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A Lead Isotope Study of Mineralization in the Saudi Arabian Shield

John S. Stacey[1], Bruce R. Doe[1], Ralph J. Roberts[2], Maryse H. Delevaux[1], and John W. Gramlich[3]

[1] US Geological Survey, Denver Federal Center, MS 963, Lakewood, Colorado 80225, USA
[2] US Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
[3] Analytical Chemistry Division, National Bureau of Standards, Washington DC 20234, USA

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, isochron model ages 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 due to the mineralizing fluids acquiring 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 longitude 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 this easterly region were mineralized 530 m.y. ago, then the age of the older continental rocks is $2{,}100 \pm 300$ m.y. (2σ).

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 material in these regions.

Reprint requests to: J.S. Stacey

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 National Bureau of Standards (Catanzaro et al. 1968). In addition, lead isotope model theory has been developed to enhance our understanding of lead isotope behavior (e.g., 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 et al. (1979), and Fleck, Coleman et al. (1976); Cooper et al. (1979); Greenwood et al. (1976); Baubron et al. (1975); Roberts et al. (1975) and Schmidt, Hadley et al. (1973), and Schmidt, Hadley and Stoeser (1978). Consequently it is now known that the Saudi Arabian Shield developed during the period from late Proterozoic through to early Paleo-

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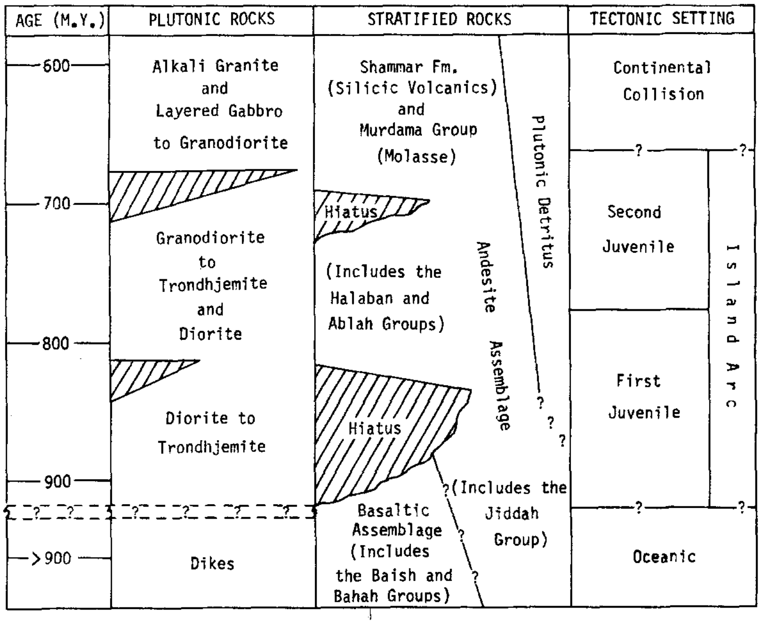

Fig. 1. Diagram showing the sequence of the main geologic events in the formation of the Saudi Arabian Shield, from Fleck and others (1979), modified by ourselves and from suggestions made by Schmidt (oral communication 1979)

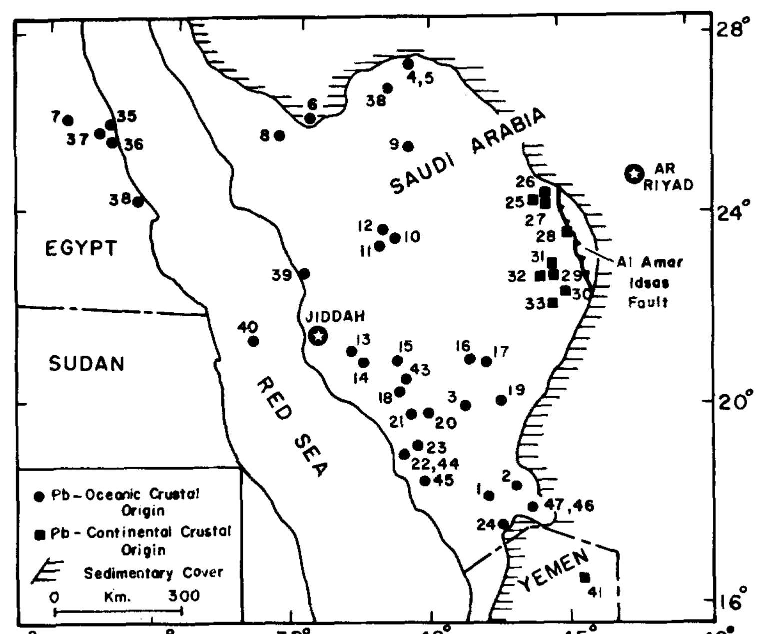

Fig. 2. Map of the Red Sea Region showing locations of samples from this study and from that of Delevaux et al. (1967). Locations for the model calibration samples 1–4 are identified in Table 1; 5–24 for Group I samples are identified in Table 2; locations 25–33 for Group II samples in Table 3; locations 34–43 for Mesozoic-Cenozoic samples in Table 4, and Table 5 identifies localities 43–47 for Precambrian massive sulfide samples

zoic. Figure 1 shows a summary of the Precambrian units and major tectonic, plutonic and orogenic events as proposed by Fleck and others (1979), 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 et al. (1967) have been reanalyzed and are included here with over 35 new analyses. The map in Fig. 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 for 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 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 National Bureau of Standards, Washington, D.C.

Most galena lead was analyzed isotopically using the triple filament thermal ionization technique, with the lead purified by electro-deposition, Catanzaro (1967). The standard sample NBS-981 was used to determine corrections necessary to obtain absolute ratios in both of the laboratories where the analyses were made. Isotopic compositions and concentrations of the trace leads in the 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% 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 et al. 1977). However, many of the samples in this study of the Arabian Shield are from vein deposits. For a vein galena, there is the possibility that a quantity of radiogenic lead 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 Saudi Arabian context 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 significantly contaminate 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 Saudi Arabian environment by examining initial lead from rocks from the shield that have been accurately dated by other methods.

In one instance a small (180 μ) cubic crystal was noticed in an electron microscope photograph of zircons separated from a peralkaline granite sample from Jabal Ajah in the north 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 μg of lead.) Results of this experiment in 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 and 30 m.y. younger than their zircon ages respectively. These data are also in Table 1. The initial

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			Pb ppm	U ppm	Zircon age m.y.	Corrected ratios		Isochron model age m.y.
		$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$				$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	
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

Sample locality and coordinates		$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	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[a] 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[a] 23°31′ N; 41°10′ E		17.741	15.503	37.254	470	
11. Mahd ahd Dhahab 23°30′ N; 40°52′ E	87520 87223 DDB-11[a] 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)[b]	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)
13. Taif[a] 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 (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[b] 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[a] 19°55.6′ N; 41°48.5′ E	DDB–4	17.854	15.515	37.326	420	Au quartz vein in Precambrian andesite
22. Suq Al Khamis 19°10′ N; 41°21′ E	E-37214	17.626	15.477	37.158	510	
23. Al Muchahal[a] 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 (1969)
24. Kutam 17°36′ N; 43°34′ E	107515 (NBS) MS–ORE	17.595	15.503	37.104	600	Cu–Zn massive sulfide some Pb. Highly metamorphosed and sheared in Jedda-Halaban pyroclastics. Smith et al. (1977)
	69–50 (vein- (galena)	17.575	15.493	37.082	580	

[a] Samples reanalyzed from Delevaux et al. (1967)
[b] Ratios corrected for in situ decay of U and Th
(NBS) – Analysis made at National Bureau of Standards

Table 3. Group II – Precambrian – late Paleozoic galenas from eastern Arabian Shield

	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[a] 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 (1976)
26.	Ardayat[a] 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 (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 (1974)
30.	Wadi Aqarah 22°46.8′ N; 45°0.5.8′ 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 (1974)
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)

[a] Samples reanalyzed from Delevaux et al. (1967)

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 et al. 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.

The conclusion of the calibration study is that the Stacey-Kramers model apparently gives reasonable age estimates in the Saudi Arabian setting, yielding ages for effectively single stage leads that 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 Fig. 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 longitude 44°20′ E. These separate regions are evident in the map of Fig. 2. The isotopic groupings can be seen in the $^{208}Pb/^{204}Pb - ^{206}Pb/^{204}Pb$ plot of Fig. 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.

For the $^{207}Pb/^{204}Pb - ^{206}Pb/^{204}Pb$ data separate plots have been made in Fig. 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 out 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.),

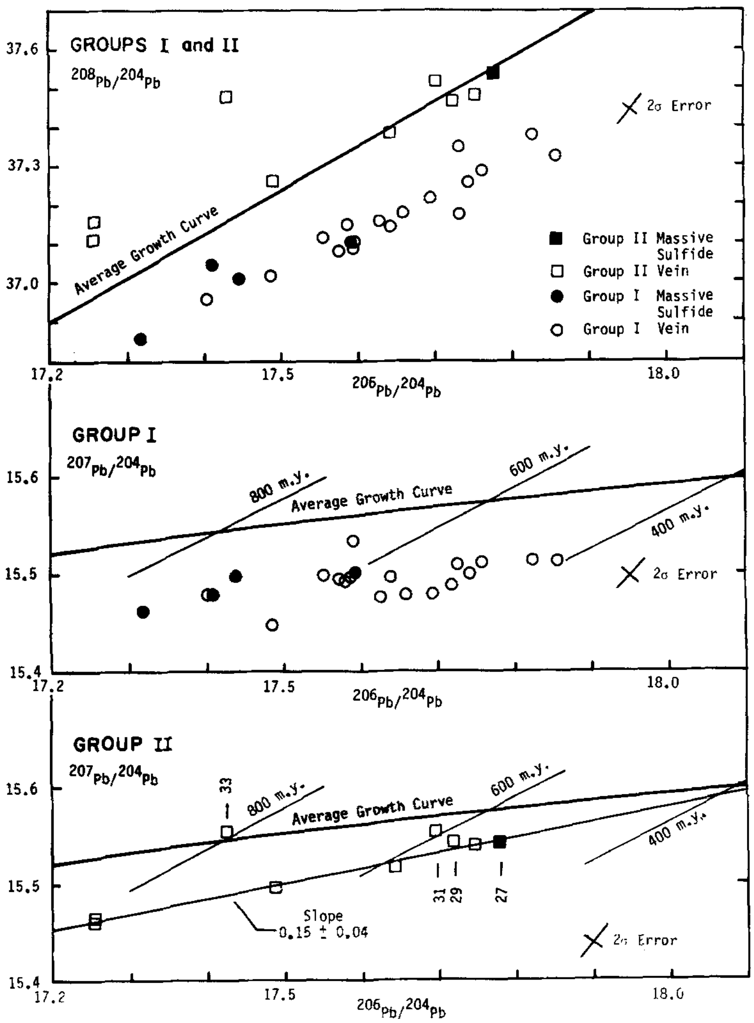

Fig. 3. Precambrian-early Paleozoic galena and massive sulfide ore data are shown, numbered as in Tables 2 and 3. Model evolution curves are shown from Stacey and Kramers (1975). Isochron model ages between 720 m.y. and 420 m.y. are assigned to the Group I galenas that are from the main part of the Arabian 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

Nuqrah (685 m.y.) and Kutam (600 m.y.). All these deposits were examined in the sulfur isotope study by Rye et al. (in press) 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 et al. 1976). The model age of 600 m.y. for Kutam seems much lower than the expected age of the enclosing rocks (~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 et al., in press). 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 680 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 over a large area of the shield had remarkably similar lead isotopic compositions.

The histogram of the data in Fig. 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 et al. (1975) 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 by R.J. Fleck (oral communication, 1979)

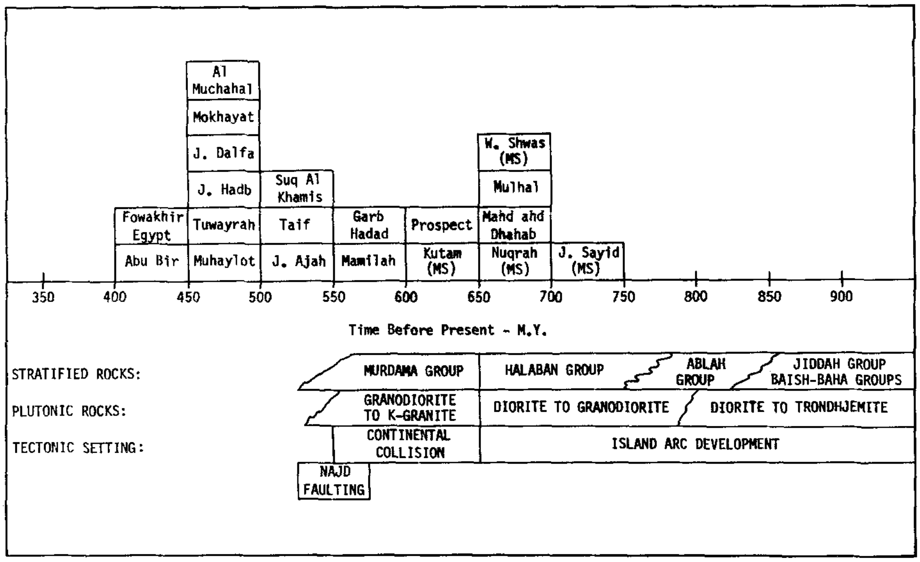

Fig. 4. Histogram of isochron model ages for Group I leads from ore deposits and prospects in the southern part of the Saudi Arabian Shield. Massive sulfide deposits are designated (MS)

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 Fig. 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 ± 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 (e.g., Stacey et al. 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 et al. (1975) 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 is a reasonable estimate for the end of the Najd faulting, Fleck et al. (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 ± 0.03 (2σ), the source rock age is computed as $2{,}100 \pm 300$ 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 Ar Ridayniyah (# 27) is the most radiogenic sample in the linear array. This is probably a manifestation of its sedimentary character. According to Rye and others (in press) 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 2,100 m.y. old. Mineralization ages then compute as approximately 570 m.y. for Bahfor, 680 m.y. for Bosnun, and 965 m.y. for Wadi Sitarah.

The most important conclusion from the Group II data is that east of about longitude 44°20′ E, and extending between latitudes 22° N and 24.5° N, the region appears to be underlain by Precambrian basement rocks about 2,100 m.y. old. This is the first

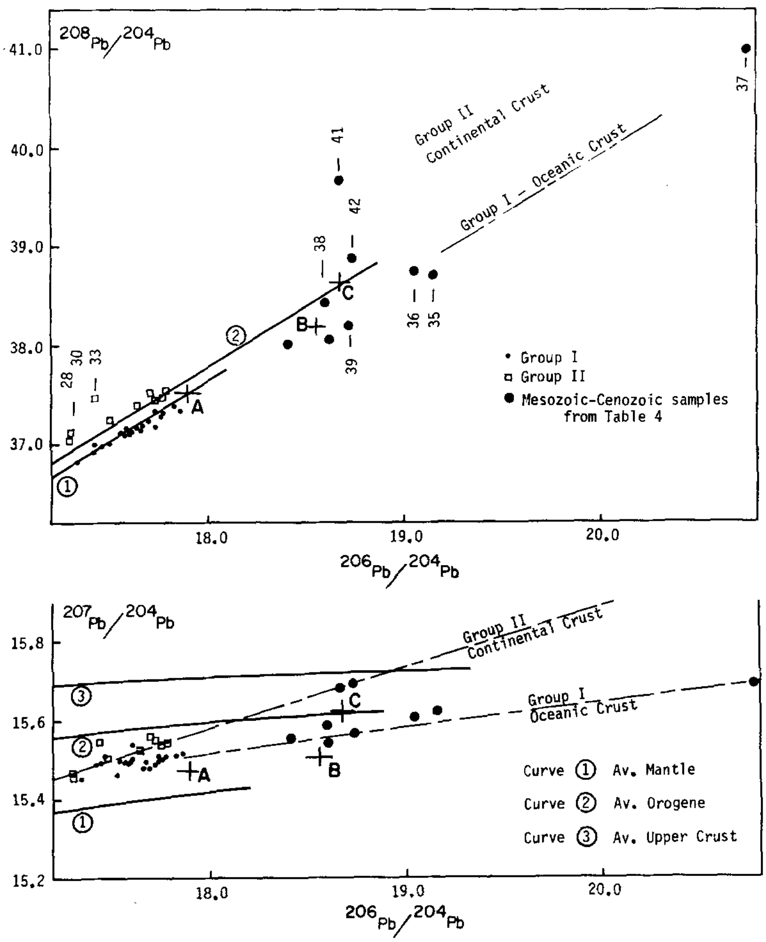

Fig. 5. Data from Groups I and II (Tables 2 and 3 respectively) are plotted together with data for Mesozoic-Cenozoic deposits, numbered as in Table 4. The plumbotectonics model evolution curves are from Doe and Zartman (1979). Also shown for comparison are (A) a galena analysis from the Triassic mining district at Mount Shasta, California, Doe and Rohrbough (1977); average present day compositions of volcanic rocks (B) and marine clays (C) from the Eocene-Miocene Mariana primitive island arc complex in the Pacific Ocean, data from Meijer (1976)

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 et al. (1977). The Saudi Arabian lead data are plotted in Fig. 5 together with the plumbotectonics model curves for the average mantle, the average orogene[1], and the average upper crust. 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 actually lie along the average mantle curve. It can be seen from both diagrams of Fig. 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, thus emphasizing 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), actually lie *above* the orogene curve, and that the $^{207}Pb/^{204}Pb$ data lie *beneath* the orogene curve in the other plot indicates that the Group II leads may be derived from

[1] The average orogene curve of plumbotectonics corresponds to the average growth curve of Stacey and Kramers (1975) that is shown in Fig. 3

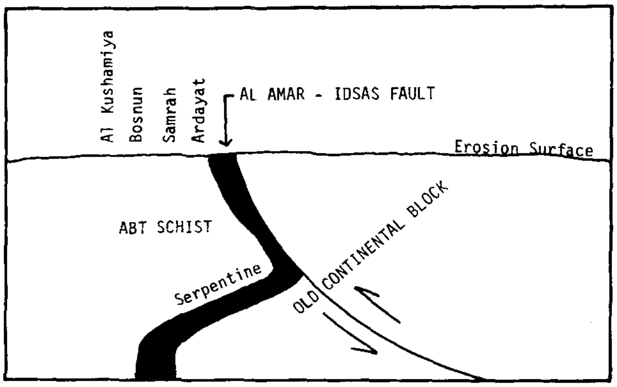

Fig. 6. Hypothetical section across the Al Amar-Idsas fault zone, as suggested by D.L. Schmidt (written communication 1979)

rocks of the lower continental crust. Actually, Jabal Sitarah (# 33), the southernmost of our Group II samples, appears to be quite different. Its data plot *above* the average orogene curve in *both* the graphs of Fig. 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 analagous to the Precambrian basement of 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 terrains, 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 terrains 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 et al. (1978), 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 may well explain the boundary between Group I and Group II lead data. A glance at Fig. 2 however, indicates that further sampling in the region between Al Amar and Jabal Hadb, 300 km to the west, will be necessary to properly locate the boundary.

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 (1976) pointed out that the fault separates two metallogenic provinces, a Pb–Ag–W–Mo province on the west, and Fe–Cu–Zn–Au–Ba on the east. The fault zone itself contains anomalous amounts of Fe, Cr, Cu, and Ni in bodies of ultramafic rocks.

The tectonic evolution of the Saudi 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 et al. (1976) and developed by Fleck et al. (1979) from strontium isotope data. They proposed that the Saudi Arabian craton evolved in an intra-oceanic island arc environment that was accreted into 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 et al. (1976), Frisch and Al-Shanti (1977), Nasseef and Gass (1977), Gass (1977), and Schmidt et al. (1978).

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 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 from an intercontinental collision in the east.

To choose between the various models is beyond the scope of this work, but the controversy prompted our reanalysis of the data of Delevaux and others (1967) to considerably extend 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 Fig. 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 Fig. 5. Its Group I type lead seems to have acquired a small but distinctly older continental component that may have originated from sediments in

Table 4. Mesozoic-Cenozoic galenas from Saudi Arabia and northeastern Egypt

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[a] 25° 40′N; 34° 31′ E		19.155	15.626	38.699	Group I	Stratiform deposit underlying Miocene gypsum
36.	Um Ans, Egypt[a] 25° 30′ N; 34° 40′ E		19.037	15.608	38.741	Group I	Replacement in middle Miocene lime grit
37.	Taleit Eid, Egypt[a] 25° 40′ N; 34° 20′ E		20.755	15.694	41.005	Group I	From slightly metamorphosed Precambrian schist
38.	Bir Ranga Egypt[a] 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[a] 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 < 0.00006 ppm
41.	Hailan, Yemen[a] 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

[a] Galena Samples reanalyzed from Delevaux et al. (1967); the brine sample data from the same study are the original data normalized to absolute values

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, 1,100–2,300 m.y. These cobbles have no obvious source in the Egyptian 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, 1,500 km to the east (# 42), exhibit data that are quite different from other Cenozoic samples discussed. Unlike the Group I data, they plot above the average orogene curve in each of the diagrams of Fig. 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 Peninsular. 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 Saudi Arabian Shield there are many Precambrian massive sulfide deposits that do not contain galena. The ores are generally 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 9 massive sulfide deposits. The lead isotopic compositions for all samples were determined and are shown in Table 5. Pb, U and Th 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 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. Unfortunately however, in almost all cases, 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 estimate the initial lead compositions at the time of ore deposition. Since most of the whole-ore samples are from drill-core, it seems unlikely that disturbance of the U−Th−Pb systems is due to recent weathering.

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 Fig. 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	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{207}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{204}Pb}$	Pb ppm	U ppm	Th ppm	$\frac{^{238}U}{^{204}Pb}$	$\frac{^{232}Th}{^{204}Pb}$	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	32,380	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 et al. (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 (1968)
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 deolomite, amphibolite, and schists of the Ablah Formation, Earhart (1969)
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	107151 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 Quatan	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	107515 NBS	17.595	15.503	37.104	3,906	0.10	0.15	0.001	0.002	Cu - Zn massive sulfides, some Pb. Highly metamorphosed and sheared. Smith et al. (1977)
17° 36′ N, 43° 34′ E	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	

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 Pb, U, and Th concentration data. The data show that for samples of this type one can assume neither that lead contents 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 Fig. 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 Fig. 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 Fig. 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

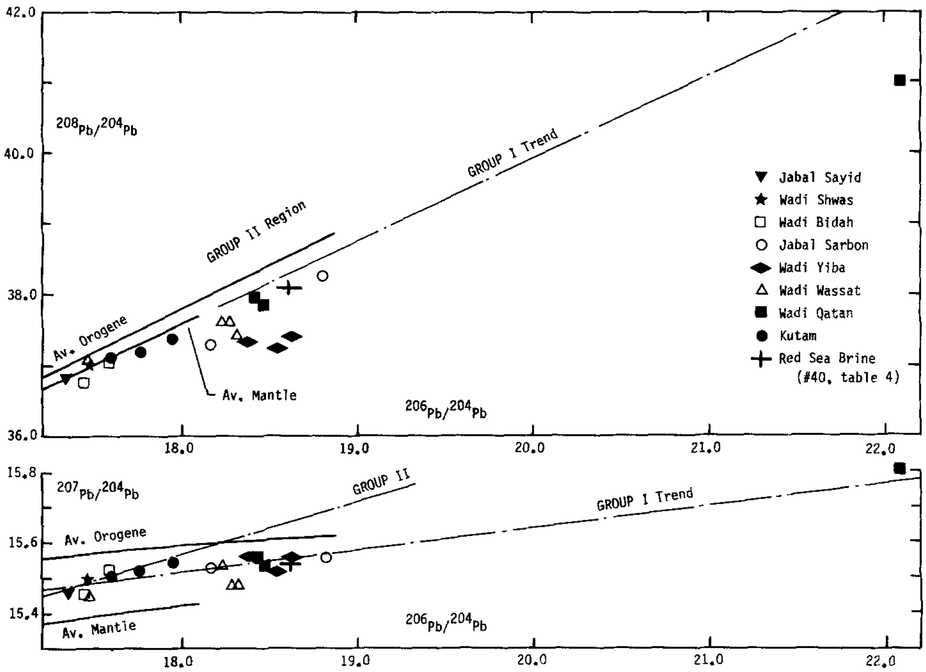

Fig. 7. Whole-ore data from Table 5 are shown for Precambrian massive sulfide deposits in the main part of the Arabian Shield. Also plotted for reference is the present day brine sample from the Red Sea, # 40 in Table 4

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.

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 Saudi Arabian Shield 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 longitude 44°20′ E and between latitudes 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 (2,100 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 (1978).

Our data, together with those from the strontium isotope studies of Aldrich et al. (1978) and Fleck et al. (1979), 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 2,100 m.y. which 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

Aldrich LT, Brown GF, Hedge CE, Marvin RF (1978) Geochronologic data for the Arabian Shield. US Geol Surv Saudi Arabian Proj rep 240:20

Al Shanti AMS, Mitchell AHG (1976) Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia. Tectonophysics 30:T41–T47

Bakor AR, Gass IG, Neary CR (1976) Jabal al Wask, Northwest Saudi Arabia: an Eocambrian back-arc ophiolite. Earth Planet Sci Lett 30:1–9

Baubron JC, Delfour J, Vialette Y (1975) Geochronological measurements (Rb/Sr; K/Ar) on rocks of the Arabian Shield, Kingdom of Saudi Arabia. Bur Rech Geol Min (Saudi Arabian Mission) rep 77–JED–30:152

Brosset R (1974) Geology and mineral exploration of the Umm Sulaym quadrangle, 22/45C. Bur Rech Geol Min (Saudi Arabian Mission) rep 74–JED–9:45

Catanzaro EJ (1967) Absolute isotopic abundance ratios of three common lead reference samples. Earth Planet Sci Lett 3:343–346

Catanzaro EJ, Murphy TJ, Shields WR, Garner EL (1968) Absolute isotopic abundance ratios of common, equal atom, and radiogenic lead isotopic standards. J Res Nat Bur Stand, SectA 72 (3):261–267

Chiron JC (1974) Preparatory geologic study for underground mining tests at Al Amar. Bur Rech Geol Min (Saudi Arabian Mission) rep 74–JED–1:48

Cooper JA, Stacey JS, Stoeser DG, Fleck RJ (1979) An evaluation of the zircon method of isotopic dating in the Southern Arabian craton. Contrib Mineral Petrol 68:429–439

Cumming GL, Gudjurgis PJ (1973) Alteration of trace lead isotopic ratios by postore metamorphic and hydrothermal activity. Can J Earth Sci 10:1782–1789

Delevaux MH, Doe BR, Brown GF (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 Planet Sci Lett 3:139–144

Delfour J (1970) Sulfide mineralization at Nuqrah and Jabal Sayid. Bur Rech Geol Min (Saudi Arabian Mission) rep 70–JED–22:34

Dixon TH Age and chemical characteristics of some pre-Pan African rocks in the Egyptian Shield. Precambrian Res (in press)

Dodge FCW, Rossman DL (1975) Mineralization in the Wadi Quatan area, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj Open-file Rep 190:71

Doe BR, Rohbough R (1977) Lead isotope data bank: 3,459 samples cited. US Geol Surv Open-file rep 77–418:127p

Doe BR, Zartman RE (1979) Plumbotectonics I, the Phanerozoic. In: H Barnes (ed) Geochemistry of hydrothermal ore deposits. John Wiley and Sons, New York, pp 22–70

Earhart RL (1968) A preliminary investigation of a copper occurrence at Jabal Sarbon, Tihamat ash Sham quadrangle, Kingdom of Saudi Arabia. US Geol Surv Proj Rep 102:11

Earhart RL (1969) A preliminary investigation of the Wadi Yiba copper prospect, Tihamat ash Sham quadrangle, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj Open-file rep 108:42p

El-Shazly EM, Engel AEJ (1978) Proterozoic rifting and refractionation of Northeast Africa. Precambrian Res 6:A20

Fleck RJ, Coleman RG, Cornwall HR, Greenwood WR, Hadley DG, Schmidt DL, Prinz WC, Ratte JC (1976) Geochronology of the Arabian Shield, western Saudi Arabia, K–Ar results. Geol Soc Am Bull 87:9–21

Fleck RJ, Greenwood WR, Hadley DG, Anderson RE, Schmidt DL (1979) Rubidium-Strontium geochronology and plate tectonic evolution of the Arabian Shield. US Geol Surv Saudi Arabian Proj Rep 245:105

Frisch W, Al Shanti A (1977) Ophiolite belts and the collision of island arcs in the Arabian Shield. Tectonophysics 43:293–306

Fujii N, Kato K (1974) Geology of copper ore deposits of the Jadmah prospect northern Wadi Shwas area. Jpn Geol Surv Saudi Arabian Mission Rep J656-5:42p

Garson MS, Shalaby IM (1976) Precambrian-Lower Paleozoic plate tectonics and metallogenesis in the Red Sea region. Geol Assoc Can, Spec Pap 14:573–596

Gass IG (1977) The evolution of the Pan-African Crystalline basement in NE Africa and Arabia. J Geol Soc London 134:129–138

Greenwood WR, Roberts RJ, Kiilsgaard TH, Paffett W, Naqvi IM (1974) Massive sulfide deposits in the Wadi Bidah district, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj Rep 175:17

Greenwood WR, Hadley DG, Anderson RE, Fleck FJ, Schmidt DL (1976) Late Proterozoic cratonization in southwestern Saudi Arabia. Philos Trans R Soc London, Ser A:280:517–527

Hadley DG (1974) Geologic map of the Wayban quadrangle, Kingdom of Saudi Arabia. Saudi Arabia, Dir Gen Miner Resour, Geol Map GM–7, scale 1:100,000

Helaby HM, Dodge FCW (1974) Ancient mines in Al Kushaymiyah Region, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj Rep 189:37

Jackaman B (1972) Genetic and environmental factors controlling the formation of the massive sulphide deposits of Wadi Bidah and Wadi Wasset. Saudi Arabia, Dir Gen Miner Resour, Tech Record TR–1972–1:243

Kanasewich ER, Farquhar RM (1965) Lead isotope ratios from the Cobalt-Noranda area, Canada. Can J Earth Sci 2:361–384

Kiilsgaard TH, Greenwood WR, Puffett WP, Naqvi M, Roberts RJ, Worl RG, Merghelani H, Flanigan VJ, Gazzaz AR (1978) Mineral exploration in the Wadi Bidah District, 1972–1976, Kingdom of Saudi Arabia. US Geol Surv Proj Rep 237:89

Leca X (1970) Mineral resources and geology of the Jabal Sahah quadrangle, 22/44 D. Bur Rech Geol Min (Saudi Arabian Mission) rep 70–JED–7:28

Meijer A (1976) Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana Island arc system. Geol Soc Am Bull 87:1358–1369

Moore J (1976) Regional metamorphism as an ore-forming process in the Saudi Arabian Shield Trans Inst Min Metall Sect B:84:59–62

Nasseef AO, Gass IG (1977) Granitic and metamorphic rocks of the Taif area western Saudi Arabia. Geol Soc Am Bull I (88): 1721–1730

Roberts RJ, Greenwood WR, Worl RG, Dodge FCW, Kiilsgaard TH (1975) Mineral deposits in western Saudi Arabia. US Geol Surv Saudi Arabian Proj rep 201:60

Routhier P, Delfour J (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. Bur Rech Geol Min Open-file rep 75–JED–10:201

Rye RO, Roberts RJ, Whelan JR, Mawad MM Reconnaissance sulfur isotope investigations of mineral deposits in the Precambrian Shield, Kingdom of Saudi Arabia. Econ Geol (in press)

Schmidt DL, Hadley DG, Greenwood WR, Gonzalez L, Coleman RG, Brown GF (1973) Stratigraphy and tectonism of the southern part of the Precambrian Shield of Saudi Arabia. Saudi Arabia, Dir Gen Miner Resour, Bull 8:13

Schmidt DL, Hadley DG, Stoeser DB (1978) Late Proterozoic crustal history of the Arabian Shield, southern Najd province, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj Rep 251:44

Smith CW, Anderson RE, Dehlavi MR (1977) Geology and ore deposits of the Kutam mine. US Geol Survey Saudi Arabian Proj rep 211:51

Stacey JS, Zartman RE, Nkomo IT (1968) A lead isotope study of galenas and selected feldspars from mining districts in Utah. Econ Geol 63:796–814

Stacey JS, Kramers JD (1975) Approximation of terrestrial lead evolution by a two-stage model. Earth Planet Sci Lett 26:207–221

Stacey JS, Doe BR, Silver LT, Zartman RE (1977) Plumbotectonics IIA, Precambrian massive sulfide deposits. In: SF Karpenko (ed) Geochronology and the problems of ore formations (in Russian). US Geol Surv open-file rep # 76–476:26

Stacey JS, Zartman RE (1978) A lead and strontium isotope study of igneous rocks and ores from the Gold Hill mining district, Utah. Utah Geology 5:1–15

Stern RJ (1979) Late Precambrian Ensimatic volcanism in the central eastern desert of Egypt. PhD thesis, University of California, San Diego, p 211

Worl RG (1978) Mineral exploration, Mahd adh Dhahab district, Kingdom of Saudi Arabia. US Geol Surv Saudi Arabian Proj rep 233:85

York D (1968) Least squares fitting of a straight line with correlated errors. Earth Planet Sci Lett 5:320–324

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