## RESUMENES DE TRABAJOS PRESENTADOS AL IUGS/UNESCO DEPOSIT MODELING WORKSHOP: HYDROTHERMAL SYSTEM IN VOLCANIC CENTERS

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## SUMMARY STATEMENT

Hydrothermal systems in volcanic centers was the theme of the fourth workshop sponsored by the IUGS/UNESCO Deposit Modeling Program. The workshop was held in Chile, November 9-18, 1987, with 45 participants, including representatives from six Latin American countries. It was cosponsored by the Servicio Nacional de Geología y Minería of Chile (SERNAGEOMIN), and consisted of a series of lectures, discussion sessions, and visits to mines that illustrated features discussed in the workshop. Additional international sponsors were the U.S. Geological Survey, the Bureau of Mineral Resources, Canberra, Australia, and the British Columbia Ministry of Energy, Mines and Petroleum Resources, Victoria, Canada. The following mining companies also acted as local sponsors: Cía. Minera El Bronce, Cía. Minera Disputada de Las Condes, Cía. Minera San José Ltda., Freeport Chilean Explorations Co., and Minera Anglo American Chile Ltda.

The workshop theme was selected because of the newly recognized importance of the spatial and genetic relationships of epithermal gold-silver deposits to eroded volcanic centers in the Central Andes. The 1970's and 1980's have seen a growing awareness that many mineral deposits of this region are located in eruptive centers marked by remnants of stratovolcanos calderas, dome complexes, diatremes, and fossil geothermal systems. Many mining companies are currently exploring for precious metal deposits in the Neogene-Quaternary volcanic complex of the Central Andes region of southern Perú, western Bolivia, and northern Chile. This young volcanic complex covers about a third of the Central Andean Mineral Province, where most known mineral deposits are Miocene in age or older. New mineral deposits are being discovered within this complex, and many others of Miocene and pre-Miocene age almost certainly exist beneath the younger cover. The El Indio gold-silver-copper deposit in northern Chile is by far the most economically important deposit discovered recently in the young volcanic complex, having produced about 65 metric tons of gold since 1979. Other deposits, some of which have been mined almost continuously since early colonial times, are now recognized as being genetically related to subvolcanic intrusions in former volcanic centers.

In her opening address to the workshop, María Teresa Cañas Pinochet, Director of SERNAGEOMIN, recognized the importance of hydrothermal systems in volcanic centers in the Central Andes and the advantages of using genetic models of these systems for exploration. She pointed out the importance of mineral deposits to the Chilean economy and the current intensive gold exploration being conducted in Chile by private industry. She also noted that the exchange of ideas in the workshop could be of great benefit to future mineral exploration in Chile. Following this opening address, George Ericksen (U.S.A.), Workshop Coordinator and Leader, gave an overview of the purpose and itinerary of the workshop and introduced the participants. He later gave an overview of the characteristics of gold-silver deposits in Neogene-Quaternary volcanic centers of the Central Andes. Charles Cunningham (U.S.A.) IUGS/UNESCO Coordinator and Leader, gave a synopsis of the IUGS/UNESCO Deposit Modeling Program. Defining a mineral deposit model as "the systematic arrangement of the essential characteristics of a group of mineral deposits", he described the various types of deposit models and their uses in mineral exploration and resources assessment.

Lectures by John Davidson and Carlos F. Ramírez of SERNAGEOMIN provided information about the regional geologic setting of mineral deposits in the Central Andes. Davidson emphasized the role of plate tectonics in the magmatic and tectonic evolution of the Andes. He reported that accretion was an important process along the western margin of ancestral South America during the Paleozoic but was insignificant or absent during post-Paleozoic time. Ramírez discussed the distribution and geochemistry of the Neogene-Quaternary volcanic complex of northern Chile.

The chemistry and structure of active geothermal systems were discussed by Richard Henley (Australia) on the basis of his extensive studies of such systems in New Zealand and elsewhere. He explained how the information gained by studying active systems could be applied to the search for precious metal deposits in fossil geothermal systems. He discussed metal contents, temperatures, and alteration patterns of active geothermal systems and explained why boiling of hydrothermal fluids was an effective process in the deposition of metals in solution. Broadlands, New Zealand, was cited as an example of an active system in which gold is currently being deposited. Finally, Henley stressed the importance of understanding the movement and mixing of fluids in geothermal systems, which are factors of prime importance in the formation of orebodies.

Inasmuch as one focal point of the workshop was the relationship of geothermal systems and precious metal deposits, Cunningham and Andrejs Panteleyev (Canada) lectured on genetic models of gold deposits in the Western United States and the Canadian Cordillera. Cunningham discussed features of hot-spring, acid-sulfates and adularia-sericite gold deposits, comparing them with similar features in active geothermal systems and showing the genetic relationships. Panteleyev described epithermal precious metal deposits in volcanic centers of western Canada, and presented a model for these deposits that relates features to magmatic-hydrothermal processes of depths of about 3 km.

In addition to the above major workshop topics, other participants presented data about mineral deposits and volcanic centers in several areas. Howard Colley (U.K.) described the volcanic terrane of Fiji, and presented the criteria that he used for recognizing deeply eroded volcanic centers of this area. Bernie Bernstein (U.S.A.) discussed the geologic features of selected precious metal deposits of the Central Andes and their relationship to volcanic centers. Milka Brodtkorp (Argentina) described the precious metal deposits of the Salle area, northwestern Argentina, which occur in an eroded stratovolcano complex. Mario Arenas (Perú), described the classic epithermal precious metal deposits in the Neogene-Quaternary volcanic terrane of southern Perú, including deposits that have been exploited almost continuously since the 16th century. Enrique Tidy (Chile) gave an overview of the geology of the major porphyry copper deposits of Chile, which together contain a large portion of the world's known resources of copper. Alvaro Puig (Chile) described the El Guanaco, Cachinal de la Sierra, and El Soldado gold-silver deposits of northern Chile, and showed them to be related to a newly discovered, eroded caldera complex.

Interspersed with the formal workshop meetings were visits to the mining districts of Los Bronces de Disputada, El Bronce de Petorca, and El Indio, which were selected because they illustrated specific characteristics of mineral deposits in volcanic centers. Los Bronces, a porphyry copper deposit operated by the Cía. Minera Disputada de Las Condes, is characterized by at least seven hydrothermal breccia pipes and a diatreme in a terrane dominated by a quartz monzonite pluton. The breccia fragments in the pipes have selvages of black tourmaline and cavities between fragments are filled with pyrite, chalcopyrite, and specularite. This deposit apparently formed in a hydrothermal system that vented to the surface but no evidence remains of any former volcanic landform. Carmen Holmgren (Chile) described the geology of the deposit in a lecture at the mine. In contrast, the El Bronce deposit consists of gold-bearing polymetallic base-metal veins genetically related to a Late Cretaceous, deeply eroded caldera. Chief Geologist Francisco Camus and other company geologists provided information about the geology of the deposit and gave the workshop participants a guided tour of surface and underground exposures of the vein system.

At a workshop meeting hosted by the University of La Serena, Ramón Moscoso (SERNAGEOMIN) described the regional geologic setting of the El Indio gold-silver-copper deposit, and Patricio Valenzuela and David Carmichael (Cía. Minera San José) discussed the geology of El Indio and the nearby El Tambo deposits. Subsequently, Valenzuela and Carmichael conducted a tour of the deposits. El Indio was discovered during an exploration program initiated in the mid-1970's by the St. Joe Minerals Corp. It consists of two types of epithermal veins: gold-quartz and massive enargite-pyrite, in an intensely altered volcanic complex of Oligocene -Miocene age, located in the high Andes near the Argentine border. Ore grades are variable, but one of the major gold-quartz veins averages about a quarter kilogram of gold per tonne, and locally has grades of as much as several kilograms of gold per tonne. The massive enargite-pyrite veins contain 4-10 g/t Au. The nearby, more recently discovered El Tambo deposit, consists of gold associated with barite and alunite in breccia pipes and veins. Typical ores contain 2-20 g/t Au and up to 50 g/t Ag.

During the closing session of the workshop, the workshop leaders led discussions of models of hydrothermal systems and their application to mineral exploration. Henley reviewed models of active geothermal systems and made comparisons to features in epithermal gold deposits. He emphasized the need to recognize the upflow and outflow parts of geothermal systems, which influence the location of ore deposition, and showed how fluid inclusions could be used to achieve this end. Cunningham discussed the use of the 1986 U.S. Geological Survey book "Mineral Deposit Models" (Bulletin 1683), pointing out that the organization of models of the different types of deposits according to host-rock lithology and the indexing of these types by commodity and mineralogy make the book a particularly useful reference. He also demonstrated ways to use fluid inclusions in paleothermal systems to determine position in a vein system relative to the paleowater table and to document processes that caused ore deposition such as boiling or effervescence. Panteleyev discussed the important features of a mineral deposit model and led a group exercise in the preparation of a model. The workshop was closed with a summary statement by Jorge Skarmeta (Sub-Director of Geology, SERNAGEOMIN).

## THE EPITHERMAL MODEL, ITS BASIS AND IMPLICATIONS FOR EXPLORATION

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Modeling of the chemical environment of ore transport and deposition in fossil epithermal systems may be achieved with perhaps greater confidence than for other families of ore deposits where, as yet, modern equivalents have not been located to provide the essential empirical constraints on interpretation and conceptual modeling. Such modeling has occurred as a result of the rapid accumulation of new information during of the last 15 years or so, largely through application of high-temperature experimental studies of metal complexing to interpretation of chemical systematics of active geothermal systems.

This part of the workshop focuses attention on: 1. Field data for ancient and modern (active) epithermal systems, which provide the empirical basis for such high-confidence modeling (e.g. Berger and Eimon, 1982; Hedenquist and Henley, 1985), and 2. The relation between the fluid recharge and gas characteristics of active systems, their consequent metal-transport capability, and simple but effective processes of ore deposition (Henley, 1985). Quite simply, low-salinity, high-gas fluids in silicic volcanic terranes are responsible for gold-silver transport and formation of ore low in base-metal sulfides. In andesite terrane, apart from an association with porphyry deposits, precious-metal deposits also may be formed by mixing of deep chloride waters and high-level, acidic volcanic-gas condensate. In contrast, high-salinity fluids (with chloride valves on the order of $10^4$ mg/kg), relatively low in gas, have been responsible for transport of silver and base metals to form silver-rich, gold-poor deposits such of those of Creede, Colorado, and Mexico. The important differences in the gas chemistry of gold-silver and silver-base metal ore systems are the result of interaction of the crust and lithosphere with mantle-derived melts and the metamorphic P-T conditions related to intrusion and to extension tectonics.

The simple chemical framework around which this paper is constructed can be used to predict the distribution of ores within a complex hydrothermal system, and, therefore, provide a powerful tool for mineral exploration. In particular, the recognition of the bimodality of metal transport and deposition provides an important discriminant function useful to mineral exploration. Provided care is taken to recognize the presence or absence of $CO_2$, and to correct apparent inclusion salinities accordingly, fluid inclusions, at an early stage of exploration, may be used to determine the salinity of the original hydrothermal system. Similarly, through comparison with alteration zones of active geothermal systems, the exploration geologist may determine the potential distribution and types of ores in a fossil geothermal system. For example, widespread advanced argillic alteration may overlay zones of deeper boiling, inclusions from veinlets in clasts of explosion breccias may provide data on fluid salinity, gas content, and temperature, and sulfur isotopes may distinguish between superficial alteration due to shallow stream-heated waters and more pervasive advanced argillic alteration of the Goldfield-type deposits (Bethke, 1984).

The continuing development of analytical techniques, experimental data for hydrothermal chemistry, and studies of large-scale geochemical processes in the crust, of which geothermal activity is but one example, will provide the essential tools for future mineral exploration.

## GENETIC MODELS FOR VOLCANIC-RELATED EPITHERMAL GOLD DEPOSITS IN THE WESTERN UNITED STATES

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Mineral deposit models for epithermal gold deposits can be efficient tools for exploration and resource assessment. Descriptive models have been proposed by many geoscientists during the past few years to systematically arrange geological, geochemical, and geophysical data that help to describe the common attributes of certain groups of gold deposits. Genetic models are attempts to explain the origin of these features by physicochemical processes.

Epithermal, volcanic-related gold deposits can be grouped into several natural categories by using genetic models (Berger, 1985, 1986a, b; Berger and Eimon, 1983; Bonham and Giles, 1983; Cox and Bagby, 1986; Hayba *et al.*, 1985; Heald *et al.*, 1987; Mosier *et al.*,1986a, b, c; Nelson and Giles, 1985; Silberman, 1982). Hot-spring deposits are characterized by the presence of siliceous sinter, hydrothermal breccia pipes, and bedded explosion breccias caused by the steep thermal and pressure gradients affecting hydrothermal systems near the surface. These deposits are commonly enriched in mercury, arsenic, and antimony, and are the fossil analogs of modern hot-spring systems such as Steamboat Springs, Nevada (White, 1980, 1985), and Waiotapu and Broadlands, New Zealand (Weissberg *et al.*, 1979; Hedenquist and Henley, 1985). Examples of hot-spring gold deposits in the United States include McLaughlin, California (Lehrman, 1986), the Buckskin-National district, Nevada (Vikre, 1985), Hasbrouck, Nevada (Bonham and Garside, 1979; Graney, 1987), and Sulfur, Nevada (Wallace, 1980).

Adularia-sericite precious-metal deposits are characterized by an alteration-mineral assemblage dominated by adularia and (or) sericite and the lack of hypogene acid-sulfate alteration and enargite (Heald *et al.*, 1987). These deposits formed well after host-rock emplacement, by circulating, nearly neutral hydrothermal solutions that apparently are related to deep heat sources. Examples of adularia-sericite precious-metal deposits in the United States include Round Mountain, Nevada (Tingley and Berg, 1985; Shawe *et al.*, 1986), Creede, Colorado (Steven and Eaton, 1975; Bethke *et al.*, 1976; Barton *et al.*, 1977; Bethke and Rye, 1979), and Bodie, California (Silberman, 1985).

Acid-sulfate gold deposits are characterized by an alteration-mineral assemblage dominated by hypogene alunite, commonly with associated enargite (Heald *et al.*, 1987). These deposits usually formed shortly after the emplacement of their host rocks from acidic solutions closely related to magmatic systems (Heald *et al.*, 1987). Examples of acid-sulfate deposits in the United States include Goldfield, Nevada (Ashley, 1979, 1982), Summitville, Colorado (Stoffregen, 1987), and Marisvale, Utah (Cunningham *et al.*, 1984).

Gold-telluride deposits are characterized by the association of gold-telluride mineral with fluorite, carbonate minerals, and adularia. These deposits are commonly associated with alkaline volcanic rocks and breccia pipes. Examples of gold-telluride deposits in the United States include Cripple Creek, Colorado (Thompson *et al.*, 1985), Golden Sunlight, Montana (Porter and Ripley, 1985), and Jamestown, Colorado (Nash and Cunningham, 1973).

The various types of epithermal deposits may be transitional from one to the other in time and space. The hypogene acid-sulfate Alunite Ridge system near Marysvale, Utah (Cunningham *et al.*, 1984), is in the uppermost part of a sericite-bearing base- and precious-metal system (Beaty *et al.*, 1986). Buckskin-National and Bodie appear to be transitional from hot-spring to adularia-sericite environments (Vikre, 1985, 1986; Hedenquist, 1986; Silberman and Berger, 1985).

Recent significant publications on epithermal, volcanic-related, gold deposits include papers in Tooker (1985); Berger and Bethke (1985); Tingley and Bonham (1986); Henley, Hedenquist and Roberts (1986), and Johnson (1987).

# PRECIOUS METAL BEARING HYDROTHERMAL SYSTEMS IN VOLCANIC CENTERS; MODELS FROM THE CANADIAN CORDILLERA

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Gold has been mined in the Canadian Cordillera (British Columbia and Yukon) since 1852. Production in 1986 was 12,752 kg (396,630 ounces), approximately 12 percent of total Canadian gold output. In recent years, traditional exploration methods (Table 1) as well as new exploration methods based on conceptual geologic models have met with success.

**TABLE 1. EXPLORATION TECHNIQUES UTILIZED IN THE SEARCH FOR PRECIOUS MOETALS IN THE CANADIAN CORDILLERA**

| | | |
|---|---|---|
| 1. | GEOLOGY | - Site selection - Regional, local |
| 2. | EXPLORATION | |
| | a. Basic prospecting | - Especially along structural breaks |
| | b. Air photography | - Especially for structure and alteration zones utilizing:<br>Black and white mosaics<br>Colour<br>Satelite imagery (*e.g.* Landsat) |
| | c. Geochemistry | - Mainly Au and Ag, other metals locally<br>- Silts (conventional and heavy media separation)<br>- Soils -including frost heaved talus (using a grid sampling)<br>- Soil gas (unsuccessful due to climate)<br>- On site Hg analyses |
| | d. Geophysics | - EM with resistivity attachment (e.g. line spacing 25 m with 12.5 m stations)<br>- IP with 800 m reconnaissance type spacing - Multipole works well for large, low-grade targets<br>- VLF mainly inconclusive, locally useful<br>- Magnetometer for alteration zoning and skarn asociations |
| | e. Trenching | - Handblasting generally ineffective<br>- Backhoe very effective to 5 m |
| | f. Drilling | - Diamond drilling with large diameter core and good recovery provides maximum geologic and economic data.<br>Percussion/reserve circulation ore cost effective |
| | g. Underground | - Ore reserve definition and bulk sampling for metallurgical testing |
| 3. | GEOLOGY | - Interpretation, Summary Reports |
| (4). | ENGINEERING / FEASIBILITY | |

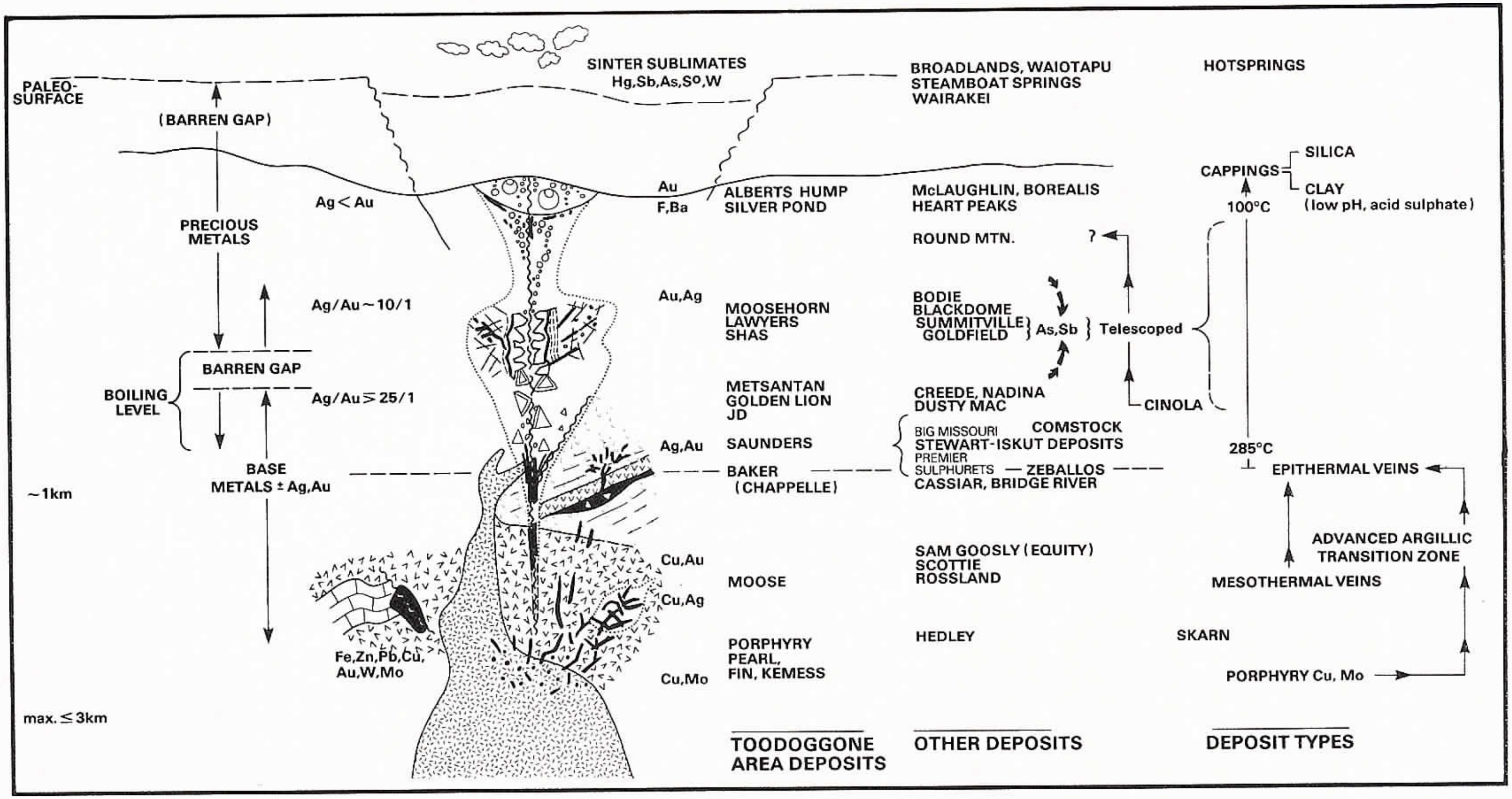


FIG. 1. British Columbia epithermal model. (Modified from Panteleyev and Schroeter, 1986.)

The western, eugeoclinal part of the Canadian Cordillera is a collage of allochthonous, predominantly island-arc and oceanic terranes, accreted to the North American miogeocline and craton along a convergent or transform plate margin. A variety of environments for precious metal mineralization are present in the various volcanic and related plutonic arcs and their overlapping continental volcanic rocks. The deep dissection and erosion of the region, with maximum relief of over 6,000 m, requires consideration of depth zoning models (Fig. 1). These describe the various mineralizing environments from surface hot springs to epizonal, transitional, and mesozonal sites. Future regional exploration will increasingly rely on the application of depth-zoning geologic models.

The primary focus for recent exploration in the Canadian Cordilleras has been on epithermal precious-metal deposits, mainly small, high-grade veins or breccia-related deposits in subaerial volcanic rocks and regions with subvolcanic plutons. A few deposits are large, low-grade occurrences in volcanic or sedimentary rocks that are amenable to open-pit mining. Most of the epithermal deposits resemble the "Tertiary-type" or bonanza-vein deposits of volcanic or fossil hot-spring association in the southwestern United States. A notable difference is that many deposits in the Canadian Cordillera are not Tertiary in age, some of the major deposits such as those in the newly discovered Toodogonne area and the historic Stewart mining camp are of Mesozoic age. Host rocks for these deposits are calc-alkaline to alkaline andesitic volcanic rocks in back-arc or accreted island-arc terranes. Other precious-metal deposits in the volcanic and plutonic arcs of the Canadian Cordilleras are epizonal porphyry-related breccias and quartz-carbonate replacement (manto) and detachment-type deposits. Deeper settings, transitional between epizonal and mesozonal, have gold and silver vein and replacement deposits and gold-bearing skarn and propylite deposits.

## TECTONIC AND MAGMATIC EVOLUTION OF THE SOUTHERN CHILEAN CENTRAL ANDES

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Over most of its length, the Central Andean region consists of a magmatic arc built over a Paleozoic and Precambrian basement. This arc was flanked to the west by a trench and to the east by a thrust-faulted and folded foreland basin. The Andes are primarily a longitudinal chain of mountains formed at a subduction system that has been active at least since Paleozoic time. However, their complex history is the result of changes in the dynamics of lithospheric plates throughout Phanerozoic time. In the southern Central Andes, variations in the development of hydrothermal systems and ore deposits correlate with changes in tectonic settings and associated igneous activity along the western margin of the South American plate (Fig. 1). Successive scenarios for this convergent margin include compressional tectonics and associated arc igneous activity, and transitional basaltic or bimodal basalt-rhyolite igneous activity, associated with intra- and back-arc extensional tectonics.

The Late Paleozoic Andes correspond to a 4,000 km long magmatic arc bounded oceanwards by an accretionary prism and towards the Gondwana continent by sedimentary foreland basins (Coira *et al.*, 1982; Forsythe, 1982). The magmatic arc was built over a collage of autochthonous and allochthonous terranes, the latter accreted to the South American magin from Late Ordovician to Triassic time. The accretionary prism that developed south of Taltal (25°S) (Bell, 1982) includes basins and subducted complexes (Davidson *et al.*, 1987) associated with paired metamorphic belts (Hervé, 1977, Hervé *et al.*,1984), fragments of ocean floor, and deep sea turbidites. Calc-alkaline, mantle-derived igneous rocks that are well exposed in the Andes north of 31°S consist of "I" and "S" type granitoids and related comagmatic volcanic rocks (Mpodozis *et al.,* 1985). Extensive exposures of thick sequences of late Paleozoic-Early Triassic rhyolitic ash-flow tuffs and intermediate lavas, closely related to large granitic plutons, crop out along crest of the Cordillera de Domeyko. Such occurrences imply the existence of calderas and composite volcanos (Davidson *et al.,* 1985). Widespread hydrothermal activity and significant vein and strata-bound metallic mineral deposits are associated with these volcanic complexes (Boric *et al.,* 1985; Davidson *et al.,* 1985).

The Mesozoic Central Andes (Triassic-Early Cretaceous) constitute a well-defined linear magmatic arc built over late Paleozoic fore-arc assemblages and bounded to the east by ensialic back-arc sedimentary basins (Coira *et al.,* 1982). During the Jurassic and Early Cretaceous the Andean margin was extensional and segmented (Mpodozis and Ramos, in press). The angle of subduction of the Aluk plate is inferred to have been steep. As is the case for the Cenozoic, no fore-arc petrotectonic assemblages of Mesozoic age have been recognized, because probably such rocks were removed by either abrasive subduction erosion (Rutland, 1971) or lateral displacement along crustal strike-slip faults in the coastal area (Forsythe *et al.,* 1987). If due to faulting, that part of the sub-alkaline volcanic arc would be considered a displaced terrane. The environment in which the hydrothermal mineral deposits of Mesozoic age formed were varied. The low-stress regimes that prevailed in the Early Mesozoic, together with submarine volcanic environments, would favor the formation of Kuroko manto-type and submarine metal-exhalative deposits hosted by Jurassic-Early Cretaceous volcanic rocks (Sillitoe, in press). In the latest Early Cretaceous, gold-rich, porphyry copper deposits associated with comagmatic, calc-alkaline, mantle-derived extrusive rocks were formed. The low initial $^{87}Sr/^{86}Sr$ ratios (< 0,7050) for both intrusive and hydrothermally altered rocks, indicate a magmatic source for the hydrothermal fluid that formed these deposits (Munizaga *et al.,* 1985). Collapse calderas of Cretaceous age, now deeply eroded, were the sites of widespread hydrothermal alteration and epithermal precious and base-metal vein-type mineralization.

The Late Cretaceous Andes of Northern Chile, including the Domeyko Proto-Cordillera, formed a positive topographic feature associated with basement-involved thrust faulting of the sedimentary sequences, probably linked to A and B subduction processes (Mpodozis and Ramos, in press). During this time a lull in igneous and hydrothermal activity occurred in northernmost Chile, probably as a consequence of a major tectonic and paleogeographic change that took place during middle Cretaceous (*ca.* 100 Ma). The paleogeographic arrangement included subduction shifts from a low-stress Marianas-type regime to a high-stress Chilean-type regime, probably due to inception of Atlantic spreading and westward movement of the South America plate (Coira *et al.,* 1982). In contrast, significant magmatic activity took place during Late Cretaceous south of Illapel (31°S) where hydrothermal alteration zones and epithermal precious and base-metal deposits are associated with volcanic structures (Camus *et al.,* 1986).

The Early Paleogene Andes (Paleocene-Eocene) consisted of a large volcanic field that formed in the position of the present-day Longitudinal Valley and Precordillera of Northern Chile (21-30°S). The volcanic rock represent a 41-70 Ma, bimodal, sub-alkaline, andesitic-basaltic and rhyolitic assemblage and related subvolcanic porphyries and large granitic plutons. Epithermal precious-metal deposits and extensive hydrothermal alteration zones are present in this volcanic terrain where deeply eroded and nested collapse calderas and domes are still recognizable (Puig *et al.,* 1988).

In the Oligocene, volcanism diminished and then ceased in Northern Chile (Coira *et al.,* 1982), perhaps as a consequence of a highly oblique convergence and subduction mode between continental and oceanic plates (Cande and Leslie, 1986). Magmatism was restricted to transtensional zones of crustal weakness related to strike-slip faults along which all major, mantle-derived porphyry copper deposits were emplaced.

The Neogene-Quaternary Andes are a non-collisional mountain belt divided into volcanic and non-volcanic segments, at least from latest Neogene. The segments coincide with well defined tectonic provinces and segments of the subducted Nazca Plate beneath South America (Jordan *et al.,* 1983). Modern magmatic activity is restricted to the north of 27°S (Central Volcanic Zone, CVZ) and to the south of 33°S (Southern Volcanic Zone, SVZ). Isotopic and geochemical data show that the CVZ volcanics have large crustal participation (Harmon *et al.,* 1984). Most of the known Neogene hydrothermal alteration zones and metallic and native sulfur deposits in the Andes of Northern Chile, Bolivia, and Peru are associated with composite volcanos, dome complexes and collapse calderas, and with subvolcanic intrusions and geothermal fields

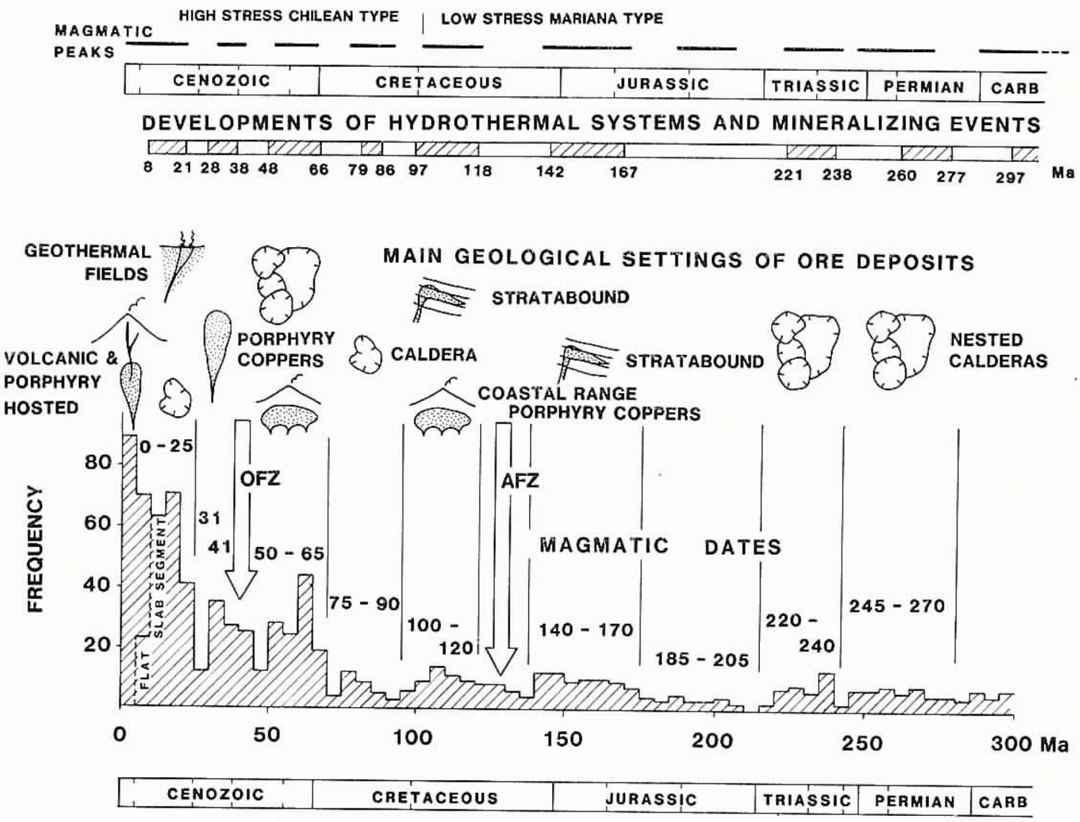


FIG. 1. Major tectonic and magmatic events in the southern Chilean Central Andes.

not known to be related to volcanic landforms. Calc-alkaline magmatic activity and subsequent deformation was influenced by the inception of the spreading on the East Pacific Rise, and cessation of activity along the Farallon-Nazca Ridge at some 10 Ma (Mammerickx *et al.*, 1980). Prior to that time, the Late Oligocene to Middle-Miocene magmatism in the southern Central Andes was probably related to the changing geometry of the subducted Nazca Plate (Kay *et al.*, 1987).

Igneous, structural, and metallogenic patterns of the southern Central Andes are expressions for sequences and trends of events that affected the entire Andean Cordillera throughout Andean Phanerozoic evolution, as follows: **a.** A continuous growth of the continental margin of Gondwanaland by accretion of allochthonous terranes and deformation by collision tectonics, beginning in Early Paleozoic; **b.** A subduction related, wide, calc-alkaline magmatic belt built over the former terranes during late Paleozoic; and **c.** Segmented arc-back-arc systems during Jurassic and Early Cretaceous, a system that evolved into a unique high-stress calc-alkaline magmatic arc dating from Late Cretaceous to the Present.

## GOLD AND SILVER DEPOSITS IN THE CENTRAL AND SOUTHERN ANDES

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The Andes Mountains were the source of large amounts of gold and silver from many deposits from northern Colombia to southern Chile. Early producers of these metals were Pre-Columbian Indians who mined the gold and silver sent to Spain by the Conquistadores. Still larger amounts of gold and silver were mined during Spanish Colonial times, from the early 16th century until independence in the early 19th century, and mining continued into Post-Colonial times. At present, the Andean region as a whole is the world's major silver producer and a significant gold producer.

Many gold and silver deposits occur in the Andean regions of Perú, Bolivia, Chile, and Argentina, in part in well-defined belts. For example, a large number of silver deposits are found in a belt extending from Hualgayoc, northern Perú, to the Sur Lipez region of southern Bolivia. Two of the world's largest silver deposits, Cerro de Pasco in central Perú and Cerro Rico de Potosí in southern Bolivia, are in this belt. Another belt to the west extends from the Salpo and Quiruvilca mining districts, northern Perú, to the Todos Santos district in west central Bolivia, near the Chilean border. This belt includes important silver deposits in the Cordillera Negra, northern Perú, the Arcata and Orcopampa mining districts, southern Perú, and the Choquelimpie deposit, northern Chile. Most of the deposits in these two belts are genetically related to hydrothermal systems in volcanic centers of late Tertiary age. Taken together, this region constitutes one of the world's greatest silver provinces.

Gold also occurs in well-defined belts in the central and southen Andes, of which one of the most important is that in which the recently discovered El Indio deposit is located. This belt, as yet incompletely explored, may be as much as 200 km long, extending both to the south and north of El Indio. Other well defined gold belts are in western Perú, extending from the Sol de Oro district in the north to the Andaray district in the south, and the Pataz-Parcoy-Buldibuyo region of the eastern Peruvian Andes. Ruiz and Ericksen (1962) defined a gold belt in the coastal region of Chile, extending from near Talca in the south to Taltal in the north. A recently discovered gold district in the vicinity of Salar de Maricunga, east of Copiapó is within still another longitudinal belt of significant economic potential. The pattern of distribution of hydrothermal gold deposits in Bolivia is not clear, buy most of the known deposits are associated with late Tertiary volcanic centers north of Potosí.

The potential for discovery of new gold and silver deposits in the central and southern Andes is excellent, as is indicated by the many discoveries made during the past decade. These discoveries have enhanced our knowledge of precious metal deposit models, particularly for deposits in Tertiary volcanic terrain. Application of new information about these deposits should be of great assistance in future exploration.

## GEOLOGICAL, MINERALOGICAL, AND CHEMICAL CHARACTERISTICS OF EPITHERMAL PRECIOUS-METAL DEPOSITS IN SOUTHERN PERU

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The Cenozoic volcanic belt of the Cordillera Occidental, southern Peruvian Andes, is about 400 km long, 50 km wide, and has many precious metal deposits that belong to the silver-base metal sub-province of the Andes. These deposits are the result of hydrothermal mineralization associated with pulses of ig-

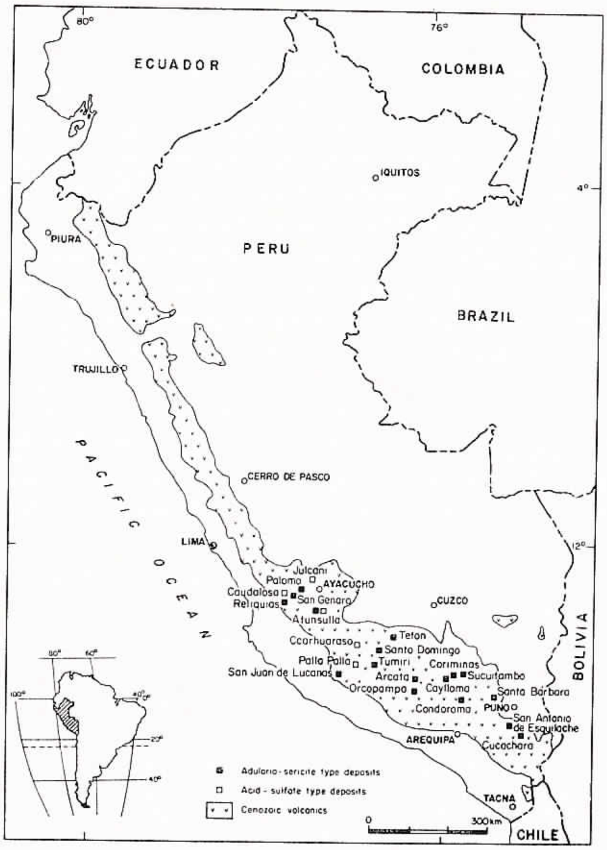


FIG. 1. Southern Perú epithermal precious-metal deposits in Cenozoic volcanics.

neous activity during three Neogene intervals called Quechua I, II, and III (19, 9.5, and 6 Ma). The volcanic host rocks are of late Oligocene of late Miocene age and include the Tacaza (30-17.5 Ma), Palca (16,9 Ma), Sillapaca (14-12.8 Ma) and Maure (12.6 Ma) Formations. Younger post-mineral volcanic rocks are of late Miocene to Pleistocene age and include the Barroso (6-1 Ma) and Ampato (1 Ma) formations (Fig. 1).

Two types of volcanic hosted epithermal precious-metal deposits are recognized in southern Perú: 1. Adularia-sericite (silver sulfosalts-gold type), and 2. Acid-sulfate (enargite-tetrahedrite-gold type). The first type is found chiefly in southern Perú and the second type in south-central Perú. Both types may be present in some mining districts, as they do in the Castrovirreyna (San Genaro, Reliquias, Caudalosa, and Bonanza) and Atunsulla districts.

Deposits of the first type represent the classic epithermal, silver-bearing sulfosalts and gold vein systems having phyllic alteration characterized by abundant adularia. The principal ore minerals are native silver, argentite, pyrargirite, polybasite, stephanite, miargirite, native gold, electrum, tetrahedrite, chalcocite, and base-metal sulfides. Gangue minerals are quartz, calcite, dolomite, rhodochrosite, adularia, and pyrite. Hydrothermal fluid temperatures range from 180° to 280°C (Arcata) or 255°C (Orcopampa), and salinities are 2 to 5 wt percent NaCl equiv. (Arcata). The deposits are associated with: 1. The resurgent caldera Nevado Portugueza (San Julián and La Libertad in Atunsulla), Chonta (Sucuitambo, Coriminas, San Miguel, Caylloma), Tumiri, Tetón (Tetón-Santo Domingo), San Martín (San Martín-Farallón); 2. Volcanic domes (San Genaro, Reliquias, Palomo in Castrovirreyna, Julcani, Orcopampa, Arcata, Santa Bárbara, and Cacachara); 3. Faults (Orcopampa, San Juan de Lucanas, Condoroma); 4. Intrusive bodies (San Antonio de Esquilache, Orcopampa, and Condoroma). Deposits have the following ages: Santa Bárbara (19.8 Ma). Orcopampa (17.0 Ma), Caylloma (17.1-15.8 Ma), Santo Domingo (11.7 Ma), Sucuitambo (11.4 Ma), Coriminas (10.5 Ma), Cacachara (7.1 Ma), Arcata (5.0-4.5 Ma), and Atunsulla (1.9 Ma).

Deposits of the second type are enargite-tetrahedrite-gold vein systems having advanced argillic alteration characterized by abundant alunite. The principal ore minerals are enargite, tennantite-tetrahedrite, native gold, electrum, bournonite, dismuthinite, silver-bismuth sulfosalts, stibnite, and base-metal sulfides. Gangue minerals are quartz, pyrite, barite, siderite, rejalgar, and orpiment. Hydrothermal fluid temperature range from 270° to 325° (Caudalosa) and from 295°C to 325°C (Julcani). Salinities are 4-18 (Caudalosa) and 5-24 (Julcani) wt percent NaCl equiv. The deposits are associated with: 1. The resurgent caldera at Nevado Portuguesa (Rosario in Atunsulla); 2. Stratovolcanos (Ccarhuaraso and Palla Palla); 3. Volcanic domes at Julcani and Castrovirreyna (Caudalosa, Candelaria, and Bonanza); and 4. Faults (Cerro Anta in San Juan de Lucanas). Radiometric ages are: Julcani (9.8 Ma) and Ccarhuaraso (1.2 Ma).

The deposits are located at distinct lineaments or fault zones. Precious metal ore in both types of deposits occurs chiefly in well defined veins, although some ore is in hydrothermal breccia bodies (Santa Bárbara, Ccarhuaraso, Caudalosa, and Anta in San Juan de Lucanas). The veins strike N25°-40°W, N40°-75°E, and E-W. The range from 200 m to 4 km in length, and are generally a few tens of centemeters to 1.5 m in width.

The Caudalosa Candelaria-Bonanza vein system in the Castrovirreyna district has an exceptional length of 9 km, whereas the Calera vein in the Orcopompa district and San Cristobal vein in the Caylloma distric have exceptional maximum widths of 10 and 25 m, respectively. Gold and silver ores extend to relatively shallow depths and gold increases with depth in some veins. Ruby silver ores give way to polymetallic base-metal ores at depths of 300-400 m (San Juan de Lucanas, Caylloma, San Genaro, Reliquias, Condoroma, San Antonio de Esquilache (they are zoned, and tetrahedrite persists at depths in the Julcani and Castrovirreyna districts.

## HYDROTHERMAL SYSTEMS RELATED TO A PALEOGENE CALDERA COMPLEX IN NORTHERN CHILE; EL GUANACO, CACHINAL DE LA SIERRA AND EL SOLDADO MINING DISTRICTS, ANTOFAGASTA REGION

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The epithermal precious metal deposits El Guanaco (Au, Cu), Cachinal de la Sierra (Ag) and El Soldado (Ag) are aligned along 69°32'W for a distance of 27 km between 24°52.1' and 25°06.5'S. They are genetically related to a Paleocene-Eocene volcanic arc that formed after a major reorganizing tectonic phase in middle Cretaceous (Subhercynian) time, as a first intracontinental arc after a fore-arc, arc, back-arc system of Late Triassic to Early Cretaceous time. The Paleogene volcanic rocks are subalkaline, ranging in composition from basalts to rhyolites, but with andesites and dacites predominant. Eroded eruptive centers showing volcanic necks or subvolcanic bodies with radial dikes have been recognized in this unit. A two-resurgent caldera model is proposed as the source of the volcanic sequence that crops out in the area between El Soldado and El Guanaco districts. This model is supported by detailed geologic mapping, by petrographic studies, and by K-Ar dating of 26 mineral concentrates of hydrothermally altered and unaltered volcanic rocks of the area.

The El Guanaco, Cachinal de La Sierra, and El Soldado deposits are in rocks of the caldera complex and were formed by hydrothermal systems related to the final phase of the caldera evolution. El Soldado, in the northern part of the area, consists of veins along faults striking N15°W. Silver and minor amounts of gold have been mined from 0.5-3.0 m wide and 600 m long quartz veins containing argentiferous galena, sphalerite, chalcopyrite, cerusite, proustite, argentite, pearceite, calcite, siderite, native gold, and copper oxides. The Cachinal de La Sierra deposit, to the south, consists of at least 14 veins having vertical ore shoots in a zone 20 m wide and 200 m long, which extends to a depth of 120 m. Hydrothermal alteration is of the adularia-sericite type; ash-flow tuff host rocks are silicified. Hypogene minerals consist of argentiferous galena associated with quartz-adularia-fluorite gangue. Supergene specularite, anglesite, cerusite, limonite, pyrargyrite, chalcocite, and covellite are found in the near-surface oxide zone. Veins at El Guanaco are related to an E-W fracture zone in intensively silicified volcanic rock surrounded by an irregularly distributed, advanced argillic alteration (quartz, alunite, kaolinite, dickite) zone. Outside this central zone of intense alteration, the rock shows weak chloritic alteration. Supergene ores have been mined in ore shoots up to 50 m in diameter consisting of fracture-filling veins of native gold, barite, hematite, and alunite. Hypogene mineral assemblages consist chiefly of pyrite, enargite, luzonite, and minor chalcopyrite, which are similar to assemblages for acid-sulfate or enargite-gold type deposits.

The Cachinal de La Sierra and El Guanado deposits are at the western margin of a caldera, called the Cachinal caldera, of which only the western part has been preserved. The El Soldado deposit is at the intersection of this caldera and the 7 Ma younger, 8 km diameter El Soldado caldera to the north. It consists of veins distributed radially along the rim of El Soldado caldera. Rocks associated with the older Cachinal caldera include a diorite porphyry stock, called the Cachinal diorite, and coeval, petrologically similar pyroxene andesite lavas; radiometric ages are 62-60 Ma. These rocks crop out to the east of El Guanaco and to the north of Cachinal de La Sierra. The Cachinal-Guanaco tuff unit, a major ash-flow sheet having a K-Ar age of 61-60 Ma, is interfingered with the youngest lavas, but overlies older lavas of this unit. This tuff unit extends throughout the area and westward for about 40 km. The Peñafiel Fracture, a remarkable N-S structure extending from Cerro La Isla to Cerro Campana, marks the ring fracture zone of the caldera. The resurgent dome lies to the east of this fracture, where the uplifted floor of the caldera shows dacitic dikes and laccolithic stocks (Cerro Islote). Dacitic domes were emplaced along the Peñafiel Fracture. Some of these domes show a vitrophyric chill margin. Paleofumarolic zones and hydrothermal breccias are present at places along the margins of the domes. The emplacement of the domes was asynchronous from north to south (59-56 Ma), and the magnitude of caldera collapse also changes from north (Cachinal de La Sierra) to south (El Guanaco). The caldera sedimentary fill consists of green conglomerates and sandstones cropping out east and south of the mine areas. The veins at Cachinal de La Sierra and El Guanaco are controlled by the local fractures, which at El Guanaco are parallel to a major ENE structure truncating the caldera in the south, whereas the veins at Cachinal de La Sierra are controlled by the Peñafiel Fracture. The mineralization is genetically related to the youngest dacitic domes as indicated by the age (59 Ma) of sericite from two different veins.

## THE EL INDIO AND EL TAMBO GOLD DEPOSITS, CHILE

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The El Indio and El Tambo gold deposits are located several kilometers apart in the Chilean Andes, approximately 180 km east of La Serena. These deposits are the first major gold operation in Chile in which gold is not a relatively minor by-product of copper ores. Full scale mining operations began in 1981 from both underground and surface workings.

The deposits are hosted by Tertiary volcanic rocks that form a prominent N-S belt between thrust faults. Volcanism changed between 8.2 and 11.4 Ma (Araneda, 1982) from extensive andesite flows to the rhyolitic and dacitic pyroclastic tuffs that are the principal host rocks of the deposits. The tuffs show the effects of intense hydrothermal alteration and contrast sharply with the dark, propylitically altered andesites. Argillically altered tuffs which are most prevalent, contain abundant kaolinite, sericite, and dickite with minor pyrophyllite and montmorillonite. Alunite, jarosite, barite, and native sulfur are widespread. Flat-lying, unaltered andesite-trachyte flows partly overly the altered tuffs.

Three distinct types of ore are recongnized at the El Indio and El Tambo deposits. The ore is structurally controlled, occurring along extensive tensional fractures and shorter, sigmoid fractures oblique to major fault zones. At El Tambo, ore is present in breccia pipes as well as veins.

The bulk of El Indio's ore is derived from massive enargite-pyrite veins having typical grades of 6-12 percent copper, 4-10 grams/ton gold, and 60-120 grams/ton silver. The veins contain 90 percent enargite and pyrite together with minor copper sulfides and sulphosalts, and 10 percent altered wall rock. Much of the enargite-pyrite ore comes from two major vein systems, the Mula Muerta and Viento, that together contain 35 percent of El Indio's plant-grade ore reserves. The massive sulfide veins change laterally to stringers and stockworks, then to weakly mineralized or barren, fracturated wall rock marked by intense argillic or propylitic alteration.

The richest gold ore is in quartz veins that are younger than the enargite-pyrite veins; much is direct shipping ore (over 100 grams/ton Au). The most famous vein is the Indio Sur "3.500" vein, named from the result of an early exploration assay of 3500 grams/ton Au (Jannas and Araneda, 1985). This vein has been tested to a depth of 270 m, but its lower limit has not been determined. It has a noteworthy increase in copper and arsenic at depth as a result of increasing amounts of enargite and copper sulfosalts (Walthier *et al.*, 1985).

The third type of ore consists of gold with occasional barite and alunite at the El Tambo deposit. The ore-bearing breccia pipes, such as the Kimberly breccia pipe, are irregularly shaped, circular to elliptical in plan view and dip steeply. The dacite wall rocks that host the pipes are most intensely brecciated, rotated, and commutated. After formation, the breccia pipes were silicified. This was followed by mineralization and the formation of barite, alunite, and locally rodalquilarite. Gold is preferentially associated with barite, to a lesser extent quartz, and least with alunite. Breccia ores pass into barite and alunite veins at depth, which are interpreted as occupying original hydrothermal conduits. Over 80 percent of the gold at El Tambo is native, but many gold-tellurides, arsenates and silver minerals are present (Siddeley and Araneda, 1986).

A recent comprenhensive description of the deposit is in Siddeley and Araneda (1986). The following information on production and reserves was presented at the workshop:

| | **Production during 1986** | | | |
|---|---|---|---|---|
| | **Metric tons** | **g/ton Au** | **g/ton Ag** | **% Cu** |
| Direct shipping ore | 18,961 | 170.1 | 93 | 2.86 |
| Plant ore | 642,224 | 9.8 | 62 | 2.96 |
| | **Ore reserves as of November 1, 1986** | | | |
| | **Metric tons** | **g/ton Au** | **g/ton Ag** | **% Cu** |
| Direct shipping ore | 46,190 | 181.3 | 116 | 4.28 |
| Plant ore | 5,535,658 | 7.7 | 95 | 4.49 |
| Heap leaching | 2,818,075 | 1.6 | -- | -- |
| | **Total metal content (production and reserves)** | | | |
| | | **kg Au** | **kg Ag** | **Metric tons Cu** |
| Production through October 1987 | | 59,110 | 145,183 | 78,531 |
| Ore Reserves on November 1, 1987 | | 54,268 | 531,246 | 250,528 |
| | Totals | 113,378 | 676,429 | 329,059 |

# NEOGENE QUATERNARY VOLCANISM IN NORTHERN CHILE

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The Andes of northern Chile form major volcanic province characterized by extensive rhyolitic and dacitic ash-flow tuff sheets and andesitic to dacitic stratovolcanos and dome complexes, and probably the greatest density of continental volcanos in the world. Volcanism has been active along a discrete belt through the Andean Cordillera in Northern Chile since Miocene time. At present, volcanism is restricted to the segment north of Copiapó, between latitudes 16° and 28°S, where volcanic activity has been continuous and intense from the Miocene to the Present. In northern Chile to the south of Copiapó, only isolated Miocene volcanic rocks are present. Oceanic lithosphere is now being subducted at an angle of 25-30° below the active volcanic area, whereas the inactive areas to the south overlie a zone of thinner lithosphere over a subduction zone dipping 10-15°. The Miocene-Quaternary volcanic complex overlies a terrane consisting of older Cenozoic, Mesozoic, and Paleozoic rocks. Recent data indicate the existence of Precambrian basement rocks in northernmost Chile, which might account for the great crustal thickness in the Central Andes, as shown by the presence of a strong positive gravity anomaly.

Major volcanic activity started during the Miocene (about 23 Ma), although geochronological studies show that in some areas volcanism began at less than 10 Ma in the region between latitudes 20° and 25°S. Stream boulders of volcanic rocks in the region show Early to Middle Miocene radiometric ages, indicating the presence of older volcanic rocks that were eroded during the Late Neogene and Quaternary. Erosion features indicate that the oldest stratovolcanos are in the westernmost parts of the volcanic region, and that volcanic centers subsequently migrated eastward into the Bolivian Altiplano and Argentine Puna. However, in recent geologic time, a reversal in this trend has occurred, and several active volcanos west of the main volcanic terrane mark a well-defined volcanic front. To the east, active volcanos are more widely scattered.

The Northern Chilean Andes are characterized by diverse volcanic landforms suchs as composite cones, calderas, domes, lava fields, and ash-flow tuff sheets. These volcanic rocks range from basalt to rhyolite. Volcanic cones are mainly andesitic; they show symmetrical profiles rising to maximum heights of 6,000 m. Monogenetic lavas form domes of dacitic to rhyolitic composition, not necessarily associated with other large volcanic landforms. Compound volcanos are composite cones that have been modified by eruption of lavas of composition different from those of the original cone. They exhibit more complex morphological profiles than the simple cones, and may have domes at summits or lower flanks. The less eroded volcanic cones commonly have native sulfur deposits and remnants of solfataras on their crests or flanks. Extensive hydrothermal alteration zones showing argillic and advanced argillic alteration and extreme silicification and hydrothermal breccia bodies are exposed in some deeply eroded volcanos. Volcanic activity, hydrothermal alteration, and mineralization show close temporal relations in many volcanic centers. Anomalous concentrations of pathfinder trace elements have been found in alteration zones at volcanic centers of Salar de Gorbea (where mineral deposits are not evident), whereas precious-metal deposits are associated with alteration and hydrothermal breccia zones in volcanic centers at Choquelimpie, northernmost Chile, and others near the latitude of Copiapó.

Ash-flow tuff sheets interbedded with lavas are widely distributed within the volcanic terrane of northern Chile, and some of the sheets extend to the Pacific coast, as much as 150 km from their source to the east. The distal parts of these sheets are interbedded with thick sequences of Miocene sedimentary rocks. Similar sequences are present in the Argentine Puna to the east. Air-fall tuffs are intercalated with alluvium at many places in valleys and in the Atacama Desert far west from the sources. Some ash-flow tuffs form shields having a lenticular cross-section and spreading outwards at low angles from a central area without a significant central collapse feature. Purico, east of Salar de Atacama, and Mamuta are examples of such a structure. Calderas showing collapse and resurgence are present at La Pacana and Cerro Caichinque. These and other calderas of the region range in size, from about 25 to 2,000 $km^2$. Many are elliptical and a few are circular in outline. The elliptical calderas generally have their long axis oriented parallel to the regional structural trend. Caldera collapse was generally followed by eruption of lavas, in some cases forming stratovolcanos and domes. Individual ash-flow tuff sheets extend over areas of as much as 7,000 $km^2$, and have volumes ranging from 0.4 to 300 $km^3$. These tuffs are calc-alkaline and, according to the chemistry of cognate inclusions and glass, range in composition from dacite to rhyolite ($SiO_2$ = 64-75%). Plagioclase feldspar is the most abundant mineral; biotite, hornblende, quartz, and sanidine occur in variable quantities, and sphene, apatite, zircon, and magnetite are common accessory minerals. Tuffs range from pumiceous, having abundant pumice fragments in a matrix of crystals, glass shards, and dust, to a porphyric rock consisting of cognate inclusions and crystals in a matrix of glass shards. Lavas are predominantly hornblende to pyroxene andesites. Biotite and hornblende dacite lavas also are abundant, whereas rhyolite and olivine basalt lavas are sparse. These typical calc-alkaline suites differ from other volcanic suite related to subduction zones in having relatively high K contents and showing enrichment in Rb and Ba. The Upper Cenozoic lavas of the Central Andes are characterized by $^{87}Sr$ enrichment, which indicates magma-crust interaction processes. Lavas in the Andes of northern Chile show $^{87}Sr/^{86}Sr$ ratios of between 0.7056 and 0.7070.

Several hypotheses have been presented to explain the origin and sources of the magmas that formed the Central Andes volcanic rocks. Information at hand indicates that they were derived from a heterogeneous mantle source but experienced assimilation, fractional crystallization, and magma mixing during ascent through continental crust.

## HYDROTHERMAL DEPOSITS IN NEOGENE-QUATERNARY VOLCANIC CENTERS OF THE CENTRAL ANDES

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Volcanic centers -including calderas, stratovolcanos, dome complexes, and fossil thermal-spring systems- in the Neogene-Quaternary volcanic complex of the central Andes (Fig. 1) contain many genetically related hydrothermal mineral deposits (Ericksen *et al.*, 1987a). Centers having some known deposits as well as others not known to have deposits are attractive targets for exploration. Most of the known deposits are of Miocene age, but deposits of Pliocene and Quaternary age also are present, and a variety of metallic minerals are now being deposited by active thermal-spring systems. By far, the most economically important types of deposits in the volcanic centers are epithermal gold-silver deposits in southern Perú and northern Chile, and polymetallic tin deposits in the central and southern part of the Bolivian tin belt. Some of these deposits have been mined almost continuously since the 16th century, whereas others have been discovered only during the past decade or two. Other deposits of known or potential economic importance are porphyry-type copper and copper-gold deposits and polymetallic base-metal deposits. Fumarolic native sulfur deposits are associated with many of the hundreds of stratovolcanos of the region. Also present are antimony, manganese oxide, uranium, wood tin, and borate deposits.

It is probable that most of the well-exposed mineral deposits in Neogene-Quaternary volcanic centers of the Central Andes have been discovered, and future exploration will require sophisticated geochemical and geophysical techniques. Mineral-deposit models will be of assistance in evaluating the numerous, apparently barren alteration zones in the volcanic centers. Recent work on the geochemistry of rhyolitic ash-flow tuffs provides new data about trace-element variations indicating that fundamental differences exist in silicic magmas with which the various types of hydrothermal deposits are associated. Such geochemical data, as yet scanty and consequently of uncertain significance, may ultimately prove useful in identify-

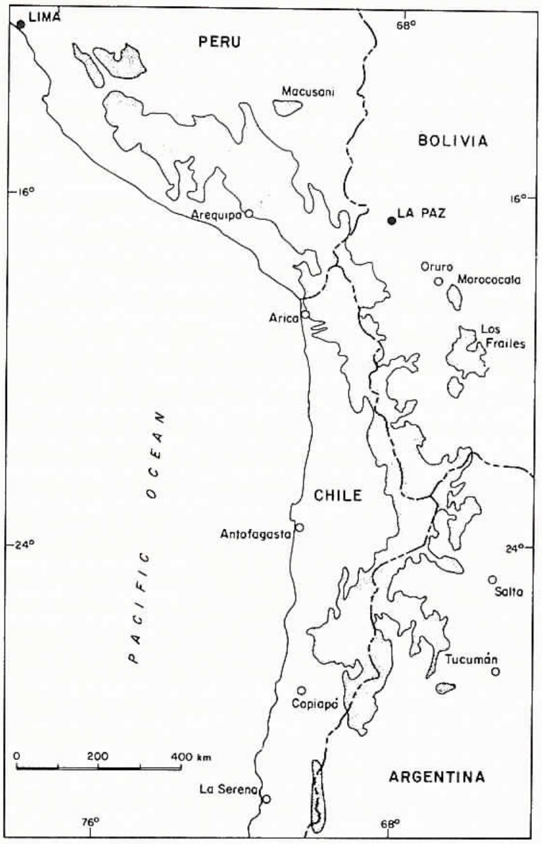


FIG. 1. Distribution of Neogene-Quaternary volcanic rocks (stipple pattern) in the Central Andes.

ing volcanic centers in which specific types of mineral deposits might be found. For example, investigations of rhyolitic ash-flow tuffs in the Central Bolivian Tin Belt, by the U.S. Geological Survey in cooperation with the Servicio Geológico de Bolivia, show that relative abundance of stable elements such as Ta, Th, Rb, and Hf are indicative of Sn-anomalous magmas (Ericksen *et al.*, 1987b). Buried intracaldera intrusions in source areas of such tuffs may have associated tin deposits. Additional work of this type may serve to distinguish magmatic sources that are favorable for the formation of other types of ore deposits.

The Neogene-Quaternary volcanic complex of the Central Andes also represents a post-mineral cover of about a third of the great central Andean mineral province, which is characterized by a great variety of hydrothermal deposits of Mesozoic and Tertiary age. Included are world-class resources of Cu, Pb, Zn, Sn, W, Sb, B, Ag, and Au, and it can be expected that many deposits of these metals remain to be found beneath the volcanic cover.

## THE GEOLOGIC SETTING AND CHARACTERISTIC FEATURES OF MAGNETITE AND COPPER DEPOSITS IN THE NORTE CHICO REGION OF CHILE

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Neocomian sedimentary and volcanic rocks of the Norte Chico region of northern Chile contain syngenetic and epigenetic deposits of copper sulfides, iron oxides, and manganese oxides that were emplaced in a back-arc basin transitional between a Jurassic marine basin and an Upper Cretaceous continental environment. Levi and Aguirre (1981) classified this Neocomian basin as an "aborted marginal basin", and considered it to have formed in a ensialic spreading regime. Although volcanism in the basin was initially bimodal, with felsic rocks predominating, subsequent Neocomian volcanism resulted in emplacement of a thick (as much as 8 km) sequence of unusual porphyritic, locally shoshonitic (Levi *et al.*, 1985) basalts and andesites, called "ocoitas" in Chile.

Of the mineral deposits in the Neocomian rocks of this region, two types, as follows, are discussed: 1. Manto-type deposits of copper that are hosted by marine and continental lavas, pyroclastic volcanic rocks, and associated sedimentary rocks, and 2. Magnetite deposits formed by replacement of andesitic volcanic rocks and genetically related to probable comagmatic diorite intrusions (Brookstrom, 1977). The copper deposits are characterized by simple mineralogy (chalcocite, bornite, chalcopyrite, pyrite, and locally, minor galena and sphalerite), by low (<250°C) temperatures of formation, and by albitic alteration halos. The dominant minerals of the magnetite deposits are magnetite, actinolite, an apatite, and minor minerals are scapolite and the sulfides pyrite >> chalcopyrite; as the result of hydrothermal alteration the host rocks are bleached and silicified. The magnetite deposits show evidence of strong structural control by deep-seated, regional faults. Some 50 magnetite deposits are recognized in a narrow belt in the Coastal Cordillera between 25° and 31°S, which coincide with the Neocomian magnetic axis. Radiometric ages of these deposits cluster around 110 Ma.

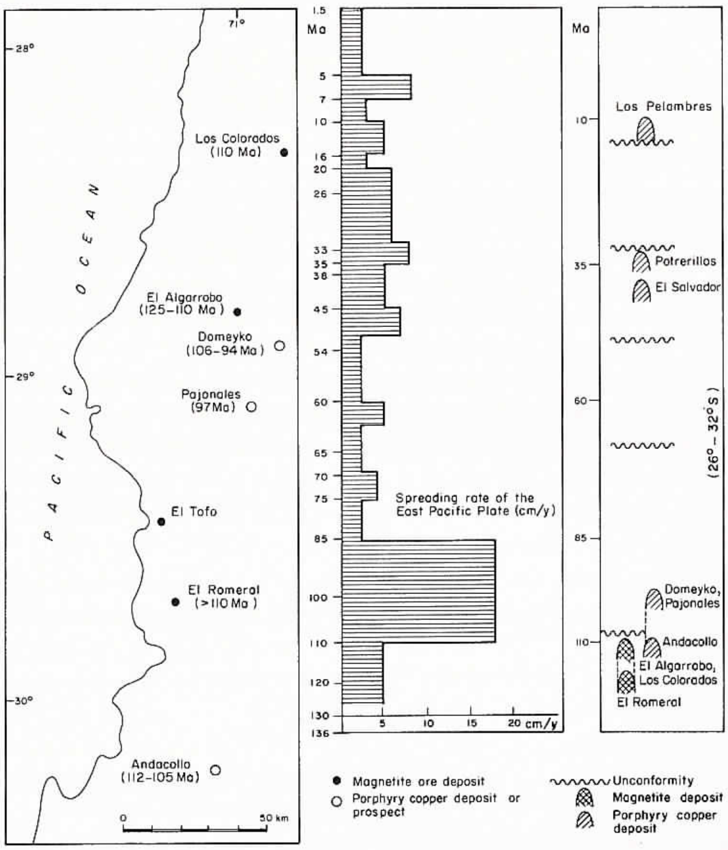


FIG. 1. Tectonic and chronological relationships for magnetite deposits in volcanic rocks and for porphyry copper mineralization.

One may speculate on the genetic relationships of the magnetite and copper deposits of this region, and on the influence of shoshonitic magmatism and spreading rates along the ancestral Pacific Rise in determining the nature and distribution of mineralization. A genetic relationship between alkali-rich residual magmas and Kiruna-type magnetite deposits has been proposed by many authors (*e.g.* Guilmour, 1985; Hildebrand, 1986). Emplacement of magnetite bodies ended about 110 Ma when there was a rapid increase in spreading rate in the Pacific Basin (Fig. 1). At about the time of this change and subsequently, porphyry copper deposits were emplaced in a belt just to the east of the magnetite deposits (Fig. 1). It is possible that the magnetite deposits were formed at deep levels in porphyry copper systems, and those now exposed are erosion remnants of former porphyry copper deposits. Magnetite is abundant in deep levels of some island-arc porphyry copper deposits, and a change from deep-level actinolitic alteration to higher level potassic alteration has been recorded at the Yerington, Nevada (U.S.A.) porphyry copper deposit (Carten, 1986). Two other possibilities exist: 1. The magnetite deposits represent the roots of former magnetite flows such as those at El Laco, northern Chile; or 2. They formely were capped by complexes of veins of apatite and magnetite or copper sulfides and gold with or without hematite, both of which are now found in areas peripheral to magnetite deposits. More information is needed to resolve the relationship between these two types of deposits.

## HYDROTHERMAL BRECCIA PIPES AT THE LOS BRONCES PORPHYRY COPPER DEPOSIT

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The Los Bronces porphyry copper deposit is the western part of the larger Los Bronces-Río Blanco porphyry copper system located on the western flank of the Andes about 69 km northeast of Santiago, Chile. This deposit formed on the eastern side of the San Francisco Batholith, a large, strongly peraluminous, calc-alkaline intrusive having alkali-calcic afinity. The batholith took a minimum of 11.5 m y, to form during the period of Early to Late Miocene (20.1-8.6 Ma). The porphyry copper mineralization, alteration, and tourmalinized breccia pipes were formed over a period of at least 2.5 m y between 7.4 and 4.9 Ma. A post-mineral rhyolite-dacite volcanic neck or diatreme, which destroyed a large part of the Los Bronces-Río Blanco porphyry copper system, was the final phase of volcanic activity in the area. K-Ar age determinations of biotites from this diatreme show it to have erupted during early Pliocene (4.9-3.9 Ma).

The pre-breccias porphyry system at Los Bronces exhibits propylitic, sericitic, silicic, and potasic alteration. A unique alteration feature of this system is the replacement of mafic minerals by specularite and/or tourmaline within the propylitic zone. The porphyry system contains disseminated and stockwork copper-iron-molybdenum sulfide minerals within an area about 12 $km^2$.

Los Bronces is composed of at least seven different copper-bearing tourmalinized breccia bodies that form a large kidney-shaped body about 2 km long and 0.7 km wide at the present erosion surface and between the altitudes of 3,450 and 4,150 m. Each of the breccia bodies is a recognizable entity characterized by differences in matrix, clasts, shape, and type and degree of mineralization and alteration. The breccias are generally monolithic but in some cases are bilithic or heterolithic, with most clasts consisting of quartz monzonite or andesite and local minor amounts of quartz latite porphyry, monzodiorite, and vein quartz. The breccia matrixes consist of variable amounts of quartz, tourmaline, specularite, anhydrite, pyrite, chalcopyrite, bornite, molybdenite, sericite, chlorite, and rock fluor. The seven different breccia bodies, from oldest to youngest, are: Ghost, Central, Western, Infiernillo, Anhydrite, Fine Gray, and Donoso. The breccia complex shows sharp contacts with the surrounding intrusive rocks and andesites, but internally, the contacts between individual breccia bodies are locally well-defined but elsewhere are indistinct or gradational. The breccias are interpreted as being emplaced explosively, followed by collapse after pressure release of hydrothermal fluids.

The primary mineral distribution is best known in the Donoso breccia, which has been the center of mining activity since discovery in 1864. The principal primary minerals -chalcopyrite, pyrite, and specularite-tend to be coarse grained and have an irregular distribution within the matrix. At the 3,670 m open pit operating level, the minerals have a tendency to be distributed in irregular shells, with one of the three minerals predominating in any shell. The transition between shells is abrupt. Several semi-ellipsoidal shells of alternating high and low copper grades also are apparent from the copper distribution on underground level

3,640 and various cross cuts. The shells are approximately vertical, being subparallel to the inward dipping contacts of the Donoso breccia.

Ore grade was enhanced by secondary enrichment in the southern two-thirds of the Los Bronces breccia complex and in much of the surrounding porphyry copper system. The degree and depth of enrichment are functions of breccia and fracture permeability. In some sectors, enrichment extends to depths of more than 500 m. The shape and depth of the enrichment blancket and the overlying leached capping indicate that the enrichment process is related to the present ground-water regime and is still active.

A recent, detailed description of the deposit is in Warnaars *et al.,* 1985.

## THE EL BRONCE EPITHERMAL GOLD DEPOSITS, CHILE-SOUTH AMERICA

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The El Bronce epithermal polymetallic vein system is 140 km north of Santiago and 8 km north of the village of Petorca. Some veins in this district have been worked sporadically since the end of the 18th century. In 1980 an 80 t/day mine and flotation operation was established by Compañía Minera El Bronce in order to exploit a small (100,000 tons) ore body, and after a successful exploration program during 1981-1984, the plant and mine operations were expanded to 1,000 t/day. At this capacity, the company produces 48,000-65,000 ounces of gold, 50,000-100,000 ounces of silver, and 1,260 t of copper per year. Total production from the district since the end of the 18th century amounts to approximately 400,000 ounces of gold and 1,000,000 ounces of silver.

The host rocks of the El Bronce district are volcanic rocks of the Cerro Morado Formation (Lower Cretaceous) and Las Chilcas Formation (Middle to Upper Cretaceous). These formations consist chiefly of breccias, tuffs, agglomerates and lava flows of andesitic composition. Volcanic sandstone and conglomerate beds are present locally. A subcircular caldera, called the Morro Hediondo Caldera, having a diameter of 14-16 km and dated as Upper Cretaceous, is just north of the district. Dacitic tuffs and andesitic flows and breccias associated with the caldera show K-Ar ages of 83-80 Ma. These and similar rocks, exposed extensively to the east of the district, have been assigned to the Lo Valle Formation.

Two types of intrusive rocks, which occur in north-south belts, are recognized in the area. The oldest is an intrusive body to the west of Petorca, which is composed largely of quartz monzodiorite, intruding the Cerro Morado Formation. This body is part of the large Illapel batolith (the Illapel Superunit of Parada *et al.,* 1985) extending from 31° to 32°30'S. K-Ar ages of the Illapel batholith are in the range of 134-86 Ma.

The youngest intrusive rocks are dioritic to granodioritic stocks and dikes, and include the Petorca porphyry (86 ± 3 Ma) and the dioritic-tonalitic ring-dike defining the Morro Hediondo Caldera (80-79 ± 3 Ma). Large hydrothermal alteration zones, which chiefly show silicification and advanced argillic alteration, are associated with these intrusive rocks.

The Morro Hediondo Caldera is the most prominent geological feature of the area, and faults and fractures related to the caldera provided structural control for mineralization. Several NE/NW-trending normal faults in the area represent both radial and concentric structures around the caldera. The principal geological features indicating the existence of the Morro Hediondo Caldera are: a. A well-defined ring-dike evidently emplaced in the ring-fracture zone of the caldera; b. Changes in attitude of the volcanic sequences at the ring-dike; outside the caldera, well stratified rocks dip eastward whereas within it, the volcanic rocks have been intensely broken to form an apparent megabreccia; c. Extensive and very thick intracaldera ash-flow tuffs showing K-Ar ages of 86 ± 3 Ma and cogenetic distal tuffs outside the caldera; d. an eroded stratovolcano(?) on the northern flank of the caldera where a sequence of 82-80 ± 3 Ma andesitic flows are interfingered with the ash-flow tuffs; e. Both radial and concentric structures (faults, dikes, and veins), apparently related to the caldera; f. Epithermal mineral deposits and alteration zones both within and marginal to the caldera. Alteration zones within the caldera show ages of 82 ± 9 and 81 ± 14 Ma, which are similar to the age of the caldera-related tuffs.

The polymetallic ores at El Bronce occur in well-defined veins, with the exception of the Dulcinea breccia pipe located to the east of Petorca. They are hosted by the Upper Cretaceous volcanic units and are related to the final stages of a complex sequence of igneous and structural events that took place during a 7 Ma interval in Late Cretaceous (86-79 Ma). About 90 veins are known in the district, most to the west, southwest, and south of the caldera. These veins contain gold, copper, lead, and zinc minerals. About a dozen other veins in the eastern half of the caldera and on to the east contain copper as the only recoverable metal.

Of the known veins, the El Bronce epithermal vein system, about 6 km southwest of the ring-dike, is the most important economically. Camus (unpublished report, 1982) gave the following information about these veins. Two general groups of veins can be recognized, one to the north and the other to the south of the N40°E trending El Bronce Creek Fault. Displacement on this fault dropped the northern block about 200 m relative to the southern block. The veins in the southern block contain only gold and silver and ore associated with the Petorca porphyry (86 ± 3 Ma), whereas the veins in the northern block are younger, contain gold, silver, copper, lead, and zinc, and are associated with faults and dikes that are radial to the Morro Hediondo Caldera. The El Bronce vein system, which belongs to this latter group, is related to a major fault striking N-N20°E that is approximately 7 km in length. Repeated movement along this fault gave rise to a complex fracture system that was subsequently mineralized. Mineralization took place by filling of fissures and fractures, and ore bodies are typically lens-shaped. The lenses vary between 100 and 600 m in length, 200-400 in depth, and 1-20 m in width. The host rocks are volcanic breccias, lapilli tuffs, and andesite flows of the Cerro Morado Formation.

Detailed studies of ore bodies show the presence of four components or zones within each vein structure: a. Massive ore consisting of quartz, pyrite, sphalerite, and chalcopyrite; b. Stockwork ore consisting of veinlets filled with the same minerals, plus some carbonate minerals; c. Disseminated ore consisting chiefly of pyrite; and d. Andesite dikes having veinlets of carbonate mineral and locally disseminated late pyrite. The contrasts between massive, stockwork and disseminated ore are generally sharp, but locally, gradational. The andesitic dikes generally show sharp contacts, which locally are strongly sheared. Post-mineral faulting generally is controlled by these dikes. Vein minerals are chiefly coarsely crystalline pyrite, sphalerite, chalcopyrite, tennantite/tetrahedrite, galena, hematite, and minor amounts of bornite, arsenopyrite, magnetite, and pyrrhotite. Gangue minerals are quartz, siderite, anhydrite, barite, and chlorite. Three phases at mineralization can be recognized: 1. Quartz-pyrite-native gold; 2. Quartz-pyrite-sphalerite-chalcopyrite-galena-tennantite/tetrahedrite and barite (the main stage of gold deposition was immediately after this phase); and 3. Amethyst-euhedral quartz-galena-tennantite/tetrahedrite-carbonates-hematite-chlorite. Hydrotermal alteration, with formation of sericite, kaolinite, chlorite, and carbonates, mainly affected the host rocks of stockwork and disseminated ores. Carbonate minerals are the principal alteration minerals in the andesitic dikes.

Preliminary fluid inclusion studies and stable isotopes analyses of vein materials from El Bronce were made in order to characterize the physico-chemical environment and composition of the mineralizing fluids. Fluid inclusions (Skewes, A.: Inclusiones fluidas en el Sistema El Bronce; unpublished report, 20 p. 1986) show homogenization temperatures 150°-340°C, higher temperatures belonging to early stages of mineralization and the lower temperatures to late stages. Gold deposition took place between 230° and 330°C. Salinity determinations show 1-10 wt percent NaCl equiv. The lower values (1-6% NaCl equiv.) were found at upper vein levels whereas the highest values (5-10% NaCl equiv.) are at the deepest levels. This wide range (1-10%) in salinity suggests dilution of the more saline hydrothemal solutions of magmatic origin by near-surface meteoric water.

No evidence of boiling was found in zones where gold was deposited, and therefore, boiling was not the mechanism responsible for deposition of the precious and base metals. Boiling was detected only in near-surface samples, in places where gold-silver and base metals are absent. The fluid-inclusion data suggest that the vein minerals probably were deposited as a consequence of dilution of the deep hydrothermal solutions by shallow meteoric waters, and that the veins were formed at depth of not more than 1,000 m below the paleosurface (assuming hydrostatic condition).

Preliminary sulfur stable isotopes (δ34S = 0.5-2.3%) suggest a magmatic source for sulfur in the sulfide minerals at El Bronce (Ohmoto and Rye, 1979).

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