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A LEAD-ISOTOPE STUDY OF MINERALIZATION IN THE ARABIAN SHIELD

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ABSTRACT

New lead-isotope data are presented for some late Precambrian and early Paleozoic vein and massive sulfide deposits in the Arabian Shield. Using the Stacey-Kramers (1975) model for lead-isotope evolution, the authors have obtained isochron model ages that range between 720 m.y. and 420 m.y. Most of the massive sulfide deposits in the region formed before 680 m.y. ago, during evolution of the shield. Vein-type mineralization of higher lead content occurred during the Pan African event about 550 m.y. ago and continued through the Najd period of extensive faulting in the shield that ended about 530 m.y. ago. Late post-tectonic metamorphism may have been responsible for vein deposits that have model ages less than 500 m.y. Alternatively, some of these younger model ages may be too low because the mineralizing fluids acquired radiogenic lead from appreciably older local crustal rocks at the time of ore formation.

The low $^{207}Pb/^{204}Pb$ ratios found for the deposits in the main part of the shield and for those in northeastern Egypt indicate that the Arabian craton was formed in an oceanic crustal environment during the late Precambrian. Involvement of older, upper-crustal material in the formation of the ore deposits in this part of the shield is precluded by their low $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ characteristics.

In the eastern part of the shield, east of long 44°20'E. towards the Al Amar-Idsas fault region, lead data are quite different. They exhibit a linear $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ relationship together with distinctly higher $^{208}Pb/^{204}Pb$ characteristics. These data imply the existence of lower crustal rocks of early Proterozoic age that apparently have underthrust the shield rocks from the east. If most of the samples we have analyzed from the easterly region were mineralized 530 m.y. ago, then the age of the older continental rocks is 2100 ± 300 m.y. (2σ).

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The presence of upper crustal rocks, possibly also of early Proterozoic age, is indicated by galena data from Hailan in South Yemen and also from near Muscat in Oman. These data are the first to indicate such old continental rocks in these regions.

INTRODUCTION

The first general study of isotopic ratios of lead in mineral deposits in Saudi Arabia, Yemen, and Egypt was published by Delevaux and others (1967). That work distinguished four age groups of significantly different isotopic ratios in this region: a Precambrian (Mahd adh Dhahab, Nuqrah); a late Precambrian or early Paleozoic (Jabal Hadb); a Jurassic (Hailan); and a Tertiary-Quaternary (Rabigh, Um Gheig, and Red Sea deposits).

Since 1967, considerable progress has been made in analytical techniques for the measurement of lead-isotope abundances. The accuracy and precision of data have been improved by the use of absolute standard samples prepared by the U.S. National Bureau of Standards (Catanzaro and others, 1968). In addition, lead-isotope model theory has been developed to enhance our understanding of lead-isotope behavior (for example, Doe and Zartman, 1979; Stacey and Kramers, 1975). Also since 1967, a much better understanding of the geologic framework and geochronology of Saudi Arabia has emerged from the studies of Aldrich and others (1978); Fleck, Greenwood, and others (in press) and Fleck, Coleman, and others (1976); Cooper and others (1979); Greenwood and others (1975); Baubron and others (1976); Roberts and others (1975); and Schmidt, Hadley, and others (1973) and Schmidt, Hadley, and Stoeser (1979). Consequently it is now known that the Saudi Arabian Shield developed during the period from late Proterozoic through to early Paleozoic. Figure 1 shows a summary of the Precambrian units and major tectonic, plutonic and orogenic events as proposed by Fleck and others (in press), and modified by ourselves and D. L. Schmidt.

This report will be concerned with lead-isotope analyses from ore deposits and prospects in many parts of the Arabian Shield and some from eastern Egypt. In order to utilize as much accurate data as possible, 15 of the samples from Delevaux and others (1967) have been reanalyzed and are included here with more than 25 new analyses. The map in figure 2 shows all the localities; the data for Precambrian-early Paleozoic samples are listed in tables 2 and 3, and for the Mesozoic-Cenozoic galenas in table 4. Table 4 contains data from a reanalyzed galena from South Yemen and from a new sample from Oman.

The objectives of the paper are twofold. In the first part, the lead isotopic compositions are used to determine model ages for the Precambrian-early Paleozoic samples. We shall attempt to relate these ages to significant tectonic events in the Arabian Shield. In the second part, all the lead-isotope data are used

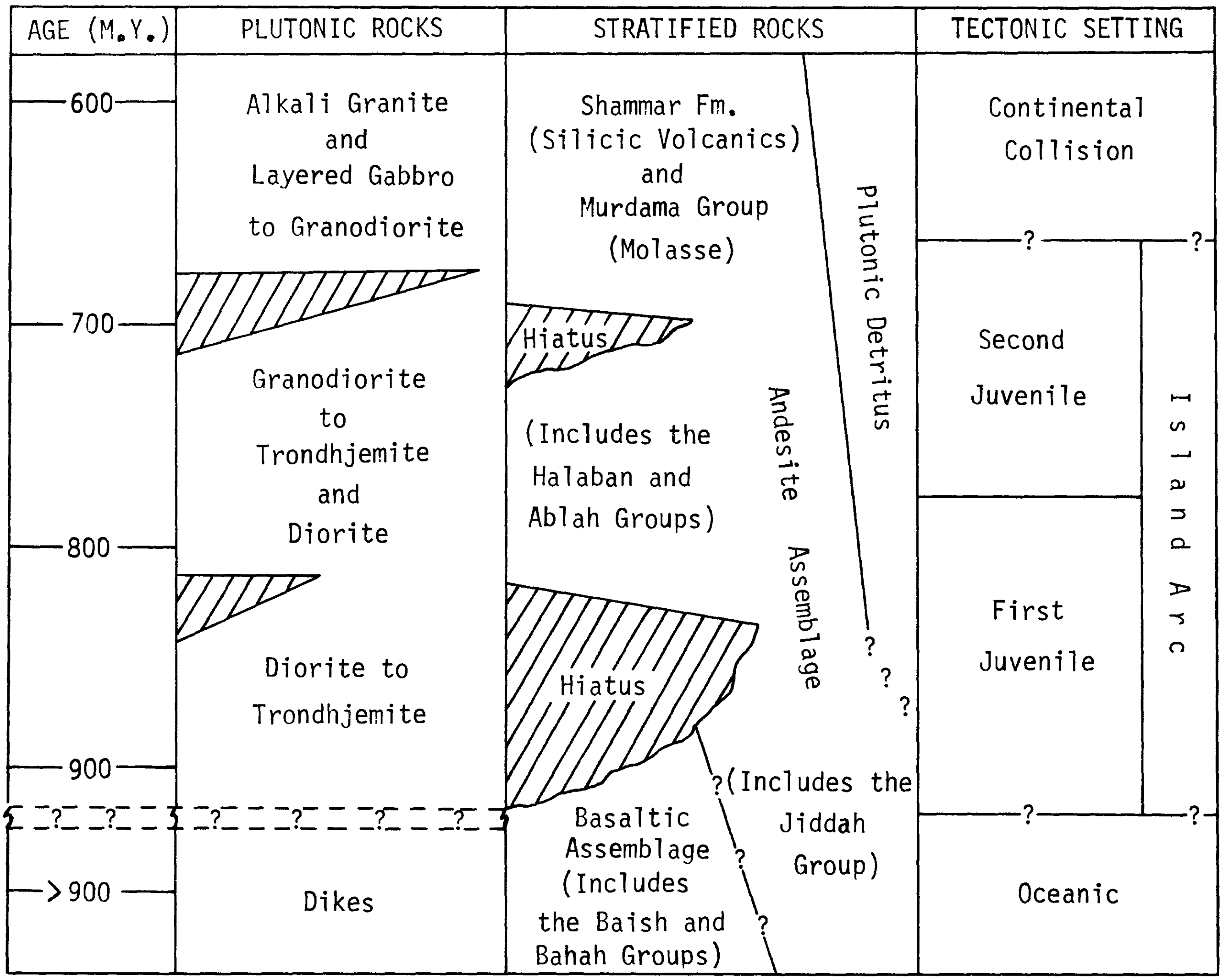

Figure 1.--Diagram showing the sequence of the main geologic events in the formation of the Arabian Shield, from Fleck and others (in press), modified by ourselves and from suggestions made by Schmidt (oral communication, 1979).

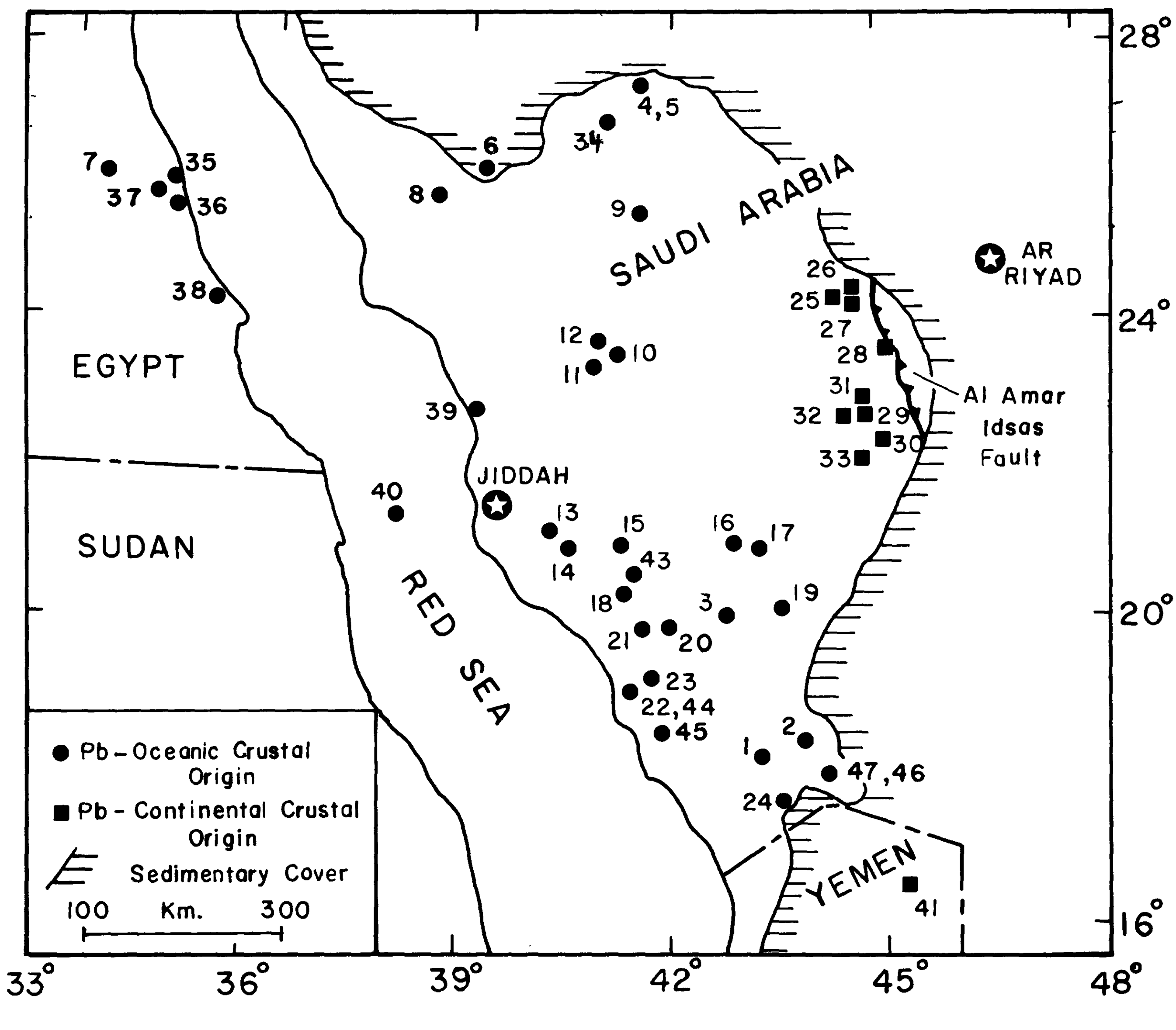

Figure 2.--Map of the Red Sea region showing locations of samples from this study and from that of Delevaux and others (1967). Locations for the model calibration samples 1-4 are identified in table 1; locations 5-24 for Group I samples in table 2; locations 25-33 for Group II samples in table 3; locations 34-42 for Mesozoic-Cenozoic samples in table 4; and locations 43-47 for Precambrian massive sulfide samples in table 5.

to distinguish different tectonic zones in the region and to relate these to existing models of evolution of the Arabian Shield.

ANALYTICAL TECHNIQUES

Analyses were made at the Denver Laboratory of the U.S. Geological Survey and also by the Analytical Chemistry Division of the U.S. National Bureau of Standards, Washington, D. C.

Most galena lead was analyzed isotopically by means of the triple filament thermal ionization technique, with the lead purified by electro-deposition (Catanzaro, 1968). The standard sample NBS-981 was used to determine corrections necessary to obtain absolute ratios in both laboratories in which analyses were made. Isotopic compositions and concentrations of the trace leads in three massive sulfide samples and in several potassium feldspars were analyzed by the silica-gel emitter technique with lead purified by use of a combination of resin columns and electro-deposition. All isotopic compositions were determined twice from a single chemical purification because this procedure helps to ensure that all ratios are within 0.1 percent of absolute. Concentrations of uranium, thorium, and lead were made by the isotope-dilution technique and should be within one percent of absolute.

LEAD-ISOTOPE MODEL AGES

For galenas, the U/Pb and Th/Pb ratios are extremely low, and thus their lead isotopic compositions remain effectively unchanged after initial crystallization. The lead-isotope ratios measured in galenas are therefore the initial values, and may be used to estimate model ages, if the assumptions of the model are valid. The system of isochrons in the model proposed by Stacey and Kramers (1975) has yielded reasonable age estimates for lead that has had a simple history since its introduction into the crust. This model is particularly applicable for galenas from Precambrian volcanogenic massive sulfide deposits that presumably were formed at the same time as the enclosing rocks (see Stacey and others, 1976). However, many of the samples in this study of the Arabian Shield are from vein deposits. In vein galena, some radiogenic lead possibly could have been leached from crustal rocks to contaminate the initial lead in the mineralizing fluids. Such a process would lower the model age, but for many cases in the Arabian Shield this effect may have been small for the following reasons. The rocks of the shield evolved during the period between about 950 and 550 m.y. ago. Thus for many of the Precambrian-early Paleozoic vein deposits, less than 200 m.y. elapsed between formation of the crust and introduction of mineralization. In such instances this might be too short a time in which to generate sufficient radiogenic lead to contaminate significantly the mineralizing fluids.

From the foregoing, it is clear that model ages for vein deposits in the shield will be most reliable for the oldest and largest deposits of high lead content. Model ages will be least reliable for small prospects where the difference between age of host rocks and time of mineralization is significant.

Calibration of lead isochron model

We have attempted to calibrate the Stacey-Kramers model in the Arabian Shield by examining initial lead from rocks from the shield that have been accurately dated by other methods.

In one instance a small (180μ) cubic crystal was noticed in an electron microscope photograph of zircons separated from a peralkaline granite sample from Jabal Ajah in the northern part of the Arabian Shield. The crystal was identified as galena by X-ray analysis and its lead-isotope composition measured by mass spectrometry. (The crystal contained less than 5 micrograms of lead.) Results of this experiment (table 1) show that the galena lead has a model age of 540 m.y.; the zircons from the granite indicated 570 m.y. This work was done by John Aleinikoff in the course of another study, and we appreciate the use of his data.

Lead in potassium feldspars from two plutonic units in the Wadi Tarib batholith, when corrected for decay of in situ uranium, gave model ages that were 50 m.y. and 30 m.y. younger than their zircon ages respectively (table 1). The initial lead in feldspar crystals is very susceptible to absorption of radiogenic lead, as may be seen in the feldspar data from the red granite at Bishah. The zircon age for this granite is 676 m.y. (Cooper and others, 1979) but the feldspar model age is only 385 m.y. Thus model ages we have obtained from potassium feldspars should be considered as minimum values.

We conclude from the calibration study that the Stacey-Kramers model apparently gives reasonable age estimates in the Arabian Shield and that the ages yielded for effectively single-stage leads may be too young by no more than 30-50 m.y.

RESULTS AND DISCUSSION

Data from the Precambrian-early Paleozoic samples are listed in tables 2 and 3 and plotted in figure 3. Isotopically they fall into two groups that also correspond to two distinct geographic regions. All Group I samples are from the main part of the Arabian Shield, all Group II are from the region east of about long 44°20'E. These separate regions are evident in the map of figure 2. The isotopic groupings can be seen in the $^{208}Pb/^{204}Pb-^{206}Pb/^{204}Pb$ plot of figure 3. In this diagram, all the Group I data plot below the average growth curve. All the Group II data plot distinctly higher, on or above the average curve.

Table 1. Measurements of initial lead isotopic compositions in K-feldspars and a galena crystal from 4 rocks of known age in the Saudi Arabian Shield. The Stacey-Kramers isochron model ages are computed for comparison with the zircon age. Thorium contents of the minerals were not measured.

	Sample No., rock type, and Coordinates	Mineral analyzed	Measured Ratios $^{206}Pb/^{204}Pb$	Measured Ratios $^{207}Pb/^{204}Pb$	Measured Ratios $^{208}Pb/^{204}Pb$	Pb ppm	U ppm	Zircon age m.y.	Corrected Ratios $^{206}Pb/^{204}Pb$	Corrected Ratios $^{207}Pb/^{204}Pb$	Isochron model age m.y.
1.	112680 Wadi Tarib granodiorite 18 15.9'N, 43°18.5'E	K-feldspar	17.570	15.460	37.022	11.9	0.24	660	17.444	15.460	610
2.	111541 Al Ar tonalite 18°19.3'N, 43°43.4'E	K-feldspar	17.587	15.510	37.194	22.9	0.04	644	17.577	15.510	615
3.	112671 Bishah red granite 20°05.9'W, 42°47.6'E	K-feldspar	17.785	15.473	37.106	28.2	0.05	676	17.773	15.472	385
4.	112991 Jabal Ajah peralkaline granite	Galena	17.803	15.560	37.535	--	--	570	17.803	15.560	540

Table 2. Group I lead-isotope data from Precambrian-early Paleozoic galenas and ore lead from 3 massive sulfide ores. Samples are from the main part of the Arabian Shield. Sample #7 is from northeastern Egypt.

*Samples reanalyzed from Delevaux and others (1967).
†Ratios corrected for in situ decay of U and Th.
(NBS) - Analysis made at U.S. National Bureau of Standards.

	Sample locality and coordinates		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Isochron model age m.y.	Geologic environment
5.	Jabal Ajah 27°40.5'N; 41°37.0'E	128590	17.728	15.510	37.351	500	
6.	Muhaylot 26°17.5'N; 39°8.5'E		17.583	15.492	37.147	490	
7.	*Fowakhir-Egypt 26°00'N; 33°38'E		17.826	15.513	37.381	430	Quartz vein in Precambrian granite.
8.	Tuwayrah 25°43'N; 38°36'E	74878	17.658	15.480	37.180	490	Cu quartz vein in layered gabbro, Hadley (1974).
9.	Nuqrah 25°38.5'N; 41°26.5'E		17.406	15.476	37.039	680	Ag, Au massive Zn-Cu-Pb sulfides, stratabound in Halaban volcanic and sedimentary rocks, Delfour (1970).
10.	*Jabal Hadb 23°31'N; 41°10'E		17.741	15.503	37.254	470	
11.	Mahd adh Dhahab 23°30'N; 40°52'E	87520 87223 *DDB-11 69115	17.402 17.405 17.406 17.407	15.477 15.474 15.477 15.485	36.957 36.978 36.959 36.975	685	Au-Ag quartz veins with galena in Halaban pyroclastic rocks. Worl (1978).
	†(vein feldspar)	64026	17.408	15.471	36.917		
12.	Jabal Sayid 22°55'N; 40°51'E	107510 (NBS) MS-ORE	17.317	15.460	36.854	720	Massive Zn-Fe sulfides. Stratabound in Halaban pyroclastic rocks. Routhier and Delfour, (1975).

Table 2. Group I lead-isotope data from Precambrian-early Paleozoic galenas and ore lead from 3 massive sulfide ores. Samples are from the main part of the Arabian Shield. Sample #7 is from northeastern Egypt. [continued]

*Samples reanalyzed from Delevaux and others (1967).
†Ratios corrected for in situ decay of U and Th.
(NBS) - Analysis made at U.S. National Bureau of Standards.

	Sample locality and coordinates		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Isochron model age m.y.	Geologic environment
13.	*Taif 21°12.5'N, 40°18'E	5731	17.641	15.498	37.146	540	Precambrian quartz vein.
14.	Prospect 20°57'N; 40°26.1'E		17.555	15.500	37.114	610	No data available.
15.	Mamilah 21°04'N; 41°19'E	64132	17.589	15.496	37.109	575	Au quartz vein cutting Bahah metamorphic rocks, Kiilsgaard and others (1978).
16.	Jabal Dalfa 20°15'N; 42°32.3'E	64115	17.695	15.480	37.217	460	
17.	Garb Hadad 21°05'N; 43°14'E	64117	17.486	15.448	37.016	560	Vein in Halaban metasedimentary and meta volcanic rocks.
18.	Mulhal 20°20'N; 41°15'E	64683	17.592	15.534	37.091	650	Au quartz vein in Baish mafic pyroclastics.
19.	Mokhayat 20°12'N; 43°28'E	64112	17.758	15.513	37.290	480	Au quartz vein in Halaban pyroclastic and sedimentary rocks.
20.	†Wadi Shwas 20°00'N; 41°58'E	70050 MS-ORE	17.442	15.498	37.007	695	Massive Fe-Cu sulfides in Halaban meta-volcanic rocks Fujii and Kato (1974).
21.	*Abu Bir 19°55.6'N; 41°48.5'E	DDB-4	17.854	15.515	37.326	420	Au quartz vein in Precambrian andesite.
22.	Sug Al Khamis 19°10'N; 41°21'E	E-37214	17.626	15.477	37.158	510	
23.	*Al Muchahal 19°17'N; 41°41'E	B-8 (NBS) B-7	17.730 17.742	15.503 15.505	37.174 37.261	480	Au-Ag quartz vein in Ablah sedimentary rocks, Earhart (1969b).
24.	Kutam 17°36'N; 43°34'E	107515(NBS) MS-ORE 69-50 (vein-galena)	17.595 17.575	15.503 15.493	37.104 37.082	600 580	Cu-Zn massive sulfide some Pb. Highly metamorphosed and sheared in Jedda-Halaban pyroclastics. Smith and others (1978).

Table 3. Group II - Precambrian - early Paleozoic galenas from eastern Arabian Shield.
*Samples reanalyzed from Delevaux and others (1967)

	Sample locality and coordinates		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Model age from secondary Isochron-m.y.	Geologic environment
25.	*Samrah 24°23'N; 44°20.4'E	DDB-10	17.491	15.498	37.263	530	Ag-Zn quartz veins in N.E. Najd faults, Al-Shanti and Mitchell (1976).
26.	*Ardayat 24°22'N; 44°38'E	DDB-7	17.750	15.538	37.482	530	Galena-quartz vein.
27.	Ar Ridayniyah 24°22'N; 44°38'E	126066A ARP-13(MS)	17.773 17.783	15.545 15.542	37.536 37.532	530	Zn-Fe sulfides - stratabound in calcareous sedimentary rocks, Al-Shanti and Mitchell (1976).
28.	Al Amar 23°47'N; 45°04'E	87300	17.255	15.464	37.116	530	Au-Zn-Cu veins in felsic pyroclastics west of Idsas fault, Chiron (1974).
29.	Bahfor 22°48.4'N; 44°38.1'E	72401	17.726	15.544	37.471	570	Ag, Pb, Zn-quartz vein in fault zone in granodiorite, Helaby and Dodge (1975).
30.	Wadi Aqarah 22°46.8'N; 45°05.8'E	RR-14M	17.256	15.465	37.161	530	Quartz "blow" in andesitic volcanics (Brosset, 1974)
31.	Bosnun 22°43.8'N; 44°39.2'E	82115	17.698	15.555	37.518	680	Ag, Pb, Zn-quartz vein in fault in granodiorite, Helaby and Dodge (1975).
32.	Al Kushamiyah 22°43.9'N; 44°22.6'E	72314	17.642	15.518	37.387	530	
33.	Jabal Sitarah 22°07.5'N; 44°39.5'E		17.428	15.550	37.475	965	Quartz vein in andesitic volcanics at margin of granodiorite pluton (Leca, 1970)

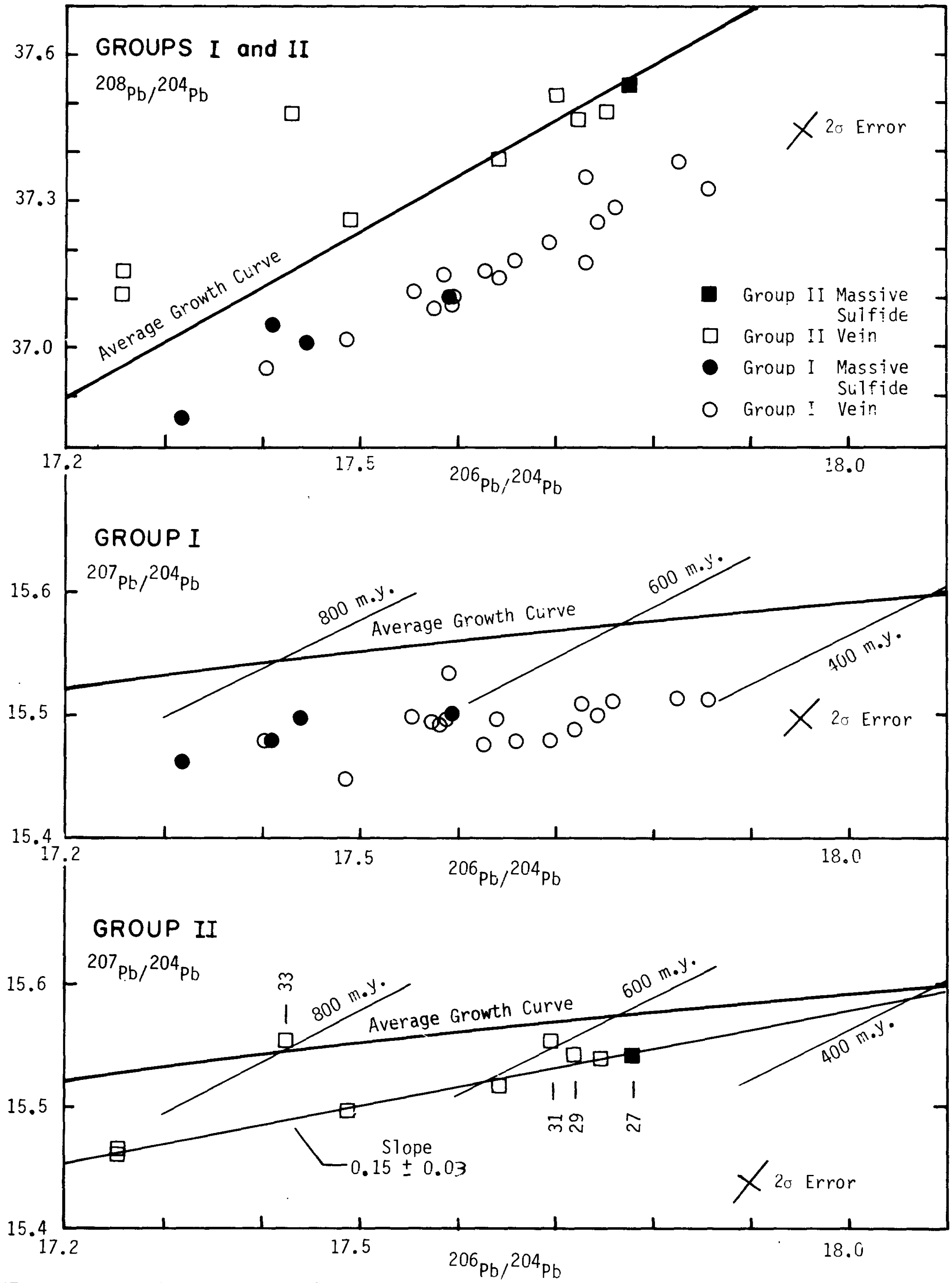

Figure 3.–Lead-isotope data from Precambrian-early Paleozoic galena and massive sulfide ores from the Arabian Shield. Data are numbered as in tables 2 and 3. Model evolution curves are from Stacey and Kramers (1975). Isochron model ages between 720 m.y. and 420 m.y. are assigned to the Group I galenas from the main part of the Shield. Group II galenas from the eastern part of the Shield are distinctly different, and most lie on a secondary isochron of slope 0.15 ± 0.03.

For the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ data separate plots have been made in figure 3. Except for the sample from Jabal Sitarah (#33), all the data in both groups plot below the average curve, but for the Group II data, six of the nine points form a very linear array that we regard as significant. The $^{208}Pb/^{204}Pb$ data for Group II data average about 0.8 percent higher than those of Group I for the same $^{206}Pb/^{204}Pb$ values. The $^{207}Pb/^{204}Pb$ values for Group II average 0.3 percent higher than their Group II counterparts.

Group I model ages from the main part of the shield

The model ages of the Group I data range between 720 m.y. for the massive sulfide deposit at Jabal Sayid to 420 m.y. for the small vein prospect at Abu Bir. Figure 4 shows a histogram of the data. There are four massive sulfide deposits among the Group I samples: Jabal Sayid (720 m.y.), Wadi Shwas (695 m.y.), Nuqrah (680 m.y.), and Kutam (600 m.y.). All these deposits were examined in the sulfur isotope study by Rye and others (unpub. data) and appear to be of volcanogenic origin. All are in volcanoclastic rocks stratigraphically assigned to the Halaban group that developed between about 800 to 650 m.y. ago (Greenwood and others, 1975). The model age of 600 m.y. for Kutam seems much lower than the expected age of the enclosing rocks (about 750 m.y.). However, this deposit has been severely sheared and remobilized during metamorphism, so that the ore bodies now occur at fault junctions (Rye and others, unpub. data). Under these circumstances it may be that the lead in the deposit was introduced during metamorphism about 600 m.y. ago.

The large gold-silver vein deposit at Mahd adh Dhahab has an extremely uniform lead isotopic composition that supports the validity of our using the model age, which in this case is 685 m.y. This figure also agrees with the Rb-Sr feldspar model age of 675 ± 20 m.y. obtained by Zell Peterman (oral communication) from microcline, an early vein-forming mineral in the deposit. Although the lead isotopic composition of the Mahd adh Dhahab deposit is identical to that at Nuqrah, 230 km to the north, no direct genetic association is implied. However, the data do indicate that the original sources for the lead in a large area of the shield had remarkably similar lead isotopic compositions.

The histogram of the data in figure 4 shows a large number of model ages in the range 460-500 m.y. Presently there is little geochronologic evidence to indicate such late igneous activity in the shield. In addition, most of our young model ages come from small vein prospects and are therefore most likely to have acquired radiogenic lead from older crustal rocks. However, from a number of K-Ar and Rb-Sr analyses in the Al Amar region, Baubron and others (1976) concluded that a major metamorphic event occurred at about 560 m.y. ago and that volcanic rocks in the region tend to be younger, at 500-460 m.y. Unpublished data

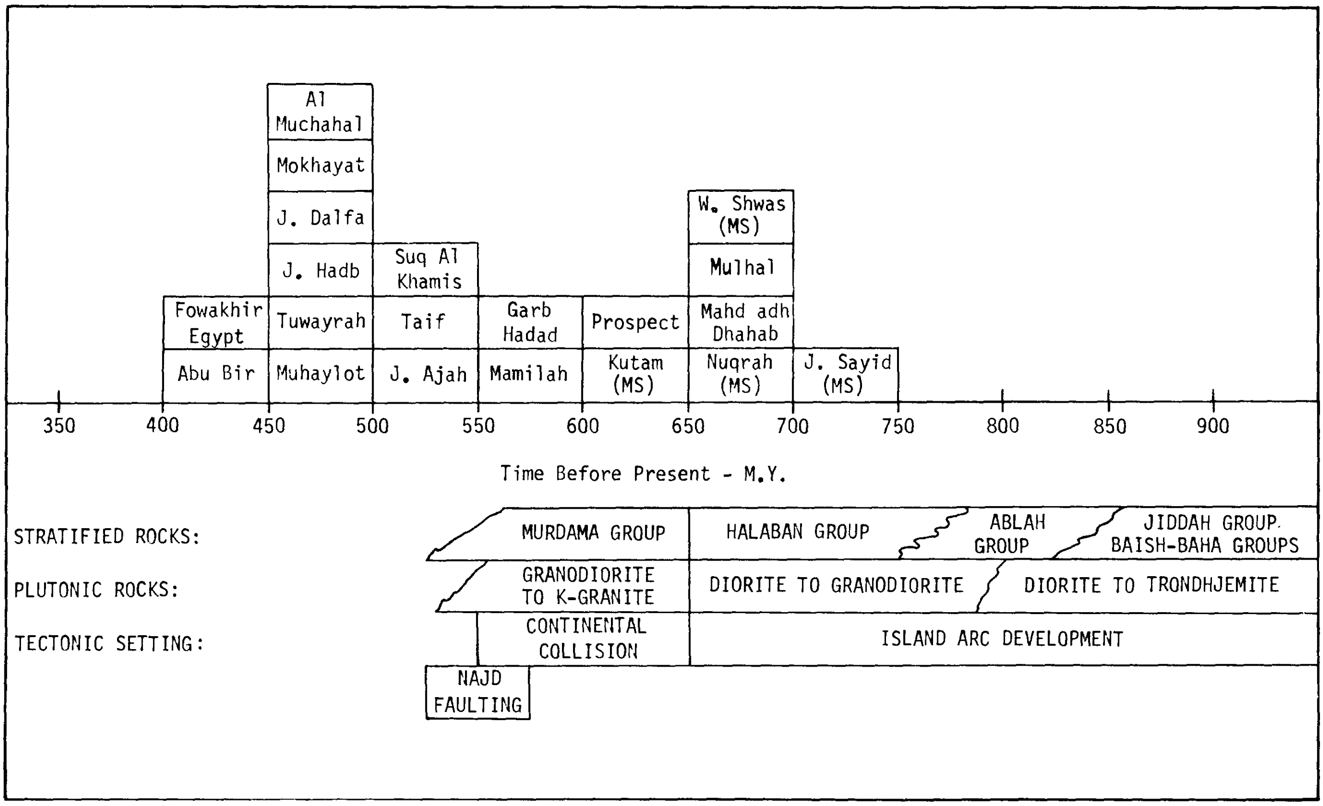

Figure 4.--Histogram of isochron model ages for Group I leads from ore deposits and prospects in the southern part of the Arabian Shield. Massive sulfide deposits are designated (MS).

by R. J. Fleck (oral communication, 1979) confirm this situation; other unpublished data by Fleck indicate a late metamorphic event in the Taif area in the western part of the shield. Although the significance of our model ages less than 500 m.y. should remain equivocal, it is apparent that the Pan African orogeny, approximately 550 m.y. ago, and the subsequent rifting of the shield by the northwesterly-trending Najd fault system coincided with much of the vein mineralization in the shield. Occurrence of galena in the vein deposits is much more common than in the earlier massive sulfides of the region.

Group II data from the eastern Arabian Shield

The Group II data are listed in table 3 and plotted in figure 3. In the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ graph, six of the nine points exhibit a short though very well defined line. The slope is estimated to be 0.15 $\pm$ 0.03 (2σ) by the York (1968) regression analysis that includes uncertainty due to analytical error. Such linear relationships are very common in galena studies from mining districts in many parts of the world (for example, Stacey and others, 1968; Kanasewich and Farquhar, 1965). The interpretation requires a two-stage rather than the effectively single-stage crustal history that we applied in Group I. The linear relationship implies that for the six samples on the line, there was a common time of mineralization. Moreover, the lead from these samples was derived from older Precambrian source rocks all of the same age.

If we can estimate the mineralization time, then the source rock age can be computed. In an earlier section we stated that Baubron and others (1976) found evidence for a major metamorphic event 560 m.y. ago in the Al Amar region. Also, because the deposit at Ar Ridayniyah is the only massive sulfide among the Group II samples, its isochron model age of 530 m.y. is the one most likely to be valid. Moreover, this estimate is reasonable for the end of the Najd faulting (Fleck and others, 1976), at which time, as we have shown, much mineralization seems to have occurred in the western shield. Thus if we choose a mineralization age of 530 m.y., and utilize the linear slope of 0.15 $\pm$ 0.03 (2σ), the source rock age is computed as 2100 $\pm$ 300 m.y. Notice that, unlike most of the Group I data, those of Group II exhibit a large time difference between the age of associated crustal rocks and time of mineralization.

It is notable that the sample from Ar Ridayniyah (#27) is the most radiogenic in the linear array. This is probably a manifestation of its sedimentary character. According to Rye and others (unpub. data), sulfur-isotope measurements indicate that it was formed by biogenic action in a stagnant lake.

There remain three samples in Group II that do not lie on the line. These are Bahfor (#29), Bosnun (#31), and Jabal Sitarah

(#33). Analytical error might account for the discrepancy only in the case of the Bahfor data. One possible interpretation of the deviations is that these three samples were mineralized at different times from source rocks all 2100 m.y. old. Mineralization ages then compute as approximately 570 m.y. for Bahfor, 680 m.y. for Bosnun, and 965 m.y. for Jabal Sitarah.

The most important conclusion from the Group II data is that east of about long 44°20'E., and extending between lats 22°N. and 24.5°N., the region appears to be underlain by Precambrian basement rocks about 2100 m.y. old. This is the first substantial evidence of such old ages anywhere in the shield.

Plumbotectonics in Saudi Arabia

Even though the plumbotectonics model of Doe and Zartman (1979) describing lead evolution in the Phanerozoic has been published only recently, it has actually been used for interpretation of lead-isotope data in our laboratory for several years. The concepts of the model were first extended to the Precambrian by Stacey and others (1976). The Saudi Arabian lead data are plotted in figure 5 together with the plumbotectonics model curves for the average mantle, the average orogene, and the average upper crust. (The average orogene curve of plumbotectonics corresponds to the average growth curve of Stacey and Kramers (1975), which is shown in figure 3.) All the Group I data lie below the average orogene curve in each diagram, and in fact, on the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plot, they lie along the average mantle curve. It can be seen from both diagrams of figure 5 that the Group I samples are similar in character to data from other parts of the world that are interpreted to have evolved in primitive island arc environments. The examples shown of such data are the Devonian and Triassic mining districts in Shasta, California, and the Eocene-Miocene Mariana Island Arc system in the Pacific Ocean (Meijer, 1976).

The significance of the linear trend for the Group II data on the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plot has already been discussed. On the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram most of the Group II points lie along the average orogene curve--distinctly offset from the mantle character of the Group I samples. Notice that the present-day average composition of continental-derived sediments from the Pacific Ocean basin in the Mariana Arc also lies close to the average orogene curve and thus emphasizes the similarity of continental material and the Group II samples. The fact that the $^{208}Pb/^{204}Pb$ data for the two samples from Al Amar (#28) and Wadi Aqarah (#30) lie above the orogene curve whereas the $^{207}Pb/^{204}Pb$ data lie below the orogene curve in the other plot indicates that the Group II leads may be derived from rocks of the lower continental crust. Actually, the Jabal Sitarah sample (#33), the southernmost of our Group II samples, appears to be quite different. Its data plot above the average

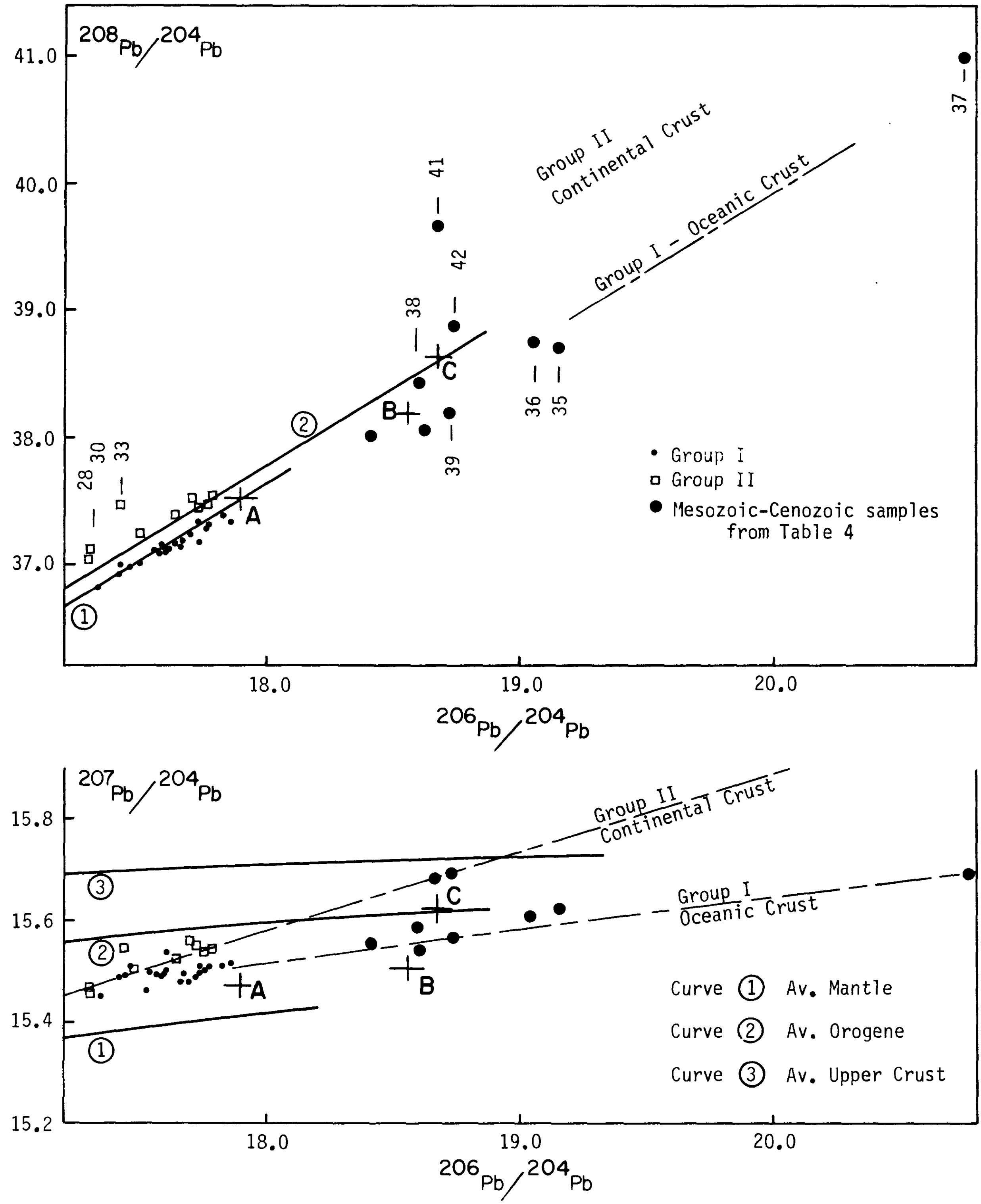

Figure 5.--Lead-isotope data from Groups I and II and Mesozoic-Cenozoic rocks from the Arabian Shield. Data for Groups I and II are from tables 2 and 3 respectively and data for Mesozoic-Cenozoic rocks are from table 4. The plumbotectonics model evolution curves are from Doe and Zartman (1979). Also shown for comparison are: (A) a galena analysis from the Triassic mining district at Mount Shasta, California (Doe and Rohrbough, 1979); (B) average compositions of volcanic rocks and (C) marine clays, both from the Eocene-Miocene Mariana primitive island arc complex in the Pacific Ocean (Meijer, 1976).

orogene curve in both the graphs of figure 5. These are characteristics of continental rocks that may themselves have had a complex history involving periods of residence in both the upper and lower parts of the crust. As such they may be analogous to the Precambrian basement at Gold Hill, Utah (see Stacey and Zartman, 1978). The Jabal Sitarah data therefore make that region of great interest for further study.

Geologically, the Group II eastern area is characterized by two contrasting terranes, mostly sedimentary rocks on the west (Abt schist and Ar Ridayniyah formation) and volcanic and sedimentary rocks on the east (presently assigned to the Halaban group). Both terranes have been cut by numerous granitic bodies, and are separated by the Al Amar-Idsas fault zone (fig. 2), a north-trending structural break along which small ultramafic bodies have been emplaced. Al-Shanti and Mitchell (1976) have considered this break to be a zone of thrusting that dips eastward and represents a major suture that marks a continental-arc collision. Schmidt and others (1979), on the other hand, agreed with the major suture concept but considered the zone of thrusting to dip westwards. Figure 6 shows a hypothetical section through the Al Amar-Idsas fault zone that was suggested by D. L. Schmidt (written communication, 1979) and that explains very well the boundary between Group I and Group II lead data.

Certainly the Al Amar-Idsas fault is a major geologic feature in the shield that has attracted the attention of many geologists. For instance Moore (1975) pointed out that the fault separates two metallogenic provinces, a lead-silver-tungsten-molybdenum province on the west, and an iron-copper-zinc-gold-barium province on the east. The fault zone itself contains anomalous amounts of iron, chromium, copper, and nickel in bodies of ultramafic rocks.

The tectonic evolution of the Arabian Shield and of the eastern desert of Egypt has been the subject of much recent study. Two main theories emerge from such studies: an arc-collision model, and a Precambrian proto-Red Sea hypothesis. The arc-collision theory was originated by Greenwood and others (1975) and developed by Fleck and others (in press) from strontium-isotope data. They proposed that the Arabian craton evolved as an intraoceanic island arc accreted onto the northeast flank of the African continent in late Precambrian time. Other workers who have contributed to the island arc concept include Al-Shanti and Mitchell (1976), Bakor and others (1976), Frisch and Al-Shanti (1977), Nasseef and Gass (1977), Gass (1977), and Schmidt and others (1979).

On the other hand, Garson and Shalaby (1976), El-Shazly and Engel (1978), and Stern (1979) have maintained that whereas the Arabian-Nubian craton has clearly evolved in an oceanic crustal environment, the region lacks several characteristics that are

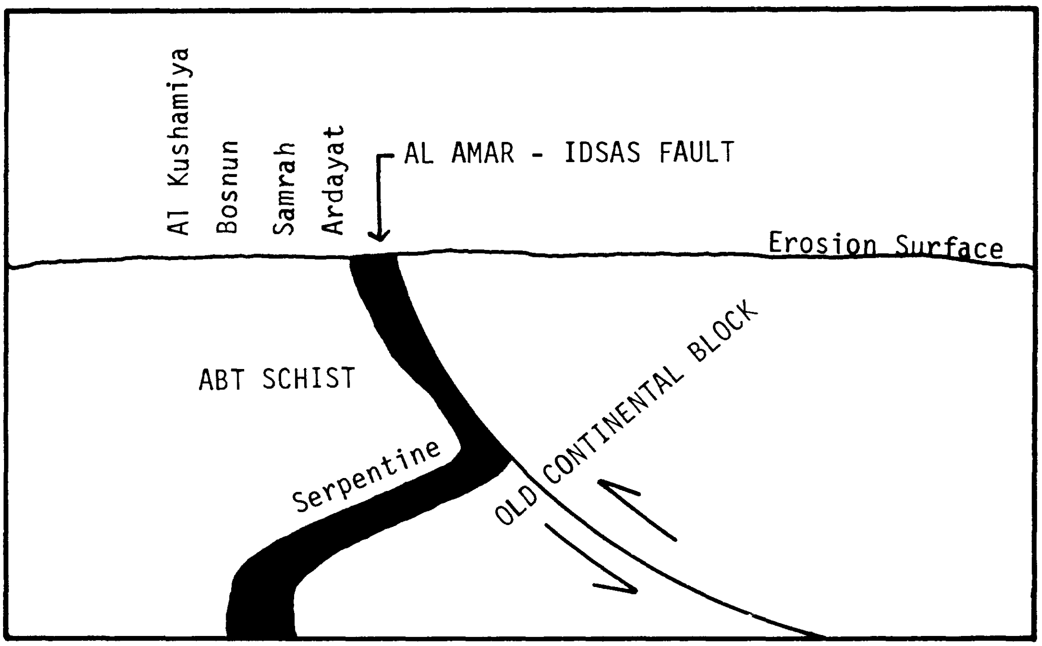

Figure 6.--Hypothetical section across the Al Amar-Idsas fault zone, as suggested by D. L. Schmidt (written communication, 1979).

normally found in island arc systems elsewhere in the world. Instead, they envisage an older Afro-Arabian continent that in the late Precambrian rifted and spread apart to form a proto-Red Sea in a similar location to the present one. During the Pan-African orogeny, this oceanic basin was closed by compression resulting from an intercontinental collision in the east.

To choose between the various models is beyond the scope of this work, but the controversy prompted us to reanalyze the data of Delevaux and others (1967) and to extend considerably the areal coverage of our study. The Precambrian-Paleozoic samples from that work have been included with the Groups I and II samples. We should perhaps point out that the one Paleozoic sample from Egypt, from Fowakhir, is in the center of the oceanic crustal terrane studied by Stern (1979). Its lead-isotope characteristics clearly belong in Group I, confirming its oceanic crustal derivation. Our new data for Cenozoic samples from Delevaux and others (1967) appear in table 4 and are plotted in figure 5. Data from Um Gheig (#35), Um Ans (#36), and Taleit Eid (#37) in Egypt and Rabigh (#39) in Saudi Arabia are consistent with their derivation from Group I shield rocks. Data for the Egyptian deposit at Bir Ranga (#38) lie somewhat higher on both plots in figure 5. Its Group I-type lead seems to have acquired a small but distinctly older continental component that may have originated from sediments in the area that perhaps derived from as far away as the Sudan-Tanzanian craton to the southwest. The presence of older continental material in sediments, in the region of Fowakhir, has been investigated by Dixon (in press), who has dated zircons in cobbles from conglomerate beds and has obtained a wide range of Precambrian ages, 1100-2300 m.y. These cobbles have no obvious source in the Nubian Shield and the author concludes that they were derived from adjacent continental areas and were deposited in an evolving arc-ocean basin complex.

The sample from Hailan in Yemen (#41), to the south of Saudi Arabia, and that from near Muscat in Oman, 1500 km to the east (#42), exhibit data that are quite different from data from other Cenozoic samples discussed. Unlike the Group I data, they plot above the average orogene curve in each of the diagrams of figure 5. Because very little ^{207}Pb has been generated since the end of Precambrian time, their high ^{207}Pb components relative to ^{204}Pb must be interpreted as indicating the existence of older Precambrian rocks in the vicinity of these widely separated localities in the Arabian Peninsula. Perhaps such upper crustal rocks are similar in age to the Proterozoic lower crustal source rocks in eastern Saudi Arabia, the existence of which is implied by the Group II data.

Precambrian whole-ore samples

In the Arabian Shield, many Precambrian massive sulfide deposits do not contain galena. The ores are generally

Table 4. Mesozoic-Cenozoic galenas from Saudi Arabia and northeastern Egypt. *Galena Samples reanalyzed from Delevaux and others (1967); the brine sample data from the same study are the original data normalized to absolute values.

	Sample Names and Coordinates		$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Lead-isotope Characteristics	Geologic environment
34.	Al Mahash 26°52'N; 41°20'E	128138	18.409	15.554	38.007	Group I-oceanic crustal type	No data available.
35.	*Um Gheig-Egypt 25°40'N; 34°31'E		19.155	15.626	38.699	Group I	Stratiform deposit underlying Miocene gypsum.
36.	*Um Ans--Egypt 25°30'N; 34°40'E		19.037	15.608	38.741	Group I	Replacement in middle Miocene lime grit.
37.	*TaleitEid--Egypt 25°40'N; 34°20'E		20.755	15.694	41.005	Group I	From slightly metamorphosed Precambrian schist.
38.	*Bir Ranga--Egypt 24°22'N; 35°13'E		18.595	15.589	38.405	Group I with small continental component	Replacement of middle Miocene gypsum.
39.	*Rabigh--Saudi Arabia 22°56.7'N; 39°08.8'E	DDB-2	18.716	15.571	38.195	Group I	Barite vein paralleling Tertiary rift in Precambrian complex.
40.	Red Sea Brine 21°20.5'N; 38°3.5'E		18.61	15.54	38.07	Group I	Dissolved lead, Pb 0.5 ppm; U 0.0005 ppm; Th$\leq$0.0000 6 ppm.
41.	*Hailan, Yemen 16°32.1'N; 45°13.3'E	DDB-3	18.652	15.674	39.639	Derived from Precambrian upper crust	Vein filling in Jurassic limestone.
42.	Wadi Nuju, Oman 23°29'N; 58°10'E	OMG-15	18.726	15.680	38.906	Derived from Precambrian upper crust	In silicate-carbonate rock in basal thrust of Semail ophiolite nappe.

variable mixtures of pyrite, chalcopyrite, and pyrrhotite. In order to extend the scope of our study, a total of 21 such samples were selected from nine massive sulfide deposits. The lead isotopic compositions for all samples were determined and are shown in table 5. Lead, uranium, and thorium concentration data for 12 of the samples are also included. Much to our surprise, in many cases the lead concentrations were found to be very low--less than 6 ppm. In addition, these low lead contents were accompanied by comparatively significant amounts of uranium and thorium (0.1 to 2.1 ppm). In such samples, radiogenic lead generated by the uranium and thorium since formation of the ores has significantly changed the lead isotopic compositions. In almost all cases, however, the U/Pb and Th/Pb systems seem to have been disturbed. Thus the data cannot be relied on to yield the times of mineralization, nor to provide the means by which to estimate the initial lead compositions at the time of ore deposition. Because most of the whole-ore samples are from drill core, it seems unlikely that disturbance of the uranium-thorium-lead systems is due to recent weathering. More probably the disturbance is due to the Pan African orogeny or other events, such as uplift, to which the deposits have been subjected. As far as we know, this is the first study of massive sulfide ores to include lead, uranium, and thorium concentration data. The data show that for samples of this type, one can assume neither that lead constants are high nor that U/Pb values are negligible. The presence of low lead concentrations and significant U/Pb values may explain the highly variable lead-isotope compositions found for massive sulfide ores by other workers, such as Cumming and Gudjurgis (1973) in their study of the Quemont deposit in Canada.

Our lead-isotope data for the ores from table 5 are plotted in figure 7. In the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plot, we note that the ore data lie close to the trend for the Group I Precambrian and Mesozoic-Cenozoic galenas that we noted in figure 5. In addition, the least radiogenic ore samples are similar in composition to the Precambrian galenas. Similarly, on the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plot in figure 7, the ore data, especially the least radiogenic samples, plot close to the Group I galena trend. The data from Wadi Yiba lie well below the others, but they do lie on a trend that would correct them back towards the least radiogenic Group I galena data. It seems unlikely that any of the ore data would correct back into the Group II field above the average orogene growth curve on this plot.

In summary, although the massive sulfide ore data are disappointing from the geochronologic point of view, they are sufficiently definitive to confirm that these deposits belong isotopically to the Group I type, as indeed they do geographically.

Table 5. Pb-U-Th data from Precambrian massive sulfide ore deposits in the main part of the Arabian Shield. Locality numbers in the first column are shown on the map of figure 2. For completeness, the high Pb content samples 107510 from Jabal Sayid, 70050 from Wadi Shwas, and 107515 from Kutam are listed here as well as in table 1

Sample locality and coordinates	Sample No. and lab. analyzed	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Pb ppm	U ppm	Th ppm	$^{238}U/^{204}Pb$	$^{232}Th/^{204}Pb$	Geologic environment
12. Jabal Sayid	107502 NBS	17.339	15.452	36.840						Massive Zn-Fe sulfides stratabound in Halaban pyroclastic rocks, Routhier and Delfour (1975).
22°55'N, 40°51'E	107510 NBS	17.317	15.460	36.855	32380	12.70	0.06	0.02	0.0001	
	107514 NBS	17.322	15.467	36.875						
20. Wadi Shwas 20°00'N, 41°58'E	70050 USGS	17.458	15.499	37.007	1223	2.78	0.01	0.14	0.005	Massive Fe-Cu sulfides in Halaban metavolcanics, Fujii and Kato (1974).
43. Wadi Bidah: A. Rabathan 20°24'N, 41°23'E	76770 USGS	17.445	15.454	36.783	20.70	0.62	0.002	1.8	0.01	Massive Cu-Zn sulfides in volcanic, pyroclastic and sedimentary rocks of Baish Group, Greenwood and others (1974).
B. Sh'ab El Tare 20°31'N, 41°22'E	68516 USGS	17.587	15.524	37.087						
44. Jabal Sarbon	107540 NBS	18.818	15.556	38.276	5.52	0.37	0.59	4.4	7.1	Cu mineralization in chloritic garnetiferous amphibolite of Ablah Formation, Earhart (1969a).
18°52'N, 41°57'E	107541 NBS	18.166	15.530	37.318	1.45	0.08	0.05	3.3	2.3	
45. Wadi Yiba	107526 NBS	18.544	15.508	37.218						Stratiform Cu deposits in siliceous dolomite amphibolite, and schists of the Ablah Formation, Earhart (1969b).
19°10'N, 41°19'E	107527 NBS	18.619	15.562	37.435						
	107533 NBS	18.369	15.558	37.362						
46. Wadi Wassat	35112 USGS	18.31	15.48	37.42	4.38	0.77	1.04	11.0	15.3	Massive Fe sulfides in lenticular bodies that separate andesite breccia from overlying andesite correlated with Jiddah Group, Jackaman (1972).
18°19'N, 44°12'E	10715[illegible] NBS	18.213	15.535	37.642						
	107500 NBS	18.272	15.473	37.633	4.96	0.52	1.30	6.6	16.9	
	107213 NBS	17.474	15.448	37.120	5.32	0.10	0.21	1.1	2.5	
47. Wadi Qatan	107517 NBS	18.418	15.561	37.946						Ni-Fe massive sulfides in volcanic and pyroclastic rocks correlating with Jiddah Group, Dodge and Rossman (1975).
18°09'N, 44°07'E	107519 NBS	22.078	15.807	40.019	2.96	0.80	2.09	18.7	50.3	
	107522 NBS	18.461	15.536	37.849	2.18	0.32	0.70	9.2	20.9	
24. Kutam 17°36'N, 43°34'E	107515 NBS	17.595	15.503	37.104	3906	0.10	0.15	0.001	0.002	Cu-Zn massive sulfides, some Pb. Highly metamorphosed and sheared. Smith and others (1978).
	107516 NBS	17.676	15.508	37.161	101.3	0.75	1.51	0.46	0.94	
	107525 NBS	17.943	15.545	37.325	49.31	0.14	0.13	0.17	0.16	

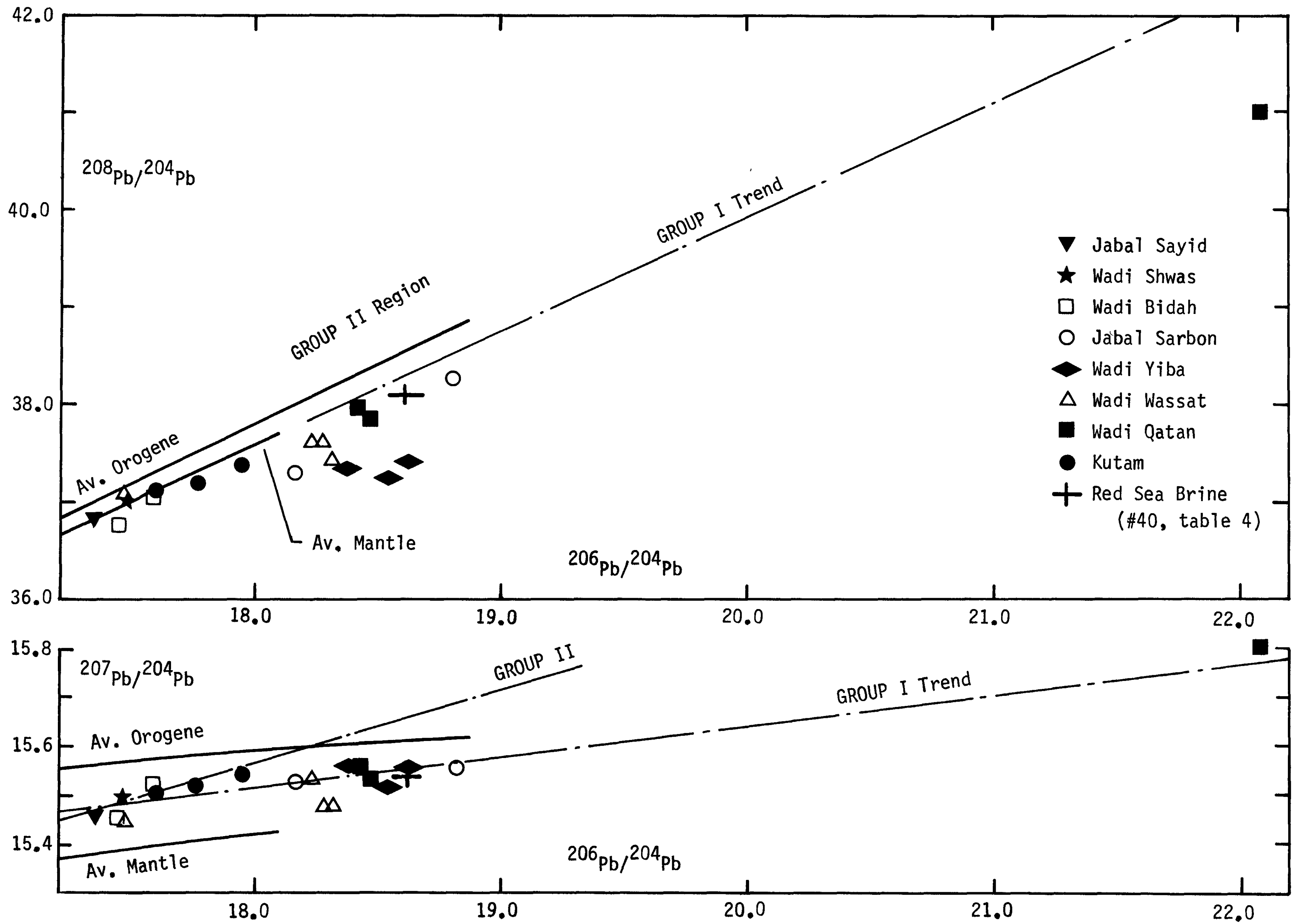

Figure 7.--Whole-ore lead-uranium-thorium data for Precambrian massive sulfide deposits in the main part of the Arabian Shield. Data are from table 5. Also plotted for reference are data from a brine sample from the Red Sea, #40 in table 4.

CONCLUSIONS

Using lead-isotope model ages that should be regarded as minimum ages and accurate to within 50 m.y. for effectively single-stage leads, we have shown that much late Precambrian to early Paleozoic mineralization in the main part of the Arabian Shield in Saudi Arabia occurred between 720 m.y. and perhaps as late as 460 m.y. ago. Low-lead, massive-sulfide, volcanogenic mineralization mostly occurred before 680 m.y. ago. Most higher lead content vein deposits were formed during and immediately after the Pan African event that culminated in the formation of the Najd fault system about 530 m.y. ago.

The low, near-mantle values of $^{207}Pb/^{204}Pb$ exhibited by the ore deposits in the main part of the Arabian Shield preclude the possibility of the involvement of older crustal material in their formation. The data from this region indicate that the craton developed from an oceanic crustal environment.

Data from the region of the shield east of long 44°20'E. and between lats 22°N. and 24.5°N. exhibit distinctly different lead-isotope characteristics that we interpret as indicating the presence of lower crustal rocks of early Proterozoic age (2100 m.y.) in this region.

The lead isotopic compositions of two Mesozoic galena samples, one from Oman and the other from Yemen, also indicate the presence of continental basement of similar early Proterozoic age in those parts of the Arabian Peninsula. In these cases however the ancient lead component is of upper crustal origin.

Our new lead-isotope data do not seem to conflict in principle with any of the models for crustal evolution that we have discussed. However, the nature of the changes near the Al Amar-Idsas fault and the evidence we have found for continental material underlying the surface to the west of the fault zone do lend support to the concept of continental underthrust from the east, and perhaps give credence to the idea of a westerly dipping subduction zone as suggested by Schmidt and others (1979).

Our data, together with those from the strontium isotope studies of Aldrich and others (1978) and Fleck and others (1980), require rather drastic changes of scale in the proto-Red Sea model of Stern (1979). Certainly the proto-sea basin would have had to cover at least the region from which the Group I samples were taken, a very much greater area than Stern originally envisioned. In addition, the ocean basin would have had to remain open for a considerably longer period than from 650 to 625 m.y. ago. Presently available data show that the process of craton building in the shield commenced at least as early as 950 m.y. ago and ended about 550 m.y. ago. More encouraging support for the proto-Red Sea proponents might be that the age of 2100 m.y. that we postulate for the continental block to the east of the shield is similar to that of the continent to the west of the Egyptian basin, at least as indicated by the older zircon ages of the Egyptian pebbles as measured by Dixon (in press).

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REFERENCES CITED

Aldrich, L. T., Brown, G. F., Hedge, Carl, and Marvin, Richard, 1978, Geochronologic data for the Arabian Shield: U.S. Geological Survey open-file rept. 78-75, (IR)SA-240, 22 p., 1 fig.

Al-Shanti, A. M. S., and Mitchell, A. H. G., 1976, Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia: Tectonophysics, v. 30, no. 3-4, p. T41-T47.

Bakor, A. R., Gass, I. G., and Neary, C. R., 1976, Jabal al Wask, Northwest Saudi Arabia; an Eocambrian back-arc ophiolite: Earth and Planetary Science Letters, v. 30, no. 1, p. 1-9.

Baubron, J. C., Delfour, Jacques, and Vialette, Yves, 1976, Geochrono-logical measurements (Rb/Sr; K/Ar) on rocks of the Arabian Shield, Kingdom of Saudi Arabia: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 76-JED-22, 152 p.

Brosset, Rene, 1974, Geology and mineral exploration of the Umm Sulaym quadrangle, 22/45 C: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 74-JED-9, 45 p.

Catanzaro, E. J., 1968, Absolute isotopic abundance ratios of three common lead reference samples: Earth and Planetary Science Letters, v. 3, p. 343-346.

Catanzaro, E. J., Murphy, T. J., Shields, W. R., and Garner, E. L., 1968, Absolute isotopic abundance ratios of common equal atom and radiogenic lead isotopic standards: Journal of Research of the U.S. National Bureau of Standards, 1. Physics, 2. Chemistry, 72A, v. 3, p. 261-267.

Chiron, J. C., 1974, Preparatory geologic study for underground mining tests at Al Amar: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 74-JED-1, 48 p.

Cooper, J. A., Stacey, J. S., Stoeser, D. B., and Fleck, R. J., 1979, An evaluation of the zircon method of isotopic dating in southern Arabian craton, Kingdom of Saudi Arabia: U.S. Geological Survey open-file report 79-1187 (IR)SA-257, 32 p.; Contributions to Mineralogy and Petrology, v. 68, 429-439.

Cumming, G. L., and Gudjurgis, P. J., 1973, Alteration of trace lead isotopic ratios by postore metamorphic and hydrothermal activity: Canadian Journal of Earth Sciences, v. 10, no. 12, p. 1782-1789.

Delevaux, M. H., Doe, B. R., and Brown, G. F., 1967, Preliminary lead isotope investigations of brine from the Red Sea, galena from the Kingdom of Saudi Arabia, and galena from United Arab Republic (Egypt): Earth and Planetary Science Letters, v. 3, no. 2, p. 139-144.

Delfour, Jacques, 1970, Sulfide mineralization at Nuqrah and Jabal Sayid: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 70-JED-22, 34 p.

Dixon, T. H., Age and chemical characteristics of some pre-Pan African rocks in the Egyptian Shield: Precambrian Research [in press].

Dodge, F. C. W., and Rossman, D. L., 1975, Mineralization in the Wadi Qatan area, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. 75-309, (IR)SA-190, 71 p., 1 pl., 5 figs.

Doe, B. R., and Rohrbough, Randall, 1979, Lead isotope data bank; 3,459 samples and analyses cited: U.S. Geological Survey Open file Report 79-661, 152 p.

Doe, B. R., and Zartman, R. E., 1979, Plumbotectonics I, the Phanerozoic: in Geochemistry of hydrothermal ore deposits, H. L. Barnes, editor, New York, John Wiley and Sons, p. 22-70.

Earhart, R. L., 1969a, Preliminary investigation of a copper occurrence at Jabal Sarbon, Tihamat Ash Sham quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. (IR)SA-102, 11 p., 2 figs.

Earhart, R. L., 1969b, Report on exploration of the Wadi Yiba copper prospect, Tihamat Ash Sham quadrangle, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. (IR)SA-108, 42 p., 10 figs., 2 tables.

El-Shazly, E. M., and Engel, A. E. J., 1978, Proterozoic rifting and refractionation of Northeast Africa: Precambrian Research, v. 6, no. 1, p. A20.

Fleck, R. J., Coleman, R. G., Cornwall, H. R., and Greenwood, W. R., 1976, Geochronology of the Arabian Shield, western Saudi Arabia; K-Ar results: Geological Society of America Bulletin, v. 87, no. 1, p. 9-21.

Fleck, R. J., Greenwood, W. R., Hadley, D. G., Anderson, R. E., and Schmidt, D. L., ~~in press,~~ 1980, Rubidium-strontium geochronology and plate tectonic evolution of the southern part of the Arabian Shield: U.S. Geological Survey Prof. Paper. 113[illegible] 38 p.

Frisch, Wolfgang, and Al-Shanti, A.M., 1977, Ophiolite belts and the collision of island arcs in the Arabian Shield: Tectonophysics, v. 43, no. 3-4, p. 293-306.

Fujii, Noriyuki, and Kato, Komi, 1974, Geology and copper ore deposits in the Jadmah prospect, northern Wadi Shwas area: Japanese Geological Survey Saudi Arabian Mission Report JGS 6-5, 42 p.

Garson, M. S., and Shalaby, I. M., 1976, Precambrian-Lower Paleozoic plate tectonics and metallogenesis in the Red Sea region: Geological Association of Canada, Special Paper no. 14, p. 573-596.

Gass, I. G., 1977, The evolution of the Pan African crystalline basement in NE Africa and Arabia: Journal of the Geological Society of London, v. 134, p. 129-138.

Greenwood, W. R., Roberts, R. J., Kiilsgaard, T. H., Puffett, Willard, and Naqvi, I. M., 1974, Massive sulfide deposits in Wadi Bidah mining district, Kingdom of Saudi Arabia: Arab Conf. Mineral Resources, 2d, Jiddah, Saudi Arabia, 1974, Conf. Doc. Background Papers, Copper p. 86-99.

Greenwood, W. R., Hadley, D. G., Anderson, R. E., Fleck, R. J., and Schmidt, D. L., 1975, Late Proterozoic cratonization in southwestern Saudi Arabia: Royal Society, Symposium, The Global tectonics in Proterozoia Times, London, March 1975, p. 10.

Hadley, D. G., 1974, Geologic map of the Wayban quadrangle, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Geologic Map GM-7, 10 p., scale 1:100,000.

Helaby, A. M., and Dodge, F. C. W., 1975, Ancient mines in Al Kushaymiyah region, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. 75-58, (IR)SA-189, 37 p., 7 figs., 6 tables.

Jackaman, Barry, 1972, Genetic and environmental factors controlling the formation of the massive sulphide deposits of Wadi Bidah and Wadi Wassat, Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Technical Record TR-1972-1, 244 p.

Kanasewich, E. R., and Farquhar, R. M., 1965, Lead isotope ratios from the Cobalt-Noranda area, Canada: Canadian Journal of Earth Sciences, v. 2, no. 4, p. 361-384.

Kiilsgaard, T. H., Greenwood, W. R., Puffett, W. P., Hawvi, M., Roberts, R. J., Worl, R. B., Merghelani, H., Flanigan, V. J., and Gazzaz, A. R., 1978, Mineral exploration in the Wadi Bidah district, 1972-1976, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. 78-771, (IR)SA-237, 95 p., 17 figs.

Leca, Xavier, 1970, Mineral resources and geology of the Jabal Sahah quadrangle, 22/44D: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 70-JED-7, 28 p.

Meijer, Arend, 1976, Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana Island arc system: Geological Society of America Bulletin, v. 87, no. 9, p. 1358-1369.

Moore, J. M., 1975, Regional metamorphism as an ore-forming process in the Saudi Arabian Shield: Transactions of Institution of Mining and Metallurgy, sec. 8, v. 84, p. 59-62.

Nasseef, A. O., and Gass, I. G., 1977, Granitic and metamorphic rocks of the Taif area, western Saudi Arabia: Geological Society of America Bulletin, v. 88, no. 12, p. 1721-1730.

Roberts, R. J., Greenwood, W. R., Worl, R. G., Dodge, F. C. W., and Kiilsgaard, T. H., 1975, Mineral deposits in western Saudi Arabia--a preliminary report: U.S. Geological Survey open-file rept. 75-654, (IR)SA-201, 60 p., 1 fig., 8 tables.

Routhier, Pierre, and Delfour, Jacque, 1975, Gitology of massive sulfide deposits associated with acid volcanism and its application to the search for such deposits in the Precambrian of Saudi Arabia: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 75-JED-10, 201 p.

Schmidt, D. L., Hadley, D. G., Greenwood, W. R., Gonzalez, Louis, Coleman, R. G., and Brown, G. F., 1973, Stratigraphy and tectonism of the southern part of the Precambrian Shield of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources no. 8, 13 p.

Schmidt, D. L., Hadley, D. G., and Stoesser, D. B., 1979, Late Proterozoic crustal history of the Arabian Shield, Southern Najd Province, Kingdom of Saudi Arabia: King Abdulaziz University Institute of Applied Geology's Symposium on the Evolution and Mineralization of the Arabian-Nubian Shield, Proc., v. 2, p. 41-58.

Smith, C. W., Anderson, Ernest, and Dehlavi, M. R., 1978, Geology and ore deposits of the Kutam mine, Kingdom of Saudi Arabia: U.S. Geological Survey open-file rept. 78-519, (IR)SA-211, 55 p., 15 figs., 5 tables.

Stacey, J. S., Zartman, R. E., and Nkomo, I. T., 1968, A lead isotope study of galenas and selected feldspars from mining districts in Utah: Economic Geology, v. 63, no. 7, p. 796-814.

Stacey, J. S., and Kramers, J. D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, no. 2, p. 207-221.

Stacey, J. S., Doe, B. R., Silver, L. T., and Zartman, R. E., 1976, Plumbotectonics IIA, Precambrian massive sulfide deposits: U.S. Geological Survey Open-File Report 76-476, 26 p.

Stacey, J. S. and Zartman, R. E., 1978, A lead and strontium isotopic study of igneous rocks and ores, from the Gold Hill mining district, Utah: Utah Geology, v. 5, p. 1-15.

Stern, R. J., 1979, Late Precambrian ensimatic volcanism in the central eastern desert of Egypt: University of California, San Diego, Ph.D. thesis, 211 p.

Worl, R. G., 1978, Mineral exploration: Mahd adh Dhahab district, Kingdom of Saudi Arabia: U.S. Geological Survey open-file report 78-1073, (IR)SA-233, 89 p., 3 pls., 19 figs.

York, Derek, 1968, Least squares fitting of a straight line with correlated errors: Earth and Planetary Science Letters, v. 5, p. 320-324.