DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

U-Pb isotopic evidence for accretion of a continental microplate in the Zalm region of the Saudi Arabian Shield

by

John S. Stacey[1/] and Robert A. Agar

Open-File Report 86- 166

Report prepared for Ministry of Petroleum and Mineral Resources,
Deputy Ministry for Mineral Resources, Saudi Arabia

1/ U.S. Geological Survey, Menlo Park, CA

1986

TABLE OF CONTENTS

ILLUSTRATIONS

Page

TABLES

U-Pb ISOTOPIC EVIDENCE FOR ACCRETION OF A CONTINENTAL MICROPLATE IN THE ZALM REGION OF THE SAUDI ARABIAN SHIELD

by

John S. Stacey[1/] and Robert A. Agar

ABSTRACT

The region covered by this work includes three of the main tectonic units of the Arabian Shield: the Afif continental terrane, the Nabitah suture with its associated mobile belt, and the Asir ensimatic arc terrane. The geology of the area is well understood, and this geochronologic and isotopic study confirms that the Afif terrane was a continental microplate in the late Proterozoic. The study also provides a time frame for the crustal evolution of this part of the Shield.

U-Pb zircon age data from a pelitic garnet-sillimanite gneiss of the Kabid formation shows that this part of the continental basement in the Afif terrane may be as old as 1830 Ma. Isotope data indicate that lead from the Kabid gneiss resided in the upper continental crust for a long period before 1830 Ma, and require that Archean rocks exist at depth beneath the Afif terrane.

Lead isotope data reveal a change in the nature of the underlying crust, from continental basement in the northeast, to less radiogenic, marginal arc rocks in the southwest. This change is coincident with both aeromagnetic data, and a facies change within a pre-collision marginal basin. Miogeosynclinal continental shelf facies of the Siham group lie unconcormably over the Kabid formation, and are in the area of continental lead signatures. Eugeosynclinal deep water sediments and volcanics, in association with ultramafic rocks, occur in the area of marginal arc signatures.

U-Pb zircon age determinations show that this "Andean" continental margin developed before about 720 Ma, and emplacement of calc-alkaline plutonic rocks continued until about 690 Ma. During the period 690-640 Ma, the continental Afif microplate collided with the Asir terrane as part of the Nabitah orogeny. At approximately 640 Ma ago, the Najd strike-slip orogen commenced with a dextral phase that controlled the emplacement of granitic plutons as well as the development of a series of large pull-apart grabens. Some of these grabens were floored by new oceanic crust and were filled with volcano-sedimentary rocks of the Bani Ghayy group. Subsequently, the Najd fault system changed to sinistral strike slip motion at about 620 Ma ago.

1/ U.S. Geological Survey, Menlo Park, CA

INTRODUCTION

The final phases of cratonization of the Arabian Shield involved microplate collisions and subsequent orogeny along the N-S trending Nabitah and Al Amar sutures (fig. 1; Stoeser and Camp, 1985). These suture zones are located on either side of the Afif terrane, and are dated at 690-650Ma and 670-640 Ma, respectively (Stoeser and others, 1984; Stacey and others, 1984). Common-lead data from galenas, and feldspars in igneous rocks, demonstrate a contrast between lead-isotope ratios characteristic of ensimatic arc sources in the western Shield, and signatures derived from older sialic crust in the east (Stacey and others, 1980; Stacey and Stoeser 1983; Stacey & Hedge, 1984). The lead data are evidence for the presence of older continental basement in the southern part of the Afif terrane. Older continental crust or basement has also been recognized from independent field studies in the Zalm area (Agar, 1984), which is bounded to the west by the ensimatic Asir terrane, and lies across both the Nabitah suture zone and the western margin of the sialic Afif terrane (figs. 1 and 2). Detailed mapping in this area (Agar, 1984) reveals a volcano-sedimentary sequence that is older than the suturing event, and that lies unconformably upon the older basement rocks of the Afif terrane. Agar (1985a) interpreted this as direct evidence for a western continental margin to the Afif terrane in late Proterozoic time. The main object of this study is to use zircon U-Pb geochronolgy to provide a time frame for the major tectonic events in the region. In addition, lead-isotope data from feldspars of the same samples act as tracers to indicate some of the mechanisms involved.

Precambrian rocks of the Zalm area record three major tectonic events. Evidence for the earliest event (D_1) is preserved only in the gneisses of the Kabid formation. The second event (D_2) is equivalent to the Nabitah collision orogeny (Agar, 1984) and the third (D_3) records the Najd, NW-SE strike-slip orogeny that followed directly afterwards (Moore, 1979).

The Kabid rocks are the oldest in the region, and comprise high grade amphibolite facies paragneisses in which the foliation (S_1) is refolded about north-south trending D_2 fold axes (Agar, 1985a). The Kabid formation is overlain unconformably by volcano sedimentary rocks of the Siham group which are metamorphosed only to upper greenschist facies, medium grade, and preserve only D_2 and D_3 structures (fig. 3). A facies change, from shallow water continental shelf sedimentation over continental basement in the east of the area, to deep water oceanic sedimentation and volcanism in the west, has been demonstrated within this group. The rocks, as well as the facies change, are typical of volcanism and sedimentation in marginal basins of active continental margin (Andean) tectonic environments (Agar, 1985a).

The Siham group is unconformably overlain by volcanosedimentary rocks of the Bani Ghayy group (fig. 3). The latter group was deposited and deformed in large encratonic north-trending grabens produced during the final regional deformation (D_3). Both graben formation and deformation were the products of large-scale transcurrent movements of the Najd fault system (Agar, 1985b and c).

Pre-D_1 intrusions are amphibolite dikes and sills in the Afif terrane. Post-D_1 and pre-D_2 intrusions include ultramafic and mafic rocks of the Siham group and calc-alkaline rocks of the Jidh suite (fig. 3). Younger calc-alkaline intrusions, syntectonic with D_2, comprise the Naim complex and the Subay suite. Post-D_2 but pre-D_3 plutonism forms a series of gabbro-diorite-granite complexes and ultramafic rocks that are emplaced in faults of the Bani Ghayy group. Post-D_3 plutonic rocks include the Haml suite, many units of which show syntectonic features with respect to the Najd faults in the area.

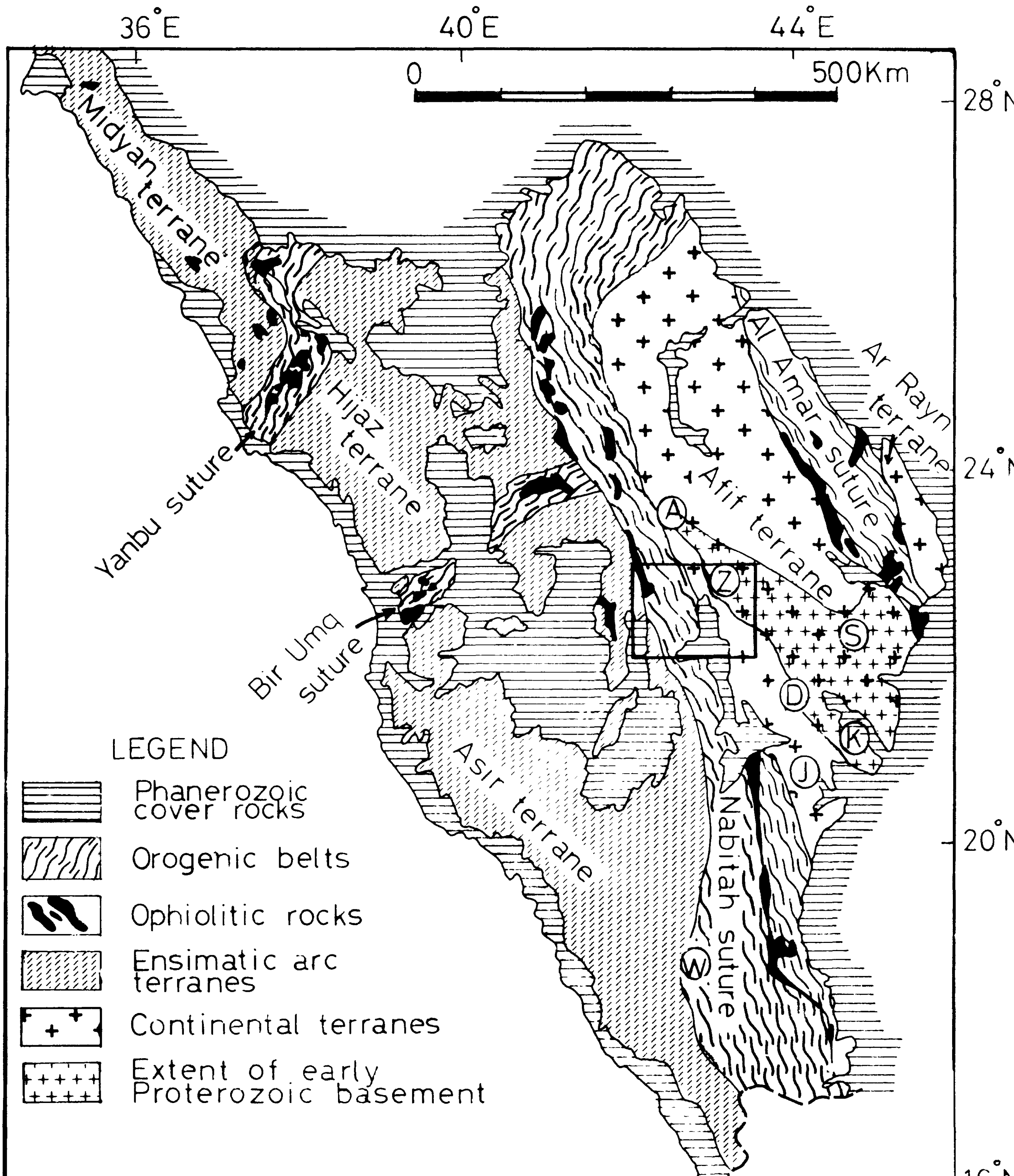

Figure 1.--*The location of the Zalm quadrangle (Z) relative to the main structural elements of the Arabian Shield (after Stoeser and Camp,1985). Other localities mentioned in the text are: (A) Afif; (S) Jabal Sitarah; (D) Jabal Dahul; (K) Jabal Khida; (J) Juq Juq; (W) Wadi Tarib batholith.*

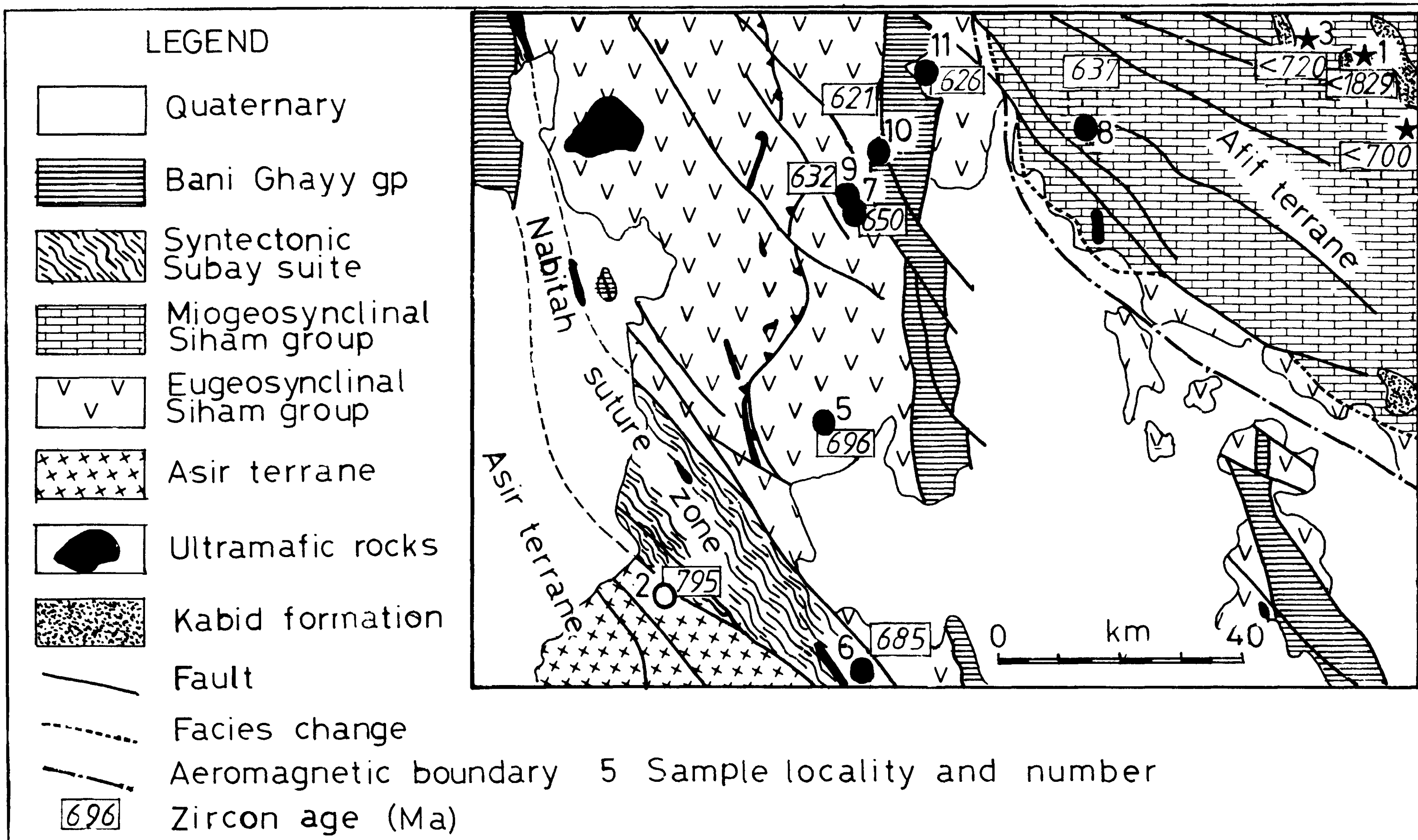

Figure 2.--*Zircon-age determinations, Pb-isotope types, and Sr-isotope data for sample localities in the Zalm quadrangle relative to the main geological elements.*

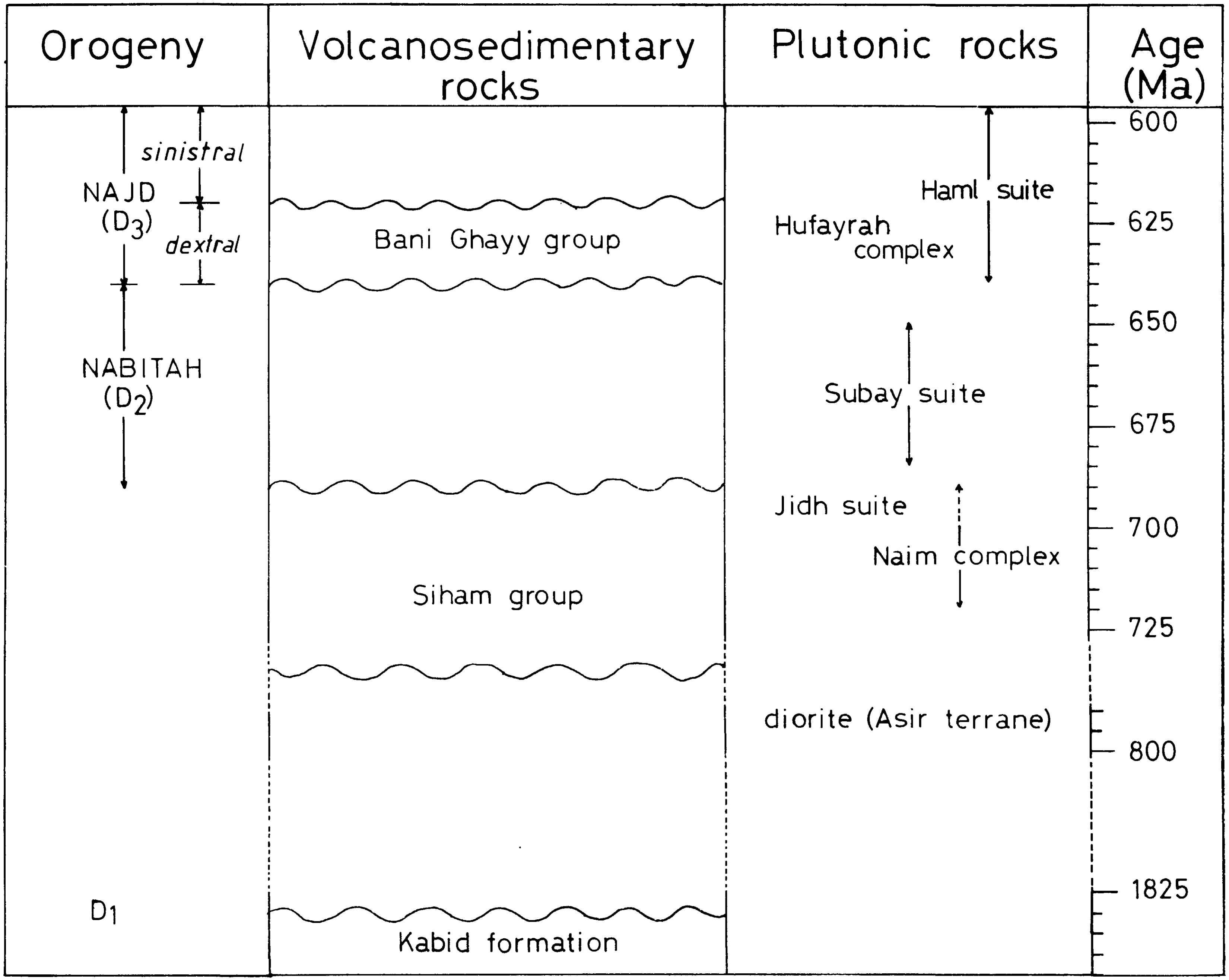

Figure 3.-- *A time frame for the tectonic, stratigraphic and plutonic evolution of the Zalm area (after Agar, 1984).*

ANALYTICAL METHODS

Chemistry and mass spectrometry of lead and uranium from zircons follow the procedures of Krogh (1973) with minor modifications. Laboratory-blank levels for lead in zircons were monitored within the range 0.3 to 1.0 nanograms. Corrections for common lead inherent in the zircons were made by using either the composition of lead from feldspar in the same samples, or a version of the Stacey Kramers (1975) model using $^{238}U/^{204}Pb$=9.22 since 3.7 Ma ago.

Feldspar concentrates were washed with 7N HNO_3 and 6N HCl and then leached in warm 5-percent HF, a procedure adopted by Ludwig and Silver (1977) in order to minimize any surficial radiogenic lead component. This was followed by dissolution at 160 C using a solution of 48 percent HF, 15N HNO_3 and 50 percent $HClO_4$. Lead was extracted using a bromide-form, anion-exchange resin column.

Isotope ratios were measured with a 30-cm radius, 90^{o} sector, automated mass spectrometer. For uranium analyses, a triple-filament assembly was used, and lead was analyzed with silica-gel on a single rhenium filament. Corrections for lead fractionation were determined from analysis of the standard NBS SRM-981 at about 0.12% per mass unit. For feldspar lead, precision of isotope ratios with respect to ^{204}Pb is $\pm$0.10% (95% confidence limits). Uranium and lead concentrations are precise to $\pm$1.2 percent.

Uncertainties for the intercepts between regression lines and concordia are also 95% confidence limits. They are calculated by the method of Ludwig (1982) in which errors are propagated throughout the entire analytical procedure, and from which the $^{206}Pb/^{238}U$ - $^{207}Pb/^{235}U$ correlation coefficients are computed (table 1). These coefficients determine the size of the error envelopes for the data points in concordia diagrams and help to determine the intercept errors. Significant common lead corrections adversely affect the correlation coefficients when $^{206}Pb/^{204}Pb$ ratios are less than about 800. Uranium decay constants used for age calculations are those of Jaffey and others (1971).

In order to develop chords from data on concordia plots, it is common practice to analyse sized zircon fractions of different magnetic susceptibility. Recently, abrasion of zircons has been shown to yield data that are more concordant (Krogh, 1982). In our study, abrasion has significantly increased the concordance of the data for some of the early Proterozoic zircons from the Kabid pelitic paragneiss (locality 1, fig. 2; table 1; fig. 4) but made virtually no difference to the data from the granite sample (locality 9, fig. 2; table 1, fig. 6).

U-Pb GEOCHRONOLOGY

ANALYTICAL DATA AND AGE DETERMINATIONS

Sufficient zircon for analysis was obtained from 11 of the 14 samples collected, and the data are shown in tables 1, 2, and figures 4 to 6.

The pelitic garnet-silliminite gneiss was collected from the Kabid formation that constitutes the basement (locality 1, fig. 2). In appearance, all the zircon grains from this sample are very rounded, some being almost spheroidal. Their surfaces are invariably pitted, and the lighter-colored grains have frosted surfaces. There is also a darker-colored group in which surface frosting is less apparent. There can be little

Table 1.--*U-Pb data for zircons from the Zalm region.*

[Zircon fraction: M magnetic; NM non-magnetic; A abraded; A75 abraded 75 minutes; Rho is 207Pb/235U-206Pb/238U correlation coefficient (Ludwig, 1982).]

Locality & Sample Nos. (Mesh size)	Sample weight mgm	U ppm	Pb ppm total	Atomic Ratios 206Pb/238U	Atomic Ratios 207Pb/235U	Atomic Ratios 207Pb/206Pb	Apparent Ages Ma 206Pb/238U	Apparent Ages Ma 207Pb/235U	Apparent Ages Ma 207Pb/206Pb	Rho	Measured 206Pb/204Pb
1. 363402											
(-150+200)NMA	2.37	438	118.1	0.26219	3.8923	0.10779	1499	1612	1763	0.991	4164
(-150+200)NM	9.63	387	86.8	0.21819	3.0970	0.10294	1272	1432	1678	0.932	3772
(-200+250)NMA	9.11	440	98.4	0.21910	3.1527	0.10440	1277	1446	1703	0.992	7365
(-200+250)NM	9.71	433	92.6	0.20958	2.9459	0.10194	1227	1394	1660	0.989	5344
(-250+325)NM	9.32	443	93.8	0.20608	2.8856	0.10155	1208	1378	1653	0.988	3054
(-325)M	6.30	615	119.7	0.18820	2.5933	0.09990	1112	1299	1623	0.993	3027
2. 363410											
(-150+200)NM	9.71	312	39.1	0.12156	1.0927	0.06519	740	750	780	0.984	5985
(-250+325)NM	7.74	316	37.7	0.11686	1.0475	0.06501	712	728	775	0.904	3940
3. 363401											
(-250)NM	1.20	1057	122.7	0.10213	0.8897	0.06318	627	646	714	0.869	993
4. 363403											
(-100+150)A	1.09	960	106.8	0.10069	0.8868	0.06388	618	645	738	0.951	799
(-100+150)	1.53	593	82.8	0.10817	0.9571	0.06417	662	682	747	0.838	243
(-150+200)NM	7.78	828	92.5	0.10440	0.9134	0.06348	640	660	724	0.977	1666
(-325)M	4.20	2731	267.6	0.09012	0.7769	0.06249	556	583	691	0.979	739
5. 363411											
(+100)NMA	9.54	526	57.5	0.10676	0.9223	0.06266	654	664	697	0.980	4759
(+100)NM	14.99	511	55.2	0.10566	0.9126	0.06264	647	658	696	0.965	3626
(-150+200)NM	15.36	548	59.9	0.10768	0.9309	0.06270	659	668	698	0.978	6490
(-325)M	1.70	1087	112.6	0.09322	0.8073	0.06281	575	601	702	0.787	521
6. 363409											
(+150)NM	10.86	162	15.6	0.09436	0.8084	0.06213	581	602	678	0.933	1465
(-325)M	5.58	420	26.8	0.05946	0.5042	0.06151	372	415	657	0.915	579
7. 363413											
(+150)NM	2.74	1851	132.0	0.06942	0.5816	0.06076	433	465	631	0.977	915
(-150+250)NM	1.23	2433	184.8	0.07414	0.6233	0.06098	461	492	638	0.878	884
(-250)NM	5.48	2066	153.7	0.07369	0.6230	0.06131	458	492	650	0.976	1312
8. 363404											
(+100)NM	10.06	224	24.0	0.09886	0.8295	0.06085	608	613	634	0.933	1167
(-325+400)NM	9.05	414	40.8	0.09378	0.7862	0.06080	578	589	632	0.960	2694
(-400)NM	10.36	435	43.2	0.09458	0.7916	0.06070	582	592	628	0.958	3549
9. 363412											
(+150)A120	3.40	3227	292.3	0.08878	0.7421	0.06062	548	564	626	0.988	2252
(+150)A75	1.61	2711	242.2	0.08755	0.7315	0.06060	541	557	625	0.961	1637
(+150)NM	9.42	3064	275.9	0.08800	0.7368	0.06072	544	560	630	0.989	2630
(-250)M	13.15	3878	229.2	0.05408	0.4481	0.06009	340	376	607	0.981	836
10. 363414											
(+100)NM	13.56	334	36.4	0.09719	0.8128	0.06066	598	604	627	0.898	1428
(-250+325)NM	9.81	456	50.7	0.09900	0.8261	0.06052	608	611	622	0.983	2565
(-325)	1.00	507	53.6	0.09062	0.7609	0.06090	559	574	636	0.948	630
11. 363405											
(+100)NM	2.10	1613	52.5	0.02844	0.2371	0.06046	181	216	620	0.490	415
(-150+200)NM	7.36	1181	52.3	0.04157	0.3474	0.06062	263	303	626	0.949	1024
(-325)M	4.65	4446	90.4	0.01496	0.1278	0.06192	96	122	671	0.695	187

doubt of the detrital nature of the crystals. When analyzed, four sized zircon fractions yielded $^{207}Pb/^{206}Pb$ ages of 1623 to 1670 Ma, and are the oldest yet obtained in the Arabian Shield. On the concordia diagram, the rather short chord gave upper and lower intercept ages of 1817±40 Ma and 442±84 Ma, respectively. Abrasion of the largest size fraction (-150+200) produced a more concordant point, with a $^{207}Pb/^{206}Pb$ age of 1760 Ma, that considerably extended the data trend. Abrasion of the (-200+250) fraction yielded a data point that lies slightly to the right of the original line in fig. 4. All data for this sample regressed together give concordia intercepts of 1829±45 Ma and 471±94 Ma.

Our oldest late Precambrian sample is a diorite gneiss from the southwest of the study region (locality 2, fig. 2). It preserves a tectonic fabric which is refolded about D_2 fold axes, but which is quite distinct from F_1 of the Kabid gneiss. On the concordia diagram (fig. 4), two almost concordant zircon data points yield an age of 794±10 Ma.

The next youngest ages are given by two samples collected from the Naim complex, which intrudes the Kabid formation and the Siham group (localities 3 and 4, fig. 2). The apparently older sample, a granodiorite gneiss (locality 3), yielded only sufficient zircon for one analysis, and the data point is shown in figure 4. The $^{207}Pb/^{206}$ age is 718 Ma and must be regarded as a maximum age. Four zircon fractions from a monzogranite (locality 4) gave scattered data on concordia (also fig. 4) that do not yield meaningful intercepts (table 2). The scatter is doubtless due to assimilation of older zircons from the enveloping basement rocks. The best estimate for the age of intrusion is the lowest $^{207}Pb/^{206}Pb$ age of the four fractions and is about 700 Ma (fig. 3). However, as with the previous sample, this must be regarded as a maximum.

Zircon data from a granodiorite gneiss of the Jidh suite (locality 5, fig. 2) indicate intrusion at a well-determined time of 696±8 Ma (fig. 5), contemporaneous with the Naim complex to the northeast. The concordia diagram shows that abrasion of the +100 non-magnetic fraction of the apparently homogeneous zircons did not appreciably affect the nearly concordant data (fig. 5).

A sample of the syntectonic Subay suite, a granodiorite gneiss (locality 6, fig. 2) produced two zircon fractions that give a chord with an upper intercept age of 685±7 Ma (fig. 5). Thus, the Nabitah orogeny had commenced in the Zalm region by that time. Three fractions from a Jidh-suite monzogranite (locality 7, fig. 2) show it to be somewhat younger, with an age of about 640 to 650 Ma (fig. 5). Field checking of this pluton revealed it to be a diapiric intrusion with a foliated margin and an homogeneous core. Its contact is mainly concordant, but locally discordant with D_2 structures in both the Siham group and other rocks of the Jidh suite. Thus it is syn- to post-tectonic relative to the Nabitah orogeny, and is not a member of the pre-tectonic Jidh suite.

Post-tectonic intrusives include a Haml granodiorite (locality 8, fig. 2), which yields a nearly concordant age of 637±11 Ma (fig. 6). The granodiorite, and an alkali feldspar granite of the Hufayrah complex (locality 9, fig. 2) both show mechanisms of emplacement controlled by Najd fractures (Agar, 1984). The concordia plot for the Hufayrah monzogranite yields an age of 632±3 Ma (fig. 6).

Bani Ghayy rhyolite (locality 10, fig. 2) yields a well-defined concordant age of 621±5 Ma (fig. 6). A Haml monzogranite (locality 11, fig. 2) appears to be the youngest sample in this study, and three zircon fractions were analyzed (table 1). All of these high-uranium zircons (1000-4000 ppm U) have quite recently lost more than 50 percent of their lead, and two fractions have such high common-lead contents ($^{206}Pb/^{204}Pb$ ratios of 415 and 187, respectively) that use of their data for the concordia diagram leads to extremely high errors in the computed age (table 2, fig. 6). However, the mid-sized fraction (table 1) does have an acceptable common lead content ($^{206}Pb/^{204}Pb$ ratio is 1024) and consequently its $^{207}Pb/^{206}Pb$ age of about 626 Ma is the best estimate we have for the age of this monzogranite (table 2).

INTERPRETATION OF AGES AND THEIR SIGNIFICANCE

The Kabid formation represents the sialic basement upon which the miogeosynclinal sediments of the Siham group were unconformably deposited. It is of higher metamorphic grade than the Siham group and, as we have observed, preserves evidence of an older tectonic event (Agar,1984). Although the upper amphibolite-grade metamorphism must have severely disturbed the U-Pb system, it is clear from the detrital appearance of the zircons that they were not recrystallized by that event. The abraded data give some indication of an older history, but the substantial movement of the data point for the (-150+200) fraction along an almost unchanged chord is strong evidence that the U-Pb system was almost completely reset at about 1830 Ma, and records the time of metamorphism. Thus, the most likely interpretation of the data is that these detrital zircons were derived from an older terrane, and were metamorphosed in the Kabid gneiss at about 1830 Ma. The alternative, that the metamorphism of the Kabid gneiss only partially reset the zircon U-Pb system, would imply that the 1830-Ma event is an artifact, and that the metamorphism occurred sometime after 1830 Ma. Geologic considerations fix a lower limit for the metamorphism as sometime prior to intrusion of the Naim complex, about 720 Ma ago. The ages of the source rocks of the pelitic sediment remain undetermined, but we shall see that lead isotope analyses indicate these were probably Archean.

The diorite from locality 2 (fig. 4) has a relict tectonic fabric refolded about the D_2 fold axes, but is quite distinct from S_1 in the Kabid gneiss. The zircon age of 794±10 Ma is also clearly pre-tectonic, and the rock is interpreted to be a part of the older Asir terrane to the west of the suture zone (figs. 1 and 4).

As analyzed, ages are yielded that show syntectonic emplacement of the Naim complex in the period 718-700 Ma, of the Subay suite at about 685 Ma, but pre-tectonic emplacement of the Jidh suite at 695 Ma. Uncertainties in the Naim complex ages still permit the Naim complex to be younger than the Jidh suite. However, plutonic emplacement during episodic compressional phases at destructive plate margins has been shown to produce sequential orthogneisses and homogeneous unfoliated granitoids (Moore and Agar, 1985). Rapid plate convergence and regional compression at the time of Naim emplacement, followed by a quiescent period during emplacement of the Jidh suite, and then major compressional orogeny coincident with emplacement of the Subay suite, would explain the observed geology and isotopic ages. The relatively young age of 640-650 Ma for the Jidh monzogranite (locality 7, fig. 2) is consistent with its intrusion late in the orogeny. The pluton is one of a north-trending line of diapiric intrusions that are typical of forceful mesozonal emplacement (Agar, 1984) and represent the last phase of syntectonic plutonism along the mobile belt.

Table 2.--*Summary of U-Pb zircon ages for samples in this study.*

[Uncertainties are 95% confidence levels, computed by the method of Ludwig (1982). For four fractions or less, scatter was assumed to be due to analytic error only.]

Locality	Sample No.	Coordinates	No. of Fractions	Upper Intercept Ma	Upper Intercept Ma	Preferred Age Ma	Sample Descriptions
1.	363402	22 56.26'N 43 24.51'E	6	1829±45	471±94	1829±45	Kabid formation: garnet-sillimanite gneiss (pelite).
2.	363410	22 10.74'N 42 18.76'E	2	794±10	200±75	794±10	Diorite gneiss
3.	363401	22 57.83'N 43 19.67'E	1	-	-	<718	Naim complex: granodiorite gneiss.
4.	363403	22 50.74'N 43 28.42'E	4	-	-	<700	Naim complex: granite gneiss.
5.	363411	22 23.76'N 42 32.99'E	4	696±8	-29±135	696±8	Jidh suite: granodiorite gneiss.
6.	363409	22 00.43'N 42 37.64'E	2	685±7	39±13	685±7	Subay suite: granodiorite gneiss.
7.	363413	22 43.43'N 42 36.66'E	3	-	-	640-650	Jidh suite: young diapiric monzogranite
8.	363404	22 49.44'N 43 00.87'E	4	637±11	79±142	637±11	Haml suite: granodiorite.
9.	363412	22 43.81'N 42 36.13'E	4	632±5	34±9	632±5	Hufayrah complex: granite.
10.	363414	22 47.92'N 42 47.99'E	3	621±5	-179±157	621±5	Bani Ghayy group: rhyolite.
11.	363405	22 15.13'N 42 42.84'E	3	-	-	~626	Haml suite: Awjah monzogranite.

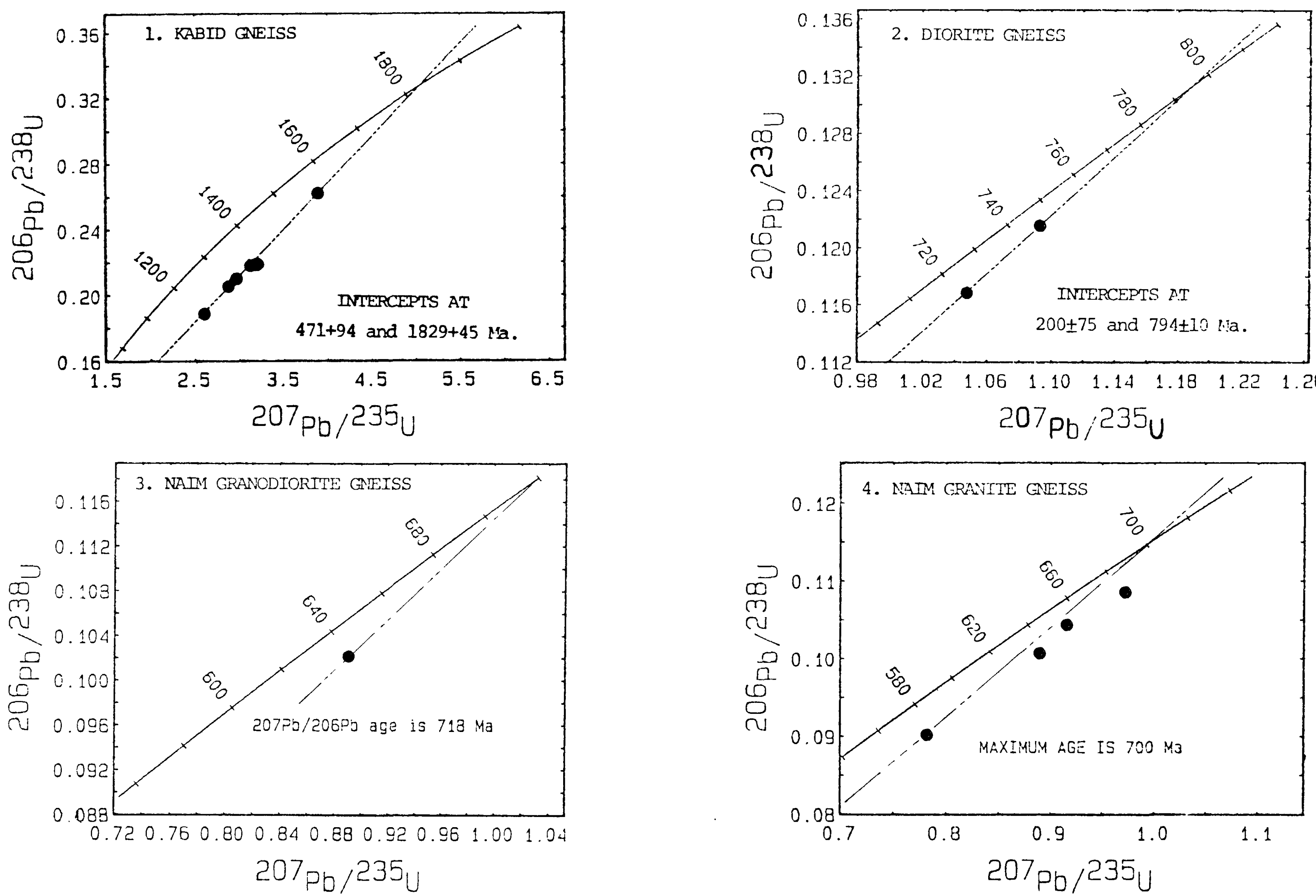

Figure 4.--*U-Pb concordia diagrams of zircon for pre- and syntectonic samples, localities 1 to 4, fig 2.*

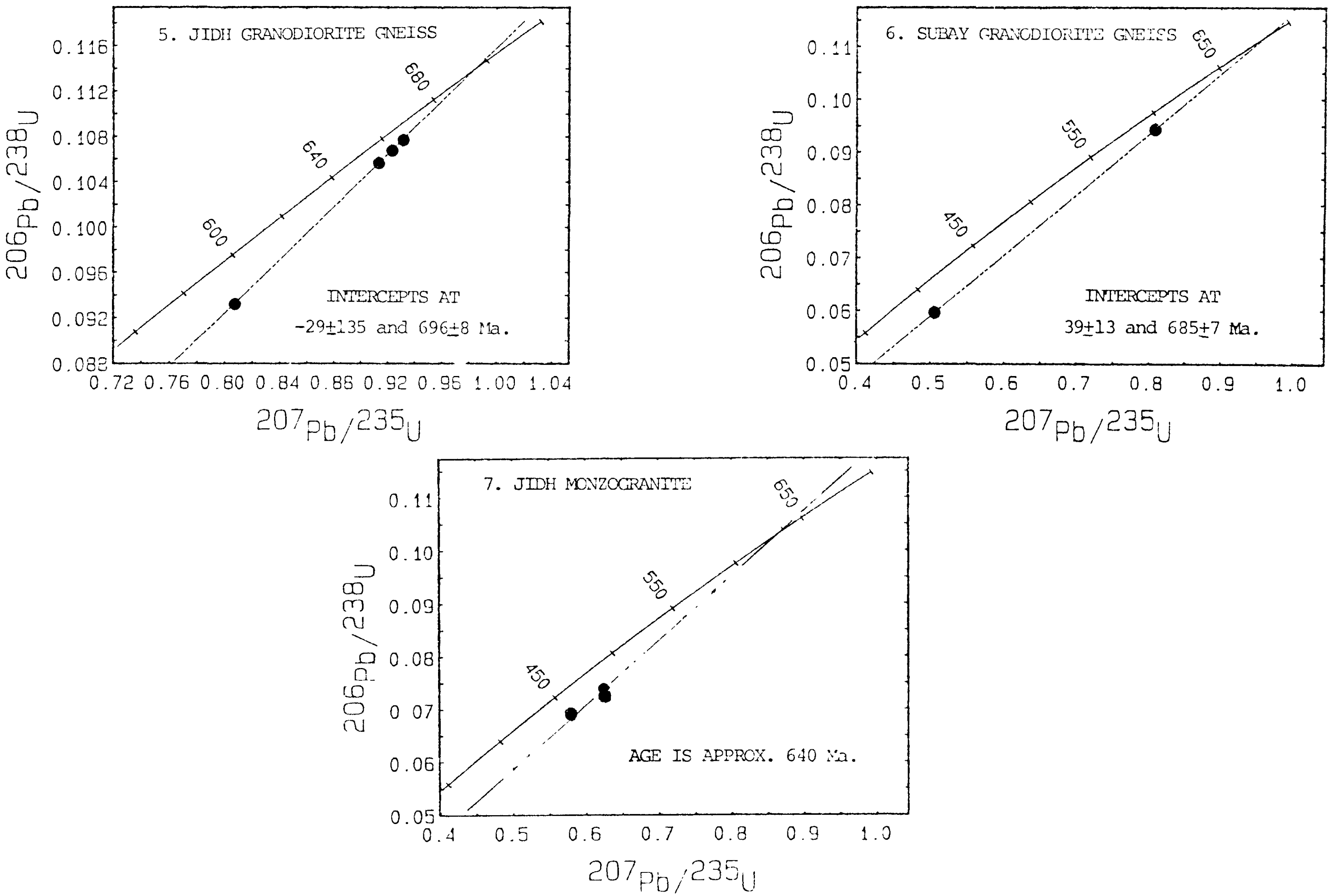

Figure 5.--*U-Pb concordia diagrams of zircon for pre- and syntectonic samples, localities 5 to 7, fig. 2.*

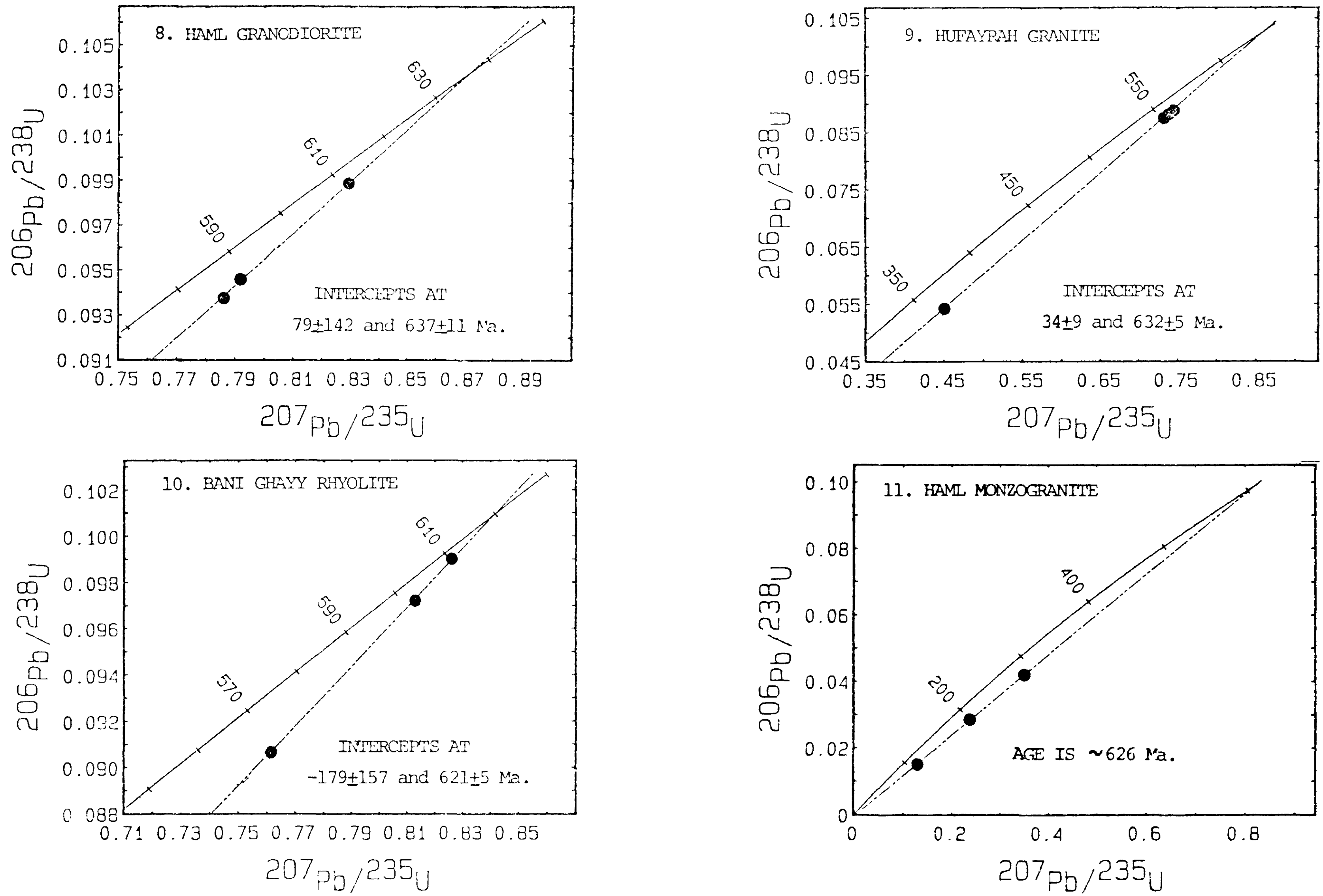

Figure 6.--*U-Pb concordia diagrams of zircon for post-tectonic samples, localities 8 to 11, fig. 2.*

The post-tectonic Hufayrah complex is older than the Bani Ghayy volcano-sedimentary rocks, and is one of a number of gabbro-granite complexes in the Zalm area which show a complex interrelationship between the gabbro and the granite. At Hufayrah, gabbro emplacement was both preceded and followed by intrusion of alkali feldspar granite. The two granites are indistinguishable petrologically. However, the granite sampled (locality 9, fig. 2) was intruded by the gabbro, and hence is older. These gabbro-granite complexes are thought to represent the roots of volcanoes from which were extruded the bimodal volcanics of the Bani Ghayy group (Agar, 1984). The Bani Ghayy group lies unconformably upon the older alkali feldspar granite of the Hufayrah complex. The basal conglomerate at locality 11 (fig. 2) contains thick rhyolite flows and sills, one of which was sampled, but both the rhyolite and conglomerate are intra-formational further south, where older conglomerates and volcanics occur (Agar 1985b). Thus, the sampled rhyolite lies midway through the Bani Ghayy succession. The concordant zircon age of 621 ± 5 Ma is slightly younger than that of the older Hufayrah granite (632 ± 5 Ma), but not by so much as to preclude the possibility that the granite was the parent magma for some of the older rhyolites exposed further south, or that the younger Hufayrah granite was coeval with this rhyolite.

Emplacement of the Hufayrah complex and formation of the Bani Ghayy grabens were both controlled by early, right-lateral strike-slip faults of the Najd fault system (Agar, 1985c). Thus, both post-date the onset of the Najd orogeny (D_3). The Haml granodiorite (locality 8, fig. 2) was selected as one of the oldest Haml members, and also because its foliation is consistent with syntectonic emplacement with the dextral phase of the Najd strike-slip orogen (Agar, 1984). The nearly concordant zircon age of 637 ± 11 Ma is the oldest age so far reported for a pluton that is syntectonic with Najd faulting in the Arabian Shield. The second Haml pluton sampled, a monzogranite (locality 11, fig. 2), was selected because it post-dates dextral Najd fractures and deformation in the Bani Ghayy group, but is displaced by sinistral Najd fractures. The rather poorly defined zircon age of about 626 Ma is not statistically different from the age of the Bani Ghayy rhyolite (locality 10, fig. 4). However, the field relationships between the monzogranite, the Bani Ghayy group and Najd structures are very clear, and a maximum age of about 620 Ma is the best estimate for the time of change from dextral to sinistral shear in this part of the Najd orogen.

LEAD ISOTOPIC DATA AND THEIR GEOLOGIC IMPLICATIONS

Previous lead isotope studies in the Shield have shown that the data fall into three main groups. Lead isotope data from the western terranes show that the rocks were probably formed in ensimatic island-arc environments 900 to 700 Ma ago, where there was little or no contribution from older continental material (Stacey and others, 1980; Stacey and Stoeser, 1983). Rocks of the Wadi Tarib batholith in the southern Shield ("W" in fig. 1) are typical of this group, and the fields for their lead isotopic compositions are shown in figure 7.

Analyses from the same studies showed that lead isotopic compositions from galenas and feldspars in the Al Amar region of the eastern Shield (fig. 1) form a distinctly different group. They exhibit somewhat more elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios than those in the west, and their fields are shown in figure 6. Some of the Al Amar results were interpreted to be characteristic of continental lower crust, perhaps as old as 2000 Ma. Stacey and Stoeser (1983) also showed isotope ratios to be considerably more elevated in the southern part of the Afif terrane at Jabal Sitarah, Jabal Dahul, and at Afif (figs. 1 and 7). Furthermore, Stacey and Hedge (1984) found 1630-Ma zircons in a granodiorite from Jabal Khida in the Afif terrane (figs. 1 and 7). Neodymium and strontium data, utilizing a simple single stage model for the formation of this rock, indicated separation from the mantle 1600-1800 Ma ago, thus apparently concurring with the zircon data. The lead-isotope ratios, however, indicated a more complex situation involving not only the 1630-Ma event, but a long, upper crustal pre-history for the lead extending back into the Archean. On the basis of these data, the Afif terrane is considered to be underlain, at least in part, by continental basement of early Proterozoic to Archean age (Stoeser and Camp, 1984).

The lead-isotope data (table 3, fig. 7) are from the same samples that we have dated (fig. 2). In the southwest of the study area, data from the 794-Ma diorite (locality 2) in the Asir terrane plot below the other Zalm data and close to the fields for the Wadi Tarib Batholith (Stoeser and others, 1984). In contrast, lead from the 1840-Ma Kabid formation (locality 1, figs. 2 and 7) has the most elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios yet found in the Shield. The extremely high $^{207}Pb/^{204}Pb$ value of 15.69 can only be the product of a very long period of development in the upper continental crust prior to the metamorphic event at 1830 Ma. This is because only in the Archean was the comparatively short-lived isotope ^{235}U sufficiently abundant, relative to ^{238}U, to produce the Pb-isotope ratios we observe today. We do not know when the feldspar lead of the Kabid gneiss was last equilibrated with its whole rock lead, but assuming it was about 650 Ma ago, computation shows that for an arbitrary time of separation from the mantle of 2800 Ma ago, the $^{238}U/^{204}Pb$ (μ) value for evolution of the lead from that time to 1840 Ma, was about 13.7. This compares with μ about 8.7 for average mantle, and (μ) about 10 for average crust. The other rocks in this study associated with the Kabid gneiss (localities 3 and 4, fig. 2) also have very elevated ratios in figure 7, and they clearly acquired lead from the older basement rocks that they intruded about 700 Ma ago.

The remainder of the lead analyses are from Zalm rocks that were emplaced in the transition zone between the Asir and Afif terranes. The data plot above those of the Wadi Tarib batholith (fig. 7). It is probable that these more evolved isotopic compositions at Zalm result from the interaction of mantle, oceanic crust, and a significant contribution from continental sedimentary material in the evolution processes of the marginal arc. In this regard, we note that the Wadi Tarib batholith rocks are emplaced west of the Nabitah suture, where the presence of older continental material would have been less likely. We also note that the Zalm data plot in the same fields in figure 7 as those from Al Amar, on the eastern margin of the Afif terrane. Because suturing occurred in both regions during approximately the same period of time, 690 to 640 Ma ago, the lead data suggest that in each region, source rocks with a similar range of ages and of isotopic compositions were involved in the orogenic processes.

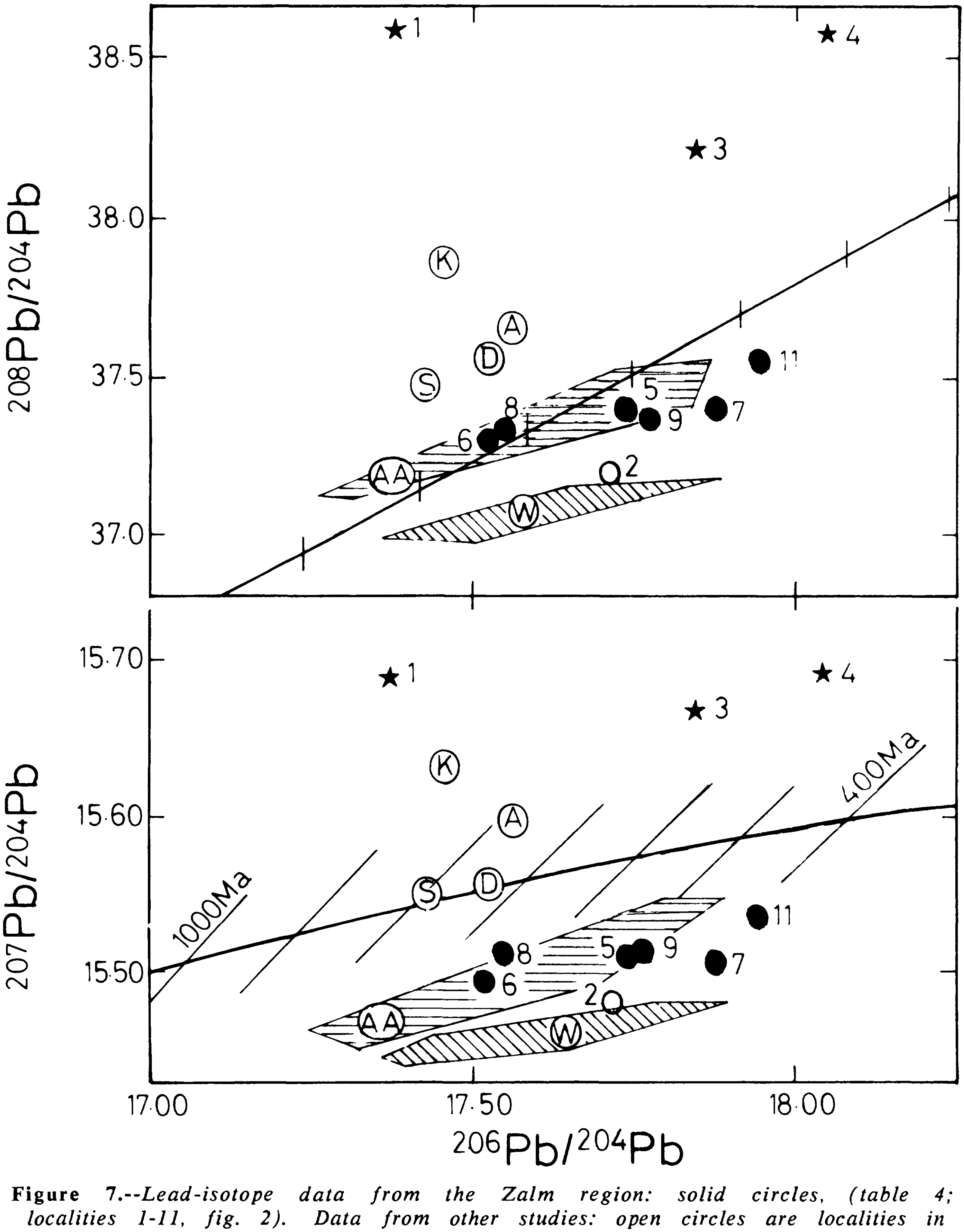

Figure 7.--*Lead-isotope data from the Zalm region: solid circles, (table 4; localities 1-11, fig. 2). Data from other studies: open circles are localities in figure 1; K: Jabal Khida - Stacey and Hedge (1984); A: Afif & D: Dahul - Stacey & Stoeser, 1983; S: Jabal Sitarah (galena) - Stacey & others, 1980. WTB shaded field: data from Wadi Tarib batholith (Stoeser and others, 1985). AA shaded field: Al Amar region. Average crustal-growth curves from Stacey and Kramers (1975).*

Table 3.--*Lead isotope data from feldspars in the samples of this study. Isochron model ages are from Stacey and Kramers (1975).*

Locality	Sample No.	206Pb / 204Pb	207Pb / 204Pb	208Pb / 204Pb	Isochron model Age Ma	Zircon Age Ma
1.	363402	17.379	15.690	38.593	1080	1829+45
2.	363410	17.716	15.474	37.196	434	794+10
3.	363401	17.850	15.665	38.231	702	<718
4.	363403	18.050	15.690	38.595	605	<700
5.	363411	17.745	15.508	37.388	480	696+8
6.	363409	17.521	15.491	37.298	619	685+7
7.	363413	17.881	15.507	37.377	373	640-650
8.	363404	17.551	15.519	37.330	651	637+11
9.	363412	17.769	15.511	37.358	467	632+5
11.	363405	17.947	15.532	37.557	372	~626

CRUSTAL EVOLUTION OF THE ZALM REGION

The Zalm quadrangle lies across the Nabitah suture, which separates the continental Afif terrane from the ensimatic arc terranes of the western Shield (fig. 1). The continental nature of the southern part of the Afif terrane was indicated by common-lead-isotope data (Stacey and others, 1980; Stacey and Stoeser, 1983) and a 1630-Ma zircon age from Jabal Khida (Stacey and Hedge, 1984). Recognition of older basement upon which pre-tectonic sediments and volcanics were unconformably deposited (Agar, 1985a), and our subsequent dating of zircons from the Kabid paragneiss, confirm the continental status of the Afif terrane. The detailed zircon geochronology and common-lead-isotope data presented here, provide a model for crustal evolution of the western margin of the Afif continental microplate in late-Proterozoic times.

The common-lead-isotope data for the Zalm quadrangle, shows a contrast between marginal arc and oceanic signatures in the south and west of the area, and continental signatures in the northeast. Significantly, the continental signatures are coincident with the area in which the Kabid formation is exposed, and the marginal arc signatures occur in the same area as outcrops of ultramafic rocks (fig. 2). The transition between marginal-arc and continental-type lead takes place in the same narrow zone as the transition between eugeosynclinal, deep-water oceanic sediments, and the miogeosynclinal, shallow-marine continental-shelf sediments of the Siham group. Also, there exists a contrast in the aeromagnetic data across the same zone (fig. 2). In the south and west, clearly defined, strong north-south-trending anomalies occur, whereas in the northeast, subtle westerly trends are apparent (Rodwell, 1984). This wealth of data collectively defines the westernmost limit of late Proterozoic continental crust in the Afif terrane in the Zalm quadrangle. These findings confirm the interpretation of earlier lead isotope data (Stacey and Stoeser, 1983; Stacey and Hedge, 1984) and permit extrapolation of the continental margin to the north and southeast.

Although the Kabid formation is clearly the basement of the Siham group, its absolute age remains undetermined. However, the age of the oldest tectonometamorphic event (D_1) is probably about 1830 Ma, and may be younger. Lead-isotope analyses indicate that the source of detritus for the Kabid pelite is of Archean age. Such rocks are not obviously exposed in the Zalm quadrangle, but further east in the Afif terrane, our field observations show high grade polydeformed paragneisses, orthogneisses, and migmatites that preserve relicts of structural events older than D_1 in the Kabid formation, and these may represent the source of clastic Kabid sediments. In order to firmly establish the older age relationships in the region, a number of the older gneisses are being sampled for further work.

The older, Siham-group volcanosedimentary rocks are typical of subduction at an active continental margin (Agar, 1985a). Thus, from before 720 Ma ago, the western margin of the Afif terrane was a destructive plate margin in which oceanic crust was being subducted beneath sialic material (fig. 8A). Andesitic volcanism, which marked the beginning of the Siham volcanic arc (Agar, 1985a), is also not precisely dated. However, the Siham was intruded by both the Naim complex and the Jidh suite between 720 and 690 Ma ago (fig. 8B). Both the Naim and the Jidh rocks are calc-alkaline, and are the product of subduction-related magmatism over an easterly dipping Benioff zone (Agar, 1985a). Therefore, the western margin of the Afif plate remained destructive throughout the period from 720 to 690 Ma ago (fig. 8B).

Intrusion of the syn-tectonic Subay granodiorite gneiss at 685 Ma marks the beginning of the Nabitah orogeny in the Zalm area. The gneiss was emplaced along the suture zone between the Afif and the Asir terranes. The diorite (locality 2), dated here at 794$\pm$10 Ma, represents part of the eastern margin of the Asir terrane. The age of this diorite is broadly similar to that of the An Nimas batholith (816$\pm$4 Ma) that is located further south in the Asir terrane (Cooper and others, 1979).

Thus by 685 Ma, the older continental crust of the Afif terrane was apparently in collision with the previously accreted ensimatic terranes of the western Shield (fig. 8C). This collision produced the Nabitah orogeny, which involved folding and easterly directed overthrusting of the Siham group, as well as syntectonic plutonism along the suture itself (Agar, 1984). The monzogranite at locality 7 is a late syntectonic diapiric intrusion. Its emplacement occurred during the final phase of the orogeny at about 640 Ma. Consequently, data from the Zalm area brackets the Nabitah orogeny between about 690 and 640 Ma, and correlates well with events in the southern part of the orogenic belt (Stoeser and others, 1985). Nonetheless, unlike the data from the Wadi Tarib batholith, the Zalm data do not show continuous activity during that period. The two study areas are on different sides of the Nabitah suture, and this may account for the difference. However, it suffices to say that while deformation was certainly in progress at about 650 Ma, by 635 Ma ago it had ceased in both regions.

The Hufayrah alkali-feldspar granite and the Haml granodiorite are plutons whose emplacement was controlled by Najd fractures. Thus, the Najd orogeny began between about 640 and 630 Ma ago, following decline of the Nabitah. The early part of the Najd orogen has been described as being controlled by dextral shear along northwest-trending fractures (Agar, 1985c). Both the Hufayrah complex and the Haml granodiorite show structural evidence for emplacement in a region of dextral shear. Furthermore, the Bani Ghayy group was deposited in north-trending grabens (fig. 8D) that are typical of encratonic pull-apart basins within a dextral strike-slip regime (Agar, 1985b and c). The Bani Ghayy rhyolite yields a good concordant age of about 620 Ma, and thus dextral movements of the Najd continued at least until then. Between

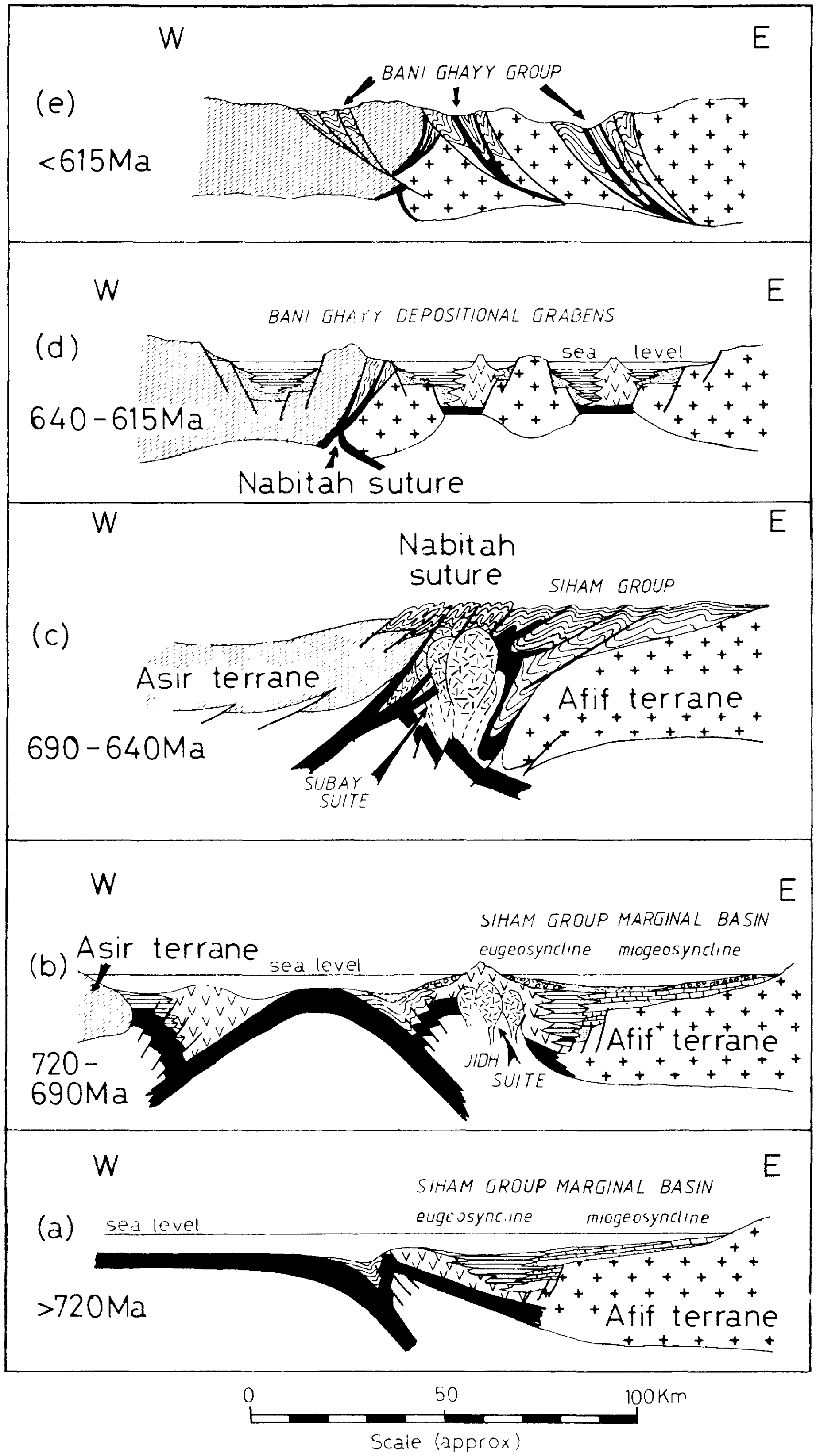

Figure 8.-- *Schematic cartoon tracing the crustal evolution of the Zalm area from 720-600 Ma. Plate tectonic models (A, B, and C) after Dewey and Bird (1970). For the distribution of plutonic units in the area, see Agar (1985a).*

extrusion of the rhyolite and emplacement of the Haml monzogranite, dextral Najd movements ceased, and the Bani Ghayy grabens were closed and deformed (fig. 8E). Deformation of the Bani Ghayy marks the onset of sinistral Najd movements (Agar, 1985c). The Haml monzogranite (locality 11) post-dates this deformation and the dextral Najd structures, but yields an approximate age of 626 Ma. Thus, the best estimate of change from dextral to sinistral Najd faulting is about 620 Ma. The Haml monzogranite and younger Haml plutons are displaced by sinistral Najd fractures, and consequently the end of the Najd orogeny in the Zalm area could not be determined.

THE BASEMENT CONTROVERSY AND CONCLUSIONS

Our study of the Zalm region confirms the presence of sialic basement within the southern part of the Afif terrane that was indicated by Stacey and Stoeser (1983) and Stacey and Hedge (1984). The question of older basement in the Arabian Shield has been quite controversial. Delfour (1981) has maintained that older basement underlies extensive regions of the northern Shield, but other workers have denied its existence altogether (Gass, 1982; Duyverman and others, 1982; Duyverman and Harris, 1982). When the very large area of the Shield is considered, it appears that the latter workers have reached their conclusions on the basis of very sparsely scattered samples, and often on inadequate mapping. For instance, Duyverman and others (1982) sampled only one locality within the Afif terrane. Kroner and others (1979) are more pragmatic on the subject, but although some $^{87}Sr/^{86}Sr$ initial ratios were slightly elevated, they concluded that older basement did not exist at either Dahul or Juq Juq in the east central Shield. More recent mapping has shown that older basement crops out not far north of their sample site at Dahul, and that the Juq Juq gneisses are located southeast of the exposed older basement, and were emplaced syntectonically within the Nabitah mobile belt (Thieme, 1984).

Lead-isotope evidence has outlined the extent of older continental basement in the southern part of the Afif terrane. The data show older basement to underlie the region immediately northeast of a line running southeast from Afif through Dahul to Jabal Khida (fig. 1). Older basement continues northward to Jabal Sitarah, and probably into the Al Amar region where Calvez and others (1985) report data for 2000-Ma inherited zircons in a trondjhemite from Bir Assaliyah. Field studies have identified basement rocks in the Zalm and Jabal Khida areas (Agar, 1984; Thieme, 1984). In addition, highly deformed gneissic rocks that may be older than the Kabid gneiss have been found in our recent fieldwork in the area southwest of Al Amar, and north of Jabal Khida. The lead isotopic evidence for older basement is thus corroborated by completely independent field observations.

Continental basement to the Siham group comprises high grade paragneisses metamorphosed in a tectonic event that may be as old as 1830 Ma. Isotopic data indicate that lead from the Kabid gneiss resided in the Archean upper crust before that time, and therefore, Archean rocks may exist at depth beneath the Afif terrane. In the late Proterozoic, approximately 720 Ma ago, the western margin of the Afif terrane was "Andean" in character, and volcanosedimentary rocks of the Siham group were accumulating in an extensional, eugeosynclinal marginal basin, as well as on the miogeosynclinal continental shelf. Typical calc-alkaline plutonic rocks were emplaced between 720 and 690 Ma, which provides a minimum age for the Siham group and a maximum age for the Nabitah orogeny. The decline of the orogeny around 640 Ma marked the onset of the Najd strike-slip orogen that continued for at least another 20 Ma.

ACKNOWLEDGMENTS

The work on which this report is based was performed in accordance with an agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey (USGS). During preparation of the manuscript, C. E. Hedge and D. B. Stoeser often helped with cheerful advice and encouragement. The analytical work was carried out by L. B. Fischer in the timely and competent manner we have come to expect from her. We are grateful to J. D. Aleinikoff for stimulating discussions, for abrading the various zircon fractions reported herein, and for guiding some of the mineral separations procedures that were competently performed by R. Ogg, D. Plume, C. Benson, and G. Elliott.

DATA STORAGE

Data work and materials used in preparation of this report are archived as data-file USGS-DF-05-6 stored in the office of the U.S. Geological Survey Mission in Jeddah, Saudi Arabia. No Mineral Occurrence Documentation System (MODS) localities were established in connection with work on this report.

REFERENCES

Agar, R. A., 1984, Geology of the Zalm Quadrangle, Sheet 22F, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-89-B. scale 1:250,000.

Agar, R. A., 1985a, Stratigraphy and palaeogeography of the Siham group; Direct evidence for a late Proterozoic continental microplate and active continental margin: Journal Geological Society London, in press.

Agar, R. A., 1985b, The Bani Ghayy group; sedimentation and volcanicity in pull-apart graben of the Najd strike-slip orogen: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report DGMR-OF-05-17.

Agar, R. A., 1985c, The Najd Fault System; a two-way strike slip orogen: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report DGMR-OF-05-18.

Calvez, J. Y., Delfour, J., and Feybesse, J. L., 1985, 2000 million years old inherited zircons in plutonic rocks from the Al Amar region: New evidence for an early Proterozoic basement in the Eastern Arabian Shield?: Saudi Arabian Deputy Ministry for Mineral Resources Report BRGM-OF-05-11, 27p.

Cooper, J. A., Stacey, J. S. , Stoeser, D. B., and Fleck, R. J., 1979, An evaluation of the zircon method of isotopic dating in the southern Arabian craton: Contributions to Mineralogy and Petrology, v. 68, p. 429-439.

Delfour, J., 1979, Geologic map of the Halaban Quadrangle, Sheet 23G, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-46-A., scale 1:250,000.

-----------, 1981, Geologic, tectonic, and metallogenic evolution of the northern part of the Precambrian Arabian Shield (Kingdom of Saudi Arabia): Bulletin du BRGM (2), Section II, p. 1-19.

Duyverman, H. J., and Harris, N. B. W., 1982, Late Precambrian evolution of Afro-Arabian crust from ocean arc to craton: Discussion and reply: Geological Society of America Bulletin, v. 93, p. 174-178.

Duyverman, H. J., Harris, H. B. W., and Hawkesworth, C. J., 1982, Crustal accretion in the Pan African: Nd and Sr isotope evidence from the Arabian Shield: Earth and Planetary Science Letters, v. 59, p. 315-326.

Gass, I. G., 1982, Upper Proterozoic (Pan African) calc-alkaline magmatism in north-eastern Africa and Arabia: in Thorpe, R. S. (ed.), New York-Wiley, p. 591-609.

Jaffey, A. H., Flynn, K. F., Glendenin, L. E., Bentley, W. C., and Essling, A. M., 1971, Precision measurements of half lives and specific activities of ^{235}U and ^{238}U: Physical Review, 4C, p. 1889.

Krogh, T. E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochim Acta, v. 37, p. 485-491.

Krogh, T. E., 1982, Improved accuracy of uranium-lead zircon ages by the creation of a more concordant system using an air abrasion technique: Geochimica et Cosmochim Acta, v. 46, p. 637-649.

Kroner, A., Roobol, M. J., Ramsay, K. C., and Jackson, N. J., 1979, Pan African ages of some gneissic rocks in the Saudi Arabian Shield: Journal Geological Society of London, v. 136, p. 455-461.

Ludwig, K. R., and Silver, L. T., 1977, Lead isotope inhomogeneity in Precambrian igneous K-feldspars: Geochimica et Cosmochimica Acta, v. 41, p. 1457-1471.

Ludwig, K. R., 1982, Calculation of uncertainties of U-Pb data: Earth and Planetary Science Letters, v. 46, p. 212-220.

Moore, J. M., 1979, Tectonics of the Najd Transcurrent Fault System Saudi Arabia: Journal Geological Society of London, v. 136, p. 441-454.

Moore, N. D., and Agar, R. A., 1985, A segmental contrast: the Arequipa segment. in W. S. Pitcher, and others (Eds.), Magmatism at a plate edge - the Peruvian batholith: Blackie and Son Ltd., Glasgow, 256 p.

Rodwell, G. N., 1985, Basic regional magnetic interpretation of the Zalm quadrangle, Sheet 22F: Saudi Arabian Directorate General of Mineral Resources Open-File Report, in press

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207-221.

Stacey, J. S., Doe, B. R., Delevaux, M. H., and Roberts, R. J., 1980, A lead-isotope study of mineralization in the Arabian Shield: Contributions to Mineralogy and Petrology, v. 74, p. 175-188.

Stacey, J. S., and Stoeser, D. B., 1983, Distribution of oceanic versus continental leads in the Arabian-Nubian Shield: Contributions to Mineralogy and Petrology, v. 84, p. 91-105.

Stacey, J. S., and Hedge, C. E., 1984, Geochronologic and isotopic evidence for early Proterozoic continental crust in the eastern Arabian Shield: Geology, v. 12, p. 340-343.

Stacey, J. S., Stoeser, D. B., Greenwood, W. R., and Fischer, L. B., 1984, U-Pb zircon geochronology and geologic evolution of the Halaban-Al Amar region of the Eastern Arabian Shield, Kingdom of Saudi Arabia: Journal Geological Society of London, v. 141, p. 1043-1055.

Stoeser, D. B., Stacey, J. S., Greenwood, W. R., and Fischer, L. B., 1985, U-Pb zircon geochronology of the Nabitah mobile belt and the Pan African continental collision in the Saudi Arabian Shield: U.S. Geological Survey Open-File Report 85-239, 92 p.

Stoeser, D. B., and Camp, V. E., 1985, Pan-African microplate accretion of the Arabian Shield: Geological Society of America Bulletin, v. 96, no. 7, July 1985, p. 816-826.

Thieme, J. G., 1984, Geologic Map of the Jabal Khida Quadrangle, Sheet 21G, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Geologic Map GM-90-B, scale 1:250,000.