INVESTIGACIONES DE METALES PRECIOSOS EN EL COMPLEJO VOLCANICO NEOGENO-CUATERNARIO DE LOS ANDES CENTRALES

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CAPITULO III

SUMMARY OF Pb ISOTOPIC COMPOSITIONS IN EPITHERMAL PRECIOUS METAL DEPOSITS, ORCOPAMPA AREA OF SOUTHERN PERU, BERENGUELA AREA OF WESTERN BOLIVIA, AND THE MARICUNGA BELT IN NORTH-CENTRAL CHILE

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Pb ISOTOPIC PROVINCES IN THE CENTRAL ANDES

The Mesozoic and Cenozoic Central Andes are divided into three Pb isotopic provinces, based upon the Pb isotopic compositions of ore minerals (MacFarlane et al., 1990). MacFarlane et al., (1990), furthermore, argue that the Pb isotopic compositions of the ore minerals reflect those of the igneous rocks associated with the deposits. Province I lies along the coast of Perú, Chile, and westernmost Bolivia. Mesozoic and early Cenozoic volcanic and plutonic arcs built upon a rifted and thinned continental margin dominate this province. Three subprovinces are distinguished based upon slight differences in Pb isotopic compositions. Province Ia includes northern and central Chile south of 19°S; province Ib includes central Perú north of 13°S; whereas province Ic includes central and southern Perú between the two other subprovinces. Province II lies in the high Andes of central Perú and, perhaps, in northern Chile and Argentina, where miogeoclinal sedimentary rocks crop out and the crust underwent a lower magnitude of extension in the early Mesozoic. This region generally represents a back-arc position relative to the Mesozoic and early Cenozoic magmatic arcs, and extensive magmatism related to the Andean cycle has only occurred since the Oligocene. Paleozoic arcs are the dominant basement in this province. Province III lies in the Cordillera Oriental and Altiplano of Perú and Bolivia where Paleozoic, Mesozoic, and Cenozoic sedimentary rocks are multiply deformed by thrust faults. Magmatic episodes of Triassic to Jurassic and Oligocene to Miocene age are documented. Proterozoic rocks of the Brazilian shield are underthrust beneath the Cordillera Oriental, with the youngest shortening episode beginning in the Oligocene. Province III is subdivided into two subprovinces: IIIa lies in southeastern Perú where both episodes of magmatism occurred, whereas IIIb lies in Bolivia where magmatism is primarily of Oligocene and Miocene age.

Pb isotopic compositions for Province I are slightly less radiogenic than those from province II, whereas province III isotopic compositions are much more varied with consistently higher ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb at a given ^{206}Pb/^{204}Pb. Province I Pb isotopic compositions (^{206}Pb/^{204}Pb = 18.21-18.82; ^{207}Pb/^{204}Pb = 15.55-15.69; ^{208}Pb/^{204}Pb = 38.11-38.95) overlap with and extend below the average crustal growth curve of Stacey and Kramers (1975) on the uranogenic diagram (^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb). Province II Pb isotopic compositions (^{206}Pb/^{204}Pb = 18.76-18.90; ^{207}Pb/^{204}Pb = 15.62-15.73; ^{208}Pb/^{204}Pb = 38.63-39.16) and Province III Pb isotopic compositions (^{206}Pb/^{204}Pb = 17.97-25.18; ^{207}Pb/^{204}Pb = 15.51-16.00; ^{208}Pb/^{204}Pb = 37.71-40.07) lie above the average crustal growth curve on the same diagram. The Pb isotopic compositions from these last two provinces require contribution from a high mu (^{238}U/^{204}Pb) Proterozoic or Archean source. On the thorogenic Pb isotopic variation diagram (^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb), isotopic compositions for province I, II, and IIIa scatter along the average crustal growth curve of Stacey and Kramers (1975) indicating that a time averaged Th/U ratio ~ 4 (the average crustal value) characterizes the Central Andes. Pb isotopic compositions for province IIIb are the most radiogenic and also the most heterogeneous. The variable radiogenic Pb isotopic compositions of province III suggest heterogeneous upper crustal sources, whereas the isotopic compositions of province I probably reflect a mafic crustal lithospheric source, probably modified by subduction processes. Province II isotopic compositions conceivably represent a mix between the two model reservoirs.

STUDY AREAS

Pb isotopic compositions were determined for sulfide minerals and rocks from three mining districts in the Central Andes as part of the Inter-American Development Bank funded project "Precious-metal deposits in volcanic terranes of the Central Andes". Studies areas are located in southern Perú around Orcopampa, in the western Altiplano of Bolivia around Berenguela, and in north-central Chile in the Maricunga belt. Discussions of the geology of these areas are available in other chapters within this volume

Orcopampa area, southern Perú

Pb isotopic compositions have been determined for sulfide minerals from the Miocene polymetallic veins at Orcopampa, Shila, Arcata, and Cailloma. Isotopic compositions were also determined for whole rock and feldspar samples from the Miocene volcanic rocks that host the veins at Orcopampa and whole rock samples from the Mesozoic sedimentary rocks that are the exposed basement to the veins. This area was included in province II by MacFarlane et al., (1990), although the Pb isotopic compositions on sulfides determined in this study only partly overlap the narrow range of values that characterize that province. Only isotopic compositions for sulfides from Cailloma lie within the province II field, whereas those from Orcopampa, Shila, and Arcata lie outside that field at lower ^{206}Pb/^{204}Pb values.

On thorogenic and uranogenic diagrams (Fig. 1A and 1B), Pb isotopic compositions for sulfides and rocks generally lie above the average crustal growth curve of Stacey and Kramers (1975) and at slightly more radiogenic values (higher ^{208}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, ^{206}Pb/^{204}Pb) than those

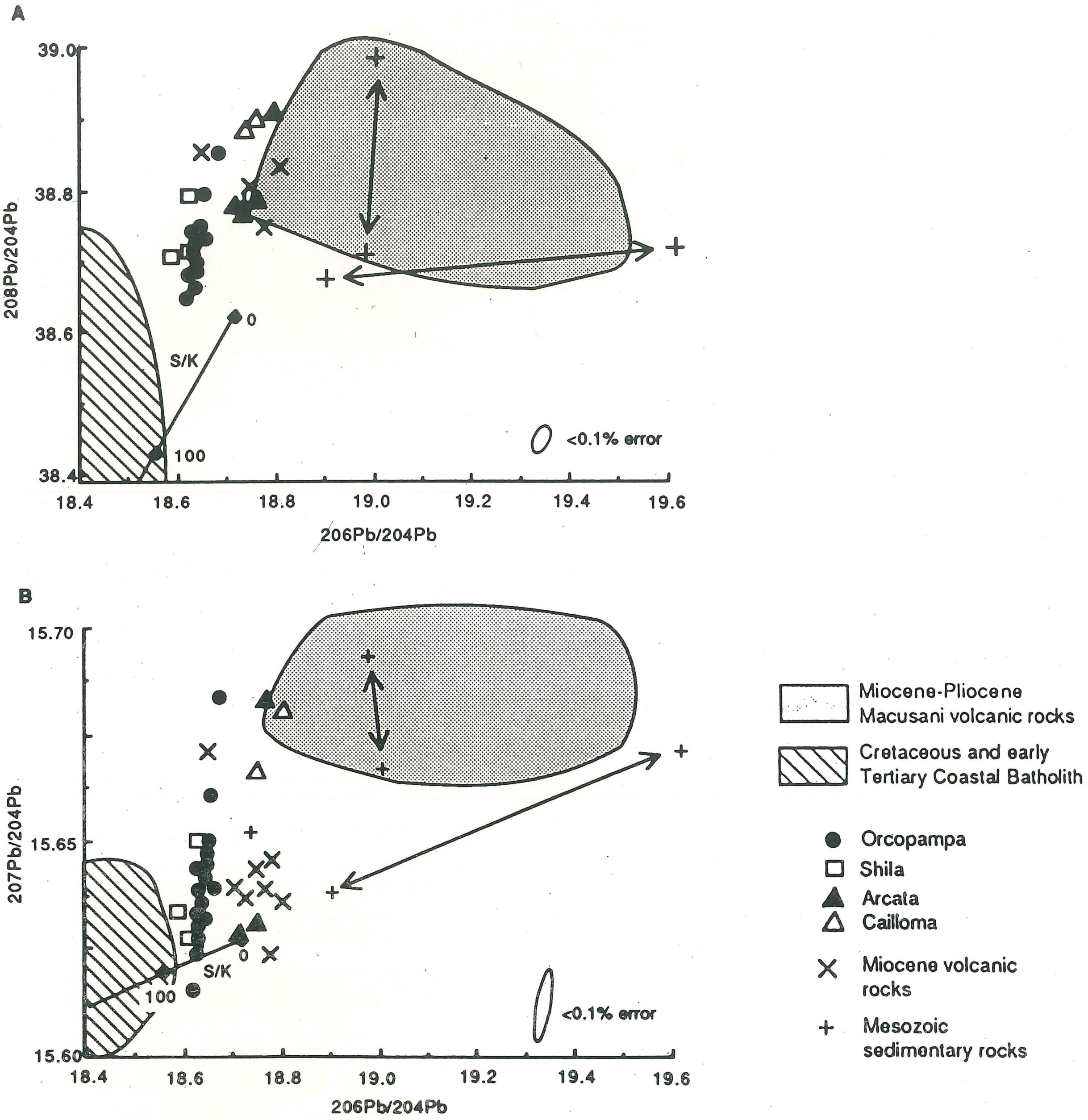

Figure 1.— *(A) Thorogenic and (B) uranogenic Pb isotope variation diagrams for sulfides from polymetallic veins and from rocks in the Orcopampa area, southern Perú. Field (1) for Miocene and Pliocene Macusani volcanic rocks of the Macusani field is from Pichavant et al., (1988) and (2) for the Arequipa segment of the Cretaceous and early Tertiary Coastal Batholith of Peru is from Mukasa (1986). Tie lines with double-headed arrows connect the Pb isotopic compositions of leached and residue components of the Mesozoic sedimentary rocks that were produced during acid leaching experiments; whole rock values would lie along the tie lines. Error on individual isotopic compositions is <0.1% (2σ) and the maximum error ellipses are shown. S/K--average crustal growth curve of Stacey and Kramers (1975).*

of the Cretaceous and early Tertiary plutonic rocks composing the Arequipa segment of the Coastal Batholith, located to the west (Mukasa, 1986). The Mesozoic sedimentary rocks, consisting of quartzite, shale, and limestone, have the most radiogenic values, which are interpreted to reflect the presence of detritus that was probably shed from a cratonal terrane to the east. Miocene volcanic rocks, consisting largely of rhyodacitic and dacitic lavas, domes, and ash-flow tuffs, have isotopic compositions that are either slightly less radiogenic (lower $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$) than, or overlapping with, those of the Mesozoic sedimentary rocks (Fig. 1B). The volcanic rocks, which all come from near Orcopampa, have lower $^{207}Pb/^{204}Pb$ compositions than do Miocene and Pliocene peraluminous volcanic rocks of the Macusani field (Fig. 1B), located to the northeast (Pichavant et al., 1988). These latter rock are crustal melts, and their isotopic compositions have been interpreted to reflect the heterogeneous composition of radiogenic crust in southeast Perú.

Sulfide Pb isotopic compositions from Shila and Orcopampa are less radiogenic (lower $^{206}Pb/^{204}Pb$) than those of the volcanic and sedimentary country rocks and form a tight group on the variation diagrams. Pb isotopic compositions for Shila are slightly less radiogenic (lower $^{206}Pb/^{204}Pb$) than those from Orcopampa. The isotopic database for polymetallic veins in the Orcopampa district is the most complete, and the isotopic compositions form a steep array on the uranogenic diagram (Fig. 1B). This array is interpreted to indicate that the hydrothermal fluids responsible for the veins represented a mix between radiogenic crustal source(s), interpreted to be rocks similar to those from which the Macusani volcanic rocks were derived, and less radiogenic mafic lithospheric source(s). This fluid can not have been generated directly from the magma associated with the volcanic rocks in the Orcopampa area as the latter have distinctly higher $^{206}Pb/^{204}Pb$ compositions. Rather, the fluid is inferred to have originated at depths, and might have been derived from a subjacent pluton (Gibson et al., 1990).

In general, the Pb isotopic compositions in the region lie along extensions of the growth curves for the Cretaceous and early Tertiary Coastal Batholith (Mukasa, 1986). This suggest that the Miocene magmas and sources for the hydrothermal fluid were derived from a source similar to that of the older igneous rocks, which Mukasa (1986) infers to have been enriched subcontinental mantle. Assimilation of radiogenic Pb must have occurred in a crustal environment. One volcanic rock from the Orcopampa area that lies on the projection of the sulfide array at higher $^{207}Pb/^{204}Pb$ values (Fig. 1B) may represent the crustal component that was present in the hydrothermal fluids.

Samples from late Miocene Arcata and Caylloma veins have more radiogenic Pb isotopic compositions (higher $^{206}Pb/^{204}Pb$) than those from early Miocene Shila and Orcopampa veins. Some of this difference in isotopic composition may be due to the slightly younger ages of these deposits. The sulfide isotopic compositions from Arcata and Caylloma also overlap those of volcanic rocks from the Orcopampa area. However, because no volcanic rock samples from the Arcata and Caylloma areas have been analyzed, we do not know whether volcanic rocks there have isotopic compositions similar to those from Orcopampa, or if the volcanic rocks, like those at Orcopampa, have compositions shifted toward more radiogenic $^{206}Pb/^{204}Pb$ values than those in sulfides from veins. Clearly, more samples of sulfides and associated igneous rocks are needed to determine if the isotopic evolution of the Arcata and Caylloma districts is similar to that at Orcopampa.

Berenguela area, western Bolivia

Pb isotopic compositions were determined for galenas from Oligocene and Miocene polymetallic veins cutting red sandstone of the Eocene(?) and Oligocene Berenguela Formation and for galena and oxidized mineralized rock from veins cutting a Miocene rhyolite dike and Miocene tuffaceous sedimentary rocks. Pb isotopic compositions were also determined for (1) boulders of Late Proterozoic (U-Pb geochronology on zircon) gneiss and Phanerozoic (Paleozoic, Mesozoic, or early Cenozoic) granitoids that are interpreted to represent the basement rock present in the subsurface (Jiménez et al., this volume) and that were sampled from conglomerate beds in the lower Mauri Formation; and for (2) sandstones from the Berenguela Formation. The Berenguela Formation crops out and is also present in the subsurface around Berenguela. The sandstones of that formation are either hosts for polymetallic veins or are intruded by rhyolite dikes or buried by volcanic rocks that host other polymetallic veins (Wallace et al., 1992; Jiménez et al., this volume).

The sandstone-hosted veins are the older of the two deposit types and are interpreted to have formed during basin dewatering, whereas the volcanic-hosted veins are igneous-related (Wallace et al., 1992).

Pb isotopic compositions for sulfides and sandstones from the Berenguela area lie above the average crustal growth curve on the thorogenic Pb isotope diagram and along the average crustal growth curve on the uranogenic diagram (Fig. 2A and 2B). The sulfide isotopic compositions of the sandstone-hosted veins are unique in the Central Andes as they do not correspond to any of the provinces defined by MacFarlane et al., (1990). In contrast, the volcanic-hosted veins have isotopic compositions consistent with province Ic. Pb in both vein types have nonradiogenic compositions ($^{206}Pb/^{204}Pb<18.2$) and have significantly lower ratios than most Cretaceous and early Tertiary igneous rocks and sulfides in the Cordillera Occidental of southern Perú and northern Chile, some 50 km to the west (Barreiro and Clark, 1984; Mukasa, 1986; Puig, 1988). The exception is Jurassic plutonic units of the southern Arequipa and Toquepala segments of the Coastal Batholith, which also have nonradiogenic compositions (Mukasa, 1986). Nonradiogenic Pb isotopic compositions of sulfides in the Berenguela area are interpreted to reflect a Proterozoic crustal source(s) that had undergone a granulite-grade metamorphic event where uranium was lost with respect to thorium (Th/U>4).

The sulfide Pb isotopic compositions of the sandstone-hosted veins overlap the field for latest Oligocene and younger volcanic rocks from the Central Volcanic Zone in southern Perú (Barreiro and Clark, 1984) (Fig. 2). The overlap in isotopic composition could be interpreted to imply an igneous source. However, we consider it more likely that the sulfide isotopic compositions were strongly influenced by the composition of the detrital components in the sedimentary rocks from which the fluids were derived during basin dewatering. Pb isotopic compositions for sandstones from the Berenguela Formation scatter between the field for Late Proterozoic and Phanerozoic crystalline rocks and the field for the Cretaceous and early Tertiary rocks and sulfides (fig. 2A), presumably reflecting the mixed detrital components in the clastic rocks. The Pb isotopic data is, therefore, consistent with sedimentologic observations that clasts in the Berenguela Formation, and also in overlying formations, represent granitic rocks of the Mesozoic and early Cenozoic Andean arc in the Cordillera Occidental and Late Proterozoic gneissic rocks.

Pb in volcanic-hosted veins have isotopic compositions similar to those determined for volcanic rocks of late Oligocene and Miocene age in the Berenguela area (Fig. 2A and 2B). Together, the volcanic-hosted veins and the volcanic rocks plot within the field for the latest Oligocene and younger volcanic rocks from the Central Volcanic Zone in northern Chile (Davidson et al., 1990) (Fig. 2A and 2B). It is an inescapable conclusion that Pb in these veins in the Berenguela area was derived from an igneous source.

Barreiro and Clark (1984) argue that the shift of the Pb isotopic compositions to nonradiogenic values for the Late Cenozoic volcanic rocks in southern Perú represents the influence of the Early Proterozoic Arequipa massif in magma genesis. In the Berenguela area, a similar shift in the Pb isotopic compositions is evident in the sulfides and late Oligocene and Miocene volcanic rocks (Fig. 2). The shift is particularly evident in the elevated $^{208}Pb/^{204}Pb$ values Fig. 2A). These nonradiogenic compositions must also reflect the influence of Proterozoic continental crust. However, in this case it seems that a Late Proterozoic terrane rather than an Early Proterozoic terrane provided the Pb found in the rocks and ore deposits in the Berenguela area.

Maricunga area, north-central Chile

In the Maricunga belt of north-central Chile, Pb isotopic compositions have been determined for sulfide minerals from the Esperanza and La Coipa districts, with additional samples from the Marte Mine, La Pepa Mine, and Aldebaran prospect. All deposits are associated with late Oligocene and Miocene volcanos and satellite centers. Pb isotopic data on sulfide minerals are also available from Eocene and older deposits in north-central Chile (Puig, 1988; Zentilli et al., 1988). In addition, the isotopic character of the major rock units in the Maricunga area is known (McNutt et al., 1979; this study) (Fig. 3). These data are briefly summarized here.

Most of the Pb isotopic compositions for late Oligocene and Miocene sulfides from the Maricunga belt lie within the province Ia field of MacFarlane et al., (1990). With the exception of a

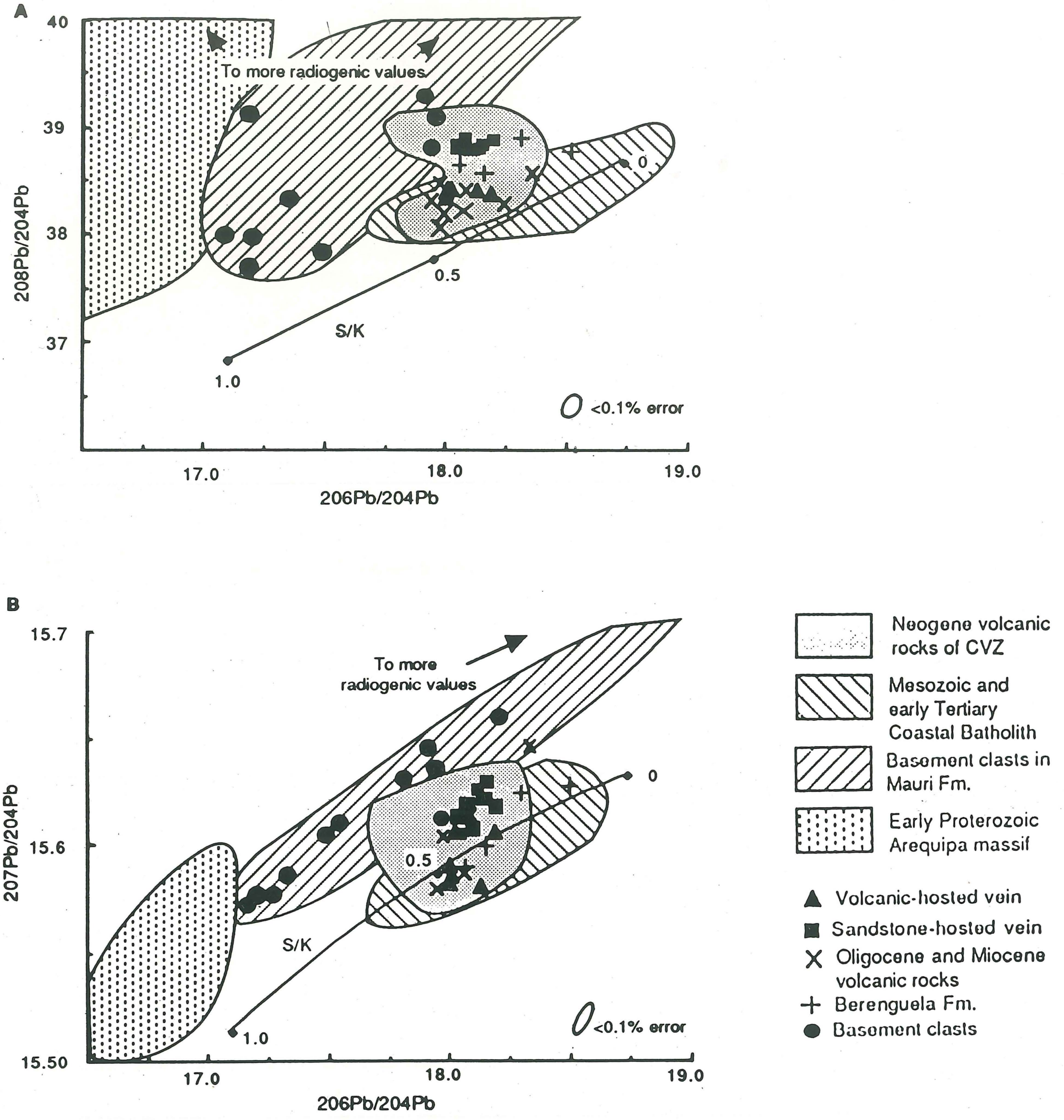

Figure 2.— *(**A**) Thorogenic and (**B**) uranogenic Pb isotope variation diagrams for sulfides from polymetallic veins and from rocks in the Berenguela area, western Bolivia. Field (1) for Neogene volcanic rocks of the northern Central Volcanic Zone (CVZ) is from Barreiro and Clark (1984) and Davidson et al., (1990), (2) for southern Arequipa and Toquepala segments of the Mesozoic and early Tertiary Coastal Batholith of Peru is from Mukasa (1986), (3) for Late Proterozoic and Phanerozoic(?) basement clasts is from this study, and (4) for the Early Proterozoic Arequipa massif is from Barreiro and Clark (1984). Error on individual isotopic compositions is <0.1% (2σ) and the maximum error ellipses are shown. S/K--average crustal growth curve of Stacey and Kramers (1975).*

pyrite from the Cancan prospect, isotopic compositions from the deposits plot in a tight cluster on thorogenic and uranogenic diagrams and are indistinguishable from the isotopic compositions of late Oligocene and Miocene volcanic and subvolcanic rocks with which the deposits are associated (Fig. 3A and 3B). The outlying sulfide composition is interpreted to indicate a component of country rock Pb (Triassic sedimentary rocks, Permian granites, or Permo-Triassic granite and rhyolite) in the pyrite. This radiogenic component probably was scavenged by the hydrothermal fluids as they circulated though the country rocks to the deposits.

On the thorogenic diagram, all sulfides and rocks lie along the average crustal growth curve (Fig. 3A). The Permian and Triassic granites and rhyolites, and derivative sedimentary rocks, extend to more radiogenic isotopic compositions than do rocks formed during the Mesozoic and Cenozoic Andean cycle.

Uranogenic isotopic compositions of igneous rocks in the Maricunga region vary with time and with tectonic setting (Fig. 3B). Permian and Triassic(?) igneous rocks in the region have radiogenic isotopic compositions that lie well above the average crustal growth curve. Pb from a high mu, or Proterozoic, source was incorporated in these rocks during their genesis and emplacement. Their isotopic compositions, thus, strongly reflect the influence of radiogenic crustal reservoirs. On the other hand, Jurassic, Cretaceous, and early Tertiary rocks from the region generally have isotopic compositions that lie below the average crustal growth curve. Sulfides from deposits of this age in the region to the west of the Maricunga belt also lie within this field. These isotopic compositions probably reflect the mafic crustal lithosphere of the region that has been generated and modified by subduction processes occurring beneath the west coast of Chile in the Mesozoic and early Cenozoic. There is little evidence for modification of this reservoir by the input of radiogenic crustal material.

In contrast, late Oligocene and Miocene volcanic rocks form a steep array on the uranogenic diagram (Fig. 3B) that suggest mixing between mafic crustal lithosphere, characteristic of the region and represented by Mesozoic and early Cenozoic rocks and ore minerals, and radiogenic crust, represented by Permian and Triassic rocks. The mixing trend includes Pliocene and Quaternary volcanic rocks present in the Central Volcanic Zone (e.g. Harmon et al., 1984). Isotopic compositions for these younger rocks lie at slightly more radiogenic $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values than do the Oligocene and Miocene volcanic rocks (Fig. 3A and 3B). The simplest explanation for the mixing trend is the assimilation of radiogenic crustal rocks by magmas either during ascent or during fractionation in the magma chamber (e.g. Davidson et al., 1990). The gradual increase in $^{207}Pb/^{204}Pb$ values with increasing SiO_2 content in a dacite dome in the Esperanza prospect support this mechanism. Assimilation of radiogenic crustal rocks by the magmas was probably enhanced by crustal thickening that occurred in the late Eocene or early Oligocene (Moscoso and Mpodozis, 1988; Olson, 1989). At this time radiogenic crustal rocks, or their lithospheric sources, were tectonically buried during the shortening deformation, thereby increasing the chance for their assimilation into the rising magmas, or their involvement at the source of the magmas.

SUMMARY AND SPECULATIONS

Pb isotopic compositions of ore minerals in these three areas in the Central Andes reflect the isotopic compositions of associated country rocks. The origin of their contained metals are, thus, linked to the evolution of the associated rocks. Some modification of the original Pb isotopic compositions of the ore minerals apparently occurred as hydrothermal fluids flowed through the country rocks to the deposits. Intuitively, the potential for this type of modifications to Pb isotopic compositions is probably greatest in small deposits or during the early stages of the formation of an ore deposit.

The Pb isotopic data for the Neogene ore deposits in southern Perú and north-central Chile also suggest an hypothesis for explaining the perplexing question about the precious metal budget of the central Andes. In other words, why is gold common in deposits in Chile, whereas Perú and Bolivia are blessed with enormous quantities of silver, but little gold? In the Orcopampa area, the least radiogenic uranogenic Pb isotopic compositions generally lie above the average crustal growth curve. In the Maricunga district, the least radiogenic uranogenic isotopic compositions lie along, or below, the average crustal growth

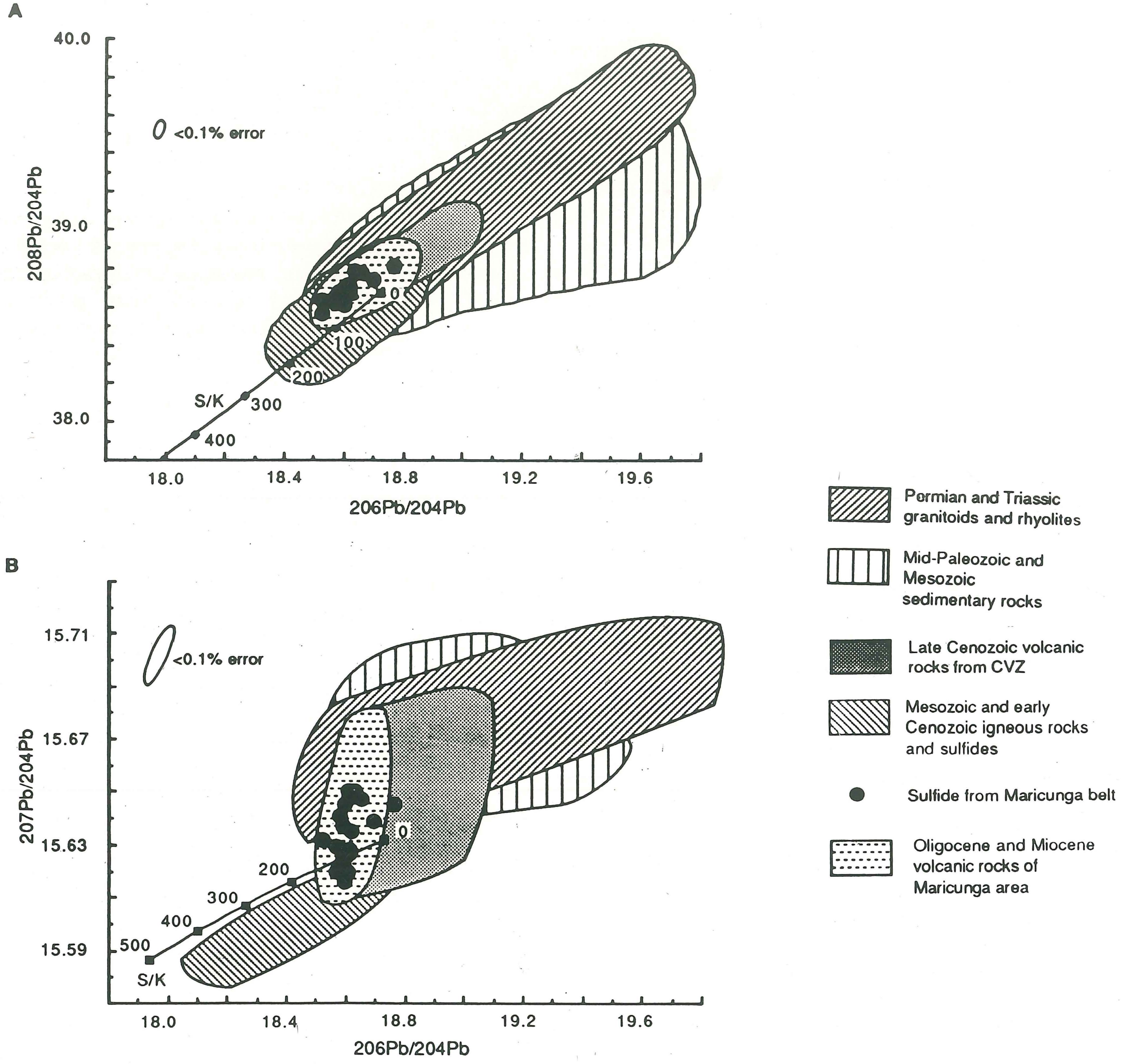

Figure 3.— *(**A**) Thorogenic and (**B**) uranogenic Pb isotope variation diagrams for sulfides from acid-sulfate systems and gold-rich porphyry deposits and from rocks in the Maricunga belt, north-central Chile. Fields for Oligocene and Miocene volcanic rocks from the Maricunga area, for Permian and Triassic granitoids and rhyolites, and for mid-Paleozoic and Mesozoic sedimentary rocks were determined during this study. Field (1) for Mesozoic and early Cenozoic igneous rocks and sulfides is from McNutt et al., (1979), Zentilli et al., (1988), Puig (1988), and this study, and (2) for the Late Cenozoic volcanic rocks of the Central Volcanic Zone (CVZ) is from Harmon et al., (1984). Error on individual isotopic compositions is <0.1% (2σ) and the maximum error ellipses are shown. S/K--average crustal growth curve of Stacey and Kramers (1975).*

curve. The thorogenic Pb isotopic composition from the Orcopampa area also are slightly more radiogenic (higher $^{208}Pb/^{204}Pb$) than equivalent isotopic compositions from the Maricunga area. These very subtle differences in isotopic compositions may reflect a greater influence of crustal Pb in the peruvian deposits than in the Chilean deposits. If so, then the enrichment of silver in Perú and Bolivia may have its origin in the nature of the crust in those countries, and the influence that the crust and its associated lithosphere exerted on magmas during generation, ascent, and emplacement.

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