LEAD ISOTOPE RATIOS IN THE BAYHORSE MINING DISTRICT
CUSTER COUNTY, IDAHO

BY
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B.S., Oregon State University
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MASTER OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(August, 1977)

Signature of Author . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
Department of Earth and Planetary Sciences, August 12, 1977
Certified by. . . . . .
Thesis Supervisor

Accepted by. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
Chairman, Departmental Committee

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by

Karleen Ethel Davis

Submitted to the Department of Earth and Planetary Sciences on August 12, 1977 in partial fulfillment of the requirements for the Degree of Master of Science

ABSTRACT

Lead isotope ratios of galena and pyrite from different ore deposits in the Bayhorse Mining District, central Idaho, have been determined. These values demonstrate a correlation between lead isotope ratios and the relationship of a deposit to Cretaceous/Tertiary igneous activity (emplacement of the Idaho Batholith). Ore deposits which are related to this intrusive episode fall on a line of equation \((207/204) = (.147)(206/204) + 12.902\) and yield slope and intercept ages of about 2.3 b.y. This age may represent the average age of the ore source-rock. The Pacific Mountain replacement Pb-Zn deposit in this district does not lie on this line and is interpreted to be Ordovician \((206/204 = 21.35, 207/204 = 15.78)\).

Thesis supervisor: Dr. Stanley R. Hart
Title: Professor of Earth and Planetary Sciences
ACKNOWLEDGEMENTS

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Graduate students within the department provided support in innumerable ways. In particular, Carla Montgomery, Bill Olszewski and Marc Loiselle provided assistance and advice with laboratory and analytical procedures without which this project might never have been completed.

I owe my greatest debt to Stan Hart for his contagious enthusiasm, constant encouragement and cognizance of the important things in life.
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I. General Introduction

The source of metals in ore deposits has been a point of speculation, no doubt, since man's first mining operation. Subterranean demons have given way to igneous emanations, but it is not clear that this is an improvement. Certainly many ore deposits are largely a result of the concentration of heavy metal compounds in the residual fraction of a differentiating magma (Bowen, 1933), but some of the most valuable deposits in the world clearly are not (Davis, 1977). For example, lead isotope studies in the Mississippi Valley lead districts have ruled out a magmatic source for the metals there (Doe and Delevaux, 1972).

The Idaho batholith is a good example of an intrusion that has been assigned a more important role as a mineralizer than is warranted. In the Coeur d'Alene Mining District of northern Idaho, the rich lead-zinc-silver deposits were attributed to late magmatic fluids of the Cretaceous/Tertiary Idaho batholith or its outliers (Ransome and Calkins, 1908), until Long et al. (1960) reported concordant lead isotope ages of 1250 m.y. for separation of the lead from its source. It is not known what proportion of the deposits in Idaho have been attributed erroneously to the batholith.
Evaluation of the contribution of the Idaho batholith to the mineral wealth of Idaho and western Montana will improve our understanding of magmatic ore generation and may aid in future ore exploration. By identifying ore deposits that are genetically unrelated to the batholith, the patterns of Paleozoic and Precambrian episodes of mineralization may emerge. Trace element analysis of ores known to be deposited by late-stage magmatic fluids will help to characterize the source for batholith magma.

The best way to approach the problem of ore source is by analysis of radiogenic isotopes, such as lead, strontium and possibly neodymium and ytterbium. The isotope ratios of these elements in a rock are like fingerprints of the source at the time of ore separation. Other methods of studying ores (such as trace element analysis, light-isotope work, fluid inclusion studies, stability-range experiments and textural studies) are more sensitive to transport and deposition processes than to source processes.

The study described here deals with the lead isotope ratios of ores in the Bayhorse Mining District of Idaho where several ore deposits have been attributed to igneous intrusion during the Cretaceous. Three types of mineralization are conspicuous in this district: Mississippi Valley type Pb-Zn-Ag mineralization in the Ordovician Bayhorse Dolomite; stratiform veins of siderite gangue with argentiferous (and some
auriferous) tetrahedrite and chalcopyrite in the Ordovician Ramshorn Slate; and pyrite and galena veinlets in a sericitized portion of the Cretaceous, granodioritic, Nevada Moutain Stock. Lead isotope ratios have been used to determine the relationships of these deposits to each other, to Cretaceous intrusions and to other ore deposits near the Idaho Batholith.
I. Geology

A. The Idaho Batholith and the Geologic History of Idaho

The Idaho Batholith is a prominent geographic feature and represents a major episode in Idaho's geologic history. (Map 1). It intruded an area approximately 400 by 130 km in central Idaho and affected the country rock over a much larger area. Heat from the intrusion of the batholith caused a wide contact metamorphic zone along its northeastern boundary. Along the Snake River, the westward thrusting and regional metamorphism which accompanied emplacement of the batholith strongly deformed the Triassic Martin Bridge Limestone and imparted a gneissic texture to the batholith (Hamilton, 1963).

The complexity of this composite body has been noted and no map exists which separates the batholith into individual plutons. These plutons are predominantly granodioritic and quartz monzonitic and tend to be most mafic at the boundaries of the batholith. Many outliers are exposed apart from the main body of the batholith. Those in the west tend to be quartz dioritic or trondhjemitic, while those in the east are closer to the average composition of the batholith (Hamilton, 1963).

The age of the Idaho batholith has only recently been well defined. The first workers (Lindgren, 1904) concluded
Map 1: Generalized Geology of Idaho. Rock units in Idaho are separated into six units: Precambrian rocks including the Belt Supergroup of northern Idaho; Paleozoic sedimentary rocks; Mesozoic sediments; Cretaceous intrusives; Eocene Challis volcanics and related intrusives; and Post-Eocene volcanics and alluvium. The border zone of the Idaho Batholith is cross hatched. The Bayhorse Mining District (BMD) is seen to lie at the northern end of a window in the Challis volcanic.
from the metamorphic grade in the west that the batholith was Archean, but further work showed that it intruded Paleozoic rocks (Ross, 1963). In 1958 (Larsen et al.) and 1959 (Jaffe et al.) lead-alpha dates were reported, ranging from 90 to 135 m.y. More recently, K/Ar dating (McDowell and Kulp, 1969) suggested a thermal history spanning the range from 156 to about 38 m.y. However, erroneous ages are easily obtained from Idaho Batholith rocks for the following reasons. First, Eocene igneous activity (Challis Volcanics), though genetically unrelated to the batholith (Armstrong et al., 1977) has reset the isotopic clocks in some areas, resulting in ages that are too young. In addition, erroneously old ages are measured in some areas due to assimilation of some of the very old rock into which the batholith was intruded. After eliminating data affected by either of these processes, the span of intrusive dates is reduced to between 95 and 65 my ago (Armstrong et al., 1977) making the intrusion Late Cretaceous to Early Tertiary. Rocks at the edges of the batholith systematically show ages slightly older than those nearer the center.

Two massive lobes of the Idaho Batholith, the Atlanta in the south and Bitteroot in the north, are partially separated by a schist and gneiss terrane interspersed with granitic rocks. This metamorphism was thought to be partly the result of intrusion of the batholith until very recently (Ross, 1963).
Rb/Sr analyses of four of the presumably Cretaceous plutons yielded ages between 1.3 and 1.5 b.y., making them among the oldest rocks identified in Idaho. (Gneisses in the Albion Range of southern Idaho give an age of 2.5 b.y. (Armstrong and Hill, 1967), and elsewhere Precambrian basement is inferred on the basis of metamorphic grade and contact relationships.) The metasedimentary rocks into which these gneissic Salmon River plutons were intruded were previously correlated with the Precambrian Belt Supergroup rocks in northern Idaho (Ross, 1963; Anderson, 1942), but these ages make such a correlation unlikely.

The Belt rocks form a 21,000 foot-thick wedge which covers an area larger than 45,000 square miles in southern Canada and the northwestern United States. They are predominantly carbonates but include large amounts of quartzite, siltite and argillite. The elongate shape of this rock sequence has suggested to some that it is an aulocogene, the result of Precambrian rifting of North America (Burchfiel and Davis, 1975; Burke and Dewey, 1973). The age of this sedimentation is limited by Rb/Sr and K/Ar dating of glauconite and argillaceous sediments (Obradovich and Peterman, 1973) which yields ages between 1325 and 1100 m.y., generally younger than the ages of the Salmon River plutons. Armstrong (1977) has suggested that it is likely that no correlatives of the Belt Rocks were deposited in central Idaho, and that
the Precambrian arc which interrupts the Idaho Batholith (the Salmon River Arch) has been an influential structural feature since the Precambrian rifting phase. Restriction of the Belt Rocks to northern Idaho strengthens their interpretation as an aulocogen (the outcrop pattern becomes more elongate) and helps to explain some of the complexities in central Idaho. In northern Idaho Belt Supergroup overlies the Precambrian basement (as exposed in western Wyoming) and are in turn overlain by some minor Paleozoic shelf sediments. In central Idaho, the reinterpretation of the metasedimentary rocks in the Salmon River area as Precambrian basement, puts Paleozoic sediments directly on top of the basement (Armstrong, 1977).

No simple Paleozoic paleogeography has been suggested for central Idaho. Rocks that indicate a stable shelf environment are exposed in windows in the Eocene Challis Volcanics, but stratigraphic correlation between exposures is hampered by Mesozoic thrusting, metamorphism and a general lack of fossils. Clearly, the paleogeographic provinces of Nevada and southern Idaho do not continue northward in a simple way, nor do the relationships in Canada continue south. The Salmon River Arch apparently interrupted sedimentation along the Paleozoic shelf (Armstrong, 1977).

Volcanics have covered a significant portion of Idaho since the Mesozoic. The Eocene Challis Volcanics in central
Idaho, the Miocene Columbia River Basalts of western Idaho and the Quaternary Snake River Basalts in the south obscure the geologic relationships of the older rocks. Very few exposures of sedimentary rocks of this age are found around the Idaho Batholith and the Tertiary paleogeography of this area must be inferred from work in Oregon, Washington, Wyoming and the very southern part of Idaho.
B. The Bayhorse Mining District

The Bayhorse Mining District (BMD) occupies one of the windows in the Challis volcanics which exposes Paleozoic shelf sediments on the east side of the Idaho Batholith (Map 1).

The stratigraphy of the area is summarized below and on Map 2 (Wade Hodges, personal communication; Hobbs, Hayes, and McIntyre, 1976; and Ross, 1962).

1. Garden Creek Phyllite (Cambrian ?) - Dark gray to black slightly calcareous phyllite; bedding indistinct and frequently crenulated; exposed only in Garden Creek and Bayhorse Creek; underlain in Bayhorse Creek by an unnamed featureless dolomite unit; age uncertain, Pre-Ordovician based on relationship to Bayhorse Dolomite; total thickness estimates range from 755 to 1245 feet.

2. Bayhorse Dolomite (Ordovician) - Finely crystalline, creamy to yellowish-gray dolomite with varying proportions of limestone; pisolite and silty layers in upper portion; lower contact with Garden Creek Phyllite conformable to gradational; upper surface erosional, brecciated, vuggy, suggesting karst topography; age based on fossil fragments from a carbonaceous unit near the base; 1295 feet minimum thickness; host rock for the Pacific Mountain Mississippi Valley-type Pb-Zn deposit.
Map 2: Generalized Geology of the Bayhorse Mining District.
(From Hobbs, Hays and McIntyre, 1975, and Wade Hodges, personal communication).
3. Ramshorn Slate (Ordovician ?) - Well-laminated, thin-bedded argillaceous and silty phyllitic rock with well developed cleavage oblique to bedding; infrequent carbonate layers; altered to hornfels for several hundred feet around the Nevada Mountain Stock; age based on 1) fossils from the underlying Bayhorse Dolomite and 2) inferred age of overlying rocks which underlie the Ella Dolomite (for which fossils suggest a Middle Ordovician age); total thickness greater than 2000 feet; host for Ramshorn, Skylark Shamrock, Bull of the Woods and Juliette Creek siderite-tetrahedrite veins.

4. Clayton Mine Quartzite (undifferentiated) (Lower Ordovician) - Predominantly poorly sorted coarse to medium grained feldspathic quartzite with intercalated conglomerate, pebbly, silty and argilaceous layers; bedding ranges from thick to thin; color varies from gray to white to yellowish-orange to pink; 6400 feet thick in parts; dolomite layers near Clayton are hosts for Clayton mine Pb-Zn mineralization.

Following a detailed geologic study of the area, Wade Hodges (personal communication) has suggested that the Ramshorn Slate/Clayton Mine Quartzite contact in the BMD is a thrust fault. This thrusting may be related to either the Antler Orogeny or the Laramide Orogeny.

Elsewhere in Idaho (Clayton area and the Pioneer Mountains), the Devonian Antler Orogeny is represented by a change in sediment source region from an eastern source to a
western source, a large influx of mud, erosion of Devonian and Silurian strata, and eastward thrusting which emplaced Ordovician and Silurian strata on top of Devonian strata (Armstrong, 1975). It is possible that in the Bayhorse mining district, the Antler thrusting juxtaposed the upper Clayton Mine Quartzite with the lower Ramshorn Slate. Yet, in the Bayhorse area, the Bayhorse anticline has been attributed to a later orogeny (Ross, 1937) and if the Ramshorn Slate/Clayton Mine Quartzite thrust is Devonian, it should be folded parallel to this anticline. Unfortunately, it is not possible to tell because of the poor stratigraphic control and limited distribution of the small Clayton Mine Quartzite klippen.

It is possible, then, that the Laramide Orogeny, which is represented by the intrusion of the Idaho Batholith in central Idaho, by eastward thrusting in Montana and Wyoming and westward thrusting in western Idaho, Washington and Oregon, may be represented in the BMD by the Ramshorn Slate/Clayton Mine Quartzite thrust as well as the Bayhorse anticline.

Although in the Bayhorse mining district the Bayhorse Anticline appears to be domal (see Map 2), its extensions can be traced north through Garden Creek and south possibly as far as approximately parallels the edge of the later Mesozoic craton as outlined by Armstrong et al. (1977).

The Nevada Mountain Stock is an outlier of the Idaho Batholith within the BMD. On its eastern side it is in fault
contact with Challis volcanics and on all other sides it is seen to intrude the Ramshorn Slate. K/Ar data for biotites near the center of the stock yield an age of 95.9 ± 3.3 my (Hobbs, personal communication) making it one of the older members of the Idaho batholith group. Alteration of the stock along the fault and clustering of other intrusives along the fault to the north, suggest some contemporaneity of faulting and intrusion. The clustering of Cretaceous intrusives about it and offset of the Eocene Challis volcanics show that the fault has been a fairly important influence in the BMD.
III. Ore Deposits in Idaho

Placer gold discoveries brought prospectors to Idaho in the 1860's. Pleistocene moraines, glacial terraces and flood plains produced over 30 million dollars in gold between 1860 and 1870 and the gold lodes in the Idaho Batholith and small Eocene plutons which fed the placers produced about 3 million dollars in gold (Ross, 1963). Additional gold revenues were taken from placers and lodes in areas such as the Thunder Mountain Mining District of central Idaho where the predominantly rhyolitic Challis volcanics contain gold disseminated in pyroclastics and silicified plant material (Ross, 1933). Lodes were worked as they were discovered near placers, but the climate and recent glaciation had resulted in only shallow oxidized zones and the mineralogy and grade of the unoxidized ores frequently prevented them from being mined economically with the technology of the day.

Lode mining was begun in earnest in Idaho in the 1880's. Most of the larger mines of that time were shear zones with ankerite or siderite gangue containing argentiferous galena or tetrahedrite. Deposits were frequently discontinuous and so innumerable small mines were begun.

The Bayhorse Mining District was established at about this time (Umpleby, 1913). The first claim in the area was staked at the Riverview Mine in March of 1877, and the follow-
ing August the Ramshorn, Beardsley and Excelsior mines were staked. By 1880 the district was keeping two sixty-tons-per-day smelters busy, one in Clayton and one in the town of Bayhorse.

The Ramshorn and Skylark mines (Map 2) were responsible for about 2/3 of the ten million dollars worth of silver, lead, and copper produced in the district between 1880 and 1898 (Umpleby, 1913). Much of the ore from these mines contained more than 100 ounces of silver to the ton as "impurities" in tetrahedrite (and galena to a minor extent). These minerals occur in siderite veins 6 to 14 inches wide which follow 4- to 6-foot wide shear zones in the Ordovician Ramshorn Slate. The Ramshorn lode veins strike approximately N25W and have dips of 0° to 20° W, while the Skylark and Shamrock veins are largely vertical. Minor faulting has disrupted some of the veins but no major offsets have been mapped.

This type of mineralization is common in south and central Idaho. For example, in the Wood River District southeast of the Bayhorse Mining District (see Map 3), shear planes in Permian, Mississippian and Ordovician sediments localize ore shoots of carbonate (especially siderite) gangue bearing argentiferous galena with sphalerite, tetrahedrite and pyrite. Some of the shearing in associated Tertiary granitic rocks is mineralized in the same way.
Map 3: Location Map of Idaho Mining Districts. Dashed line is Armstrong, Taubeneck and Hales (1977) edge of the continental crust during the Mesozoic. The border zone of the Idaho Batholith is cross-hatched.
Irregular replacement deposits in the Bayhorse Dolomite account for the remainder of the mineral production in the Bayhorse Mining District. In these deposits, silicified zones of dolomite generally encase stratiform layers of fluorite with argentiferous galena. Some of the smaller mines are located just below the contact with the Ramshorn Slate, suggesting that ore solutions percolating upward were localized beneath this less permeable shaley unit. The Pacific Mountain ore body seems, however, to follow the bulging western flank of the Bayhorse Anticline (Map 2 and 4), possibly following a zone of least stress during mineralization.

The third type of mineralization in the Bayhorse Mining District is the porphyry copper-type mineralization of the Nevada Mountain Stock along Bayhorse Creek. Veinlets of pyrite and galena intrude this highly altered portion of the pluton, but no mines have been developed on this mineralization as yet.

Mining around Bayhorse has been sporadic since the turn of the century. The rush for metal supplies which accompanied both World War I and World War II led to a flurry of activity in this district as in the rest of Idaho, but production has been minimal. The Pacific Mountain ore body is currently being investigated as a possible source of fluorite.
IV. Lead Isotope Data

One hundred pounds of rock were collected from the Bayhorse Mining District over a period of five days in the summer of 1976. Sample localities were decided upon in advance and abundant samples were collected. Eighteen of these were chosen for isotopic analysis, but time constraints have prevented completion of the analyses for five of these. Reported here (Figure 1) are raw analyses for thirteen galenas from Pn-Zn deposits in the district (analysis 1 through 13) and a preliminary analysis of a pyrite separate from a small siderite vein in the Juliette Creek area (analysis 18).

Complete sample descriptions are contained in Appendix 1 and full description of the physical and chemical methods used to treat these samples is in Appendix 2. Sample localities are indicated on Map 4.

Lead isotopic ratio analyses were done on a fully automated, high precision, 9" mass spectrometer at MIT. Samples were loaded on 1 by 20 mil Re filaments with silica gel and phosphoric acid. Analysis of the Cal Tech Standard PN-2 led to the conclusion that $^{204}$Pb was being measured systematically .2% too low, yielding 206/204, 207/204, and 208/204 ratios which are too high by about .2%. Sample analyses reported in Figure 1 have not been corrected for this problem or for the lead isotope ratio in the blank, but only
Figure 1: Table of Isotope Ratios of the Bayhorse Mining District. Uncorrected values for all completed analyses are tabulated. Analysis 18 is a preliminary value from a Juliette Creek siderite-tetrahedrite vein. Starred analyses are of dubious quality and have not been used in subsequent diagrams.
Figure 2. Lead isotope analyses from the Bayhorse Mining District. Uncorrected ratios are quoted with $2\sigma$ = twice the standard deviation from the mean.

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<th>Analysis No.</th>
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<td>18</td>
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<td>0.203</td>
<td>15.780</td>
<td>0.200</td>
<td>n.d.</td>
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Map 4: Mines of the Bayhorse Mining District. Sample localities for this study are labeled by analysis number. Daugherty Gulch (analysis 3) is to the north of the area covered by the map.
corrected values have been used on in subsequent diagrams. Corrected data for the Bayhorse Mining District are plotted in Figure 2.

The analysis quality of numbers 2 through 5 and 13 is questionable based on the standard error, linearity and systematic variation of the ratios during the run. They are all from the Pacific Mountain ore body, but they do not fall within the cluster of points for that deposit. Rather they lie on a line with slope approximately equal to the 206/207 ratio in the samples suggesting an error in 204 measurement. Although ratios for these samples are reported in Figure 1 they are not used or accounted for in the discussion of these data.

V. Discussion

The available lead isotope ratios for ore deposits in Idaho have been plotted in Figure 3. Data from the Wood River District (Doe and Zartman, 1976), the Coeur d'Alene District (Zartman and Stacey, 1971), and the Bayhorse Mining District (this project) are plotted together with Stacey and Kramers' (1975) two stage growth curve.

It is obvious from this plot that lead isotope ratios from the Pacific Mountain ore deposit of the Bayhorse Mining District are unique with respect to lead isotope data from the other ore deposits in Idaho. The neat clustering of ratios centering on 206/204 = 21.35 and 207/204
Figure 2: $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ Diagram for the Bayhorse Mining District Samples.
Figure 3: $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{207}\text{Pb}/^{204}\text{Pb}$ Diagram for the Deposits of Idaho. Values from the Coeur d'Alene, Bayhorse and Wood River mining districts are plotted with Stacey and Kramers (1975) two-stage growth curve. A linear regression line is plotted using the Wood River and Coeur d'Alene values.
15.78 differs from patterns found anywhere else around the Idaho Batholith. This should not be surprising because, despite interpretation of this ore body as a Cretaceous hydrothermal deposit (Ross 1937) no direct field evidence has linked the Pacific Mountain ores to nearby intrusives. In fact, the Pacific Mountain mineralization is most similar, geologically, to the low-temperature diagenetic (Davis, 1977) Pb-Zn deposits of the Mississippi Valley. This is reflected in the similarity of lead isotope ratios (see Figure 4).

An age of mineralization for the Pacific Mountain ore has not been established, but comparison with ores of the very similar Mississippi Valley Pb-Zn district may provide a good approximation. Workers in the Viburnum Trend of the Mississippi Valley have gathered detailed information on stratigraphy, structure, zoning, sedimentary facies and structure, ore mineralogy, fluid inclusion compositions, and isotope ratios. Davis (1977) summarized this work and concluded that all the data are compatible with mineralization during diagenesis of the dolomite which is host to the ores. By analogy, mineralization of the Bayhorse Dolomite probably occurred very soon after deposition of this carbonate unit, and the age of ore deposition is probably Ordovician.
Figure 4: Comparison of Bayhorse ores with Mississippi Valley ores and the mantle evolution curve. This diagram compares the Pacific Mountain ores with the Mississippi Valley Pb-Zn deposits (Doe and Delevaux, 1972) and Sun and Hanson's (1975) mantle evolution curve.
The points that represent lead from the Pacific Mountain ore body define neither a mixing line nor an isochron, but from the position of this cluster to the right and above the conformable lead growth curve (Stacey and Kramers, 1975) some inferences can be drawn regarding the source of the metal in the deposit. The high 206/204 value, relative to 207/204, can be explained by addition of highly radiogenic lead. The geometry of lead isotope growth curves requires that the radiogenic source be relatively young, young enough that the $^{235}\text{U}/^{238}\text{U}$ ratio will cause the $^{206}\text{Pb}$ abundance to increase drastically without increasing the 207/204 ratio. Postulation of a highly radiogenic lead source is easily justified in Idaho because of the large number of uranium deposits which occur in both the Precambrian and Phanerozoic terranes. The tight clustering of lead ratios for the Pacific Mountain ores requires either thorough mixing of leads from different sources or a homogenous source.

The Pacific Mountain ore leads are compared in Figure 4 with an extension of the trend of values for oceanic island volcanic rocks and ocean ridge basalt (Sun and Hanson, 1975, figure 2, mantle evolution curve). It is interesting to note that an extension of this curve passes very close to the average lead ratios for this deposit. Thorough mixing of mantle lead with highly
radiogenic lead could produce Pb of the observed isotopic composition.

The Pacific Mountain lead ratios are different from those in other mines in the Bayhorse Mining District. One of the points which lies outside the main cluster of Pacific Mountain ore values represents a sample of argentiferous galena from the Riverview Mine. This mine has been included in discussions of the Pacific Mountain ores, but the lead isotope ratios and the higher proportion of sphalerite in the Riverview Mine distinguish it from the Pacific Mountain ore deposit. This deposit has been studied cursorily and evidence concerning its relationship to nearby igneous rocks has not been noted.

The other point from the Bayhorse Mining District which lies outside the Pacific Mountain cluster is a preliminary value for ore from the Juliette Creek area, where small siderite-tetrahedrite vein deposits similar to those of the Ramshorn and Skylark mines have produced minor quantities of Cu and Ag. For the purpose of this discussion, the Pb isotope ratios in this sample will be considered representative of the Ramshorn, Skylark, Shamrock and Bull of the Woods ores. It will be shown by comparison with other mines in Idaho that this is a reasonable assumption.

There is excellent evidence that in Idaho the siderite
vein deposits of Ag, Pb and Cu are related to Cretaceous and Tertiary igneous activity. As mentioned in an earlier section, alteration of the Nevada Mountain stock along its faulted western boundary, and the clustering of Cretaceous intrusions near the fault suggest interrelationship of the fault, the intrusions, and the alteration of the intrusions. The zoning of Cu and Ag concentrations approximately parallel to the fault in the Ramshorn and Skylark mines (Kenneth Snyder, personal communication) indicates that this mineralization is also related to the fault and possibly, therefore, to the intrusion and mineralization of the Nevada Mountain Stock. In addition, K/Ar dating of sericite from the shear zone through which the ore solutions passed gives a closure age of 92.9±3.3 m.y. (Warren Hobbs, personal communication), probably a good approximation of the age of mineralization of the Ramshorn Slate. Comparison of the isotope ratios from Juliette Creek and the Riverview Mine with the other batholith-related ores of Idaho is interesting (see Figure 3).

One of the most surprising features of Figure 3 is the linear trend defined by the majority of the ore deposits near the Idaho batholith (excepting, of course, the tight clusters representing the Precambrian ore deposits in the Coeur d'Alene district and the Pacific
Mountain deposit in the Bayhorse mining district). Two interpretations of this trend are suggested below.

Analyses of lead isotopes in the Butte porphyry copper ore body were published by Murthy and Patterson in 1961. Mineral separates from the Boulder Batholith and whole rock samples of the sedimentary country rock yielded isotope ratios incompatible with the ratios in the ores, and the authors postulated a 400-million year-old, non-shallow source for the ores, which is different from that of the batholith. If a similar situation exists for most ores (that is, that their primary metals source is different from that of temporally associated igneous rocks) and if a reasonable degree of mixing is assumed, then lead isotopes for the ores must lie along a mixing line between the primary ore source and the source of the intrusion. For the Idaho ores this mixing line is described by $\frac{207}{204} = (0.147)(\frac{206}{204}) + 12.902$. However, without whole-rock analyses of the Pb isotopes in the Cretaceous/Tertiary intrusives of Idaho, it is not possible to discern which end of the trend in Figure 4 represents the ore source and which the source of the intrusive rocks.

Another possible explanation of the trend is that it is an isochron. The best fit ($r = .96$) of a line
through the primary field of Idaho ore leads has a slope which corresponds to an age of about 2.3 b.y. This line intercepts the Stacey and Kramers growth curve in two places, one at about 2.25 b.y. and one at about 150 m.y. The agreement of the Pb-Pb slope age and the intercept age suggests that this line is an isochron, not a mixing line. In addition, the age of mineralization as deduced from other evidence agrees with the 150 m.y. intercept age within the uncertainty of the regression line. (Considerable variation in the age of the source is to be expected considering the size of the Idaho Batholith). The isochron age of about 2.3 b.y. may represent the average age of the source of the ore leads.

A crustal source for the ore lead is inferred from this data. The Precambrian basement around the Idaho Batholith has been dated in only a few places: the Albion Range (2.5 m.y., Armstrong and Hill, 1967); near the Salmon River (1.3 to 1.5 b.y., Armstrong, 1975); and in the Little Belt Mountains of Montana (1.8 to 1.9 b.y., Obradovich and Peterman, 1973). These ages are very similar to those in the Churchill Province of Canada, where the Hudsonian (about 1.7 b.y.) and Orogeny has overprinted large portions of Archean (2.4 b.y.) terrane, and it is very likely that the basement beneath the northwestern United States is a continuation of the Churchill
Province. The western extent of the Precambrian craton during the Cretaceous has been determined by Armstrong et al. (1977) using initial strontium isotope ratios. Their line representing the edge of the continent at the time of Idaho batholith emplacement is included in Map 3.
VI. Conclusions

The study of Pb isotopes from the Bayhorse Mining District and comparison of these ores to other ores in Idaho and elsewhere, has produced the following conclusions.

1. Pb isotope ratios from the Pacific Mountain ore body form a cluster centering on $^{206}\text{Pb}/^{204}\text{Pb} = 21.35$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.78$. These values are different from other ores in the Bayhorse Mining District and, in fact, are unique compared with lead data from other ores around the Idaho Batholith.

2. Similarity of the lead ratios in the Pacific Mountain deposit and those in the Mississippi Valley Pb-Zn district reflects their geologic similarity. By analogy with the Mississippi Valley deposits, it is hypothesized that the Pacific Mountain ores are syngeneric, Ordovician ores.

3. Batholith-related ores in Idaho lie along a well-defined line that is quite possibly an isochron. The slope and intercept ages indicated by this line agree on a source age of 2.3 b.y.

4. Although only a preliminary value is available from the Juliette Creek area, it appears that Cretaceous/Tertiary siderite-tetrahedrite veins in the Bayhorse Mining District lie along the same line as other intrusion
related ores around the Idaho Batholith.

5. The Riverview Mine is not related genetically to the Pacific Mountain ores. Lead isotopes for the Riverview fall on the trend of Idaho Batholith-related ores, and ore deposition at this site was probably Cretaceous/Tertiary.
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APPENDIX I:
SAMPLE PREPARATION

The physical and chemical procedures followed for separation of the lead from each of the groups are outlined below. All reagents were prepared using a subboiling two-bottle still (Mattinson, 1969) unless otherwise indicated.

1. Galena

Samples were hand picked and ground to powder with an agate mortar and pestle. For each sample approximately .5 grams of ground galena was added to about 6 mls of 6.2 N HCl in a TFE beaker, covered, and placed on a hot plate at about 100°C for approximately 6 hours. Then, with all the galena dissolved, the lid was removed and the solution was evaporated to dryness. White, rhomboidal crystals of cotunite (PbCl₂) remained. In the few cases in which a residue remained after 6 hours in HCl, the solution was transferred to a clean beaker to be evaporated.

Because Pb contamination from air is insignificant for galena work and because it seemed unwise to introduce such large amounts of lead into a lab that would later be used for whole rock chemistry, this work was not conducted in an ultra-clean laboratory. The ultrapure acid and TFE beakers were used to minimize contamination by elements which might
interfere with mass spectrometer work (such as Na and K).

To load the lead onto filaments for use in the mass spectrometer, the following procedure was followed. Silica gel was evaporated onto a clean, degassed rhenium filament using a low current. A portion of the cotunite was dissolved in ultra clean .95 N phosphoric acid, loaded and dried on top of the silica.

At some time during the months that galenas were being run, the phosphoric acid was contaminated with galena lead (206/204 = 21). This contamination (loading blank about 28 nanograms) was discovered when running a trial spiked whole rock sample. Although it would have affected any pyrite or whole rock values, 28 ng is insignificant compared with the number of micrograms of lead loaded for galena runs. This is substantiated by the facts that 1) one of the last galena samples run showed a 206/204 value of 19.7, considerably different from the cluster of galena values and 2) the cluster about 206/204 = 21 shows no linear trend to suggest mixing of sample lead with loading lead.

2. Whole rock granodiorite

Fresh rock samples were reduced to lima bean and pea size in a jaw crusher and then pulverized in a steel shatterbox to slightly coarse powder. Both machines were blown clean with air and wiped out with acetone between samples.
About 0.1 g of each sample was weighed into a TFE capsule (design and procedure follows Krogh (1973), and Montgomery (1977)) with approximately 1 ml of concentrated HNO₃ and 3 ml of HF. This was slipped into a stainless steel bomb and placed in an oven at 205ºC for a week or more.

(The purpose of this lengthy dissolution period was to dissolve any zircons present. However, because this study focused on the initial ratios of the lead, it was undesirable to measure zircon lead. The contribution of zircons to rock lead is entirely radiogenic and necessitates an age correction for Pb ratios. Fortunately the rocks used for this study are young enough that an age correction is negligible, but valuable time was wasted.)

The assembly was cooled to room temperature (about 3 hours) before the teflon capsule was removed. The contents were evaporated to dryness on a teflon covered hot plate in a stream of doubly filtered air in MIT's new ultra-clean lab. About 4 ml of 3.1 N HCl was added to the residual fluorides, the capsule recapped and the assembly returned to the oven for at least overnight.

Again the assembly was cooled to room temperature and opened. Half of the enclosed solution was weighed into each of 2 TFE beakers. One of the pair was spiked with a 208-enriched lead solution (206Pb/208Pb = 0.002) so as to approximately double the amount of 208 in the load.
To separate the lead from both spiked and unspiked samples a sequence of 2 two ion exchange columns was used (see Montgomery, 1977). Filter discs of hydrophilic polyethylene were cut out with a #3 cork borer and each was slipped into the end of a 25 cm length of FEP heat-shrink teflon. This frit was held in position at one end of the tube with glass or ceramic rods while rolling the tube on a hot plate. This shrank the tube around the frit to hold it in place.

One tube thus prepared was used to make an anion exchange column which, with the following procedure, is designed to separate lead from all major elements. It is not very effective for separating lead from large amounts of iron. Eight to ten centimeters of Dowex 1-X8 reagent grade, 200 - 400 mesh chloride form resin was loaded from a slurry with water and subsequently cleaned with 8 ml of 6.2 N HCl and 8 ml of water. The column was conditioned with 4 ml of 3.1 N HCl and then the sample, already in 3.1 N HCl, was loaded onto the column. The lead was eluted from the column with 4 ml of 6.2 N HCl and caught in the beaker from which it was loaded. This solution was evaporated to dryness and the sample was redissolved in 2 ml of concentrated HCl to prepare it for the second column.

The second column, a cation exchange column, was used to separate lead from iron. Eight to ten centimeters of resin (Dowex 50X8-400, hydrogen form, strongly acid cation exchange
resin) was loaded from a slurry with water and then washed with 8 ml of concentrated HCl and the sample was then loaded in the column with concentrated HCl. The lead was eluted from about 2 ml of concentrated HCl and eluted from the column with 4 more mls of concentrated HCl. This solution was dried to form cotunite and loaded for mass spectrometer work in a manner similar to that used for the galena samples.

3. Pyrite

Samples were crushed with a jaw crusher and pyrite was separated by one of several methods, depending on the sample matrix. Some were panned, some were separated by heavy liquids and some were hand picked. The resulting grit was washed in 6.2 N HCl to remove an outer layer which may have been contaminated during separation.

At first it seemed most practical to try to leach lead from the pyrite with 3.1 N HCl, dissolving any lead which might be present in the form of microscopic crystals of galena. However, while this process was being carried out, further reading (Wampler and Kulp, 1964) indicated that the success of this method was unpredictable at best. So, the samples were evaporated to dryness and the remaining Pb and Fe sulfides and chlorides were dissolved in nitric acid. Again they were evaporated to dryness and then redissolved in 3.1 N HCl to make them suitable for loading onto the anion exchange column.
The pyrite samples were put through the columns in the same way as the whole rocks and were loaded onto rhenium filaments as previously described.
APPENDIX II:
SAMPLE DESCRIPTIONS

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<th>Analysis No.</th>
<th>Collection No.</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>72-9 124'</td>
<td>PbS in quartz vein; fractured Obd; drill core sample from about 25 feet above main ore body on Pacific Mountain</td>
</tr>
<tr>
<td>2</td>
<td>72-5 131-5'</td>
<td>PbS in CaF₂ breccia; drill core assay 3.9% Pb and about 30% CaF₂; Obd in main body of Pacific Mountain core</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>PbS in sparry quartz; associated with Cu oxides; surface outcrop of Obd near 1976 Aztec drill site (between Daugherty Gulch and Garden Creek)</td>
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<tr>
<td>4</td>
<td>68</td>
<td>PbS in quartz; associated CaF₂, Cu and As oxides; ore from K-7 mine dump, east side of Beardsley Gulch</td>
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<td>5</td>
<td>68</td>
<td>Same as 4</td>
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<tr>
<td>6</td>
<td>68</td>
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<td>7</td>
<td>PbS disseminated in ZnS mineralization; Obd outcrop near 1976 Riverview drill site</td>
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<td>74-P9-5B 19-20'</td>
<td>PbS in CaF₂ breccia within main Pacific Mountain ore body; PbS finely disseminated; associated with FeS₂ and Ag - sulfide</td>
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<tr>
<td>9</td>
<td>74-P9-5B 19-20'</td>
<td>Same as 8</td>
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</tr>
<tr>
<td>10</td>
<td>73-4 161-75'</td>
<td>PbS in Obd breccia; assay 1% CaF₂; drill core sample at top of main body of Pacific Mountain ore body</td>
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<tr>
<td>11</td>
<td>69</td>
<td>PbS in CaF₂ breccia</td>
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<tr>
<td>12</td>
<td>77 2/3</td>
<td>PbS in massive quartz; associated with Cu and As oxides; surface outcrop of Obd at top of Pacific Mountain near Krazy Karl Adit</td>
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<tr>
<td>13</td>
<td>71-12 5B</td>
<td>PbS in CaF₂ breccia zone of Obd 46 feet below Ors contact; core from near center of CaF₂ ore body map outline but not part of main ore body which lies 110 feet below</td>
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**Whole Rocks**

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<tr>
<td>14</td>
<td>14</td>
<td>Fresh granodiorite from eastern side of Nevada Mountain Stock</td>
</tr>
<tr>
<td>15</td>
<td>23</td>
<td>Sericitized (?), hematite stained granodiorite from western side of stock near fault contact</td>
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**Pyrites**

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<th>Page</th>
<th>Sample</th>
<th>Details</th>
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</thead>
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<tr>
<td>16</td>
<td>12 1/2</td>
<td>Pyrite veinlet from mineralized Nevada Mountain stock at its northwestern corner</td>
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<tr>
<td>17</td>
<td>30</td>
<td>Ore from Ramshorn-type siderite vein; pyrite and chalcopyrite replacement in siderite skeletons; from small mine on east side of Nevada Mountain Stock</td>
</tr>
<tr>
<td>18</td>
<td>33</td>
<td>Pyrite and quartz gangue from Julliette Mine; east side of Nevada Mountain Stock</td>
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</tbody>
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