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Plumbotectonics IIA, Precambrian Massive Sulfide Deposits

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Introduction

Professor Tugarinov has long recognized the importance of common lead in rocks and ore deposits as an age indicator. The paper he authored with L. K. Gavrilova and V. P. Bedrinov in 1963, and the work of Cantanzaro and Gast (1960), are two of the most extensive studies of the evolution of lead isotopes in feldspars. Such studies are very important to our understanding of crustal evolution because of our ability to calibrate feldspar ages by other means. The pioneer paper by Stanton and Russell (1959) opened the way for dating certain deposits--submarine volcanic exhalative massive sulfide deposits--in the orogene. It is now generally accepted that these deposits formed during volcanism or shortly thereafter (Hutchinson, 1973). Therefore their lead isotope evolution may be correlated with time by dating the enclosing rocks. Over the last eight years, investigators have gradually realized that lead isotopic analyses, coupled with geochronologic studies, may yield much additional information about ore deposits and their origins.

This paper evaluates the lead isotopic characteristics of Precambrian massive sulfide deposits of all types. The treatment here will be similar to that used by Doe and Zartman (1976) in their "plumbotectonics" model for Phanerozoic deposits of this type. The submarine volcanic exhalative ores were chosen for emphasis because they are the type class for "conformable" or "stratiform" leads used in lead isotope model theory. We suggest that any deviation from a strictly average isotopic composition for a given age of deposit can often be explained by differences in the tectonic settings in which the ores were formed. This paper is a "state-of-knowledge" discussion of that thesis.

Historical survey

Stanton and Russell (1959) began a new era in lead isotope investigations when they identified a suite of ore deposits whose lead isotopic compositions lay on a unique growth curve on each of the lead isotope diagrams ($^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$). The authors concluded that the samples were derived from a source isotopically uniform throughout the world, with a single value for each of the $^{238}U/^{204}Pb$ and $^{232}Th/^{204}Pb$ ratios normalized to the present day. Their intent was to consider ore bodies with lead derived from the mantle, which was then assumed to be isotopically uniform at any particular geologic time (Stanton and Russell, 1959; Ostic et al., 1967); thus, their studies focused on ore bodies of the submarine volcanic exhalative massive sulfide type, such as those found in orogenes (Phanerozoic island arcs and their Precambrian equivalent). They originally used the non-genetic term "conformable" for their suite of ores, but they later changed it to "stratiform".

Of the nine deposits Stanton and Russell studied, the one at Bleiberg, Austria, which occurs in carbonate rocks, was soon excluded from the list of volcanogenic deposits. Ostic et al. (1967) also omitted the Canadian deposits Geneva Lake, Sullivan, and Yukon-Treadwell. However, Sangster (1972a; oral communication, 10 November, 1975) still believes Geneva Lake to be submarine volcanic exhalative, and he refers to Sullivan as "hidden exhalative" in origin.

The Broken Hill deposit in Australia is in granulite facies metamorphic rocks, hence its origin is obscure, according to Stanton (1972), although he prefers to describe it as submarine exhalative. He suggested (p. 1131) a possible origin through "...subsurface brines debouching on the contemporary sea floor...". The laminated ore is concentrated in sillimanite-bearing gneisses thought to be more pelitic than volcanic in origin. Hutchinson (1973) did not list Broken Hill as a submarine volcanic exhalative deposit. Stanton

(1972, p. 1144) assigned the Mount Isa deposit in Australia to a class "...which seems to be closely related to the environment of sedimentation...". Mount Isa is not in volcanogenic sediments either; it is actually in carbonaceous calcareous shales that contain only sparse distal tuff layers in the sequence. The tuffs are found in non-mineralized as well as mineralized units. Thus it is doubtful if either Broken Hill or Mount Isa should be included in the volcanogenic exhalative class.

Of the original nine deposits, only four (all Canadian) can still be confidently classified as volcanogenic. These are (1) Bathurst, New Brunswick (Paleozoic); (2) Buchans, Newfoundland (Paleozoic); (3) Geneva Lake, Ontario (Precambrian); and (4) Manitouwadge, Ontario (Archean).

Several similar deposits (all Paleozoic and all Australian) were added to the list by Ostic et al. (1967). These were (1) Rosebery, Tasmania; (2) Captain's Flat, New South Wales; (3) Cobar, New South Wales; and (4) Halls Peak, New South Wales. Of these, only the first two were acknowledged to be volcanogenic exhalative by Hutchinson (1973).

Ostic et al. (1967) also included Mt. Farrell (a vein deposit close to Rosebery) and fumarolic products from White Island, New Zealand. Apparently, the White Island deposit was included as an attempt to obtain a control point for zero time. However, since Doe (1970) has shown that subaerial oceanic island volcanics often have quite different isotopic characteristics from submarine volcanics, inclusion of the White Island sample now seems equivocal.

Kanasewich and Farquhar (1965), and Kanasewich (1968), selected several new suites of data from deposits that exhibited "single stage" lead isotope evolution, as they had defined it. One of these deposits, the Errington Mine in the Sudbury basin of Ontario, Canada, shows no abundance of volcanic rocks, and its genesis is still uncertain (D. F. Sangster, oral communication, 10 November 1975). The vein deposits at Cobalt, Ontario, which were also named, do not appear to have any association with volcanic rocks. Furthermore, the Finnish deposits that Kanasewich and Farquhar identified at Kisko and Körsnas are thought by Kahma (1973) to be related to contact metasomatism rather than to submarine volcanism.

Stacey et al. (1969) added the Precambrian deposit at Flin Flon, Manitoba, Canada, to the volcanogenic category. In an attempt to find a deposit older than 3 b.y., they also included Barberton, South Africa. However, Barberton is a secondary vein deposit in a greenstone belt, and so cannot be included because of its similarity to Broken Hill in Australia (King, 1973). At Balmat, although some paragneiss and phacolithic granite gneiss are probably of volcanic origin, the deposit is in calc-silicate rocks. Its origin is thus obscured in the metamorphic sequence and its assignment to the volcanic exhalative group is questionable.

Brown (1965) pointed out that the only source material with appropriate lead isotopic composition for the submarine volcanic exhalative deposits seemed to pelagic sediments; however, he suggested no mechanism for transporting lead from sea floor sediments into ore bodies. To accomplish this mobility of lead, Armstong (1968) proposed a tectonic process now known as subduction. Studies of oceanic volcanic rocks, including those by Gast et al. (1963), Cooper and Richards (1966), and Tatsumoto (1966a and b), made it apparent that the mantle is not isotopically uniform. In fact, there is a systematic difference, especially in $^{207}Pb/^{204}Pb$, between most submarine volcanic exhalative deposits and the oceanic mantle, the mantle having the lower value. Tatsumoto (1969) showed that subduction of pelagic marine sediments was a viable explanation for the lead isotope trends in subaerial volcanic rocks of

Japan. By 1972, Russell had abandoned the hypothesis of a mantle source for stratiform ore deposits (Russell, 1972), and then Sato (1975) showed that the lead isotope trends observed by Tatsumoto were repeated in the submarine volcanic exhalative ores of Japan--notably the famous Miocene Kuroko ores. Doe and Zartman (1976) confirmed Sato's observation with data of increased precision. Furthermore, they pointed out that when the available data are reviewed, the previously considered Phanerozoic submarine volcanic exhalative deposits seem to have a large component of pelagic sediment lead, or even lead with a distinctly continental affinity, possibly due to the "mature" nature of most volcanic arcs. On the other hand, they showed mantle lead is not precluded from all submarine volcanic exhalative deposits, since data on the Cyprus deposits indicate its presence. These deposits are in an ophiolite zone, presumably a former ocean spreading center, and they have lead isotopic compositions similar to those of oceanic volcanics. Doe and Zartman also analyzed lead from deposits in the East Shasta and West Shasta districts of California. These ores are associated with volcanic rocks like those found in primitive island arcs and are therefore comparable to deposits in the complex of Tonga-Kermadec in the western Pacific Ocean.

Although Doe and Zartman (1976) utilize an "orogene", or a multistage mixing approach, previously Stacey and Kramers (1975) demonstrated that a good approximation for average lead development in the upper part of the earth may be obtained from a two-stage model. The first stage describes the early evolution of lead isotopes--probably prior to the formation of the earth's crust. The second stage approximates lead isotope evolution in the average orogene since 3.7 b.y. ago. It was probably at that time that the first permanent crust was formed.

If we apply the most narrow geological classification to Precambrian deposits, it seems that all published theoretical work involved only three major deposits accepted as belonging to the submarine volcanic exhalative category. These deposits, Manitouwadge, Flin Flon, and possibly Geneva Lake, represent a limited suite of data for so very large a time span. Our intent here is to add new data to the Precambrian suite and to discuss implications of published data from other geologically similar desposts.

The plumbotectonics model

In the plumbotectonics model of Doe and Zartman (1976), portions of the mantle, the lower crust and the upper crust are mixed in the orogene at regular intervals of 400 m.y., beginning with the first appearance of permanent crust 4.0 b.y. ago. Immediately after each mixing, fixed portions of the new material build new upper and lower crust, and the remainder is returned to the mantle. In each orogeny, lead, thorium and especially uranium are partitioned strongly in favor of the newly forming upper crust, leaving the lower crust deficient in these elements. Only a small increase occurs in the U/Pb ratio of the mantle as a result of material returned from the orogene. Continental evolution is modelled by balancing processes of crustal destruction and creation during each orogeny.

Thus lead evolves in the orogene, the mantle, the lower crust and the upper crust, from quite different relative concentrations of uranium, thorium and lead. Although considerable heterogeneity exists in all these reservoirs, a separate average lead evolution curve can be constructed for each. fig. 1

Fig. 1.--Near Here.

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shows these curves, as predicted by the plumbotectonics model.

Fig. 1. Average lead isotope evolution curves for the mantle, the lower crust, the upper crust, and the orogene, as generated by the plumbotectonics model of Doe and Zartman (1976).

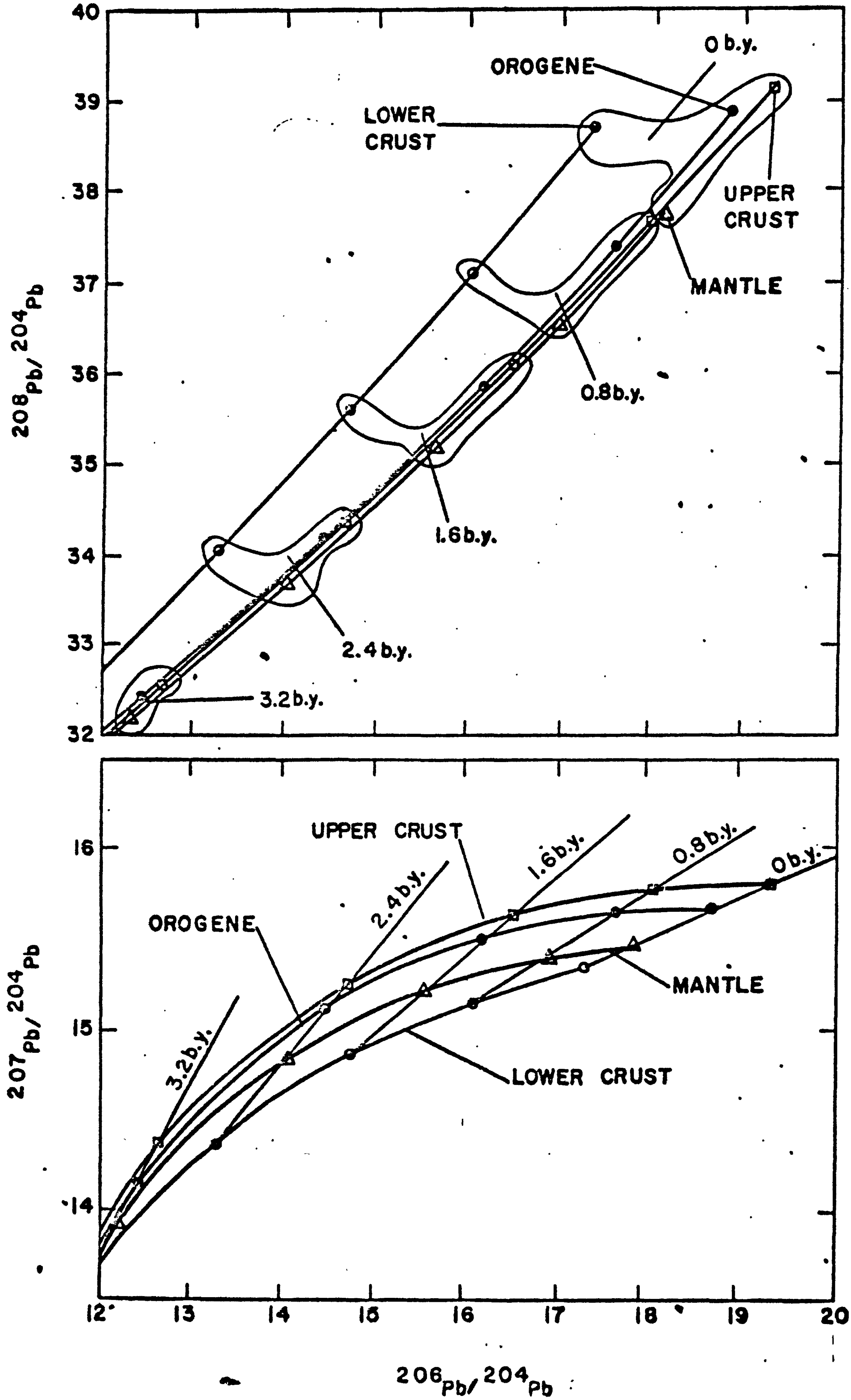

40
39
38
37
36
35
34
33
32
O b.y.
OROGENE
LOWER
CRUST
UPPER
CRUST
MANTLE
0.8b.y.
1.6b.y.
2.4 b.y.
3.2b.y.
208Pb/204Pb
16
15
14
UPPER CRUST
1.6b.y.
0.8b.y.
O b.y.
2.4b.y.
OROGENE
MANTLE
3.2b.y.
LOWER CRUST
207Pb/204Pb
12
13
14
15
16
17
18
19
20
206Pb/204Pb

Figure 1.

Since orogenies occur in many different tectonic settings, the proportions of mantle and crustal materials incorporated by the orogenic process may vary considerably. Ore deposits may be associated with subduction zones or rift centers involving both continental-and mantle-type materials in different proportions. Alternatively, some ore deposits are formed at mid-ocean spreading centers where mantle type material predominates. On the $^{207}Pb/^{204}Pb$ - $^{206}Pb/^{204}Pb$ graph, lead from deposits formed near an older continental plate would be expected to plot above those formed at the same time from oceanic material. In regions where the orogenic components are poorly mixed, steep regression lines may be produced by the lead isotope ratios. Lead from the Kuroko deposits in Japan (Sato, 1975) exhibits such a line, the slope of which has no direct application to dating the deposits or their source material. On this basis, the significance of some less steeply sloped lines might also be questioned.

Throughout this paper, all age data taken from the literature have been normalized to the decay constants for Rb, U and Th listed in table 1. As far

Table 1.--Near Here.

as possible, all lead isotope data have been normalized to absolute values.

We have selected from the literature deposits most likely to be of submarine volcanic exhalative origin, and have added new data of our own from deposits in Finland, and New Jersey, Wisconsin, Arizona, New Mexico and Wyoming in the U.S.A. Lead isotope ratios and model ages for these deposits are listed in table 2, $^{207}Pb/^{206}Pb$. Isochron ages were computed using the Stacey and Kramers (1975) model, which was also used as a guide for generating the Plumbotectonics orogene curve. Isochron ages for the two models are in good agreement, but the shape of the plumbotectonics orogene curve is such that, in the Precambrian, it lies above the Stacey-Kramers average curve.

Table 1. Decay constants used throughout this paper.

Nuclide	Decay Constant	Reference
^{87}Rb	1.41×10^{-11} yr. $^{-1*}$	
^{238}U	0.155125×10^{-9} yr. $^{-1}$	Jaffey et al. (1971)
^{235}U	0.98485×10^{-9} yr. $^{-1}$	
^{232}Th	0.049475×10^{-9} yr. $^{-1}$	LeRoux and Glendenin (1963)

Present day ratio $^{238}U/^{235}U = 137.88$

*This value is consistent with the decay constants shown for uranium.

Table 2.--Near Here.

Deposits older than 2500 m.y.--accepted as volcanic exhalative

In Table 2, only six deposits are listed for this age group; all are in Ontario, Canada, and their lead isotope data are plotted in fig. 2. One reason why there are so few analyses for the Archean is that deposits of this

Fig. 2.--Near Here.

age contain very little galena. The Manitouwadge district has been extensively examined, probably because one deposit, the Willroy mine, does contain economically significant lead. About 500 km east-southeast of Manitouwadge are the Noranda and Val d'Or districts which, according to Sangster (1972a), belong to the volcanic exhalative category. Cumming and Gudjurgis (1973) studied the Quemont mine at Noranda in detail, analyzing trace lead in the ore as well as galena, and they found the lead to be isotopically quite complex. Linear trends were exhibited by the data (see fig. 2), which are compatible with *in situ* radioactive decay of uranium and thorium, but unfortunately no measurements were made of uranium, thorium and lead concentrations. The other analyses, from Noranda and Val d'Or were made by Russell and Farquhar (1960) and Kanasewich and Farquhar (1965). Now that all data have been normalized to absolute values, it is clear that the least radiogenic leads from these two districts are very similar to the Manitouwadge lead. Moreover the linear trend of the Quemont suite almost intercepts the Manitouwadge data. The Stacey-Kramers model yields an isochron age of 2700 m.y. for lead of this composition. The data lie approximately on the mantle evolution curve and well below that for the orogene, computed from the model of Stacey and Kramers (1975).

Location	District	Deposit and Sample No.	Coordinates Latitude, Longitude	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Isochron Model Age m.y.	Age of enclosing rocks m.y.	References
Deposits older than 2500 m.y.--accepted as volcanic exhalative.									
Canada, Ont.	Manitouwadge	Willroy (MG38A)	49°09'N, 85°50'W	13.211	14.401	33.069	2700	2690	(1,2)
Que.	Noranda	Noranda (T1005)	48°15'N, 79°01'W	13.27	14.40	32.89	2615	2720	(3,4)
	Least radiogenic	Quemont (Q-Pq)	48°16'N, 79°01'W	13.91	14.60	33.69			(5)
	Most radiogenic	Quemont (B.T.)	48°16'N, 79°01'W	21.304	16.188	44.634			(5)
Que.	Val d'Or	Manitou (T661)	45°05'N, 77°40'W	13.23	14.41	33.00	2690		(6)
		Barvue (T641)	48°26'N, 77°38'W	13.27	14.43	33.05	2680		(6)
Ont.	Sudbury region	Geneva Lake	46°47'N, 81°32'W	14.002	14.870	33.716	2590	<2700	(2)
Deposits 1500-2500 m.y. old--accepted as volcanic exhalative.									
U.S.A., Az.	Jerome-Prescott-Bagdad	United Verde	34°45'N,112°07'W	15.725	15.270	35.344	1645	1730-1755	New data, (7)
		Old Dick	34°33'N,113°14'W	15.805	15.318	35.422	1660	1730-1755	New data, (7)
		Bruce	34°33'N,113°14'W	15.81	15.33	35.42	1670	1730-1755	(8,9)
N.M.	Pecos	Terrero	35°46'N,105°40'W	15.606	15.260	35.236	1710	1650-1800	New data
		Jones	35°43'N,105°41'W	15.705	15.304	35.328	1720	1650-1800	New data
Canada, Man.	Flin Flon	Flin Flon (T648)	54°54'N,101°52'W	15.315	15.106	34.846	1720	1750	(10,11)
		Chisel Lake (T652)		15.387	15.116	34.940		1750	(10,11)
		Snake Lake (T659)		15.709	15.256	35.176		1750	(10,11)
		Flin Flon (T660)	54°54'N,101°52'W	15.745	15.228	35.297		1750	(10,11)
U.S.A., Wisc.	Ladysmith	Flambeau (ore)	45°26'N, 91°07'W	15.323	15.167	35.016	1820	1800-1900	New data, (12)
	Rhinelander	Pelican (ore)	45°34'N, 89°16'W	15.668	15.359	35.202	1835	1800-1900	New data, (12)
Finland		Pyhäsalmi (G258)	63°40'N, 27°15'E (approximately)	15.111	15.147	34.835	1970	≈2000??	New data, (13,14,15)
Deposits 1500-2000 m.y. old-of uncertain affinity.									
Australia, N.S.W.,	Broken Hill	U.B.C. #1	32°05'S,141°27'E	16.007	15.397	35.675	1625	1650-1850	(2,16)
Queensland,	Mount Isa	Mount Isa	20°50'S,139°30'E	16.111	15.460	35.847	1640	1650-1850	(2)
Canada, Ont.,	Sudbury Basin	Errington (ore,T359)	46°30'N, 81°30'W	15.49	15.31	35.36	1880	?	(17)
		Errington (ore,T358)	(approximately)	15.90	15.39	35.60		?	(17)
		Errington(pyrite,T361)		16.17	15.43	35.66		?	(17)
U.S.A., Colo.	Park Range	Greenville	40°41'N,106°53'W	15.673	15.234	35.134	1630	1730-1830	(18,19)
		Lower Slavonia	40°47'N,106°43'W	15.686	15.247	35.176	1640	1730-1830	(18,19)
Deposits 1500-2000 m.y. old--associated with mafic rocks.									
Finland	Svecokareledic	Outokumpu(G30A)	62°44'N, 29°00'E	14.731	15.016	34.476	2100	1840-2470	New data (13,14,15)
	Pihtipudas	Ritovuori (G16)	63°22'N, 25°35'E	15.577	15.287	35.164	1800	1700-1800	New data (13,14,15)
U.S.A., Wyo.	Sierra Madre Mtns.	Broadway	41°03'N,106°45'W	15.809	15.286	35.251	1600	1730-1830	New data (18)
Deposits 500-1500 m.y. old--of uncertain affinity.									
U.S.A, New York	Balmat-Edwards	(F-19)	44°16'N, 75°24'W	16.935	15.505	36.423	1090	≈1200	(2, 20, 21, 22)
N. J.	Franklin Furnace Sterling Hill	Sterling	41°05'N, 74°37'W	16.924	15.445	36.297	990	>1100	New data (23)
Canada, B. C.	Kimberly	Sullivan (243)	49°44'N,116°00'W	16.507	15.460	36.153	1340	≈1400	New data
		Sullivan (233)	49°44'N,116°00'W	16.530	15.477	36.176	1350	≈1400	New data
Deposits 0-500 m.y. old--accepted as volcanogenic exhalative (discussed in Plumbotectonics I, Doe and Zartman (1976).									
U.S.A., Cal.	West Shasta	Mammoth	40°46'N,122°28'W	17.893	15.454	37.453	250	≈350	(24)
	East Shasta	Afterthought	40°44'N,122°04'W	17.897	15.462	37.493	265	≈220	(24)
Australia	Tasmania	Rosebery	41°46'S,145°33'E	18.250	15.599	38.050	280	550	(25)
	N.S.W.	Captain's Flat	35°36'S,149°27'E	18.050	15.619	38.145	470	420	(25)
		Cobar	31°32'S,145°51'E	18.082	15.624	38.125	455	410	(25)
		Hall's Peak	30°51'S,152°04'E	18.350	15.607	38.347	220	240	(25)
Canada,	N.B.	Bathurst(T807)	47°35'N, 65°51'W	18.204	15.655	38.122	425	460	(2)
Japan		Toya (K142)	42°39'N,140°55'E	18.455	15.582	38.552	90	≈25	(24)
	Akita	Kosaka (1053)	42°39'N,140°46'E	18.463	15.589	38.623	95	≈25	(24)
	Yamagata	Yoshino (1303)	38°09'N,140°10'E	18.475	15.607	38.633	125	≈25	(24)
		Taro (K71T38)	39°46'N,141°56'E	18.712	15.621	38.669	-25	≈60	(24)

References

(1) Tilton and Steiger (1969), (2) Stacey et al. (1969), (3) Krogh and Davis (1971), (4) Russell and Farquhar (1960), (5) Cumming and Gudjurgis (1973), (6) Kanasewich and Farquhar (1965), (7) Anderson et al. (1971), (8) Clayton and Baker (1973), (9) Silver (1966), (10) Mukherjee et al. (1971), (11) Slawson and Russell (1973), (12) Van Schmus et al. (1975), (13) Kouvo (1958), (14) Kouvo and Tilton (1966), (15) Wetherill et al. (1962), (16) Reynolds (1971), (17) Ulrych and Russell (1964), (18) Hedge et al. (1967), (19) Antweiler, Doe and Delevaux (1972), (20) Doe (1962), (21) Silver (1969), (22) Silver (1965), (23) Long and Kulp (1962), (24) Doe and Zartman (1976), (25) Ostic et al. (1967).

thus a mantle-type source is suggested for these deposits. They occur in the Abitibi greenstone belt of Canada, and zircons from the volcanic pile at Noranda give an age of 2720 m.y. Zircons from Algoman granites at Manitouwadge Lake were dated as 2690 m.y. old by Tilton and Steiger (1969); these data suggest a similar age for both deposits. The Abitibi greenstone belt contains abundant mafic volcanic rocks, and the ores are associated with felsic volcanics near the top of the orogenic sequence. (Lang et al., 1970). In addition, the regions in which the ores are found seem to be well separated from significantly older rocks. The ores therefore appear to be in a primitive orogene which should indeed yield isotope data representative of the mantle.

The Geneva Lake deposit is one originally selected by Stanton and Russell (1959). Its lead isotope model age is 2590 m.y. and its relatively high $^{207}Pb/^{204}Pb$ ratio suggests its source had much greater continental affinity than the sources of the previously discussed samples.

Deposits 1500-2500 m.y. old--accepted as volcanic exhalative

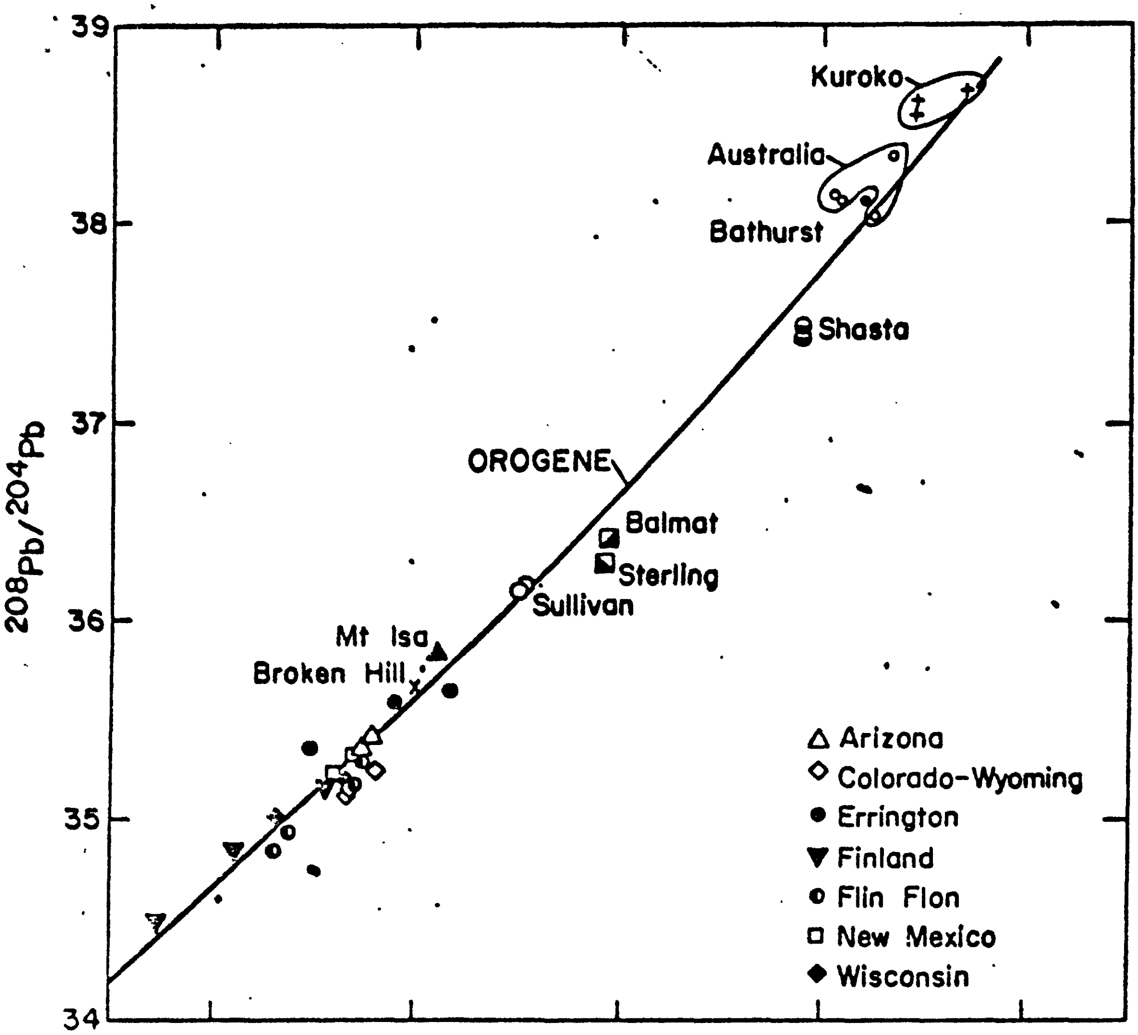
Data from Canada, Finland, and three regions of the U.S.A. comprise this group, which is listed in Table 2. Lead isotopic data for this group are plotted in Fig. 3.

Fig. 3.--Near Here.

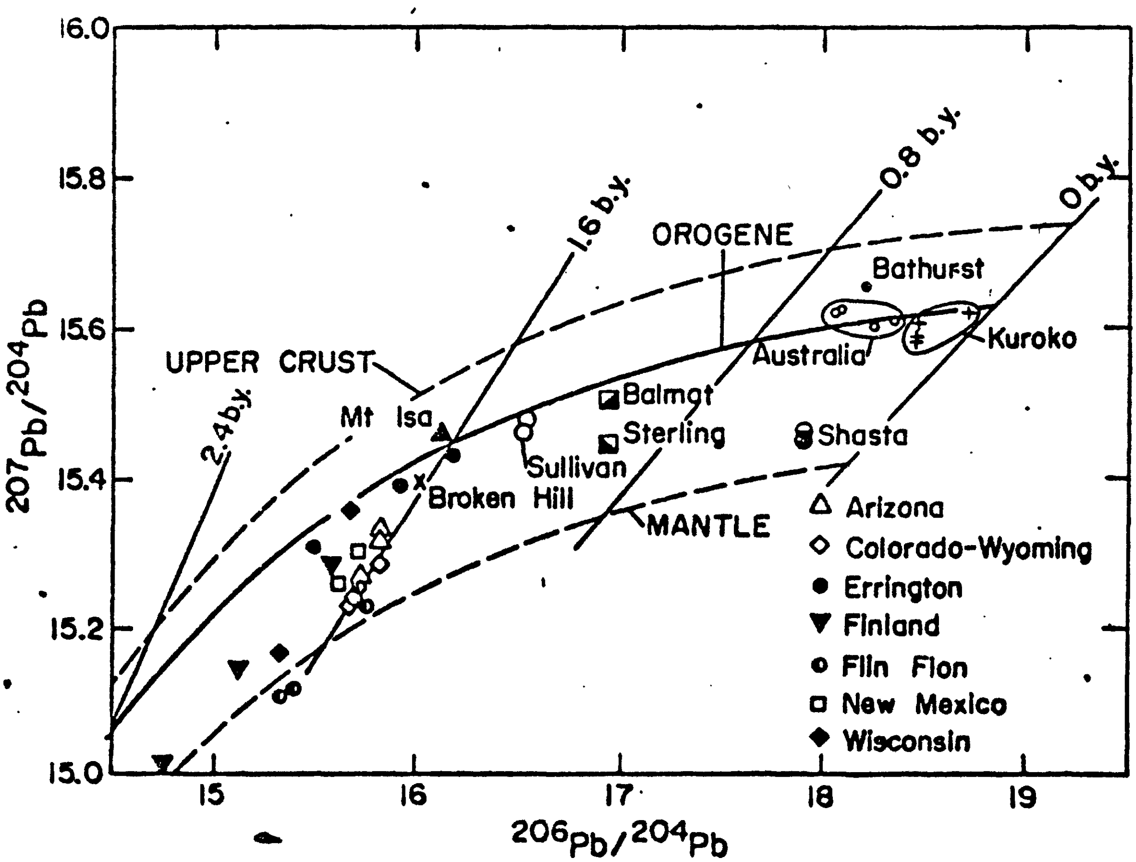
Deposits that are approximately 1800 m.y. old occur in the Jerome-Prescott-Bagdad belt of Arizona (Anderson et al., 1971 and Anderson and Silver, 1976) the Pecos district of New Mexico (Giles, 1974), the Hanson Lake-Flin Flon-Snow Lake belt in Saskatchewan and Maintoba, Canada (Sangster, 1972b), and the Rhinelander-Ladysmith belt in Wisconsin (Sims, 1976).

The volcanic sections containing the massive sulfide deposits in the Jerome-Prescott-Bagdad area of central Arizona contain units with

Fig. 3.--Plots of lead isotope data for all deposits listed in Table 2 that are younger than 2500 m.y. Evolution curves and isochrons are those generated by the plumbotectonics model of Doe and Zartman (1976).



Kuroko
Australia
Bathurst
Shasta
OROGENE
Balmat
Sterling
Sullivan
Mt Isa
Broken Hill
Arizona
Colorado-Wyoming
Errington
Finland
Flin Flon
New Mexico
Wisconsin
$^{208}Pb/^{204}Pb$
34
35
36
37
38
39



2.4 b.y.
1.6 b.y.
0.8 b.y.
0 b.y.
OROGENE
UPPER CRUST
Bathurst
Australia
Kuroko
Mt Isa
Balmat
Sterling
Shasta
Sullivan
Broken Hill
MANTLE
Arizona
Colorado-Wyoming
Errington
Finland
Flin Flon
New Mexico
Wisconsin
$^{207}Pb/^{204}Pb$
15.0
15.2
15.4
15.6
15.8
16.0
15
16
17
18
19
$^{206}Pb/^{204}Pb$

well-established ages of accumulation of 1755-1800 m.y. (Anderson et al., 1971; Silver, 1968; Anderson and Silver, 1976; Silver, unpublished data). In each district, an association of interstratified basaltic and andesitic rocks with more acid felsites has been demonstrated. At the United Verde mine in Jerome, the massive sulfides are concordant stratabound lenses in massive quartz-bearing tuffs which probably accumulated as subaqueous pyroclastic flows. The mineralization is probably syngenetic. The Old Dick and Bruce mines in the Bagdad district are located in a section of predominantly andesitic and basaltic flows in close association with intercalated tuffs and intrusive rhyolites. Several arguments suggest the ore is probably syngenetic.

The mineralization at the Pecos Mine in the southern Sangre de Cristo Mountains, San Miguel County, new Mexico, is found in sheared amphibolite [the "diabase" of Krieger (1932) and Harley (1940)] in which quartz-sericite schists are intercalated. The precise origin of these rocks is not well established because of their intense alteration. They appear, however, to be part of a nearby section of polymetamorphic stratified rocks which contains identifiable relict igneous textures suggesting it originated from basalitic flows, tuffs, or sills with intercalated felsites. The entire section is intruded by relatively undeformed granites with ages of ~1650 m.y. (Silver, unpublished data), providing a probably minimum age for the time of mineralization. Tentative correlations with other sections in northern New Mexico would suggest that the felsitic volcanics are probably between 1700 and 1800 m.y. old. The sulfide areas themselves show fabrics suggesting that they were emplaced prior to at least some of the regional orogenic deformation. An estimated age for this mineralization is 1650-1800 m.y.

The central Arizona deposits are at least 1000 km, and the Pecos Mine is at least 700 km from the nearest exposures of Archean rocks. There is no evidence of older continental crust in the southwestern United States. There might well be slightly older rocks in the vicinity of the Pecos deposit, but they could not be much different in isotopic character. All the data for these deposits do lie below our orogene curve, but the presence of a continental component is indicated. This component might possibly have come from well-mixed marine sediments derived from somewhat older continental material.

The model ages indicate a difference in age of about 60 m.y. between the Arizona (1660 m.y.) and the New Mexico (1720 m.y.) deposits. Model ages of the Arizona deposits are thus demonstrably less than the age of their associated volcanics (1730-1755 m.y.). It seems significant that the $^{208}Pb/^{204}Pb$ data all lie on the average orogene curve with $^{208}Pb/^{204}Pb$ ages from 1700 to 1780 m.y., and this may suggest that a small amount of uranogenic lead has been added since the time of deposition.

The Flin Flon deposit, which is in the Churchill Province of Canda, has been reviewed by Sangster (1972b). He concluded that the rocks containing the deposit are Aphebian in age, and he accepted the Rb-Sr isochron age of 1750 ± 80 m.y. of Mukherjee et al. (1971). At the Universities of Saskatoon and Alberta, zircon studies on the associated volcanic rocks are corroborating the approximate age of 1800 m.y. (M. R. Stauffer, oral communication, 8 November, 1975). Unlike the Arizona-New Mexico belt, the belt including Flin Flon is adjacent to 2.8-b.y.-old Archean rocks in a setting similar to that found in Japan by Tatsumoto (1969) and Sato (1975). This proximity increases the possiblity that, 1800 m.y. ago, much older poorly mixed continental material might have entered into the magmatic and ore-forming processes. Therefore, lead isotopes might reflect the presence of a nearby Archean continent. Slawson and Russell (1973) have precisely determined the isotopic composition of four lead samples from the Flin-Flon area, and have found nearly 4 percent variation in $^{206}Pb/^{204}Pb$ values and about 1.3 percent variation in $^{208}Pb/^{204}Pb$ values. Both the highest and lowest values were from the Flin Flon mine itself (Fig. 3). Using their preferred regression slope of 0.330 and a mineralization age of 1.75 b.y., we calculate a source age of 2.88 b.y. In view of this age determination, it is possible that these deposits were derived largely from a nearby Archean continent, rather than from a 1.8-b.y.-old metamorphism of 2.8-b.y.-old deposits. However, the less radiogenic leads seem to represent a large mantle component, and confirmation of this may result from lead isotope work on the basalts in the sequence.

The recently analyzed deposits in Wisconsin, U.S.A., are in a greenstone belt not yet well described or dated. Results of our lead isotope analyses of samples from Ladysmith and Rhinelander suggest a pattern similar to that at Flin Flon and may indicate a similar age. The age of the greenstone belt is comparable with the 1800-1900 m.y. age determined by Van Schmus et al. (1975) for an area to the east, which is near the Wisconsin-Michigan border, and which lies 50-100 km south of the contact with Archean rocks. Using a mineralization age of 1.9 b.y. (the upper age limit for rocks to the east, reported by Van Schmus et al., 1975) and the $^{207}Pb/^{206}/Pb$ slope of 0.555 between the two data points in Fig. 3, a hypothetical source age of 3.78 b.y. would be calculated. This older figure may not have geologic significance because mixing of material from a variety of sources may be involved; however, rocks about 3.5 b.y. old have been found in northern Michigan (P. K. Sims, Z. E. Peterman, oral communication, 8 November 1975) so the possibility of rocks of that age adjacent to or beneath the Rhinelander-Ladysmith belt cannot be excluded at this time. We interpret the lead isotopes data here in much the same way we interpreted those at Flin Flon. Whether ancient greenstone belts were island arcs is a matter for dispute, but the lead isotope patterns for the Flin Flon and for the

Rhinelander-Ladysmith areas are very similar to those found in young mature island arcs such as the Miocene Kuroko deposits of Japan. The Stacey-Kramers model indicates an age of about 1830 m.y. for the Wisconsin deposits.

The Rhinelander analysis lies on the orogene curve and thus a significant continental component is indicated (Fig. 3). However, we hope to obtain more data and to learn more about the geologic setting of this interesting area. A valuable contribution has been made by E. R. May (1976).

At Pyhäsalmi, Finland, a large massive zinc-copper-pyrite deposit is described (Kahma, 1973) as "...situated in a gently folded monocline of a schist complex composed of Svecokarelidic acidic and basic metavolcanics and cordierite-anthophyllite and sericite rocks" within the main sulfide ore belt. The accepted age of mineralization--2050 m.y.--is unfortunately highly dependent on model lead ages. The Stacey-Kramers Model yields an age of 1970 m.y., and a mantle origin is indicated for this deposit by the lead isotope data.

Deposits 1500-2000 m.y. old--of uncertain affinity

The data from Table 2 for these deposits are plotted in Fig. 3. Of those in this group, the two that have been given most thorough consideration are Broken Hill, New South Wales, and Mount Isa, Queensland, Australia.

The Broken Hill massive zinc-lead ore is in sillimanite gneiss, thought to be metamorphosed pelagic sediments; however, the sillimanite gneiss has gradational contacts with the Potosi Gneiss, a unit of rhyodacitic composition (Stanton, 1972). The lead isotopic composition of the ore does not preclude a submarine volcanic exhalative origin for the deposit, but suggests a mature rather than a primitive orogene category. The geology would seem to be compatible with such an origin.

There is little volcanic material in the Urquhart Shale, which is the host rock for the ore at Mount Isa. Tuffaceous material occurs in the non-mineralized Native Bee Formation that underlies the Urquhart. The isotopic composition of the lead at Mount Isa has a high $^{207}Pb/^{204}Pb$ value, compared to its $^{206}Pb/^{204}Pb$. Fig. 3a shows that the data point for Mount Isa lies above the orogene curve; thus it appears that the Mount Isa lead either was deposited in an intracratonic basin environment, or was derived from a distant Archean continent.

At the Errington mine in the Sudbury Basin of Canada, the ores are found in the Vermilion Formation, which consists of interbedded argillite, limestone and cherty carbonate rock, as well as chert breccia (Thomson, 1956). Ore deposition seems to be closely associated with the presence of the Onaping Tuff unit throughout the whole basin. In view of the controversial origin of features connected with the Sudbury Basin, i.e., whether they were formed by volcanic action or meteoritic impact, the origin of these deposits is likewise controversial. In fig. 3 the analytical points for Errington are distributed along the "orogene" curve, adding further uncertainty to the classification of this deposit.

The lead isotope data from the Errington mine are from pyrites, and they definitely indicate a large continental component for these trace leads. The least radiogenic sample has a model age of 1880 m.y. Considerably more study of this very complex area is necessary before the significance of these data can be evaluated. A more thorough discussion of the lead data is found in Ulrych and Russell (1964).

The Greenville and Lower Slavonia mines, in the Park Range of northern Colorado, U.S.A., are small zinc-copper-lead deposits in highly metamorphosed rocks which may have been formed by incomplete replacement of calc-silicate rocks (George Snyder, written communication, 28 October 1975). At the Greenville locality, Snyder reported that the strata-bound deposit occurs between a pelitic schist and a unit of interlayered felsic gneiss and amphibolite. At Lower Slavonia he found the mineralized unit interlayered in a section of felsic gneiss, amphibolite, and pelitic schist. Although Precambrian plutons and pegmatites as well as Tertiary stocks and dikes are present in the area, none were seen in contact with the mineralized horizons; no intrusive rocks are known within one kilometer of the Lower Slavonia mine.

The rocks containing the Greenville and Lower Slavonia mines occur south of a major, northeast-trending, tectonic shear zone, which has a metamorphic age of 1730 m.y. (Hedge et al., 1967; Hedge, oral communication, 11 November 1975). The initial $^{87}Sr/^{86}Sr$ values, as well as other analyses, suggest a depositional age that does not exceed the metamorphic age by more than 100 m.y. Lead isotope data suggest a mantle source, perhaps related to a primitive island arc system.

For these two deposits, the lead model ages are 1630 and 1640 m.y. respectively, about 200 m.y. younger than the likely age of deposition. However, the $^{208}Pb/^{204}Pb$ model age for both is 1830 m.y. Thus we cannot exclude the possibility that the metamorphism at 1730 m.y. introduced a uranogenic lead component into these comparatively low-lead deposits. The nearby Broadway deposit in Wyoming may have been similarly affected.

<u>Deposits 1500-2500 m.y. old--associated with mafic rocks</u>

Although Precambrian equivalents of submarine volcanic exhalative deposits are rare along recognized mid-oceanic spreading centers, a possible example may be recorded by the Outokumpu deposit in the Svecokarelian of Finland. This occurs in a heavy mineral-free quartzite without visible graded or current bedding. Such quartzites are always found adjacent to large serpentinite bodies, and their thickness and extent depend on the size of the serpentinite body (Huhma and Huhma, 1970). The serpentinite-quartzite bodies are enveloped by black schist, which is in a matrix of greywacke flysch. Although this association does not seem compatible with modern ocean rises, it is similar in many respects to rift-related submarine features such as Cyprus and perhaps the Red Sea. On the basis of sulfur isotope data and on consideration of the geologic setting, Mäkelä (1973) concluded that the deposit is of the submarine exhalative type. The primary age of the deposit is younger than the 2470 m.y. zircon age obtained on the Pre-Karelian gneiss dome by Wetherill et al. (1962), and is older than the 1840 m.y. Rb-Sr mineral age reported for a crosscutting pegmatite by Kouvo (1958) and Kouvo and Tilton (1966). Kouvo (written communication, 11 December 1974) is determining the age of the surrounding rocks and the age of mineralization. The low $^{207}Pb/^{204}Pb$ value places the data point for Outokumpu almost on the mantle curve (Fig. 3), and the somewhat higher $^{207}Pb/^{204}Pb$ value for the Pyhasalmi deposit (see Table 2) exhibits a more continental character. The proximity of both deposits to Archean terranes suggests that a near-continent environment may have existed for both.

The Ritovuori deposit in Finland and the Broadway deposit in Wyoming, U.S.A., both of minor economic significance, are closely associated with mafic metamorphosed rocks. The Ritovuori deposit is in brecciated and tourmaline mineralized basic schists at the contact with quartz-feldspar schists (Aho, 1975). The basic schists are described as amphibolites, plagioclase-uralite porphyrites, and schists containing hornblende metacrysts. The quartz-feldspar schists are described as felsic or intermediate with quartz, plagioclase, and K-feldspar as main constituents and with biotite and (rarely) muscovite present. The deposit is being dated by O. Kouvo (written communication, 11 December 1975).

The Broadway mine, located in the Sierra Madre Mountains of southern Wyoming has been described by K. DeNault (Univ. Wyoming, unpublished thesis, 1967). Mineralization is mainly concentrated in pyroxenite composed of massive diopside which is separated from pink granite by a shear zone. The shear zone contains blocks of mineralized amphibolite and pyroxenite and has numerous cavities containing large hornblende crystals. Sphalerite and galena are found concentrated in massive spessartite garnet. The mineralizationa age of the Broadway Mine "...should be comparable to that found in the Front Range, since it is south of the areas of Archean rocks" (R. S. Houston, written communication, 20 March 1974). Although the Broadway and Pihtipudas (Ritovuori) mines are in mafic metamorphosed rocks that have wide geographic separation, they have similar lead isotopic compositions which are also similar to those of the 1700-1800 m.y.-old deposits of Arizona.

Deposits 500-1500 m.y. old--of uncertain affinity

The data in this category, from U.S.A. and Canada, are listed in table 2 and plotted in fig. 3. Lead isotope data are not yet available for any deposits in this age group that are accepted as being of submarine volcanic exhalative origin. However, we are including 3 districts in this uncertain category. These are the Balmat-Edwards zinc district, New York, U.S.A.; the Franklin Furnace-Sterling Hill in New Jersey, U.S.A., and the Sullivan deposit in British Columbia, Canada.

In the Balmat-Edwards district, the sphalerite-pyrite-galena massive sulphide ores are tabular deposits in calc-silicate rocks from marble of Grenville age. Balmat has been considered as single-stage (Stacey et al., 1969), on the basis of similarities to the Broken Hill deposit in Australia, but this is by no means certain. Silver (1964) analyzed zircons from several hornblende gneisses throughout the Adirondack Mountains and interprets their age of 1200 m.y. as a time point in the accumulation of the Grenville Series from material perhaps 2.7 b.y. old. Silver (1969) also states that several lines of evidence indicate the last period of intense metamorphism in the Adirondack Mountains occurred between 1020 m.y. and 1100 m.y. ago. From lead isotope analysis, the isochron model age for Balmat is 1120 m.y.

At the Franklin Furnace-Sterling Hill district in New Jersey, about 200 miles south of Balmat, the ores are franklinite-willemite in calc-silicate rocks of the Franklin limestone. They are not in volcanic rocks and relations to any gneisses or tuffs are not obvious. Frondel and Baum (1974) have suggested a volcanogenic sedimentary origin for these deposits. The galena analyzed from the Sterling Mine has a lead isochron model age of 990 m.y. Long and Kulp (1962) dated the marble in the Franklin Limestone as 800-900 m.y. old, and this should be taken as a minimum age for Sterling Hill. In fact, analyses of monazite indicate an age greater than 1100 m.y.

The approximately 1400-m.y.-old Sullivan deposit of Canada is in carbonate-free shales, and has been classified as "hidden exhalative" by Sangster (1972a), on the basis of a tourmaline halo beneath the ore body. Such a description appears to be similar to the sedimentary exhalative category of others. The lead isotopic composition does indicate a continental type origin with a model age of 1350 m.y.

Conclusions

The main object of this paper has been to determine how well the principles of plumbotectonics, proposed for Phanerozoic massive sulfide deposits by Doe and Zartman (1976), could be extended into the Precambrian. For the Phanerozoic, evolution of the mantle and crustal components has made is possible to distinguish between their lead isotopic compositions. In the Precambrian, however, lead isotope differences were much smaller, and subsequent metamorphic events are more likely to have obscured the geology, and perhaps to have changed the isotopic compositions of the ores and surrounding rocks.

Notwithstanding these difficulties, it is apparent that for Precambrian as well as the Phanerozoic ores, the data do fall in the band of values between the mantle and upper crustal curves. Moreover, it is most encouraging that we can identify the development of mantle lead from the ore data. The Shasta districts for the Phanerozoic, Outokumpu and Flin Flon for the Proterozoic, and deposits at Noranda, Val d'Or and Manitouwadge for the Archean, all appear to be examples of mantle lead. This conclusion is based on their geologic settings as well as on their isotopic compositions. Of all the deposits discussed here, Mount Isa in Australia appears to have the greatest continental lead isotope component, and a large continental component seems to be consistent with its depositional environment.

On the basis of lead isotope data, we are unable to distinguish between deposits truly of submarine volcanic exhalative origin, and those whose membership in this group is equivocal. A possible exception is the deposit at Mount Isa. The best information presently available indicates that lead isotope models apply as well to sedimentary exhalative deposits as to submarine volcanic exhalative deposits.

Finally, we find that the data we have studied are compatible with the concept of different domains of lead isotope evolution for the mantle, the orogene, and the upper and lower crust, as proposed by the plumbotectonics mixing model for the whole earth throughout geologic time. Such systematics agree with the findings of Professor Tugarinov and his colleagues in 1963 that "there is no essential difference between the isotopic evolutions of the lead from the rocks of various ancient continental nucleii (3200 to 2800 m.y. old)". Also, "The subsequent history of the Precambrian shields is characterized by an increasing differentiation of the material of the earth's crust, leading in particular to the unequal distribution of uranium, thorium and lead, chiefly as a result of the processes of weathering and sediment accumulation. Epochs of magmatism interrupted these processes and led to the local mixing or averaging (usredneniye) of material".

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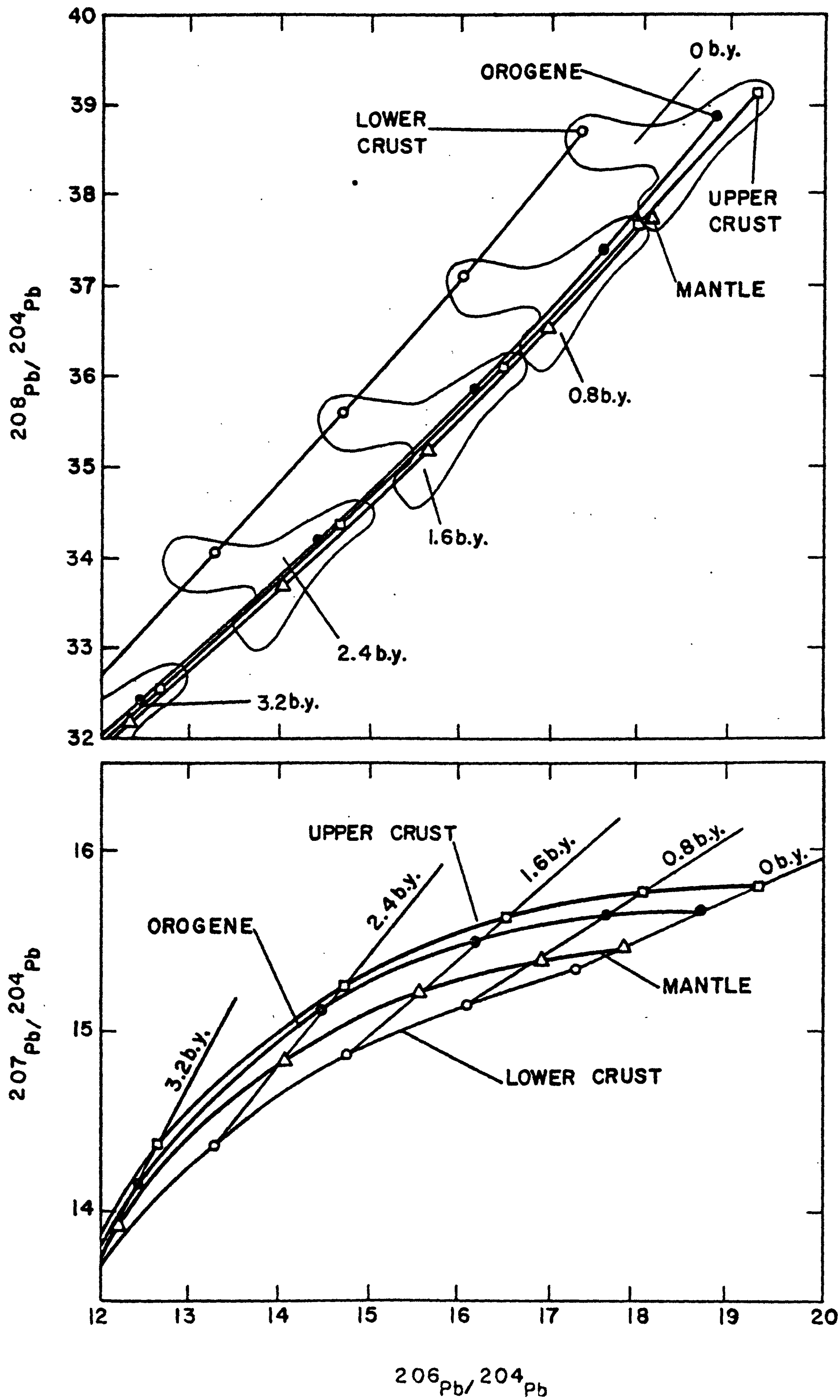
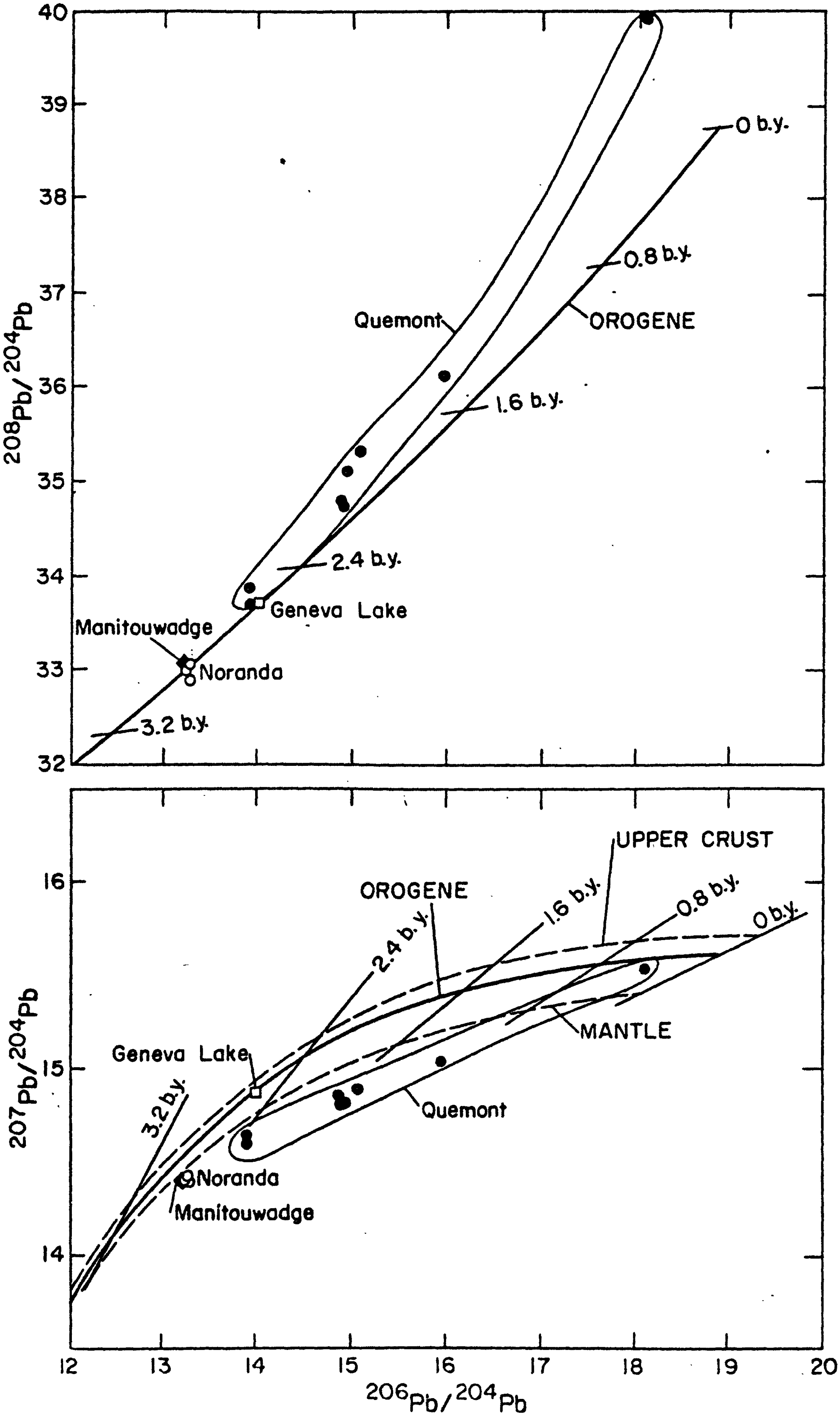
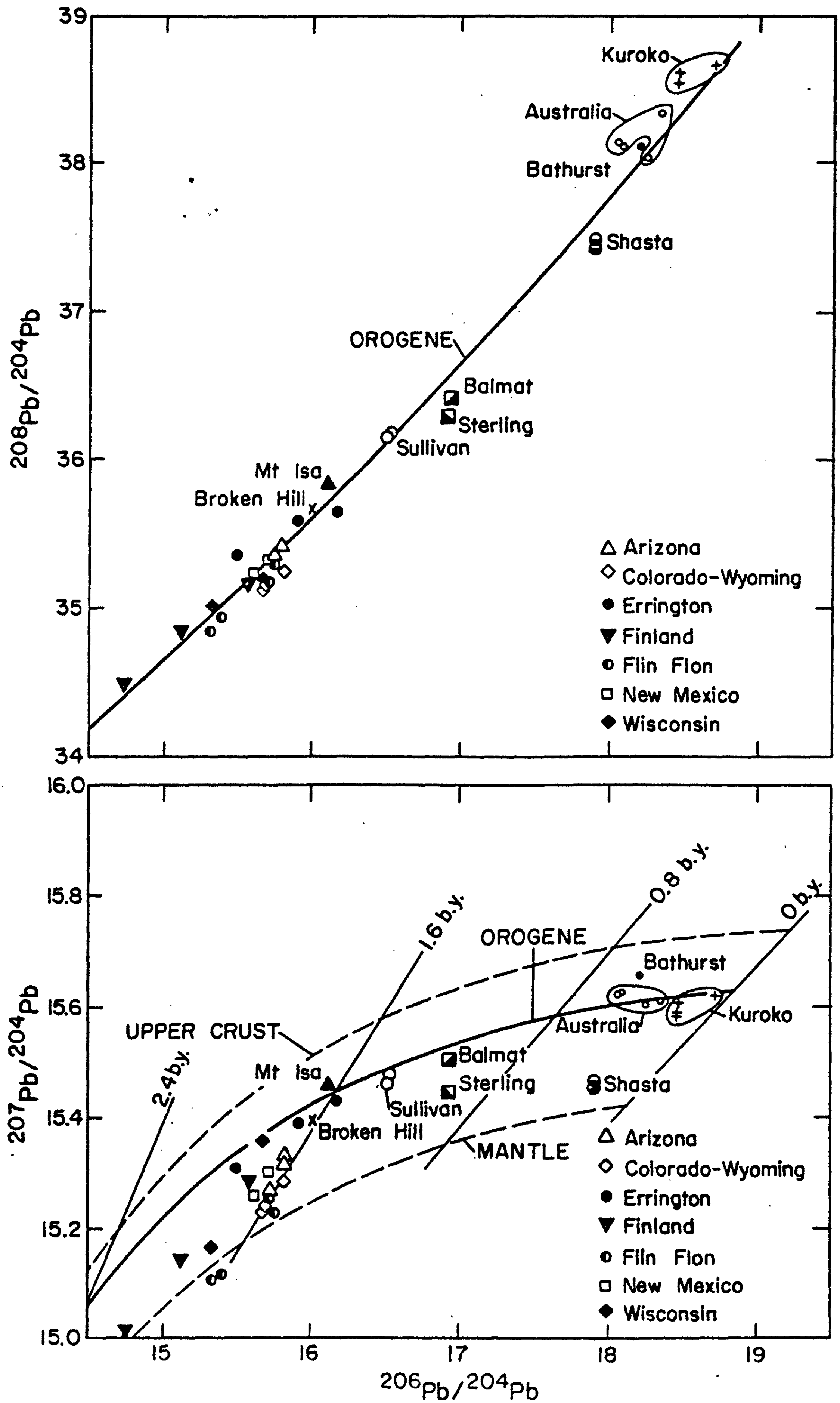


OROGENE
0 b.y.
LOWER CRUST
UPPER CRUST
MANTLE
0.8b.y.
1.6b.y.
2.4b.y.
3.2b.y.
$^{208}Pb/^{204}Pb$
UPPER CRUST
1.6b.y.
0.8b.y.
0 b.y.
2.4b.y.
OROGENE
MANTLE
3.2b.y.
LOWER CRUST
$^{207}Pb/^{204}Pb$
$^{206}Pb/^{204}Pb$



40
39
38
37
36
35
34
33
32
$^{208}Pb/^{204}Pb$
0 b.y.
0.8 b.y.
Quemont
OROGENE
1.6 b.y.
2.4 b.y.
Geneva Lake
Manitouwadge
Noranda
3.2 b.y.
16
15
14
$^{207}Pb/^{204}Pb$
UPPER CRUST
OROGENE
1.6 b.y.
0.8 b.y.
0 b.y.
2.4 b.y.
MANTLE
Geneva Lake
3.2 b.y.
Quemont
Noranda
Manitouwadge
12
13
14
15
16
17
18
19
20
$^{206}Pb/^{204}Pb$



39
38
37
36
35
34
208Pb/204Pb
Kuroko
Australia
Bathurst
Shasta
OROGENE
Balmat
Sterling
Sullivan
Mt Isa
Broken Hill
Arizona
Colorado-Wyoming
Errington
Finland
Flin Flon
New Mexico
Wisconsin
16.0
15.8
15.6
15.4
15.2
15.0
207Pb/204Pb
1.6 b.y.
0.8 b.y.
0 b.y.
2.4 b.y.
OROGENE
UPPER CRUST
MANTLE
Bathurst
Australia
Kuroko
Balmat
Sterling
Shasta
Sullivan
Mt Isa
Broken Hill
15
16
17
18
19
206Pb/204Pb