Metallogeny of Bolivia*

Osvaldo R. Arce-Burgoa† (SEG 2008 F), ANTIS SRL. La Paz-Bolivia; E-mail osvaldo_arce@ya
osvaldoarce.com
Richard J. Goldfarb (SEG 1989 F), U.S. Geological Survey, Box 25046, Mail Stop 973, Denver Federal Center, Denver, CO, 80225-0046,USA, and School of Earth and

Study published in the October 2009 issue of the SEG (Society of Economic Geologists) Newsletter, No. 79, USA

INTRODUCTION

Bolivia covers an area slightly larger than 1 million km2 and has long been recognized as one of the world's most remarkably metal rich regions. Many metalliferous deposits have been worked for more than 3,000 years (Mesa et al., 1997); silver, gold, copper and tin were extracted by Incan and earlier civilizations (Capriles, 1977).

Soon after conquest of "Upper Peru" by the Spaniards in the 1530s, discovery of the exceptionally rich Cerro Rico de Potosi veins made Bolivia the largest silver producer in the world for more than two centuries. By the early 1900s, the great tin deposits had been discovered and had replaced silver as the most valuable metal for the nation's economy, and continued as such until collapse of the tin market in 1985.

Throughout the 20th century, mining was the country's top industry, producing much of the world's antimony, bismuth, lead, silver, tin, tungsten, and zinc. Bolivia is presently ranked as the third largest producer of antimony in the world, as well as ranking fourth in tin and zinc, and sixth in tungsten. In addition, the salt lakes (salars) of the southern Altiplano are estimated to contain >50% of the world's lithium resources. Finally, Bolivia has large resources of gold, platinum, palladium, tantalum, chromium, nickel, cadmium, indium, bismuth, antimony, potassium, boron, iron ore, natural gas, and petroleum. The underexplored and underdeveloped resources of Bolivia today represent one of industry's most prospective global targets for an exceptionally broad group of commodities (e.g., Arce-Burgoa, 2007, 2009).

Diverse metallic mineral deposit types have been recognized in the geologically varied and metallogenically favorable environments. The "Guaporé craton," representing the Precambrian Shield in Bolivia, underlies the eastern part of the country, where resource potential is very poorly known. The most highly endowed part of the country is that of the central Andean physiographic provinces in western Bolivia. Polymetallic vein deposits, rich in tin and base metals, dominate the resource inventory in this part of Bolivia.

Bolivia, however, is also favorable for economically significant epithermal precious metal deposits, orogenic gold in slate belts, platinum-group metals (PGM) and nickel in mafic and ultramafic intrusions, base metals in volcanogenic massive sulfide (VMS) and sedimentary exhalative (SEDEX) deposits, and iron in banded iron formations (BIF).

Mining in Bolivia has traditionally been conducted in underground operations. Development of the Kori Kollo gold deposit in 1983 represented the first large-scale open pit operation in the country. Subsequently, additional open-pit mines have been put into operation at Toldos, Puquio

Norte, Don Mario, Kori Chaca (Iroco), and San Cristobal.

GEOLOGIC FRAMEWORK OF BOLIVIA

The geologic-tectonic framework of Bolivia can be divided into six physiographic provinces. From east to west (Fig. 1), these are the Precambrian Shield, the Chaco-Beni Plains, the Subandean zone, the Eastern Cordillera (or Cordillera Oriental), the Altiplano, and the Western Cordillera (or Cordillera Occidental). The latter four provinces make up the Mesozoic-Cenozoic Andean orogen in Bolivia (Arce-Burgoa, 2002, 2007), which hosts an abundance of mineral deposits (Tables 1, 2), many of which have been mined for centuries. The landward Precambrian Shield, exposed far to the east of the Andes, represents a region of great mineral potential, but has had little exploration.

Rocks of the Precambrian Shield in easternmost Bolivia have commonly been suggested as defining the southwestern part of the Amazon craton and cover an area of approximately 200,000 km2, or 18% of Bolivia (Fig. 1). The units are mainly Mesoproterozoic medium and high-grade metasedimentary and meta-igneous rocks, which are widely covered by Tertiary laterites and Quaternary alluvial basin deposits. Previous workers have referred to this as the Guaporé craton, but Santos et al. (2008) suggest that these may not be basement rocks of the craton; rather, they could represent a small inlier within the ca. 1.45–1.10 Ga Sunsas orogen, formed along the craton margin. Major tectonic events in the orogen are dated at 1465–1420, 1370–1320, and 1180–1110 Ma.

Subsequent Brazilian tectonism (ca. 600–500 Ma) had only minor effects on the orogen (Litherland et al., 1986, 1989). The Chaco-Beni plains are located in the central part of the country (Fig. 1) and cover 40% of Bolivia. The topography is dominated by the southwestern Amazon basin wetlands, which lie below 250 m elevation, with little relief and outcrops. These extensive plains are part of the foreland basin of the Central Andes, and include 1 to 3 km of Cenozoic foreland alluvial sediment in the west and much thinner accumulations atop a broad forebulge to the east (Horton and DeCelles, 1997). These overlie Tertiary red-bed sediments that are >6 km thick and cover the Precambrian crystalline basement to the east and Paleozoic and Mesozoic sedimentary rocks to the west.

These alluvial accumulations are products of several Neogene to Holocene episodes of postkinematic and epeirogenetic isostatic adjustment in the Eastern Andes and its piedmont. Rocks of the Bolivian Andean orogen underlie approximately 42% of Bolivia and include those of the Subandean zone, Eastern Cordillera, Altiplano, and the Western Cordillera. These physiographic provinces form a series of mountain chains, isolated mountain ranges, and plains, with a north-to-south trend (Ahlfeld and Schneider-Scherbina, 1964; Fig. 1). This part of the orogen has a length of 1,100 km, a maximum width of 700 km, and an average crustal thickness of 70 km; the orogen includes
a distinct oroclinal bend at the called Arica Elbow (18°–19°S).

The Subandean zone (Fig. 1) is the thin-skinned, inland margin of an orogen-parallel fold-and-thrust belt, which is partly covered by sediments of the western side of the active foreland basin. It is characterized by north-south–trending, narrow mountain ranges with elevations between 500 and 2,000 m.

Rock types in this province include Paleozoic siliciclastic marine and Mesozoic and Tertiary continental sedimentary rocks. The Eastern Cordillera (Fig. 1), the uplifted interior of the Andean thrust belt, includes polydeformed Ordovician to Recent shale, siltstone, limestone, sandstone, slate, and quartzite sequences.

These mainly Paleozoic clastic and metamorphic rocks have an approximate area of 280,000 km2, and represent flysch basin sediments that were deposited along the ancient Gondwana margin and first deformed in the middle to late Paleozoic. Subsequent to Permian to Jurassic rifting, they were uplifted to high elevation and folded and thrusted again during Andean compression, which may have begun as early as Late Cretaceous (McQuarrie et al., 2005).

The Altiplano is a series of intermontane, continental basins, which have a combined length of approximately 850 km, an average width of 130 km, and an area of approximately 110,000 km2. They form a high plateau at elevations between 3,600 and 4,100 m (Fig. 1). Geomorphologically, the province consists of an extensive flat plain that is interrupted by isolated mountain ranges. Crustal shortening, rapid subsidence, and, simultaneously, as much as 15 km of sedimentation took place during the Andean orogeny (Richter et al., in USGS and GEOBOL, 1992). Basin fill was dominated by erosion of the Western Cordillera during Late Eocene-Oligocene, but Neogene shortening in the Eastern Cordillera and Subandean zone led to a subsequent dominance of younger sediments derived from the east (Horton et al., 2002). The Western Cordillera consists of a volcanic mountain chain that is 750 km in length and 40 km in average width, with an area of about 30,000 km2 (Fig. 1). Late Jurassic and Early Cretaceous flows and pyroclastic rocks and marine sandstone and siltstone sequences dominate the Cordillera in Peru and Chile.

Lesser Late Cretaceous continental sediment was deposited above the marine rocks and, simultaneously, large granitoid plutons, many of which are associated with large copper porphyry orebodies, were emplaced along the coasts of adjacent Peru and Chile. In Bolivia, this province is dominated by high andesitic to dacitic stratavolcanoes, formed since ca. 28 Ma, that define the narrow, main Central Andes modern magmatic arc.

METALLIFEROUS DEPOSIT DISTRIBUTION

Bolivia contains parts of three important South American metallogenic provinces: the Precambrian Shield, the Chaco-Beni plains, and the Central Andes. Precambrian terranes are highly underexplored but have great undiscovered mineral resource potential; on its part the Chaco-Beni plains have been the locus of extensive placer gold recovery; and the Central Andes host most of the known significant metalliferous lode deposits in Bolivia.

Eastern Bolivia: The Precambrian Shield and Chaco Beni Plains

Although very poorly explored, a few scattered, high-grade orogenic gold deposits of unknown age in the Precambrian Shield indicate considerable resource potential. Auriferous veins, commonly along saddle reefs, are located in the San Simón area near the Brazilian border (SERGEOMIN-YPFB, 2000), on a plateau above the Amazonian lowlands, in a region called the Paragua craton Au-Mn belt (Fig. 2). The 22 t San Simón deposit, mined at small scale since the mid-1700s, is hosted by ca. 1450 Ma graywacke. Several auriferous placers are associated with erosion of the San Simón ridge gold veins. The 10 t Au Puquio Norte deposit, within the San Ramon district along the western edge of the Sunsas province, consists of quartz-carbonate veins hosted by the early Mesoproterozoic BIF of the Sunsas orogen. These deposits may be related to those of the Guapore gold belt in adjacent Brazil, which includes the recently developed São Francisco (40 t Au) and São Vincente (19 t Au) deposits.

A scattering of ore-related dates between 1.0 and 0.8 Ga for the gold belt (Geraldes et al., 1997) are coeval with Sunsas tectonism and might indicate a regional metallogenic event. High-grade gneissic parts of the Precambrian Shield host the Don Mario deposit and similar Au-Ag-Cu prospects. The 31 t Au Don Mario deposit, from which copper oxide was mined beginning in the 1700s, also includes Pb, Zn, W, and Bi (Arce-Burgoa, 2007). Ore-bearing veins and stockworks in the deposit would be overprinted by a magnetite-rich skarn. These auriferous occurrences have been referred to as IOCG deposits, but more detailed geologic information is needed before the alternative possibility of Fe-Cu-Au skarn systems can be ruled out. Disseminated to massive polymetallic sulfide deposits are associated with Neoproterozoic rift basins in the southern part of the Bolivian Precambrian, particularly the 650 × 55 km Tucavaca basin. Disseminated Cu-Pb-Zn mineralization and quartz-barite-galena veins, mainly localized along lithologic contacts in both oxidized clastic rock sequences and in reduced black shale units, would be indicative for undiscovered SEDEX deposits. Lead- and Zn-rich zones in ferruginous dolomites and stromatolitic reefs in the northern part of the Tucavaca basin indicate potential for Mississippi Valley-type (MVT) mineralization.

In addition, the Mutún-Tucavaca ferromanganiferous belt, approximately 230 × 30 km in size and trending northwest, hosts the largest and highest grade sedimentary Fe-Mn ores in Bolivia (Fig. 1). These Rapitan-type BIFs include the El Mutún, Cerro Rojo, and Cerro Colorado-Murciélago deposits that are located in grabens within the Tucavaca basin. These deposits are hosted within Rapitan type BIF. The Guarayos greenstone belt, along the western edge of the province, hosts Cu-Au-Ag-Zn VMS occurrences, mainly in rocks of the La Pastora Formation, which is exposed along a 20-km strike length. Massive to laminated pyrite-chalcopyrite ± galena-sphalerite bodies are localized in rhyolite and meta-sedimentary rocks of a Mesoproterozoic bimodal volcanic sequence at the Miguela deposit (Arce-Burgoa, 2009).

A series of poorly understood magmatic-related mineral occurrences are also recognized in the Precambrian Shield. Syn- to late-kinematic, ca. 1.0 Ga pegmatites (e.g., Los Patos, La Bella, Ascencion de Guarayos) that cut schists are favorable for Be, Sn Ta, Nb, Th, and U resources (Bennet and Zerain, 1985). In addition, hydrothermal events are related to emplacement of a series of rift-related, alkaline syenitic bodies that host Lovozero-type Nb, Ta, and REE mineralization of both suggested Jurassic-Cretaceous (Velasco and Manomó Hill) and Proterozoic (Mercedes rift and the El Tigre Complex) ages (Fletcher and Litherland, 1981; Fletcher et al., 1981; Arce-Burgoa, 2007, 2009; SERGEOMINYPFB, 2000). Mesoproterozoic metasedimentary rocks near the southern border of the Bolivian Precambrian province were intruded by the ca. 990 Ma Rincón del Tigre Complex, one of the largest mafic-ultramafic complexes in South America and part of a 1,100-km long, north-south belt of similar intrusions (Annels et al., 1986; Arce-Burgoa, 2009). The chronology of Santos et al. (2008) suggests that these intrusions are representative of post-Sunsas, ca. 1060–990 Ma A-type magmatism, although the rocks of the Rincón del Tigre Complex were nevertheless deformed sometime after emplacement. Magnetite gabbro in the upper part of the complex contains a Skaergaard type, strata-bound, precious metal zone and anomalous but subeconomic concentrations of PGM and Au (Prendergast, 2000).

The great Madera, Madre de Dios, Beni, and Mamoré rivers and their numerous tributaries drain the northeastern slopes of the Central Andes and their abundant Paleozoic orogenic gold deposits (see below), and then transect the northern part of the Chaco-Beni plains. Several of these river systems contain exceptional amounts of placer gold (Fig. 1) and they define the so called Amazonian gold basin. The placer deposits have an average grade of approximately 0.5 g/m3 Au, although concentrations in some localities surpass 4 g/m3 (Heuschmidt and Miranda, 1995). Historic production from these placers has been estimated at >1,200 t Au (Arce-Burgoa, 2009), which constitutes a world-class placer environment. Most of this gold was recovered from the late Tertiary Cangalli Formation, which has been reworked by modern river channels. Significant resources are still present in these alluvial deposits; for example, in the headwaters of the Alto Madidi River, a series of thick conglomerates may contain 54 M m3 of material grading 0.05 g/m3 Au.

Western Bolivia: The Central Andes

The Bolivian part of the Central Andes is characterized by a diverse series of deposits (Fig. 1) and metallogenic belts (Fig. 2). These include the Miocene to Pliocene red-bed copper deposits and epithermal deposits of the Altiplano and Western Cordillera, and the Miocene tin belt, Paleozoic gold-antimony belts, and the poorly dated lead zinc belt principally in the Eastern Cordillera. In addition, the high salars of the Altiplano and Western Cordillera contain economically important evaporite deposits that constitute more than 50% of the world’s lithium resources.

Sedimentary-Rock Hosted Copper Deposits of the Altiplano

More than 80 Miocene to Pliocene stratiform copper deposits are scattered along the length of the Bolivian Altiplano; these include those of the most productive Corocoro district, which has been mined since Inca times (Arce-Burgoa, 2009). Red-bed copper ore generally occurs along contacts and unconformities between Tertiary units.
Although widespread, these deposits, except for Corocoro and Chacarilla, are generally small, which reflects the absence of broad marine transgressive sequences that are required to form the favorable reductants above continental red beds in areas of world-class deposits (USGS-GEOBOL, 1992). The most significant copper deposits of the Altiplano are associated with gypsum diapirs that serve as local reductant traps.

The Polymetallic Belt of the Altiplano and Western Cordillera

The 800 × 200 km polymetallic belt of the Altiplano and Western Cordillera provinces (Fig. 2) is mainly composed of epithermal Ag-Au-Pb-Zn-Cu deposits. These formed during the Middle-Late Miocene and Early Pliocene, when volcanism and shallow magmatism led to formation of widespread precious and base metal-bearing epithermal deposits (USGS-GEOBOL, 1992; Redwood, 1993).

The most important metallogenic features include epithermal mineralization of intermediate- and high-sulfidation type associated with small, shallow porphyritic subvolcanic plugs, flow domes, stratovolcanoes, flows, pyroclastic rocks, ignimbrite shields, and/or volcanic calderas of dacitic, rhyodacitic, rhyolitic, and andesitic composition. The giant San Cristobal disseminated Ag- and Znrich deposit may reflect porphyry dome emplacement into a lacustrine environment (Phillipson and Romberger, 2004).

Most deposits exhibit structural control along lineaments, large transcurrent faults, and local-scale tension fractures. Mineralization style varies from vein lodes and stockworks to disseminations in breccias, porous pyroclastics, and porphyries. Mineralized rock is commonly banded, brecciated, and drusy to vuggy. Vertical deep to shallow metal zoning, sometimes telescoped, ranges from enrichments of Cu, Zn-Pb-(Ag), Pb-(Ag), to Ag-(Au) near the surface.

Hydrothermal alteration of the igneous rocks is generally penetrative and zoned; system cores exhibit phyllic or silicified alteration, widespread argillic and/or propylitic haloes, and apical zones altered to advanced argillic assemblages or silicic plugs. Silver-rich epithermal deposits are mainly intermediate sulfidation types (Arce-Burgoa, 2009). Important examples of these include Pulacayo, Berenguela, Carangas, Salinas de Garci Mendoza, San Cristobal, San Antonio de Lipez, and Jaquegua. High-sulfidation epithermal deposits are less common but include those at Laurani in the Altiplano and La Española in the Western Cordillera. At La Española, vuggy silica and quartz-alunite alteration appear to overprint an earlier low-sulfidation event (Arce-Burgoa, 2009). The intermediate sulfidation epithermal deposits include the ca. 15.7 Ma Kori Kollo deposit, which, with a pre-mining reserve of 161 t Au and 907 t Ag (Redwood, 1993), was the largest gold producer in South America during the early 1990s. At the Lipena-Lamosa epithermal deposit, Au, Bi, and Cu were mined in colonial times.

The Bolivian Tin Belt

The Bolivian tin belt (Fig. 2) extends for approximately 900 km in a northwest to north-south–trending direction in the Eastern Cordillera of Bolivia, where continental crust is thickest (Turneaure, 1971; Arce-Burgoa, 1990; Fig. 2). Highgrade (1–5% Sn) hydrothermal tin lodes, which typically also contain significant amounts of Ag and W, are spatially associated with peraluminous granite and porphyry intrusions of different ages between Late Permian and 4 Ma, with most being late Tertiary. The intrusions are dominantly deep crustal melts of Paleozoic sedimentary rock. According to Arce-Burgoa (2009), deposits of the tin belt can be divided into four groups:
porphyry-(Sn); volcanic rock-(Sn-Ag-Pb-Zn, which includes bonanza-type Ag-Sn); sedimentary rock-hosted (Sn-Ag-Pb-Zn), which are together defined as Bolivian polymetallic vein deposits; and distinct pluton-related tin-polymetallic deposits (Sn-Au-W-Zn).

The polymetallic vein deposits, located in the southern half of the Bolivian tin belt, include veins, veinlets, stockworks, and disseminated ores within the various host rocks. Mineralization ages vary between 22 and 4 Ma. The porphyry-hosted veins are mainly hosted in subvolcanic dacite and latite bodies. The Llallagua deposit, which produced >1 Mt Sn, is probably the largest Sn vein-type deposit discovered to date anywhere in the world. Ore recovered from veins along the margins of the host porphyry initially ranged from 12 to 15% Sn. However, most low grade ores generally graded 0.2 to 0.3% Sn. These deposits are recognized as products of orthomagmatic processes active late in the history of the evolution of coeval overlying stratovolcanoes (Sillitoe et al., 1975).

Bonanza-type Ag-Sn veins are hosted by rhyodacitic, dacitic, and quartz latitic composition volcanic dome complexes (Cunningham et al., 1991). The most voluminous stage of ore formation in the southern part of the tin province occurred between 18 and 16 Ma (Grant et al., 1979; SERGEOMIN-YPFB, 2000). Sillitoe et al. (1998) indicated that lithocaps of vuggy residual quartz in this less eroded part of the province are consistent with high-sulfidation epithermal deposits, although low sulfidation-type mineral assemblages in deeper massive sulfide zones formed at temperatures much higher than typical epithermal ores.

The Cerro Rico de Potosi polymetallic vein deposit, mined since the mid-1500s, is the world's largest silver deposit. It has yielded 60,000 t of silver, and estimated resources are 540 Mt of 102 g/t Ag and 0.10–0.17% Sn (Bernstein, 1989). The deposit formed at ca. 13.8 to 13.5 Ma and subsequently underwent at least 7.5 m.y. of supergene oxidation (Rice et al., 2005). Sedimentary rock hosted polymetallic veins are found in clastic units of both early Paleozoic and Tertiary age, although igneous rocks are present within a few kilometers of almost all of these deposits.

Pluton-related, tin-polymetallic vein deposits are dominant in the Cordillera Real in the more deeply eroded northern part of the tin province, where two distinct ages of mineralization are recognized. Ore is hosted by faults and fractures in Paleozoic sedimentary rocks, contact aureoles, pegmatites, and intrusive complexes. Late Permian to Jurassic igneous rocks (Grant et al., 1979) are associated with numerous Sn-W ±Au-Bi-Zn-Pb-Ag-Sb vein-type deposits in the northern part of the belt (e.g., La Chojlla, Enramada, Bolsa Negra, Milluni). Tin and polymetallic mineralization in the southern part of the Cordillera Real are hosted by 28 to 19 Ma granitoid plutons and Paleozoic sedimentary rocks (e.g., Rosario de Araca, Colquiri; Grant et al., 1979). These deposits, which are locally telescoped, are zoned with a W-Sn ± Au core and outer, base metal-rich veins.

The Gold-Antimony Belts of the Eastern Cordillera

Three distinctive belts of orogenic Au ±Sb deposits (Fig. 2), containing more than 500 known deposits and occurrences, are recognized along the length of the Eastern Cordillera (Tistl, 1985; Lehrberger, 1992). These include (1) a northwest-trending belt from near La Paz, through the Oruro-Challapata belt, to the Amayapampa district; (2) a northsouth–trending belt from the Caracota-Carma districts to the Candelaria district on the Argentinian border; and (3) a northwest-trending belt from the Apolobamba district near the Peruvian border, through the Aucapata-Yani and Cajuata-Los Machos districts, to the Cocapata-El Molino district. The linearity of all three belts is consistent with major crustal structures in the Central Andes; the former two belts follow the Altiplano-Eastern Cordillera boundary, whereas the latter belt is solely within the center of the northern half of the Bolivian Eastern Cordillera.

Many of the gold districts are in the same general parts of the Eastern Cordillera that have tin mineralization related to Mesozoic and Tertiary intrusions. The orogenic gold deposits, which form ribbon veins, stockworks, saddle reefs, and disseminated ores, are mainly hosted by Middle Ordovician to Early Silurian sedimentary rocks. Many deposits, particularly those of the Caracota-Carma-Candelaria belt, contain as much as 10 to 20% Sb; consequently, many of these were originally mined for antimony. These deposits typically have relatively uniform mineralogy and preserve two principal paragenetic events. Products of the earlier event include gold, pyrite, arsenopyrite, and tungstenbearing minerals in milky quartz. The later, lower temperature event involved deposition of Pb-Zn-Cu– and Sb-bearing sulfides in microgranular, bluish-gray quartz (Lehrberger, 1992; Dill, 1998; Arce-Burgoa, 1999, 2002). Conflicting dates of ca. 314 Ma (K-Ar) and 59 Ma (Ar-Ar) characterize the San Bernardino deposit (Arce-Burgoa, 2007); the older date seems most realistic based on the timing of orogenic gold formation in the nearby Eastern Cordillera of Peru and Argentina (e.g., Haeberlin et al., 2002).

The majority of these deposits have been and are being exploited on a small scale from the precolonial days to the present, although the future Amayapampa mine will be a medium-scale operation (16 t Au) and the entirely of the Amayapampa district may contain 80 t Au. Other significant gold resources include deposits at El Molino (15.5 t Au), Iroco (Kori Chaca, 32 t Au having been recovered from the most recent open pit in Bolivia) in the Oruro district, Carma (24 t Au), and San Bernardino (73 t Au). Additionally, some of these deposits were the main source of gold in the numerous placer deposits of the Subandean zone and Chaco-Beni plains (Arce-Burgoa, 2007). Most gold deposits have reported average grades of 1 to 3 g/t Au, which are somewhat low for orogenic gold lodes. Consequently, these epizonal vein systems are much more likely to be prospective as future low-grade, bulk minable systems, similar to Sb-rich ores at Donlin Creek, Alaska, rather than as high-grade underground mines.

The Lead-Zinc Belt of the Eastern Cordillera

A series of sedimentary rock-hosted Ag-Pb-Zn veins, with anomalous concentrations of Au and Sb, and with no clear association to magmatic centers, are located along the length of the central part of the southernmost Eastern Cordillera in Bolivia (Figs. 1 and 2). Important districts include Huara Huara, San Lucas, Toropalca, Cornaca, Tupiza, and Mojo. The deposits have a combined estimated resource of 40 to 45 Mt of 10% Zn, 5–7% Pb, and 70–80 g/t Ag (Arce-Burgoa, 2009). These Coeur d’Alene-type veins occur in faults and along fold hinges in mainly Ordovician shale and, less commonly, siltstone. Their age is uncertain; they may have formed during the major episode of deformation at ca. 320–290 Ma in southern Bolivia (e.g., Jacobshagen et al., 2002), essentially coevally with orogenic gold formation. Alternatively, they may have formed during later Tertiary magmatism, although the lack of a spatial association between the deposits and intrusive bodies makes this less likely. The importance of small, Early Ordovician SEDEX-type Pb-Zn-(Cu-Ag-Ba) occurrences in the shales (Troeng et al., 1993) to later formation of the Ag-Pb-Zn veins is unknown. Some of the SEDEX mineralization is economic, such as in the Aguilar deposit, just across the border in Argentina (Gemmell et al., 1992).

Evaporitic Deposits of the Altiplano and Western Cordillera

Dozens of salars in the Altiplano and Western Cordillera of southwestern Bolivia contain large resources of B, K, Li, Mg, and other evaporitic minerals. Evaporation in closed basins concentrates these elements in residual brines and precipitated salts. Given the recent global interest in the possible future use of lithium-ion car batteries, the Bolivian lithium resources have attracted a great deal of interest. The brines at Salar de Uyuni are estimated to contain 8.9 Mt Li, the largest resource of that metal in the world, as well as 194 Mt K, 7.7 Mt B, and 211 Mt Mg (Arce-Burgoa, 2009).

The surface area of the salt lake is approximately 10,000 km2 and evaporation to form the average 121-m-deep ancient salar layer below the present lake surface was completed 3,520 years ago. Present-day brines, located 5 to 20 cm below the salt crust surface, have concentrations of between 80 and 1,150 ppm Li (Garrett, 2004). A relatively high Mg/Li ratio of these brines could, however, inhibit lithium recovery.

CONCLUSIONS

The Precambrian of eastern Bolivia, although not adequately evaluated, has great potential for discovery of Mesoproterozoic through early Paleozoic precious metal-(orogenic gold, IOCG) and base metal-(VMS, MVT, SEDEX, sedimentary Fe-Mn) bearing deposits. The Chaco-Beni plains contain one of the world’s greatest, yet least familiar, alluvial gold concentrations, with source regions in the high elevations of the Eastern Cordillera of northernmost Bolivia. The diversity in metallogeny and an abundance of mineral occurrences in the Central Andes, particularly Cenozoic Bolivian-type polymetallic vein and more classic epithermal deposits, reflect the complex tectonic framework of this part of the Andes, which is characterized by the greatest amount of crustal thickening and the most crustal shortening along the length of the orogen (e.g., McQuarrie et al., 2005).

ACKNOWLEDGMENTS

Ed du Bray and Steve Luddington are thanked for their insightful comments on an original version of this manuscript. An additional detailed review from Stewart Redwood made this a much more through contribution.

REFERENCES

Ahlfeld, F. and Schneider-Scherbina, A., 1964, Los yacimientos minerales y de hidrocarburos de Bolivia: Departamento Nacional de Geología (DENAGEO), Bolet. 5 (especial), 388 p.

Arce-Burgoa, O., 1990, Fundamental study on processing of ore from the Huanuni mine, Bolivia: Unpublished Ph.D. thesis, Sendai, Japan, Tohoku University, 168 p.

——1999, Sediment-hosted gold mineralization at Pederson (San Bernardino) project, Bolivia: Bolivia Mining Conference, Santa Cruz, Bolivia, 1999, 10 p.

——2002, Potencial geológico-minero de Bolivia: Memorias del XV Congreso Geológico Boliviano, Santa Cruz, Bolivia, October 2002, Revista Técnica de YPFB, v.20, p. 18–24.

——2007, Guía a los yacimientos metalíferos de Bolivia: La Paz, Bolivia, SPC Impresores, Minera San Cristóbal and Empresa Minera Unificada S.A. (EMUSA), 298 p.

——2009, Metalliferous ore deposits of Bolivia: 2nd edition, La Paz, Bolivia, SPC Impresores S.A., 233 p.

Annels, R.N., Fletcher, C.J.N., Burton, C.C.J., and Evans, R.B., 1986, The Rincon del Tigre igneous complex: A major leayered ultramafic-mafic intrusion of Proterozoic age in the Precambrian shield of eastern Bolivia. I. Geology and mineral potentrial: Overseas Geology and Mineral Resources, no. 63, p.1–24.

Bennet, M.J., and Zerain, M., 1985, The La Bella pegmatite field: Santa Cruz, Bolivia, Informe No. 22. Proyecto Precámbrico (IGSGEOBOL), Unpublished report, 92 p.

Bernstein, M., 1989, Expectations for bulk tonnage hard rock and alluvial ores [Cerro Rico]: United Nations Development Program, Project BOL/87/012, La Paz, Bolivia, Unpublished report, 18 p.

Capriles, O., 1977, Historia de la minería Boliviana: Banco Minero de Bolivia, La Paz, 256 p.

Cunningham, C.G., McNamee, J., Pinto Vásquez, J., and Ericksen G.E., 1991, A model of volcanic dome-hosted precious metal deposits: Economic Geology, v. 86, p 415–421.

Dill, H.G., 1998, Evolution of Sb mineralization in modern fold belts: a comparison of the Sb mineralisation in the Central Andes (Bolivia) and the Western Carpathians (Slovakia): Mineralium Deposita, v. 33, p. 359–378.

Fletcher, C.J.N., and Litherland, M., 1981, The geology and tectonic setting of the Velasco Alkaline Province, eastern Bolivia: Journal of the Geological Society of London, v. 138, p. 541–548.

Fletcher, C.J.N., Appleton, J.D., Webb, B.C. and Basham, I.R., 1981, Mineralization in the Cerro Manomó carbonatite complex, eastern Bolivia: Transactions of the Institution of Mining and Metallurgy, v. 90, p. B37–50.

Garrett, D.E., 2004, Handbook of lithium and natural calcium chloride: San Diego, Academic Press, 476 p.

Gemmell, J.B., Zantop, H. and Meinert, L.D., 1992, Genesis of the Aguilar zinc-lead-silver deposit, Argentina: Contact metasomatic vs. sedimentary exhalative: Economic Geology, v. 87, p. 2085–2112.

Geraldes, M.C., Figueiredo, B.R., Tassinari, C.C.G., abd Ebert, H.D., 1997, Middle Proterozoic vein-hosted gold deposits in the Pontes e Lacerda region, southwestern Amazonian craton, Brazil: International Geology Review, v. 39, p. 438–448.

Grant, J.N., Halls, Avila, W and Snelling, N.J., 1979, K-Ar ages of igneous rocks and mineralization in part of the Bolivian tin belt: Economic Geology, v. 74, p. 838–851.

Haeberlin, Y., Moritz, R., and Fontbote, L., 2002, Paleozoic orogenic gold deposits in the eastern Central Andes and its foreland, South America: Ore Geology Reviews, v. 22, p. 41-59.

Heuschmidt, B., and Miranda, R., 1995, Precious-metals districts and resources of Bolivia: La Paz, Bolivia, Bolinvest, Publicacion Especial, 162 p.

Horton, B.K., and DeCelles, P.G., 1997, The modern foreland basin system adjacent to the Central Andes: Geology, v. 25, p. 895–898.

Horton, B.K., Hampton, B.A., LaReau, B.N., and Baldellon, E., 2002, Tertiary provenance history of the northern and central Altiplano (Central Andes, Bolivia)—A detrital record of plateau-margin tectonics: Journal of Sedimentary Research, v. 72, p. 711–726.

Jacobshagen, V., Muller, J., Wemmer, K., Ahrendt, H., and Manutsoglu, E., 2002, Hercynian deformation and metamorphism in the Cordillera Oriental of southern Bolivia, central Andes: Tectonophysics, v. 345, p. 119–130.

Lehrberger, G., 1992, Metallogenese von Antimonit-Gold Lagerstätten in marinen Sedimenten der Ostkordillere Boliviens: Müncher Geologische Hefte, v. 6, 204 p.

Litherland, M., Annels, R.N., Appleton, J.D., Berrangé, J.P., Bloomfield, K., Burton, C.C.J., Darbyshire, D.P.F., Fletcher, C.J.N., Hawkins, M.P., Klinck, B.A., Llanos, A., Mitchell, W.I., O'Connor, E.A., Pitfield, P.E.J., Power, G. and Webb, B.C., 1986, The geology and mineral resources of the Bolivian Precambrian shield: Overseas Memoirs British Geological Survey, no. 9, 153 p.

Litherland, M., Annels, R.N., Darbyshire, D.P.F., Fletcher, C.J.N., Hawkins, M.P., Klinck, B.A., Mitchell, W.I., O'Conner, E.A.,Pitfield, P.E.J., Power, G., and Webb, B.C., 1989, The Proterozoic of eastern Bolivia and its relationship to the Andean mobile belt: Precambrian Research, v. 43, p. 157–174.

McQuarrie, N., Horton, B.K., Zandt, G., Beck, S., and DeCelles, P.G., 2005, Lithospheric evolution of the Andean fold-thrust belt, Bolivia, and the origin of the central Andean plateau: Tectonophysics, v. 399, p. 15–37.

Mesa, J., de Mesa T.G., y Mesa, C., 1997, Historia de Bolivia: Editorial Gisbert, 779 p.

Phillipson, S.E., and Romberger, S.B., 2004, Volcanic stratigraphy, structural controls, and mineralization in the San Cristobal Ag-Zn-Pb deposit, southern Bolivia: Journal of South American Earth Sciences, v. 16, p. 667–683.

Prendergast, M.D., 2000, Layering and precious metals mineralization in the Rincón del Tigre Complex, Eastern Bolivia: Economic Geology, v. 95, p. 113–130.

Redwood, S., 1993, The Metallogeny of the Bolivian Andes: Vancouver, British Columbia, University of British Columbia, Mineral Deposit Research Unit, Short Course no. 15, 59 p.

Rice, C.M., Steele, G.B., Barfod, D.N., Boyce, A.J., and Pringle, M.S., 2005, Duration of magmatic, hydrothermal, and supergene activity at Cerro Rico de Potosi, Bolivia: Economic Geology, v. 100, p. 1647–1656.

Santos, J.O.S., Rizzotto, G.J., Potter, P.E., McNaughton, N.J., Matos, R.S., Hartmann, L.A., Chemale Jr., F, and Quadros, M.E.S., 2008, Age and autochthonous evolution of the Sunsas orogen in West Amazon craton based on mapping and U-Pb geochronology: Precambrian Research, v. 165, p. 120–152.

SERGEOMIN-YPFB (Servicio Nacional de Geología y Minería and Yacimientos Petrolíferos Fiscales Bolivianos), 2000, Compendio de Geología de Bolivia: Revista Técnica de YPFB, v. 18, 212 p.

Sillitoe, R.H., Halls, C., and Grant, J.N., 1975, Porphyry tin deposits in Bolivia: Economic Geology, v. 70, p. 913–927.

Sillitoe, R.H., Steele, G.B., Thompson, J.F.H., and Lang, J.R., 1998, Advanced argillic lithocaps in the Bolivian tin-silver belt: Mineralium Deposita, v. 33, p. 539–546.

Tistl, M., 1985, Die Goldlagerstätten der nördlichen Cordillera Real/Bolivien und ihr geologischer: Reimer, Berlin, Berliner geowiss. v. 65, 93 p.

Troëng, B., Claure, H., Oliveira, L., Ballón, R. and Walser, G., 1993, Tarija and Villazon Sheets. Boletin del Servicio Geologico de Bolivia, no. 3 (Thematic Maps of the Mineral Resources of Bolivia. Memoir 178 p. plus 6 thematic maps, scale, 1:250,000).

Turneaure, F.S., 1971, The Bolivian tin-silver province: Economic Geology, v. 66, p. 215–25.

USGS and GEOBOL (U.S. Geological Survey and Servicio Geólogico de Bolivia), 1992, Geology and Mineral Resources of the Altiplano and Cordillera Occidental, Bolivia: USGS Bulletin 1975, 365 p.

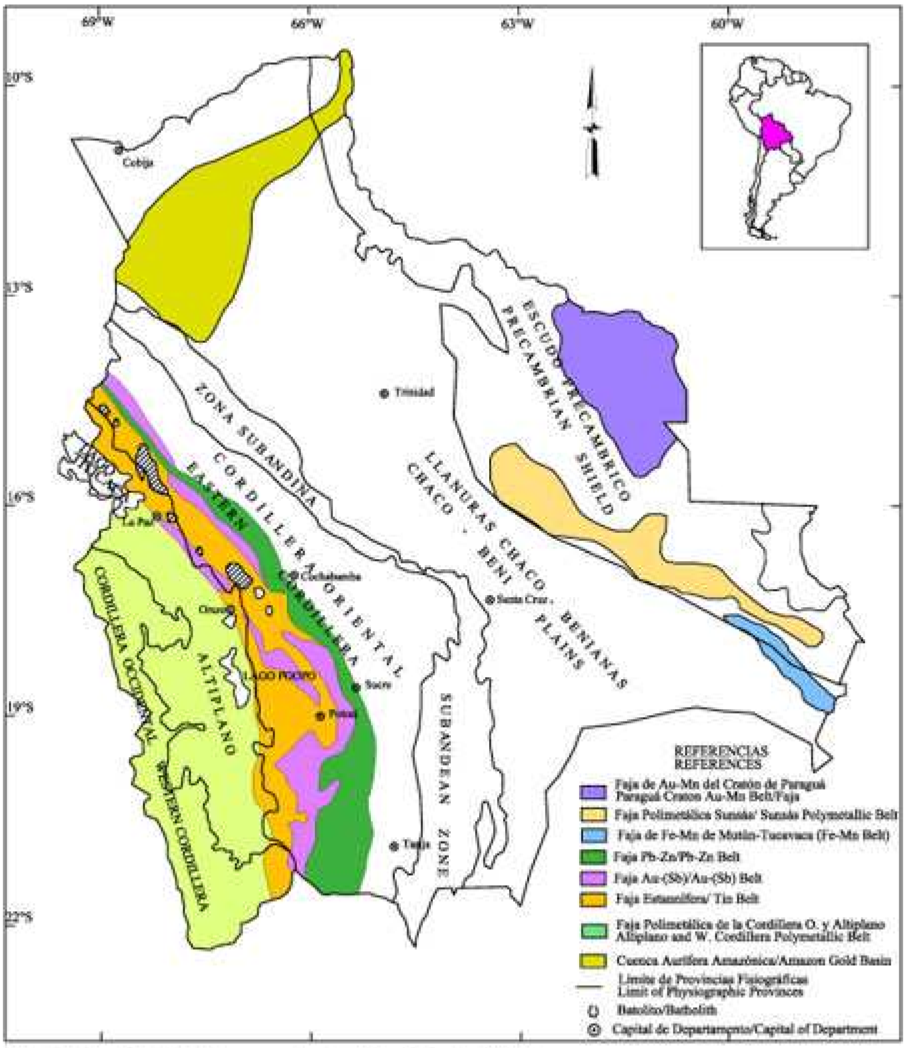

Fig. 1 Fajas Metalogénicas y provincias fisiográficas de Bolivia.
Fig. 1 Metallogenic belts and physiographic provinces in Bolivia.

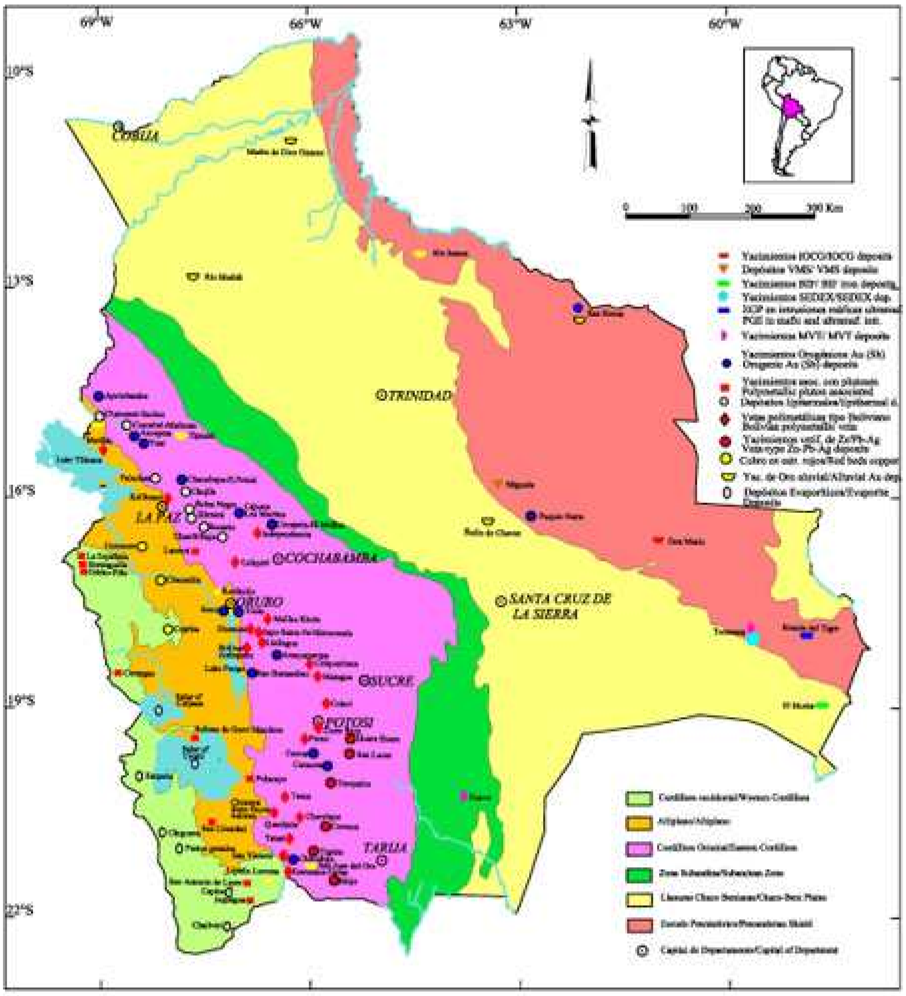

Fig. 2 Principales yacimientos en las provincias fisiográficas de Bolivia.
Fig. 2 Major ore deposits on physiographic provinces in Bolivia.