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METAL SOURCES FOR MIOCENE PRECIOUS-METAL VEINS OF THE ORCOPAMPA, SHILA, CAILLOMA AND ARCATA MINING DISTRICTS, SOUTHERN PERÚ

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ABSTRACT

Neogene adularia-sericite type epithermal veins of the economically important Orcopampa, Shila, Cailloma and Arcata mining districts in southern Perú contain rich and varied Ag-Au ores. Lead isotopic analyses of ore minerals, principally from the Calera vein in the Orcopampa district, indicate that the hydrothermal fluids in each district had limited ranges of $^{206}Pb/^{204}Pb$ but more significant ranges of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, resulting in steep arrays on Pb isotopic evolution diagrams. At Orcopampa, the ore minerals in the main paragenetic stages have $^{206}Pb/^{204}Pb$=18.59-18.64, $^{207}Pb/^{204}Pb$=15.61-15.67, and $^{208}Pb/^{204}Pb$=38.61-38.81. Ore minerals from the Shila district lie at slightly lower $^{206}Pb/^{204}Pb$. In contrast, the Pb isotopic compositions of ore minerals from the Cailloma and Arcata districts have higher $^{206}Pb/^{204}Pb$ (18.68-18.76) but ranges of $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ similar to those of ore minerals from Orcopampa and Shila. The distinctly higher $^{206}Pb/^{204}Pb$ values of the Cailloma and Arcata ore minerals imply that their sources had different time-averaged U/Pb ratios than those that characterize the sources for the Orcopampa and Shila districts.

The steep Pb isotopic arrays defined by the ore minerals in part mimic other geochemical and mineralogical changes within the veins and are interpreted to reflect mixing between leads from an «enriched mantle» source and a radiogenic crustal source. The «enriched mantle» source is inferred to be a pluton, whereas the radiogenic crustal source is probably one of the many pre-Miocene rock units composing the crust in the Central Andes. Comparing the mixing arrays with the isotopic compositions of these sources in the Central Andes suggests that the «enriched mantle» source was probably the same as the one that underlay southern Perú and from which the Cretaceous to Tertiary Coastal batholith was derived. The lower Paleozoic sedimentary rocks that underlie much of the Andean Cordillera appear to have the appropriate Pb isotopic compositions to constitute the radiogenic crustal source. The isotopic data on rocks and ores from the Orcopampa and Shila districts are consistent with models in which gold is derived from deeply-sourced intrusive bodies that have had relatively little involvement with radiogenic crust.

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INTRODUCTION

Adularia-sericite type epithermal veins in volcanic terranes are important economic targets because of their locally rich ores (e.g., Buchanan, 1981; Heald et al., 1987). Many of these deposits have distinct metal budgets with notable differences in the absolute and relative contents of gold and silver and base and precious metals between nearby mining districts in the same or spatially related volcanic centers, veins within a single district, and different paragenetic stages within a single vein (e.g., Gibson et al., 1990). In the Creede mining district in the San Juan volcanic field, Colorado, U.S.A., the variations in precious metal content correlate with the Pb isotopic compositions of the ore minerals, a difference that might prove to be a useful exploration criterion (Foley and Ayuso, 1994). The important Orcopampa, Shila, Cailloma, and Arcata precious-metal mining districts in southern Perú (Noble et al., 1989; Noble and Vidal, 1994; Ericksen et al., 1995) (Fig. 1) provide a unique opportunity, through an integrated Pb isotopic study of the ore minerals and host rocks, to extend the understanding of metal sources and fluid evolution in this type of epithermal ore deposit because of their closeness, ranges of precious-metal contents, and different ages. Initial results of such a study are presented in this report, which focuses principally on the veins and rocks in the Orcopampa district, and interprets the data in the context of Pb isotopic data available from other parts of the Central Andes.

The four mining districts under study are characterized by generally high-base-metal epithermal-type veins hosted by high-angle normal faults cutting Miocene volcanic rocks. Time of mineralization ranges from 18.8 Ma at Orcopampa to 5.5 Ma at Arcata (Silberman et al., 1985; Candiotti et al., 1990; Gibson et al., 1995; E. H. McKee, K. E. Swanson and D. C. Noble, unpublished data). Arcata and Cailloma are silver districts with subordinate, but significant gold production. Gold and silver are of subequal importance at Orcopampa. Shila produces primarily gold.

GEOLOGIC SETTING AND ORE DEPOSITS

The mining districts are situated within the broad high plateau of southern Perú. Volcanic rocks, mostly of Miocene age, overlie a moderately folded sequence of shelf sedimentary rocks of Mesozoic age. The volcanic sequence consists of large-volume units of silicic ash-flow tuff related to a number of collapse calderas, as well as appreciable amounts of lava of intermediate to silicic composition (Noble et al., 1989; Candiotti et al., 1990; Swanson et al., 1993). Normal faults cutting the volcanic rocks that host the ore are of tectonic origin at Orcopampa and Cailloma and unrelated to any nearby volcanic activity (Fletcher et al., 1989; Noble, 1992; Gibson et al., 1995). The origin of the vein-hosting faults at Arcata and Shila is equivocal, but may be related to magmatic activity shortly before mineralization (Noble et al., 1989; Candiotti et al., 1990).

At Orcopampa, ore is produced from veins of fracture-filling type hosted by generally east-northeast trending normal faults (Arenas, 1975; Gibson et al., 1990). A complex paragenetic sequence of five stages has been recognized in the district: the *Early*, *Manganese*, *Quartz*, *Bonanza*, and *Late Stages* (Gibson et al., 1990; 1993a; Gibson, 1992). Although certain stages, particularly the *Manganese* and *Quartz Stages* can be recognized in a number of veins, all stages are present only in the centrally located Calera vein system. Ore contains variable amounts of sphalerite, galena, and chalcopyrite, depending on the paragenetic stage. Although silver to gold ratios are generally very high in the district, the *Bonanza Stage*, found only in the Calera system, is characterized by very high grades and Ag/Au ratios of about 10. Tetrahedrite is the principal silver-bearing phase, although various silver sulfosalt minerals are also present in the *Bonanza Stage* (Gibson et al., 1990; Gibson, 1992). Gold is present mainly as electrum, although gold telluride minerals also are found in the *Bonanza Stage* and locally in the *Manganese Stage*.

Veins in the Shila, Cailloma, and Arcata district are generally similar to those at Orcopampa. Manganese silicates and manganese-bearing carbonate minerals are important gangue minerals along with quartz and, in places, calcite. Although tetrahedrite dominates, silver sulfosalt minerals are more common and broadly distributed. Vertical zoning can be recognized in veins at Cailloma and Arcata as well as at Orcopampa, and the upper and lower limits of ore zones are relatively well defined (Stephan, 1974; Petersen et al., 1990; Candiotti et al., 1990; Gibson, 1992).

MATERIALS ANALYZED AND ANALYTICAL METHODS

Present-day Pb isotopic compositions were determined for an extensive suite of ore minerals (tetrahedrite, silver sulfosalts, galena, chalcopyrite, pyrite, sphalerite, and native gold) from veins in the Orcopampa mining district (Table 1). Only reconnaissance studies of three samples from each of the Shila,

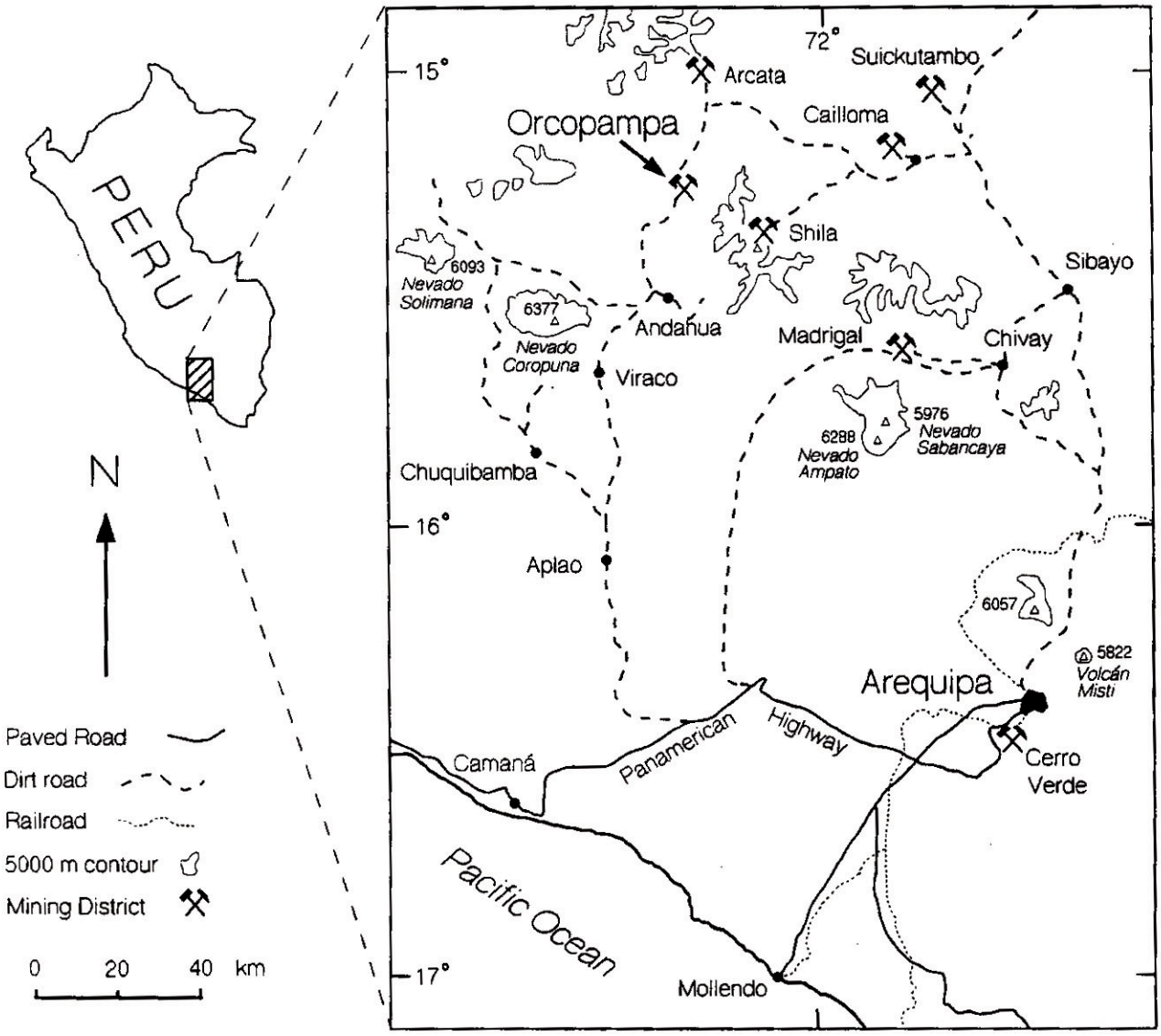


FIG. 1 LOCATION OF THE ORCOPAMPA, SHILA, CAILLOMA AND ARCATA MINING DISTRICTS IN SOUTHERN PERÚ.

Cailloma, and Arcata mining districts were completed (Table 1). Most of the analyzed ore minerals are from the well-characterized Calera vein in the Orcopampa district (Gibson et al., 1990; 1993a). Additionally, present-day whole-rock and feldspar Pb isotopic compositions were determined for a small suite of Miocene volcanic rocks that host the veins in the Orcopampa district. Two samples require special discussion. Sample KS-358, although of the Santa Rosa volcanics, is from an areally restricted intermediate volcanic center located about 30 km southeast of Orcopampa. The Upacabana tuff (sample ORC-12) is related to the Huayta caldera, which formed southeast of Orcopampa at about 11.5 Ma (Swanson et al., 1993). Moreover, whereas the other rocks that were analyzed are fresh, the Upacabana sample has been thoroughly hydrothermally altered, and its isotopic composition probably reflects the composition of lead in altering solutions rather than that of the original rock. The Shila district is located on the southern margin of the Huayta caldera and mineralization there took place within several million years of eruption and collapse (Swanson et al., 1993; K. E. Swanson, E. H. McKee, and D. C. Noble, unpublished data).

Sample	Mineral or Rock Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Orcopampa, Calera Vein				
Early Stage				
CCG-112	Adularia	18.664	15.664	38.812
		18.667	15.663	38.820
	Pyrite	18.654	15.641	38.742
380CH-310	Adularia	18.679	15.641	38.750
	Pyrite	18.642	15.636	38.720
Manganese Stage				
CCG-86	Tetrahedrite/Pyrite	18.629	15.669	38.808
		18.613	15.645	38.737
CCG-316	Galena	18.620	15.651	38.750
		18.620	15.651	38.740
CCG-403	Galena	18.617	15.648	38.734
CCG-6	Tetrahedrite	18.607	15.645	38.735
CCG-503	Pyrite	18.627	15.655	38.777
		18.631	15.660	38.789
Quartz Stage				
CCG-85	Tetrahedrite	18.607	15.636	38.705
CCG-300	Tetrahedrite	18.603	15.632	38.693
CCG-104	Tetrahedrite/Chalcopyrite	18.593	15.615	38.640
		18.595	15.617	38.642
Bonanza Stage				
25571	Galena	18.612	15.644	38.735
		18.601	15.632	38.687
	Tetrahedrite	18.605	15.628	38.671
Ramal 16/22	Galena	18.598	15.623	38.660
7501-185S	Galena	18.642	15.672	38.806
	Tetrahedrite	18.601	15.631	38.684
		18.605	15.636	38.697
		18.613	15.643	38.723
CCG-120	Tetrahedrite	18.608	15.635	38.695
	Tetrahedrite**	18.611	15.637	38.704
	(replicate data)*	18.611	15.637	38.703
	Electrum	18.612	15.637	38.701
CCG-442	Galena	18.603	15.626	38.670
	Tetrahedrite**	18.604	15.628	38.674
	Electrum	18.610	15.632	38.689

TABLE 1
Lead isotopic compositions of ore minerals and adularia from veins of the Orcopampa, Shila, Cailloma and Arcata mining districts, southern Perú. Uncertainties on individual compositions are less than 0.1% at the 95% confidence (2σ) level. Only the first of the replicate analyses of the same mineral is used on Figures 2 and 3. * indicates replicate data obtained during the same mass spectrometer run. ** indicates isotopic compositions of leads obtained by dissolving sulfosalt/sulfide material from electrum.

Table 1, Continued.

Sample	Mineral or Rock Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Orcopampa, Calera Vein (continued)				
Bonanza Stage (continued)				
CCG-311	Tetrahedrite**	18.604	15.630	38.683
	Electrum	18.590	15.609	38.608
CCG-530A	Galena	18.590	15.619	38.648
	Tetrahedrite**	18.615	15.642	38.721
	Tetrahedrite/Chalcopyrite	18.615	15.647	38.737
	Pyrite/Sphalerite	18.610	15.635	38.708
	Electrum	18.581	15.608	38.607
Late Stage				
CCG-103	Galena	18.613	15.642	38.721
CCG-28	Galena	18.597	15.634	38.706
CCG-533	Pyrite	18.601	15.629	38.675
CCG-445	Galena	18.619	15.647	38.740
CCG-98	Galena	18.612	15.637	38.702
CCG-308	Galena	18.599	15.635	38.694
		18.574	15.637	38.702
Other Veins, Orcopampa District				
TCG-1	Tetrahedrite	18.608	15.634	38.691
B-2	Tetrahedrite	18.599	15.626	38.666
SAN-3	Tetrahedrite	18.628	15.641	38.734
	(replicate data)*	18.623	15.637	38.724
CV-30	Galena	18.601	15.640	38.720
	Pyrite	18.602	15.632	38.689
Macfarlane	Galena	18.609	15.641	38.740
Shila District				
SHILA-2	Galena	18.603	15.651	38.797
SHILA-1	Pyrite	18.596	15.630	38.717
SHILA-En	Tetrahedrite	18.556	15.628	38.685
		18.562	15.636	38.714
Cailloma District				
San Pedro	Galena	18.703	15.638	38.735
CAY-SC	Galena	18.756	15.680	38.910
Bateas	Galena	18.699	15.666	38.794
Arcata District				
MAR-235	Galena	18.681	15.631	38.786
N-160	Pyrite	18.707	15.633	38.780
M-120	Galena	18.729	15.682	38.904

Sample	Rock / Mineral Type	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Volcanic Rocks (Miocene)				
Santa Rosa Volcanics				
ORC-30	Volcanic Breccia	18.765	15.638	38.837
KS-358	Plagioclase	18.656	15.634	38.760
Manto Tuff				
ORC-30	Whole Rock Tuff	18.715	15.645	38.806
KS-361	Sanidine	18.726	15.638	38.778
Manto	Sanidine	18.734	15.648	38.811
Sarpane Volcanics				
SARDAC	Plagioclase	18.686	15.637	38.747
ORC-2†	Dacite Lava	18.741	15.626	38.752
Upacabana tuff				
ORC-12	Whole Rock Tuff	18.620	15.671	38.851
Sedimentary Rocks (Mesozoic)				
Hualhuani Formation				
ORC-9	Quartzite	18.703	15.653	38.785
Murco Formation				
ORC-10 (R)	Red Sandstone	18.932	15.692	38.720
ORC-10 (L)'	Red Sandstone	18.960	15.667	38.976
Arcurquina Formation				
ORC-11 (R)	Limestone	18.865	15.640	38.683
ORC-11 (L)	Limestone	19.529	15.671	38.723

TABLE 2
Lead isotopic compositions of Miocene volcanic rocks and Mesozoic sedimentary rocks of the Orcopampa district. L indicates leachate from hydrothermal HCl leach of whole-rock powders; R indicates residue remaining after leach. Uncertainties on individual compositions are less than 0.1% at the 95% confidence (2σ) level.

Also reported are the Pb isotopic compositions of Mesozoic sedimentary rocks exposed in the Orcopampa district (Table 2). Whole-rock powders for Mesozoic sedimentary rock were first leached in dilute HCl at 80°C, and the leachate decanted and then treated as a whole-rock sample. Residues from the leach were also treated like whole-rock samples. Whole-rock Pb isotopic compositions for the sedimentary rocks should lie along the tie lines between the residue and leachate Pb isotopic compositions.

Four samples from the *Bonanza Stage* in the Calera vein were specifically selected because of the presence of abundant electrum in the ores, where it is complexly intergrown with other ore minerals (Gibson, 1992). From these samples, pure tetrahedrite or other silver-bearing sulfosalt minerals were handpicked and processed as separate samples. Electrum samples containing minimal amounts of another contaminating ore mineral were first leached in dilute HNO_3. The solutions were decanted and treated as a separate ore mineral. Leaching removed the other ore minerals, leaving electrum as a residue. Electrum was then dissolved in aqua regia, and analyzed isotopically in the same manner as the other ore minerals.

Sample dissolution techniques, column chromatography, and error analysis used in the laboratories of the U.S. Geological Survey in Menlo Park, California, are described by Wooden et al. (1993) and Arribas and Tosdal (1994). Measured Pb isotopic compositions were corrected for 0.125 percent fractionation per atomic mass unit, based on replicate analyses of the National Bureau of Standards 981 and 983 standards. Laboratory procedural blanks were 1 ng Pb or less and the precision of the isotopic measurements was generally better than 0.05 percent at the 2σ confidence level. Lead isotope compositions are reproducible to ±0.8,

±0.10, and ±0.14 percent (2σ), respectively, for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$.

REGIONAL PB ISOTOPIC PATTERNS

The part of southern Perú located in the high Andes constituting Pb isotopic province II of Macfarlane et al. (1990) includes the Orcopampa, Shila, Cailloma, and Arcata districts. Province II Pb isotopic compositions are characterized by a narrow range of $^{206}Pb/^{204}Pb$ values and ranges of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ such that the data arrays have steep slopes on Pb isotopic evolution diagrams. Only the Pb isotopic compositions for ore minerals from Cailloma lie entirely within the province II field as defined by Macfarlane et al. (1990), whereas those from Orcopampa, Shila, and Arcata lie somewhat outside that field at lower $^{206}Pb/^{204}Pb$ values, an their total range also overlaps part of the fields for province I and III leads of Macfarlane et al. (1990; Petersen et al, 1995). Despite this overlap in Pb isotopic compositions of ore minerals from the veins in this study, we consider them to belong to province II Pb because they share the characteristic feature of the Pb isotopic compositions in province II Pb: steep trends on the Pb isotopic evolution diagrams (Macfarlane et al., 1990; Petersen et. al., 1993; Macfarlane, 1995).

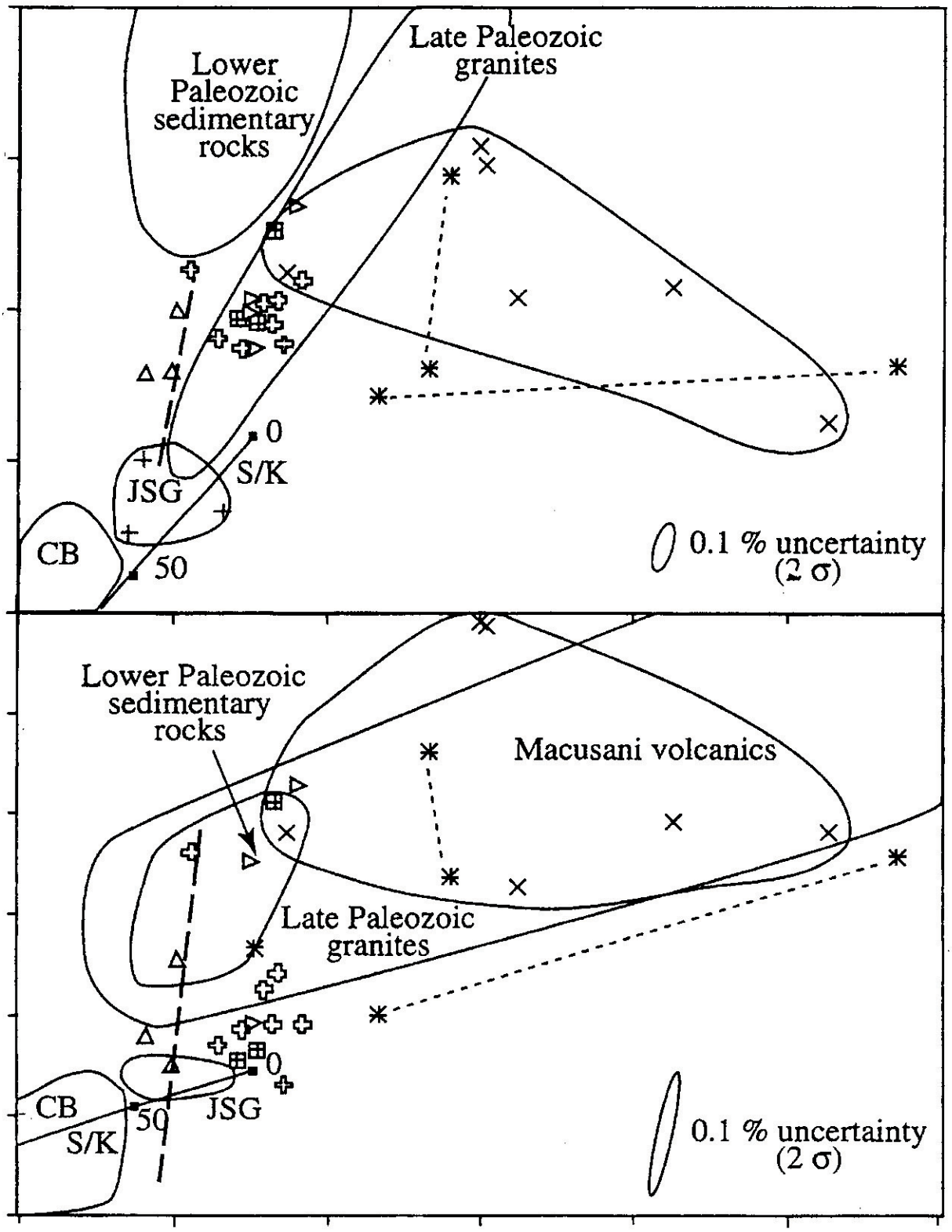
On thorogenic ($^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) and uranogenic ($^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) Pb isotopic diagrams (Fig. 2), present-day Pb isotopic compositions for ore minerals and rocks generally lie above the average crustal growth curve of Stacey and Kramers (1975), indicating a dominance of crustal Pb. Correcting the measured whole-rock Pb isotopic compositions for 6 to 20 m.y. of growth would change the measured isotopic compositions by very small amounts, and any Pb isotopic differences, outside the analytical uncertainties, between ore minerals and rocks from the same or different localities are considered significant.

The present-day Pb isotopic compositions of the ore minerals are slightly more radiogenic (higher $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$) than those characteristic of the Cretaceous and early Tertiary plutonic rocks of the Arequipa segment of the Coastal Batholith, located to the west (Mukasa, 1986) (Fig. 2). Pb isotopic compositions for feldspars from the Early Jurassic San Gabán complex in southeastern Perú (Kontak et al., 1991) overlap part of the field for ore minerals from Orcopampa, but those Pb isotopic values represent whole-rock Pb isotopic compositions as existed at about 200 Ma, and present-day whole-rock $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values would be higher. The $^{207}Pb/^{204}Pb$ of the whole rocks from the San Gabán complex, and their source, would change little in the Cenozoic because of their low abundance of ^{235}U.

The Mesozoic sedimentary rocks, consisting of quartzite, shale and limestone, in the Orcopampa district have higher $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ values than those of the ore minerals (Fig. 2). The $^{208}Pb/^{204}Pb$ values of the sedimentary rocks are similar to those of the ore minerals. Six fresh Miocene volcanic rocks, consisting of dacitic and andesitic lava and rhyolitic ash-flow tuff, from the Orcopampa district have Pb isotopic compositions characterized by $^{206}Pb/^{204}Pb$ values that are either slightly lower than, or overlapping, those of the Mesozoic sedimentary rocks. Although their isotopic signatures overlap those of the ore minerals from Cailloma and Arcata, the rocks have distinctly higher $^{206}Pb/^{204}Pb$ values than do the ore minerals that they host in the Orcopampa district. The altered Upacabana tuff, related to the Huayta caldera, has $^{206}Pb/^{204}Pb$ values similar to those of the ore minerals from the Shila and Orcopampa districts, but has higher $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ than do most of the ore minerals (Figs. 2 and 3). In addition, the Miocene volcanic rocks around Orcopampa have lower $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ values than those that characterize the peraluminous volcanic rocks of the late Miocene and Pliocene Macusani field (Pichavant et al., 1988), located some 130 km to the north (Fig. 2). The latter rocks largely represent upper crustal melts (Noble et al., 1984; Pichavant et al., 1988), and the wide range of their Pb isotopic compositions are interpreted to reflect the heterogeneous composition of the radiogenic crust in southeastern Perú.

The fact that $^{206}Pb/^{204}Pb$ for the ore minerals and Miocene volcanic rocks in this part of southern Perú is greater than 18.5 indicates little interaction of the magmas and hydrothermal fluids with a low-$^{206}Pb/^{204}Pb$ (<18.0) depleted Proterozoic crust such as is evident for Neogene and Quaternary volcanic rocks and ore minerals in southern Perú (about 130 km to the south), western Bolivia, and northern Chile (Barreiro and Clark, 1984; Aitcheson et al., 1995).

The Pb isotopic compositions of the ore minerals and Miocene volcanic rocks lie at generally lower $^{207}Pb/^{204}Pb$ but higher $^{208}Pb/^{204}Pb$ values at a given $^{206}Pb/^{204}Pb$ than do present-day whole-rock Pb isotopic compositions for late Paleozoic granites in Perú and northern Chile between 23° and 27°S (Tosdal, 1994) (Fig. 2). These rocks form large dispersed fields that extend to high $^{206}Pb/^{204}Pb$ on the Pb isotopic evolution diagrams. In contrast, Pb isotopic compositions of five lower Paleozoic sedimentary and metasedimentary rocks from the Cordillera Oriental in central Bolivia


Lower
Paleozoic
sedimentary
rocks
Late Paleozoic
granites
0
S/K
JSG
CB
50
0.1 % uncertainty
(2 σ)
Lower Paleozoic
sedimentary
rocks
Macusani volcanics
Late Paleozoic
granites
0
CB
S/K
50
JSG
0.1 % uncertainty
(2 σ)

(Macfarlane et al., 1990; Aitcheson et al., 1995) form a small field that encompasses the range in $^{206}Pb/^{204}Pb$ for the ore minerals in this study and lies at $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values equal to or higher than those of the ore minerals. These lower Paleozoic sedimentary rocks are part of a marine sequence as much as 10-km-thick that filled a rift basin that occupied that region now underlying much of the interior and eastern parts of the cordillera in Perú, Bolivia, Chile and Argentina (Laubacher and Mégard, 1985). Even though these samples come from the Cordillera Oriental in central Bolivia, it is possible that their Pb isotopic compositions are representative of the Pb isotopic compositions of the sedimentary rocks along the length of the belt because the source terranes were similar and because the Pb isotopic heterogeneities from varied source terranes are homogenized during sedimentation. In this case, the source of lower Paleozoic rocks in the Central Andes was principally the Arequipa-Antofalla craton along the southwestern margin of the basin in southern Perú, western Bolivia, northern Chile, and northern Argentina (Isaacson, 1975; Laubacher and Mégard, 1985; Ramos, 1988). The Amazon craton along the northeastern margin of the basin probably also contributed detritus to the basin (Isaacson, 1975; Laubacher and Mégard, 1985). Each of these cratonal regions have Pb isotopic compositions characterized by $^{207}Pb/^{204}Pb$ values that lie along or above the average crustal growth curve and by geographically variable ranges of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ that depend upon their time-averaged U-Th-Pb histories. In the Arequipa-Antofalla craton, the $^{206}Pb/^{204}Pb$ values are between 16 and 18.7 (Barreiro and Clark, 1984; Aitcheson et al., 1995; Tosdal, 1996). In the Guyana and Amazon craton, the $^{206}Pb/^{204}Pb$ values are similar to those of the Arequipa-Antofalla craton, but also extend to $^{206}Pb/^{204}Pb$ values that are greater than 22 (Montgomery, 1979; Tassinari, 1984; Bettencourt et al., 1995). In fact, the whole-rock Pb isotopic compositions of the various Paleozoic and subjacent Proterozoic rock packages that underlie the Andes suggests that they are characterized by elevated $^{207}Pb/^{204}Pb$ values, which ultimately reflects the presence of recycled old Pb. It is also probable that the high $^{207}Pb/^{204}Pb$ of ore minerals in Pb isotopic province III of Macfarlane et al. (1990) in the Cordillera Oriental of southeastern Perú and Bolivia reflects the role of these rocks, and their sources, as Pb reservoirs in the Andes (Petersen et al., 1993).

PB ISOTOPIC COMPOSITIONS OF VEINS

ORCOPAMPA

Pb isotopic compositions of 36 ore minerals from 29 samples from the four main paragenetic stages in the Calera vein (see above) as well as 3 samples from the Tudela and Santiago veins in the Orcopampa district are characterized by a very limited range of $^{206}Pb/^{204}Pb$ (18.59-18.64) but show a significant range in $^{207}Pb/^{204}Pb$ (15.61-15.67) and $^{208}Pb/^{204}Pb$ (38.61-38.81) (Table 1; Figs. 2 and 3). Two samples of pyrite and two of adularia from the *Early Stage* in the Calera vein (Gibson et al., 1990; 1993a; Gibson, 1992) have higher $^{206}Pb/^{204}Pb$ but similar $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values than do the remainder of the ore minerals from the district. Their Pb isotopic compositions lie approximately midway between those of the ore minerals in the main stages and the host volcanic rocks (Figs. 2 and 3).

SHILA, ARCATA AND CAILLOMA

Pb isotopic compositions were determined on three ore minerals each from the Shila, Cailloma, and Arcata mining districts (Table 1; Fig. 2). Although the Pb iso-

FIG. 2
Present-day thorogenic ($^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) and uranogenic ($^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) Pb isotopic compositions for ore minerals from the precious-metal veins of the Orcopampa, Shila, Cailloma, and Arcata districts, southern Perú. The main-stage ore minerals from Orcopampa are represented by the heavy dashed line. Also shown are the present-day whole-rock Pb isotopic compositions for Miocene volcanic rocks and Mesozoic sedimentary rocks exposed in the Orcopampa district. Tie lines connect the Pb isotopic compositions of acid-leachable and residue components of whole-rock powders of the Mesozoic sedimentary rocks; whole-rock Pb isotopic compositions should lie along the tie lines. The uncertainty on individual Pb isotopic compositions is <0.1% (2σ) and the maximum uncertainty ellipses are shown. S/K, average crustal growth curve of Stacey and Kramers (1975). Pb isotopic compositions for the Miocene and Pliocene Macusani volcanic rocks are after Pichavant et al. (1988); field for the Cretaceous and early Cenozoic Coastal Batholith (CB) is after Mukasa (1986); field for the Early Jurassic San Gabán complex (JSG) is from Kontak et al. (1989; R.M. Tosdal, unpub. data, 1994); field for Lower Paleozoic sedimentary rocks from the Cordillera Oriental, Bolivia, is after Macfarlane et al. (1990) and Aitcheson et al. (1995); and the field for late Paleozoic granitic rocks from Perú and Chile is from Tosdal (1994), Pichavant et al., (1988) and Vidal et al. (1995). In the field for the late Paleozoic granitic rocks, the Pb isotopic compositions for the plutons in northern Perú lie at higher $^{207}Pb/^{204}Pb$ values than do those for the plutonic rocks in north-central Chile.

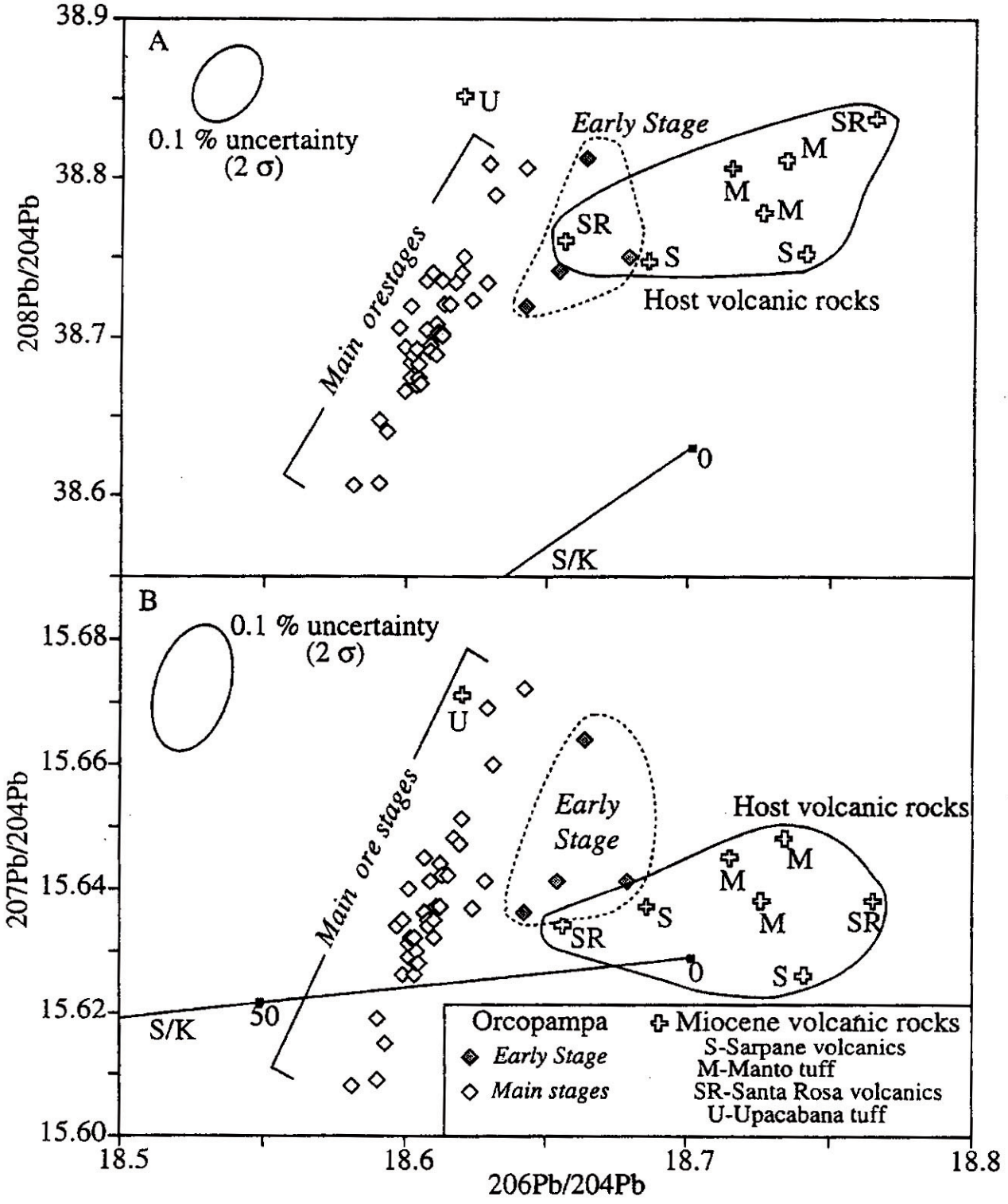


FIG. 3
Present-day thorogenic ($^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) and uranogenic ($^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$) Pb isotopic compositions for ore minerals from the Orcopampa district, principally the Calera vein, showing the steep mixing arrays defined by the main paragenetic stages and the addition of Pb from the hybrid hydrothermal fluid to the host Miocene volcanic rocks during the *Early Stage* of mineralization.

topic compositions for ore minerals from the Shila district have slightly lower $^{206}Pb/^{204}Pb$ values than those of Orcopampa, the limited data suggest a similar range in $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Lead isotopic compositions of the hydrothermally altered Upacabana tuff lie along extensions of the Pb isotopic arrays for the ore minerals of the Shila district, which is located on the southern margin of the Huayta caldera from which the Upacabana tuff appears to have been erupted (see above). In contrast, the three samples from Arcata and the three from Cailloma have higher $^{206}Pb/^{204}Pb$ values than those from Shila and Orcopampa, and overlap the isotopic compositions of the volcanic and sedimentary rocks exposed near and in the Orcopampa district (Tables 1 and 2; Fig. 2). The limited Pb isotopic data from these districts also suggest that the Pb isotopic compositions of more comprehensive suites of samples would also form steep arrays, similar to the Pb isotopic arrays defined by the Orcopampa ore minerals.

In the case of Arcata, only a very minor portion of the difference in $^{206}Pb/^{204}Pb$ can be attributed to the late Miocene age of 5.5 Ma of mineralization, allowing for growth in the sources. Such radiogenic growth cannot have contributed significantly to the Pb isotopic differences between Cailloma and Orcopampa, because Cailloma is only a few million years younger than Orcopampa (Silberman et al., 1985). Rather, the higher $^{206}Pb/^{204}Pb$ character of the ore minerals from Cailloma and Arcata must reflect a Pb isotopic reservoir, or reservoirs, of slightly different time-averaged U/Pb history than that which characterized the nearby Shila and Orcopampa districts. Cailloma and Arcata lie farther inland to the north and northeast (Fig. 1) and are less well endowed in gold than are the Orcopampa and Shila districts. Is it possible that these first-order differences in contained precious metals ultimately reflect the different sources of the hydrothermal fluids in the respective districts?

ORIGIN OF THE STEEP PB ISOTOPIC ARRAYS

Steep arrays defined by Pb isotopic compositions of multiple related samples are most commonly interpreted in two ways. In the first, the arrays are interpreted to reflect the effects of thermal fractionation during mass spectrometric analysis. During this study, different ore minerals from the same sample yielded Pb isotopic compositions that are either identical or agree within the maximum ±0.1% analytical uncertainty (2σ). Likewise, replicate mass spectrometric analyses of the same sample during the same day and replicate Pb isotopic analyses of the same ore mineral at different times also agree within this 2σ analytical precision (Table 1). Moreover, forming the steep arrays through such a mechanism would require thermal fractionation 2 to 4 times greater than the two sigma uncertainties on the measured Pb isotopic compositions, which themselves are conservative. Lastly, this effect would have had to fortuitously occur over the course of the analytical work (1991-1994) but not in other Pb isotopic studies completed in the laboratory during the same time period (e.g., Wooden et al., 1992; Tosdal, 1996). We, therefore, exclude laboratory-induced thermal fractionation as the fundamental cause of the steep arrays.

Steep arrays of Pb isotopic compositions have also been interpreted as the result of mixing of Pb from two, or more, sources with one characterized by high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and the other by low $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$. Implicit in the mixing model is the assumption that the process either: (1) involved large volumes of rocks, (2) operated over sufficient time and/or otherwise was such that source heterogeneities in each reservoir were averaged, and/or that (3) one or both of the sources had relatively homogeneous Pb isotopic compositions prior to mixing. Mixing, a commonly invoked mechanism to explain Pb isotopic patterns in late Cenozoic Andean volcanic terranes (Barreiro and Clark, 1984; Harmon et al., 1984) and ore deposits (Gunnesch et al., 1990; Macfarlane and Petersen, 1990), is considered to be the best explanation for the steep Pb isotopic arrays for ore minerals in this study.

If the Pb isotopic compositions in the ore minerals formed by mixing of Pb from two sources, one source must have average $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values greater than the most radiogenic value in the mixing arrays. The other source must have average $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values that are less than the least radiogenic values in the mixing arrays. If we focus on the possible sources utilizing the large and paragenetically characterized set of Pb isotopic compositions from the Orcopampa district, some constraints can be placed on the metal sources in the veins.

In the Orcopampa district, the Pb isotopic compositions of ore minerals are distinct from those of the host Sarpane volcanic rocks and the slightly older Manto tuff and Santa Rosa volcanics (Fig. 3) The veins were previously considered to be genetically related to the Sarpane volcanic rocks or to an unexposed pluton of similar character, as their formation is most closely related in space and time to the eruption of those rocks

(Gibson et al., 1990; 1995; Gibson, 1992; McKee et al., 1994). The Pb isotopic compositions of ore minerals in the Calera vein and other veins in the district clearly preclude such a causal and genetic relation (Gibson et al., 1993b). In fact, the distribution of the Pb isotopic compositions of pyrite and adularia from the *Early Stage* can best be interpreted as a mixture between the Pb isotopic compositions of the ore minerals in the younger main four vein-forming stages and the host volcanic rocks (Tosdal et al., 1994). The scatter in the Pb isotopic compositions for the *Early Stage* appears to reflect the heterogeneous Pb isotopic compositions of the higher $^{206}Pb/^{204}Pb$ host volcanic rocks and the variable degrees of mixing with the lower $^{206}Pb/^{204}Pb$ hydrothermal fluids.

The Pb isotopic compositions for the least radiogenic ore minerals that form the lower end of the steep arrays on the thorogenic and uranogenic diagrams (Fig. 2) lie along the extension of the growth curve for the Cretaceous and early Tertiary Coastal Batholith, which crops out in the vicinity of Arequipa (Fig. 1), and overlaps the field for the 200-m.y.-old Early Jurassic San Gabán plutonic complex to the northeast. Both these batholithic terranes are considered to have been derived from an enriched mantle (Mukasa, 1986; Kontak et al., 1991), although the fact that the $^{206}Pb/^{204}Pb$ values of the San Gabán rocks are higher than those of the Coastal Batholith implies that two distinct «enriched mantle» sources were present beneath southern Perú at different times. As the mixing trend for the main vein-forming stages bottoms along the heterogeneous «enriched mantle» trend, we consider such «enriched mantle» to be the likely ultimate source for the low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ component in the veins. As the $^{206}Pb/^{204}Pb$ values of the Miocene ore minerals are slightly higher than those for the older Coastal Batholith, this low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ source was similar in many respects to the source of the plutons of the Coastal Batholith, if time for growth in the source region is allowed. We, therefore, consider the low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ source of Pb in the ore minerals to be magmatic, as suggested by other geochemical data (Gibson et al., 1990, 1993b; Gibson, 1992; Tosdal et al., 1994). As the Pb isotopic compositions of ore minerals at Shila are similar to those at Orcopampa, a magmatic source with similar Pb isotopic characteristics presumably underlies that district. Indirect support for this inference is provided by the altered Upacabana tuff, which lies along the Pb isotopic mixing array defined by the ore minerals but at high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, suggesting additional contamination by radiogenic crust (see below) (Fig. 3).

The high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ source must be of crustal origin and contain Pb of Proterozoic, or older, heritage (Zartman and Doe, 1981). The fact that the Orcopampa mixing arrays end in the fields for the lower Paleozoic sedimentary rocks suggests that these rocks, their stratigraphic equivalents, and/or their connate fluids are the most likely radiogenic end member for the mixing arrays defined by the ore minerals. Other possible crustal sources, represented by late Paleozoic batholith and «upper crustal» sources of the Macusani volcanics (Fig. 2) could have contributed elevated $^{207}Pb/^{204}Pb$ to the ore minerals, but their range of Pb isotopic compositions would appear to require some mechanism or sufficient time to homogenize them to the proper Pb isotopic composition. In addition, the distinctly lower $^{208}Pb/^{204}Pb$ values for the ore minerals effectively exclude these sources from being significant contributors of Pb to the ores. Similar arguments are applicable to the ore minerals from Shila, Cailloma and Arcata, although in the latter two districts, exclusion of a source similar to the late Paleozoic batholith or the «upper crustal» source for the Macusani volcanics is weaker because the Pb isotopic compositions for the ore minerals overlap the fields for those rocks.

The difference between the Pb isotopic compositions of the volcanic rocks in the Orcopampa district and the younger ore minerals is an important question, as the magmatic sources for the volcanic rocks should have had similar low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ values as those inferred for the magmatic source for Pb in the ore minerals. The same inference should also apply to the Pb source for ore minerals in the Cailloma and Arcata districts, as there is no reason to expect that their magmatic source had any higher $^{206}Pb/^{204}Pb$ than the magmatic source for Pb in ore minerals in Orcopampa and Shila (Fig. 2). A general scarcity of Pb isotopic compositions for rocks throughout the region hinders resolution of the conundrum, but the limited data do offer a model for testing. In this model, the high $^{206}Pb/^{204}Pb$ in the volcanic rocks in Orcopampa and perhaps in the ore minerals from Arcata and Cailloma represent interaction, or mixing, between a low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ magma and crust characterized by more elevated and presumably more heterogeneous Pb isotopic compositions. The Mesozoic sedimentary rocks and the material incorporated to produce the peraluminous character of the Macusani volcanic rocks (Fig. 2) would be appropriate Pb isotopic contaminants for the intially low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ magma. Assimilation of appreciable amounts of upper crustal material by high-level magma bodies is well demon-

strated by isotopic tracer studies of large compositionally zoned ash-flow sheets (e.g., Johnson, 1989; Farmer et al., 1991) and plutons (e.g., Larson & Geist, 1995). Such assimilation in a high-level magma chamber would produce either a chemically and isotopically zoned magma body or change the isotopic and chemical compositions of the entire body of magma depending upon the nature, the intensity of magma convection, and degree of interaction and time permitted for assimilation. The Manto tuff exhibits appreciable vertical compositional zonation, and the small isotopic differences of the three samples may reflect a real isotopic variability within the ash-flow sheet (cf. Matty et al., 1987).

Implicit in this model is the conclusion that the low $^{208}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{206}Pb/^{204}Pb$ plutonic sources for the ore minerals in Orcopampa and Shila could not have interacted as extensively with the higher $^{206}Pb/^{204}Pb$ crust. In the case of Orcopampa, the magmatic source for the ore minerals must represent a different and younger pluton(s), or a deeper and appreciably less contaminated part of the youngest of the magmatic systems that produced the host volcanic rocks. The Shila district is within the central part of the large Chinchón collapse caldera that formed on eruption of the Manto tuff (Noble, 1992; Swanson et al.; 1993). The relatively low $^{206}Pb/^{204}Pb$ ratios of the Shila ores argue that the source of the low $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ component of the fluids that produced these ores had not interacted with either the very thick intracaldera tuff prism of high $^{206}Pb/^{204}Pb$ Manto tuff or with the inferred high $^{206}Pb/^{204}Pb$ basement rock that had given the Manto tuff its isotopic signature. The above genetic interpretation is consistent with models (e.g., Bartos, 1993) in which gold-bearing paragenetic stages reflect major input from deeply-derived magmatic bodies that have been little modified by interaction with radiogenic crust.

FLUID-ROCK INTERACTION

The Pb isotopic compositions of ore minerals from the Orcopampa, Shila, Cailloma, and Arcata mining districts are explained by the mixing of Pb from two isotopically distinct sources. The Pb isotopic, geologic, and paragenetic relations are consistent with a model in which metal-bearing hydrothermal fluids emanating from Miocene plutons obtain varying amounts of more radiogenic Pb that, based upon available Pb isotopic data, is most likely derived from lower Paleozoic sedimentary rocks or their isotopically equilibrated connate fluids. In the case of Orcopampa, the model requires two stages: an early mixing of Pb from two isotopically distinct Pb reservoirs at depth, and a second local mixing at the site of ore deposition between the hybrid hydrothermal fluid and the local volcanic wall rocks. Evidence for the local addition of hydrothermal Pb from the wall rocks has not been obtained at the Shila, Cailloma or Arcata districts, but the limited number of samples does not preclude such an event.

The likely sequence of events leading to the mixing of Pb of different isotopic composition to form the Pb carried by the hydrothermal fluids is as follows: Incorporation of radiogenic Pb occured when fluids derived from a cooling pluton with low $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ values encountered the lower Paleozoic sequence characterized by relatively homogeneous Pb isotopic compositions with high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$. The relative influence of these two sources on the Pb isotopic composition of the evolving hydrothermal fluid depended upon the accessibility of the magma-tically derived hydrothermal fluid to the radiogenic sedimentary rock source, and upon their relative Pb concentrations. For example, the Pb isotopic compositions of hydrothermal fluids or magmas of low Pb concentration quickly change their Pb isotopic compositions to reflect that of a second source if that source has significantly higher Pb concentrations. In the case under consideration, there is no reason to expect that fine-grained, continentally derived, lower Paleozoic sedimentary rocks are particularly impoverished in Pb. It seems more likely that fluids emanating from the pluton may have had variable Pb concentrations. Tosdal et al. (1994) noted that as the Calera vein evolved during the main stages of evolution, there was a systematic change in the Pb isotopic composition of the ore minerals between successive paragenetic stages. The *Manganese Stage*, the earliest of the four main stages, is characterized by generally higher $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, with the ore minerals lying toward the upper end of the mixing array. In contrast, ore minerals from the *Quartz Stage* and subsequent gold-rich *Bonanza Stage* lie toward the lower end of the mixing array, closest to the Pb isotopic compositions of the inferred magmatic source, an observation consistent with general interpretations of the timing and genesis of gold-rich paragenetic stages in other adularia-sericite type epithermal systems (e.g., Milési et al., 1994). The changing Pb isotopic compositions in the Calera vein with time suggest that the early magmatic fluids may have had relatively low Pb concentrations when they encountered the sedimentary rocks, thereby facilitating the acquisition of a high $^{208}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ component. This observation also suggests that the later gold-bearing fluids may have been shielded from exchange with Paleozoic sedimentary rocks by the development of alteration selvages, and/or

had sufficiently elevated Pb concentrations such that extraction of radiogenic Pb from the sedimentary rocks only slightly modified their Pb isotopic concentrations. The fluid-rock interaction model, furthermore, provides a possible mechanism to explain the changes in amount and proportion of ore and gangue minerals in successively deposited bands of ore in the main paragenetic stages.

A later or second stage of local isotopic mixing is required at the site of ore deposition in the Calera vein. The early hydrothermal fluid added Pb to the wall rocks surrounding the veins, producing Pb isotopic compositions intermediate between those of the host rocks and the hybrid hydrothermal fluids. This *Early Stage* alteration effectively sealed the volcanic wall rocks from the hydrothermal fluids responsible for the main ore stages, and the volcanic rocks contributed virtually no Pb to the evolving hydrothermal system.

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