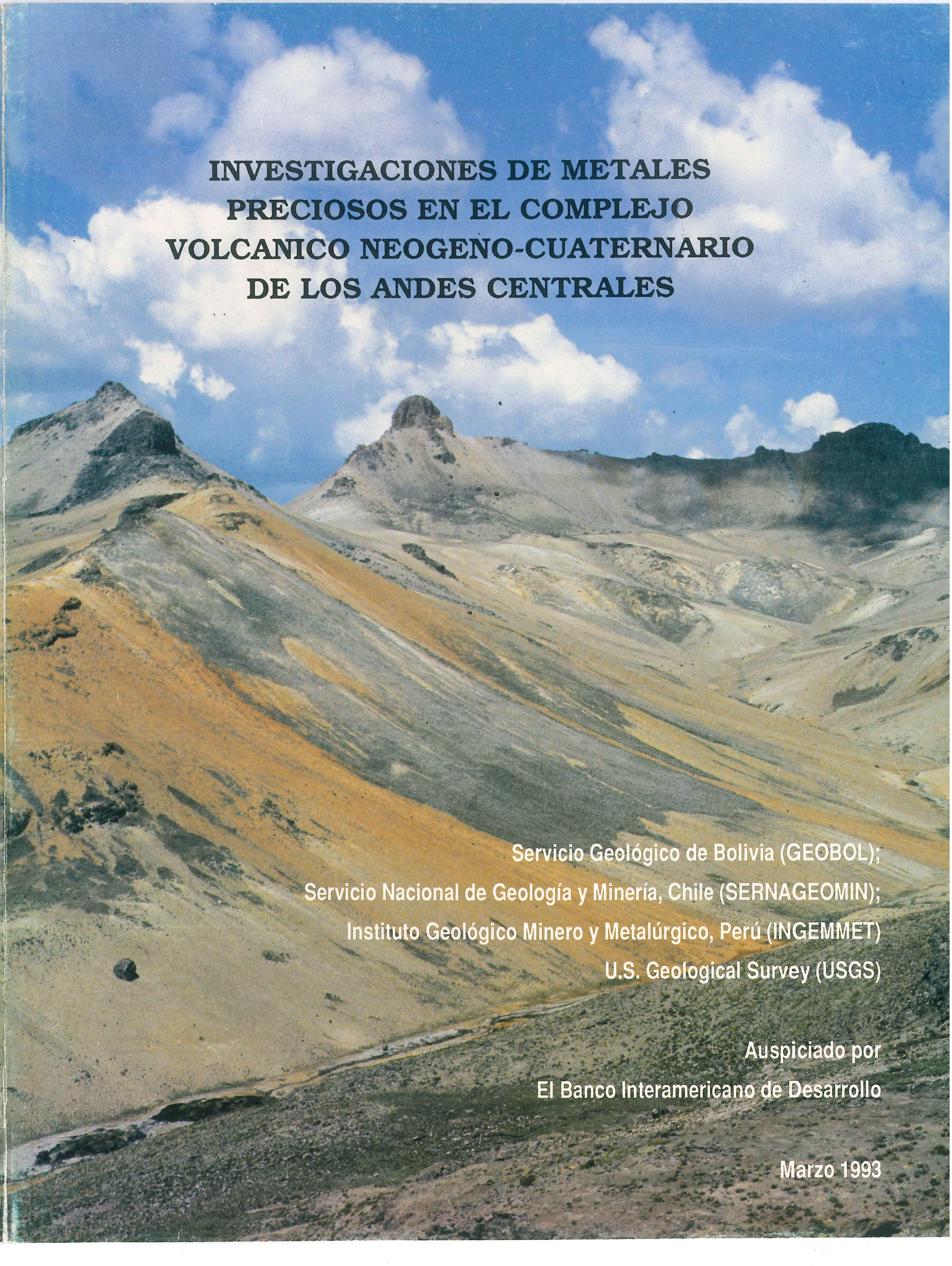

INVESTIGACIONES DE METALES PRECIOSOS EN EL COMPLEJO VOLCANICO NEOGENO-CUATERNARIO DE LOS ANDES CENTRALES

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CAPITULO I

PRECIOUS-METAL DEPOSITS IN THE NEOGENE-QUATERNARY VOLCANIC COMPLEX OF THE CENTRAL ANDES

by George E. Ericksen and Charles G. Cunningham
U.S. Geological Survey

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ABSTRACT

The Neogene-Quaternary volcanic complex of the central Andes contains hundreds of hydrothermally altered zones, several of which are associated with world-class epithermal precious-metal deposits, but most of which are either unexplored or inadequately explored. These young volcanic rocks, chiefly andesitic to dacitic lavas and rhyolitic ash-flow tuffs, extend over an area of about 300,000 km^2 in the Andean Highlands of southern Perú, northern Chile, western Bolivia, and northwestern Argentina. At least a dozen major deposits have been discovered in the young volcanic complex since the late 1970's by exploration programs stimulated by the phenomenal rise in gold and silver prices. Not only are eruptive centers in the complex prime exploration targets, but the volcanic complex covers older rocks and associated mineral deposits of one of the world's greatest metallogenic provinces. Future exploration should reveal the presence of more deposits both within and beneath the volcanic rocks.

The volcanic-hosted epithermal precious-metal deposits are spatially and temporally related to eruptive centers--stratovolcanoes, calderas, and domes--within the volcanic complex. Included are both adularia-sericite and acid-sulfate types of deposits for which distinct sub-types can be distinguished and corresponding descriptive models constructed. Adularia-sericite-type deposits include (1) silver-rich polymetallic base-metal veins, (2) polymetallic tin-silver-rich veins, and (3) stockwork porphyry deposits. Acid-sulfate-type deposits, which are characterized by the presence of enargite and magmatic-hydrothermal alunite, include (1) silver- and gold-silver-rich polymetallic base-metal veins and (2) low-grade vuggy silica and breccia gold-silver deposits. Radiometric ages show that most of the precious-metal deposits are of middle Miocene age (17-9 Ma), but several are as young as Pliocene and Pleistocene (5-1.2 Ma), and others may be forming today in association with active thermal spring systems and fumarolic-stage stratovolcanoes.

Grade and tonnage data for both high-grade (generally multi-vein) deposits and low-grade (generally stockwork or vuggy silica) deposits show that most contain between 500 and 5,000 metric tons (t) of silver and less than 60 t of gold. Cerro Rico de Potosí, a polymetallic tin-silver deposit, is the world's largest silver deposit, having produced an estimated 30,000 t of silver from ores that probably averaged more

than 500 grams per metric ton (g/t) silver. A comparable amount of silver is estimated to remain in Cerro Rico in veins and stockworks, disseminated into the wallrock, and in waste dumps, all having grades of 150-250 g/t silver. Silver-rich base-metal ores generally contain 500 or more g/t silver but less than 2 g/t gold; ore shoots in some veins may contain 100 or more g/t gold. The richest gold ore recently found in the central Andes has been the 3500 vein of the El Indio district, Chile, which has yielded about 30 t of gold from ores averaging about 250 g/t gold. Significant amounts of the ore in this vein contain more than 1,000 g/t gold. Low-grade stockwork, vuggy silica, and breccia deposits, of which at least a dozen have been discovered during the 1980's and 4 or 5 are currently in operation, have average grades on the order of 1.5-2 g/t gold and 20-100 g/t silver. Resources of such deposits range from 25 to 60 t of gold and to as much as 3,000 t of silver.

INTRODUCTION

The Neogene and Quaternary volcanic complex in the central Andes (Fig. 1) became recognized as an important exploration target in the late 1970's and early 1980's when several important new gold and silver deposits were discovered. This complex constitutes part of the late Tertiary and Quaternary cover within the central Andean metallogenic province, one of the great metalliferous provinces of the World, which is characterized by the presence of thousands of ore deposits that are chiefly of Mesozoic and Cenozoic age. Included are world-class deposits of base- and precious-metals, tungsten, tin, and antimony major deposits of sedimentary manganese and iron oxides, porphyry copper deposits, strata-bound copper and polymetallic base-metal deposits of possible volcano-sedimentary origin, and magmatic iron-oxide deposits. Most of these deposits are hosted by sedimentary, volcanic, and plutonic rocks that are of pre-Miocene age.

Exploration during the late 1970's and the 1980's, stimulated by the phenomenal rise in prices of gold and silver, resulted in the discovery of at least a dozen major new deposits both in areas without indications of previous prospecting or mining as well as in established mining districts. Although many gold and silver deposits were known to be hosted by volcanic rocks in this region, and some deposits were discovered and mined during both pre-Columbian and Spanish Colonial times, the relation of these deposits to the young volcanic rocks was not well understood until radiometric ages became widely available in the 1970's. These ages now clearly show that most of these deposits are temporally and spatially related to volcanic centers of chiefly Miocene age (17-9 Ma), but a few deposits are of Pliocene and Pleistocene age (5-1.2 Ma) (Noble and McKee, 1982; Ericksen et al., 1987; Vidal et al., 1989; Sillitoe et al., 1991). Host rocks include andesitic to dacitic lavas erupted from hundreds of stratovolcanoes, quartz latitic to rhyolitic ash-flow tuffs from at least 30 calderas, many dacitic to rhyolitic domes, and explosive breccias and pyroclastic deposits (Ericksen et al., 1987).

Estimated grades and tonnages of ores (production plus reserves) of some of the deposits shown in figure 1 are listed in table 1. As can be seen, most have relatively high values for silver and low values for gold. By far the greatest silver production from any one deposit is that of Cerro Rico de Potosí, which Murillo et al., (1968) estimated to be 30,000 metric tons (964.5 million ounces). This deposit is estimated to contain at least an equal amount of silver in low-grade (150-250 g/t silver) stockworks, veins, and in waste dumps (Bernstein in Suttill, 1988).

Several polymetallic silver deposits in southern Perú (Arcata, Caylloma, Orcopampa, Julcani) have each produced between 50 and 100 million ounces (1,555-3,110 t) from ores that probably averaged on the order of 12-15 oz/t (373-467 g/t) silver (Silberman et al., 1985; Candiotti et al., 1990; Alberto Benavides, oral commun., 1991) Although these deposits had locally high-grade gold ore containing several grams to a few tens of grams per metric ton, most of the ore in these deposits averaged less than 2 g/t gold. Total production from any one of these deposits or districts probably has not been more than about 500,000 oz (15.6 metric tons). The richest gold ores encountered during recent mining (1980-1990) have been those from the 3500 vein at the El Indio deposit (Table 1), which during a 10-year period (1979-1989) yielded about 30 t of gold (Jannas et al., 1990) from direct-shipping ore averaging 250 g/t gold (Siddeley and Araneda, 1986). Some of the low-grade vein-type deposits, such as La Joya, Bolivia, and the vuggy silica and breccia-hosted

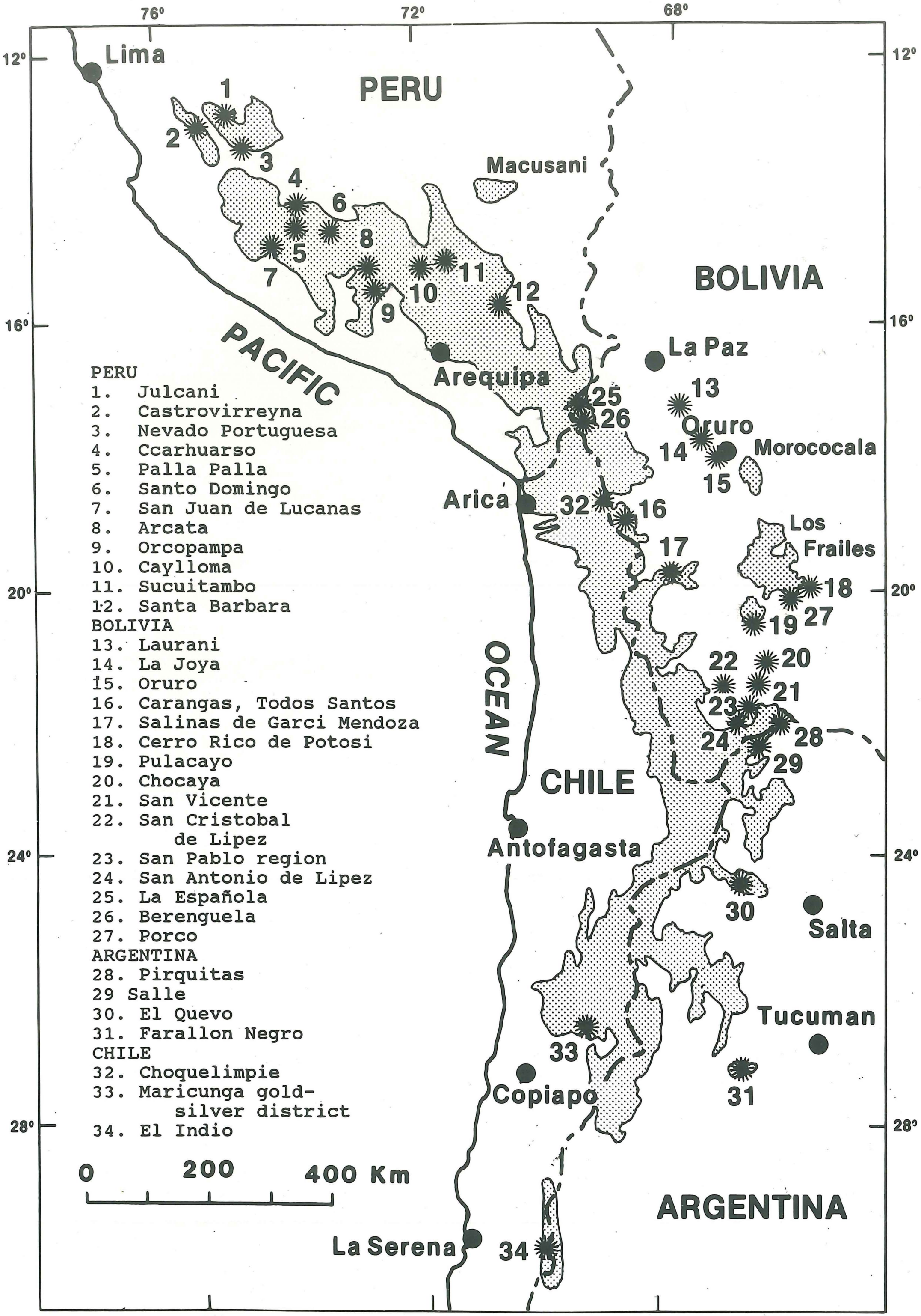

Figure 1.— *Epithermal precious-metal deposits associated with the Neogene and Quaternary volcanic complex (stippled) in the central Andes.*

Table 1.— Estimated grades and tonnages (production and reserves) of ores and gold and silver production of volcanic-hosted, precious-metal deposits of Neogene age in the central Andes. (t=metric tons; g/t= grams per metric ton)

District or deposit	ore (t)	Au (g/t)	Au (t)	Ag (g/t)	Ag (t)
PERU					
Julcani[1]	6,000,000	1.0	6	400	2,400
Arcata[1]	5,000,000	2.0	10	400	2,000
Caylloma[1]	9,000,000	1.5	13.5	400	3,600
Orcopampa[1]	6,000,000	3.0	18	400	2,400
Santa Barbara[2]	1,500,000	--	--	335	550
BOLIVIA					
Cerro Rico de Potosi[3]					
Production to 1989	60,000,000	--	--	500	30,000
Reserves (1989)	825,000,000	--	--	150-250	30,000
Pulacayo[4]	5,000,000	--	--	1,000	5,000
La Joya[5]					
Kori Kollo (oxide)	10,100,000	1.61	16.3	24.7	250
Kori Kollo (sulfide)	53,100,000	2.32	123.2	14.5	770
CHILE					
Choquelimpe[6]					
pre-1986	--	1.5	--	--	200
post-1986	6,700,000	2.23	15	87	583
Maricunga district					
La Coipa[7]					
Ladera-Farellón	52,100,000	1.58	82	60.4	3,145
Coipa Norte	9,150,000	0.19	1.8	171.7	1,571
Marte[8]	46,000,000	1.43	66	--	--
Lobo[8]	80,000,000	1.6	128	--	--
Refugio[8]	200,000,000	0.96	192	--	--
La Pepa[8]					
(high grade)	440,000	23.7	10.4	--	--
(low grade)	3,200,000	1.3	4.2	--	--
Esperanza[9]	4,300,000	0.14	0.6	320	1,376
El Indio[10]					
Bonanza ore	180,000	218	39	109	20
Plant-grade ore	7,400,000	9.1	67	91	673
Heap-leach ore	1,150,000	1.7	2	--	--

[1] Estimates by authors, based on available published and unpublished data about production and grade; Petersen et al., (1977) gave Julcani production for 1962-1976 and reserves as of 1976; Silberman et al., (1985) reported total production for Caylloma and Orcopampa to be 100 million and 50 million oz, respectively.

[2] Grades and reserves from Fletcher et al., (1989); past production estimated by authors.

[3] Murillo et al., (1968) estimated total production of silver to be 30,000 t since discovery by the Spanish in 1545; grade and tonnage of low-grade ores according to estimates by M. Bernstein cited by Suttill (1988); 30,000 t of recoverable silver from low-grade ore is based on Bernstein's estimate that silver in low-grade ores is equal to all silver produced to date (note the amount of silver in the 825 million tons of ore of grade 150-250 g/t is several times greater than the 30,000 t estimated).

[4] Pinto (in press).

[5] Columba and Cunningham (in press).

[6] Gröpper et al., (1991).

[7] Unpublished data, Compañía Minera Mantos de Oro (1990); Vila and Sillitoe (1991).

[8] Vila and Sillitoe (1991).

[9] Vila (1991)

[10] Jannas et al., (1990); Siddeley and Araneda (1986).

deposits such as La Coipa and Choquelimpie, Chile, are gold-silver deposits, whereas stockwork deposits such as Marte and Lobo, Chile, are gold deposits containing little or no silver (Table 1). Three deposits, La Coipa, Marte, and La Pepa began operation in 1988-89. A crushing and leaching plant at La Coipa that processed 1,000 metric tons per day (tpd) was expanded in late 1991 to process 15,000 tpd. An 8,000 - tpd crushing plant and heap-leaching facilities were in operation at Marte, and similar crushing and heap-leaching facilities were in operation at La Pepa. Marte closed in 1991.

DESCRIPTIONS OF DEPOSITS

The volcanic-hosted, epithermal precious-metal deposits in the central Andes include both adularia-sericite and acid-sulfate types (Heald et al., 1987), which together show features representative of at least five distinctive types. Adularia-sericite deposits include (typical deposits are shown in parens): (1) silver-rich polymetallic base-metal veins (Arcata, Caylloma, and Orcopampa, Perú; Pulacayo, Bolivia; El Soldado and Cachinal de la Sierra, Chile), (2) polymetallic tin-silver veins and stockworks (Cerro Rico de Potosí, Oruro, and Chocaya, Bolivia), and (3) gold-rich stockwork porphyry deposits (Marte, Lobo, and Casale Hill

(Aldebaran), Chile). Acid-sulfate-type deposits include: (1) silver- and gold-silver-rich polymetallic base-metal veins (Julcani, Perú; El Indio, Chile), and (2) low-grade vuggy silica and breccia, gold and gold-silver rich (La Coipa, Esperanza, El Guanaco, and Choquelimpie, Chile).

Adularia-sericite type deposits

Silver-rich polymetallic base-metal veins

Caylloma, Orcopampa, and Arcata districts, southern Perú (Fig. 1), are multi-vein deposits that are typical examples of polymetallic, silver-rich, base-metal deposits in which gold is sparse (silver/gold ratios generally are greater than 300:1). All three districts have had a large production of high-grade (probably averaging at least 15 oz/t silver) silver ores from quartz-carbonate veins containing a wide variety of silver, copper, lead, sulfides and sulfosalts, and sphalerite. The richest silver-gold ores, such as those in the Calera vein at Orcopampa, contain several hundred oz/t silver and up to several oz/t gold (oral commun., geological staff, Orcopampa, 1987) with total production and reserves as of 1989 being over 40,000,000 oz (1,244 t) silver and 400,000 oz (12.4 t) gold (Gibson et al., 1990). All three of these depo-sits were discovered during Colonial times and have been worked sporadically to the present. The largest production of silver is more than the 100,000,000 oz (3,110 t) silver reported by Silberman et al., (1985) for Caylloma. These authors also reported silver production at Orcopampa to be 50,000,000 oz (1,555 t). Production from the three districts in 1989 from ores averaging about 1/2 kg/t silver was as follows: Orcopampa—161 t silver and 1.2 t gold, Arcata—110 t silver and 0.33 t gold, and Caylloma—71 t silver and 0.26 t gold (Blanca Huaco, written commun. 1990).

All three districts are located in major eruptive centers that include volcanic domes, but the genetic relation between volcanism and mineralization is uncertain. The veins at Caylloma are near the intersection of two large calderas, both of which are younger than the mineralization. The veins at Orcopampa may be related to a caldera (Ericksen et al., 1987). In all three districts, the ores occur as fissure-filled veins along subparallel faults; the faults cut predominantly andesitic flows, breccias, and pyroclastic rocks at Arcata and Caylloma (Candiotti, 1988; Candiotti et al., 1990) and chiefly quartz latitic ash-flow tuffs and dacitic breccias and lavas at Orcopampa (Arenas, 1975). The subparallel mineralized faults at Caylloma, of which there are at least 25, are normal faults that formed between two intersecting regional faults (Candiotti, 1988). The four major subparallel vein systems at Orcopampa are mineralized faults (Arenas, 1975), whereas the four major vein systems at Arcata appear to be related to a graben (Candiotti, 1988; Fletcher et al., 1989). The age of mineralization at both Caylloma and Orcopampa is 17-16 Ma and that at Arcata is 5-4.5 Ma (Silberman et al., 1985; Candiotti, 1988).

According to company data (Cia. de Minas Buenaventura S.A.; Mauricio Hochschild y Cia. Ltda. S.A.), the major veins in the three districts are on the order of 500 to 3,000 m in length and have average widths ranging from about 50 cm to 2 m; locally, they attain widths of as much as 8 m. The vertical ranges of the precious-metal ores are 300-450 m. Above some ore zones, the metal values decrease rapidly to trace amounts associated with vein quartz and calcite, whereas downward they may give way to galena-sphalerite-chalcopyrite ores having less silver than the overlying precious-metal ores (Candiotti et al., 1990). The veins tend to be strongly banded and vuggy or cavernous, and many veins were repeatedly brecciated by fault movement during mineralization (Fornari and Vilca, 1979; Candiotti, 1988).

The veins crop out as relatively barren quartz and intensely altered wall rock. For example, exposures of the Marion vein, in the Arcata district, consist chiefly of barren quartz veins in a zone of intensely kaolinized andesite (locally the host volcanic rock consists almost entirely of dickite) that locally is several tens of meters wide. This barren zone extends downward to the top of high-grade silver ore, at a depth of as much as 250 m (Fig. 2; Candiotti et al., 1990).

The silver-rich polymetallic ores contain a variety of silver and base-metal sulfides and sulfosalts. The most abundant silver minerals are the ruby silvers, of which pyrargyrite is generally much more abundant than proustite, and silver-bearing tetrahedrite/tennantite. Tetrahedrite is by far the most abundant silver mineral at Orcopampa, whereas both tetrahedrite and ruby silver minerals are abundant at Arcata and

Caylloma (Arenas, 1975; Silberman et al., 1985). Gold, which occurs as native gold, electrum, and auriferous pyrite, tends to be most abundant in the upper parts of the veins, and a few such veins were famous early sources of bonanza gold ore. The San Cristobal vein at Caylloma, which is the longest and richest vein in the district, reportedly had significant gold values in the upper mine levels (Silberman et al., 1985). The Calera vein at Orcopampa, which was discovered in the late 1970's, contains 50 percent of its precious metals in a paragenetically late bonanza stage that includes native gold, miargyrite, pyrargyrite, several other silver sulfosalts, and precious and base metal tellurides in quartz gangue (Gibson et al., 1990).

Many silver-rich, volcanic-hosted, epithermal polymetallic base-metal veins occur in the volcanic terrane of the southernmost part of the Bolivian Altiplano (Ahlfeld and Schneider-Scherbina, 1964), a region referred to as Sur Lípez. Mining was extensive during Colonial times when significant amounts of silver were produced. Most of the veins were worked out at this time, but some mining in this region has continued sporadically to the present. Ahlfeld and Schneider-Scherbina (1964) described the principal mines of this region, which are in four centers, San Pablo, San Vicente, San Antonio de Lípez, and San Cristobal de Lípez (Fig. 1). Veins are associated chiefly with dacitic stocks and (or) domes in a region of widespread volcanic flows, breccia, and tuffs overlying continental sedimentary rocks of Tertiary age. Major veins are a few hundred meters to about 3 km in length and a few tens of centimeters to about 2 m wide. They are along faults and fracture systems and consist of fillings of vuggy quartz, commonly chalcedonic, and variable amounts of rhodochrosite, calcite, and barite. The most widespread and abundant metallic minerals are pyrite, galena, sphalerite, tetrahedrite/tennantite, and chalcopyrite. Argentiferous tetrahedrite/tennantite and pyrargyrite are the principal silver-bearing minerals; polybasite, stephanite, argentite, and argentiferous galena are present in some veins. Small amounts of cassiterite and stannite have been reported as occurring in veins of the eastern part of the region marginal to the Bolivian tin belt.

Other volcanic-hosted silver-rich, polymetallic base-metal deposits of Neogene age, shown in figure 1, include veins in the region of Carangas-Todos Santos and Salinas de Garci Mendóza which are similar to the veins in the Sur Lípez area (Ahlfeld and Schneider-Scherbina, 1964). The deposits are hosted by domes and volcanic rocks related to stratovolcanoes (Salinas de Garci Mendoza) and a caldera (Carangas-Todos Santos) (Ahlfeld and Schneider-Scherbina, 1964; Cunningham et al., 1991). A single vein at Pulacayo (Fig. 1), which is about 3 km long and mined to a depth of about 1,100 m below the surface, yielded an estimated 5,000 t of fine silver during mining that began in the latter part of the 19th century and ended in the 1950's. This vein, as well as other veins of the district, is related to a dacitic dome (Cunningham et al., 1991; Pinto, in press). Silver is still being recovered in this district from mine fill and waste dumps. The Santa Barbara deposit, southern Perú (Fig. 1), is unique

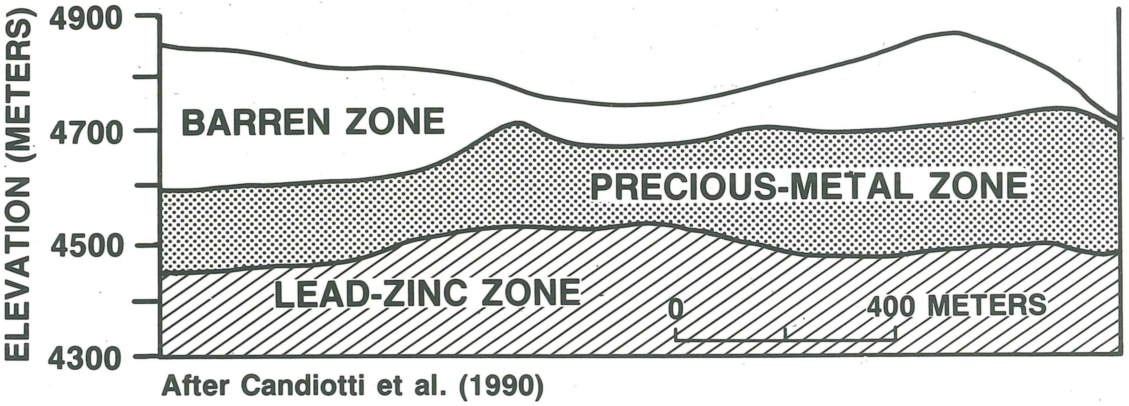

Figure 2.— Longitudinal section along the Marión vein, Arcata mining district, Perú. From Candiotti et al., (1990).

in that the ore occurs in a concentric breccia zone surrounding a tuff-filled diatreme (Fletcher et al., 1989) and is currently being worked for silver and base-metal ores. The deposit at Porco, Bolivia, (Fig. 1) is one of the oldest mines in Bolivia. It was reportedly being mined for silver before the Spanish discovery of Cerro Rico de Potosí (Departamento Nacional de Geología, República de Bolivia, 1965). The zinc, silver, lead ores at Porco are in curvilinear veins that cut dacitic tuff and are mostly locallized along the structural margin of a recently recognized, 5 km by 3 km, caldera. The ores are vertically zoned with galena and silver sulfosalts at the top and sphalerite and pyrite at depth (Aparicio, 1990). The Kori Kollo deposit in the La Joya district, Bolivia, (Table 1; Fig. 1), is the only operating, bulk-minable, open-pit gold deposit in Bolivia. The gold-silver-copper-lead-zinc ore is in NE-trending veins that cut 15 Ma dacitic domes (Redwood, 1987) and are zoned with a precious-metal zone overlying a base-metal zone (Columba and Cunningham, in press).

Polymetallic tin-silver deposits

Polymetallic tin-silver deposits occur only in the central and southern part of the Bolivian tin belt, a distinct metallogenic province that extends from southernmost Perú through the eastern Andean cordillera of Bolivia into northernmost Argentina. The major deposits are Oruro, Cerro Rico de Potosí, and Chocaya in Bolivia and Pirquitas in northernmost Argentina (Turneaure, 1971). The tin-silver deposits are characterized by complex mineralogy dominated by cassiterite and a wide variety of silver, copper, lead, zinc, bismuth, antimony, arsenic, iron, and tin sulfides and sulfosalts. They are distinctly different mineralogically from the tin and tin-tungsten deposits in the northern part of the tin belt, which have a relatively simple mineralogy dominated by cassiterite and (or) wolframite and quartz, pyrrhotite, and sphalerite (Ahlfeld and Schneider-Scherbina, 1964; Turneaure, 1971). The polymetallic tin-silver deposits are associated with intensely altered quartz latitic domes and subvolcanic porphyry intrusions (Sillitoe and Bonham, 1984; Pinto, 1988; Cunningham et al., 1991) of middle Miocene age (about 14 Ma) (Grant et al., 1979). In contrast, the tin and tin-tungsten deposits in the northern part of the tin belt are associated with granitic plutons of middle Triassic to earliest Jurassic (225-202 Ma) and late Oligocene to early Miocene (28-19 Ma) ages (McBride et al., 1983).

The most famous deposit of this type is Cerro Rico de Potosí, which is the world's largest silver deposit, having produced an estimated 30,000 t of fine silver (Murillo et al., 1968) from ores estimated to average about 1/2 kg/t silver (Suttill, 1988). Veins in the upper part of the Cerro Rico hill that were exploited during the 16th century commonly contained 30-40 percent silver (Suttill, 1988). On the basis of a recently completed study of Cerro Rico, Bernstein & Thompson Ltda. estimated that remaining low-grade tin-silver ore (0.3-0.4 percent tin and 150-250 g/t silver) in Cerro Rico itself and in waste dumps from former mining operations contains as much silver as already has been extracted (Suttill, 1988). Cerro Rico consists of many narrow, less than 1 m-wide, veins in and near an intensely altered dacitic porphyry dome that flared upward and outward over a sequence of explosion breccias and tuffs that were erupted from the vent (Cunningham et al., 1991). Basement rock consists of Ordovician shales. Mineralization at Cerro Rico and other tin-silver deposits in the Bolivian tin belt is characterized by deposition of high temperature cassiterite in the center of the system with peripheral, lower temperature, lead-zinc-silver minerals. The lead-zinc-silver mineralization was then superimposed on the tin minerals as the hydrothermal system waned and cooled. Oxidized and enriched ores, which extend to depths of as much as 300 m, contain abundant silver minerals chlorargyrite, acanthite, and native silver (Murillo et al., 1968). Such enriched ores probably were the source of much of the silver during the early days of mining.

The other major tin-silver deposits--Oruro and Chocaya in Bolivia and Pirquitas in northern Argentina--are similar to Cerro Rico in that the principal ores in the central zone contain admixed tin and silver minerals (Turneaure, 1971). The veins at Oruro occur in a complex of coeval dacitic domes and lavas containing hydrothermal and (or) intrusive breccia bodies (Chase, 1948). In contrast to Cerro Rico, silver ores at Oruro show a greater vertical range than the tin ores; below a depth of 350 m, silver is the principal metal whereas typical tin-silver ore occurs above this level (Turneaure, 1960). The most abundant silver minerals at Oruro are freibergite, which contains as much as 14 percent silver, and andorite (Ahlfeld and Schneider-Scherbina, 1964). The tin-silver veins at Pirquitas are reported to be related to dacitic stocks in clastic sedimentary rocks of Ordovician age (Angelelli et al., 1970). Pinto (1988) reported the polymetallic tin-silver veins at Chocaya to be associated with an intensely altered dacite dome within a sequence of dacitic pyroclastic rocks and lavas cut by a few small dikes. Silver and gold were most abundant in near-surface stockwork ores at Chocaya, silver associated with lead and zinc was predominant at intermediate depth, and tin, lead, and zinc predominated in the deepest mine levels. Pinto (1988) reported the presence of large amounts of low-grade stockwork and disseminated ores at Chocaya, perhaps several hundred million metric tons, having grades on the order of 100 g/t silver, 0.5 g/t gold, 4 percent zinc, and 2 percent lead.

Gold-rich stockwork porphyry deposits

Gold-rich stockwork porphyry systems have recently been recognized in Chile (Vila and Sillitoe, 1991; Rytuba and Cox, 1991) and all occur in the Maricunga district (Fig. 3). The deposits are localized in intrusions in andesitic-dacitic stratovolcanoes. Vila and Sillitoe (1991) believe that gold-copper mineralization was initially introduced with potassium-silicate alteration and later overprinted with quartz-sericite alteration. Marte and Lobo are excellent examples of this type of deposit. At Marte the ore zone can be clearly seen in the center of an andesitic stratovolcano (Vila et al., 1991). At Lobo the orebody has been drilled out and cross sections are in Vila and Sillitoe (1991). At Casale Hill part of the Aldebaran deposit located at the southern end of the Maricunga District, and at the caldera-hosted La Pepa deposit, exploration activities have exposed the upper part of the stockwork porphyry and its transition to overlying acid-sulfate systems. Also at Aldebaran, the porphyry-epithermal transition is complete to the paleosurface where the remains of an epithermal system is exposed at Cathedral Peak (Vila and Sillitoe, 1991).

Acid-sulfate type deposits

Silver- and gold-rich polymetallic base-metal veins

Acid sulfate precious-metal deposits all over the world contain certain features in common as noted by Heald et al., (1987) and the two groups delineated here may form a continium. Acid-sulfate-type silver-rich base-metal veins are present in several mining districts in southern Perú (Vidal and Cedillo, 1988), the best known being those in the multi-vein Julcani district (Fig. 1). The deposits are characterized by the presence of enargite and magmatic-hydrothermal alunite. The Julcani veins contain silver-rich copper-lead-zinc-bismuth ores and local concentrations of gold and tungsten. The average silver/gold ratio of most of the Julcani ores is greater than 500/1. The district has been known and worked sporadically since Spanish Colonial times, when it was first famous for gold production. Total production of metals from the Julcani district is not known, but, during the latter half of the present century, Julcani has been one of the major silver producers in Perú. Production during this period has been on the order of 50,000,000 oz (1,555 t) of fine silver (Alberto Benavides, oral commun., 1990). In addition to precious metals, Julcani has produced significant amounts of copper, lead, bismuth, and tungsten.

The Julcani deposit consists of many fissure-filling veins in a complex of many interpenetrating dacitic to rhyolitic domes in a sequence of rhyodacitic pyroclastics that were erupted from a diatreme in the central part of the district (Noble and Silberman, 1984). Radiometric ages show that the host rocks were emplaced between 10.3 and 9.7 Ma and that mineralization took place between 9.6 and 9.3 Ma (Noble and Silberman, 1984). Vein mineralogy is complex, consisting of a variety of base-metal sulfides and sulfosalts, bismuthinite, wolframite, native gold, and antimony sulfides. District-wide metal and mineral zoning is particularly prominent in the southeastern part of the district where gold- and tungsten-rich ores in veins from the central part of the district grade towards the southeast first to ores containing abundant enargite-pyrite-tetrahedrite-tennantite, then to ores containing abundant bismuthinite together with silver and bismuth sulfosalts, next to ores having abundant galena, and finally, in the outermost veins, to abundant lead sulfosalts, realgar, and orpiment (Goodell and Petersen, 1974; Petersen et al., 1977). Recent studies have documented the acid-sulfate nature of the deposit and that have demonstrated the pre-ore vuggy silica, main-stage ore and even the late-stage ore are distinctly magmatic in origin (Deen, 1990).

Figure 3.— Location of ore deposits in the Maricunga district, northern Chile. Mine symbols indicate location of deposits; faults are shown with teeth on upthrown side.

Other major acid-sulfate-type silver-rich base-metal veins occur at the Caudalosa mine in the Castrovirreyna district, the San Juan de Lucanas deposit, and the Sucuitambo deposit in southern Perú (Vidal and Cedillo, 1988). All these deposits have produced significant amounts of high-grade silver ores, and in addition, the Sucuitambo deposit has yielded significant amounts of gold. The Laurani deposit, Bolivia (Fig. 1), contains silver-gold-rich veins, some of which contain abundant enargite.

The gold-silver-copper and gold-silver-quartz veins at El Indio, northern Chile (Fig. 1), represent a subtype of acid-sulfate-type polymetallic precious-metal veins characterized by a high gold/silver ratio, a relative abundance of gold telluride minerals, and a preponderance of copper minerals over lead and zinc minerals. El Indio was discovered in the late 1970's and has yielded (through 1989) about 2 million oz (62.2 t) gold, 6 million oz (186.6 t) silver, and 100,000 t copper (Jannas et al., 1990). Two distinct types of ore are present at El Indio (Jannas et al., 1990): (1) massive enargite-pyrite ores containing 6-10 percent copper, 120 g/t silver, and a few grams of gold per metric ton and (2) gold-quartz ores of two average grades: (a) bonanza-type, direct-shipping ores averaging more than 100 g/t gold and which have common assay grades of >1,000 g/t gold, and (b) plant-grade ores containing between 18 and 25 g/t gold, <2.5 percent copper, and about 40 g/t silver.

The gold-quartz veins consist of 70-90 percent silica, chiefly as quartz and chalcedony, and are distinctly banded due to multiple generations of silica deposition (Jannas and Araneda, 1985). Gold principally occurs in the native form and as the telluride calaverite. Tennantite, chalcopyrite, and pyrite are common in the gold-quartz ores, and galena, sphalerite, tellurides, huebnerite, bornite, and various sulfosalts are present in lesser amounts (Jannas et al., 1990).

Low-grade vuggy silica and breccia

Many of these deposits in the Neogene-Quaternary volcanic belt of the Andes are hosted in, or related to, volcanic domes (Cunningham et al., 1991). In these deposits, "vuggy silica" is a textural term used to describe a host rock that has been intensly leached and only porous silica remains. Vertical zones of vuggy silica are commonly bounded progressively outward on either side by bands of alunite (called magmatic-hydrothermal alunite to distinguish it from other forms of alunite), kaolinite, and a propylitic mineral assemblage. This textural assemblage results from the condensation of an SO_2-rich vapor plume and subsequent reaction of the extremely acidic solution with the host rock (Rye et al., 1992).

The silver-gold deposits at Esperanza, in the Maricunga district, northern Chile, are associated with a 23 Ma dacite volcanic dome complex (Vila, and Sillitoe, 1991; Vila, 1991). The silver ore, with subordinate gold, is hosted both in vuggy silica and hydrothermal breccias and also in intensely altered Triassic sedimentary rocks.

The La Coipa area in the Maricunga district includes at least three deposits, La Coipa, Can Can, and Coipa Norte, which together with the nearby Codocedo native sulfur-silica deposit, appear to be related to a caldera and associated dacite domes. Both the La Coipa deposit and the Can Can deposit are acid sulfate deposits formed both in Triassic shales and overlying Miocene tuffs and flows (Oviedo et al., 1991; Cecioni and Dick, 1992). At La Coipa, the Ladera and Farellón orebobies have the highest ore grades spatially associated with faults and fractures as well as some lithologic controls; however, Ladera and western Coipa Norte are mushroon shaped and have high silver contents whereas Farellón and eastern Coipa Norte are steeply inclined, semitabular and are rich in gold (Oviedo et al., 1991). As shown by Oviedo et al., (1991) and at the mine, the Ladera orebody is hosted mostly in vuggy silica developed in the tuffs, whereas the Farellón oreboby is mostly in argillically and advanced-argillically altered sedimentary rocks. The Coipa Norte deposit was formed near the paleoground surface as evidenced by the presence of siliceous sinter and hydrothermal explosion breccias. Ore minerals at La Coipa include pyrite-chalcopyrite-tetrahedrite-tennantite-enargite-galena-sphalerite-metallic gold at depth, metallic gold-cinnabar-realgar-arsenopyrite-pyrite at intermediate levels, and silver sulfosalts-cinnabar-realgar-arsenopyrite-pyrite-metallic gold in the upper parts (Oviedo et al., 1991). The orebody at Can Can is funnel-shaped, widens upward, and transgresses Triassic sedimentary rocks and overlying Tertiary breccias and tuffs (Cecioni and Dick, 1992). At the base of the volcanic rocks is a mineralized, subhorizontal breccia layer that is both cut by and overlain by flow-banded dacite. This breccia is interpreted by us to be an explosion breccia and the flow-banded dacite to be the base of a volcanic dome; the existence of 2-cm wide, vertical, veinlets of coarsely crystalline alunite together with local tuff-dikes that cut the flow-banded dacite support this interpretation. The ore minerals are native gold and cerargyrite, and the ore grade and the gold/silver ratio are high in the shales but decrease toward the surface (Cecioni and Dick, 1992).

In addition to the deposits in the Maricunga area, low-grade precious-metal deposits were discovered during the 1980's at Tambo, near El Indio, as well as in the old mining district of Choquelimpie, northernmost Chile (Fig. 1). The Choquelimpie gold-silver deposit is associated with dacite domes in the center of a deeply eroded, andesite stratovolcano of Miocene age (Gröpper et al., 1991). Most ore has been mined from hydrothermal breccias that contain breccia fragments of vuggy silica--attesting to the presence of acid-sulfate alteration prior to the hydrothermal eruption--and are cut by base and precious-metal veins. Precious-metal mineralization was paragenetically late and resulted in an ore assemblage that includes native gold and silver, electrum, argentite, aramayoite, and schapbachite (Gröpper et al., 1991). Bulk mining and heap-leaching of the low-grade ores at Choquelimpie began on a small scale in the early 1980's, and the operations were expanded during the late 1980's. In 1989-90, production at Choquelimpie was 5,500 tpd of ore averaging about 2 g/t gold and 60 g/t silver; the mine closed in 1991. The Tambo deposit, which started production in the early 1980's, consists of mineralized breccia pipes and veins containing barite-gold ore that averages between 7 and 22 g/t gold and up to 54 g/t silver.

The deposits show considerable variation of gold/silver ratios (Table 1). For example, some of the Maricunga deposits (Marte, Lobo) contain gold as the only recoverable metal (silver occurs in traces only), whereas others are gold-silver deposits (La Coipa, Coipa Norte, Can Can). The Esperanza deposit is primarily a silver deposit; the small amounts of gold present are restricted to vuggy silica zones in the southern part of the district. Pyrite is the dominant sulfide mineral in the primary ores at the Lobo deposit where other sulfide minerals identified as occurring in trace amounts at Lobo are chalcopyrite, bornite, molybdenite, and enargite (Tomas Vila, oral commun., 1990). It is probable that auriferous pyrite is the principal primary gold-bearing mineral in this deposit as well as in the other Maricunga deposits.

The Choquelimpie and La Joya deposits contain both gold and silver and are characterized by the presence of a variety of base-metal sulfides and sulfosalts. Choquelimpie consists of veins and mineralized hydrothermal breccias in dacite domes in the core of a deeply eroded stratovolcano. La Joya consists of gold- and silver-bearing base-metal veins and stockworks in an intensely altered (silicified, kaolinized, and sericitized) dome of Miocene age (15.7 Ma). Gold occurs chiefly in auriferous pyrite, and the principal silver mineral is tetrahedrite.

CONCLUSIONS

On the basis of primary metallic mineral suites, structural control of mineralization, and nature of alteration, five types of volcanic-hosted, epithermal precious-metal deposits in the central Andes are defined. These include three types of adularia-sericite deposits: (1) silver-rich polymetallic base-metal veins, (2) polymetallic tin-silver deposits of the Bolivian tin belt, and (3) stockwork porphyry deposits; and two types of acid-sulfate deposits: (1) silver- and gold-silver polymetallic base-metal veins and (2) low-grade vuggy silica and breccia gold-silver deposits. Most of the polymetallic vein deposits have high silver/gold ratios, generally greater than 300:1, and are characterized by a wide variety of silver and base-metal sulfides and sulfosalts. The principal gold minerals in these types of deposits are native gold, electrum, and auriferous pyrite. Bismuthinite and bismuth sulfosalts are abundant in some deposits. Native gold and calaverite are the principal gold minerals at El Indio, and other tellurium- as well as selenium-bearing gold minerals are present (Jannas et al., 1990). Tellurium- and selenium-bearing minerals are known to be present in trace to minor amounts in only a few of the other precious-metal deposits in the central Andean region.

During the 1980's, most of the silver produced by mines in the central Andean region came from polymetallic base- metal ores having grades on the order of 450 g/t silver and less than 2 g/t gold. Bonanza gold ores mined at El Indio, Chile, during the 1980's had an average grade of about 250 g/t gold, whereas direct-shipping bonanza silver-gold ores mined at Orcopampa, Perú, produced during the 1980's contained several hundred ounces of silver per metric ton and several grams to several tens of grams of gold per metric ton. Typical low-grade, stockwork porphyry gold and gold-silver ores, such as those of the Maricunga district, contain 1.5-2 g/t gold and a few to more than 100 g/t silver.

Most of the deposits are spatially and temporally related to eruptive centers--stratovolcanoes, calderas, volcanic domes, diatremes--within the 300,000 km^2 Neogene and Quaternary volcanic complex in the central Andes. Many deposits are associated with major hydrothermal alteration zones that are easily recognized in digitally enhanced LANDSAT Thematic Mapper images. At least a dozen new deposits were discovered in this region during the 1980's, and we believe that many other deposits remain to be discovered.

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