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Ages and strontium initial ratios of plutonic rocks in a transect of the Arabian Shield

by

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AGES AND STRONTIUM INITIAL RATIOS

OF PLUTONIC ROCKS

IN A TRANSECT OF THE ARABIAN SHIELD

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ABSTRACT

Geochronologic studies using Rb-Sr, K-Ar, and $^{40}Ar/^{39}Ar$ techniques document a decrease in age of orogenic events in the Arabian Shield from southwest to northeast. These events include the emplacement of the oldest, dioritic plutonic units, the deformation of these dioritic units and the stratified units intruded by them, and the intrusion of late-orogenic and postorogenic plutons.

Initial $^{87}Sr/^{86}Sr$ ratios in the northern and eastern parts of the Shield are generally less than 0.704. The few exceptions are restricted to low-strontium, postorogenic plutons that may have incorporated marine sedimentary materials. No plutons of early Proterozoic age were found, and the low initial ratios support the contention that no sialic crust of that age is present in the areas studied. It is suggested that elevated lead isotope ratios reported for galenas from the eastern part of the Arabian Shield may have resulted from mobilization or incorporation of lead from sedimentary rocks of middle or late Proterozoic age and not from partial melting of, and intrusion into, an Early Proterozoic continent from which the high Rb/Sr upper crust had been stripped. Rb-Sr results are consistent with an origin by accretion of intraoceanic island arcs, the more easterly of which may have had a larger sedimentary component in source materials of arc magmas.

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INTRODUCTION

Rubidium-strontium (Rb-Sr) studies by Fleck and others (1980) of the southern part of the Arabian Shield (fig. 1) indicate the presence of Late Proterozoic crust characterized by low Rb/Sr and initial $^{87}Sr/^{86}Sr$ ratios throughout the region. Data reported by Baubron and others (1975) for the central and eastern part of the Shield indicate the presence of a number of plutons having higher initial ratios, which might suggest an older or higher Rb/Sr source. The present study was undertaken to evaluate these apparent differences and to obtain ages for those plutonic units amenable to total-rock Rb-Sr geochronology. Samples were collected along a northeast-southwest transect of the Arabian Shield, extending from the area of Ad Dawadimi to Jiddah (figs. 1,2). Only plutonic rocks were examined for this purpose in order that initial $^{87}Sr/^{86}Sr$ ratios would be least affected by subsequent metamorphism and would be representative of source terranes in the immediate area sampled. As shown by Kistler and Peterman (1973,1978), the high sensitivity of initial $^{87}Sr/^{86}Sr$ ratios of plutonic rocks to the presence of ancient sialic crust permits a high degree of resolution in ascertaining the positions of old continental (sialic) margins. The present report presents Rb-Sr and K-Ar (potassium-argon) ages and initial $^{87}Sr/^{86}Sr$ ratios (r_i) for units sampled in this transect.

Previous geochronologic studies by Brown and Jackson (1960), Baubron and others (1975), Aldrich and others (1978), and Stacey and others (1980) include samples from the area of this transect. Baubron and others presented total-rock Rb-Sr ages for this area that are generally consistent with results reported here when recalculated using current decay constants (Steiger and Jager, 1977). Initial ratios (r_i) reported by Baubron and others, however, are generally higher than those reported here and by Fleck and others (1980). The majority of the units studied by Baubron and others have high Rb/Sr ratios, however, which lead to large uncertainties in r_i values. The r_i values of the small number of samples having low Rb/Sr ratios are consistent with values reported here.

ANALYTIC TECHNIQUES

Sample preparation techniques utilized for rocks analyzed in this study were essentially as described by Fleck and others (1980), except that all material analyzed was crushed to less than 200 mesh. All concentrations reported were the result of isotope-dilution measurements made by standard silicate-digestion and ion-exchange techniques. Rb-Sr isochron parameters were calculated by the least-squares regression of York (1969), which provides for correlation of errors and assignment of error to individual data points. The

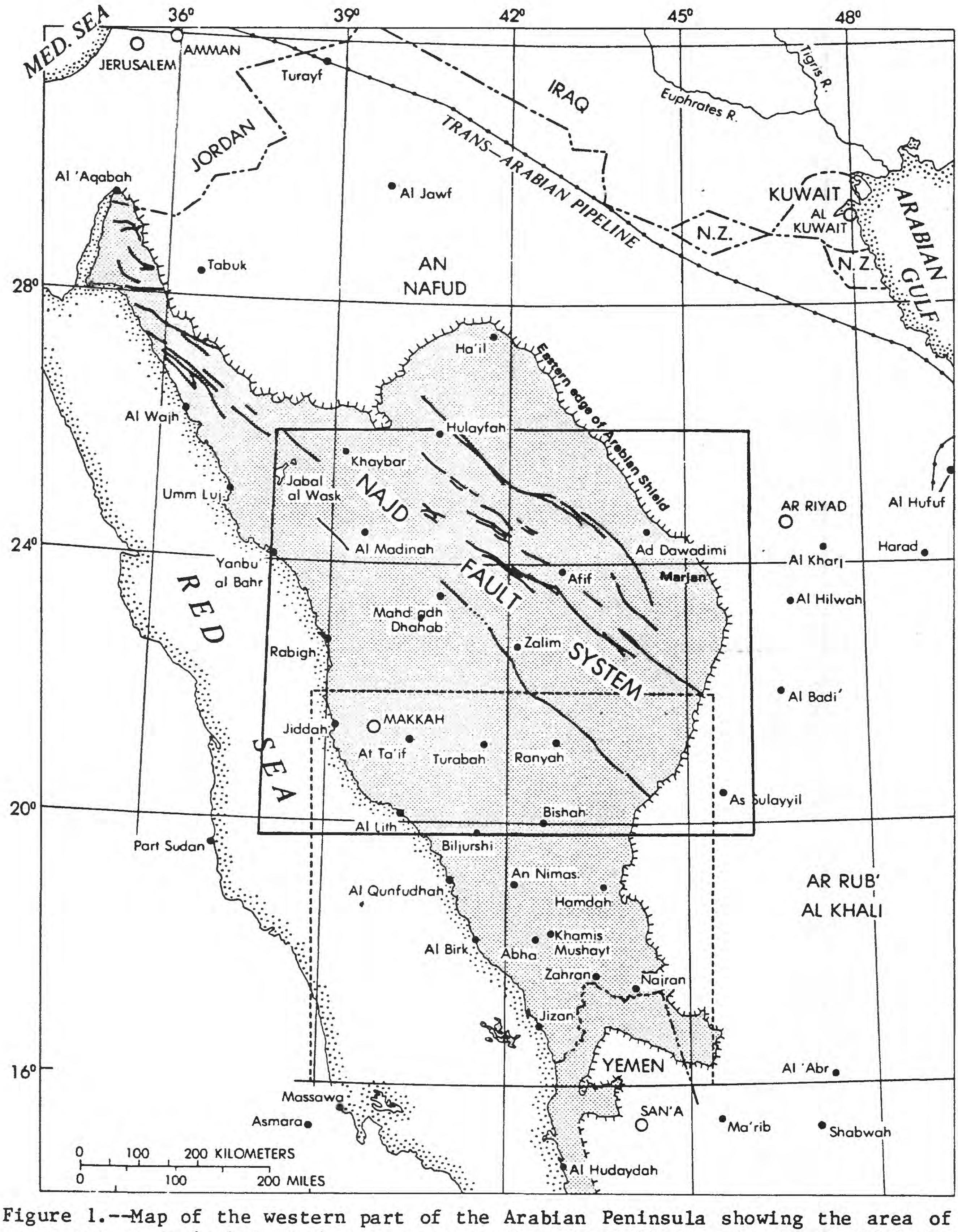

Figure 1.--Map of the western part of the Arabian Peninsula showing the area of the present study (solid line) and the area of study of Fleck and others (1980) (dashed line). The exposed area of the Arabian Shield is delimited by the margin of the Red Sea on the west and the hachured line marking the edge of onlapping Paleozoic sedimentary strata on the east. Hachures are on the Paleozoic side of the contact.

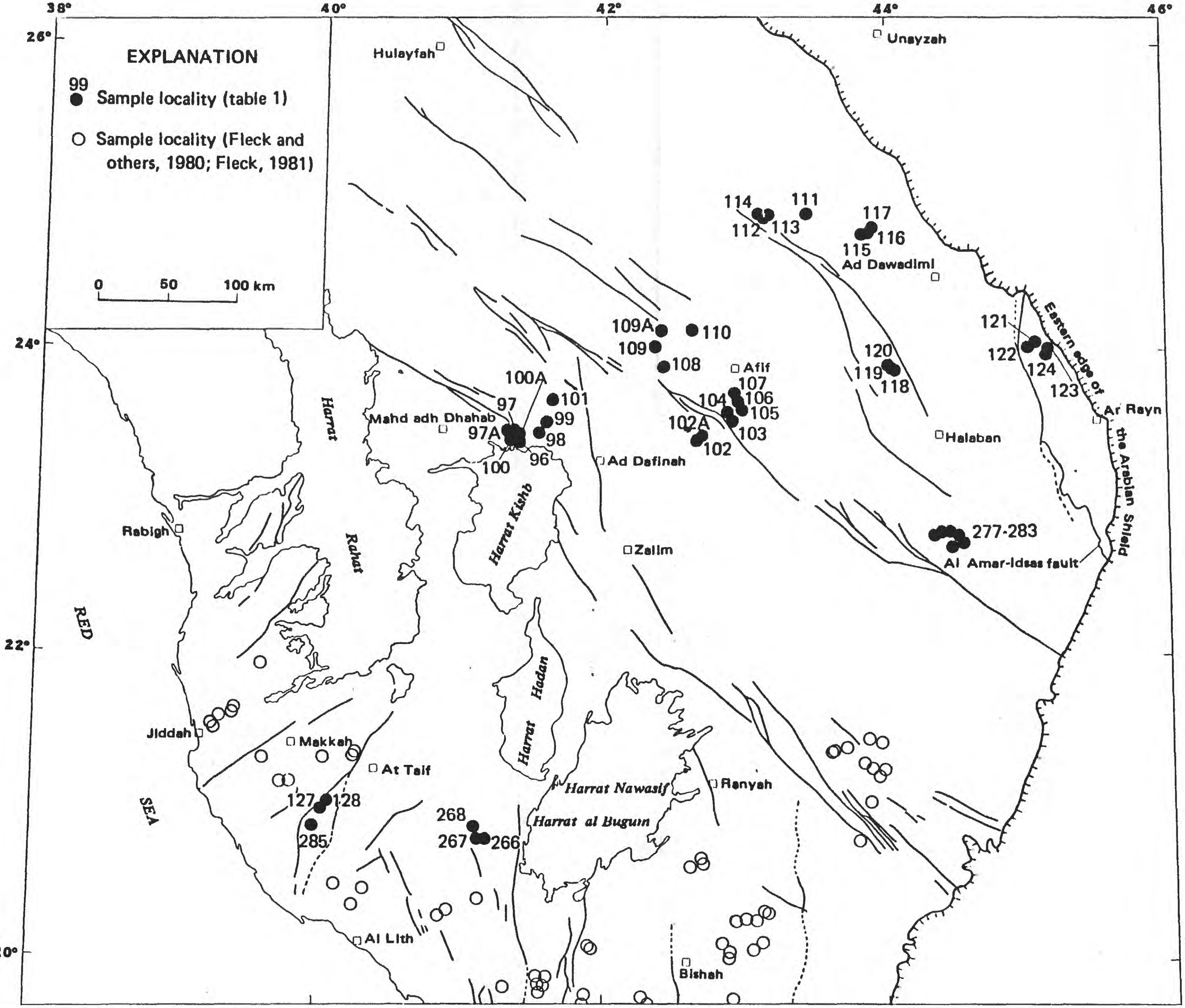

Figure 2.--Map of part of the Arabian Shield showing locations of analyzed samples (solid circles) and previously published data (open circles), major faults of the Shield, and Tertiary to Quaternary basalt fields (harrats). Eastern edge of exposed part of Arabian Shield shown by hachured line, with hachures on side of onlapping Paleozoic strata.

measure of goodness of fit quoted here is the "mean square of weighted deviates" or MSWD of McIntyre and others (1966), calculated as (SUMS/(N-2)) in the York regression (Roddick, 1978). Uncertainties assigned to age and r_i values are quoted at one standard deviation and are always the larger of the two estimates from the York regression: either the simple (observed) scatter about the isochron or the scatter modified by estimates of analytical uncertainty (York, 1969; Brooks and others, 1972; Roddick, 1978). In all but two cases, observed scatter is less than that estimated from assigned analytical errors. This observation suggests that the estimates of analytical error may be larger than those actually incurred (and that uncertainties assigned r_i and age are too large) or that some systematic bias exists whereby divergent data that cause high MSWD values are excluded. In fact, both factors may be present in this work. Because data sets having high MSWD values undoubtedly receive more than the average scrutiny, replicate analyses of divergent points often result. These replicate analyses, however, commonly indicate reproducibility better than indicated by the original estimates of analytical uncertainty, thereby demonstrating the presence of the first factor, overestimation of analytical uncertainty. Because error propagation cannot be quantitatively addressed here, it must suffice to conclude that quoted analytical uncertainties may well be too large and that this tendency leads to underinterpretation rather than overinterpretation of the results.

Decay constants and atomic abundances used here are those recommended in 1976 by the IUGS Subcommission on Geochronology (Steiger and Jager, 1977). Measurements of the $^{87}Sr/^{86}Sr$ ratio of National Bureau of Standards SRM 987 $SrCO_3$ in the Menlo Park laboratory between 1973 and 1981 yield a weighted mean of 0.71023 ± 0.00002 (n=91). Strontium isotopic ratios are normalized to $^{86}Sr/^{88}Sr = 0.1194$. Conventional K-Ar and $^{40}Ar/^{39}Ar$ techniques utilized in this study are the same as those described by Fleck and others (1976).

RESULTS OF ANALYSES

Locations of samples analyzed in this study are shown in figure 2. Locality numbers shown correspond to those in table 1, where analytical results are presented for all samples. Rubidium concentrations and $^{87}Rb/^{86}Sr$ ratios are not listed for the sake of brevity but may be calculated directly from table 1. Values for the $^{87}Rb/^{86}Sr$ ratio are found by multiplying the Rb/Sr ratio by a factor equal to $2.693 + (0.28204)(^{87}Sr/^{86}Sr)$. Rock units sampled are discussed by geographical area rather than by age groupings. Because the traverse crossed the entire exposed width of the Arabian Shield, including many well-mapped tectonic features, no attempt is made here to correlate rock units or even rock types. Isochron results are summarized in table 2.

Table 1.--Results of Rb-Sr analyses

[Rb/Sr values calculated from $^{87}Rb/^{86}Sr$]

Locality number	Sample number	Latitude (north)	Longitude (east)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$
96	761-25A	23°26.2'	41°24.4'	52.7	4.581	0.81827
	761-25B	23°26.2'	41°24.4'	55.5	5.008	.82745
97	761-25H	23°29.1'	41°22.0'	307	0.4385	.71335
	761-25I	23°29.1'	41°22.0'	315	.4063	.71255
97A	761-25J	23°29.8'	41°20.4'	350	.3474	.71119
98	761-26A	23°29.6'	41°33.3'	429	.0557	.70428
	761-26B	23°29.6'	41°33.3'	462	.0491	.70408
	761-26C	23°29.6'	41°33.3'	361	.0395	.70394
	761-26D	23°29.6'	41°33.3'	333	.0688	.70476
	761-26E	23°29.6'	41°33.3'	310	.0763	.70504
99	761-26F	23°33.4'	41°36.0'	291	.0710	.70478
	761-26G	23°33.4'	41°36.0'	489	.0247	.70333
100	761-25C	23°26.1'	41°23.6'	472	.0102	.70281
	761-25D	23°26.1'	41°23.6'	511	.0293	.70412
100A	761-25E	23°28.0'	41°24.0'	620	.0436	.70410
101	761-26H	23°41.7'	41°39.0'	782	.0103	.70304
	761-26I	23°41.7'	41°39.0'	814	.0137	.70313
	761-26J	23°41.7'	41°39.0'	797	.0130	.70316
102	761-26K	23°26.8'	42°40.9'	220	.8485	.72424
	761-26L	23°26.8'	42°40.9'	319	.5441	.71644
102A	761-26M	23°27.3'	42°41.3'	226	.9274	.72543
103	761-27A	23°35.6'	42°53.8'	388	.0782	.70712
	761-27B	23°35.6'	42°53.8'	371	.0787	.70694
104	761-27C	23°36.5'	42°53.5'	233	.3373	.71376
	761-27D	23°36.5'	42°53.5'	223	.3817	.71514
	761-27E	23°36.5'	42°53.5'	280	.1959	.70960
105	761-27F	23°38.6'	42°58.8'	306	.3809	.71422
	761-27G	23°38.6'	42°58.8'	289	.4155	.71527
106	761-27H	23°40.1'	42°58.0'	244	.3774	.71387
	761-27I	23°40.1'	42°58.0'	276	.2927	.71272
	761-27J	23°40.1'	42°48.0'	228	.4961	.71696
107	761-27K	23°44.9'	42°56.2'	404	0.0408	0.70578
	761-27M	23°44.9'	42°56.2'	400	.0167	.70483
108	761-27N	23°55.3'	42°25.8'	170	1.0370	.73187
	761-27P	23°55.3'	42°25.8'	15.0	11.992	1.0111
109	761-27R	24°0.31'	42°22.0'	21.0	7.309	.88951
	761-27S	24°0.31'	42°22.0'	11.2	11.190	.99079
109A	761-27T	24°09.1'	42°25.5'	7.75	43.58	1.8931
110	761-27U	24°08.8'	42°38.2'	256	.3883	.71509
	761-27V	24°08.8'	42°38.2'	242	.3889	.71612
111	761-28J	24°55.1'	43°26.7'	476	.0064	.70292
	761-28K	24°55.1'	43°26.7'	639	.0084	.70297
112	761-28L	24°54.1'	43°09.5'	26.1	6.662	.85981
113	761-28M	24°54.8'	43°10.1'	32.4	4.514	.80967
114	761-28N	24°54.9'	43°08.4'	35.1	4.738	.81099
115	761-29A	24°47.7'	43°51.2'	58.5	3.160	.77986
	761-29B	24°47.7'	43°51.2'	70.1	2.730	.76959

Table 1.--Results of Rb-Sr analyses--Continued

Locality number	Sample number	Latitude (north)	Longitude (east)	Sr (ppm)	Rb/Sr	$^{87}Sr/^{86}Sr$
116	761-29C	24°47.9'	43°53.5'	25.9	7.764	.89448
	761-29D	24°47.9'	43°53.5'	9.56	25.15	1.33163
	761-29E	24°47.9'	43°53.5'	22.0	9.927	.94763
117	761-29F	24°48.6'	43°54.9'	26.5	8.000	.89849
	761-29G	24°48.6'	43°54.9'	21.2	10.96	.96752
118	761-29H	23°53.7'	44°03.8'	1,383	.0059	.70302
	761-29I	23°53.7'	44°03.8'	1,357	.0059	.70300
119	761-29J	23°54.4'	44°02.4'	1,695	.0013	.70302
120	761-29K	23°54.9'	44°02.1'	1,233	.0087	.70306
121	761-30A	24°03.9'	45°04.2'	603	.0314	.70399
	761-30B	24°03.9'	45°04.2'	557	.0457	.70429
	761-30C	24°03.9'	45°04.2'	561	.0441	.70420
	761-30D	24°03.9'	45°04.2'	593	.0387	.70416
122	761-30E	24°02.8'	45°02.4'	463	0.1005	0.70576
	761-30F	24°02.8'	45°02.4'	418	.1139	.70596
	761-30G	24°02.8'	45°02.4'	472	.0760	.70494
123	761-30H	24°00.8'	45°09.3'	442	.0422	.70437
	761-30I	24°00.8'	45°09.3'	439	.0769	.70515
	761-30J	24°00.8'	45°09.3'	393	.0576	.70475
124	761-30K	24°00.6'	45°08.3'	591	.0386	.70438
	761-30L	24°00.6'	45°08.3'	434	.0650	.70486
	761-30M	24°00.6'	45°08.3'	356	.0834	.70531
127	762-1F	21°01.3'	40°03.2'	341	.2834	.70937
	762-1G	21°01.3'	40°03.2'	439	.2266	.70879
	762-1H	21°01.3'	40°03.2'	397	.2158	.70812
128	762-1I	21°02.9'	40°04.9'	244	.4612	.71382
	762-1J	21°02.9'	40°04.9'	386	.2892	.71008
266	794-1R	20°48.9'	41°10.7'	538	.0540	.70457
267	794-1S	20°49.0'	41°08.1'	521	.0613	.70483
	794-1T	20°49.0'	41°08.1'	491	.0874	.70566
	794-1U	20°49.0'	41°08.1'	456	.0975	.70590
268	794-2A	20°53.8'	41°06.7'	618	.0384	.70392
	794-2B	20°53.8'	41°06.7'	576	.0476	.70413
277	72076	22°43.7'	44°27.1'	418	.2798	.71036
277A	72121	22°47.3'	44°31.6'	390	.3483	.71182
278	72215	22°46.4'	44°32.6'	653	.1091	.70623
279	72222	22°44.5'	44°29.6'	296	.5364	.71674
280	72504	22°49.5'	44°27.1'	421	.3057	.71120
281	72510	22°46.9'	44°21.1'	485	.1792	.70797
282	72512	22°47.9'	44°21.8'	473	.2235	.70881
283	72535	22°49.7'	44°24.3'	483	.2615	.70966
285	794-5M	20°54.0'	39°59.8'	376	0.2873	0.70991
	794-5N	20°54.0'	39°59.8'	382	.2753	.70983
	794-5P	20°54.0'	39°59.8'	492	.2065	.70821
	794-5Q	20°54.0'	39°59.8'	507	.2185	.70850

Table 2.--Total-rock Rb-Sr isochron data

[All uncertainties (±) are quoted at one standard deviation. MSWD (mean square of weighted deviates) calculated as SUMS/(N-2) by regression of York (1969)]

Rock unit	Locality number	Figure number	Number of points	Mean Rb/Sr	Apparent age (Ma)	$(^{87}Sr/^{86}Sr)_0$ (r_i)	MSWD
Alse-Hairah pluton	97,97A	5	3	0.397	567±86	0.7031±0.0014	0.01
Tonalite gneiss of Jabal Abu Aris quadrangle	98,99	3	7	.055	774±101	.7025±0.0002	.07
Granite of the Al Bara batholith	102,102A	6	3	.773	571±19	.7036±0.0005	.96
Granodiorite, Afif quadrangle	104	7	3	.305	718±25	.7038±0.0003	.07
Syenogranite of Jabal al Usaybiyat	108-109A	8	5	15.0	602±9	.7061±0.0005	.02
Granite of Jabal Tukhfah	112-114	9	3	5.30	563±71	.703±0.008	3.32
Granite of Jabal Jabalah	115-117	10	7	9.67	575±7	.7044±0.0011	.38
Northern pluton of Nebert (1970)	121,122	11	7	.064	604±61	.7032±0.0002	.18
Al Mizil pluton of Nebert (1970)	123,124	13	6	.061	509±157	.7035±0.0004	.03
Granite gneiss of Bir ad Damm	127,128,285	14	9	.274	542±23	.7035±0.0003	2.42
Tonalite of Wadi Dhurah	266-268	15	6	.064	838±93	.7026±0.0003	.20
Granitic rocks of Uyaijah	277-283	16	8	.280	595±15	.7034±0.0002	.57

Areas north of Harrat Kishb

Diorite and tonalite units

Tectonically foliated diorite and tonalite bodies are exposed in low hills and in patches in a nearly flat, broad plain covered by a thin veneer of altered bedrock and sand north of the basalt field of Harrat Kishb, west of Ad Dafinah. A major trace of the Najd fault system (Brown and Jackson, 1960; Brown, 1970, 1972; Delfour, 1970, 1979; Greenwood and others, 1980) projected into this area complicates correlation in a northeast-southwest direction. Tonalite gneiss in the northern part of the Jabal Abu Aris 30-minute quadrangle (sheet 23/41 C) and the area to the north (loc. 98, 99) yields a coherent group of data (fig. 3), which indicates an age of 774±101 Ma and r_i of 0.7025±0.0002. Analyses of diorite bodies to the west (loc. 100, 100A) and to the north (loc. 101) of the tonalite show significantly larger amounts of scatter (fig. 4) and do not yield reliable age information. Localities 100 and 100A lie between two younger plutons, and rocks from these localities may not represent closed systems. Both groups of diorite samples yield low $^{87}Sr/^{86}Sr$ ratios, however, which are consistent with an r_i less than 0.703.

Granitic units

Two late-orogenic or postorogenic granitic bodies in the northern part of the Jabal Abu Aris quadrangle were sampled in this study. The larger of these, the Alse-Hairah pluton (loc. 97, 97A), is an oval body of coarsely porphyritic, rapakivi granite that intrudes the hornblende diorite described above (loc. 100, 100A). When plotted on an isochron diagram (fig. 5), the results of analyses of the samples define a line with low dispersion corresponding to an age of 567±86 Ma, an r_i of 0.7031±0.0014, and an MSWD of 0.01. The large uncertainty in r_i is due to the relatively small spread in Rb/Sr ratio of the data as compared to their distance from the intercept (Rb/Sr = 0). Because the body appears to be truncated at both its northeastern and southwestern margins by faults of the Najd system, at least some displacement along that system occurred subsequent to pluton emplacement.

The second granitic body sampled (loc. 96) is a small, elongate body of red-weathering, low-strontium, fluorite-bearing granite, similar to so-called "red granites" in the Bishah area (Schmidt,1980). The two samples of this unit are not sufficient to define an isochron but have such large Rb/Sr ratios that assumption of any reasonable r_i will produce the same age within analytical uncertainties. Fleck and others (1980) reported a mean r_i for late-orogenic or

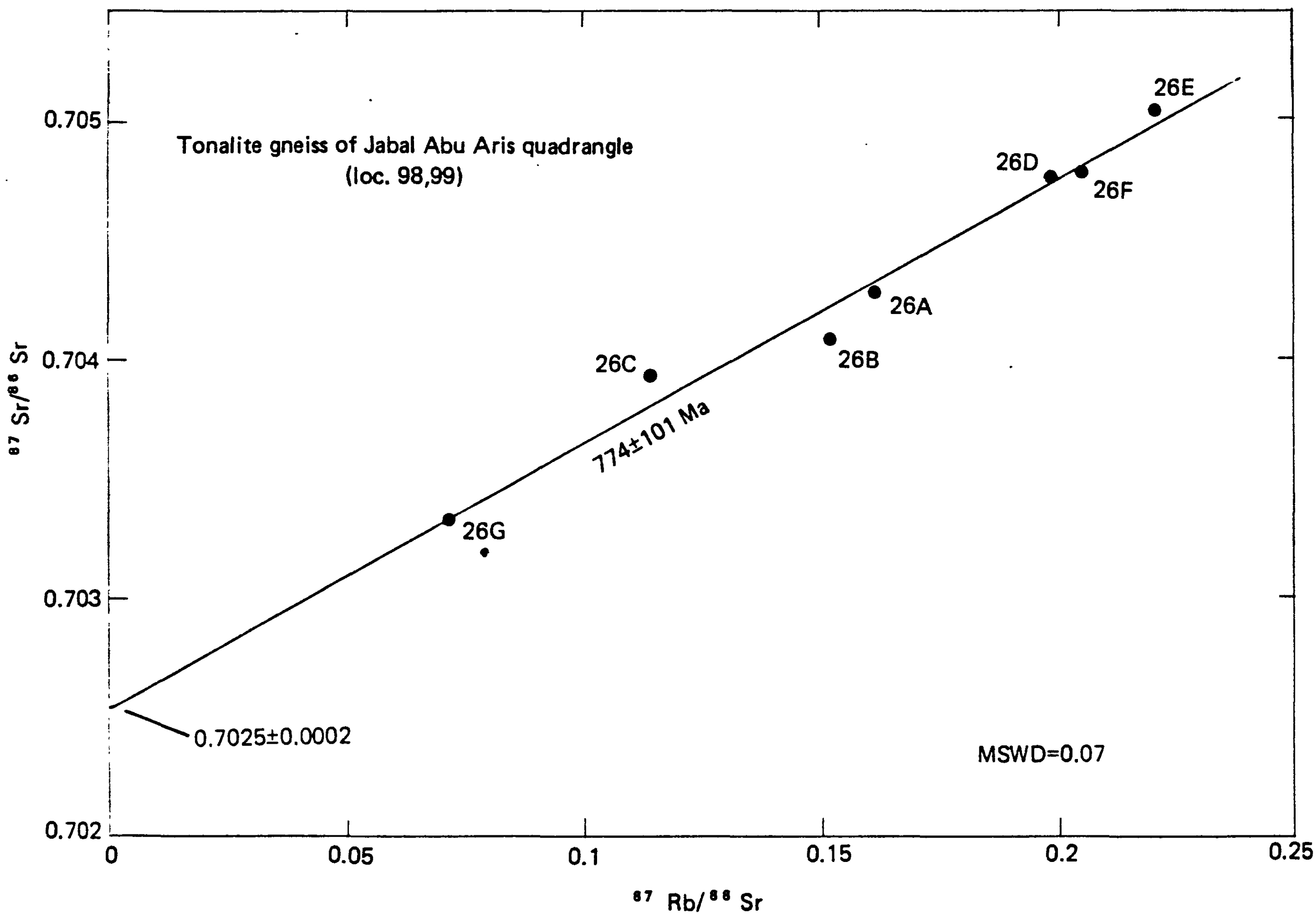

Figure 3.--Total-rock rubidium-strontium isochron diagram of tonalite gneiss of the Jabal Abu Aris quadrangle (sheet 23/41 C). Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

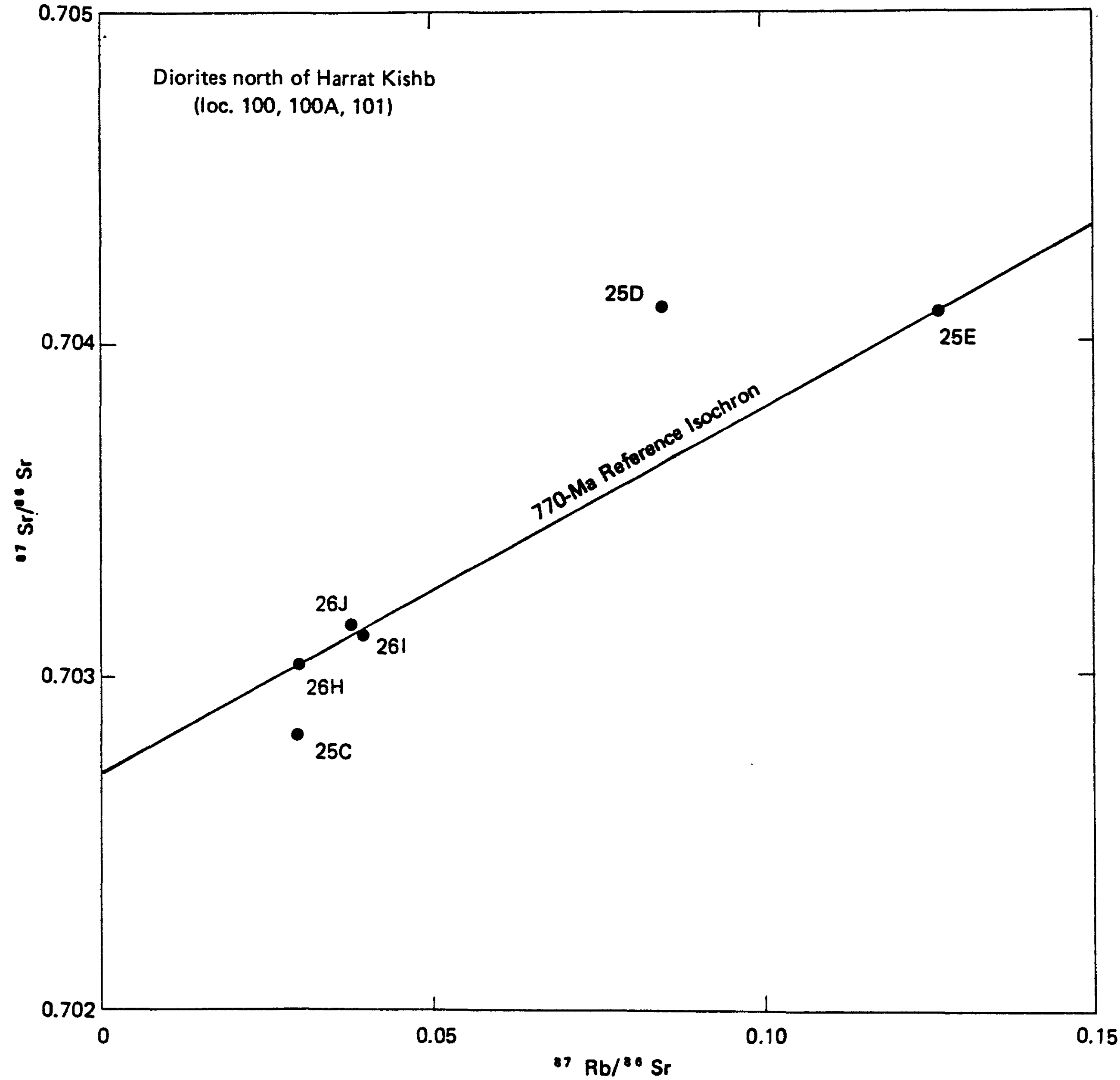

Figure 4.--Total-rock rubidium-strontium isochron diagram of diorites north of Harrat Kishb. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

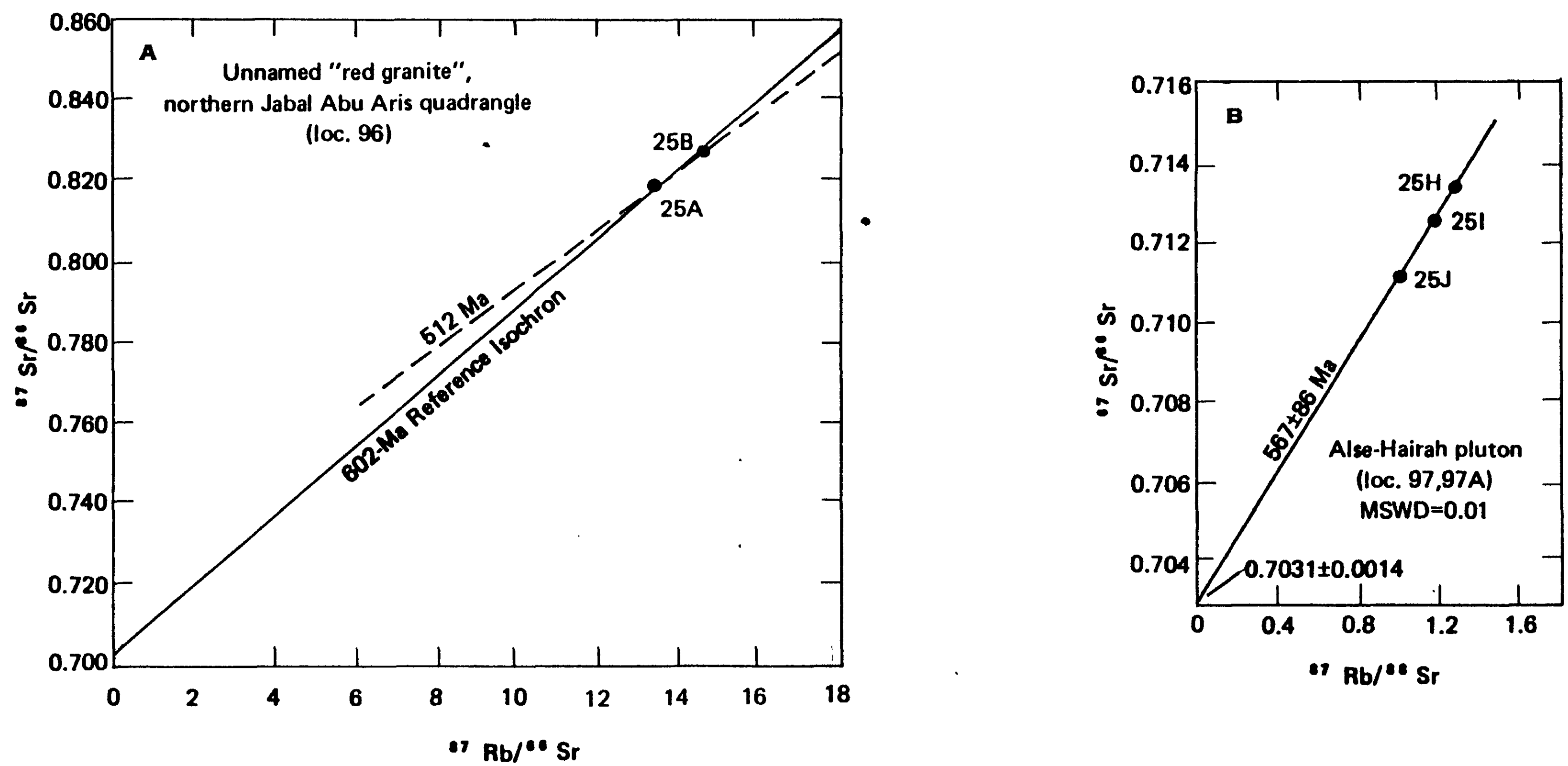

Figure 5.--Total-rock rubidium-strontium isochron diagram of unnamed (A) "red granite" and (B) Alse-Hairah pluton, northern Jabal Abu Aris quadrangle. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

postorogenic granitic plutons of 0.7032. The r_i of 0.7031±0.0014 obtained for the nearby Alse-Hairah pluton is probably a reasonable value for late-orogenic bodies of the Jabal Abu Aris area as well. This r_i yields apparent ages for the two samples of 602 and 594 Ma or a mean of 598 Ma.

Numan quadrangle

Granite of the Al Bara batholith

Samples of myrmekitic, muscovite-bearing, biotite granite were collected from low hills south of Bir Qamah in the northwestern part of the Al Bara batholith of Letalenet (1979) (loc. 102, 102A; Numan quadrangle, sheet 23/42 D; east-northeast of Ad Dafinah). Textural and mineralogic considerations suggest that the unit sampled may be a shallowly emplaced, posttectonic intrusion rather than a body of batholithic proportions, but exposures in the flat, grus-covered plain are limited and no mapping was done in this study. Results of analyses (fig. 6) indicate an age of 571±19 Ma and r_i of 0.7036±0.0005. This age is consistent with those of other late-orogenic and postorogenic granite plutons in this part of the Arabian Shield.

Afif area

As shown by Letalenet (1979), the area south of Afif includes a wide variety of rock types and geologic units as well as structural complexities imposed by intersection of faults of the Najd system and older orogenic trends. Samples of plutonic units range from hornblende diorite and quartz norite to alkali granite and document an extended magmatic history.

Quartz norite

Samples collected from locality 103 (fig. 2, table 1) northwest of Jabal Humaymat al Khafqan are from an area mapped as "d2" diorite by Letalenet (1979). Petrographic examination reveals a quartz norite mineralogy, including hypersthene, clinopyroxene, biotite, andesine, and quartz as the major phases. Samples collected about 2 km north-northwest (loc. 104, fig. 2) of locality 103 are also in the area of "d2" but are hornblende-biotite granodiorite, as discussed below. This diversity suggests that the "d2" unit is a complex intrusive terrane rather than a single diorite unit. The quartz norite may be related to the Jabal Humaymat al Khafqan gabbro (Letalenet, 1979), which intrudes units assigned to the An Nayzah formation. Rb/Sr ratios of the quartz norite samples are nearly identical at 0.078, and $^{87}Sr/^{86}Sr$ values are about 0.707 (table 1). Mineralogically, the rock is best described as a hybrid, a description that also applies to the isotopic results. Assumption of an

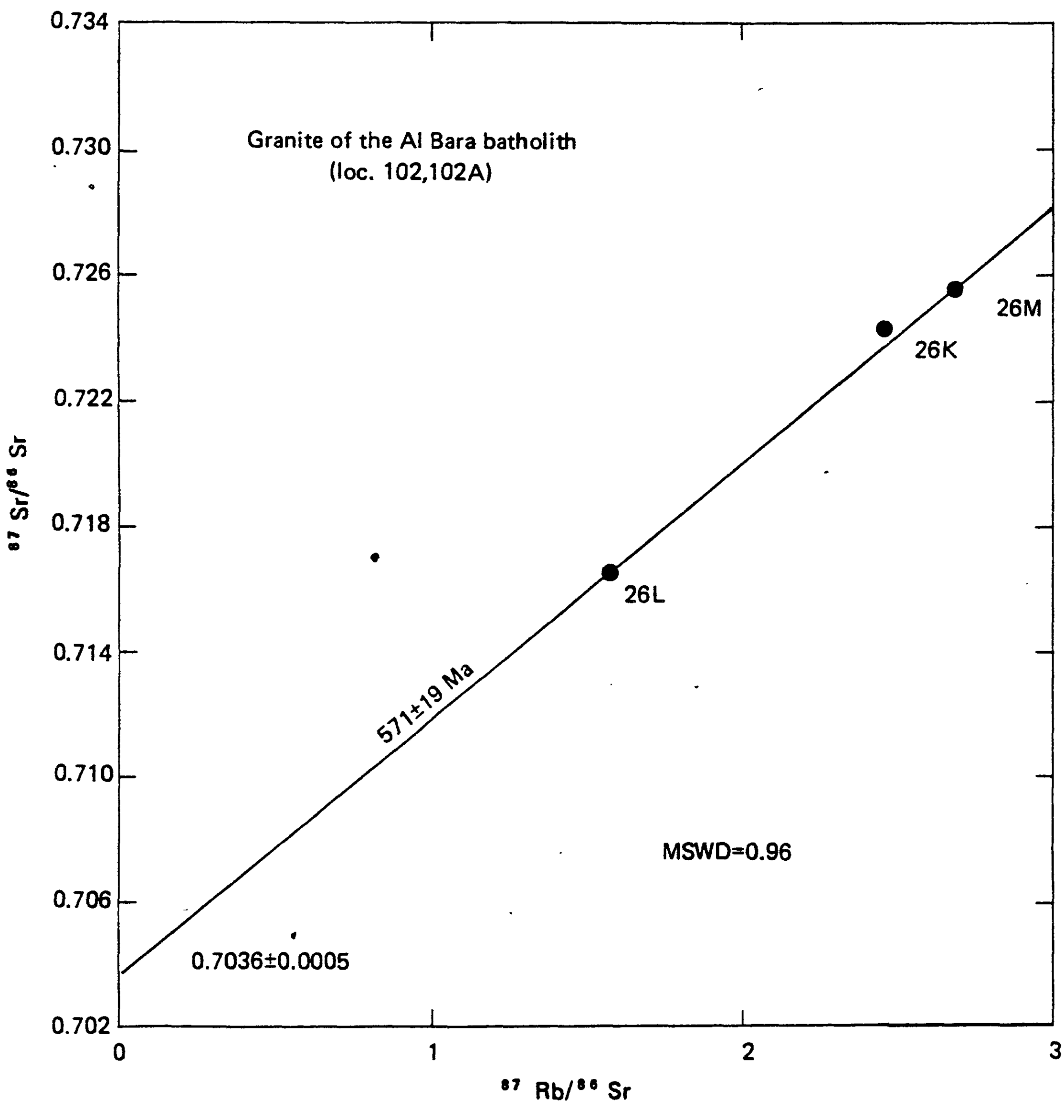

Figure 6.--Total-rock rubidium-strontium isochron diagram of granite of the Al Bara batholith (Letalenet, 1979). Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

r_i of less than 0.703 would indicate an age in excess of 1,200 Ma. Such an age is not inconceivable but would require significantly more documentation. Assimilation of granitic material, such as that at locality 104, by magma that formed the Jabal Humaymat al Khafqan gabbro immediately to the south is favored here because of the hybrid mineralogy. Because of low r_i values for other intrusive units in the Afif area, an uncontaminated noritic magma having an r_i of 0.705 or greater at about 700-600 Ma ago is considered a less probable explanation. Data for the quartz norite samples are shown in figure 7 for comparison with other units of the Afif area.

Granodiorite south of Afif

Gneissic hornblende-biotite granodiorite was sampled at three localities south of Afif (loc. 104-106). All are within complex terranes mapped as diorite but are within several kilometers of an elongate granodiorite gneiss within or defining the eastern edge of the An Nayzah Belt of Letalenet (1979). Granodiorite northwest of Jabal Humaymat al Khafqan (loc. 104), discussed with quartz norite above , is strongly foliated but in places contains abundant xenoliths that clearly document the rock's magmatic origin and proximity to its intrusive contact. Rb-Sr results (fig. 7) indicate an age of 718 ± 25 Ma and r_i of 0.7038 ± 0.0003.

A granodiorite mineralogically similar to that at locality 104 was sampled to the northeast (loc. 105) in an area shown as "d3" diorite by Letalenet (1979). The two samples from this locality yield Rb-Sr data that are not colinear with the first group (fig. 7), but the slope of the line connecting the two data points yields an apparent age of 728 Ma, similar to that of locality 104. The r_i obtained for the two points (0.7028) would be significantly below that of the previous locality but consistent with the range reported by Fleck and others (1980) for rocks of this age.

The third locality of granodiorite samples south of Afif (loc. 106) is about 0.5 km west of a small, red-weathering granite that intrudes the granodiorite, and data from the samples may reflect the younger event. The granodiorite is somewhat different from those described above in that much of the hornblende has clinopyroxene cores. Data from these samples (fig. 7, table 1) are not internally consistent, yielding an MSWD of 3.0 and an apparent age of about 560 Ma. Whether this apparent age is related to resetting of total-rock strontium systems at that time or is simply the statistical result of open-system behavior of one or more of the samples at some undetermined time cannot be ascertained from available information. No temporal significance is attached here to the results from this locality.

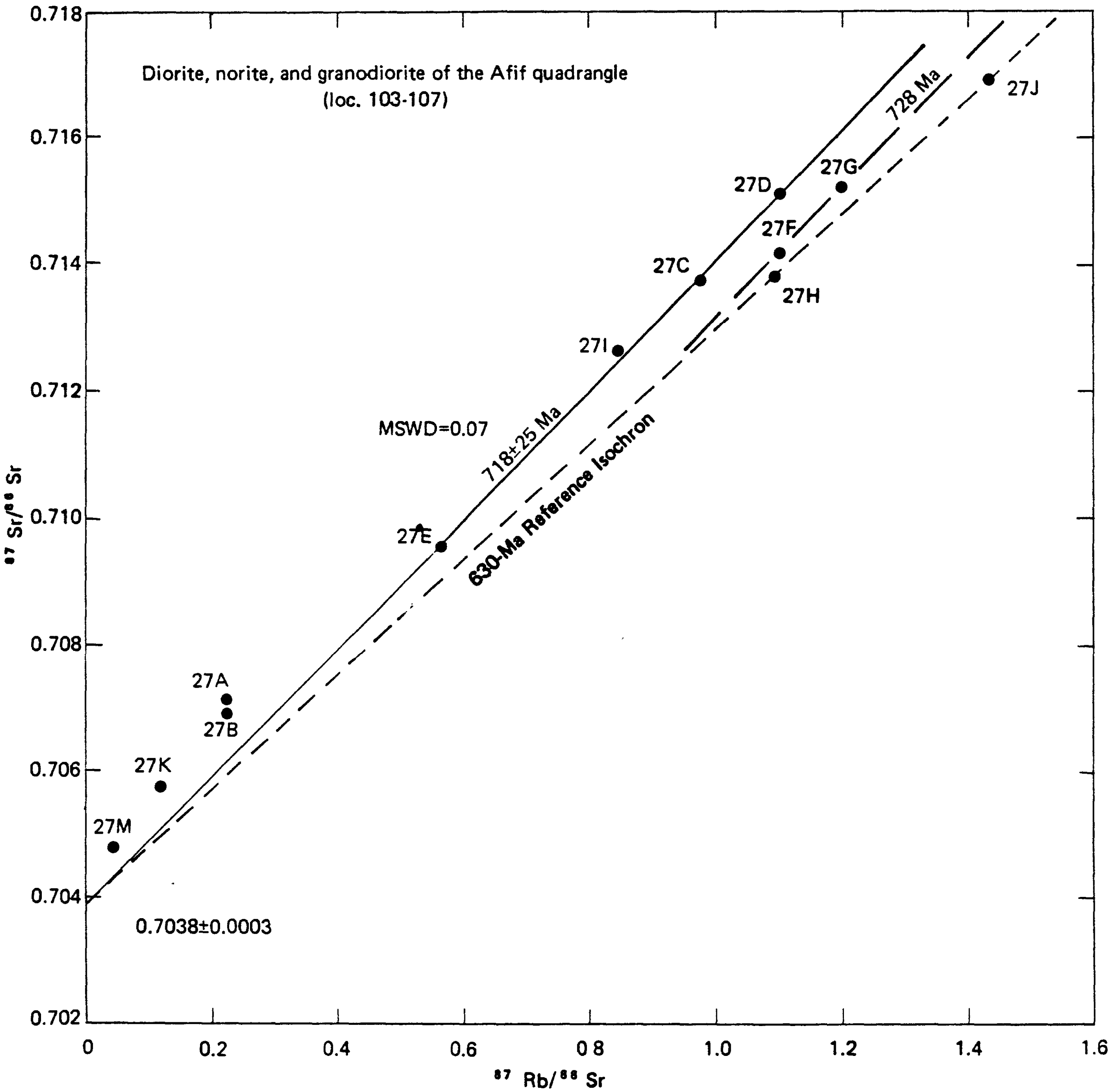

Figure 7.--Total-rock rubidium-strontium isochron diagram of diorite, norite, and granodiorite of the Afif area. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table. Sample locations are shown on figure 2.

Hornblende quartz diorite south of Afif

Samples of quartz-bearing hornblende diorite and hornblende quartz diorite containing abundant sphene were collected south of Afif (loc. 107) from the same "d3" unit of Letalenet (1979) as the granodiorite samples from localities 105 and 106. Amphiboles in these samples show evidence of chloritization and the possibility of late-magmatic iron enrichment of the magma. Rb/Sr ratios of these rocks are very low and have inadequate range to yield age information of even moderate reliability (fig. 7). The fact that measured $^{87}Sr/^{86}Sr$ ratios are somewhat higher than expected for rocks 650-800 Ma old associated with the granodiorites discussed suggests a possible exchange of strontium during a postconsolidation event (chloritization?) or a contribution of more radiogenic strontium to the magma. The latter alternative would indicate either a sedimentary component in the source materials or an older or more sialic source terrane.

Syenogranite of Jabal al Usaybiyat

Biotite-bearing perthitic syenogranite containing minor amounts of amphibole and epidote forms composite ring structures west of Afif at Jabal al Usaybiyat and areas to the north (loc. 108-109A). Strontium concentrations are low, ranging from 7 to 170 ppm (mean, 45 ppm), and result in very high total-rock Rb/Sr ratios (table 1). Results of analyses define an excellent isochron (fig. 8) and indicate an age of 602 ± 9 Ma, r_i of 0 061 ± 0.0005, and MSWD of 0.02. The r_i obtained for this unit is the only such value found to be statistically greater than 0.7045, and it affirms the observation of a modest elevation of initial ratios in the Afif area.

Granodiorite northwest of Afif

Hornblende-biotite granodiorite northwest of Afif was sampled at locality 110 (table 1). Rb-Sr ratios of the two samples collected are nearly identical, whereas $^{87}Sr/^{86}Sr$ values differ by more than 0.001. The samples, which were collected from grus-covered outcrops, may have had disturbed strontium-isotopic systems because the isotopic ratios differ at the 99-percent level of confidence. The rock type is similar to those at localities 104 and 105 south of Afif and quite different from the syenogranite at Jabal al Usaybiyat (loc. 108-109A). If an age similar to those for the granodiorites to the south (about 720 Ma) is assumed, the mean of the two samples would indicate an r_i of about 0.7038, almost exactly that of locality 104. Stated differently, the mean of Rb-Sr data from granodiorite northwest of Afif falls very close to the isochron obtained for locality 104, and results are consistent with the interpretation of an age of about 720 Ma for locality 110. It should be noted, however, that an r_i of 0.7038 is significantly greater than

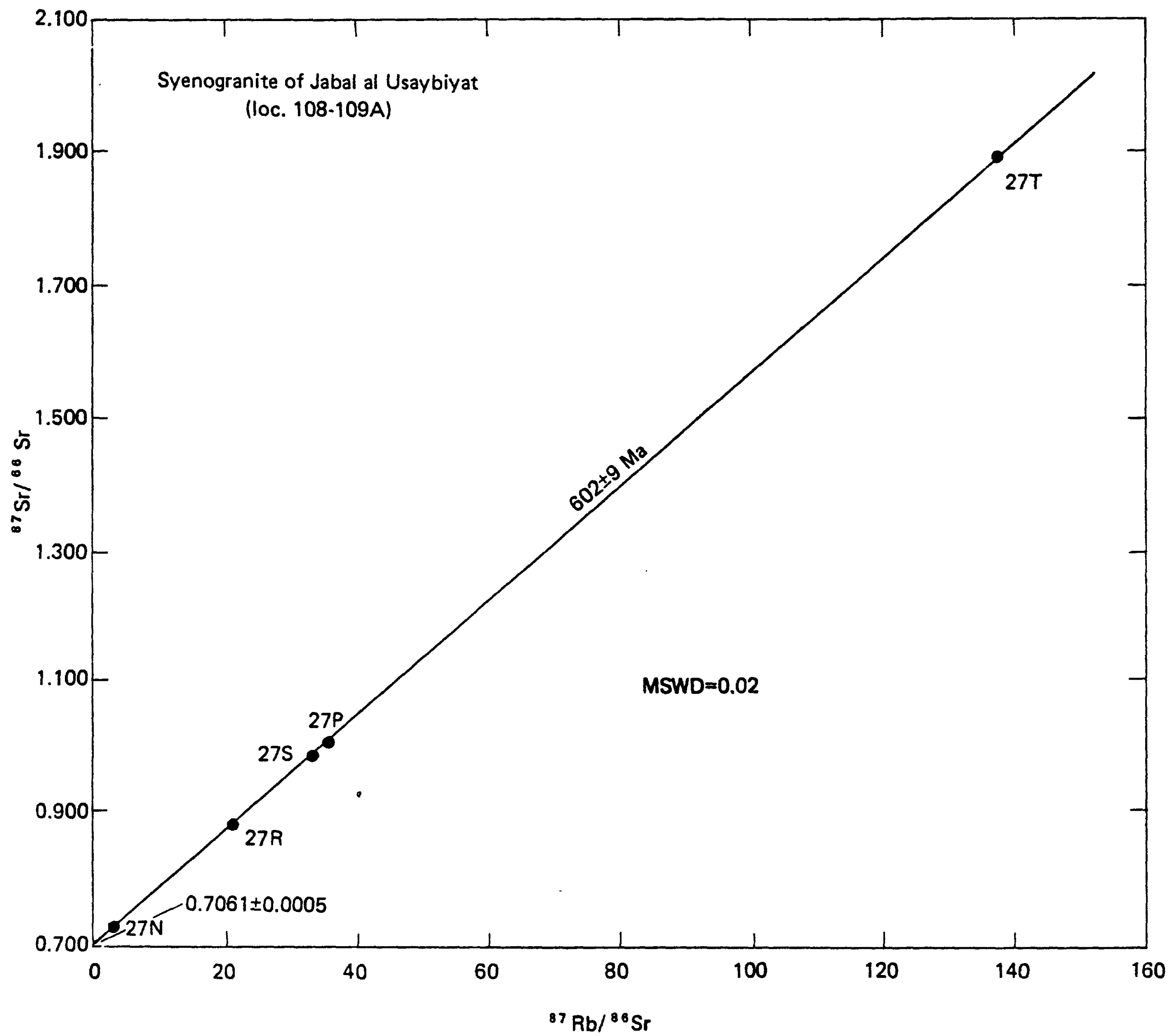

Figure 8.--Total-rock rubidium-strontium isochron diagram of syenogranite of Jabal al Usaybiyat. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

r_i values obtained from similar units of similar age in the southern part of the Shield (Fleck and others, 1980) and may indicate substantial differences in the crustal types or histories of the two regions.

Areas northwest of Ad Dawadimi

Samples collected in the areas northwest of Ad Dawadimi include amphibolite, gabbro, diorite, and granite. Amphibole-rich rocks, collected from a terrane of gabbro, norite, hornblende diorite, and mafic volcanic rocks in the area around and north of Umm Adhir (loc. 111), contain abundant strontium, but rubidium contents are less than 6 ppm. These amphibolites are medium grained and were considered to be hornblende diorite in field identification. Rb-Sr data are presented (table 1) for these rocks, but because of their uncertain origin, the term "amphibolite" is used in a purely descriptive sense. Considered with the low Rb/Sr ratios, measured for $^{87}Sr/^{86}Sr$ indicate an absence of ancient crust in the source materials for these rocks. Although small, a statistically significant difference can be observed between r_i values in the Ad Dawadimi area and the areas south and west of Afif.

Granite of Jabal Tukhfah

Low-strontium, high Rb-Sr granites, intruding most of the other shield-forming units, are the youngest plutons in the Ad Dawadimi region. The granite of Jabal Tukhfah, west of Al Qurayyah, may even postdate major movement on a main segment of the Najd fault system. Samples of this granite (loc. 112-114) contain biotite and ferrohastingsite as well as abundant zircon, and they have low strontium contents (between 26 and 35 ppm) and high Rb/Sr ratios. The poor index of fit (MSWD = 3.32), yielded by regression of the three data points (fig. 9), suggests the possibility of at least minor postconsolidation disturbance of strontium-isotopic systems. However, the age indicated by the regression line (563$\pm$71 Ma) is probably more representative of the true age than might be inferred from the uncertainties and MSWD because the high Rb/Sr ratios and small variation in r_i for rocks of the Shield place further constraints on the data. If values of 0.702 and 0.707 are assumed to be the minimum and maximum limits of r_i reasonable for rocks of the Shield, then the respective maximum and minimum ages for the measured samples would be 588 and 509 Ma at the 95-percent level of confidence (so-called "limiting isochrons").

Granite of Jabal Jabalah

Seven samples of the biotite granite of Jabal Jabalah collected in three different areas (loc. 115-117) had a wide range in Rb/Sr ratios. The samples with lower Rb/Sr ratios contain more epidote-group minerals, but all samples contain

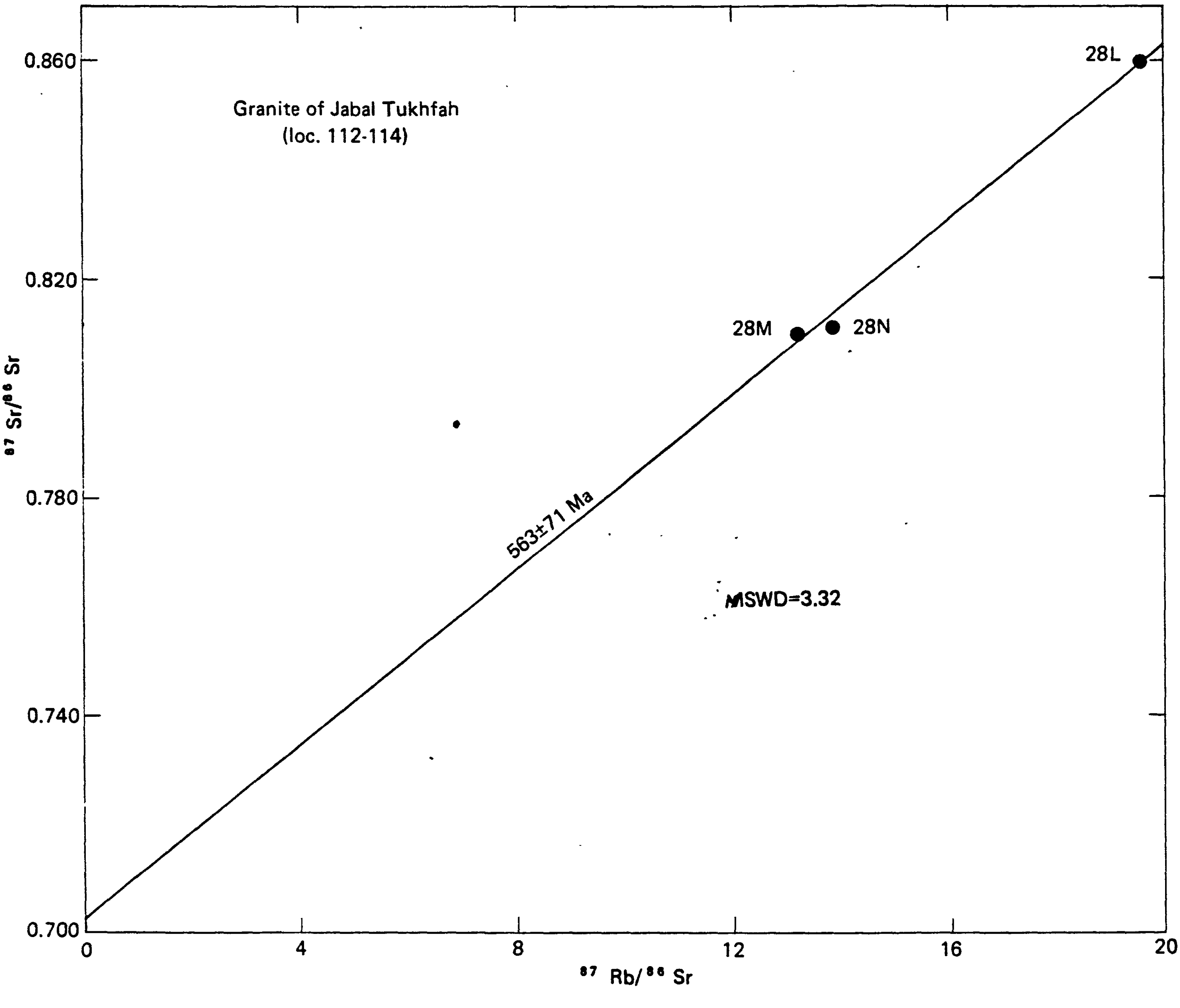

Figure 9.--Total-rock rubidium-strontium isochron diagram of granite of Jabal Tukhfah. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

biotite, potassium feldspar, plagioclase, and quartz. Rb/Sr ratios are controlled primarily by strontium content, which ranges from less than 10 to more than 70 ppm, whereas rubidium content, ranging from about 180 to 240 ppm, is more uniform within the pluton. No amphiboles were detected in thin section, whereas iron-rich hornblende was more abundant than biotite in the granite of Jabal Tukhfah.

Isochron results on the granite of Jabal Jabalah indicate an age of 575$\pm$7 Ma, an r_i of 0.7044$\pm$0.0011, and a MSWD of 0.38 (fig. 10, table 2). The age is extremely well constrained by the data, which exhibit a high degree of linearity. Because the lowest Rb/Sr ratio in the data set is greater than 2.7, the r_i is not well constrained and a large uncertainty is indicated. On that basis no significance may be assigned the small apparent elevation of the r_i above values obtained to the south and west, but conversely an r_i of 0.706 cannot be ruled out.

Plutonic rocks of the Marjan area

Quartz diorite and two-mica granite units studied by Nebert (1970) east of the Al Amar-Idsas fault were collected from an area east of Marjan (fig. 1). Both of the units mapped by Nebert, the Northern pluton and the Al Mizil pluton, were considered to be postorogenic. Both intrude metavolcanic and metasedimentary units assigned to the Halaban formation.

Northern pluton

The Northern pluton is a nearly circular intrusion of tonalite to quartz diorite composition. It has a diameter of 12-13 km and is located about 15 km east of Marjan. As mapped by Nebert (1970), the southern margin of the pluton truncates folded units of the Halaban formation, but strata of the same units conform to the northern margin of the pluton. The pluton was sampled at two localities (loc. 121, 122), both of which expose hornblende-biotite quartz diorite or tonalite, although neither locality is within the mapped "border zone" of "basified" granitic rock (Nebert, 1970). Mafic xenoliths are abundant at locality 121, and clinopyroxene cores in both hornblende and biotite are noted in the samples from both localities. Although these pyroxenes could be related to assimilated mafic volcanic rock, strongly zoned plagioclase from both sites mitigates against "basification." The centers of single plagioclase grains are andesine-labradorite, and the margins are oligoclase. This strong normal zoning suggests a normal mafic-to-felsic differentiation trend. It could be argued that assimilation occurred prior to plagioclase crystallization, but total-rock Rb/Sr ratios as low as 0.03 (table 1) are as low or lower than those of much of the volcanic material intruded. It is

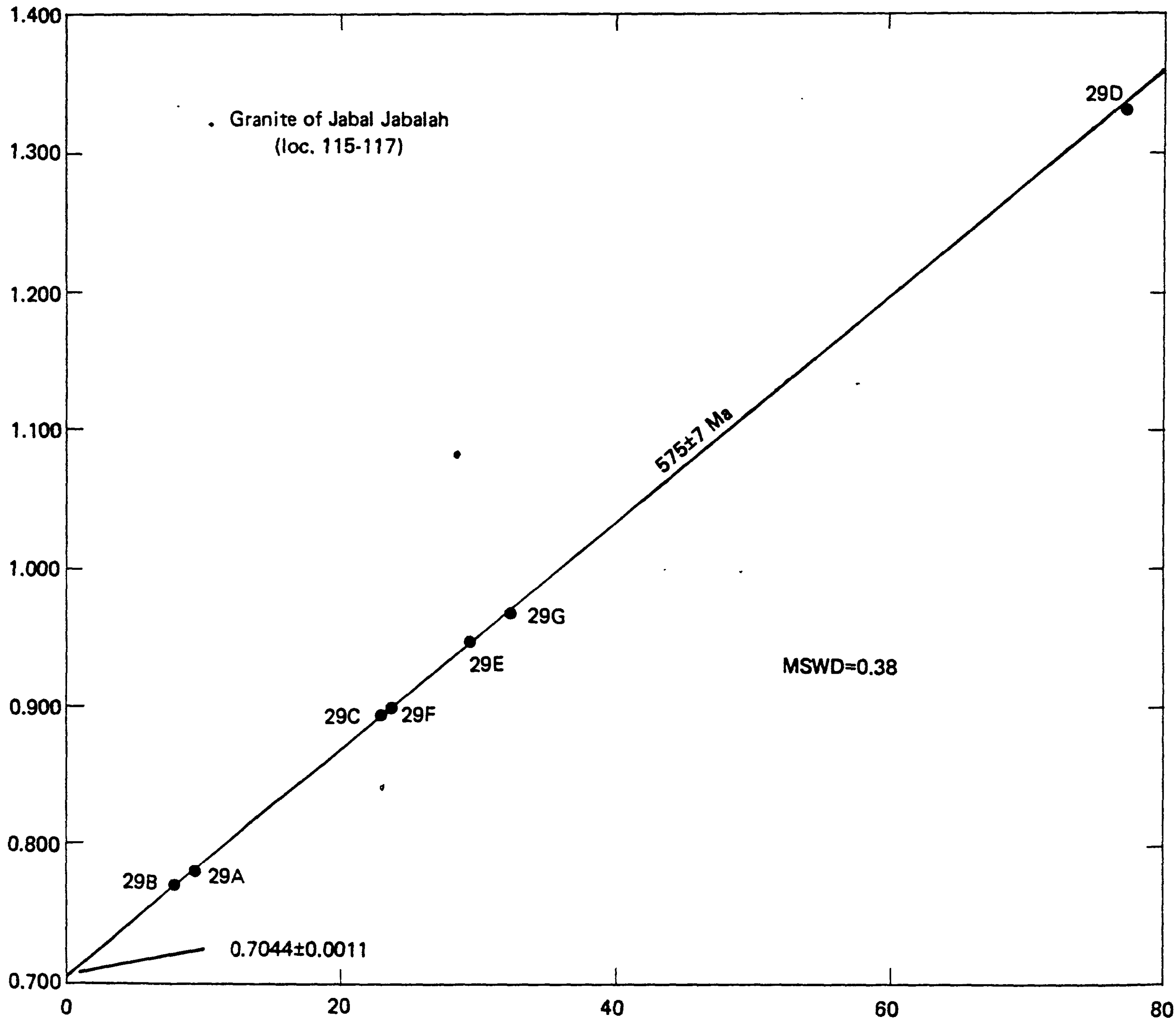

Figure 10.--Total-rock rubidium-strontium isochron diagram of granite of Jabal Jabalah. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown in figure 2.

suggested here that the circular structure exposes an older quartz diorite and tonalite mass but was formed by emplacement of a posttectonic, red-weathering granitic unit. A separate phase of this type was observed in the field and is also reported by Nebert (1970, p. 162). Similar units are described by Greenwood (1979) in the Khadra quadrangle (sheet 19/42 D) and by Anderson (1978) for the Hadadah pluton in the Mayza quadrangle (sheet 17/43 B).

Results of the Rb-Sr studies of the Northern pluton of Nebert (1970) fall into different groups by locality (fig. 11). Neither locality exhibits sufficient range in Rb/Sr ratio to yield a reliable age, and minor local disturbance of strontium-isotopic systems may be indicated. Treated as a single unit, the samples from both localities define an isochron with an age of 604±61 Ma, r_i of 0.7032±0.0002, and MSWD of 0.18.

Because this apparent age for a diorite unit appeared young, both K-Ar and $^{40}Ar/^{39}Ar$ analyses were performed on sample 761-30D from locality 121. Results of conventional K-Ar studies of biotite and hornblende (table 3) are consistent with the Rb-Sr isochron age, but data obtained on hornblende indicate significant sample inhomogeneity, probably due to fine intergrowths of biotite with the hornblende. Duplicate potassium analyses, differing by almost 9 percent, exhibit significant variations between separates. For that reason, $^{40}Ar/^{39}Ar$ total-gas and incremental-heating experiments (table 3) were performed on the hornblende to eliminate sample splitting as a source of the variation and to evaluate the distribution of argon relative to potassium as an indication of argon loss or gain. The total-gas $^{40}Ar/^{39}Ar$ age of 608±5 Ma (table 3) is close to the average of the conventional determination on hornblende and only slightly higher than the biotite ages. Mathematically combining all increments from each of the incremental-heating experiments (table 3) yields a total-gas age of 596 Ma. This value is in general agreement with the ages discussed, but variations of 5 percent in mass spectrometer sensitivity are not uncommon and uncertainties in "recombined" total-gas ages must be at least that large.

The age spectra obtained in the $^{40}Ar/^{39}Ar$ incremental-heating experiments demonstrate argon loss from the hornblende. Both spectra (figs. 12B, D) yield age plateaus that represent more than 50 percent of all the ^{39}Ar released, 93 percent for irradiation LI and 66 percent for irradiation LIV. The exceptionally good agreement between the $^{40}Ar/^{39}Ar$ isochron ages determined using plateau steps (table 3) and the plateau ages of the two experiments indicates an age of 609±5 Ma. Because the rock has retained most of its original igneous characteristics, such as zoning of plagioclase, subhedral crystal habit, and absence of obvious

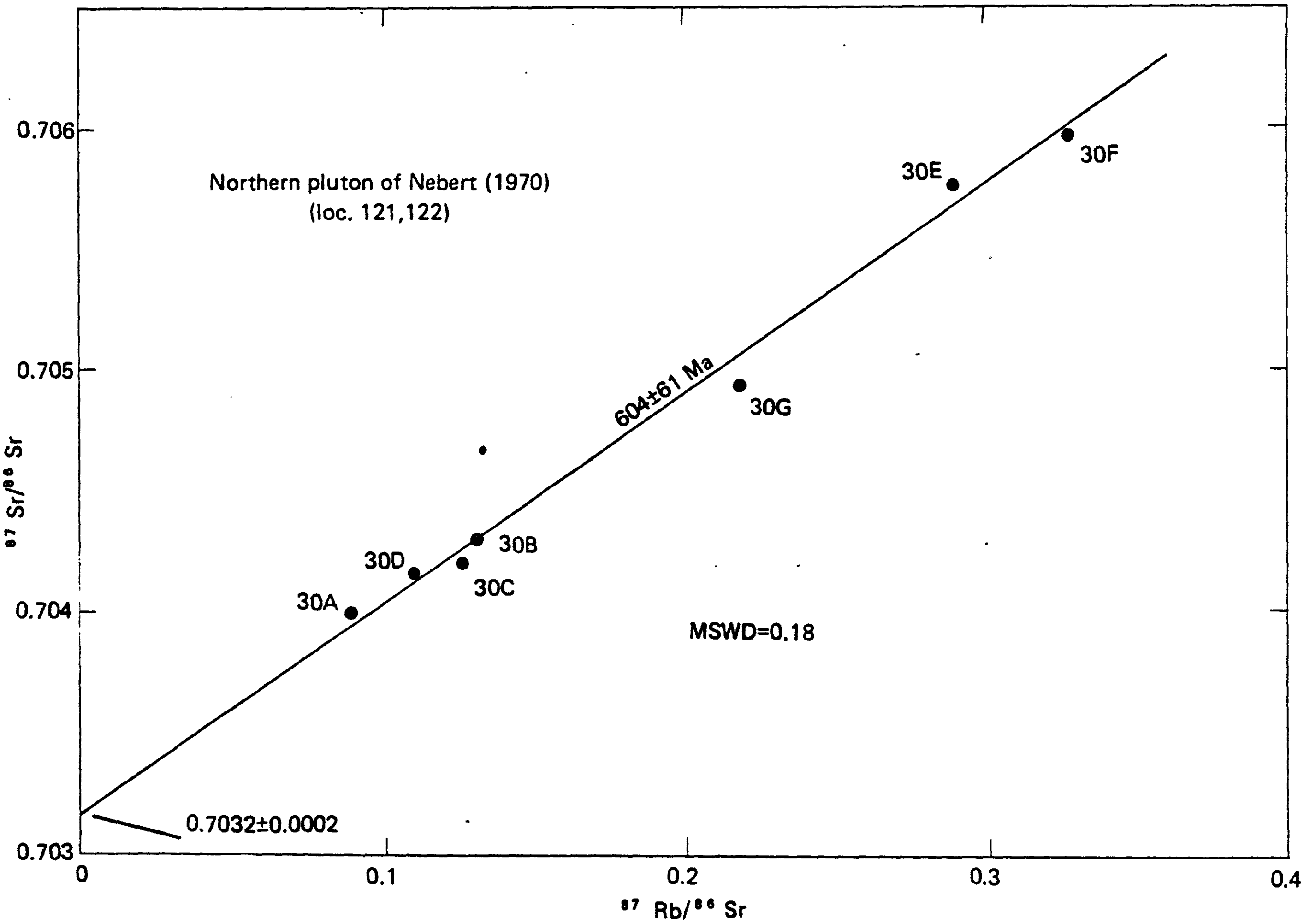

Figure 11.--Total-rock rubidium-strontium isochron diagram of Northern pluton of Nebert (1970). Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

Table 3--Results of K-Ar and $^{40}Ar/^{39}Ar$ analyses, sample 761-30D

		Conventional K-Ar		
Mineral	K_2O (percent)	Mol $^{40}Ar^*/g (x10^{-10})$	$^{40}Ar^*$ (percent)	Apparent age (Ma)
Biotite	9.005	92.265	97.4	600±4
		92.376	86.5	601±4
Hornblende	0.311, 0.312	3.198	73.1	601±5
	.344, .336	3.631	84.6	621±5
		3.599	46.8	617±5

	$^{40}Ar/^{39}Ar$ total-gas age J=0.006476		
	$^{40}Ar^*/^{39}Ar_K$	$^{40}Ar^*$ (percent)	
Hornblende	61.109	75.1	608±5

		$^{40}Ar/^{39}Ar$ incremental heating (hornblende)					
Temperature step (°C)	$^{39}Ar_K$ (percent of total)	$^{40}Ar^*$ (percent)	$^{36}Ar_{Ca}$ (percent)	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	
		Irradiation LI: J=0.006206					
750	7.094	62.2	0.53	95.12	2.381	0.1224	565±8
850	9.417	83.0	7.19	76.08	12.44	.0471	600±8
900	11.082	85.2	9.62	74.41	14.60	.0413	603±7
940	24.690	89.5	13.99	71.43	15.20	.0296	607±7
975	10.796	92.0	17.81	70.22	15.18	.0232	613±7
1,000	4.203	82.2	8.18	79.23	15.63	.0520	617±10
1,040	3.306	84.6	9.71	78.36	16.17	.0453	627±9
1,100	6.522	90.6	17.44	71.69	17.65	.275	617±7
Fuse	22.080	90.9	18.00	70.75	17.50	.0265	612±7
		Irradiation LIV: J=0.006476					
750	10.121	46.7	.25	99.88	1.688	.1805	477±7
850	23.160	76.3	5.88	74.44	13.70	.0633	569±5
900	20.720	87.3	11.87	69.99	14.83	.0340	607±6
925	8.092	82.0	8.38	75.33	15.41	.0500	612±8
950	4.898	76.5	6.70	78.99	16.55	.0672	601±11
975	7.190	85.8	12.52	70.96	17.91	.0389	606±8
1,020	15.081	89.5	16.47	68.06	17.52	.0289	606±6
1,060	9.746	91.2	17.94	67.72	16.21	.0246	612±7
1,100	0.784	53.1	2.21	98.81	13.06	.1605	531±67
Fuse	.208	11.6	.19	730.4	15.38	2.189	797±704

	LI	LIV	Mean
Total-gas age	606 Ma	586 Ma	596 Ma
Plateau age	612±8 Ma (850°-fuse)	607±4 Ma (900°-1,060°)	609±4 Ma
$^{40}Ar/^{39}Ar$ isochron age	609±12 Ma (MSWD=2.46)	609±6 Ma (MSWD=0.03)	609±6 Ma
$^{40}Ar/^{36}Ar$ intercept	298±35	289±15	

*Radiogenic.

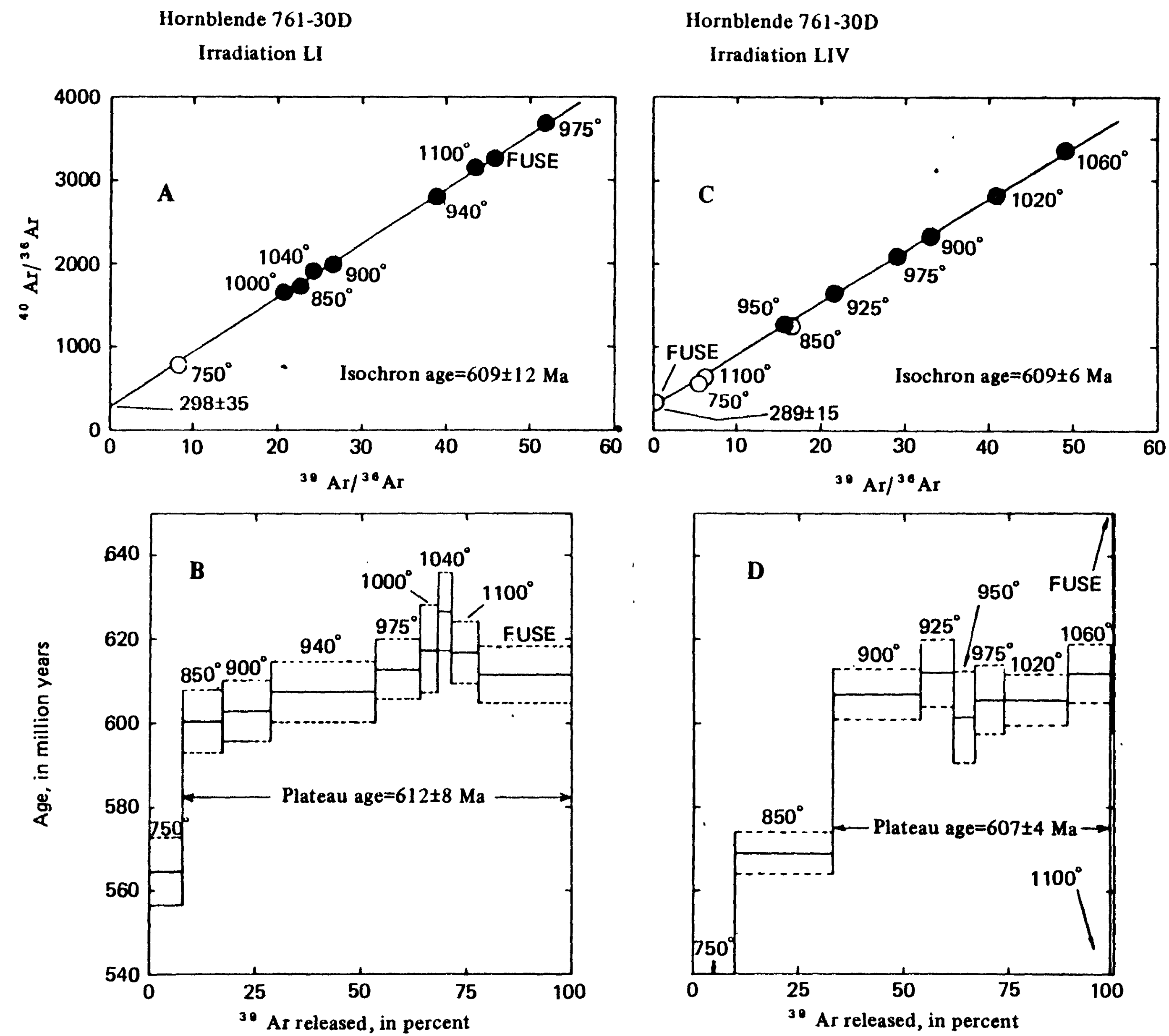

Figure 12.—$^{40}Ar/^{39}Ar$ isochron (A, C) and age-spectrum (B, D) diagrams of hornblende from the Northern pluton of Nebert (1970), locality 121 (table 1). See text for discussion.

recrystallization textures, this age is considered the best estimate of the time at which it first cooled below about 500°C. The agreement between the $^{40}Ar/^{39}Ar$ ages and the Rb-Sr total-rock isochron age suggests that an age of 604±61 Ma probably represents the emplacement of the Northern pluton and that any uncertainty is on the upper side of the age as the body cooled below about 500°C at 609±5 Ma ago. The age spectra are consistent with minor loss of argon at, or subsequent to, about 565 Ma ago. The $^{40}Ar/^{39}Ar$ results indicate that the abnormally large variation in conventional K-Ar ages on the hornblende is the result of sample inhomogeneity in those aliquots.

Al Mizil pluton

The Al Mizil pluton was originally described by Nebert (1970) as having no "basified" border zone as was suggested for the Northern pluton, although the central zone of the pluton is described as being separated from the Halaban wall rocks by a transition zone of migmatites. Two localities were sampled for this study, one in the central part of the body (loc. 123) and the second at the margin (loc. 124). All samples are tonalite to trondhjemite in composition and contain little potassium feldspar. Foliation in the body is well developed, and cataclasis was evident in all samples. The foliation is concordant with that in the surrounding wall rocks, which are schistose and described as metamorphic rocks by Nebert (1970). Garnet was observed in hand specimens of the granite from the central zone, although none was observed in thin section. Muscovite was present in minor amounts in five of the six samples, but hornblende was abundant in the remaining sample, 761-30K, collected very near the margin of the unit. Although described by Nebert as posttectonic, the unit, representing the gneissic core of an antiform, is considered here to be syntectonic. This pluton or gneiss dome is similar in structure and composition to the granodiorite gneiss of Wadi Bagarah (Cooper and others, 1979; Fleck and others, 1980), and an anatectic origin should be considered.

The results of Rb-Sr analyses (fig. 13) are difficult to assess. The data form a linear array with an excellent MSWD of 0.03, but the range in Rb/Sr ratio is limited and leads to a large uncertainty in the apparent age. An age of 509±157 Ma and r_i of 0.7035±0.0004 are calculated by using all samples. If the texturally and mineralogically distinct sample, 761-30K, is omitted, then scatter about the regression line is changed slightly (MSWD = 0.02) and an age of 539±200 Ma is obtained. The r_i for this regression is 0.7034±0.0005. The larger uncertainties calculated for age and r_i for this regression result from the smaller number of samples that more than offsets the effect of reduced scatter. The results do not permit a definitive statement

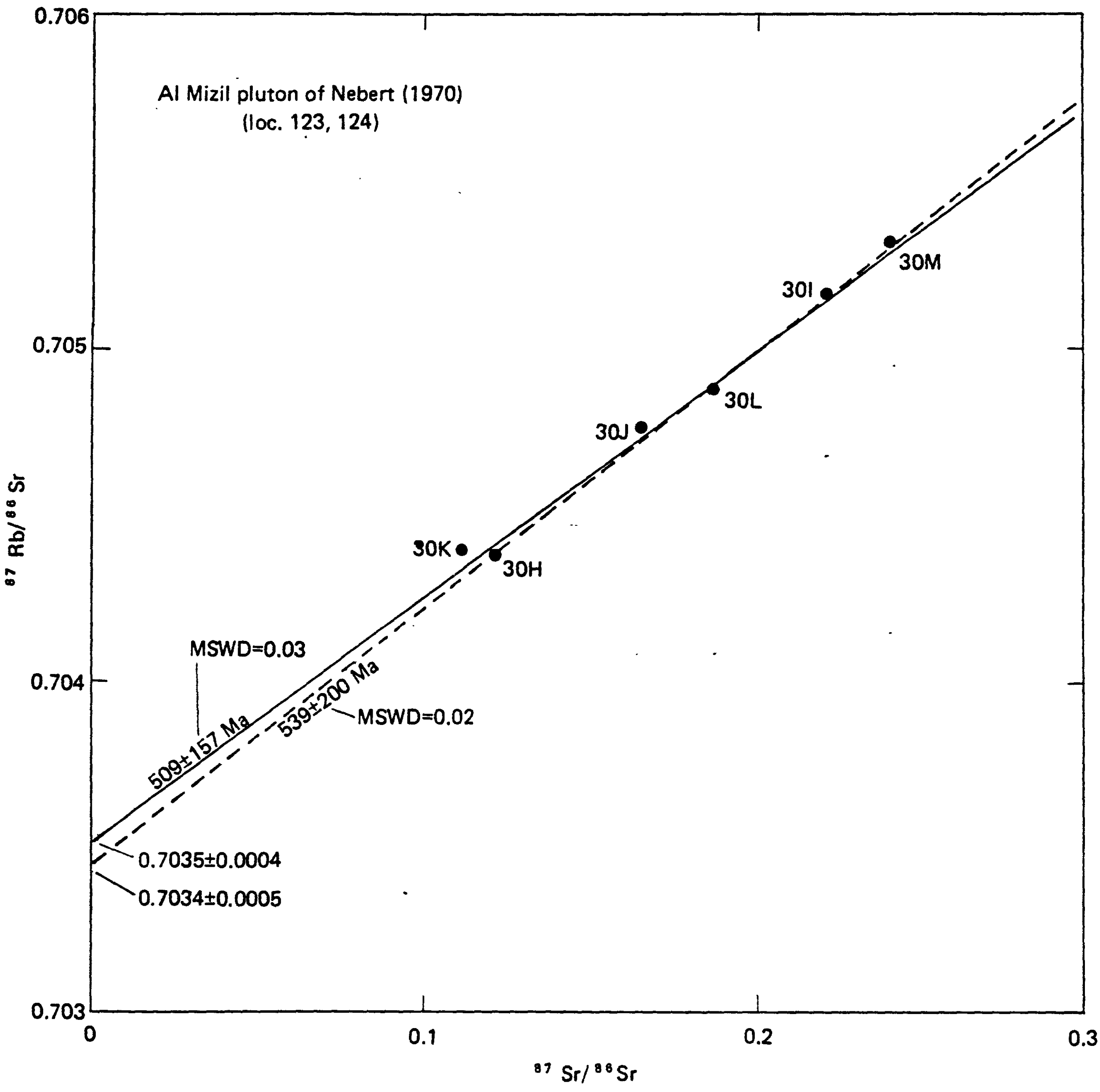

Figure 13.--Total-rock rubidium-strontium isochron diagram of Al Mizil pluton of Nebert (1970). Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

regarding the age of the Al Mizil pluton because, as discussed in the section on analytical techniques, estimates of potential analytical error are large. However, if it is presumed that all such error is reflected in scatter about the regression line, then an uncertainty of 26 Ma would be calculated, whether sample 761-30K is included or excluded . It is suggested that anatexis and emplacement of the Al Mizil pluton may have occurred during the event responsible for minor argon loss in the Northern pluton.

Granite gneiss of Bir ad Damm

Gneissic biotite granite crops out over a broad area southwest of At Taif and north of Wadi Sadiyah and over much of the northwestern part of the Wadi Sadiyah quadrangle (Wier and Hadley, 1975; sheet 20/40 A). The rocks are strongly sheared and granulated and exhibit cataclastic textures. Samples were collected at three localities in the area northeast of Bir ad Damm (loc. 127, 128, 285).

The sample suite exhibits a significant amount of scatter on an isochron diagram (fig. 14). The regression of all data yields an apparent age of 542 ± 23 Ma and an r_i of 0.7035 ± 0.0003 but an elevated MSWD of 2.42. Not only is this age significantly younger than those obtained for most other deformed rocks of this part of the Arabian Shield, but it is also younger than ages of the undeformed rocks. This geologic paradox, and the fact that the MSWD is greater than those of a majority of other units reported here, suggests that significant redistribution of radiogenic strontium may have occurred subsequent to emplacement of the granite. Considering the mean Rb/Sr ratios of the samples and assuming the lowest r_i reasonable for these rock types (about 0.7028), the age of the unit could not be significantly greater than about 620 Ma. Because of the proximity of the localities to a major northeast-trending fault system (Brown and others, 1963), we suggest that deformation of these relatively youthful rocks may be related to that structure. The age of 542 ± 23 Ma may be a reasonable estimate for any strontium redistribution that may have occurred during movement along faults in this system.

Tonalite of Wadi Dhurah

Samples of a unit referred to here as the tonalite of Wadi Dhurah were collected at three localities (loc. 266-268) in the Wadi Shuqub quadrangle (Green and Gonzalez, 1980; sheet 20/41 A), where dioritic units occupy much of the western half of the area. The rocks are hornblende-biotite tonalite and quartz diorite with abundant primary(?) epidote. They display a well-developed foliation at some localities (for example, loc. 268), whereas foliation is vague or unrecognizable elsewhere.

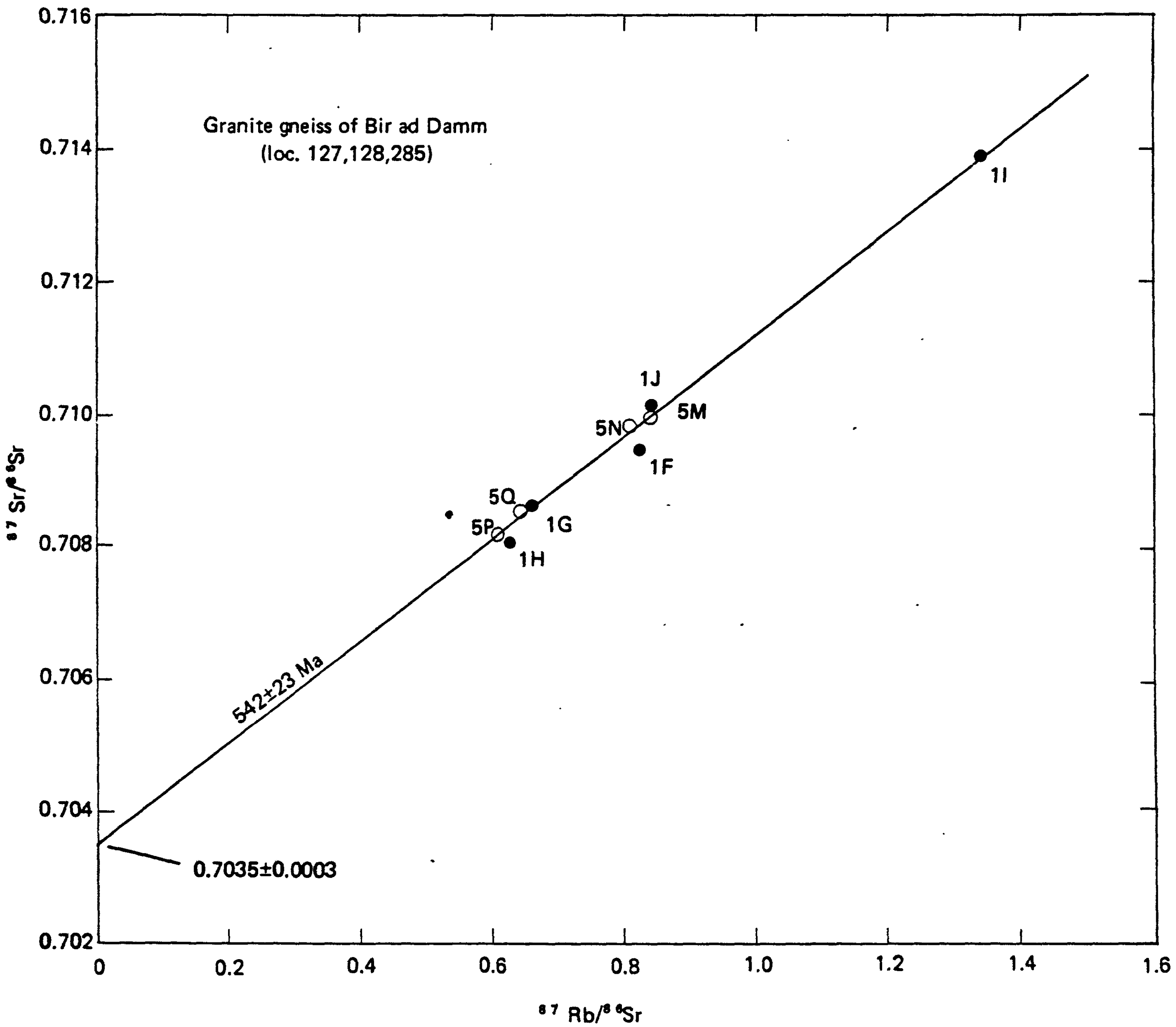

Figure 14.--Total-rock rubidium-strontium isochron diagram of granite gneiss of Bir ad Damm. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

Data obtained from Rb-Sr studies (fig. 15) define an isochron having an apparent age of 838±93 Ma, an r_i of 0.7026±0.0003, and an MSWD of 0.20. The isochron is nearly identical to that obtained for the An Nimas batholith to the south (Fleck and others, 1980), which lies in a structural block east of the Wadi Dhurah body. The rock types, age, and r_i demonstrate that the tonalite of Wadi Dhurah is part of the "older group" (greater than 800 Ma old) of diorite-trondhjemite batholiths of Fleck and others (1980) and demonstrate that this unit probably extends as far north as Wadi Dhurah. Mafic volcanic rocks in the Wadi Bidah area have been assigned to the Baish group (Greenwood and others, 1980) or, less specifically, to the basaltic assemblage of Fleck and others (1980), and the correlation of these volcanic rocks with the oldest volcanic units of the Shield is consistent with the Rb-Sr data for the Wadi Dhurah tonalite. Jackaman (1972) concluded that the volcanic strata of the Wadi Bidah area are chemically and petrologically similar to tholeiitic rocks of modern calc-alkaline island arcs. Reconnaissance Rb-Sr results for these volcanic rocks are consistent with this conclusion and with an age greater than 900 Ma.

Granitic rocks of Uyaijah

Granitic units belonging to a series of coalescing ring structures in the area of Uyaijah south of Halaban were mapped and sampled by Dodge (1979). Four samples from each of the two main units, the granodiorite of Al Areyef and the granite of Jabal Thaaban, were analyzed as part of our study.

Rb-Sr results for the two granitic units are so nearly coincident that only a composite isochron is displayed in figure 16. Regression of the granodiorite data yields an age of 595±16 Ma, an r_i of 0.7035±0.0002, and an MSWD of 0.03. Data from samples of the granite of Jabal Thaaban define an isochron having an apparent age of 584±61 Ma, r_i of 0.7034±0.0008, and MSWD of 0.51. Although the measured ages appear to be consistent with observed contact relationships, the age difference cannot be considered significant because of the uncertainties. The conclusion of Dodge (1979) that the granite of Jabal Thaaban evolved by continuous differentiation of the original granodiorite magma (granodiorite of Al Areyef) is entirely consistent with the Rb-Sr results. If the two units are treated as a cogenetic suite, an isochron is formed having an apparent age of 595±15 Ma, r_i of 0.7034±0.0002, and MSWD of 0.57--the best estimate of the age of emplacement of the composite pluton. The r_i is consistent with Dodge's model of formation of the magma by low-pressure fractional crystallization of an andesitic melt that had originally formed by high-pressure partial melting of "eclogitic equivalents of crustal rocks" (Dodge, 1979, p. 13)--provided that those "crustal rocks" were mafic crust, were juvenile, and (or) had low Rb/Sr ratios. The r_i is

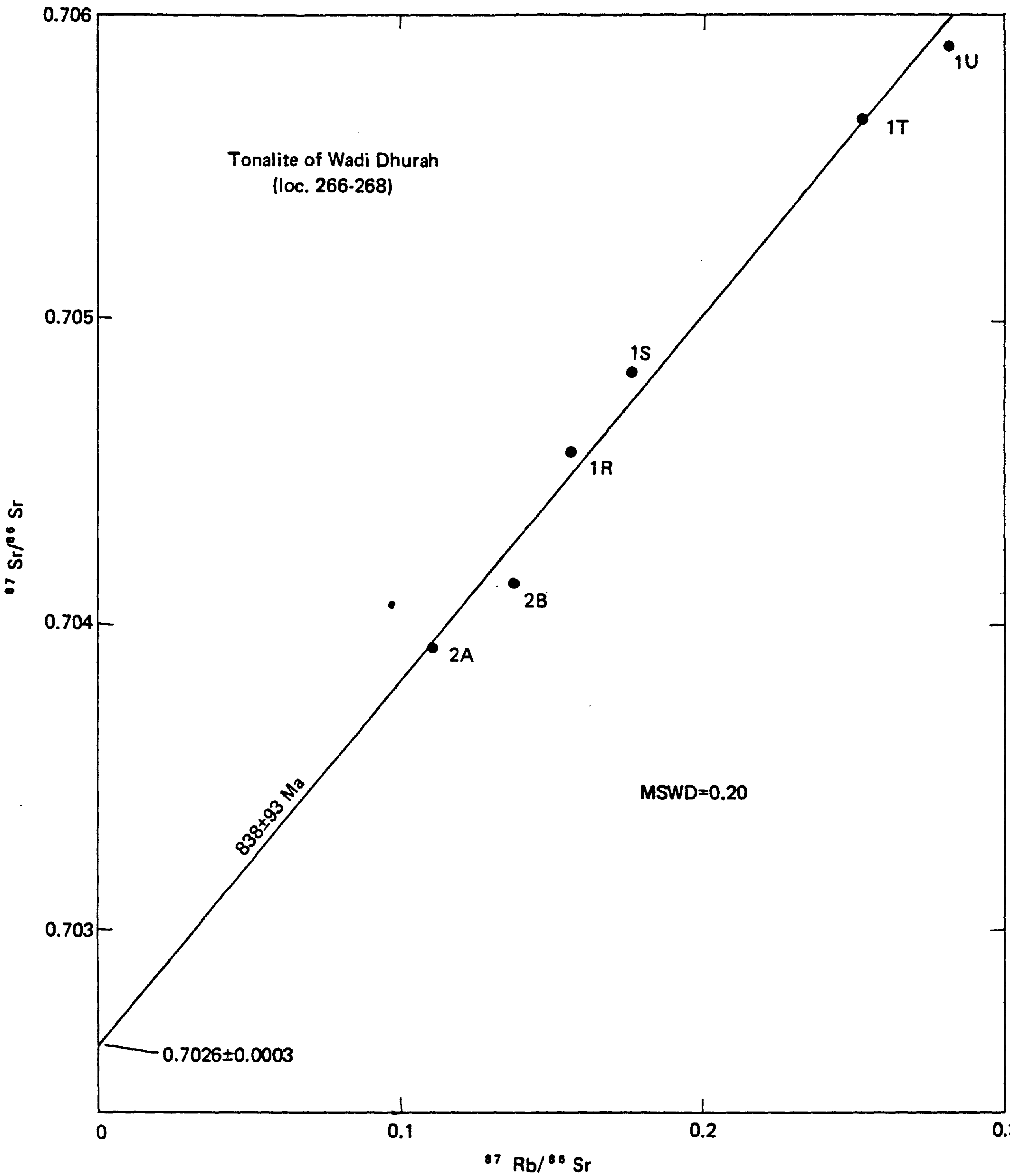

Figure 15.--Total-rock rubidium-strontium isochron diagram of tonalite of Wadi Dhurah. Sample numbers, with the three-digit prefix omitted for clarity, refer to data in table 1. Sample locations are shown on figure 2.

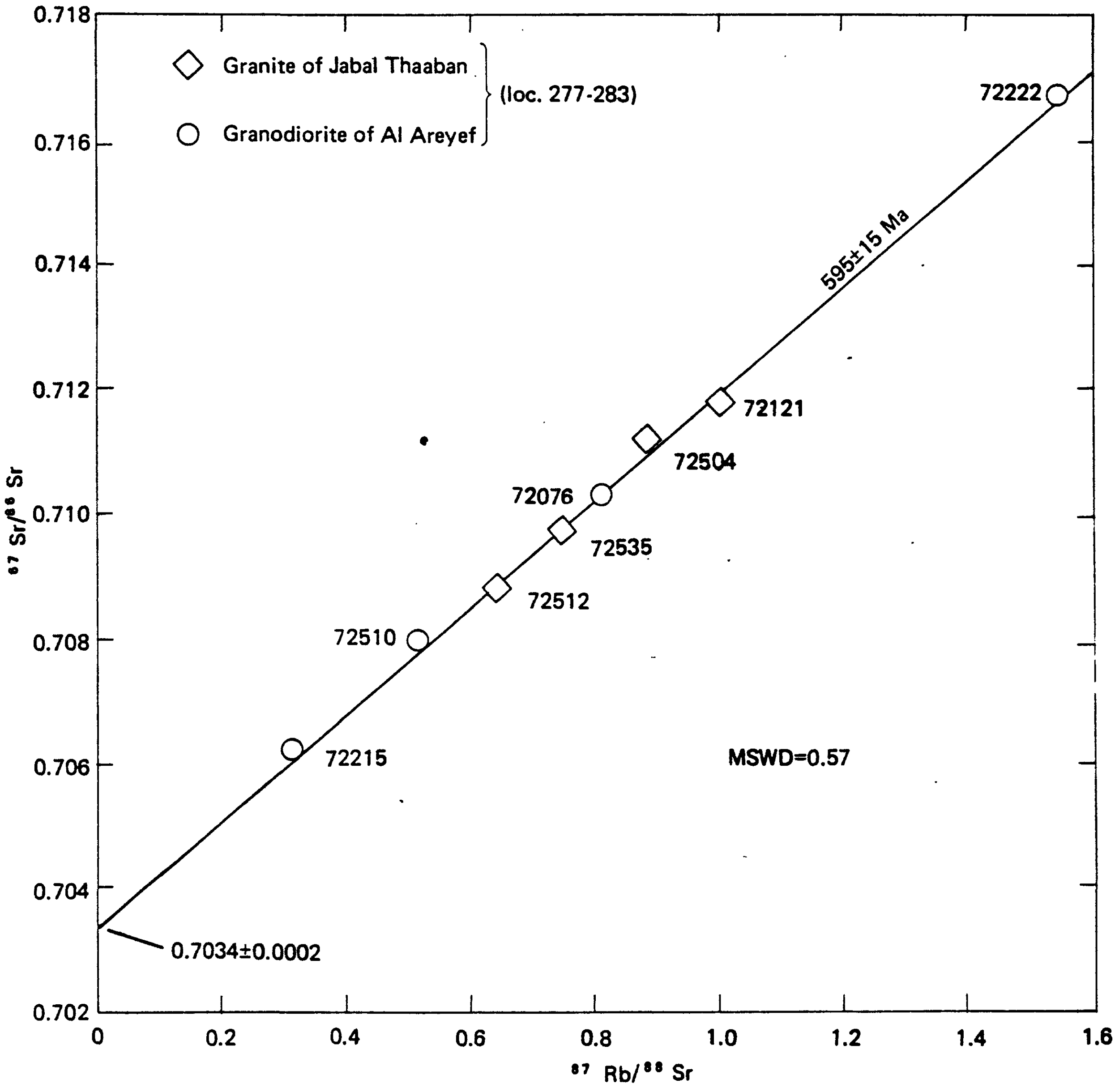

Figure 16.--Total-rock rubidium-strontium isochron diagram of granitic rocks of Uyaijah: granite of Jabal Thaaban and granodiorite of Al Areyef. Sample numbers refer to data in table 1. Sample locations are shown on figure 2.

not consistent with formation by melting of old sialic crust unless that melting were restricted solely to rocks having low Rb-Sr content, probably mafic lower crust.

DISCUSSION OF RESULTS

The purpose of analyzing suites of samples in a southwest to northeast transect of the Arabian Shield was primarily to define and evaluate age and (or) strontium-isotopic trends across a maximum expanse of that terrane and, secondarily, to compare the results with those of the southern part of the Shield studied previously by Fleck and others (1980). In the southern part of the Shield, ages of diorite and granodiorite bodies, which represent the oldest and most voluminous plutonic units in a given area, decrease "from west to east (or southwest to northeast)" (Fleck and others, 1980, p. 31). In the area transected for this study, the oldest units are indeed in the southwest or south and the youngest are in the northeast. Ages of the oldest plutonic units in the areas studied (fig. 17) define a range from 820-840 Ma in the west to about 610 Ma in the area east of the Al Amar-Idsas fault, with the possible exception of those of hybrid rock units south of Afif. Although the data are sparse and additional samples will undoubtedly refine or revise the present pattern, the general easterly decrease in age of the oldest plutonic rocks appears to be confirmed.

No systematic geographic variation in age was detected in late-orogenic and postorogenic rocks of the southern part of the Arabian Shield (Fleck and others, 1980). The present study, however, suggests that on a shieldwide basis an easterly or northeasterly decrease in age of late-orogenic and postorogenic plutons can be documented (fig. 18). The results presented here, together with those of Baubron and others (1975, recalculated to new decay constants) and Fleck and others (1980), suggest that the oldest of the subcircular, nearly undeformed granites in the southwest are about 640 Ma old, whereas the oldest such rocks in the northeast are 595 Ma old. The youngest plutons in the southwest are about 620 Ma old, whereas those in the Ad Dawadimi region may be as young as 560 Ma. Apparent ages of less than 550 Ma are not uncommon in the northern and eastern parts of the Shield, but most are mineral ages and are interpreted here as representing metamorphic (reset) or cooling ages. Data from east of the Al Amar-Idsas fault, however, are insufficient to permit extension of these conclusions to that area. The total-rock isochron age obtained from the Al Mizil pluton has too large an uncertainty to permit more than a speculation that deformation, and therefore late-orogenic and postorogenic plutonism, occurred much later than about 540 Ma ago. However, stratigraphic considerations might lend some support to this late Cambrian or even early Ordovician orogeny. As shown on the geologic compilations of Bramkamp and others

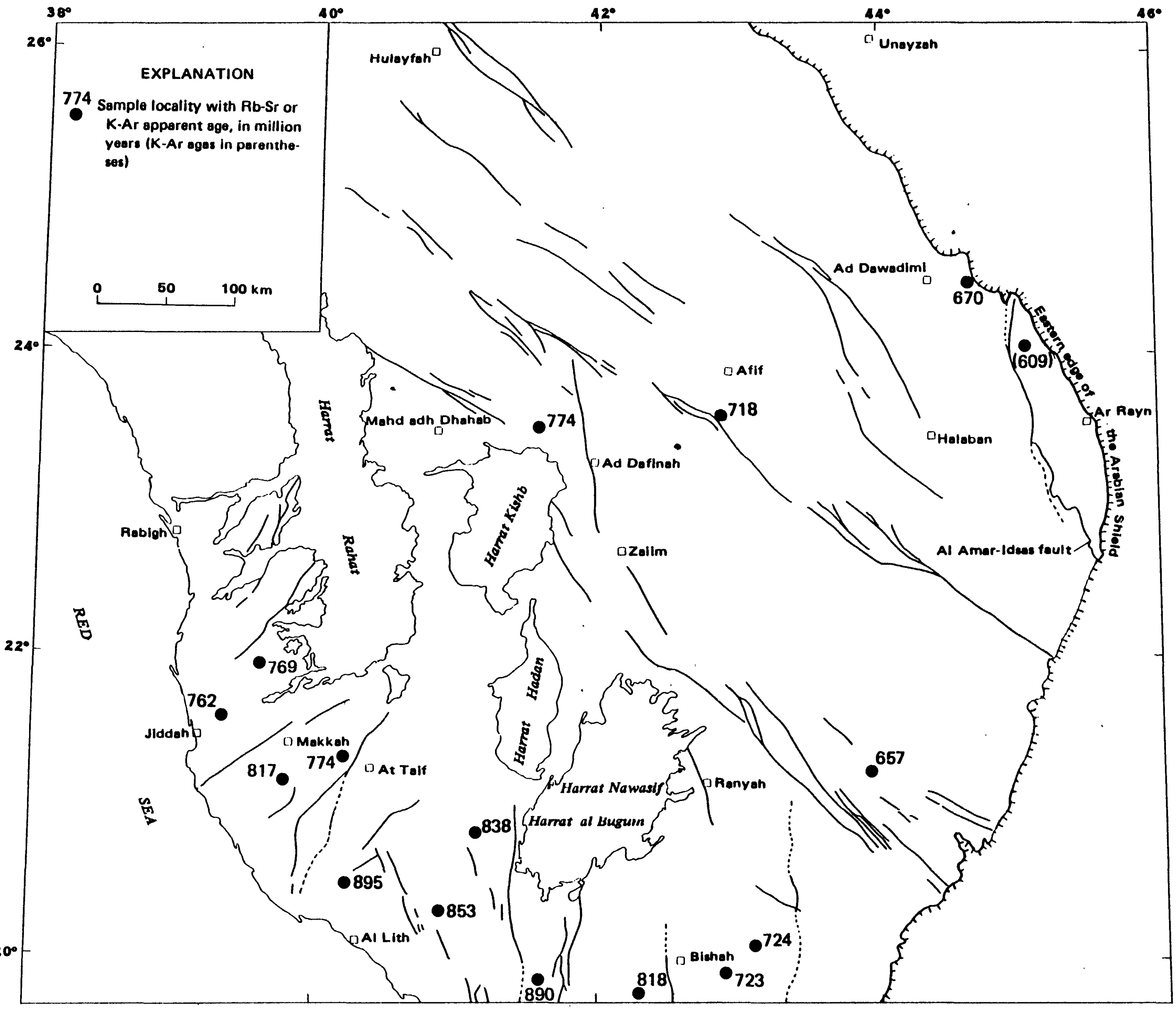

Figure 17.--Map showing distribution of ages of dioritic plutonic rocks in the central part of the Arabian Shield as reported in table 2 and by Baubron and others (1975), Fleck and others (1980), and Fleck (1981).

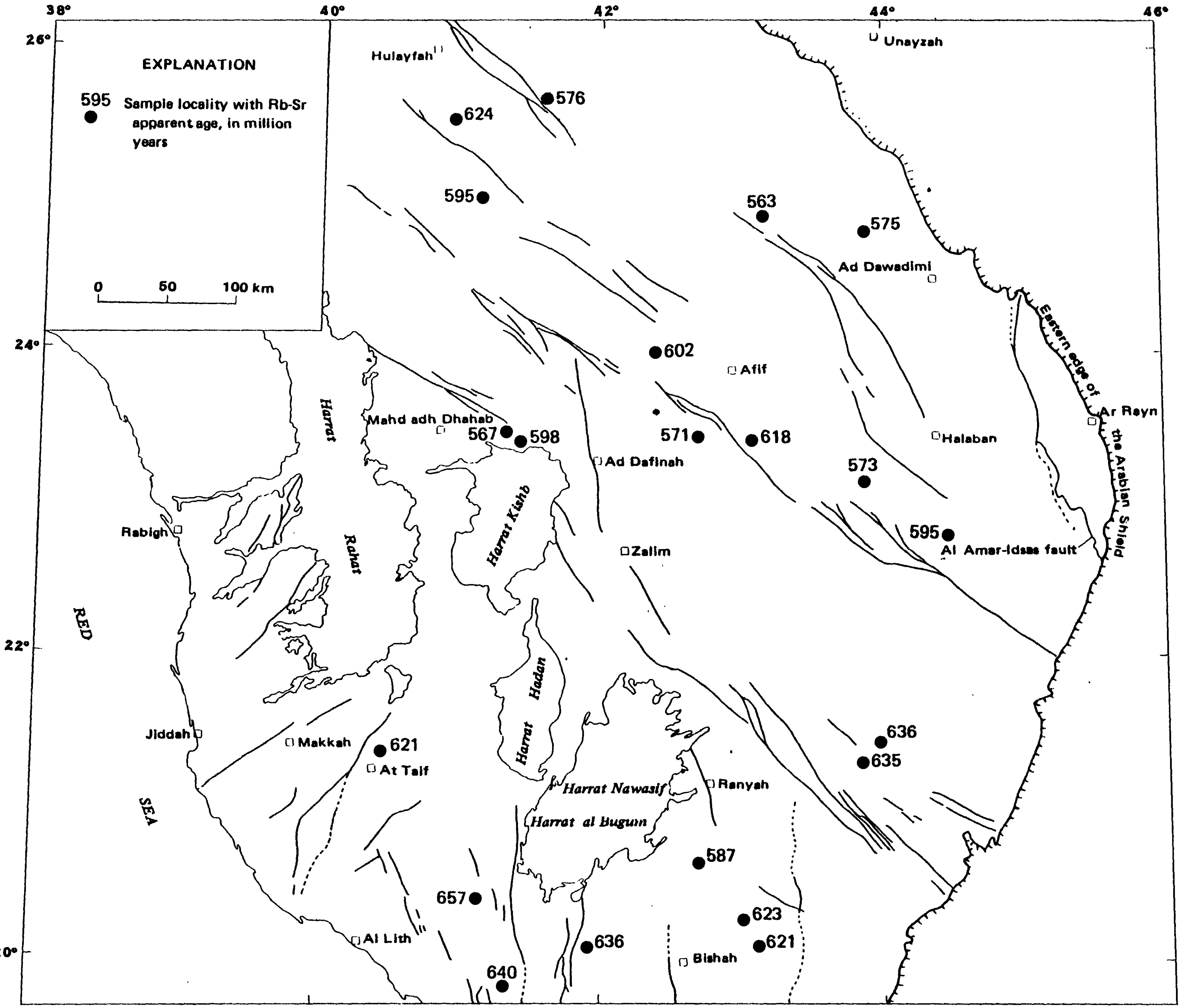

Figure 18.--Map showing distribution of ages of late-orogenic and postorogenic granodiorite to granite plutonic rocks in the central part of the Arabian Shield. Data from table 2 and from Baubron and others (1975), A. T. Mishwit (written commun., 1975), Fleck and others (1980) [redacted]

(1963) and Bramkamp and Ramirez (1958), the Saq Sandstone of probable Cambrian and Ordovician age rests nonconformably on deformed units of the Shield north and west of the Al Amar-Idsas fault but is absent south and east of that structure. South and east of the fault, Permian units rest directly on rocks of the Shield, whereas to the northwest these units rest unconformably on the Saq Sandstone or on middle Paleozoic strata. The location of this stratigraphic break at the Al Amar-Idsas fault may be coincidence, but alternatively the lowest Paleozoic strata may never have been deposited southeast of the fault and orogenesis might well have extended into late Cambrian or even early Ordovician time.

The range of r_i values reported here (from 0.7025 ± 0.0002 to 0.7061 ± 0.0005) is greater than that reported for the southern part of the Arabian Shield (Fleck and others, 1980). If the one value for the syenogranite of Jabal al Usaybiyat is excluded, however, r_i values for the two regions are nearly identical. In general these data extend conclusions about the origin and evolution of the Shield drawn for the southern areas to those of the north and east. Only results from Jabal al Usaybiyat and adjacent areas south of Afif suggest a more radiogenic component in the source of magmas. No evidence is found to support inferences from lead isotope studies (Stacey and others, 1980) that old continental crust is present in the easternmost part of the Shield. As also implied by the lead isotope data, lower Proterozoic and Archean upper crustal rocks are precluded by the low r_i values. Because we consider the presence of old lower crust without any remnants of high-Rb/Sr upper crust extremely improbable, we suggest that the lead in the group II samples of Stacey and others (1980) contains a sedimentary component derived secondarily from upper Proterozoic marine sedimentary (metasedimentary) units. A source of this type might also explain the elevated r_i of the Jabal al Usaybiyat syenogranite, which because of its low strontium concentration (about 45 ppm) would be more affected by a small amount of assimilated contaminant than would rocks with higher strontium concentrations. The presence of sedimentary components in the sources of some magmatic units of the Shield is strongly indicated by the high $\delta^{18}O$ values reported by Radain and Kerrich (1979). Values as high as 10 to 16 per mil are reported, as compared to an average $\delta^{18}O$ of about 8 per mil for "normal" granites (Taylor, 1968). Although other factors may produce elevated whole-rock $\delta^{18}O$ values, the presence of granitic plutons having such values makes marine sediments an attractive source of high $^{87}Sr/^{86}Sr$, $\delta^{18}O$, and radiogenic lead. The apparent restriction of these units to the northern and eastern parts of the Shield suggests that those areas were closer to a source of these materials than areas to the south and west.

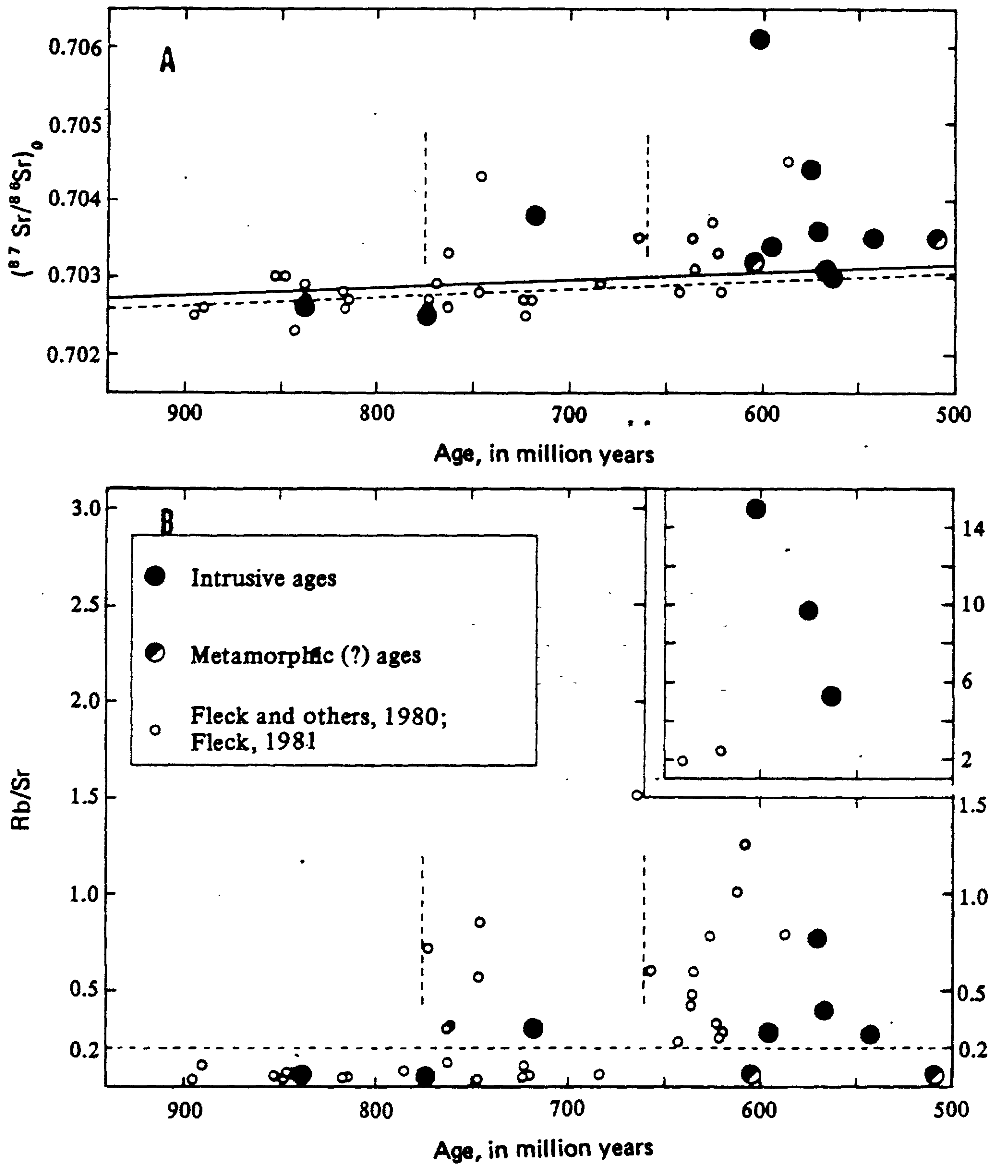

Figure 19.--Diagrams showing variation of (A) initial $^{87}Sr/^{86}Sr$ ratio and (B) Rb/Sr ratio with age for rocks of the Arabian Shield. Vertical dashed lines are drawn at two periods of major change in Rb/Sr ratio and strontium-isotopic composition of magmas. Strontium-evolution line (solid line) in (A) represents single-stage evolution from a meteorite initial $^{87}Sr/^{86}Sr$ ratio of 0.699 to a modern island-arc value of 0.7037 (Dickinson, 1970; Faure and Powell, 1972). Dashed evolution line is least-squares fit of data of Fleck and others (1980) that have Rb/Sr ratios below 0.2; this line yields intercepts of 0.7036 for the present and 0.6989 at 4,500 Ma ago.

The variation of Rb/Sr ratio and r_i with age in rocks of the Arabian Shield supports an intraoceanic island-arc model of crustal evolution (Jackaman, 1972; Greenwood and others, 1976; Fleck and others, 1980; Fleck, 1981). If the results of this study are compared to those from the southern part of the Shield (fig. 19), the primary difference noted is the definition of rocks younger than 660 Ma that have low Rb/Sr ratios. Initial ratios (r_i) remain low, except for those around Afif and those discussed above that fall in the age group in which r_i values have already shown some moderate variation above the strontium-evolution line for the "mantle" (Fleck and others, 1980). The appearance of diorite-tonalite bodies younger than 660 Ma east of the Al Amar-Idsas fault extends the period of active arc formation from about 850 or 900 Ma ago to about 600 Ma ago. The length of this period alone suggests either multiple arcs or juxtaposition of the products of intraoceanic-arc orogenesis by tectonic processes. We would conclude that the data now imply the presence of multiple orogenic belts or island arcs because the postorogenic plutons of the earlier belts are actually contemporaneous with, or even younger than, the chemically and isotopically more primitive, "shield-building" dioritic and andesitic units of the younger (eastern) terranes. Documentation of the distribution of these units both temporally and geographically will require study of additional units in these and adjacent areas. Further studies are clearly indicated for rocks of the Afif area to evaluate the cluster of elevated r_i values in that area.

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