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DEPOSITOS METALIFEROS ASOCIADOS A LOS CENTROS VOLCANICOS NEOGENOS-CUATERNARIOS EN LOS ANDES CENTRALES

METALLIFEROUS DEPOSITS ASSOCIATED WITH NEOGENE-QUATERNARY VOLCANIC CENTERS IN THE CENTRAL ANDES

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A variety of precious-metal, base-metal, tin, iron, manganese, and uranium deposits are associated with volcanic centers in the Neogene-Quaternary volcanic complex in the central Andean Highlands. This complex, which covers an area of about 300,000 km^2 in southern Perú, western Bolivia, northern Chile, and northwestern Argentina, consists principally of rhyolitic ash-flow tuffs erupted from more than 30 calderas and andesitic lavas, breccias, and tuffs that are associated with more than 1,000 stratovolcanos (Ericksen and Cunningham, 1993). Metalliferous deposits are related to some of these stratovolcanos and calderas, and with volcanic domes and diatremes. In addition, most of the eruptive centers that lack known mineral deposits show evidence of intense hydrothermal alteration similar to that in centers having known mineral deposits. Such alteration zones, of which few have been adequately explored, are favorable targets for future mineral exploration, particularly for epithermal precious-metal deposits.

Precious-metal deposits (Fig. 1) are by far the most numerous and economically important metalliferous deposits in the central Andean volcanic complex. They have yielded large amounts of gold and silver since mining of them began in Precolumbian times, and they continue

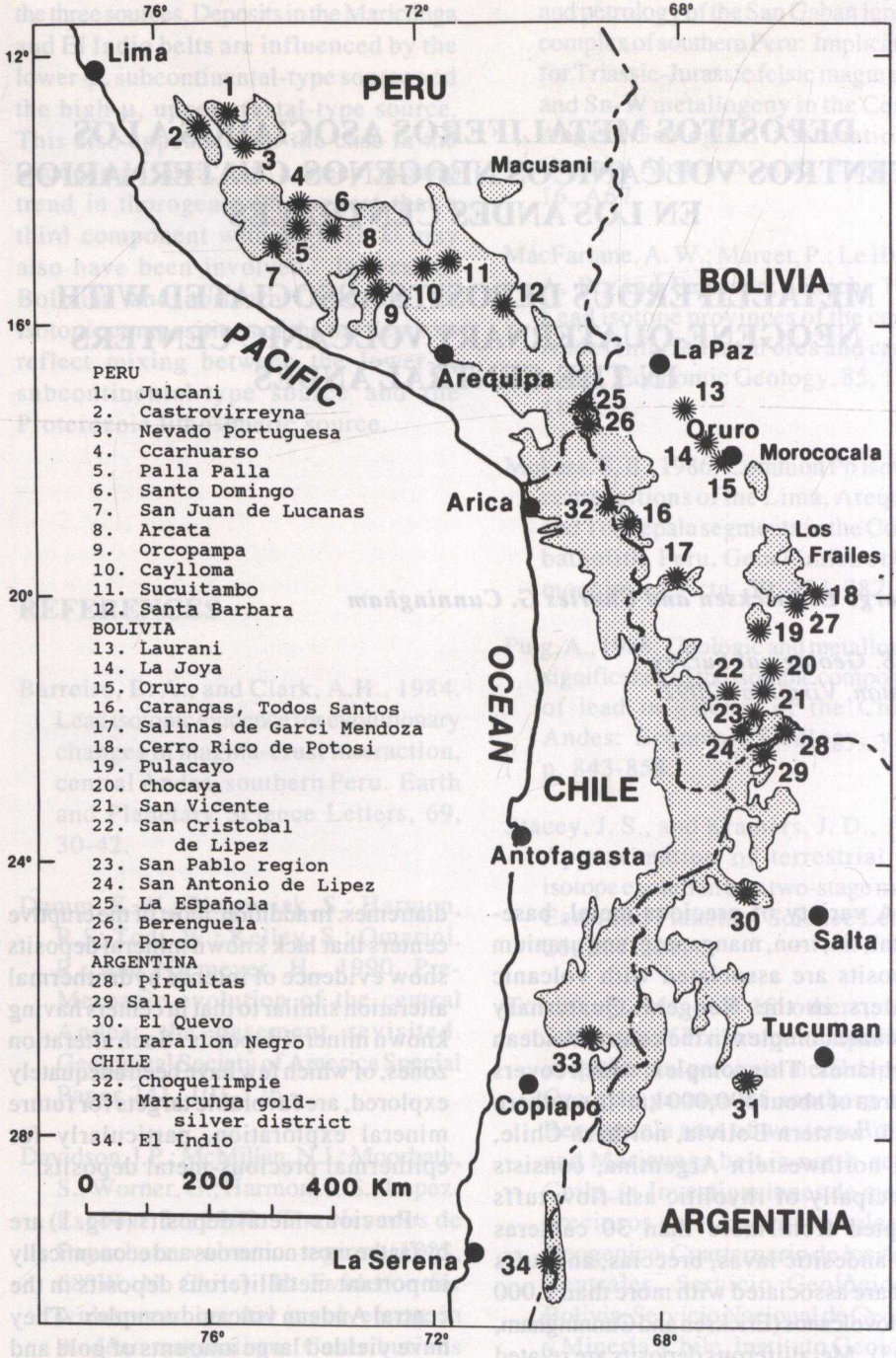

Fig. 1: Precious-metal deposits in the Neogene-Quaternary volcanic complex of the central Andes.

to account for a significant portion of these metals produced by Perú, Bolivia, and Chile today. Included are high-grade vein deposits of both acid-sulfate and adularia-sericite types and low-grade, bulk-minable, disseminated or porphyry deposits (Ericksen and Cunningham, 1993). Large amounts of Ag (probably more than 10,000 metric tons of fine silver) and moderate quantities of Au (less than 2,000 metric tons) have been produced from high-grade polymetallic Ag deposits in southern Perú since Colonial times. These are Ag-rich base-metal deposits in which Ag is the dominant or only metal recovered; historic ore grades are unknown—operating mines in the 1980's and 1990's exploited ores averaging about 0,5 kg/t Ag and 2 g/t Au, with the highest grade ores containing as much as several kg/t Ag and 250 g/t Au. The principal deposits (Julcani, Arcata, Caylloma, Suquitambo, Orcopampa, Castrovirreyna, San Juan de Lucanas) are associated with volcanic domes and calderas (Ericksen and Cunningham, 1993). A similar Ag-rich vein at Pulacayo, Bolivia, produced an estimated 5,000 metric tons of Ag since its discovery in the late 19th Century. Gold-rich Ag and Cu veins at El Indio, Chile, discovered in the late 1970's, yielded (through 1989) 62.2 t Au, 186.6 t Ag, and 100,000 t Cu; the highest grade vein, the 3,500 vein, has yielded more than 30 t Au from ore averaging about 250 g Au/t (Jannas et al., 1990).

High-grade Sn-Ag veins are associated with volcanic domes in the Bolivian tin belt (Cerro Rico de Potosi, Oruro, Chocaya) and have yielded large amounts of Ag. Cerro Rico de Potosi, the world's largest Ag deposit, produced an estimated 30,000 t Ag (Ericksen and Cunningham, 1993). New geochronologic data and U-Th-Pb isotope systematics on zircon from the Potosi dacite dome (R. Zartman, written communication, 1993; Cunningham and others, in press) constrain the timing of dome extrusion to between 14.5 and 12.5 Ma. The main epsoide of alteration and mineralization is temporally bracketed by K-Ar age determinations on sericite of 11.1±0.4 Ma and 10.5±0.4 Ma (E. McKee, written communication, 1993) and a fission-track age on zircon of 12.5±1.1 Ma (C. Naeser, written communication, 1993). Prelimimary dating of alunite and sericite by E. H. McKee have identified a second significant episode of mineralization of about 6-8 Ma, similar to the age of the nearby Los Frailes ash-flow tuffs. Partitioning of ^{18}O between SO_4 and OH in the young alunites indicates deposition temperatures of 240-290°C and δD values of -69 to -74 per mil (R. Rye, written communication, 1993) require a magmatic fluid origin for the alunite.

The Porco, Bolivia, Sn-Pb-Zn-Ag deposit, the first major Andean Ag deposit exploited in Colonial times, consists of high-grade veins in the ring-fracture zone of a small resurgent caldera (Cunningham et al., 1993). New geochronologic data (K-Ar, biotite) indicate the caldera formed about 12.0 Ma and that the mineralization is related to the resurgent dome that was emplaced 8.6±0.3 Ma (K-Ar, sanidine; E. H. McKee, written communication, 1993). Pb-Zn-Ag veins at Illimani and Sn-bearing base-metal and Ag veins at Andacaba and Cunarana, southern Bolivia, are in the resurgent dome of the early Miocene Kari Kari caldera, southern Bolivia, which was formerly thought to be a batholith (Ericksen et al., 1987).

Recently discovered, low-grade, large-tonnage, bulk-minable precious-metal deposits in the central Andean volcanic complex are among the largest and economically most important Au and Ag deposits in the Andes. These typically

are disseminated or porphyry type deposits, most of which have reserves ranging from about 10 million to 100 million metric tons of ore having grades of 1.5-2 g/t Au and a few grams to about 100 g/t Ag. Most are genetically related to andesitic stratovolcanos and/or domes. Some 14 deposits of this type, which were discovered in the Maricunga region of northern Chile during the 1980's, contain an estimated total of 420 t Au and 14,000 t Ag (Vila and Sillitoe, 1991). One of these deposits, La Coipa, is currently being mined at the rate of 15,000 t/day, and another, Marte, an 8,000 t/day operation, closed in 1991 because of poor recovery of Au from 1.5 g/t sulfide ores (Ericksen and Cunningham, 1993). The low-grade, bulk-minable deposits at Choquelimpie, northern Chile, and at La Joya, Bolivia, which are associated with volcanic domes, were formerly worked for polymetallic Au- and Ag-rich ores in well-defined veins and only recently for low-grade ores. La Joya is currently (1993) a heap-leaching operation (Columba and Cunningham, 1993), but the low-grade ores at Choquelimpie were mined out and the operation closed in 1992.

Of the other types of metalliferous deposits in the Neogene-Quaternary volcanic complex of the central Andes, disseminated or porphyry-type Cu-Au/Ag and Sn-Ag deposits, and high-grade Fe deposits have large tonnages of low-grade, potentially exploitable ores, although none has yet been exploited. Three porphyry type Cu-Au deposits occur in the roots of a deeply eroded andesitic stratovolcano of Miocene age at Farallon Negro, northwestern Argentina. One of these, Bajo Alumbrera, contains an estimated 300 million metric tons of ore averaging 0.49 percent Cu and 0.7 g/t Au (Guilbert et al., 1986). The Aldebaran deposit, in the Maricunga region of northern Chile, is a porphyry-type Cu-Au/Ag deposit associated with a Miocene stratovolcano (Vila and Sillitoe, 1991). The host rocks of the high-grade Sn-Ag veins at Cerro Rico de Potosi and Chocaya, Bolivia, are volcanic domes (Cunningham et al., 1991) that reportedly contain hundreds of millions of metric tons of material grading 100-250 g/t Ag (Ericksen and Cunningham, 1993).

Magnetite/hematite flows at several localities on Volcan El Laco, an andesitic stratovolcano of late Miocene age in northern Chile, contain a total of more than 100 million metric tons of high-grade (>60 percent Fe) iron ore (Ericksen et al., 1987).

Small deposits of covellite, manganese oxides, wood tin, and uranium are also present in the Neogene-Quaternary volcanic complex of the central Andes (Ericksen et al., 1987). Of these, only a few of the known wood tin, uranium, and manganese deposits have been exploited. A small deposit of massive covellite is associated with a sulfur deposit at the top of Volcan Aucanquilcha, an andesitic stratovolcano of Quaternary age in northern Chile. This deposit, which perhaps contains several tens of metric tons of ore, consists of massive, high-purity covellite cut by veinlets of native sulfur. Other deposits include manganese oxides in veins and breccia fillings within andesitic flows, and as lacustrine accumulations at several localities in the Andean Highlands of northern Chile where they probably formed as the result of thermal spring activity. Manganiferous travertines are currently being deposited by thermal springs on the flanks of Volcan El Quevo, northern Argentina. Many small wood-tin deposits and uranium deposits are scattered in the late Miocene rhyolitic ash-flow tuffs of the Los Frailes volcanic plateau,

which is in the central part of the Bolivian tin belt. Several of the wood-tin deposits have been exploited during the present century, but not later than the 1970's, and one of the uranium deposits is currently (1993) being mined. These wood tin and uranium deposits probably formed by late-stage thermal springs.

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