6 to 11.7) (Stuckless and others, 1985).

The four analyzed samples (table 1) have a good range in ^{87}Rb/^{86}Sr and are all moderately enriched in Rb (fig. 2). The samples are not colinear within the limits of experimental error, and a model III fit to the data yields an age of 587±15 Ma and an initial ^{87}Sr/^{86}Sr of 0.7072±0.0171 (table 2). Because the age and initial ratio are within the normal range for postorogenic granites of the Arabian Shield, the model III solution is judged to be appropriate.

MISKAH

The name Miskah, in this report, is used for the large northwest-trending, elliptical batholith (50 by 20 km) that surrounds the town of Miskah and includes a 10 km circular intrusion at the northwestern end of the batholith. Rocks included under the name of Miskah are subsolvus and range from monzogranites to syenogranites, and contain biotite and sparse muscovite (Moore, 1984). The differentiation indices for 11 samples range from 87.2 to 94.2 and average 90.9 (Stuckless and others, 1985). All samples are weakly peraluminous and fairly unevolved as indicated by generally low Rb/Sr (range 0.3 to 3.3; average 1.4) and generally high K/Rb (range 153 to 639; average 348).

The eight samples chosen for dating cover the full length of the batholith and provide a large range of $^{87}Rb/^{86}Sr$ values (table 1). In spite of the large geographic area represented by the samples, all are colinear within the limits of experimental error (table 2 and fig. 2). Regression of the data yields an age of 585 ± 8 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7037 ± 0.0003.

JABAL SAQRAH

The mapped outcrop pattern for the pluton at Jabal Saqrah differs from that of the other small postorogenic plutons because it forms a large, roughly equilateral triangle approximately 25 km on a side. One side is oriented in a northwest-trending direction along a strand of the Najd fault system and is interpreted to be cut by the fault (Letalenet, 1979), but the mapped relationships suggest that the relatively straight southwestern contact is due to intrusion against a pre-existing fault. The pluton at Jabal Saqrah is a hypersolvus to subsolvus alkali feldspar granite (Moore, 1984) and weakly metaluminous to weakly peraluminous (Stuckless and others, 1985). Differentiation indices, which range from 86.7 to 96.2 and average 92.6, suggest a high degree of petrologic evolution. However, the K/Rb values are generally higher than 250 and the Rb/Sr values are generally less than 3, suggesting an unevolved granite.

The five samples chosen for dating exhibit a very large range in $^{87}Rb/^{86}Sr$ values (table 1), but this is due to inclusion of one sample that is markedly poor in strontium (sample 184404). The data show a pronounced deviation from a colinear relationship (MSWD=16). A model III fit to the data yields and age of 604 ± 9 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7050 ± 0.0045.

These results are markedly different from those of a model I fit (625 Ma and 0.7025), and this disparity is not typical for well-behaved isotopic systems. Low-strontium, high-rubidium whole-rock samples like sample 184404 are often more sensitive to disturbance than typical samples of granite. Omission of the most radiogenic sample (184404) only improves the colinearity of the data to a small degree (MSWD=9.72), and a model III fit is still required; the resulting age is 656 Ma and the initial $^{87}Sr/^{86}Sr$ is 0.7014. This age is unrealistically old if the assumption that Jabal Saqrah belongs with the group of postorogenic granites is correct. The model III fit to the entire data set probably provides the best estimate of the true age (604 Ma) and initial ratio (0.7050) of the pluton. There is, however, a suggestion in the data of a disturbed system or systematic variation of the initial ratio with Sr concentration, and therefore interpretation of the results for Jabal Saqrah are less certain than for other plutons examined in the current study.

JABAL TUQFAH

The pluton at Jabal Tuqfah is a northwest-trending elliptical body approximately 25 by 11 km, that is mapped as truncated along its southwestern edge by a N. 60°-70° W. strike-slip fault (Beurrier and Villey, 1983). This fault is shown as left-lateral and is attributed to the Najd system; however, Cole (written commun., 1986) was unable to find evidence of shearing within the granite and believes that the granite was emplaced against a pre-625 m.y. old fault. The rock is a hypersolvus alkali feldspar granite with 30 to 35 percent quartz, 60 to 70 percent microperthite, as much as 5 percent amphibole, minor amounts of biotite, and accessory zircon, opaque oxides, allanite, and fluorite. Mineralogically, the granite appears to be peralkaline (Beurrier and Villey, 1983), but chemically most samples are metaluminous (Stuckless and others, 1985). The average differentiation index for five samples is very high (93.9); whereas average K/Rb (265) and Rb/Sr (5.47) are intermediate relative to other postorogenic granites of the Arabian Shield (Stuckless and others, 1985).

The samples analyzed for this study exhibit a large range in $^{87}Rb/^{86}Sr$ (table 1 and fig. 2), and do not fit an isochron within the limits of experimental error (MSWD=3.33; table 2). A model III fit to the data yields an age of 584±37 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7032±0.0173. Fleck and Hadley (1982) also determined a three-point isochron for the pluton at Jabal Tuqfah (MSWD=3.32). Their reported age and initial $^{87}Sr/^{86}Sr$ are 563±71 Ma and 0.703±0.008 respectively. These authors suggested that the poor fit to an isochron may be due to a minor postconsolidation disturbance. They noted that the true age could not be significantly different from 563 Ma because of the high Rb-Sr ratios, that force limiting isochrons to yield ages which are near that obtained by the regression. A disturbance shortly after intrusion would not be expected to produce the observed scatter about the isochron; rather the interpretation that separate samples had variable initial ratios seems more reasonable. If the initial $^{87}Sr/^{86}Sr$ was variable, the best approximation to the true age and initial ratio is obtained by regressing a large number of data points. The data obtained in the current study combined with that reported by Fleck and Hadley (1982) yield an age of 588±12 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7039±0.0054.

JABAL KHAZAZ

The intrusion at Jabal Khazaz is exposed as a north-trending, 15 by 7 km elliptical pluton (Beurrier and Villey, 1982). The rock is a syenogranite that contains 40 to 45 percent microcline, 30 to 40 percent quartz, 20 to 25 percent sodic oligoclase, and small amounts of biotite. Accessory minerals include zircon, muscovite, and opaque oxides. Differentiation indices for 7 samples are uniformly high (average is 94.1); K/Rb ranges from 64 to 176 and averages 122, and Rb/Sr ranges from 4.1 to 165 and averages 59.5 (Stuckless and others, 1985). These values all suggest a very high degree of magmatic evolution. The pluton is moderately peraluminous as indicated by an average Al/(Na+K+Ca) of 1.12.

The $^{87}Rb/^{86}Sr$ for the three samples analyzed varies by more than a factor of 60 (table 1), and the three points exhibit a near-perfect fit to an isochron (table 2 and fig. 2). The resulting age and initial $^{87}Sr/^{86}Sr$ are 584±8 Ma and 0.7044±0.0023.

JABAL USAYBIYAT

The intrusion at Jabal Usaybiyat is a discontinuous circular ring, approximately 20 km in diameter, that contains medium-grained, subsolvus syenogranite (Moore, 1984). Biotite is the dominant mafic mineral; hornblende is rare. Zircon, epidote, opaque oxides, and apatite are the important accessory minerals. The granite has been identified as a possible exploration target for radioelement and rare-earth elements on the basis of heavy-mineral concentrates (Moore, 1984). Four analyses yield very high differentiation indices (average is 94.9), and samples range from weakly metaluminous to weakly peraluminous (Stuckless and others, 1985). The K/Rb is generally low and averages 198; Rb/Sr is highly variable and averages 93.9.

The large range in $^{87}Rb/^{86}Sr$ values (table 1) yields an isochron for which the slope is tightly controlled, even though the four points do not fit an isochron within the limits of experimental precision (table 2 and fig. 2). The resulting age and initial $^{87}Sr/^{86}Sr$ from a model III regression are 591±8 Ma and 0.7061±0.0194. Samples from the southern part of the Usaybiyat ring form a colinear Rb-Sr array (Fleck and Hadley, 1982), and yield an age of 602±9 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7061±0.0005.

JABAL TUKHFAH

The pluton at Jabal Tukhfah is a small north-trending, elliptical intrusion about 7 km long and 3 km wide whose northern end has been offset in a left-lateral sense for a distance of about 2 km to the west (Letalenet, 1979). The rock is a hypersolvus alkali feldspar granite (Moore, 1984). Like many other alkali-feldspar granites, the rock varies from weakly metaluminous to weakly peraluminous and has a high average differentiations index (93.1) (Stuckless and others, 1985). K/Rb is moderately low (156) and Rb/Sr is slightly elevated (6.55).

The three samples of the granite provide a good range of Rb/Sr values, but unfortunately, form a pseudo two-point isochron because two sets of values are so similar (table 1 and fig. 2). The data are colinear within the limits of experimental error and yield an age of 573±13 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7013±0.0022.

Jabal Tukhfah is the youngest of the postorogenic plutons that is clearly offset by northwest-trending faulting of the Najd system. The magnitude of offset suggests that displacement continued for only 200,000 to 400,000 years following intrusion (assuming 0.5 to 1.0 cm per year movement). Fleck and others (1976) have suggested that Najd faulting continued until about 530 Ma on the basis of K-Ar whole-rock ages for dikes that fill fractures parallel to those of the Najd system, but well south of the major Najd zone. Inasmuch as the time lapse between shearing and dike emplacement is unknown and the relationship of the shears to the Najd system is uncertain, the age of 530 Ma is at best an approximation for the end of Najd faulting. Cloud and others (1979) cite a K-Ar whole-rock age of 540±20 Ma for a bedded andesitic basalt within a Najd basin, which also provides only a rough approximation for the end of Najd faulting within one area of the system. Minor offsets in the Cambrian sediments marginal to the Arabian Shield along traces of Najd faults do exist, but these may represent minor remobilizations along older faults, and the sense of movement may have been dip-slip rather than strike-slip.

Movement along various strands of the Najd must have started at different times (Stacey and Agar, 1985; Cole and Hedge, 1986), but movement along some strands must have ceased earlier than 570 Ma. For example, Stacey and others (unpub. data) have determined an age of 591±6 Ma for an apparently undeformed pluton within the southern-most strand of the Najd system; therefore, offset must have ceased prior to intrusion of this pluton. Similarily, intrusions along the northern-most strand of the Najd system indicate an end to movement about 615 Ma (Cole and Hedge, 1986). If for the entire Najd System left-lateral movement started at 670 Ma (as proposed by Cole and Hedge, 1986), and the estimated total net displacement is 240 km (as proposed by Brown, 1972), the average rate of movement along this fault system that was active for 90 m.y. is well within that estimated for other strike-slip systems.

REGIONAL PATTERNS

Stuckless, Hedge, and others (1984) noted that the postorogenic granites north of the Najd fault zone seemed younger than those within the zone, but data are too few to support a firm conclusion. Table 3 lists a compilation of available ages of postorogenic granites from the eastern Arabian Shield which seem to be of high quality and applicable. The geochronologic data used were obtained by either Rb-Sr whole-rock isochron or U-Pb zircon determinations. The data, however, are not of uniform quality in terms of uncertainty, and plutons that have been dated by both methods yield uniformly older ages by the U-Pb zircon technique (Jabal al Hassir, Jabal Sabhah, Jabal Khurs, and Tindahah; table 3).

There is no obvious explanation for the differences between the two techniques. The raw data for each of the four plutons appear to be of high quality, and there is no evidence of inherited zircons (which might increase the apparent U-Pb zircon age) or excess scatter for either data set (which, in the case of Rb-Sr, might indicate a partially reset age). Because zircon ages are generally more precise, these have been plotted on figure 3 in preference to the Rb-Sr ages where duplicate determinations are reported.

The age data plotted on figure 3 are grouped by classes of one-half standard deviation such that the middle class is one standard deviation wide and centered on the mean and subsequent class boundaries are one-half standard deviation further from the mean. The plot shows that the ages of postorogenic granites south of latitude 23° N. are generally older than those in the north. There is no obvious east-west pattern to the age data, and inasmuch as the plutons near the eastern margin of the exposed Arabian Shield tend to be the most evolved (Stuckless, Hedge, and others, 1984), there is no correlation between degree of magmatic evolution and age.

Fleck and others (1976) noted that K-Ar biotite ages in the southern part of the Arabian Shield have been lowered by a thermal event about 540 to 510 Ma. The effects of this event apparently did not extend into the northern Arabian Shield (Stuckless, Hedge, and others, 1984). The four pairs of discordant Rb-Sr and U-Pb ages are all from the southern part of the Arabian Shield, and perhaps the Rb-Sr ages have been disturbed to a small degree such that calculated ages are slightly low, but that isochrons do not show excessive scatter. Such partial resetting without obvious excess scatter about isochrons can be accomplished if one phase (for example, biotite) forms the dominant site for rubidium, and that phase is the only one to lose radiogenic strontium in response to a thermal event. In this situation, data points would be displaced in proportion to their Rb/Sr such that the isochron would rotate to a lesser slope; linearity would be maintained, and initial $^{87}Sr/^{86}Sr$ would be unaffected.

Stacey and others (1980) first noted that the isotopic composition of lead in rocks and ore minerals of the Arabian Shield, could be divided into two groups.

Table 3.- Tabulation of ages (in millions of years) and initial strontium isotopic ratios (Sr(I)) for postorogenic granites of the eastern and central Arabian Shield

Pluton	Lat.	Long.	Age	Sr(I)	Reference
J. al Hassir	19° 30'N	43° 5'E	590	0.7043	1
J. al Hassir	19° 28'N	43° 7'E	628	---	2
J. Saqrah	23° 2'N	42° 57'E	604	.7050	1
J. Tuqfah	24° 48'N	43° 11'E	584	.7032	1
J. Tuqfah	24° 55'N	43° 10'E	563	.7030	3
J. Khazaz	25° 23'N	43° 35'E	584	.7044	1
Miskah	24° 40'N	42° 59'E	585	.7037	1
J. Khinzir	23° 9'N	43° 50'E	567	.7041	1
J. al Gaharra	18° 4'N	44° 0'E	575	.7377	1
J. Tarban	21° 15'N	44° 0'E	587	.7037	1
J. as Sukkah	21° 43'N	43° 42'E	609	.7034	1
Najran	17° 32'N	44° 5'E	617	.7029	1
J. Minya	24° 58'N	43° 20'E	587	.7072	1
J. Tukhfah	23° 55'N	42° 8'E	573	.7013	1
J. Usaybiyat	24° 6'N	42° 26'E	591	.7061	1
J. Usaybiyat	23° 58'N	42° 24'E	602	.7061	3
Ba'gham	26° 55'N	41° 0'E	600	.7018	4
J. Ahmar	25° 30'N	42° 46'E	574	.7030	5
J. Qutn	26° 0'N	42° 20'E	579	.7055	5
J. Tuwalah	25° 32'N	41° 0'E	628	.7019	5
An Namar	25° 37'N	40° 56'E	604	.7031	5
J. Awja	25° 50'N	40° 56'E	594	.7036	5
J. Bidayah	25° 6'N	41° 9'E	617	.7017	5
J. Salma	27° 7'N	42° 8'E	580	.7037	5
J. ar Rumman	26° 46'N	41° 26'E	581	.7030	5
J. Sabhah	23° 16'N	44° 36'E	605	---	6
J. Sabhah	23° 18'N	44° 36'E	556	.7080	7
J. Khurs	23° 36'N	44° 42'E	579	.7060	7
J. Khurs	23° 36'N	44° 43'E	595	---	6
J. al Jafara	22° 53'N	45° 7'E	631	.7033	6
J. Aja	27° 41'N	41° 37'E	566	.7070	2
Uyaijah	22° 43'N	44° 27'E	595	.7034	3
J. Jabalah	24° 48'N	43° 52'E	575	.7044	3
Alse-Hairah	23° 29'N	41° 23'E	567	.7031	3
Al Bara	23° 45'N	42° 56'E	571	.7036	3
W. al Miyah	20° 36'N	42° 43'E	587	.7045	8
J. Qal	18° 48'N	42° 13'E	620	.7034	8
W. Musayrah	20° 17'N	43° 2'E	623	.7033	8
Tindahah	18° 13'N	43° 0'E	635	---	17
Tindahah	18° 18'N	42° 54'E	626	.7037	8

Table 3.– Tabulation of ages (in millions of years) and initial strontium isotopic ratios (Sr(I)) for postorogenic granites of the eastern and central Arabian Shield--continued

Pluton	Lat.	Long.	Age	Sr(i)	Reference
W. Schuwas	19° 55'N	41° 54'E	636	.7035	8
W. Gharnak	23° 35'N	40° 32'E	575	.7031	9
E. of Sharar	23° 49'N	41° 1'E	573	.7030	9
Hadb ash Sharar	23° 47'N	40° 57'E	584	.7170	9
Unnamed	23° 31'N	40° 47'E	572	.7047	10
Haml	22° 49'N	43° 1'E	632	.7050	11
Hufayrah	22° 15'N	42° 43'E	620	.7045	11
Al Jizl	24° 19'N	39° 14'E	583	.7026	12
J. Bayda	24° 44'N	39° 25'E	561	.7033	12
Um Gerad	22° 55'N	39° 10'E	583	.7023	13
Bitran Granite	23° 30'N	45° 18'E	584	.7043	14
J. Abha	24° 23'N	40° 44'E	584	.7029	7
J. Sanam	24° 44'N	41° 17'E	607	.7031	7
J. Rahadah	25° 41'N	41° 34'E	574	.7129	7
J. Yanufi	23° 27'N	43° 4'E	614	.7044	7
Ad Darah	23° 14'N	43° 54'E	576	.7100	7
J. Arwah	23° 47'N	44° 37'E	587	.7056	7
J. Kursh	22° 12'N	43° 47'E	579	.7039	7
Ash Shufayiyah	24° 35'N	43° 41'E	593	---	7
Baid al Jimalah	25° 11'N	42° 41'E	569	---	15
J. Dahul	22° 12'N	43° 47'E	601	---	2
J. Ashirah	18° 3'N	44° 16'E	637	---	2
Ar Rukhamah	23° 53'N	44° 22'E	623	---	6
J. Silsilah	26° 4'N	42° 41'E	587	---	16

1. This Report.
2. Aleinikoff and others, 1986
3. Fleck and Hadley, 1982
4. Stuckless, Quick, and VanTrump, 1984
5. Stuckless, Hedge, and others, 1984
6. Stacey and others, 1984
7. Calvez and others, 1984
8. Fleck and others, 1980
9. Calvez and Kemp, 1982
10. Brown and others, 1978
11. Stacey and Agar, 1985
12. Kemp and others, 1980
13. Al Shanti and others, 1984
14. Radain and others, 1984
15. Cole and Hedge, 1986
16. du Bray, 1984
17. Stoeser and others, 1984

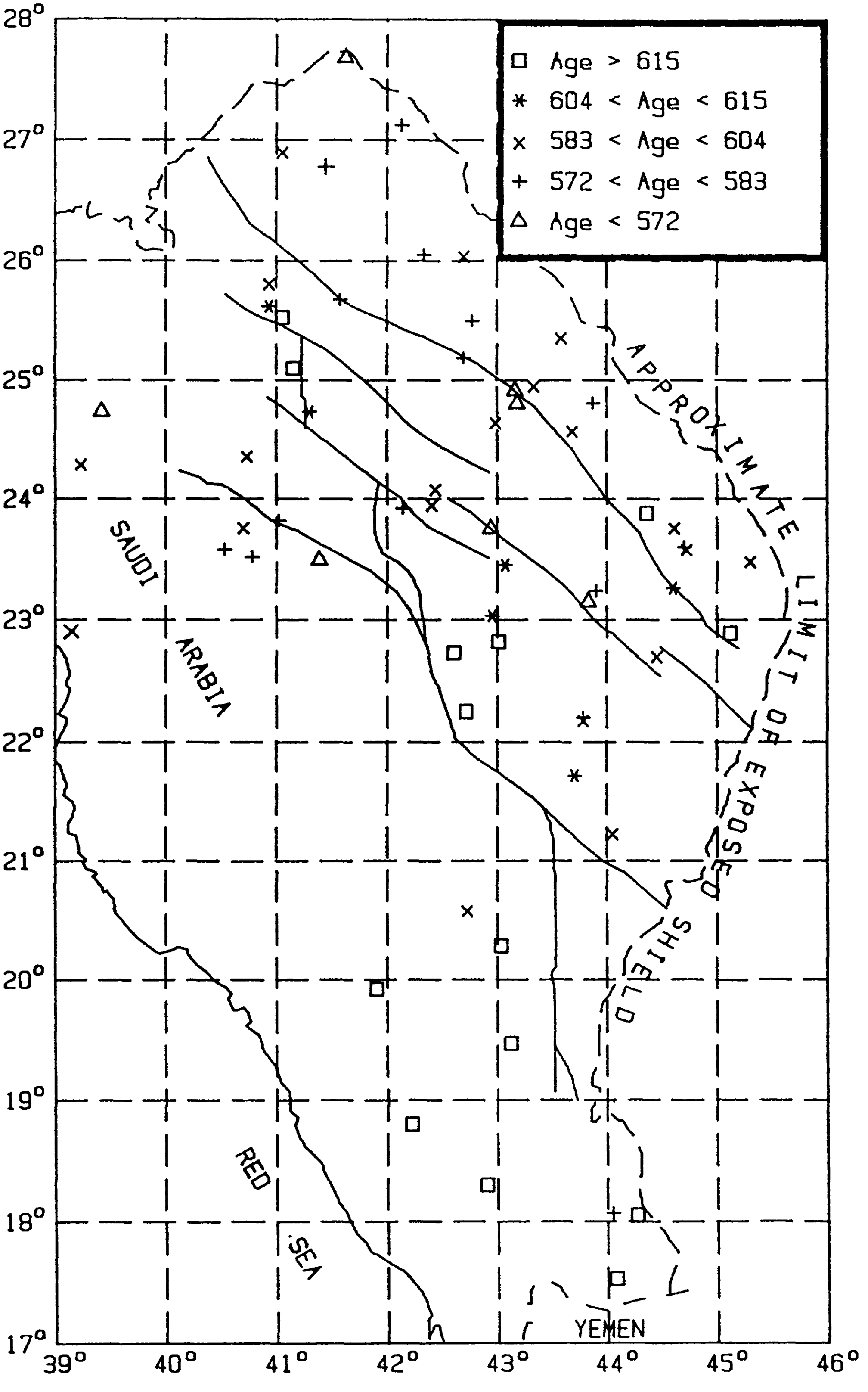

Figure 3.--Map showing the ages (Ma) of postorogenic plutons. Data and references are given in table 3. Data are grouped on statistical basis as explained in the text.

Lead compositions with low 207Pb/204Pb and 208Pb/204Pb relative to an average lead-growth curve were designated as group I and were attributed to an oceanic-type source. Lead compositions with a slightly higher 207Pb/204Pb and a high 208Pb/204Pb relative to an average lead-growth curve were designated as group II and were attributed to a continental-type source. Stacey and Stoeser (1984) extended the work and showed that the group II leads were found along the northeastern edge of the Arabian Shield (plus one sample at the far southeastern limit of exposed Arabian Shield), and that group I leads were all located west of the group II localities.

Stuckless, Hedge, and others (1984) found that average K/Rb and Rb/Sr values for the postorogenic plutons formed a similar pattern in that the most evolved plutons (high Rb/Sr and low K/Rb) tended to be located along the eastern edge of the Arabian Shield and that the less evolved plutons tended to be located west of the more evolved plutons. However, the trace-element data showed a larger area of evolved granite than the area characterized by group II leads. Furthermore, the trace-element data did not define discrete subsets, but rather graded laterally into one another. Similar regional patterns for data from the postorogenic granites have been reported for the degree of alumina saturation (Stuckless and others, 1985) and for other trace elements such as the rare earths (Stuckless and others, 1986).

Initial ^{87}Sr/^{86}Sr data are less numerous than the lead data, but the strontium data plotted on figure 4 are restricted to postorogenic granites whereas plots of lead data include samples of all Precambrian stata. By limiting the data set to rocks formed during a brief time interval, differences among samples can be attributed to primary differences in the isotopic composition of the source regions (because the addition of radiogenic strontium to the source region from the decay of ^{87}Rb over a span of 40 to 50 m.y. is negligible). Most of the highest ^{87}Sr/^{86}Sr initial ratios plot in the same area as the group II leads, and all of the very low ^{87}Sr/^{86}Sr initial ratios plot in the area of the group I leads. However, the two plutons with the highest ^{87}Sr/^{86}Sr initial ratios (Jabal al Gaharra and Hadb ad Dayahin, table 3) are distinctly within group I lead areas, and there are a large number of plutons with non-elevated ^{87}Sr/^{86}Sr initial ratios within the group II lead area. Thus, the pattern defined by initial strontium isotopic compositions is more complex than that defined by initial lead compositions.

CONCLUSIONS

Two models have been proposed to explain observed geochemical and isotopic patterns over the Arabian Shield. Stoeser and Camp (1985) have proposed that the Arabian Shield formed by accretion of contrasting microplates (terranes) and that the area typified by group II lead isotopes (Afif Terrane) is underlain by older continental rocks. Stuckless, Hedge, and others (1984) have suggested that the regional data patterns result from laterally gradational changes in the protolith for the postorogenic granites. These lateral variations are attributed to the mixing of sediments that were of dominantly oceanic affinity to the west and of dominantly continental affinity to the east.

Older basement, of Middle Proterozoic age, has been identified within the Afif Terrane of the eastern Shield. Stacey and Hedge (1984) have dated a granodiorite in the Jabal Khida area that formed about 1630 Ma and was remobolized and

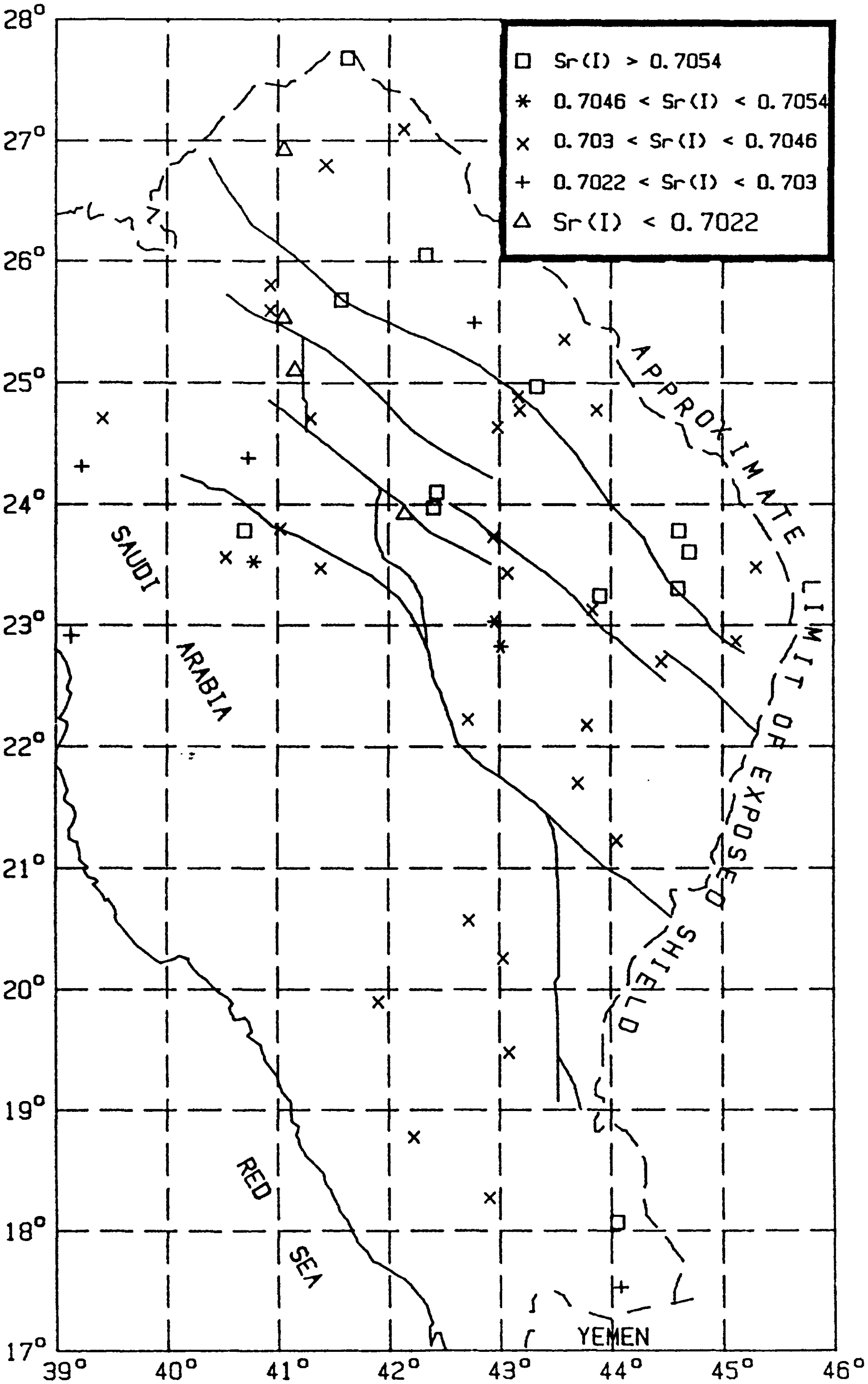

Figure 4.--Map showing initial 87Sr/86Sr (Sr(I)) for postorogenic plutons. Data and references are given in table 3. Data are grouped on the basis of visual inspection of histograms.

emplaced about 660 Ma. The $^{87}Sr/^{86}Sr$ during the time of postorogenic-granite generation would have been 0.7083, which is similar to most of the elevated initial $^{87}Sr/^{86}Sr$ values for postorogenic granites within the Afif Terrane. However, chemical constraints show that the highly evolved, peraluminous granites could not have been derived from a granodioritic protolith similar to Jabal Khida. Pelitic and evolved source materials that formed about 1630 Ma would match the necessary chemistry of the protolith, but would yield much higher initial $^{87}Sr/^{86}Sr$ values for the postorogenic plutons than those observed within the Afif Terrane.

The initial $^{87}Sr/^{86}Sr$ data do not provide a clear cut choice of one shield-evolution model over the other, but the concept of a variable protolith formed by mixing of end members seems somewhat more attractive. Such a model allows for the presence of plutons with very high initial $^{87}Sr/^{86}Sr$ values outside the group II lead region whereas the microplate model would predict old and evolved continental crust only beneath the group II lead areas. By appropriate assumptions of degree of chemical evolution and age of the protolith, either model allows for plutons with non-elevated initial $^{87}Sr/^{86}Sr$ values within the group II lead province. However, in the case of Jabal Tarban, the protolith must have been highly evolved and could not have been markedly older than the postorogenic plutons or the initial strontium ratio would have been higher than observed. These conditions are more consistent with a mixed sedimentary protolith than with an older continental crust.

DATA STORAGE

All data acquired during this study are presented in this paper, and no base data files were established. The results and conclusions are regional in scope and have no bearing on specific localities; therefore, no entries were made to the Mineral Occurrence Documentation System (MODS).

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