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AN EVALUATION OF THE ZIRCON METHOD OF ISOTOPIC DATING IN THE SOUTHERN ARABIAN CRATON KINGDOM OF SAUDI ARABIA

by

J. A. Cooper, J. S. Stacey, D. B. Stoeser, and R. J. Fleck

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

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CONTENTS

Page

ABSTRACT.. 1

INTRODUCTION.................................... 2

Methods used.................................... 6

Acknowledgements................................ 7

RESULTS... 8

DISCUSSION...................................... 17

STRATIGRAPHIC IMPLICATIONS...................... 25

REFERENCES...................................... 28

ILLUSTRATIONS

Figure 1. A generalized geologic map of the southern part of the Arabian craton................. 3

2. $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ plots for 10 zircon samples (41 fractions) from the southern part of the Arabian craton................. 10

3. Distribution of zircon model ages determined in this study for the southern part of the Arabian craton........ 19

4. Sketch map showing the geologic relations and zircon-sampling sites at Wadi Baqarah pertinent to this study............ 21

TABLES

Table 1. Pb, U, and Th concentration and isotopic composition measurements, together with simple decay, apparent age data for all fractions of zircon samples measured....... 9

2. Model ages derived from U/Pb isotopic analyses and use of the $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ diagram........................ 11

3. A summary of sample descriptions and zircon data made in this study................... 18

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J.A. Cooper[1], J.S. Stacey[2],

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ABSTRACT

A zircon study has been made on 11 samples of igneous rocks from the Saudi Arabian craton. Ages of sized and magnetic fractions of zircon concentrates show variable degrees of discordance, which seem to result from a very young disturbance that produces linear arrays in the Concordia plot. Model age calculations based on a statistically and geologically reasonable lower intercept produce very consistent internal relationships. The Pan African Orogeny, considered to be responsible for loss of radiogenic argon and strontium from minerals of many rocks, does not appear to have affected the zircon data, even though uplift had exposed the rocks of the Arabian Shield at that time.

Tonalite, granodiorite, and crosscutting leuco-adamellite bodies in the southern part of the An Nimas batholith yield ages in the time range 820-760 m.y. A narrow time range of 660 to 665 million years was indicated for ages of widely

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separated and compositionally different intrusive bodies all to the east of the An Nimas batholith. This work suggests that the younger end of the age spectrum established from regional K-Ar and Rb-Sr measurements may be underestimated, and that magmatic activity could have been more episodic than previously assumed.

INTRODUCTION

The Precambrian of Saudi Arabia is exposed on the eastern side of the Red Sea for approximately one third of the area of the Kingdom (fig. 1). In cooperation with the Directorate General of Mineral Resources, Kingdom of Saudi Arabia, the early geologic work in this large region was done by Glen F. Brown and his group of co-workers of the U.S. Geological Survey. In the early 1960's these investigations were complemented by the pioneering K-Ar and Rb-Sr mineral isotopic dating studies of L.T. Aldrich at the Carnegie Institute of Washington (Aldrich, 1978), and other later measurements reported by Brown and others (1978). The results of these initial efforts have been summarized in the papers of Brown and Jackson (1960), Brown and Coleman (1972), and the tectonic map of Brown (1972). Mapping on the 1:100,000 scale has continued since that time. The oldest rocks known are in the southwestern part of the Kingdom, and comprise a thick section of submarine basalts that give way to a dominantly sedimentary graywacke sequence. Deposition of these rocks was followed by andesitic volcanics and minor basalt accompanied by clastic and carbonate sediments. Intruded during this andesitic period were batholiths of quartz

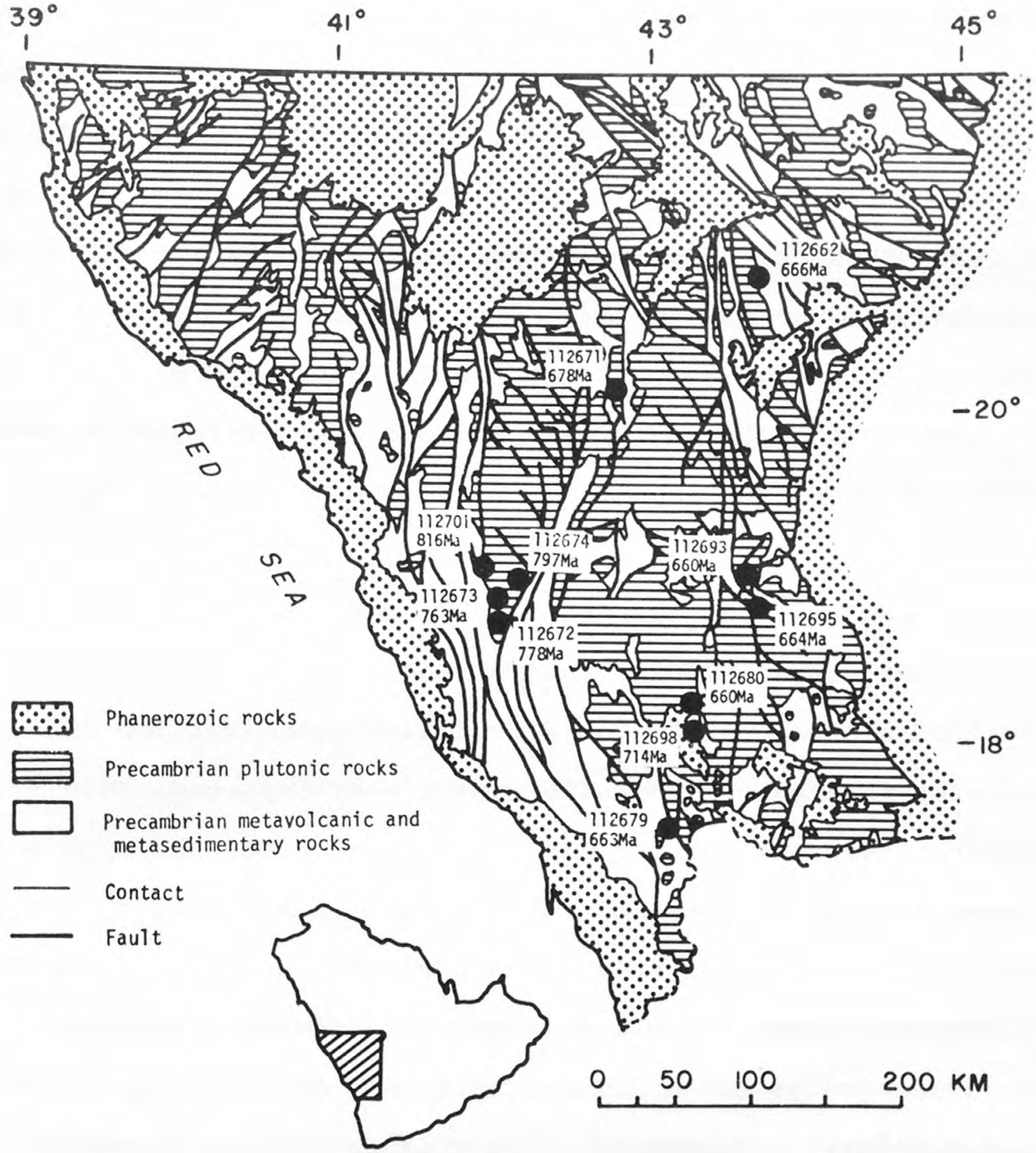

Figure 1. A generalized geologic map of the southern part of the Arabian craton (modified from Greenwood and others, 1976) showing sample locations and zircon-model ages. Ma = million years.

diorite, tonalite, trondjhemite, and granodiorite (the "older" diorite series of Greenwood and others, 1976). The layered rocks, as well as the intrusives, are now strongly deformed and aligned north-south. Schmidt and others (1973) developed a model for the southern part of the Saudi Arabian shield based on the stratigraphic continuity of volcanic and sedimentary rocks. This model indicated six stratigraphic units in four sequences: three major orogenies, an earlier tectonism, and the suggestion of a still earlier crustal history.

Fleck and others (1976) reported the results of a broad K-Ar survey of the southern portion of the exposed shield. They deduced that two thermal pulses 570-620 m.y. (million years) and 520-550 m.y. ago had lowered many of the ages of the older rocks. During this period, considerable volumes of syntectonic to post-tectonic granodiorite-adamellite and granite-peralkaline granite magmas were emplaced. Minor gabbro that commonly formed layered intrusions accompanied these magmas (Coleman and others, 1972). All this activity was probably related to the Pan African orogeny of the African continent. Some hornblende ages indicated that earlier-deformed groups had minimum ages of 658-690 m.y. and 775 m.y., respectively. Subsequent total rock Rb-Sr data indicated the existence of 760 m.y. old granodiorite gneiss and even older tonalitic gneiss (Fleck and others, 1973). Greenwood and others (1976) used the chemical composition of volcanic rocks, the nature of the sediments, and the Rb-Sr total-rock dating of Fleck and others (1973) and Fleck and others (1978) to suggest that the whole pretectonic sequence exhibits characteristics similar to those of rocks formed in an island arc system. Fleck and others (1978), reinforced with more Rb-Sr measurements, added that the arc complex subsequently collided with the African continent. That collision, they suggested, generated the southwest-trending Najd Fault system that dominates the tectonic structure in the northeast part of the craton. During this Pan African event in the northern shield, large quantities of compositionally similar rhyolites were erupted, and large volumes of molasse were deposited. In the southern third of the shield wherever these volcanics were deposited, they were subsequently removed by erosion before deposition of the presently overlying Paleozoic rocks.

The Pan African plutonism waned rapidly just before or during the early Cambrian. The shield was then covered by a thick Paleozoic blanket of sediments that remained essentially undisturbed until Tertiary time when the Red Sea rifting began. The rifting was preceded or accompanied by regional doming that exposed the Arabian-Nubian shield.

By 1976 it was obvious that, in view of the complexity of the Arabian craton, a supporting tool was required for dating the older rocks that could see through the widespread deformational and thermal events already detected. Such a tool would also have to function satisfactorily with the calcic-dioritic and quartz-diorite materials that appear to form a major part of the older units. It was for these reasons that a zircon dating study was initiated, and samples were collected from a variety of rock units within the Qal' at Bishah-An Nimas-Khamis Mushayt area of the craton (fig. 1 and table 3). This area includes the eastern part of the An Nimas batholith and the western part of the Wadi Tarib batholith (Fleck and others, 1978), the two of which are separated by a north-trending belt of metamorphosed andesitic, volcanic, and volcano-clastic rocks.

Methods used

Zircon concentrates were obtained from 40 to 50 kilograms of samples. The rock was broken in a jaw crusher and pulverized to -50 mesh. A heavy concentrate was obtained by panning with water, and this was further upgraded by separation in tetrobromoethane and methylene iodide heavy liquids. A Franz magnetic separator was used to concentrate zircon, but for some samples, Clerici solution was necessary to give a clean concentrate. After the crystals were boiled gently in aqua regia for 20 minutes, zircon fractions were obtained by either sieving or magnetic partition. For the chemical separation of U, Th, and Pb, the ion exchange procedures of Krogh (1973) were used with minor modifications. Solutions were spiked with ^{235}U, ^{230}Th, and ^{208}Pb tracers, and concentrations of U, Th, and Pb were determined by isotope dilution. Mass spectrometry was done with a 30 cm radius, 90° sector instrument using the single-filament, silica-gel method of Cameron and others (1969) for lead and triple filament for U and Th. Constants utilized in the age calculations are $\lambda^{238}U = .155125 \times 10^{-9}y^{-1}$, $\lambda^{235}U = 0.984850 \times 10^{-9}y^{-1}$,

$\lambda^{232}Th = 0.049475 \times 10^{-9} y^{-1}$, $^{238}U/^{235}U = 137.88$. Common-lead corrections were made using the isotopic composition of Arabian galena of equivalent age (Doe, written communication). In this manuscript, all ages quoted from previous studies have been adjusted using constants recommended by the International Subcommission on Geochronology (Steiger and Jager, 1977). Our analytical precision is considered to be $\pm$ 0.1 percent (2 σ) for $^{207}Pb/^{206}Pb$ and $\pm$ 1 percent (2 σ) for concentrations of U, Th, and Pb.

The uncertainties quoted in table 2 for the intercepts between regression lines and concordia are the 95 percent confidence limits, and require the appropriate Students t multiplier. They have been computed using an analysis developed by K. Ludwig of the U.S. Geological Survey, and he has been kind enough to permit our use of his program. The concepts used by Ludwig to solve this problem are similar to those developed by Cumming (1969, p. 732) and York (1969).

Acknowledgements

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RESULTS

The determination of U, Th, and Pb elemental concentrations, daughter/parent isotope ratios, and ages for all sample fractions are reported in table 1. The analytical data are plotted in figure 2, where it can be seen that the discordance patterns on the $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ plot indicate loss of lead. Table 2 lists the total range of discordance for the fraction of each sample as well as the age estimates calculated by pooling the measurements on the fractions from each sample according to three different models. Model 1 utilizes the average of the ages corresponding to the $^{207}Pb/^{206}Pb$ ratios of the fractions from each sample. These data are of significance for crystallization ages of concordant or slightly discordant samples. They are also of significance when the data exhibit a linear trend that passes close to the origin on a $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ "concordia diagram". The 95 percent confidence limits for the $^{207}Pb/^{206}Pb$ ages for most of the samples are $\pm$ 10 m.y. or better (table 2).

Model 2 presents the ages indicated by the upper and lower intercepts with concordia of least squares regression lines through the analytical points for each sample on the

Table 1.--*Pb, U, and Th concentration and isotopic composition measurements, together with simple-decay, apparent-age data for all fractions of zircon samples measured*

Sample No.		Size Fraction	Pb (ppm)	U (ppm)	Th (ppm)	Atomic Ratios $^{206}Pb/^{238}U$	Atomic Ratios $^{207}Pb/^{235}U$	Atomic Ratios $^{207}Pb/^{206}Pb$	Atomic Ratios $^{208}Pb/^{232}Th$	Age Estimates $^{206}Pb/^{238}U$	Age Estimates $^{207}Pb/^{235}U$	Age Estimates $^{207}Pb/^{206}Pb$	Age Estimates $^{232}Th/^{208}Pb$	$^{206}Pb/^{204}Pb$
112662	(A)	+100	6.6	60	16.5	.10749	.9168	.06194	.03208	658	661	672	638	1503
	(C1)	-150 +200	10.8	103	24.0	.10687	.9101	.06185	.03226	655	657	669	642	2938
	(C2)	-100 +150	8.9	85	22.0	.10446	.8911	.06195	.03115	641	647	672	620	2154
	(E)	-250 +325	13.6	132	27.7	.10480	.8895	.06164	.03177	642	646	662	632	2564
112671	(B)	-150 +200	33.3	516	288	.06373	.5447	.06207	.00992	398	441	676	200	2033
	(C)	-200	39.7	560	218	.07070	.6053	.06218	.01580	440	481	680	317	4202
	(D)	all sizes, mag 2°	49.2	684	367	.07093	.6047	.06191	.01178	442	480	671	237	2853
	(E)	all sizes, non mag 2°	44.6	506	229	.08717	.7436	.06195	.01671	539	564	672	335	2762
112672	(A)	+100	16.0	173	102	.08744	.7803	.06480	.01909	540	586	768	382	1580
	(B)	-100 +150	27.7	241	128	.10591	.9531	.06535	.02853	649	680	786	569	1459
	(E)	-250 +325	33.4	328	216	.09708	.8699	.06507	.02071	597	636	777	414	6047
	(F)	-325	47.5	415	274	.10556	.9465	.06512	.02416	647	676	778	482	1723
112673	(A)	+150	57	521	642	.10305	.9184	.06472	.01220	632	662	765	245	5871
	(B)	-150 +200	92	783	825	.11257	1.0033	.06473	.01386	688	705	765	278	6540
	(D)	-250 +325	125	1073	952	.10540	.9375	.06459	.01298	646	672	761	261	682
	(E)	-325	115	1019	1084	.10954	.9748	.06462	.01183	670	691	762	238	5719
112674	(A)	+100	9.6	99	44	.09235	.8369	.06581	.02362	569	617	800	472	1285
	(B)	-100 +150	9.9	88	38	.10852	.9831	.06579	.02979	664	695	799	593	3028
	(E)	-250 +325	16.9	139	77	.11521	1.0414	.06564	.02645	703	725	795	528	2247
	(F)	-325	20.5	162	104	.11471	1.0363	.06561	.02348	700	722	794	469	893
112679	(C1)	-100 +150 hand picked	56	607	172	.09159	.7764	.06156	.02469	565	583	659	493	1711
	(C2)	-100 +150 clerici	57	596	169	.09320	.7916	.06168	.02520	574	592	663	503	1614
	(F)	-250 +325	56	719	240	.06959	.5922	.06179	.01491	434	472	667	299	451
	(G)	-325	87	960	325	.09048	.7676	.06161	.02221	558	578	660	444	4740
112680	(A)	+100	25.7	282	61	.09364	.7939	.06156	.02715	577	593	659	541	7519
	(C1)	-150 +200, non mag 2°	24.7	265	66	.09500	.8055	.06157	.02561	585	600	659	511	5922
	(D)	-200 +250	22.3	291	67	.06732	.5706	.06155	.01959	420	458	659	392	373
	(E)	-250 +325	27.3	299	73	.09346	.7947	.06175	.02425	576	594	665	484	5245
112693	(A)	-50 +100	53	440	256	Data were inadequate owing to the				490-495	520-530	660-690	240-250	130.9
	(B)	-100 +150	55	456	280	high common Pb component from				480-490	515-525	660-690	220-230	126.9
	(C)	-150 +250	81	471	280	clerici solution.				480-485	510-530	660-730	250-260	67.66
112695	(B1)	-100 +150, non mag 2°	33.6	417	163	.08135	.6888	.06148	.01763	504	532	656	353	15,887
	(B2)	-100 +150, mag 2°	34.4	464	227	.07418	.6322	.06189	.01380	461	497	670	277	5856
	(D)	-200 +250	31.2	391	151	.08071	.6837	.06152	.01641	500	529	657	329	6862
	(E)	-250 +325	31.3	397	155	.07961	.6763	.06169	.01564	494	525	663	314	5016
112698	(A+B)	+150	30.3	385	39	.08295	.7162	.06270	.01982	514	548	698	397	2710
	(C)	-150 +200	23.5	320	39	.07722	.6767	.06364	.01565	480	525	730	314	2527
	(D)	-200 +250	39.4	540	53	.07730	.6749	.06340	.01934	480	524	722	387	4207
	(E)	-250 +325	38.4	533	56	.07609	.6561	.06262	.01614	473	512	695	324	2988
112701	(A)	-100 +150	13.1	96	53	.12715	1.1601	.06626	.03493	772	782	814	694	2727
	(B)	-150 +200	13.0	100	53	.12342	1.1274	.06634	.03445	750	767	817	685	4411
	(C)	-200 +250	14.6	105	56	.12992	1.1898	.06651	.03720	787	796	822	738	2167
	(D)	-250 +325	15.9	117	63	.12735	1.1617	.06625	.03559	773	783	814	707	2893
	(E)	-325	19.5	141	77	.12520	1.1445	.06639	.03354	760	775	819	667	960

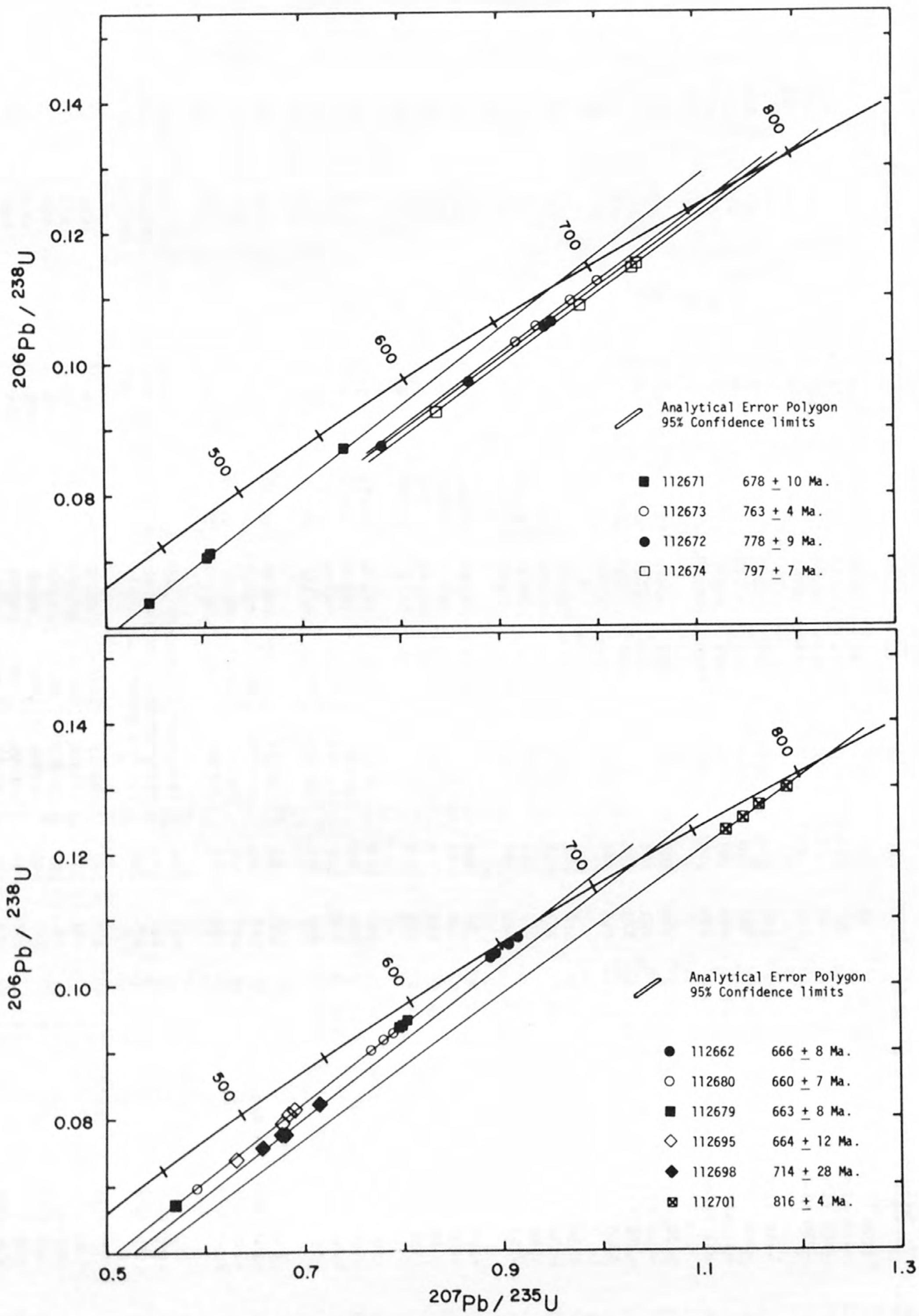

Figure 2. $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ plots for 10 zircon samples (41 fractions) from the southern part of the Arabian craton.

Table 2.--*Model ages derived from U/Pb isotopic analyses and use of the $^{206}Pb/^{238}U$ vs $^{207}Pb/^{235}U$ diagram*

[Ages tabulated according to three different models]

Model No.		(1)	(2)		(3)	
			Regression of Analytical Points		Upper-Intercept Age (for regression line through 15 ± 15 m.y. lower intercept)	
Sample No.	Range of Discordance (percent)	Average $^{207}Pb/^{206}Pb$ Age (m.y.)	Upper-Intercept Age (m.y.)	Lower-Intercept Age (m.y.)		General Description
112680	15-39	660 ± 5	659 ± 12	7 ± 48	660 ± 7	Wadi Tarib damellite
112679	15-37	662 ± 6	653 ± 9	-21 ± 41	663 ± 8	Wadi Atf tonalite gneiss
112695	26-32	661 ± 10	626 ± 29	-149 ± 159	664 ± 12	Markas metagabbro
112662	2-7*	669 ± 13	671 ± ?	171 ± ?	666 ± 8	Jabal Yafikh hornblende metatonalite
112671	21-42	675 ± 7	667 ± 36	-12 ± 77	678 ± 10	Bishah "red" granite of Junaynah
112698	31-36*	711 ± 28	676 ± ?	-106 ± ?	714 ± 28	Wadi Tarib gneiss dome grano-diorite gneiss
112673	13-20	763 ± 3	762 ± 36	8 ± 188	763 ± 4	Baqarah leuco-adamellite gneiss
112672	19-33	777 ± 12	792 ± 28	70 ± 94	778 ± 9	Baqarah granodiorite gneiss
112674	11-29	797 ± 5	790 ± 11	-27 ± 62	797 ± 7	Baqarah biotite tonalite gneiss
112701	2-7	817 ± 4	819 ± 29	84 ± 350	816 ± 4	An Nimas biotite tonalite gneiss

* These two samples have very short regression lines whose error envelopes do not cut Concordia twice.

$^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ diagram (table 2). The precision of the upper intercept age is a function of the length of the regression line (range of discordance) and the proximity of the data to concordia. In our analyses, six of the ten samples exhibit moderate ranges of discordance (14 to 24 percent; see table 2); the other four have very small ranges of discordance (5 to 7 percent). For the first group, the upper intercept ages are fairly well defined (95 percent confidence limits range from ± 10 to ± 36 m.y.). With one exception, sample 112672, these five age estimates are almost identical to the $^{207}Pb/^{206}Pb$ ages. For sample 112672 the difference is 15 m.y., but this is the shortest regression line of the group and the data are the farthest from concordia.

Among four samples exhibiting much smaller ranges of discordance, samples 112662 and 112701 are very nearly concordant, and their upper intercept ages agree with the $^{207}Pb/^{206}Pb$ results to within 2 m.y., although the statistical uncertainties are quite high. For 112662 the data points are grouped so closely together that the 95 percent-confidence envelopes for the regression line do not each cut concordia twice. For samples 112695 and 112698, similarly short regression lines (the range of discordance is six percent in each case) are displaced from concordia. In these two cases, not only are the upper intercept uncertainties high, but the corresponding ages are 35 m.y. less than the $^{207}Pb/^{206}Pb$ ages. These are the only two samples exhibiting such a difference, and we feel justified in concluding that the

$^{207}Pb/^{206}Pb$ model ages are the better estimates for these zircon samples. In fact, the $^{207}Pb/^{206}Pb$ model ages for all samples we have analyzed may well be better estimates for their zircon ages than those yielded by the simple regression lines. In order to explore the nature and timing of the process that caused discordance in the data, we have developed the model theory a stage further by the following reasoning.

Provided the sample fractions do not exhibit more than about 60 percent discordance, then for data in which good agreement exists between "upper intercept" and $^{207}Pb/^{206}Pb$ ages it is implicit that the process that caused discordance should be of recent occurrence. Information on the timing of this event is provided by the lower-intercept ages (Model 2, table 2). For all the samples, the lower intercepts have large uncertainties, owing to the comparatively small discordances observed. If a single value for the lower intercepts could be chosen with sufficiently wide confidence limits to account reasonably for the geological and statistical uncertainties for all samples, then the precision of the upper-intercept ages might be considerably enhanced. It can be argued that because all the samples come from the same general terrane, then similar tectonic processes as well as the same physical laws governing a lead-loss process would have applied to each. Also, because there is a comparatively small range of crystallization ages (600-800 m.y.), then the weighted mean of the lower-intercept ages is also of real significance to our theory of discordance. Therefore, the weighted mean was calculated for the lower intercept with concordia for the eight groups of samples that gave meaningful error envelopes. This weighted mean was -9 ± 15 m.y. at the 95 percent confidence level. The 95 percent confidence level indicated by this calculation for each individual group was -9 ± 42 m.y. These figures are clearly different from the intercept of at least 100 m.y. required by any of the continuous-diffusion processes discussed by either Nicolayson (1957), Tilton (1960), or Wasserburg (1963). Of course, the -9 m.y. intercept is merely a calculation and has no meaning in a specific time sense. However, this weighted-mean value along with the uncertainty indicates that lead loss in the late Tertiary, including modern lead loss, can readily explain the systematics observed in the data.

It is quite possible that recent deep weathering could have produced similar lead-loss patterns that pass through the origin (Stern and others, 1966). However, our samples were quite fresh, and it is difficult to blame weathering for the larger discordances observed. It is also difficult not to suspect that the massive geological upheaval associated with the opening of the Red Sea and Gulf of Aden, and the large-scale doming of the Arabian and African blocks (Gass, 1970), followed by the removal of Phanerozoic overburden, may not be associated with the lead loss problem. Some thermal activity certainly occurred at that time due to crustal extension and rifting. Inland from the immediate rift areas, this local heating was supplemented by wide-spread volcanism occurring since Oligocene times (Brown, 1972). However, this heating was not sufficient to significantly disturb potassium-argon systems throughout the craton, and therefore, temperature alone is unlikely to be the direct cause of the zircon discordance. A possible cause of lead loss in metamict zircons is hydrothermal activity, and it is conceivable that the plutonic rocks from the Arabian Shield were uplifted into the groundwater zone within the last 30 m.y. Such low-temperature hydrothermal activity during that time could also be responsible for the open-system behavior of some whole rock and mineral rubidium-strontium systems in both the Wadi Baqarah body and the "red granites" of the Bishah area (Fleck, unpublished data). Another, possibly more significant, factor disturbing the zircon systems in the Tertiary could be the dilatancy effect proposed by Goldich and Mudrey (1972). This hypothesis suggests that, when the pressure drops as a result of cover removal from previously buried rocks, radiogenic lead is extracted from metamict zircons by fluids released internally.

The question then arises, "why these processes, dilatancy and perhaps hydrothermal activity, do not appear to have disturbed the zircon systems during the Pan African Orogeny ($\sim$600 m.y. ago) even though some potassium-argon and rubidium-strontium systems appear to have been opened during that event (Fleck and others, 1978)." The most likely answer seems to be that because none of the zircons we have analyzed is older than 820 m.y., then by 600 m.y. ago none was sufficiently metamict (that is, damaged by radiation) to be susceptible to lead loss at that time. (The geologic record shows that early Paleozoic sediments were deposited directly on top of already-exposed plutonic rocks, clearly indicating that the shield had been uncovered and exposed in the late Precambrian-early Paleozoic time (Hadley and Schmidt, 1975)).

It appeared logical to treat our data further by regressing the data for each group of sample fractions through a lower-intercept point that would be as consistent as possible with the value obtained from the weighted mean of the lower-intercept points as well as with the geologic events to which the craton was subjected in Tertiary times. Negative values from lower intercepts are meaningless, so a lower intercept of 15 $\pm$ 15 m.y. was chosen to cover the meaningful confidence limits of the weighted mean. The resulting data are listed in table 2, Model 3.

All Model 3 ages and their calculated uncertainties are almost identical to those obtained from the $^{207}Pb/^{206}Pb$ values, Model 1. For all samples, Model 3 upper-intercept ages are within 3 m.y. of those obtained by Model 1. In addition, the 95 percent confidence limits of the upper-intercept ages in Model 3 have been reduced to be almost identical to those of the Model 1 $^{207}Pb/^{206}Pb$ ages. Apart from their reduced uncertainties, for only three samples, 112672, 112695, and 112698, is there disagreement with the ages calculated in Model 2. These cases were discussed previously, and the age differences yielded between Models 1 and

2 were attributed to the inability of the shorter regression lines to define accurately the upper intercepts, especially when the data are displaced from concordia. In all other cases, ages agree among the three models to within 11 m.y. Although it is clear that if discordance of the samples is due to a single recent episodic event, then Model 1 $^{207}Pb/^{206}Pb$ data are likely to be very close to reality. In this instance our final selection of a preferred model is tempered by our knowledge of events in Tertiary times to which the Arabian craton was subjected. Therefore, we shall regard the regressions through the 15 ± 15 m.y. intercept, Model 3, as yielding our preferred-model ages.

Thorium-lead data are generally more discordant than the uranium-lead or lead-lead ages (table 1). In this study, a somewhat scattered pattern is obtained on a $^{208}Pb/^{232}Th$ versus $^{207}Pb/^{235}U$ diagram, indicating that ^{208}Pb has been lost preferentially to ^{207}Pb and ^{206}Pb. No reasonable upper-intercept-type interpretation seems possible, and so such a diagram is not presented here.

A summary of sample descriptions, their geologic relations, and the zircon data are tabulated in table 3. Distribution of zircon model ages is depicted in figure 3.

DISCUSSION

The oldest model age found from this work is 816 ± 4 m.y. for sample 112701 from the tonalitic gneiss from the central part of the southern half of the An Nimas atholith. This

Table 3.--*A summary of sample descriptions and zircon data made in this study*

Sample No. Coordinates	Map, Scale, and Authorship	Geologic Unit	Sample Description and Relationships	Zircon Data: Range of Discordance (percent)	Zircon Data: Model 3 Age (m.y.)
112662 20°47.3'N, 43°41.6'E	Southern Najd 1:500,000 Jackson and others (1963)	ggd	Hornblende, tonalite gneiss	2-7	666 ± 8
	Jabal Yafikh 1:100,000 Schmidt (in preparation)	ggd			
112671 20°05.9'N, 42°47.6'E	Southern Najd 1:500,000 Jackson and others (1963)	gr	Bishah "red" granite. Appears related to a group that cross-cuts most others in immediate area	21-42	678 ± 10
	Junaynah 1:100,000 Schmidt (in preparation)	rgr			
112672 18°43.9'N, 42°01.9'E	Asir 1:500,000 Brown and Jackson (1959)	gg	Granodiorite gneiss of Wadi Bagarah. Roof pendant in 112673	19-33	778 ± 9
	Jabal Aya 1:100,000 Prinz (1975)	at			
112673 18°49.1'N, 42°00.9'E	Asir 1:500,000 Brown and Jackson (1959)	ggd	Biotite leuco-adamellite from inner part of Wadi Bagarah gneiss that intrudes masses sampled by 112672 and 112674	13-20	763 ± 4
	Jabal Aya 1:100,000 Prinz (1975)	at			
112674 18°56.2'N, 41°59.4'E	Tihamat Ash Sham 1:500,000 Brown and Jackson (1958)	gg	Biotite tonalite gneiss. Intruded by 112673	11-29	797 ± 15
	Wadi Hali 1:100,000 Hadley (1975)	gnt			
112679 17°41.7'N, 43°03.3'E	Asir 1:500,000 Brown and Jackson (1959)	gg	Tonalite gneiss. Described by Anderson as "pretectonic mass mostly recrystallized to amphibolite facies"	15-37	663 ± 9
	Wadi Atf 1:100,000 Anderson (1978)	gd			
112680 18°15.9'N, 43°18.5'E	Asir 1:500,000 Brown and Jackson (1959)	gg	Adamellite intrusion into gdl	15-39	660 ± 7
	Wadi Tarib 1:100,000 Stoeser (in preparation)	gdl			
112693 19°5.2'N, 43°42.5'E	Asir 1:500,000 Brown and Jackson (1959)	gg	Biotite granodiorite pegmatites of this unit may be related to gold mineralization in meta-volcanics in nearby Hamdah quadrangle	-- Technical difficulties prevented good age measurement	660 - 700
112695 18°59'N, 43°47'E			Metagabbro that cuts the Hamdah serpentinite body	26-32	664 ± 12
112698 18°06.7'N, 43°19.6'E	Asir 1:500,000 Brown and Jackson (1959)	gr	Biotite granodiorite gneiss. Dome structure surrounded by migmatites. Stoeser suggested "gd2" dome intruded older gneiss "gdl"	31-36	714 ± 28
	Wadi Tarib 1:100,000 Stoeser (in preparation)	gd2			
112701 19°3.01'N, 42°12.00'E	Asir 1:500,000 Brown and Jackson (1959)	ggr	Biotite tonalite gneiss. Main phase of An Nimas batholith	2-7	816 ± 4
	1:100,000 Greenwood (in preparation)	gd			

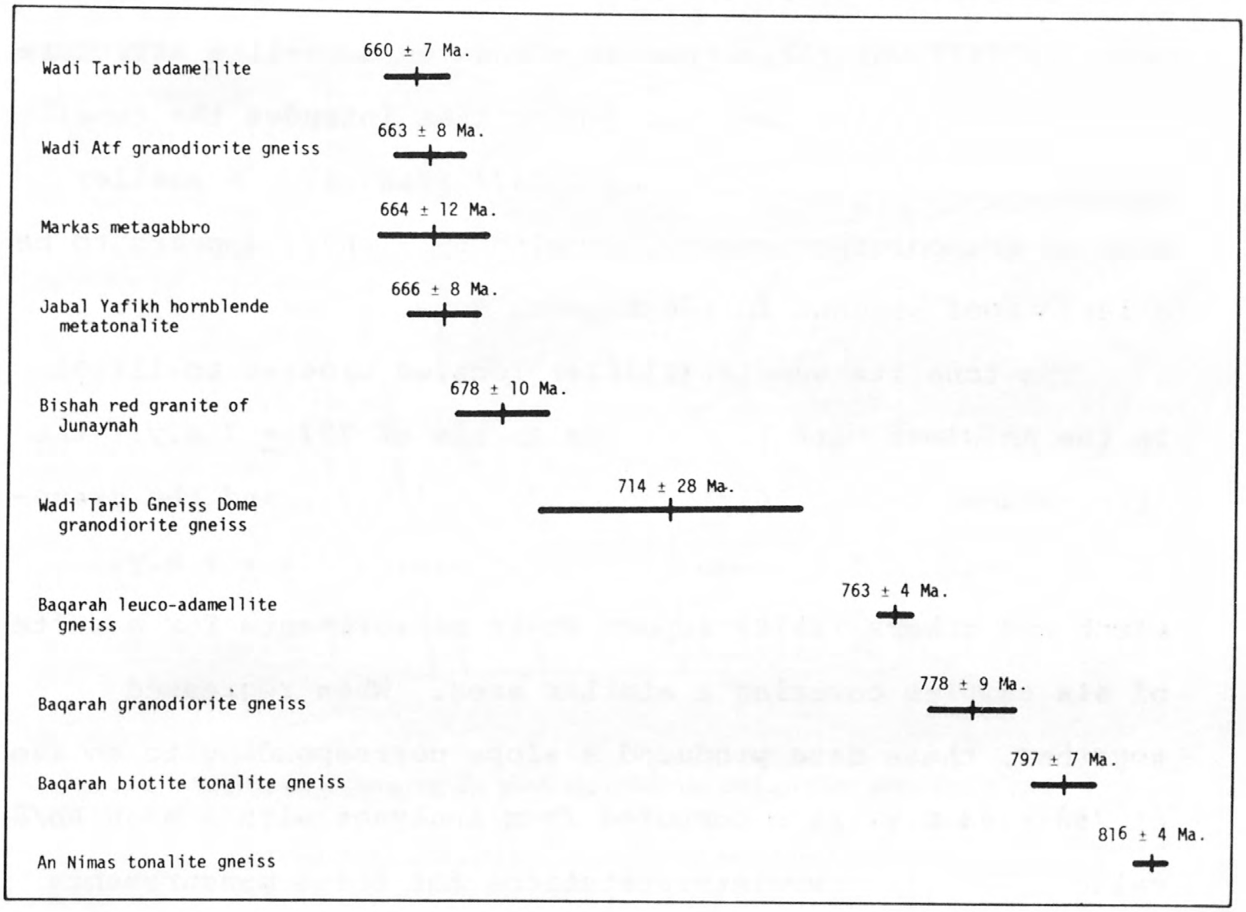

Figure 3. Distribution of zircon-model ages determined in this study for the southern part of the Arabian craton. Uncertainties are depicted for 95 percent confidence limits. Ma=million years.

age is consistent with that of 837 ± 50 m.y. (1 σ) Rb-Sr age obtained by Fleck and others (1978) from the same locality.

Gneisses from Wadi Baqarah, 40 to 80 km south of the An Nimas batholith, yield the next-oldest ages in our study. Sample 112673 was taken from an elongated dome-like structure of leuco-adamellite-to-trondhjemite that intrudes the tonalite gneiss north of it, sampled by 112674 (fig. 4). A smaller mass of granodiorite gneiss, sampled by 112672, appears to be a large roof pendant in the Baqarah dome.

The tonalite sample (112674) located closest to 112701 in the An Nimas batholith yields an age of 797 ± 7 m.y.; the leuco-adamellite (112673) yields 763 ± 4 m.y., and the granodiorite roof pendant sample (112672) yields 778 ± 9 m.y. Fleck and others (1978) report Rb-Sr measurements for a suite of six samples covering a similar area. When regressed together, these data produced a slope corresponding to an age of 763 ± 53 m.y. (1 σ computed from analyses with a mean Rb/Sr value of 0.21). Two interpretations for these measurements must be considered. If the strontium isotopes were completely homogenized throughout the Wadi Baqarah body 763 m.y. ago, then the spread in zircon model ages could represent partial updating of older An Nimas material at that time. Alternatively, the zircon-model ages could represent actual times of emplacement and suggest that pulses of plutonic activity occurred in the Wadi Baqarah region for about 50 m.y. after the emplacement of the An Nimas batholith to the north.

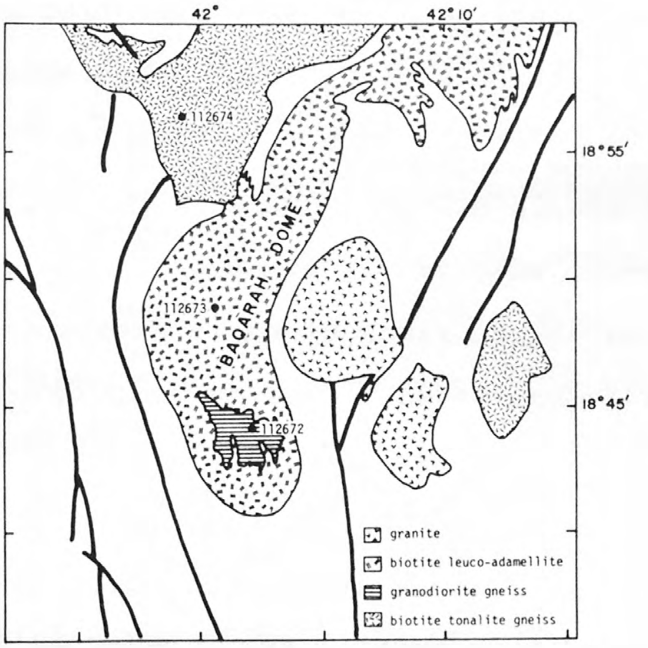

Figure 4. Sketch map showing the geologic relations and zircon-sampling sites at Wadi Baqarah pertinent to this study. The white areas of the map represent metavolcanic and metasedimentary rocks. The An Nimas batholith, sample 112701, is about 40 km north of sample 112674.

Examination of the zircon data in figure 2 reveals that the four points for each sample exhibit excellent linear arrays with no sideways scatter or overlap that could be associated with updating. In addition, the precision of the strontium data obtained for these low Rb/Sr rocks, 763 ± 53 m.y. (1 σ), is not sufficient to compel acceptance of the updating interpretation. Indeed, the strontium data seem compatible with either interpretation, and so the evidence presently available seems weighted in favor of accepting the zircon-model ages as actual times of emplacement. Further data from field observations as well as from petrologic and isotopic measurements are required to delineate the complete sequence of events at Wadi Baqarah.

The remaining seven samples in our study came from a north-south trending area to the east of An Nimas batholith. Four of these yield ages that are younger than those from the An Nimas batholith and fall within the range 660-666 m.y. These are: 112680 Wadi Tarib adamellite, 660 ± 7 m.y.; 112679 Wadi Atf granodiorite gneiss, 663 ± 8 m.y.; 112695 Markas gabbro, 664 ± 12 m.y.; and Jabal Yafikh hornblende tonalite gneiss, 668 ± 8 m.y. Because of technical difficulties[1/], sample 112693, an adamellite from the Hamdah region,

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[1/] The zircons from this sample were separated using Clerici solution, which contains a significant amount of lead. The cleaning step after this procedure was unintentionally omitted, and the data show a very high common lead component for which adequate correction could not be made.

did not yield accurate data, but its age is probably in the range 660 to 700 m.y. The Markas gabbro is petrographically similar to those studied by Coleman and others (1972, in press) and Fleck and others (1976), who found them to be of similar age.

Sample 112679 was selected in order to date one of the older tonalites of the Wadi Tarib batholith as well as to put a lower age limit on a conglomerate overlying it that is considered to belong to the Ablah group, and contains clasts of a similar tonalite (Anderson, 1978). A model age of 663 ± 8 m.y. was obtained for this sample. The zircon data pattern does not permit appreciable updating, and thus a significant age difference is indicated between this tonalite and those of the An Nimas batholith.

Sample 112680 was expected to be a quartz-diorite tonalite, and indeed is mapped as such on the Wadi Tarib sheet (Stoeser, unpublished). However, the high K-feldspar content of 20 percent in the slide examined indicates it is probably from a small intrusion of the young granodiorite-adamellite group. This possibility was not evident at the outcrop. Again, the zircon measurements do not exhibit scatter due to updating and yield a model age of 660 ± 7 m.y. Therefore this unit is significantly younger than its westward equivalents at Wadi Baqarah.

The ages obtained for the above group of samples are all remarkably similar when one considers the wide range of rock types and the great distances between sample locations. The sites extend a distance of nearly 300 km in a north-south trend, and so indicate the widespread generation of magma at that time (660-666 m.y. ago). The work of Fleck and others (1978) indicates that some similar gneisses in the same general region could be in the age range 685-725 m.y., and the relationship of these two rock groups requires further investigation.

The other two samples from east of the An Nimas batholith yielded model ages somewhat older than the 660-665 m.y. group. Sample 112698 is from a granodiorite gneiss dome in the Wadi Tarib 1:100,000 quadrangle that appears to intrude an area of migmatized quartz diorite rocks that surround it. The age obtained is 714 $\pm$ 28 m.y. and is similar to the Rb-Sr isochron age on a similar dome in the adjacent Khamis Mushayt quadrangle to the west (Fleck and others, 1978) and may be the age of several other similar domes in the area.

112671 is the other sample from the eastern part of the shield. It is from a single mica microcline "red" granite from the Junaynah quadrangle that is known informally as the "Bishah granite". Zircons from this sample contained some cores as well as inclusions of unidentified minerals. Nevertheless, a good linear relationship was obtained on the concordia diagram with lower and upper intercepts corresponding to -12 $\pm$ 77 m.y. and 678 $\pm$ 10 m.y. respectively. Because clearly defined bodies of this type appear to crosscut all other intrusive units in the area, an age somewhat younger than 666 m.y. might have been expected. The significance of this age difference has not been determined and it is not possible to decide if the inclusions in the zircons have affected the data. The high $^{206}Pb/^{204}Pb$ ratio of the analyses (2030-4020) does illustrate that no significant common lead is contributed by any included material.

STRATIGRAPHIC IMPLICATIONS

Some stratigraphic evidence results from this study. Sample 112662 intrudes the Halaban group in the Jabal Yafikh quadrangle area (Schmidt, in prep.). Our data indicate that the Halaban has a minimum age of 666 $\pm$ 8 m.y. in this region. The granodiorite gneiss of Wadi Baqarah intrudes the Ablah group, and thus indicates that the Ablah must be older than at least 763 m.y. in that area.

The site of sample 112679 from Wadi Atf was selected because it was overlain by what appears to be a conglomerate of the Ablah group, and might therefore provide us with another maximum-age estimate for that formation. The age we have obtained for this sample, 663 $\pm$ 8 m.y., would provide a much younger upper age limit for the Ablah than indicated by sample 112674 and the work of Fleck and others (1978) on the Wadi Baqarah gneiss. However, some uncertainty exists in the correlation of these sediments with those of the Ablah group, and this provides added complexity to interpretation here. Further field work and sampling will be necessary to determine the strtigraphic implications of the zircon data at Wadi Atf.

The "Bishah granite" is overlain by a basal conglomerate and sediments equated with the Murdama group in the Janaynah quadrangle (Schmidt, unpublished). The present interpretation of the data for the Bishah sample, 112671, requires only that the age of the overlying rocks be less than 678 m.y. Similar red granites in this area yield ages of 600-610 m.y. by K-Ar dating on biotite and hornblende (Fleck and others, 1976).

This work is not comprehensive enough to provide a basis on which to modify existing models for the geologic evolution of the Arabian Shield. It does, however, give a number of new magma crystallization ages that suggest an age pattern for the predominant intrusive rock types across the belt of andesitic volcanic rocks and volcanoclastic sediments to the east of the An Nimas batholith, at approximate long 42° between lats 17°30' and 20°00'. A reduction in age of about 100 m.y. is suggested for the rocks east and northeast of An Nimas but only 50 m.y. for the Wadi Tarib granodiorite gneiss dome in the southeast. A less abrupt transition is deduced by Fleck and others (1978). Current hypotheses on the development of the Arabian craton through an island arc system, based essentially on the chemistry of basaltic and andesitic extrusives (Greenwood and others, 1976) will have to accommodate these observations. Our data provide no further information on the positions of the proposed arcs, although they have added to the general picture.

An event of considerable interest in relation to this work is the status of the Pan African or Mozambiquian orogeny, which is considered to have occurred over wide areas in Africa

550 ± 100 m.y. (Clifford, 1970). Fleck and others (1976) suggest that this disturbance occurred in the Arabian Shield as two thermal pulses at about 620 m.y. and 520 m.y. ago, and that these pulses affected potassium-argon ages for older rocks. The ages we have obtained on earlier units such as those at An Nimas and Wadi Baqarah are in accord with Rb-Sr data and are therefore not likely to have been reset by those events. The younger ages in the range 660-666 m.y. that we have obtained on four of the samples are not as yet confirmed by other measurements. Considered together, however, the data present a systematic picture in spite of the comparatively small ranges of discordance observed between zircon fractions. The lack of scatter in the $^{207}Pb/^{206}Pb$ ages also argues against early disturbance of these systems.

Thus, we have no evidence that any of our zircon data were affected by the Pan African orogeny. A similar lack of response of zircon suites to metamorphic episodes that occur within a few hundred million years of the granitic crystallization, as monitored by K-Ar and Rb-Sr mineral ages, has been clearly demonstrated in other regions of the world (for example, Page, 1976, 1978).

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J.A. Cooper and others – AN EVALUATION OF THE ZIRCON METHOD OF ISOTOPE DATING IN THE SOUTHERN ARABIAN CRATON – IR 257