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Geologic Review of Tin-polymetallic Mineralization in the Oruro Mining District, Central Bolivian Tin Belt

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ABSTRACT

The global historic tin production is mainly from a few tin ore provinces within larger granite belts. These are, in decreasing importance, Southeast Asia, South China, the Central Andes and Cornwall, UK. Primary tin ore deposits are part of magmatic-hydrothermal systems invariably related to reduced and fractionated intrusions and are mostly located in continental tectonic settings. As the precipitate environments and geologic settings are different, the primary tin deposits can be classified into a few types: vein-stock, pegmatite, skarn, carbonate replacement, porphyry and epithermal.

The tin deposits in the Central Andes are largely concentrated in Bolivia. The geologic-tectonic framework of Bolivia can be divided into six physiographic provinces: Precambrian Shield, the Chaco-Beni Plains, the Subandean zone, the Eastern Cordillera, the Altiplano, and the Western Cordillera. The Eastern Cordillera hosts the famous Bolivian tin belt which is also known as the Central Andes tin belt as mentioned. High-grade hydrothermal tin lodes, which typically also contain significant amounts of Ag, W and Zn, largely occur in the belt.

The Oruro mining region is situated in the cone part of the Bolivian tin belt and the rocks in the region are mainly Silurian sedimentary and metasedimentary rocks along with some high-level porphyritic stocks of Miocene age. Numerous world-class tin deposits are located in this region, including the Llallagua Sn deposit, the Oruro Ag-Sn deposit, the Santa Fe Sn-Zn-Pb-Ag mining district, the Poopó Sn-Ag-Zn-Pb deposit and the Bolivar Sn-Ag-Zn deposit. The mineralized veins of the deposits are either within and adjacent to the high-level intrusive stocks or may be related to hidden or underlying stocks in depth.

Tincorp Metals Inc. has acquired two tin exploration projects, the Porvenir Project and San Florencio Project, both located in the Oruro region, and both are vein-type Sn-Zn-Ag deposits. The mineralization is hosted in Silurian sedimentary and metasedimentary rocks, and the ore minerals are cassiterite, sphalerite and Ag-rich galena. The two projects share plenty of common geologic characteristics with the large-scale tin mines in the Oruro region and both have great exploration potential.

Keywords Tin・Central Andes・Bolivia・Oruro・Exploration

1. Introduction

Bronze, the alloy of copper and tin, made tin a then “strategic metal” about 5000 years ago in the beginning of the Bronze Age. Tin remained a big metal in the industrial revolution, together with steel, copper, iron, and aluminum. Over the last decennies, there has been a renaissance of tin with the rapid development of the electronics industry where about 50% of the current tin production is used as (lead-free) solder. There are more high-tech applications of tin alloys, such as in superconducting magnets, advanced solar cells, and liquid-crystal displays. Tin has been assessed as a medium-scale “critical metal” essential for the transition to a low-carbon economy and is one of the ten most important metals associated with key decarbonization technology (Moss et al., 2013).

Tin provinces are one of the best examples of metallogenic provinces. They define belts on a 100- to 1000-km scale. Inside tin provinces, the association of tin ore deposits with granitic rocks has long been known. The geology of primary tin deposits shares anumber of major ingredients, which has been previously studied by Taylor (1979), Ramakrishnan (1989), Kamili et al. (2017) and Lehmann (2021).

Bolivia covers an area slightly larger than 1 million km^2 and has long been recognized as one of the world's most remarkably metal rich regions. 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 the collapse of the tin market in 1985. The Bolivian tin belt extends for approximately 900 km in a northwest to north-south–trending direction in the Eastern Cordillera of Bolivia. The region was once considered the largest tin producer in the world and produced more than two million tons of metallic tin.

Tincorp Metals Inc. has acquired 100% interest of two tin exploration projects, the Porvenir Project and SF Tin Project, which are 70 km southeast of Oruro, Bolivia. These two projects are located in the cone region of the Bolivian tin belt, the Oruro mining

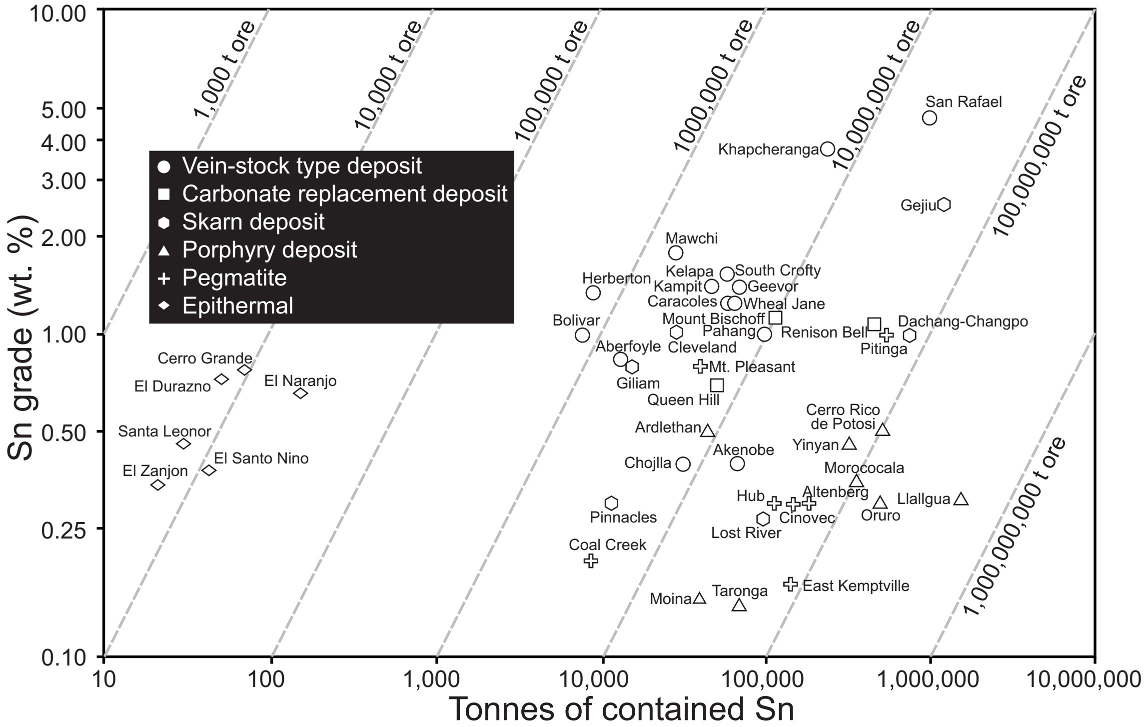

Figure 1. Grade versus tonnage for selected, large and high-grade primary tin deposits. Modified after Mlynarczyk et al. (2003).

region. SF Tin Project is 15 km away along the same North-West trend as the largest hard-rock tin deposits in the world – the Llallagua tin deposit (over 1 Mt Sn produced, Arce-Burgoa and Goldfarb, 2009, Fig. 1). Porvenir is 15 km from the largest producing tin mine in Bolivia – the Huanuni Mine (7,000t of Sn produced in 2018, Cacho et al., 2019).

The paper is aimed to (1) reassess the major geologic characteristics of primary tin deposits; (2) introduce the geologic framework of Bolivia and Bolivian tin belt; (3) summarize the geology of a number of world-class Sn deposit in the Oruro region; and (4) discuss the geology and exploration potentials of the two Bolivian tin projects of Tincorp Metals Inc.

2. Formation of tin ore deposits

The global cumulative historic tin production can be estimated to be about 27 Mt Sn (up to 2020; Lehmann, 2021). More than 99% of this tin production is from ore deposits directly (primary deposits) or indirectly (placers) related to granitic rocks (i.e., granites and their volcanic and subvolcanic equivalents). A small quantity of tin is or was recovered as a by-product of mining of base-metal massive sulfide deposits (such as Kidd Creek, Canada, or Neves Corvo, Portugal).

Four well-defined regions account for about 85% of the cumulative historic tin mining output. These are (Fig. 2):

1. The SE Asian tin belt (Myanmar, Thailand, Malaysia, Indonesia) with a 40–45% share of the total world tin production.
2. The South China tin province (20%).
3. The Central Andean tin belt (Bolivia and southernmost Peru) (14%).
4. The Cornwall tin province (7%).

There are a number of discoveries and exploration projects in development which will increase the proportion of tin mined from other parts of the world, such as the Syrymbet deposit in northern Kazakhstan and the Deputatskoe deposit in Yakutia, NE Russia, with more than 200,000 t Sn content each, or several Precambrian tin deposits under development in eastern DR Congo. For details see the World Tin and Tungsten Deposit database by Sinclair et al. (2011).

Cassiterite is the only tin species of major economic importance but stannite, teallite and even a little malayaite, the last as a minor component in an essentially cassiterite concentrate, have been utilized by the smelter.

The close relationship between tin deposits and granites has been well known since the mid-19th century. Generally, primary tin deposits are magmatic-hydrothermal deposits, and the ore-forming fluids originate from reduced and highly fractionated S-type intrusions (Fig. 3). Sn occurs as Sn^{2+} and Sn^{4+} in nature. If a silicate melt is oxidized, then Sn mostly occurs as Sn^{4+} and can substitute for Ti^{4+} and Fe^{3+} (similar ionic radii and charge) in the crystal lattice of Ti- and ferric Fe-bearing minerals, such as titanite, magnetite-ilmenite, hornblende, and biotite. When these minerals crystallize, they take away significant amounts of Sn from the melt, thereby reducing the amount of Sn available for later hydrothermal fluids (Lehmann, 1990). Therefore, for Sn to be concentrated in residual melts for the subsequent hydro-thermal processes, the melts need to be

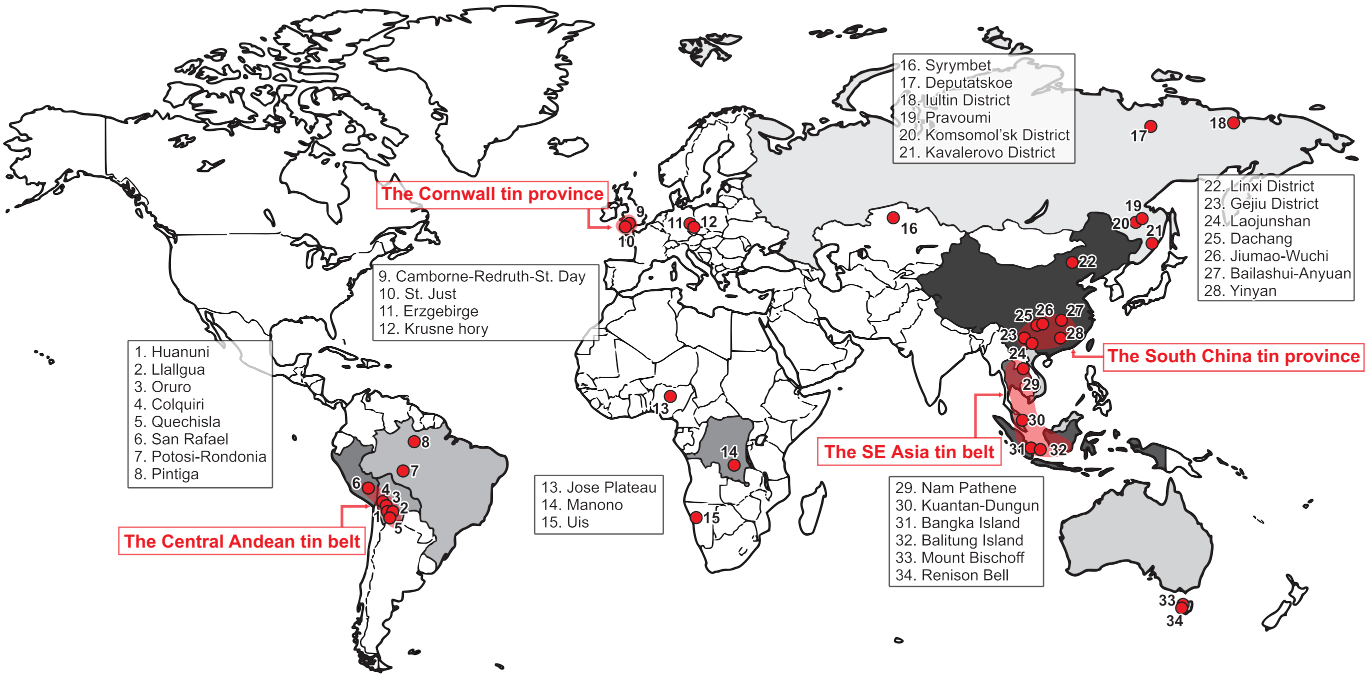

Figure 2. Distribution of world class tin deposits (>100,000 tonnes). Modified after Sinclair et al. (2011).

reduced. Tin is typically associated with highly fractionated magmas (Blevin et al., 1996), because the crustal abundance of Sn is relatively low, and to make an Sn deposit the concentration factor (ratio of minimum economic ore grade to crustal abundance) for Sn is much higher than many other metals (Evans, 1993). Fractionation of a melt is a significant way to enrich incompatible Sn under reduced conditions.

The tectonic settings of tin-bearing granites are relatively well understood and limited in variation. Tin deposits and their associated igneous rocks occur in continental settings worldwide. More than 25 percent partial melt during crustal anatexis is probably a precondition for large-scale magma segregation. Magma segregation and intrusion into an upper crustal level is favored by a brittle lithosphere in crustal extension zones (Lehmann, 1990). The tectonic settings of tin granites and porphyries, according to Lehmann (1990), are as follows:

1. Post-orogenic magmatism in continental collision belts.
2. Internal regions of active continental margins (back-arc regions).
3. Intracratonic anorogenic and continental rift zones.

Based on the various geologic settings, genesis models and precipitation environments (Fig. 4), primary tin deposits can be classified to the following general types:

Vein-stockwork tin deposits

Vein-stockwork deposits of tin occur in a wide variety of structural styles that include individual veins, multiple vein systems, vein and fracture stockworks, breccias, and replacement zones in altered wall rocks adjacent to veins (Sinclair, 1995). The deposits generally occur in or near granitic intrusions. When vein is hosted in intrusive rocks, hydrothermal alteration is commonly greisen-type alteration that is characterized by Li-, F-, and/or B-bearing minerals such as topaz, fluorite, tourmaline, and various F- and/or Li-rich micas. While when the veins are hosted in metasedimentary rocks, chlorite and sericite dominated the alteration halo.

Pegmatite deposit

Pegmatite refers to a rock whose bulk composition is granitoid and in which the constituent minerals have crystallised to an unusually large size. Most pegmatite tin deposits are of Precambrian ages. The tin-related pegmatites are of the quartz-microcline type, with albite, muscovite, spodumene, topaz, and tourmaline. Cassiterite is irregularly disseminated throughout the pegmatite body and commonly in areas where secondary processes have taken place (Taylor, 1979). In some instances, the economic importance of the bodies has depended on the presence of species other than cassiterite, particularly tantalite and columbite, and in some instances, lithium species.

Skarn deposits

Skarn deposits are characterized by containing calcium or magnesium silicates. Stanniferous skarn deposits have generally developed from carbonate rocks as a result of them being subjected to heat and later hydrothermal mineralising agents from a granite. These deposits occur near the high parts of granites in roof pendants and enclaves, as border deposits to the granitoid as bedded deposits bordering a granitoid or overlying but separated from the granitoid by non-calcareous deposits as pipes or veins and as deposits bordering granitoid dykes and sills (Hosking, 1988).

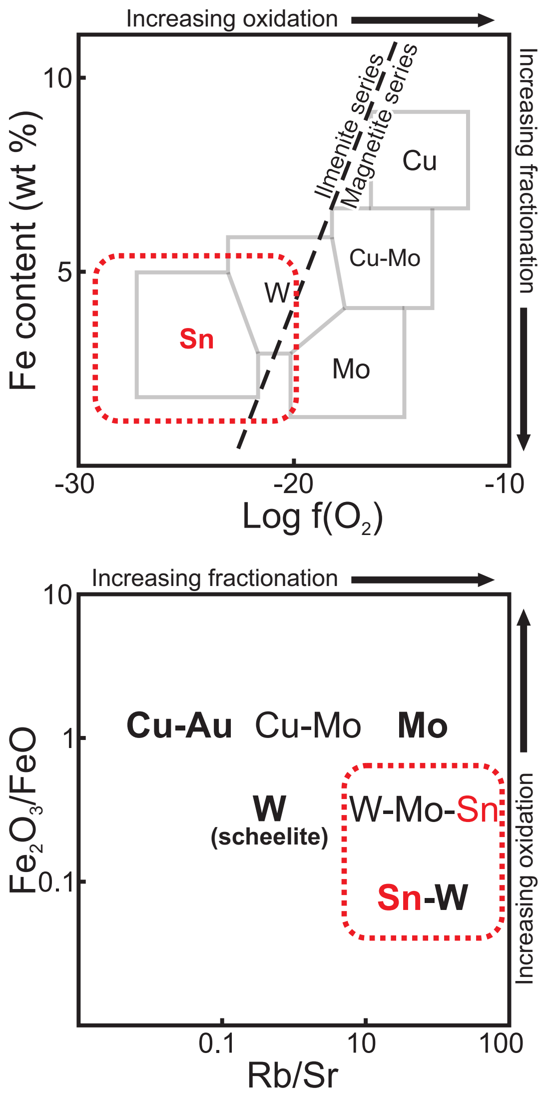

Figure 3. Schematic plot showing degree of fractionation (shown by Fe content and Rb/Sr) versus oxidation (shown by oxygen fugacity and Fe2O3/FeO). Modified after Thompson et al. (1999) and Blevin et al. (1996).

Carbonate Replacement Deposits

Carbonate replacement deposits are also known as carbonate-hosted Ag-Pb-Zn-Sn deposits. These deposits require over 250 degrees Celsius of temperature to form. A Carbonate replacement deposit is an orebody of metallic minerals formed by the replacement of sedimentary, usually carbonate rock, by metal-bearing solutions in the vicinity of igneous intrusions. When the ore forms a blanket-like structure around the bedding plane of rock, it is commonly referred to as a manto ore deposit. Carbonate-replacement deposits form some of the largest tin deposits in Australia (e.g., Renison Bell).

Porphyry tin deposits

Porphyry deposit refers to the deposits occur close to or in granitic intrusive rocks that are porphyritic in texture. Porphyry tin deposits typically occur in Bolivia (e.g., Chorolque). The granitic stocks are commonly 1 to 2 km2 in area and more than 1 km in known vertical extent. Locally sericite alteration grades outward to propylitic alteration. The cassiterite is present as part of sericite and quartz-tourmaline assemblages. Potassium silicate alteration is not common (Hosking, 1988).

Epithermal tin deposits (Mexican Type)

Epithermal deposits are formed when the fluids are directed through a structure from magmatic bodies at depth to a shallow position. The deposits of Durango, Mexico, indicate the major characteristics of the epithermal tin deposits. The deposits commonly occur in belts of rhyolites and in the same belt silver deposits are found. The tin deposits are apparently confined to rhyolites which possesses steeply dipping flow banding, which seems to be an intrusive stock or dyke rather than a true extrusive. This tin host rocks possess chilled margins consisting of very dense breccias where the mineralisation is confined to vein, disseminated and breccia deposits (Hosking, 1988).

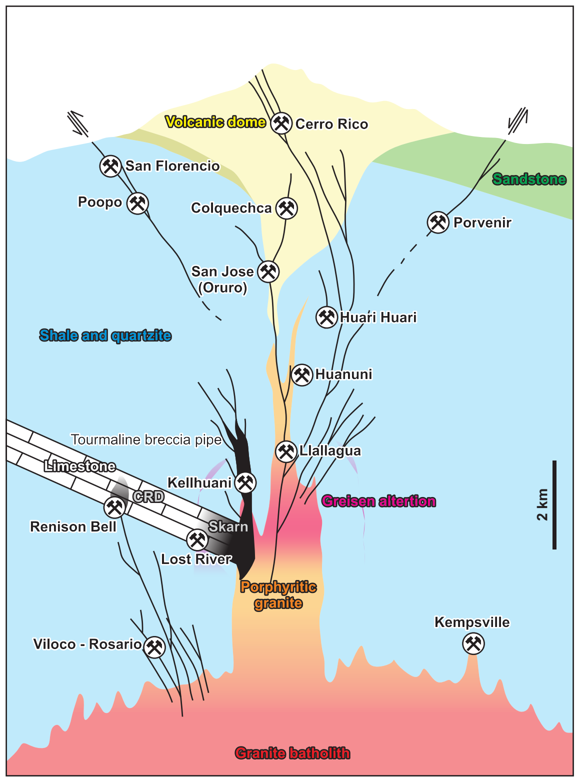

Figure 4. Classic model of primary tin deposits related to magmatic hydrothermal systems. Modified after Gemmrich et al. (2020).

3. Geologic Framework of Bolivia

The geologic-tectonic framework of Bolivia can be divided into six physiographic provinces. From east to west (Fig. 5), 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), which hosts an abundance of mineral deposits.

Rocks of the Precambrian Shield in easternmost Bolivia have commonly been suggested as defining the southwestern part of the Amazon. The units are mainly Mesoproterozoic medium and high-grade metasedimentary and meta-igneous rocks.

Figure 5. Major ore deposits in the physiographic provinces of Bolivia and Bolivian tin belt. Modified after Arce-Burgoa and Goldfarb (2009).

The Chaco-Beni plains are located in the central part of the country. The topography is dominated by the southwestern Amazon basin wetlands with little relief or outcrop. These extensive plains are part of the foreland basin of the Central Andes.

The Subandean zone is the thin-skinned, inland margin of an orogen-parallel fold-and-thrust belt. Rock types in this province include Paleozoic siliciclastic marine and Mesozoic and Tertiary continental sedimentary rocks.

The Eastern Cordillera, the uplifted interior of the Andean thrust belt, includes poly deformed Ordovician to Recent shale, siltstone, limestone, sandstone, slate, and quartzite sequences. These mainly Paleozoic clastic and metamorphic rocks 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 (McQuarrie et al., 2005).

The Altiplano is a series of intermontane, continental basins, which forms a high plateau. Crustal shortening, rapid subsidence, and, simultaneously, as much as 15 km of sedimentation took place during the Andean orogeny. 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. 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 porphyry orebodies, were emplaced along the coasts of adjacent Peru and Chile. In Bolivia, this province is dominated by high andesitic to dacitic strata volcanoes, formed since ca. 28 Ma, that define the narrow, main Central Andes modern magmatic arc (Arce-Burgoa and Goldfarb, 2009).

4. Bolivian Tin Belt

The Bolivian tin belt (Fig. 5) 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). Highgrade (1–5% Sn) hydrothermal tin lodes, which typically also contain significant amounts of Ag, W and Zn, 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. The absence of limestone is noticeable and thus there is no carbonate replacement deposit and skarn deposit in the belt.

The Bolivian tin belt is genetically connected to two major periods of magmatism related to the Andean orogeny: the first is linked to intrusions of granitic plutons of Triassic to Jurassic ages, which is restricted to the northern portion of the Bolivian tin belt, and the second is related to plutonic, sub-volcanic, and volcanic eruptive complexes of Oligocene to Miocene ages, which dominated the southern half of belt (Sillitoe et al. 1975; Evernden et al. 1977; Kontak et al. 1987, 1990; Mlynarczyk and Williams-Jones 2005). In the north, the Triassic granite intrusions were interpreted as typical of rift-related magmatism in a back-arc setting (Kontak et al. 1984, 1990; Lehmann et al. 1990). The now-inverted rift system had an axis coinciding with the axis of the current Eastern Cordillera (Sempere et al. 2002). While in the south, caldera complexes and large volumes of Late Pliocene and Miocene (and up to recent) ignimbrite deposits of dacite and rhyolite composition formed because of changes in mantle melt productivity induced by the south-migrating subduction.

In the northern part of the tin province, the deposits are intimately related with the granitic intrusions of the Cordillera Real and are characterized by a low content of silver, and essentially do not present an individual zonation (although as a group, they are zoned around the batholiths). 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 contrast, in the southern and central part of the belt, the deposits are more commonly associated with subvolcanic individual stocks and are characterized by their more complex mineralogy, and usually has high silver contents and well-developed zonation. The polymetallic vein deposits include veins, veinlets, stockworks, and disseminated ores within the various host rocks. Tin deposits associated with plutonic bodies are an exception, with an example in the Kari-Kari Batholith in Potosi.

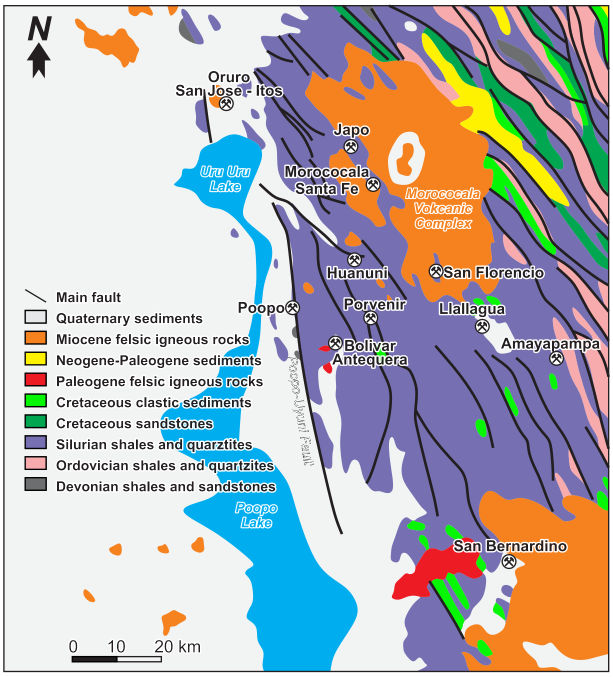

Figure 6. Regional geologic map of the Oruro region. Modified after Heuschmidt et al. (2000).

5. Oruro Mining District

The Oruro region in southwest Bolivia sits on the central part of the Bolivian tin belt, at the hinge between the northerly NW-SE part of the belt and the southerly N-S part (Fig. 6). The host rocks in the region are made up of a thick sequence of Silurian sedimentary and metasedimentary rocks composing of quartzite, sandstone and slate. High-level porphyritic stock crop out locally, which are products of Miocene igneous activity.

Twenty-one vein-type tin-polymetallic ore deposits have been identified in the Oruro mining district. Most of the veins are formed within and adjacent to the high-level stocks, whereas others may be related to hidden or underlying stocks at deeper positions. The eastern part of the Oruro district is overlain by an extensive rhyodacitic ignimbrite of the late Miocene, which forms the Altiplano plateau.

Among the tin deposits in the region, the geology of the Llallagua Sn deposit, the Oruro Ag-Sn deposit, the Huanuni Sn-W-Pb-Ag-Zn deposit, the Santa Fe Sn-Zn-Pb-Ag mining district, the Poopó Sn-Ag-Zn-Pb deposit and the Bolivar Sn-Ag-Zn deposit have been well studied.

Llallagua Sn Deposit

The Salvadora stock (1700*1000 m in surface) at Llallagua intruded into the axis of a sharply overturned, northwest-striking anticline involving the Silurian-Devonian sedimentary and metasedimentary rocks (Fig. 7). The mineralization of Llallgua is mostly confined to the Salvadora stock. Hydrothermal intrusion breccia is commonly developed at the contact of the stock with the surrounding clastic sediments and is also prevalent within both the stock and its host rocks. The matrix and the fragments in the breccia are composed of porphyry and sedimentary rock in all proportions. Breccias contain some fragments of pyrite with some cassiterite (Sillitoe et al., 1975).

Pyrite and cassiterite occur in a stockwork of multidirectional veinlets up to 2 cm wide and as disseminations in the sericite-chlorite altered rocks. Cassiterite is widespread as a replacement of the rims of breccia fragments. The stock averages about 0.3 percent Sn, and evidence points to its presence largely in breccia and in the stockwork (Sillitoe et al., 1975).

The throughgoing veins within and peripheral to the Salvadora stock postdate the disseminated and stockwork tin mineralization, although the two stages were probably transitional. The lode system consists of main and branch veins, narrow stringers, and sheeted zones 30 to 80 m wide, with a predominantly north-easterly strike. The earliest mineralization in the main veins consists predominantly of quartz followed by bismuthinite and cassiterite. This early stage is followed by pyrrhotite and franckeite, then stannite, sphalerite, and chalcopyrite.

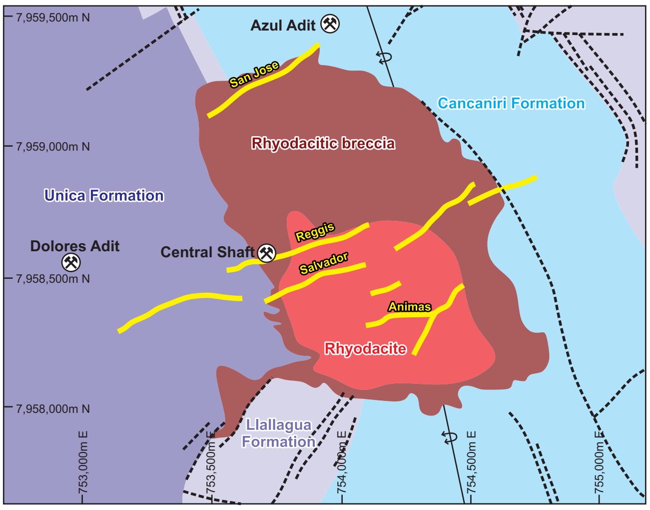

Figure 7. Simplified geologic map of the Llallagua tin deposit. Modified after Kempe et al. (2008).

Oruro Ag-Sn Deposit

The largest intrusive in the Oruro center is the San Pedro stock but a major part of the mineralization is associated with the smaller San Jose and Itos stocks (Fig. 8). The mineralized stocks are known to a depth of about 700 m below surface. A narrow contact aureole borders the stocks (Sillitoe et al., 1975). The stocks are considered to be composed of quartz latite porphyry.

Hydrothermal intrusion breccia is common at Oruro in irregular bodies, pipes, lenses, dikes, and veinlets. The main masses are on the margins of the San Jose stock, but a few cut the stocks and the wall-rock lutites. The breccias consist of subangular-to-rounded fragments of quartz latite porphyry and lutite, in varying proportions, in a matrix of finely comminuted rock, mainly lutite. Breccias are commonest in the upper parts of the stocks, but an individual body has been traced for at least 300 m vertically. Breccia dikes, transecting bodies of coarser breccia, and fragments of breccia in breccia testify to at least two periods of brecciation. The breccia dikes are filled by dark-colored rock flout and are similar to those at Llallagua. Fragments of pyrite are seen in breccia indicating that some of the brecciation was accomplished later than mineralization. Pyrite veinlets and the tin-silver veins cut the breccia.

The veins tend to be a dominance of northeast and northwest strikes within the four principal vein clusters. Early tin mineralization is followed by a silver-rich phase, but here a more evident structural break separates the two stages. Locally in the lode system a pulse of hydrothermal brecciation separates the two mineralization stages. Some structures carry exclusively tin ores or silver ores, whereas others carry both types. The early vein stage comprises minor quartz with pyrite, cassiterite, and arsenopyrite. The later silver stage commenced with the deposition of sphalerite, chalcopyrite, pyrite, stannite, franckeke, and teallite, followed by tetrahedrite and andorite, and finally by lead sulfosalts such as zinckenite, boulangerite, and jamesonite (Sillitoe et al., 1975). Mineral zoning is not conspicuous at Oruro.

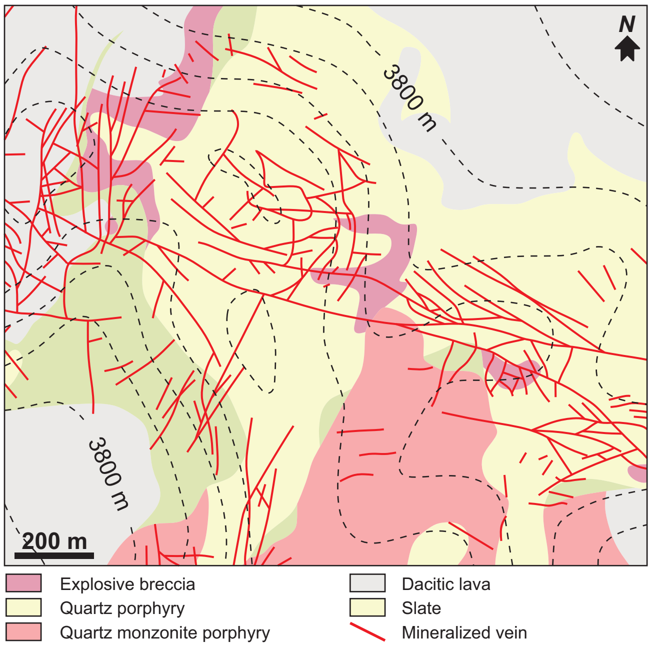

Figure 8. Simplified geologic map of the Oruro deposit. Modified after Sugaky et al. (1981).

Huanuni Sn-W-Pb-Ag-Zn Deposit

The Huanuni deposit is currently the largest tin producer in Bolivia, accounting for over a half of the total production of Bolivia (Cacho et al., 2019). The deposit is dominantly on the eastern flank and the nucleus of the locally overturned (towards the SW) Pozokoni anticline, and the mineralisation is largely hosted by Paleozoic quartzites, shales and siltstones, to a lesser extent, by the pyroclastic and lava series of the Miocene (Koeppen et al., 1987). Miocene porphyritic dikes, approximately N-S striking, crop east of the Pozokoni anticline and extend for over 2 km (Fig.9). These are inferred as the most likely source for the hydrothermal polymetallic deposits (Heuschmidt et al., 2002). Nevertheless, the occurrence of an unnamed intrusion below the Huanuni mine within the core of the homonymous anticline is inferred (Heuschmidt et al., 2002).

The Huanuni deposit consists of several tens of veins and breccias with no preferential orientation (Turneaure et al., 1960) but having roughly concentric and radial patterns, thus resembling a radial nested arrangement (Fig. 9). The veins were grouped by Cacho et al. (2019) into three main domains, a central domain around the Huanuni mine and Pozokoni hill, and two peripheral or distal domains named Bonanza and La Suerte (south and southeast of the central domain, respectively). The peripheral zones are richer in Zn relative to the central. The veins are normally less than 1 m thick. The mineralised areas extend across a ~10 hm2 quadrangle. Most veins do not crop out, but their tops are found between 100 m and 350 m below the surface, and some of them occur even deeper (480 m below surface).

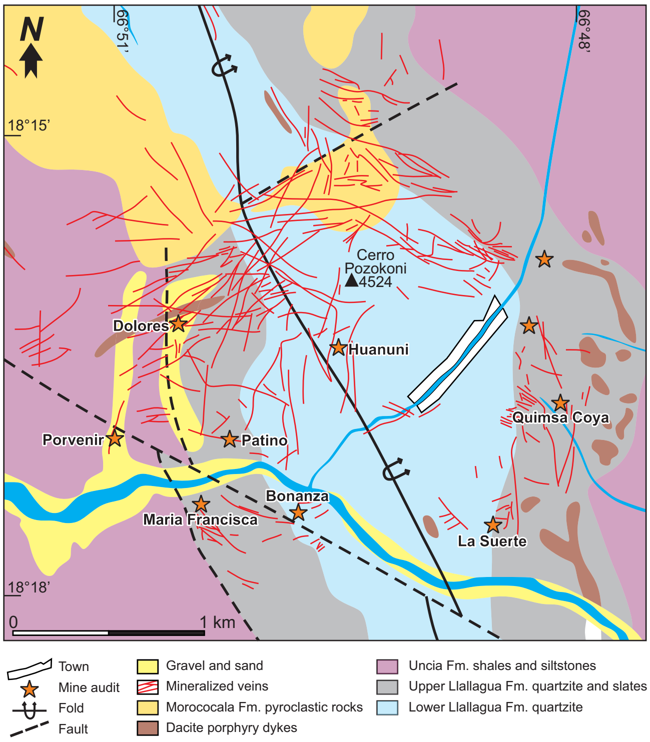

Figure 9. Simplified geologic map of the Huanuni deposit. Modified after Cacho et al. (2019).

The mineralised structures are crudely banded and involves 3 stages (Cacho et al., 2019). Stage I consists of base-metal sulphides (pyrite, chalcopyrite, arsenopyrite and pyrrhotite), quartz and may contain cassiterite and acanthite. Stage II is also base metal-rich (pyrite, pyrrhotite, arsenopyrite galena, wolframite, cassiterite and sphalerite) and is the main carrier of schorl, cassiterite and indium-bearing sphalerite in the deposit; the occurrences of cobalt, nickel and cerium minerals belong to this stage as well. Stage 3 consists of sulphosalt-rich associations and is the main carrier of silver minerals, particularly in the peripheral areas of the deposit.

Santa Fe Sn-Zn-Pb-Ag Mining District

The Santa Fe mining district contains several Sn-Zn-Pb-Ag deposits, and from economic point of view, the most important deposits of the district are Japo, Santa Fe and Morococala.

The Japo mine is situated at the eastern flank of the Santa Fe anticline axis, aligned NW-SE direction (Fig. 10) The country rocks in the Japo mine are represented by a Paleozoic metasedimentary sequence divided into the Cancañiri, Llallagua, Uncia and Catavi Formations. The Santa Fe and Morococala mines are separated one each other by about 2 km (Fig. 10). They are mainly hosted by rocks of the Cancañiri Formation, which is unconformably covered by the Pliocene Morococala Formation (Jiménez-Franco et al. 2018).

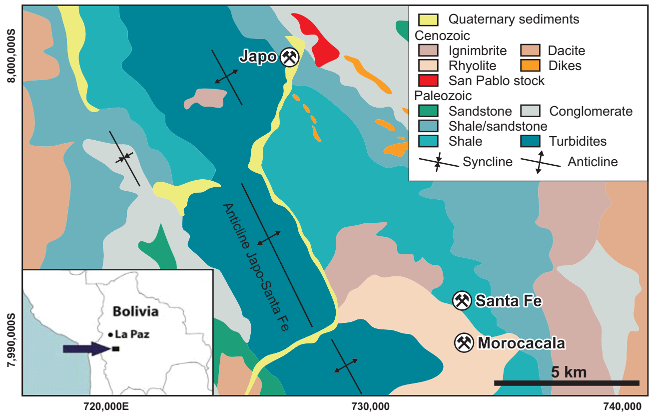

Figure 10. Geologic map of the Santa Fe District. After Jiménez-Franco et al. (2018).

Two important episodes of igneous activity are in the Santa Fe mining district. The first one is mostly constituted by rhyolite of 7.0 Ma and dacite of 5.8-6.4 Ma (Evernden et al., 1977; Lavenu et al., 1985). An intense igneous activity representing the second event produced plutonic bodies as the San Pablo stock and related dikes. The age of this plutonic suite is Miocene (Sugaki et al., 2003). The ore deposits in the district are spatially related to intrusive rocks, consisting of peraluminous granitic stocks and porphyritic intrusives formed through different magmatic pulses, most of them during Oligocene-Miocene times (Grant et al., 1979).

Two stages of mineralization are identified in the district. Stage I consists of Sn-rich cassiterite-quartz veins and stage II is composed of Zn-Pb-Ag veins with sphalerite, galena and stannite mineral phases (Jiménez-Franco et al., 2018). In the Japo deposit, ore minerals occur disseminated in intrusive rocks and also following lithological and structural contacts, fracture infillings and replacements. Hydrothermal alteration in the plutonic rocks is composed of sericite, monazite, tourmaline and sulfides (mostly pyrite) and along the contact between host rocks and quartz veins, where alunite, plumbojarosite, vermiculite, kaolinite and dickite occur. On the other hand, in the Santa Fe and Morococala deposits, ore is found as quartz veins, of few centimeters to 0.5 m thick, with cassiterite, Zn-Pb-Ag sulfides and sulfosalts. Rutile is associated with a late generation cassiterite, forming needle-like crystals.

Poopó Sn-Ag-Zn-Pb Deposit

The Poopó deposit consists of a vein system along the regional Poopó–Uyuni fault system with a general N-S strike hosted in Silurian black shales and sandstones (Fig. 11). The largest vein in the area developed directly on the main fault, dips 50–70° E, and experienced severe cata-clastic deformation due to the fault reactivation after mineralisation. Ancillary veins around the main one shows the same essential strike but milder deformation and less vertical dipping. The mineralogy of veins is ever dominated by quartz. Most veins show cata-clastic brecciation that was associated with faulting activity, and breccia

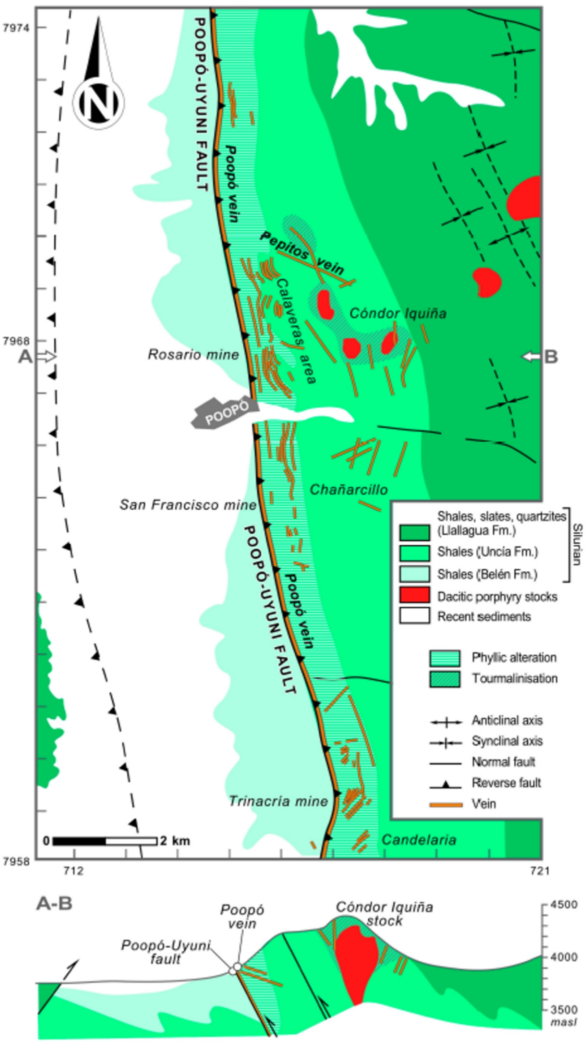

Figure 11. Simplified geologic map and the cross section of the Poopó deposit. After Heuschmidt et al. (2002).

fragments were cemented by later hydrothermal mineralisation. Brecciation can also be due to the fault reactivation after mineralisation. Ancillary veins around the main one shows the same essential strike but milder deformation and less vertical dipping. The mineralogy of veins is ever dominated by quartz. Most veins show cata-clastic brecciation that was associated with faulting activity, and breccia fragments were cemented by later hydrothermal mineralisation. Brecciation can also be due to hydrothermal processes alone, but it is a less common feature than cata-clastic brecciation in these deposits. Whether brecciated or not, all veins show a polyphase and multi-episodic character (Torres et al., 2019).

The mineralization in the deposit is composed of at least two major stages (Torres et al., 2013). Stage I consists of quartz, pyrite, arsenopyrite, sphalerite and cassiterite. These minerals are generally fine-grained since they were deposited before or during the faulting activity and they are brecciated and have a cata-clastic texture. The most abundant mineral in this stage is pyrite, accompanied by lesser amounts of Fe-rich sphalerite. Pyrite and arsenopyrite formed as small (less than 50 microns) euhedral crystals, which was broken and recemented by the rest of minerals later. Stage II took place after major faulting activity. Quartz was filled in between the stage I pyrite. Stannite and a second-generation sphalerite formed by replacing stage I cassiterite.

Bolivar Sn-Ag-Zn Deposit

The mineralization system is hosted in Cenozoic rocks of the middle to upper Silurian, constituted almost entirely by marine sediments and the associated Chualla Grande stock (Fig.12), where the following lateral ore metal zoning is observed: (i) pyrrhotite-cassiterite-tourmaline-quartz in the innermost zone; (ii) fine-grained cassiterite-jamsonite-sphalerite-pyrite represented; then (iii) the outermost zone of some galena-stibnite veins (Sugaki et al., 1981).

The Bolivar deposit crops out at the surface and is of the fissure-filling type rich in sphalerite, which occurs mostly in sheared fractures along anticlinal axes of the shale and siliceous sandstone (Ishihara et al., 2011). No felsic stock but quartz porphyry sheets and dikes occur underground. A small felsic stock is exposed 5 km SSE of the mine. The mineralized sheared zones strike NE and dip 50–70° NW, and the zones extend 300 to 1100 m in the strike side and 65 to 200 m along the dip side with widths varies from 0.5 to 3.5 m (Ishihara et al., 2011).

The main ore minerals are sphalerite, pyrite, jamsonite and cassiterite. The ore veins are banded with pyrite occurring in the outer side and aggregates of needle jamesonite in the middle. The cassiterite is very fine-grained, less than 10 mm in diameter. Other ore minerals are stannite, occurring together with cassiterite and chalcopyrite microscopically, and marcasite of a later stage (Sugaki et al., 1981).

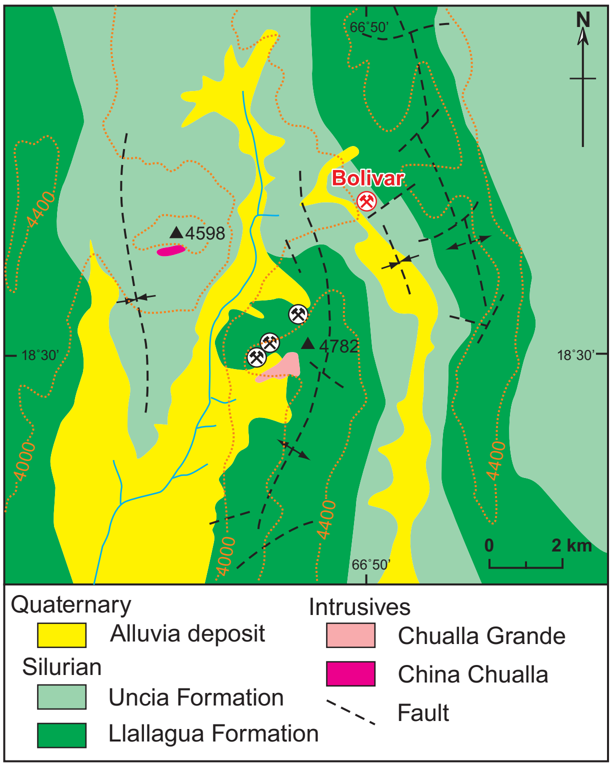

Figure 12. Geologic map of the Bolivar mining area. Modified after Sugaki (1981).

5. The Two Tin Exploration Projects of Tincorp Metals Inc.

Tincorp Metals Inc. successfully acquired two Bolivian tin exploration projects, Porvenir and San Florencio, in August 2022 and December 2022, respectively. Both exploration projects are situated in the Oruro region, the center of Bolivia Tin Belt, less than 20 kilometers away from Llallagua and Huanuni (Figure 5).

Porvenir

The Porvenir Sn-Zn-Ag project is located 65 km southeast of the city of Oruro. The 11.25 km2 property encompasses historical near surface open pit and underground workings, which exploited the deposit on a limited scale. The mineralised structures were primarily exploited for their high-grade Zn contents.

Rock outcrops at Porvenir are Silurian sedimentary and metasedimentary rocks (Fig. 13). The geological units identified in the area are the Catavi Formation with greenish gray micaceous sandstones intercalated with shales and partially silicified, and the Uncía Formation represented by greenish gray to dark gray micaceous shales and sandstones partially silicified and kaolinized by hydrothermal solutions, and the Llallagua Formation with light gray and brown quartzites, with small banks of greenish gray siltstones. There are no igneous bodies within the project. Quaternary sediments are represented by colluvial deposits, alluvial deposits are economic deposits due to their liberated tin content.

The tectonic and structural evolution of the area is manifested in folding, faulting, and low-grade metamorphism affecting the Silurian sedimentary rocks. The dominant structural feature is the flank of the Challapacheta syncline whose 144º axis is located to the west and outside the mining property. The entire mineralized zone of the mine is located on the eastern flank of the Challapacheta syncline, where minor folds with vergence to the east are observed.

The mineralization of primary hydrothermal origin of Tertiary age is presented in the form of formal tabular veins with a generalized strike of 030° and dip of approximately 75° with variable thicknesses. The mineralization control is structural that the mineralization has filled fractures in the rock and stratification planes between shales and sandstones, while the lithological control is notorious, due to the scarce and sometimes absence of mineralization in the shales and slates. Sandstones, rocks of competent behavior, give rise to fractures with wide and regular spaces, which are favorable for good mineralization. On the other hand, shales and slates have a plastic behavior, these rocks have generated minor folds and fractures that are not conducive to good mineral emplacement.

The zones of the main mineralized structures have been identified and defined; the Sillahuasai and Cóndor Nasa hills are the main orebodies in the present work (Fig. 13). Kakarchi in the north is an extension of the Sillahusa but composed of low-grade ores. Potential structures such as Palca E and Palca W have also been identified. These are located in the western part of the mining concession and have variable thicknesses and shapes that form rosary-type veins, whose lengths and thicknesses of the bodies have not been clearly defined. The exploration done so far in these areas is currently insufficient to be able to estimate the economic potential.

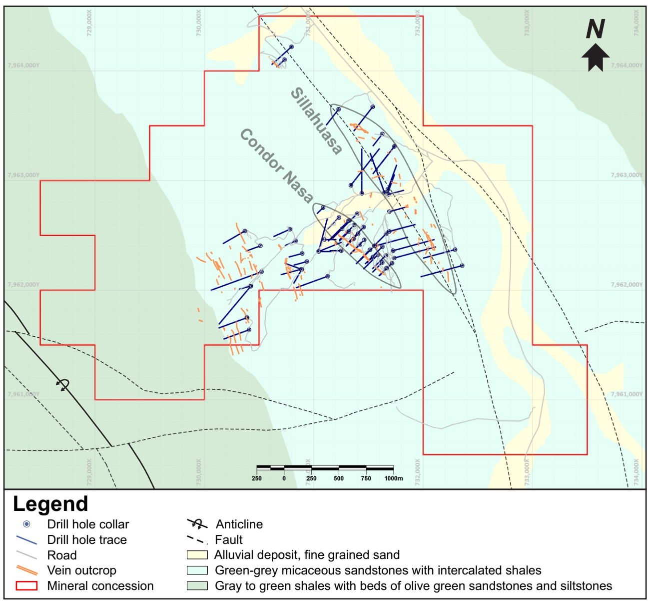

Figure 13. Simplified geologic map of the Porvenir project.

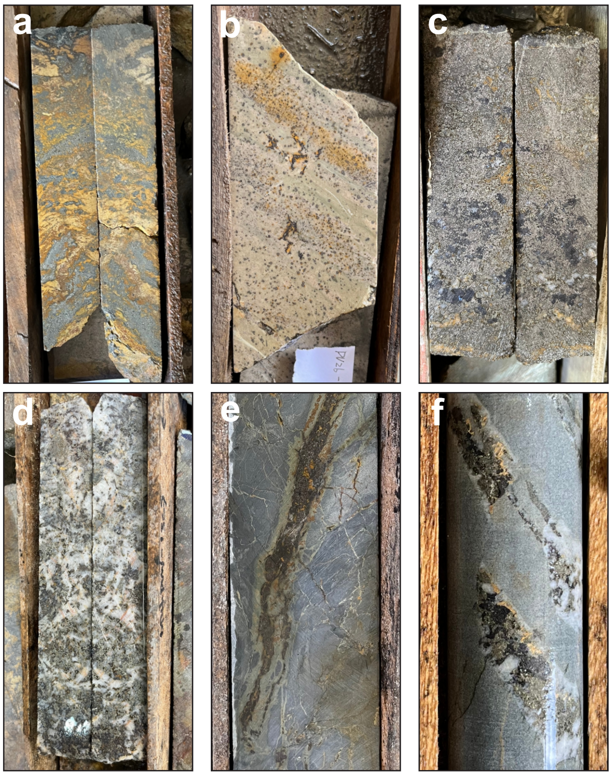

Figure 13. Photos of mineralized core from Porvernir: a. patches of sulfides hosted in bleached sandstone; b. disseminated pyrite hosted in bleached sandstone; c. massive sulfides; d. silicified sulfide breccia; e. chlorite-sericite alteration along the mineralized vein; and f. quartz and siderite in the mineralized vein.

The Sillahuasa ore-hosting structure has a length of 1000 meters, a bearing of 345° and dips varying between 55º SW and 65º SW (Fig. 13). The thickness of the structure is variable, of rosary-type, it goes from tens of centimeters to powers of several meters. The central part of the structure is hosted in bleached sandstones, where patches of sphalerite, pyrite, pyrrhotite and minor arsenopyrite occur in the middle (Fig. 14a) edged with dissemination of pyrite (Fig. 14b). A trace amount of siderite is the only gangue mineral here. Mineralization of tin and silver are not macroscopically visible.

The mineralized structure of Condor Nasa is located in the central part of the property and is approximately 700 meters long, with a strike of 315º and a dip that is practically vertical. Condor Nasa contains massive sulfides (Fig. 14c), silicified sulfide breccias (Fig. 14d) and sulfide veinlets consisting of sphalerite, pyrite, pyrrhotite and minor arsenopyrite. Chlorite-sericite alteration is strong along the mineralized veinlets as halo and is moderate to weak pervasively in the host rocks (Fig. 14e). Siderite and quartz are the major gangue minerals but only compose a small portion of the ore body (Fig. 14f). Same as Sillahuasa, tin and silver are not macroscopically visible.

San Florencio

At an elevation of 4,200m, the San Florencio Sn-Zn-Ag project covers an area of approximately 2 km2 in the Potosi department of Bolivia. The property encompasses a historical open pit (100 m by 100 m by 20m) and numerous underground workings from Spanish Colonial times, which exploited the deposit on a minor and limited scale.

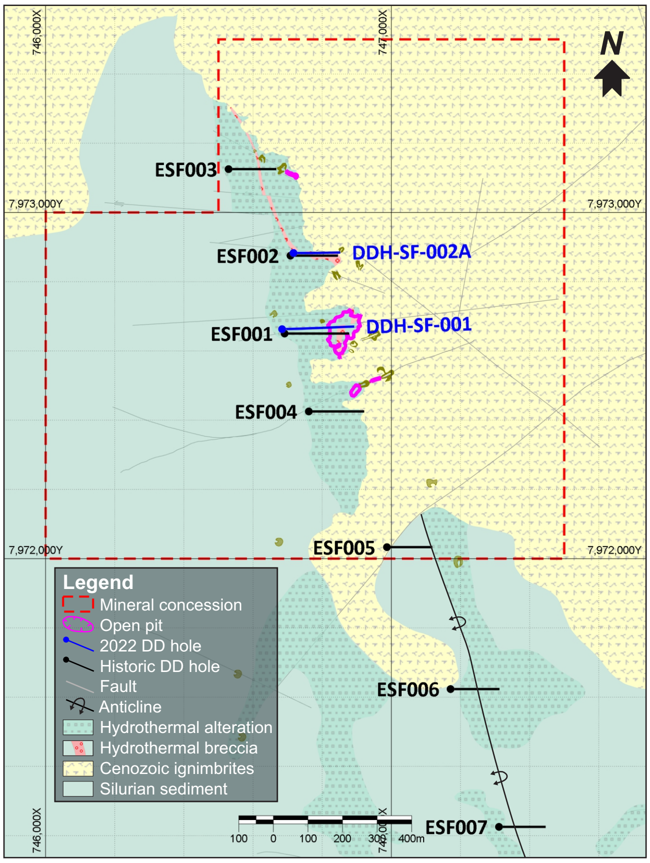

Figure 14. Simplified geologic map of San Florencio.

The project is located in the Eastern Cordillera of Bolivia; aligned on a main structure (Llallagua anticline), to the south of the Morococala volcanic field. The mineralisation is hosted within a window of Silurian age (423 – 419 Ma) diamictite comprising interbedded and layered units of greywacke, as well as interbedded sandstone, siltstone, and shale units. The sedimentary rocks are strongly fractured, supported by a feldspathic clay matrix, showing facies or channels of shaly clayey rock of variable thickness. The diamictite includes subangular to subrounded heterogeneous lithoclasts from 1 cm to > 10 cm in size and different composition: sandstones, shales, slates, quartzites, quartz, and rhyolitic to dacitic igneous rocks. In the northeast portion of the project, the Silurian aged sedimentary rocks are unconformably overlain by volcano-sedimentary and pyroclastic ignimbrites of Cenozoic age, with dacitic to rhyodacitic compositions across much of the surrounding area (Fig. 15).

The alteration occurs in an area with supergene oxidation and leaching, with strong sericitization and kaolinization being observed in variable thicknesses between 1 m to 20m. Beneath the zone of leaching and oxidation, the Silurian sedimentary rocks are weakly to moderately sericitized and the sericitization is strong along the local fracturs. Kaolinization is restricted to zones of intensive fracturing and becomes weaker towards the host rock. Silicification is moderate to strong and is confined in the mineralized veins and breccias. Minor igneous and sedimentary lithic clasts included in the rock are partially sericitized and silicified.

The mineralization appears to be structurally controlled along a NW to NNW trending zone, which comprises a stockwork framework formed by a series of mineralized stringers, less than 1cm wide (Fig 16a), as well as sulfide veins which range in thickness from 1 to 30 cm (Fig. 16b), slightly dipping west. Mineralised hydrothermal breccias, ranging in thickness from 1 cm to 30 m are found along the NW to NNW mineralized trend in the diamictite, with disseminated sulfides occurring within the matrix and clasts of the breccia (Fig. 16c), as well as cross cutting mineralized stringers. To a lesser extent, dissemination of sulfides is also observed in the sandstone matrix (greywacke), mainly pyrite up to 1%.

The sulfide minerals in the project are mainly pyrite and sphalerite. Mineralization of cassiterite is highly associated with sphalerite but is not macroscopically visible. Minor Ag-rich galena and traces of pyrrhotite, vivianite, stannite, and clay minerals (kaolin, illite, smectite) occurred associated with the sulfide veins and breccias. As oxidation products are mainly goethite, limonite, minor hematite.

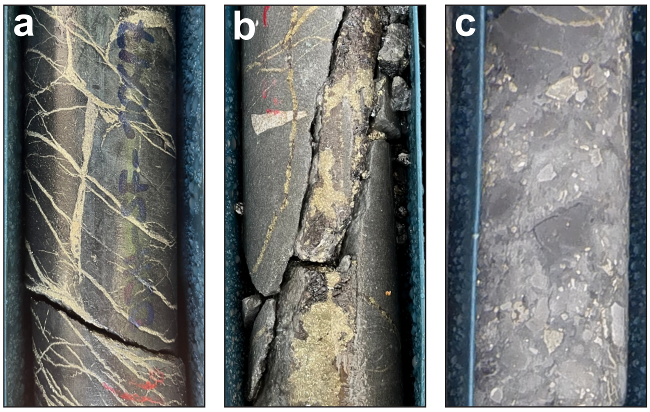

Figure 16. Photos of San Florencio mineralized core: a. mineralized stringers; b. sulfide veins of pyrite and sphalerite; and c. mineralized hydrothermal breccia.

6. Conclusion

Generally, tin deposits were largely formed in continental settings and are associated with reduced and highly fractionated intrusions. The Eastern Cordillera physiographic province of Bolivia is situated in the innermost arc of continental margin and contain abundant ilmenite-series S-type granitoids, which is favorable site for the formation of tin deposits. Hence, numerous world-class tin deposits are situated in the Bolivian tin belt, making it one of the most important Sn producing regions. Oruro mining region is located in the cone part of the Bolivian tin belt and contains numerous outstanding tin deposits in the world, which correspond to various types or models of formation. The largest two are the Oruro deposit, also known as San Jose deposit (historic production is over 0.5Mt Sn) and the Llallagua deposit, the largest hard-rock tin deposit (historic production is over 1Mt Sn). The mineralization of these two deposits is hosted in or proximal to high-level stocks. However, the mineralization of some other deposits is merely hosted in Silurian sedimentary and metasedimentary rocks that the causative intrusions are not defined yet. These deposits are also of large tonnages (e.g., the Huanuni Sn deposit, historic production over 0.2 Mt Sn).

The two tin exploration projects of Tincorp Metals Inc. are both located in the Oruro region and share a lot of common geologic characteristics with local large-scale tin mines. They are classic Bolivian polymetallic vein deposits containing significant amount of Sn, Zn and Ag. Due to the limited exploration to the date, the causative intrusions are not yet found, while the hidden or underlying stocks at deeper positions will probably be discovered in the future as the advancing of exploration. There is a big potential these two projects will become large-scale tin mines like Huanuni one day.

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