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NEOGENE-QUATERNARY VOLCANISM AND MINERALIZATION IN THE CENTRAL ANDES

by

George E. Ericksen

U.S. Geological Survey, Reston, Va.;

V. Raul Eyzaguirre, Lima, Peru;

Fernando Urquidi B., American Embassy, La Paz, Bolivia; and

Raul Salas O., Servicio Nacional de Geologia y Mineria, Santiago, Chile

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ABSTRACT

Eruptive centers, which include calderas, stratovolcanos, and flow-dome complexes in the Neogene-Quaternary volcanic complex of the central Andean region of northwestern Argentina, western Boliva, northern Chile, and southern Peru, are potential targets for hydrothermal mineral deposits. This volcanic complex, consisting chiefly of rhyolitic ash-flow tuffs and andesitic lavas, extends over an area of about 300,000 km^2 within a 1,000,000 km^2 area that is one of the world's great mineral provinces. Because many deposits of Cu, Pb, Zn, Sn, W, Sb, Bi, Ag, and Au in this area are of pre-Pliocene age, it had been believed that most of the Neogene-Quaternary volcanic rocks represented post-mineralization cover. However, recent studies have shown that metalliferous deposits as young as Pleistocene are associated with the eruptive centers. Mineral deposits in these centers were emplaced during the waning phases of volcanic activity, and available radiometric ages show they were emplaced chiefly within an interval of not more than 1 m.y. after the major eruptive phase of the center.

Polymetallic Sn deposits, epithermal Ag-Au deposits, and polymetallic Ag-base-metal deposits, some of which have been exploited since the 16th century, are by far the most economically important types of deposits associated with the Neogene-Quaternary volcanic rocks in the central Andes. Among these are the polymetallic Sn and Sn-Ag deposits in southern Bolivia, which are associated with porphyry stocks and vent breccias of former stratovolcanos or dome complexes, and Ag-Au and base-metal veins associated with dome complexes, calderas, and fossil thermal-spring systems. Other types of deposits are: (1) porphyry-type Cu, Ag-Cu, and Au-Cu deposits associated with porphyry stocks in deeply eroded stratovolcanos; (2) native S, Ag- and Sn-bearing veins, covellite impregnations, and presumed magnetite-hematite flows in the upper parts of stratovolcanos; and (3) manganese oxide, Sb, wood tin, and supergene uranium deposits associated with thermal-spring systems, some of which are still actively depositing metals. In addition, volcanic rocks, chiefly the rhyolitic ash-flow tuffs, and associated thermal springs contain abundant water-soluble salts, and are the chief sources of the widespread saline deposits of this region, which include world-class resources of Li and B.

Contents

INTRODUCTION

This report has been compiled as a preliminary phase of a proposed investigation of the relationship of mineral deposits and Neogene-Quaternary volcanism in the central Andean region of southern Peru, northern Chile, western Bolivia, and northwestern Argentina. The information presented has been abstracted from many published reports, chiefly of the last 10 years, and from unpublished information of the authors of this report. The volcanic rocks under consideration include rhyolite ash-flow tuffs or ignimbrites that have originated at many caldera centers and andesitic lavas from hundreds of stratovolcanos. These late Tertiary and Quaternary rocks cover a 300,000 km^2 area in the western Andean Highlands (fig. 1). They obscure about a third of the central Andean region, one of the most heavily mineralized areas on earth, where there are many metalliferous deposits of hydrothermal origin ranging in age from Triassic to Miocene. These deposits contain about a third of the world's resources of copper, chiefly in some 20-30 known porphyry copper deposits, and world-class resources of lead, zinc, silver, gold, antimony, bismuth, tin, and tungsten. Obviously, many deposits remain to be found beneath the late Tertiary-Quaternary volcanic cover.

Investigations during the past 10-15 years have shown that the Neogene-Quaternary volcanic rocks are not largely post-mineralization, as had been previously thought, but that many eruptive centers in them have metalliferous mineral deposits. We believe that metalliferous deposits are far more numerous and widespread in eruptive centers in the central Andes than is now known, and that they can be found by geophysical, geochemical, and geologic investigations.

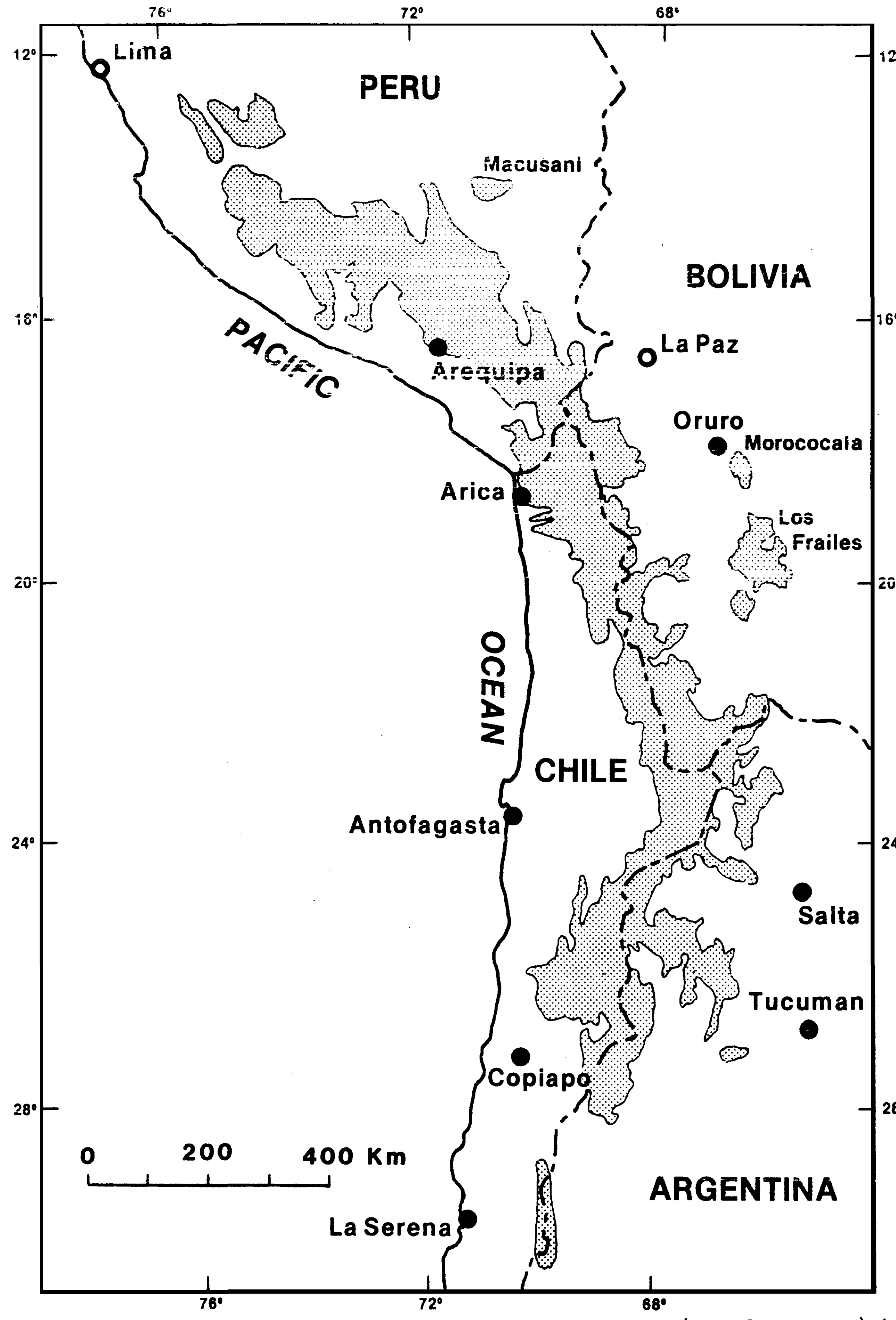

Figure 1.--Distribution of Neogene-Quaternary volcanic rocks (stipple pattern) in the central Andes. From Gardeweg and Ramirez (1984 and the Instituto de Geologia y Mineria del Peru (1975).

Although many papers about the young volcanic rocks of the Central Andes have been published since the early 1970s, relatively few are concerned with the mineral deposits in them. One of the milestone papers is that of Sillitoe (1973) showing the relation of porphyry copper deposits to stratovolcanos, which is largely based on Sillitoe's work in Chile and Argentina. Frances and others (1983) discussed the relationship between mineralization and silicic volcanism in the Central Andes. Sillitoe and Bonham (1984) compiled information about the relation of mineral deposits and volcanic landforms worldwide, which includes several examples from the central Andes. Noble and others (in press) discuss silver and gold deposits associated with calderas and stratovolcanos in southern Peru. Several reports (Sillitoe and others, 1975; Angus and others, 1977; Francis and others, 1981; Grant and others, 1977; Grant and others, 1980) discuss the relationship of polymetallic tin deposits in southern Bolivia to Miocene volcanism. Reports describing metalliferous deposits in specific eruptive centers include those of Brodtkorb and Coira (1986), Caelles and others (1971), Chase (1948), Clark (1970), Davila (1981), McKee and others (1975), Noble and McKee (1982), Sillitoe (1975), Noble and Silberman (1984), Petersen and others (1977), and Peterson and others (1983).

Geochemical studies of ash-flow tuffs offer clues to the nature and history of silicic magmas involved in caldera-type eruptions, which may provide clues to the existence of buried mineral deposits in intracaldera areas. For example, unusual tin-rich two-mica tuffs at Macusani, Peru (Noble and others, 1984), and in the Morococala volcanic field, southern Bolivia (Ericksen and others, 1985), are believed to be the extrusive equivalents of Sn-Li pegmatites or Sn-granites. We believe that subvolcanic intrusives in the eruptive centers of these tuffs are favorable exploration targets for Sn deposits.

VOLCANIC ROCKS

CHARACTER AND DISTRIBUTION OF ERUPTIVE CENTERS

The Neogene-Quaternary eruptive centers, which are the loci of most of the known mineral deposits associated with the young volcanic rocks of the central Andes include: 1) composite stratovolcanos; 2) calderas; 3) dome complexes; and 4) subvolcanic intrusions, breccia pipes, and hydrothermal alteration zones not related to known volcanic landforms. Several hundred stratovolcanos are present in the region. They range from conical peaks showing little or no erosion to deeply eroded complexes having only remnants of the original cone. The volcanic cones are the most prominent landforms of the region, generally rising to altitudes of 5,000-6,000 m and having summits that are 1,000 to 2,000 m above the surrounding terrain. Several volcanic cones are more than 6,000 m high, and the highest, Ojos del Salado, is 6,800 m.

Widespread ash-flow tuffs, which many specialists in Andean geology formerly believed to be related to fissure-type eruptions, are now recognized as having resulted chiefly from explosive eruptions from many calderas (Baker, 1981; Gardeweg and Ramerez, 1984; Kussmaul and others, 1977). Calderas were first recognized in the central Andes in 1972 (Noble and others, 1974). During the following decade, a total of more than 30 known and inferred[1/] calderas were recognized (fig. 2). Many of these calderas have resurgent domes clearly outlined by ring-fracture zones. Others are more obscure because of superimposed stratovolcanos and flow-dome complexes, and still others are broad domal ash-flow tuff fields without an obvious collapse structure, which Baker (1981) called ignimbrite shields.

1/ About a fourth of the calderas shown in figure 2 are inferred calderas, which include calderas identified in LANDSAT images but not visited, and the ignimbrite shields of Baker (1981).

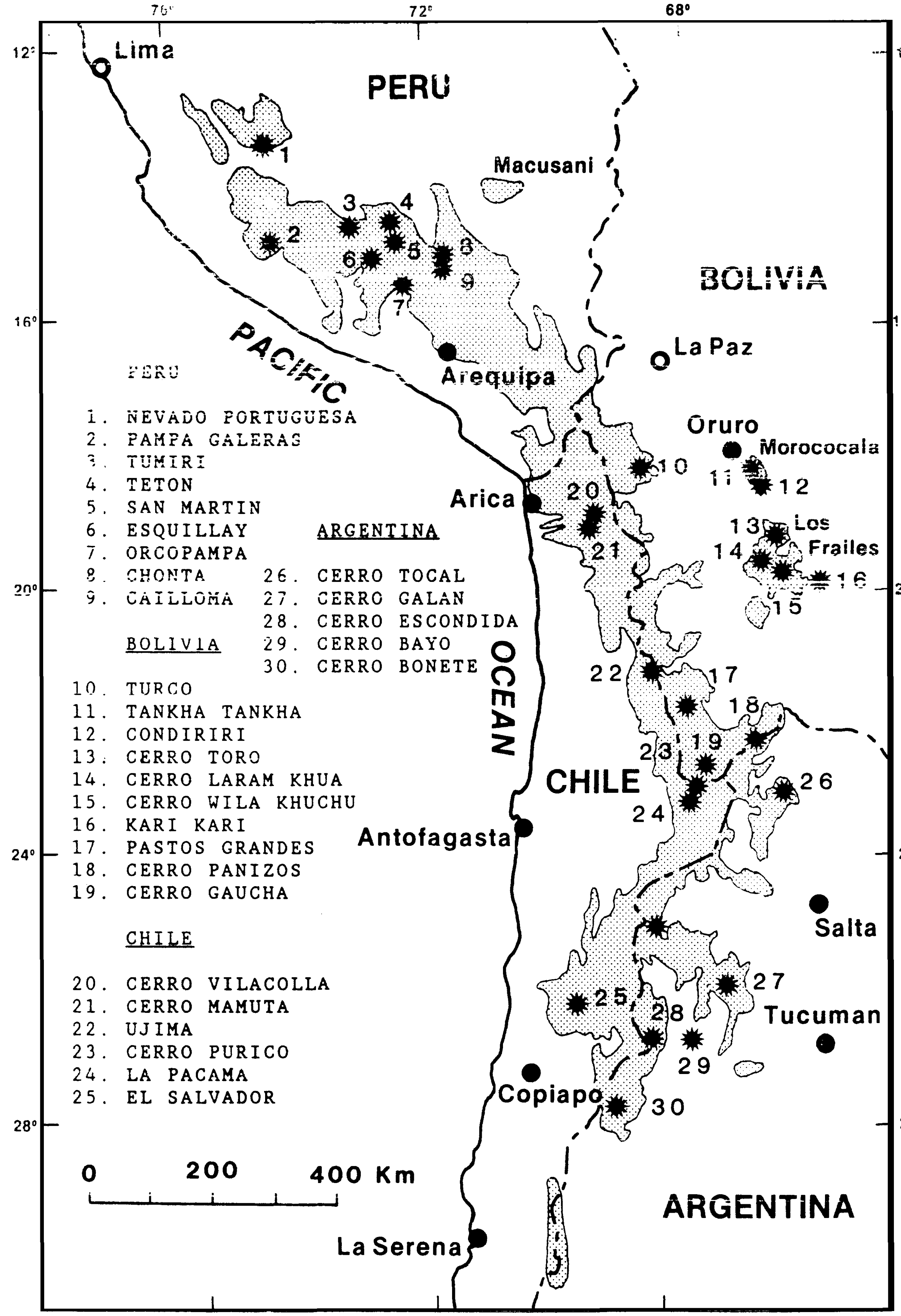

Figure 2.--Known and inferred calderas (numbered symbols) in the central Andes. Locations of calderas from Baker (1981), Francis and others (1983), Noble and others (in press), Ericksen and others (unpublished data, 1986).

Dome complexes have been recognized in and near several eruptive centers where they may or may not be genetically related to metallic mineralization. Perhaps the best examples of domes in a mining district are those at Julcani, Peru (fig. 5), where some 30 interpenetrating domes have been recognized (Noble and Silberman, 1984). Metallic mineralization took place during a late phase of dome emplacement. Domes also are found along the northern edge of the Arcata mining district, southern Peru (Noble and others, in press). The Sn-Ag deposits at Oruro, Boliva, are associated with a dome complex (Chase, 1948; Sillitoe and Bonham, 1984).

Several Neogene-Quaternary eruptive centers are characterized by subvolcanic intrusions and hydrothermal alteration zones. These include subvolcanic intrusions and hydrothermal breccias that either did not reach the surface or, if they did, they formed small volcanic cones or domes that were subsequently destroyed by erosion. The polymetallic tin deposits of southern Boliva are associated with subvolcanic intrusions of this type. Francis and others (1983) proposed that many of these tin deposits are related to former dome complexes. Other deposits were formed in a near-surface geothermal system not associated with a recognized volcanic landform.

AGES

The volcanic rocks and associated mineral deposits considered in this report range in age from earliest Miocene (23 Ma) to Holocene (<10,000 Ma). Stratovolcanos and calderas were active throughout most of this time, but rhyolitic ash-flow tuff eruptions from calderas were dominant during the Miocene and early Pliocene, whereas andesitic lavas and pyroclastic eruptions from stratovolcano centers were dominant after early Pliocene (Gardeweg and Ramirez, 1984). The youngest known ash-flow tuff sheet in the central Andes has been dated at 0.77 m.y. (Baker and Francis, 1978). Many of the stratovolcanos have fumarolic native sulfur deposits of probable late Pleistocene and Holocene age. Several of the stratovolcanos have had historic eruptions (Casertano, 1963), and some volcanos now show fumarolic activity.

In general, the level of erosion of the stratovolcanos is indicative of their relative ages. Gardeweg and Ramirez (1984) suggested that the most deeply eroded volcanos, which are those not having a recognizable cone, are chiefly of Miocene age, whereas progressively less-eroded cones are Pliocene and Pleistocene in age. Surprisingly, only a few of the volcanos show evidence of intense glaciation, indicating that an arid climate persisted in this region during the Pleistocene.

Mineralization generally occurred less than a million years after the major eruptive phase of a given volcanic center (Noble and others, in press; Francis and others, 1983). In most cases, it accompanied late phase intrusive activity characterized by subvolcanic porphyry intrusions, hydrothermal breccias, fumarolic activity, and thermal-spring systems.

MAJOR AND TRACE ELEMENT CHEMISTRY

The volcanic rocks of the central Andes are predominantly calc-alkaline. The ash-flow tuffs consist chiefly of quartz latites and rhyodacites, but range from dacites to high-silica rhyolites, whereas the lavas and other ejecta from stratovolcanos are chiefly andesites and dacites, but locally range from basalts to rhyolites (Baker and Francis, 1978; Gardeweg and Ramirez, 1984; Lawsen, 1982, Thorp and Francis, 1979). Some of the stratovolcanos in southern Bolivia and northwestern Argentina are enriched in K, and have been classified as shoshonites (Deruelle, 1978). For convenience of discussion in this presentation, ash-flow tuffs are referred to as rhyolites and lavas as andesites. Also, rhyolitic pyroclastics--ash flows, ash falls, and ignimbrites--are lumped together as ash-flow tuffs.

Our studies of ash-flow tuffs in the Bolivian tin belt, which extends from southern Peru to northern Argentina, show them to differ from tuffs elsewhere in the central Andes in being highly peraluminous ($Al_2O_3/Na_2O+K_2O+CaO>1$) and being rich in Sn, Li, and other trace elements such as Rb, Cs, Be, B, and U, relative to other ash-flow tuffs of the region. Peraluminous two-mica tuffs in the Macusani volcanic field, southern Peru (fig. 1), which have been dated at 4.2 Ma, contain 30-60 ppm Sn and as much as 260-300 ppm Li (Noble and others, 1984). Similar, late Miocene (8.5-6.4 Ma; Koeppen and others, in press) two-mica tuffs in the Morococala volcanic field, southern Bolivia (fig. 1), are anomalously rich in Sn and Li, some containing more than 25 ppm Sn and 400 ppm Li. A younger cordierite-bearing tuff in the southern part of the Morococala field is similarly enriched in Sn and Li. Other ash-flow tuffs in the Morococala field, from a still younger eruptive center to the north and similar tuffs in the Los Frailes field to the south also are peraluminous, though less so than the two-mica and cordierite-bearing tuffs, and have slightly elevated values for Sn (as much as 7 ppm) and Li (as much as 100 ppm), relative to the normal calc-alkaline tuffs (2 ppm Sn) elsewhere in the central Andes.

We believe that the above ash-flow tuffs reflect the unique composition of magmas in the Bolivian tin belt, from which the tin deposits were derived. The Andean tin deposits are confined to this belt, and with few exceptions, tin is absent in mineral deposits elsewhere in the central Andes. Furthermore, known tin mineralization took place over a period of nearly 200 m.y., from late Triassic to Miocene, and the restriction of tin mineralization to a relatively narrow belt (at no place is it more than 150 km wide) over a long span of time indicates a tin-enriched source of the magmas, probably in the lower crust, or perhaps the upper mantle. Noble and others (1984) pointed out that the Macusani tuff is similar in composition to S-type granites, which would imply a lower crustal source.

DEFORMATION

The Neogene-Quaternary volcanic rocks of the central Andes show widespread block faulting and tilting associated with Andean uplift, and some of the Miocene rocks have locally been folded (Noble and others, 1974). Some of the many closed basins within the volcanic terrain of this region are fault basins (Stoertz and Ericksen, 1974). Extensive ash-flow tuff sheets of Pliocene age along the western Andean front in Chile have been tilted westward as much as 5° from their original near-horizontal position.

Compressional deformation of the volcanic rocks is most evident in southern Peru where open, upright folds are present in volcanic rocks of Miocene age. The best documented history of Miocene deformation in this region is that of McKee and Noble (1982) for the Julcani-Huachacolpa-Castrovirreyna area (fig. 5). The volcanic rocks in this region were deformed into a series of folds during a pulse of compressional deformation beginning during the early Miocene interval of 19.5 and 17 m.y. and ending in middle Miocene (12.5-12 m.y.). Younger volcanic rocks in this area are undeformed, but those in the nearby area of Ayacucho were deformed during the intervals of 11.5-9.5 m.y. and 7-5.5 m.y.

MINERAL DEPOSITS

The mineral deposits genetically related to Neogene-Quaternary volcanism include the following types (table 1): 1) Ag-Au veins; 2) polymetallic Ag-base-metal veins; 3) polymetallic Sn veins; 4) porphyry-type Cu, Ag-Cu, and Sn deposits; 5) manganese-oxide deposits; 6) magnetite-hematite flows; 7) native S, wood-tin, and covellite deposits; and 8) uranium deposits. In addition, the volcanic rocks and associated thermal springs have been the sources of most of the saline constituents of the widespread salars and saline lakes of the central Andes. These salars contain major resources of lithium and boron. Thermal springs in the volcanic terrain of northwestern Argentina are actively depositing the borate mineral ulexite along with manganiferous travertine (Sillitoe, 1975). We have observed a thermal spring in Bolivia that is actively depositing stibnite, and another in northern Chile that is depositing pyrite or marcasite.

Table 1.--Mineral deposits associated with Neogene-Quaternary eruptive centers in the central Andes

Deposit	Type	Age of mineralization	Volcanic enviornment	Sources of information
			STRATOVOLCANOS	
1. Ccarhuaraso (Peru)	Au-Ag veins	1.2 Ma	Dacitic lavas in eroded volcano	Noble and others (in press)
2. Choquelimpie (Chile)	Porphyry Ag-Cu	Pliocene (?)	Brecciated porphyry stock in roots of deeply eroded andesitic stratovolcano	Salas and others (1966) (1)
3. Aucanquilcha (Chile)	Fumarolic covellite and native sulfur	Pleistocene-Holocene	Andesite breccia in vent zone at top of strato-volcano	(1)
4. El Laco (Chile)	Magnetite-hematite flows	Pleistocene	Magnetite-hematite lavas at 5 localities on flanks of andesitic stratovolcano	Ruiz and others (1965); (1)
5. Salle (Argentina)	Sb-Ag-Au-Sn impregnations	8.9-8.5 Ma	Hydrothermal breccia in eroded andesitic stratovolcano	Brodtkorb and Coira (1986)
6. El Quevo (Argentina)	Pb-Ag veins	Pleistocene	Dacite flows in central part of glaciated stratovolcano	Sillitoe (1975)
7. Farallon Negro (Argentina)	Porphyry Cu-Au; Mn-Au veins	7.9-7.1 Ma	Dacite porphyry stocks in roots of deeply eroded andesitic stratovolcano	Angelelli and others (1970); Caelles and others (1971); Guilbert and others (1976)
8. Many deposits	Fumarolic native S	Pleistocene	Andesite flows and breccias Holocene at tops and flanks of volcanoic cones	Ruiz and others (1966); (1)
			CALDERAS	
9. Nevado Portuguesa (Peru)	Ag-Pb-Zn-Cu veins	1.9 Ma	Resurgent dome of caldera centered on large composit andesitic volcano (3.7 Ma)	Noble amd McKee (1982)

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Table 1.--(cont.)

Deposit	Type	Age of mineralization	Volcanic enviornment	Sources of information
			CALDERAS (cont>)	
10. Tumiri (Peru)	Ag-Au veins	Late Miocene	Altered andesite flows (?) associated with Tumiri caldera	Noble and others (in press) (1)
11. Teton-Santo Domingo (Peru)	-do-	-do-	Rhyodacite tuffs and lavas associated with Teton caldera	-do-
12. San Martin-Farallon (Peru)	-do-	-do-	Rhyolitic ash flow tuffs associated with San Martin caldera	-do-
13. Esquillay (Peru)	-do-	-do-	Rim (?) of Esquillay caldera	Noble and others (in press); (1)
14. Sucuitambo (Peru)	-do-	11.4-10.5 Ma	Resurgent dome of Chonta caldera (11.4 Ma)	Peterson and others (1983); (1)
15. San Miguel (Peru)	Ag-base metal veins	-do-	Ring-fracture zone of Chonta caldera	-do-
16. Paco Paco (Peru)	Ag-Au veins	-do-	-do-	-do-
17. Cailloma (Peru)	-do-	16.5 Ma	Rim of Chonta caldera near intersection with younger Cailloma caldera	Davila (1981); Noble and others (in press); (1)
18. Orcopampa (Peru)	-do-	17 Ma	Ash flow tuffs (19.5 Ma) in resurgent dome of Orcopampa caldera	Silberman and others (1985); Noble and others (in press); (1)
19. Coyuma (Bolivia)	Pb-Zn-Ag veins	-8.5 Ma	Quartz latite dome on west side Tankha Tankha caldera	United Nations (unpublished report, 1982); (1)

Table 1.--(cont.)

Deposit	Type	Age of mineralization	Volcanic enviornment	Sources of information
			CALDERAS (cont.)	
20. Pumpuri (Bolivia)	Pb-Zn-Ag-Sn veins	Middle (?) Miocene	Dacite flows in or near ring-fracture zone of Pumpuri caldera	United Nations (unpublished report, 1982); (1)
38. La Joya (Bolivia)	Ag-Au stockwork	15 Ma	Dacite stock near south-western margin of Soledad caldera (5.4 Ma)	Redwood (1987); (1)
21. Cerro Rico de Potosi (Bolivia)	Sn-Ag veins	13.8 Ma	Quartz latite porphyry stock in ring fracture zone of Kari Kari caldera (20.8 Ma)	Francis and others (1971); Sillitoe and others (1975); Grant and others (1979); (1)
22. Illimani (Bolivia)	Pb-Zn-Ag veins	Early (?) Miocene	Ash flow tuffs in resurgent dome of Kari Kari caldera	Ahlfeld amd Schneider-Scherbina (1964); (1)
23. Cord. Andacaba (Bolivia)	Sn-Ag and Pb-Zn-	-do-	-do-	-do-
24. Cunurana (Bolivia)	Sn-Ag veins	Miocene	Granodiorite stock in ash flow tuffs of Kari Kari caldera	-do-
25. El Salvador (Chile)	Porphyry Cu	41 Ma	Porphyry stocks in ring-fracture zone of a Paleocene caldera	Gustafson and Hunt (1975); Francis and others (1983); Clark and others (1985)
			DOMES	
26. Julcani (Peru)	Ag-Cu-Bi-Pb-Zn-W-Au veins	9.8-9.4 Ma	Ash flow tuffs (10.3 Ma) cut by quartz latite domes	Petersen and others (1977); Noble and Silberman (1984); Shelnutt and Noble (1985)
27. Huachocolpa (Peru)	Pb-Zn-Ag veins	Between 8.2 and 4.0 Ma	Dacitic flows, breccias, and domes (10.4-8.2 Ma)	McKee and others (1975); Birnie and Petersen (1977)

Table 1.--(cont.)

	Deposit	Type	Age of mineralization	Volcanic enviornment	Sources of information
				DOMES (cont.)	
28.	Arcata (Peru)	Ag-Au veins	5.0-4.5 Ma	Dacite flows and rhyolitic domes	Noble and others (in press); (1)
29.	Oruro (Bolivia)	Sn-Ag veins	Miocene	Brecciated porphyry stocks and coeval quartz latite flows	Chase (1948); Grant and others (1979); Sillitoe and Bonham (1984); (1)
30.	San Cristobal de Lipez (Bolivia)	Pb-Zn-Ag veins and dissem-inations	-do-	Dacite flows and domes	Jacobson and others (1969); Sillitoe and Bonham (1984)
31.	Pan de Azucar (Argentina)	Pb-Zn-Ag vein	12 Ma	Dacite and quartz latite pyroclastics and domes	Coira (1979); Sillitoe and Bonham (1984)
				BRECCIAS AND ALTERATION ZONES OF INFERRED STRATOVOLCANOS OR DOMES	
32.	Berlenguela (Bolivia)	Ag-Cu-Pb-Zn veins	Miocene	Rhyolite breccia pipe in andesite flows (26-10.5 Ma	Evernden and others (1977); McNamee (oral commun, 1986)
33.	Llallagua (Bolivia)	Porphyry Sn	21.1-20.6 Ma	Brecciated porphyry stock in Paleozoic sedimentary rocks	Sillitoe (1975); Grant and others (1979); Francis and others (1983)
34.	Colquechaca (Bolivia)	Ag-Pb-Zn-Sn veins	22-21.5 Ma	Vent (?) in quartz latite flows of former volcano	United Nations (unpublished report (1982); Grant and others (1980)
35.	Porco (Bolivia)	Sn-Ag-Zn veins	Miocene	Rhyodacite tuffs and porphyry stocks of flow dome complex	United Nations (unpublished report (1982)
36.	Chocaya (Bolivia)	Zn-Pb-Ag-Sn veins	12.5 Ma	Rhyodacite pyroclastics and flows in vent zone (?) of eroded volcano	Sillitoe and others (1975); Grant and others (1980); Francis and others (1983)

The major metal production from deposits in Neogene-Quaternary eruptive centers has been of Ag, Au, and base metals from several deposits in southern Peru, Sn and Ag from many deposits in southern Bolivia, and Ag and Au from the El Indio and Choquelimpie deposits in Chile. In southern Peru, the mining districts of Julcani and Huachocolpa (fig. 5), have produced large amounts of polymetallic Ag-rich base-metal ores, and mines at Cailloma, Orcopampa, and Arcata (figs. 4 and 5) have been major producers of Ag-Au ores. Of the Sn-Ag deposits in southern Bolivia, the most famous is Cerro Rico de Potosi (table 1), which ranks as one of the largest, if not the largest, Ag producer in the world. Llallagua, Bolivia (table 1), a porphyry tin deposit, is the world's largest lode-tin deposit. All these deposits are currently being exploited, and several have been exploited intermittently since Colonial times. El Indio is the newest deposit, having been discovered in the late 1970s.

ALTERATION AND ORE MINERALOGY

The mineral deposits associated with the Neogene-Quaternary volcanic centers in the central Andes show various types and intensities of hydrothermal alteration and various characteristic suits of primary ore minerals. The most intense alteration is that in the tin-bearing porphyry stocks of southern Bolivia, which characteristically consist chiefly of a quartz-sericite-tourmaline rock. In contrast, the epithermal Ag-Au deposits of southern Peru (table 1) commonly show weak to moderate propylization, and wall rocks of veins may show locally intense argillic alteration. For example, the dacitic lavas that are the host of the veins at Arcata (table 1) are propylitized, and veins have halos as much as 25 m wide in which the lavas have been transformed to a white rock consisting almost entirely of dickite. The altered porphyry stock at the Choquelimpie deposit (table 1) contains the clay mineral nacrite in addition to quartz and tourmaline.

Epithermal Ag-Au and base-metal deposits in southern Peru consist of sulfides and sulfosalts of Ag, Cu, Pb, Sb, As, and Bi. Zn occurs as sphalerite, and Au, with rare exception, occurs as native gold or is contained in pyrite. Ag occurs chiefly in the ruby silver minerals and argentiferous tetrahedrite/ tennantite and galena. In a typical Ag-Au deposit, Ag is on the order of 10 to 100 times as abundant as Au, which characteristically is present in amounts of only a few grams per tonne. However, a few exceptionally rich Ag-Au veins contain several ounces of gold and several hundred ounces of silver per tonne. The richest gold vein now being mined, Veta Sur at the El Indio deposit, Chile (table 1), averages 150-200 g Au, 50-150 g Ag, and 1-5 percent Cu; assay values of more than a kilogram of Au per tonne are common. In the base-metal deposits, galena and sphalerite are the principal Pb and Zn minerals whereas chalcopyrite and tetrahedrite/tennantite and in some, enargite, are dominant Cu minerals. Some deposits also contain significant amounts of Pb sulfosalts, bismuthinite, and stibnite. The principal gangue minerals of both the Ag-Au and base-metal deposits are quartz, pyrite, rhodochrosite, rhodonite, and barite.

The tin deposits of southern Bolivia are characteristically polymetallic, containing cassiterite as the dominant Sn mineral, and a variety of sulfides, sulfosalts, and sulfostannates of Ag, Cu, Pb, Zn, Bi, Sb, and As. Depending upon the relative abundances of the principal metals, the Sn deposits are classed as either Sn-Ag, Sn-Zn, and Sn-Bi types.

The porphyry copper deposits discussed in this report--El Salvador, Chile, and Farallon Negro, Argentina (table 1)--show propylitic, argillic, and potassic alteration typical of porphyry coppers in general. Chalcopyrite is the dominant primary Cu mineral, but significant amounts of bornite, enargite, and tetrahedrite/tennantite may be present. At least one of the porphyry bodies at Farallon Negro has exceptional Au values of 0.7 g per tonne.

Many of the deposits show characteristic mineral zoning, which may be district-wide lateral zoning of many veins or both lateral and vertical zoning within single veins. For example, many of the polymetallic Sn deposits of southern Bolivia have cassiterite-rich central zones that grade laterally into Ag-rich base-metal zones. Cerro Rico de Potosi (table 1) also shows vertical zoning wherein bonanza-type primary Ag ores were encountered in upper mine levels and high-grade Sn ores in deeper levels. Petersen and others (1977) reported district-wide zoning at Julcani, Peru (table 1), to be as follows (from the district center outwards): (1) wolframite and Au-bearing pyrite; (2) enargite, pyrite, and tetrahedrite/tennantite; (3) Ag- and Bi-sulfosalts and bismuthinite; (4) galena; and (5) Pb sulfosalts, orpiment, and realgar. Veins in the Arcata district, Peru (table 1), show a characteristic vertical zoning, having rich Ag ores confined to a mid-depth range of 200-300 m, which grades upwards into a low-Ag pyrite zone and downwards into a low-Ag galena-sphalerite zone.

DEPOSITS ASSOCIATED WITH STRATOVOLCANOS

Mineral deposits associated with stratovolcanos are shown in figure 3 and briefly described in table 1. The precious- and base-metal deposits in the upper parts of volcanic cones show a variety of structures and mineral associations. For example, the Aucanquilcha covellite occurrence, Chile (table 1), consists of impregnations and masses of covellite and pyrite, cut by veinlets of native sulfur, in andesite breccia at the margin of the vent zone on top of Volcan Aucanquilcha. In contrast, El Quevo, Argentina, described by Sillitoe (1975), consists chiefly of lenses and masses of Ag-bearing galena within a fault zone high on the southwestern flank of Volcan Nevados Pastos Grandes. The deposit is exposed in a glacial cirque, and Sillitoe (1975) estimated that it was emplaced at a depth of 400-500 m below the original volcano surface. The Salle deposit consists of Sn-Ag-base-metal veins in an eroded volcanic cone (Brodtkorb and Coira, 1986).

The sulfide deposits in deeply eroded stratovolcanos--Choquelimpie, and Farallon Negro (table 1)--are associated with subvolcanic intrusions and related intrusive or hydrothermal breccias. The Choquelimpie deposit consists of disseminations and veins of Ag- and Au-bearing base-metal sulfides in and near a porphyry stock exposed in the base of a deeply eroded andesitic stratovolcano 8-10 km in diameter. The stock shows widespread hydrothermal breccia, and is pervasively argillized and silicified. A semiquantitative spectrographic analysis of a typical ore specimen, which we collected from an active open pit at Choquilimpie in 1984, shows 70 ppm Ag, 200 ppm Cu, 200 ppm Pb, and 150 ppm Sb. Cabello (1986) cited ore grades of 150-300 ppm Ag and 0.5-3 ppm Au, which were reported by A. Thomas (unpublished report, 1973). Cabello also suggested that Choquelimpie is associated with a caldera, which we believe to be unlikely.

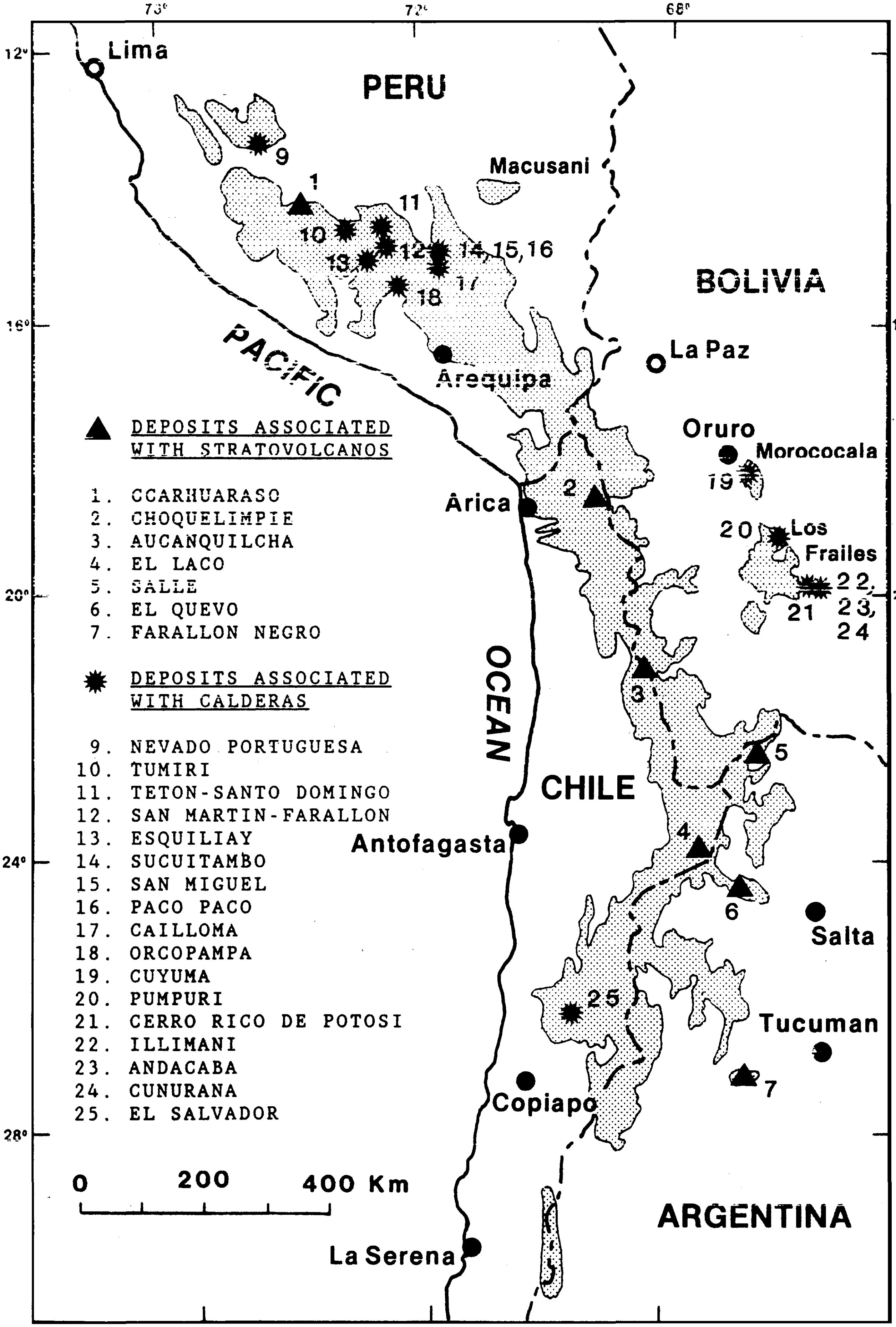

Figure 3.--Distribution of metalliferous deposits associated with stratovolcanos and calderas in the central Andes.

The Farallon Negro district, Argentina, has several small subvolcanic intrusions with porphyry-type mineralization (Caelles and others, 1971), which evidently were emplaced in the root zone of a complex stratovolcano that has been almost completely destroyed by erosion. Caelles and others (1971) cite a radiometric age for this volcanic complex of 10.7 m.y., and an age of one of the porphyry intrusions of 7.9 m.y. They further estimated the age of mineralization to be between 7.9 and 7.1 m.y. Guilbert and others (1986) show that one of these bodies, the Bajo La Alumbrera deposit is a porphyry Cu-Au deposit that contains an estimated 300 million tonnes of ore averaging 0.49 percent Cu and 0.7 g Au/ton. At 1987 prices, the gold in this deposit is worth more than the copper.

In addition to the porphyry-type deposits, a steeply dipping Au-bearing manganiferous zone is present in the Farallon Negro district. This zone has an outcrop length of about 2 km and ranges from 1 to 20 m in thickness. It forms a prominent black ledge, for which the Farallon Negro (black cliff) district is named. Angelelli and others (1970) reported the primary vein material in the manganiferous zone to consist of Au-bearing pyrite, sparse base-metal sulfides, and manganiferous carbonates and oxides. They stated that considerable Au had been produced from the zone, and estimated that ore-grade material being recovered in 1965 contained 6 g Au and 114 g Ag per tonne as well as small amounts of Cu, Pb, and Zn.

The unique El Laco magnetite-hematite deposits, which are considered to have been emplaced as lava flows (see Ruiz and others, 1965), occur at 5 localities on the flanks of Volcan El Laco, a complex andesitic stratovolcano in northern Chile (fig. 3, table 1). The deposits contain large amounts of high-grade iron ore, perhaps totaling more than 100 million tonnes. They consist of vuggy, finely to coarsely crystalline magnetite and hematite. The magnetite-hematite ore contains abundant, near-vertical, open tubes, which appear to be gas-escape tubes. These tubes are lined with octahedral crystals of magnetite, as much as 5 cm in diameter. These crystals and others in vuggy ore are partly to wholly altered to hematite, which suggests that magnetite was the dominant primary mineral of the flows, and that alteration to hematite took place during the subsequent fumarolic phase. However, the deposits also contain primary hematite in the form of tabular hexagonal crystals as much as 5 cm in diameter.

Published reports on the El Laco deposits all conclude that they were emplaced as flows of iron-oxide magmas. Park (1961) was the first to report on these deposits and he suggested these magmas were segregations highly charged with gas and were intruded at shallow depth and locally reached the surface to form flows. Ruiz and Ericksen (1962) considered them to be dome flows of iron-oxide magma. Frutos and Oyarzun (1975) suggested the iron-oxide magma originated by fusion of iron formation they presumed existed at depth in this area.

Small manganese oxide deposits of Quaternary age and of probable thermal-spring origin are widespread in northern Chile and have been reported to occur in Bolivia (Ahlfeld and Schneider-Scherbina, 1964) and Argentina (Angelelli and others, 1970; Sillitoe, 1975). These deposits consist of surficial layers and veins and impregnations in bedrock at the sites of former thermal springs, and as thin layers interbedded with clastic sediments and diatomite at the sites of former lakes and ponds (Salas and others, 1966; Cruzat, 1970). The manganese oxides in the lacustrine deposits probably were discharged by nearby thermal springs. Such deposits are found on the flanks of stratovolcanos as well as in adjacent volcanic terranes. Some thermal springs are actively depositing manganiferous travertines in northern Chile (Cruzat, 1970) and northwestern Argentina (Sillitoe, 1975). The principal manganese ores consist of pyrolusite, psilomelane, and wad (Salas and others, 1966; Cruzat, 1970). The manganese oxide deposits are small and low grade; only a few have been mined and small tonnages of hand-selected manganese ore recovered (Salas and others, 1966, Sillitoe, 1975).

Many stratovolcanos in the central Andes have fumarolic sulfur deposits in vent areas on their tops and flanks. The largest number of such deposits are in Chile and Bolivia (fig. 4). Fewer deposits are in Argentina and still fewer in Peru. The sulfur occurs as cement, veins, and irregular masses in argillically altered, andesitic to dacitic pyroclastics and brecciated or fractured lavas. Active fumaroles are present at some deposits where they are now depositing native sulfur. Several sulfur deposits were being worked during the early 1980's, and in 1984 Chile and Bolivia produced 54,000 t and 2,300 t of native sulfur, respectively, whereas Peru produced 100 t (U.S. Bureau of Mines, 1986). Argentina had no recorded production of native sulfur in that year but had produced small amounts in previous years.

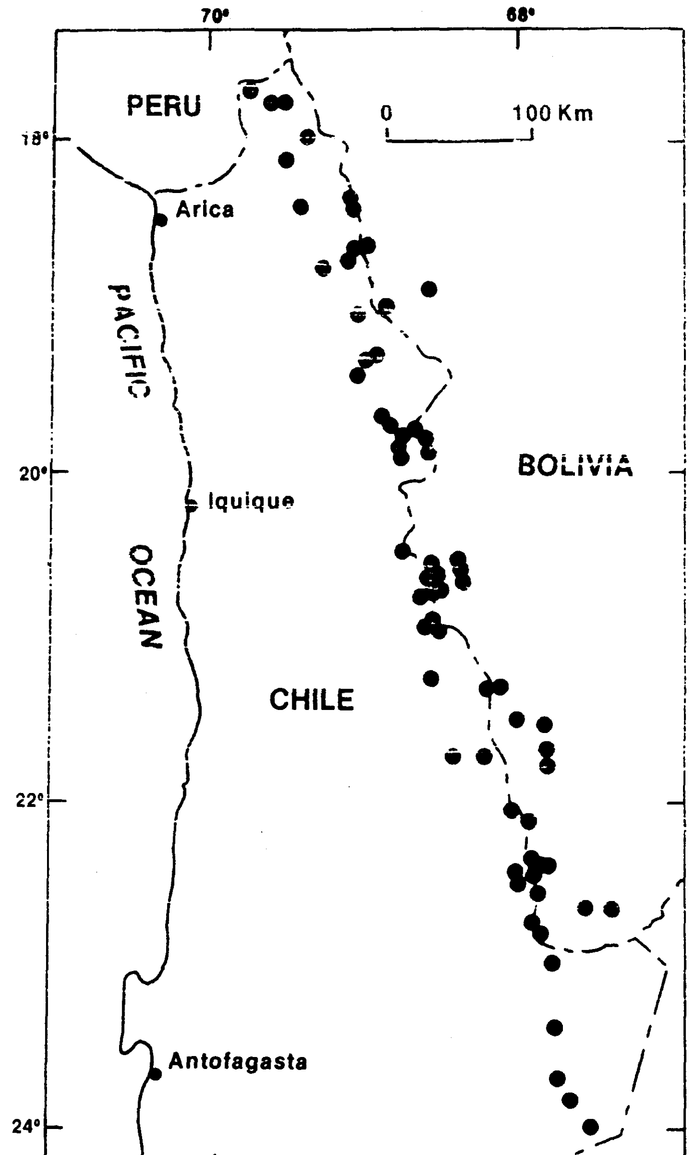

Figure .--Distribution of native sulfur deposits associated with stratovolcanos in Bolivia and Chile. Each symbol indicates one or more deposits associated with a single volcano. Modified from Montes de Oca (1982) and Ruiz and others (1965).

DEPOSITS ASSOCIATED WITH CALDERAS

Comparison of figures 2 and 3 shows that only a few of the many calderas in the central Andes are known to have associated metalliferous mineral deposits. However, among these deposits are several that rank among the most productive mineral deposits of the region. These include the Cailloma and Orcopampa, Peru, Ag-Au deposits, the Cerro Rico de Potosi, Bolivia, Sn-Ag deposit, and the Paleocene El Salvador porphyry copper deposit, Chile (table 1). Significant amounts of Ag and Au also have been produced from Sucuitambo and other districts in the Chonta caldera (table 1) and small amounts from Nevado Portuguesa and Esquillay, Peru. Moderately large amounts of Ag, Pb, and Zn have been recovered from the Illimani mine, and Sn and Ag from Cunarana and Pb and Ag from other mines in the Cordillera Andacaba, all of which are within the resurgent dome of the Kari Kari caldera, Bolivia (table 1). Veins in the Pumpuri district (table 1), which apparently are older than the associated caldera in the Los Frailes volcanic field, have had a moderately large production of Sn, Ag, Pb, and Zn. The Coyuma deposit (table 1), on the western side of the resurgent dome of the Tankha Tankha caldera in the northern part of the Morococala volcanic field, has had a small production of Ag and Pb.

The mineral deposits associated with calderas in southern Peru consist chiefly of Ag-Au veins having varying amounts of Cu, Pb, and Zn sulfide and sulfosalt minerals. Ag is more abundant in these deposits than is Au, and the dominant Ag-bearing minerals are pyrargyrite, proustite, and argentiferous tetrahedrite-tennantite. Of these deposits, by far the most important economically are those of the Cailloma district, which has produced about 100 million ounces of Ag, and Orcopampa, which has produced about 50 million ounces (Silberman and others, 1985).

The Kari Kari caldera (fig. 2) was considered to be a batholith until Francis and others (1981) first recognized that it consisted predominantly of 20 Ma ignimbrites within a resurgent caldera. Several mineral deposits occur within the resurgent dome of this caldera, and Francis and others (1981) suggested that the porphyry stock with which the famous Cerro Rico de Potosi Sn-Ag deposit is associated was emplaced in the ring-fracture zone of the Kari Kari caldera. The Cerro Rico mineralization has been dated at 13.8 Ma, and it is estimated that the stock was emplaced not more than a million years earlier. The Cerro Rico deposit is among the giant silver producers of the world. Total production is estimated to have been between 20,000 and 50,000 t of Ag since discovery in 1545 (United Nations, unpublished report, 1982). Currently, Cerro Rico is one of the major Sn mines of Bolivia. Cerro Rico consists chiefly of polymetallic Sn-Ag-base-metal veins, having a complex suite of minerals dominated by cassiterite, silver sulfosalts, and many base-metal and iron sulfides and sulfosalts. Several small mining districts in the Cordillera Andacaba, in the southern part of the Kari Kari complex, have polymetallic veins in which either Sn or Pb-Zn are the dominant metals. Veins in the Illimani district to the north have Ag-bearing Pb-Zn sulfide ores.

The Pumpuri mining district in the Los Frailes volcanic field, Bolivia, and the El Salvador porphyry copper deposit, Chile (fig. 2, table 1) may not be genetically related to the calderas with which they are associated. The Pumpuri district is in volcanic rocks of presumed Miocene age exposed in a window eroded in the late Miocene Los Frailes ash-flow tuffs. It is not known whether mineralization took place during an early phase of caldera development or whether it is unrelated to caldera magmatism. The El Salvador deposit consists of a mineralized porphyry stock complex in the ring-fracture zone of a rather obscure caldera that was identified by Francis and others (1983) in LANDSAT images. The age of mineralization is about 41 Ma, about 20-25 m.y. younger than the caldera, and Clark and others (1985) believe that mineralization at El Salvador is not genetically realted to the caldera.

The La Joya Ag-Au deposit in southern Bolivia (fig. 5, table 1) consists of an altered and mineralized dacite porphyry stock, which resembles the porphyry stocks with which the tin deposits of the nearby central Bolivian Tin Belt are associated. However, La Joya does not contain Sn minerals. La Joya is one of several porphyry stocks outside but near the southwestern margin of the recently discovered Soledad Caldera (Redwood, 1987). Both the stock and associated mineralization are older (about 15 Ma) than the major ash-flow tuff eruptions from the caldera (5.4 Ma) (Redwood, 1987). The stock is exposed as a conical hill about 100 m high and 500 m in diameter, rising above the flat alluvial plain of the Altiplano. The primary ore, averaging about 24 g Ag and 1.4 g Au, consists of closely spaced veinlets and impregnations of Ag- and Au-bearing pyrite and chalcopyrite. A 60-m thick oxide capping, having Ag and Au values similar to those of the primary ore, was being mined in the early 1980s and treated by a heap-leaching process.

Ag- and Au-bearing porphyry intrusions similar to La Joya are known in the vicinity of La Joya and elsewhere in the Altiplano to the north. Although some of these deposits have been exploited for Au and Ag in the past, little is known about them. We believe that these deposit and other porphyry intrusions in this region have a potential for significant amounts of low-grade Ag-Au ore.

Most of the other calderas in the central Andes either lack surface expression of hydrothermal alteration and mineralization or have only small alteration zones and sparse associated metallic minerals. We believe that hydrothermal mineral deposits are associated with late-stage intrusions of many of these calderas, but have not been found because erosion has not been sufficiently deep to expose either the deposits themselves or major associated alteration halos. Geochemical and geophysical studies should prove useful in locating such buried deposits.

Mineral deposits in calderas would not be expected to accumulate during the explosive eruptive phase of caldera development but, rather, during the waning phases of resurgence and intracaldera intrusion. Nevertheless, the geochemical signatures of ash-flow tuffs may give clues to the chemical nature of mineralizing fluids associated with the source magmas. Such is the case for the Sn-rich tuffs at the Macusani and Morococala volcanic fields (see p. 2), which we believe are indicative of tin-rich magmas similar to those that formed the porphyry intrusions with which the Sn deposits of the Central Bolivian Tin Belt are genetically related.

DEPOSITS ASSOCIATED WITH DOMES

Several mining districts in the central Andes are associated with intrusive-extrusive complexes whose only surface expressions are dome-flow complexes (fig. 5, table 1). The intrusions tend to contain hydrothermal breccias, and breccia-filled volcanic vents may be present. Mineral deposits associated with domes occur in the underlying intrusive bodies in the surrounding host rocks, and, rarely, in the domes themselves. In addition, some of the deposits associated with subvolcanic intrusions in eruptive centers not having known volcanic landforms, discussed in the next section, may have been associated with domes that subsequently have been destroyed by erosion.

The Julcani and Arcata Ag districts, Peru, and the Oruro Sn-Ag district, Bolivia, are by far the most productive deposits associated with the known dome complexes listed in table 3. Both have had long histories of production and are currently among the major active mining districts of the region. The Oruro deposit, which has been active since the 16th century, produced more than 271 million oz Ag up to 1948 (Chase, 1948) and an additional one million oz from 1948 to 1985 (COMIBOL, unpublished data, 1986). The Oruro district also has been one of the major producers of Sn in Bolivia during the 20th century, and mining currently is chiefly of low-grade Sn-Ag ore. Production of Ag, Pb, and Zn from San Cristobal, Bolivia, and Pan de Azucar, Argentina, both of which are associated with domes, has been relatively small.

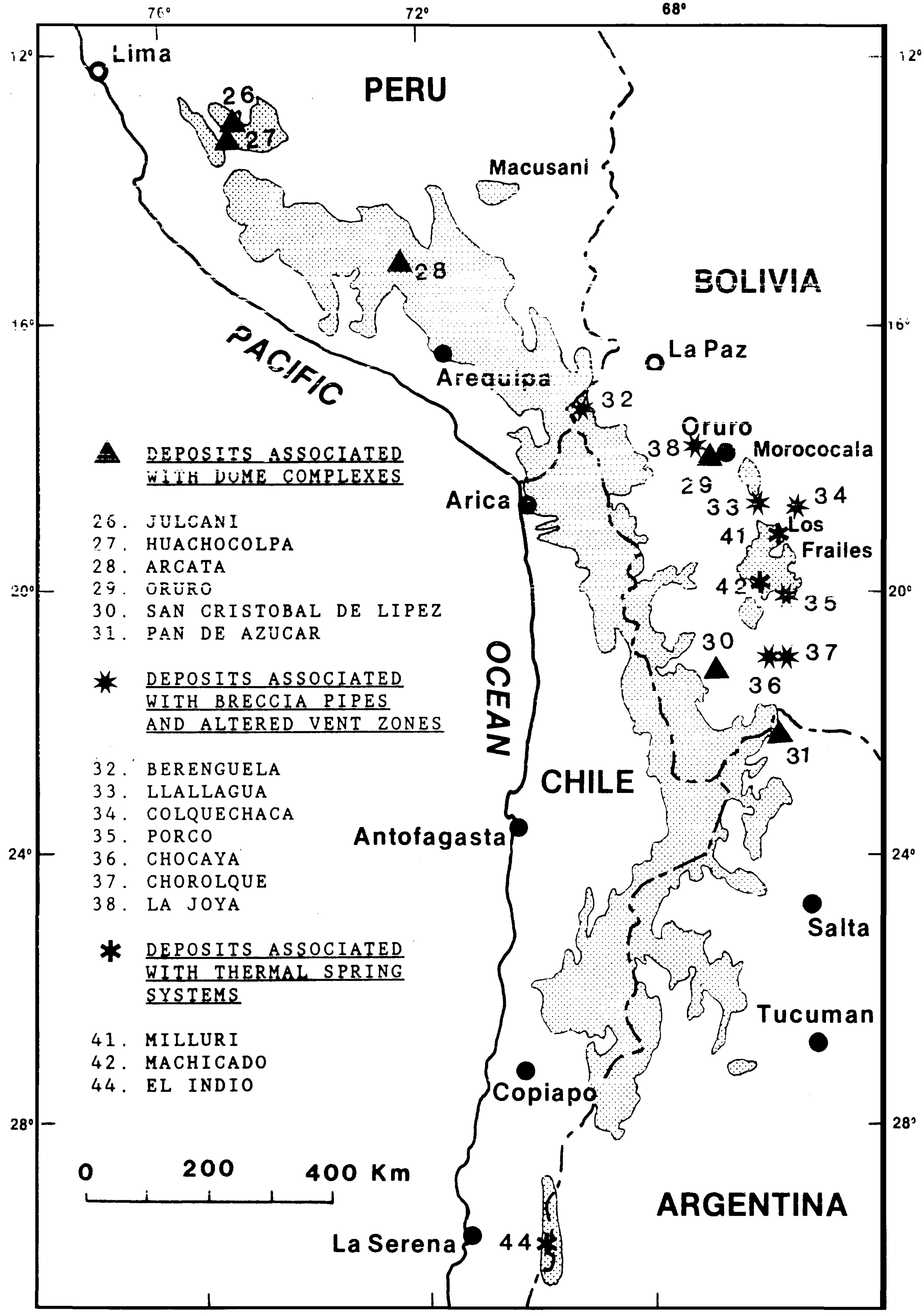

Figure 5.--Mineral deposits associated with dome complexes and with altered vent zones, breccia pipes, and thermal-spring systems not related to known volcanic landforms.

The Julcani district, Peru, shows the best documented sequence of geologic events in the development of a mineralized eruptive center characterized by domes. This sequence of volcanic and hydrothermal events began at about 10.1 Ma and continued for about 0.7 Ma (Shelnutt and Noble, 1985). The main volcanic event, at about 10.1 Ma, consisted of eruption of 15-20 km^3 of dacite and rhyodacite pyroclastics from a central vent now buried beneath a complex of younger volcanic rocks (Noble and Silberman, 1984; Shelnutt and Noble, 1985). This stage of explosive volcanic activity was followed by emplacement of a complex of 30 or more interpenetrating dacite and rhyodacite domes and associated pyroclastic eruptive material (Shelnutt and Noble, 1985). Following this phase of dome emplacement, many dikes of "fluidized" breccia were emplaced in the central part of the district and subsequently were altered to dense rock consisting almost entirely of fine-grained quartz, tourmaline, and pyrite (Noble and Silberman, 1984; Shelnutt and Noble, 1985). These dikes cut some domes but pre-date the main stage of mineralization. Fluidized dike emplacement and alteration were followed by a series of volcanic, hydrothermal, and tectonic events during which the principal Ag-base-metal ores were formed (Noble and Silberman, 1984). This was followed by emplacement of post-mineral dikes and domes (Noble and Silberman, 1984).

The Oruro mining district is centered on an elongate hill consisting of a late Tertiary intrusive-extrusive complex surrounded by lower Paleozoic sedimentary rock. The most comprehensive study of this district is that of Chase (1948), who first recognized that the complex intrusive body in this district was capped by coeval extrusive rocks, probably a dome complex. According to Chase, the complex consists of several intensely altered quartz latite stocks, dikes, irregular intrusive masses, and lavas. Hydrothermal breccias are widespread. The ores at Oruro occur as well-defined veins, stockworks, and mineralized breccias in the porphyry intrusive complex. They consist chiefly of cassiterite, stannite, Ag-sulfides, and Ag-rich base-metal sulfides and sulfosalts.

Of the other mining districts in which domes occur, the Ag-Au veins at Arcata were emplaced in a sequence of dacitic lavas during a phase of mineralization genetically related to intrusive activity that resulted in emplacement of domes along the northern side of the district (Noble and others, in press). Mineralization is similar to that of the Cailloma district. The Huachacolpa district, southern Peru (fig. 5; table 1), has been a major producer of Pb and Zn from fissure-filling veins in late Tertiary volcanic rocks. McKee and others (1975) reported the presence of domes in the Huachacolpa district. Ag-bearing Pb-Zn sulfide veins at San Cristobal de Lipiz, Bolivia, are in a complex of dacite intrusions, hydrothermal or intrusive breccias, lavas, and ash-flow tuffs of late Pliocene and Pleistocene age (Jacobson and others, 1969). Sillitoe and Bonham (1984) reported domes at San Cristobal. They also identified the Pb-Zn-Ag vein at Pan de Azucar, Argentina, as being related to a dome complex.

DEPOSITS IN OTHER TYPES OF VOLCANIC CENTERS

A number of metalliferous deposits in the central Andes are associated with altered and brecciated porphyry intrusions, vent breccias, and hydrothermal alteration zones that are presumed to represent eruptive centers where former volcanic landforms have been destroyed by erosion. By far the most productive mineral deposits in such eruptive centers are the polymetallic Sn deposits of southern Bolivia and the El Indio Au-Ag deposit, Chile (fig. 5, table 1). It has been suggested (Sillitoe and others, 1975; Francis and others, 1983) that the porphyry stocks with which the polymetallic Sn deposits are associated represent the roots of former stratovolcanos or dome complexes. Araneda (1982) suggested that El Indio is associated with a caldera, but the available evidence for such an association is not conclusive.

Most of the polymetallic Sn deposits of southern Bolivia are associated with intensely altered--silicified, sericitized, and tourmalinized--porphyry stocks, many of which have abundant hydrothermal breccias. These stocks occur as isolated bodies in lower Paleozoic (Ordovician-Devonian) and Mesozoic sedimentary rocks. As the result of intense silicification and tourmalinization, they are resistant to erosion and tend to form conical hills that rise above the surrounding terrane of less resistant sedimentary rocks.

The tin deposits of southern Bolivia have complex mineralogy, but Sn, Ag, and Bi minerals are most important economically. The minerals occur chiefly as fissure-filling veins, generally not more than a meter or two thick, and local, closely spaced veinlets. Some stocks show pervasive mineralization similar to that of the porphyry-copper deposits, and it has been suggested that these bodies are the tin-bearing analogs of porphyry copper deposits (Sillitoe and others, 1975). The Llallagua deposit (fig. 5, table 1) is the best example of such a deposit. In the early part of the present century, veins at Llallagua were exploited for relatively high-grade Sn ore, but in the 1940s the mining system was changed over to block caving of low-grade Sn ore, a method used widely in porphyry-copper mines. In addition to Llallagua, Sillitoe and others (1975) proposed that Potosi, Oruro, and Chorolque are examples of porphyry-tin deposits. Chorolque differs from other Sn deposits in southern Bolivia in that the tin mineralization is largely confined to a cylindrical breccia pipe about 1 km in diameter that is surrounded by coeval pyroclastics. Sillitoe and others (1975) suggested that the Chorolque complex is the erosion remnant of a former large volcano.

The El Indio Au-Ag deposit, which was not discovered until the late 1970s, ranks as one of the major recent mineral discoveries of the central Andes. A brochure by the St. Joe Minerals Corp. (1984), the principal owner of El Indio, gives the following information about mining and grade-reserve statistics. Direct-shipping high-grade Au ore was first extracted in 1979. A processing plant for treatment of low-grade Au-Ag ore began operating in 1981. By the end of 1982, the company had blocked out 4.3 million tonnes of ore averaging 14.0 g Au/t, 122 g Ag/t, and 5.03 percent Cu. Some of this ore is high-grade direct-shipping ore, and the above reserves include 62,284 t of such ore averaging 248.5 g Au/t, 113 g Ag/t, and 2.72 percent Cu.

El Indio has been described in several published reports, of which the most comprehensive are those of Araneda (1982, 1984), Jannas and Araneda (1985), and Walthier and others (1986). The following data about El Indio was extracted from these reports. El Indio consists of Au-Ag-Cu-bearing veins within a zone of hydrothermally altered (argillic, sericitic, and silicic) andesitic to rhyolitic volcanic rocks and small granodiorite intrusions of late Oligocene to Miocene (27-11 Ma) age. The principal host rock is ash flow tuff. Some 20-30 similar alteration zones are in a 150-200-km belt extending north and south of El Indio. The volcanic rocks are folded and faulted, and are cut off in the west by a major longitudinal reverse fault. Although the relationship of El Indio to a caldera, as suggested by Araneda (1982), remains uncertain, it is evident that the veins were emplaced in a geothermal system marked by thermal-spring and fumarolic activity at the surface, as indicated by the presence of siliceous sinter and fumarolic sulfur cappings (Araneda, 1984). Two types of veins are recognized at El Indio, one of which consists predominantly of Au-Ag-bearing quartz and the other of Au-Ag-bearing massive enargite (Areneda, 1984). The veins extend over a vertical range of about 800 m, from the surficial thermal-spring sinters to the deepest mine levels.

Ash-flow tuffs of Los Frailes volcanic field (Fig. 1) contain small wood-tin deposits and uranium deposits. Wood-tin occurs as fracture-filling veinlets of fibrous to dense, locally nodular cassiterite, generally not more than a centimeter or two in thickness. The veinlets tend to be concentrated along linear fracture zones and may occur over areas of many thousands of square meters. Streams draining such areas have small placer deposits. Both lode and placer deposits of wood-tin have been mined, but total production has been insignificant. Several small uranium occurrences are in the southwestern part of the Los Frailes volcanic field and one of these, the Cotaje deposit, was being mined in the early 1980s (A. P. Farfan, unpublished report, 1981; Leroy and others, 1984). Leroy and others (1984) distinguished four types of uranium occurrences in the Los Frailes area, as follows: (1) Magmatic--U-rich horizon (5-10 cm thick) in unaltered dacitic tuff; (2) Hydrothermal--U accumulations related to faults in highly altered (kaolinized and silicified) tuff; Cotaje is of this type; (3) U occurrences related to hot and cold springs; and (4) U occurrences in unconsolidated detritus. Farfan (unpublished report, 1981) reported the following uranium minerals to be present: uraninite, autunite, torbernite, boltwoodite, and uranophane-beta. These minerals are associated with Fe and Mn oxides. Farfan further reported the highest uranium values at Cotaje to be 1.2-2.5 percent U_3O_8, and more typical values at Cotaje and elsewhere of 0.05-0.9 percent U_3O_8.

CONCLUSIONS

The principal mineral deposits associated with eruptive centers of Neogene-Quaternary volcanic rocks of the central Andes hydrothermal precious- and base-metal deposits, polymetallic tin deposits, magnetite-hematite flows, and fumarolic sulfur deposits. The relationship of many of these deposits to eruptive centers was not generally recognized prior to the 1970s. Before that time, geologists believed that much of the late Tertiary and Quaternary volcanic rocks represented post-mineralization cover, and that the major potential for mineral deposits was beneath these rocks. To a certain extent, this thinking continues to guide mineral exploration in this region. However, accumulated information about mineral deposits, nature and ages of eruptive centers, and geochemistry of these young volcanic rocks indicates them to be prime exploration targets. Such exploration should be concerned primarily with the search for buried mineral deposits in eruptive centers, particularly collapse calderas, deeply eroded stratovolcanos, flow-dome complexes, and fossil geothermal spring systems. In addition, many mineral deposits of Miocene and Pre-Miocene age can be expected to occur beneath the volcanic cover, and some of these, particularly those beneath thin volcanic cover, can be found by modern geologic mapping and application of geophysical methods.

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Ponce, David A.

Educación - ***Education***: B.S. Geophysics, San Jose State University

Sociedades Profesionales - ***Professional Societies***:: AGU, GSA, SEG

Empleos - ***Employment***: U.S. Geological Survey

Proyectos - ***Projects:***
Research geophysicist at the U.S. Geological Survey; research includes gravity and magnetic methods, geophysical characterization of potential radioactive waste storage sites, geophysical studies related to mineral assessment and wilderness study areas, and regional gravity and magnetic studies in the Basin and Range Province.

Como geofísico investigador tiene a su cargo la investigación de métodos de gravedad y magnetismo, caracterización geofísica de sitios potenciales para almacenage de desperdicios radioactivos, estudios geofísicos relacionados con la asesoría mineral y bosques vírgenes, y estudios regionales de gravedad y magnetismo en la provincia de cuenca y cordillera.

Singer, D.A.

Educación - ***Education*** : B.A. (1966) San Francisco State University; M.S. (1968) San Francisco State University; Ph.D. (1971) Pennsylvania State University

Sociedades Profesionales - ***Professional Societies*** : SEG, ASA, Sigma Xi

Empleos - ***Employment*** : Kennecott Copper; U.S. Geological Survey

Proyectos - ***Projects*** :
Systems analyst for Kennecott Copper (1971-1973). U.S. Geological Survey (1973-to date) as geologist on six 1°x2° quadrangle mineral resource assessments, assessments at 1:1,000,000 scale of Alaska and Colombia, development of mineral resource assessment methods, mineral deposit and grade-tonnage models, development and testing of probabilistic methods for resource assessment and exploration in the U.S. and Japan.

Analista de sistemas de la compañia de cobre Kennecott. Funcionario del Servicio Geológico de los Estados Unidos como geólogo de 6 cuadrángulos (1°x2°) de asesoramiento de recursos minerales, asesoramiento a escala de 1:1.000.000 en Alaska y Colombia, desarrollo de métodos para asesoramiento de recursos minerales, modelos de depósitos minrales y grado-tonelaje, desarrollo y prueba de métodos probables para asesoramiento y exploración de recursos en los Estados Unidos y el Japón.