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Geology of the principal tin deposits of Bolivia

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ABSTRACT

The Bolivian tin belt with a length less than 1000 km and a width not exceeding 60 km does not extend outside its national frontiers, either north into Peru or south into Argentina.

In the northern part the high Cordillera contains deposits related to granitic batholiths (Jurassic, Triassic, Cretaceous and Miocene).

From Oruro to the south of the country, the lode deposits are related to small stocks and dikes of dacite and rhyolite (Pliocene) and form the famous polymetallic province, with rare associations of tin and silver like teallite, franckeite, aramayoite, andorite, argidorite, etc.

The narrow vein deposits are shallow in depth and in most of the cases their vertical range is less than 500 m.

There are about 1000 tin mines, most of them small and shallow. However, the wealth of some of these mines is extraordinary: for example the production of Llallagua (Catavi) is estimated to be 600,000 tons of tin. There are still one million tons of proven and indicated reserves in the country.

The tin veins are exploited by selective underground methods, despite high mining costs. Grades have declined to limits which can now be considered almost marginal.

INTRODUCTION

Tin was first mined in Bolivia by the Incas people who produced a rustic bronze from deposits located in the Lake Titicaca area. The Spanish were aware of the existence of the tin deposits but did not carry out any mining operation. It was not until the end of the 19th century that the Bolivians began the exploitation of cassiterite because then tin became a valuable war commodity. It is a remarkable fact that almost all the great deposits in the country were discovered at that time.

Beginning with 100 tons of tin exploited in 1861, the production grew gradually to a peak of 47,000 tons in 1929, approximately equal to a quarter of the total world production at that time and then declined. When nationalization of the tin industry took place in 1952 the production was 17,000 tons. At present an annual output of about 30,000 tons is maintained.

At the beginning of the century the grade of tin ore in Bolivia was still 12 to 15% Sn but it has declined steadily ever since. Today most of the mines work on ores of slightly less than 1%. For instance, the grade at the largest mine, Catavi has reached 0.4%.

Tin, the main product of the country, plays the same role, as copper does for Chile, in the national economy of Bolivia. This situation of having just one main export item makes the country unstable in its development.

In the Bolivian mines the standard practice is to mine the richest portions of stopes first at any cost in order to produce ores for direct shipment to smelting plants without

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any treatment. Then the ores from the poorer parts of the stopes are mined and upgraded in the mills before they are shipped for smelting.

The Bolivian Mining Corporation (COMIBOL) controls three quarters of the country's total tin reserves which consists of an estimated 200,000 tons of tin in the proven and probable ore reserve, an additional 300,000 tons in dumps, tailings and placer deposits, and a further 500,000 tons of possible and prospective material.

Tin smelting is carried out in two smelters in the city of Oruro. Only the rich concentrates are smelted locally while the low grade and complex concentrates are exported. Two volatilization plants designed for upgrading of the low grade ores are currently under construction.

REGIONAL GEOLOGY

Granites, gneisses, mica schists and other metamorphic rocks of the Brazilian shield outcrop in the northeastern part of the country (Pando, Beni and Santa Cruz provinces) and underly extensive low rolling plains (the "llanos", Bolivian counterparts of the Argentine "pampas"). West of these, rise the Andean mobile belt paralleling the Pacific coast of the continent. This belt from east to west begins with the Sub-Andean province, a chain of highly folded petroliferous ranges containing most of Bolivian oil reserves. It is succeeded westward by the essentially Paleozoic block of the eastern Andean province, which except for small facies changes, variations in thickness, and some additions and omissions of strata, does not vary significantly in the stratigraphic column throughout the country. In these rocks one can recognize a continental sequence, extending with various stratigraphic breaks from the Carboniferous to the present. Farther to the west we have the Altiplano continental unit, composed chiefly of red beds, typical of intramontane basins. Finally in the west, forming the Chilean boundary, rises the Occidental Cordillera, with late Tertiary and Quarternary volcanic cones.

The main tectonic movements in the western stanniferous part of the country are:

1. The Hercynian orogeny. This orogeny folded almost symmetrically the Paleozoic sequence with development of schistosity at the lower levels. It's later phase was responsible for the strong angular discordance between the Paleozoic and the Cretaceous. Near the end of this phase an important Triassic and Jurassic magmatic activity occurred (in the northern part of the Lake Titicaca area), which gave rise to an important period of tin mineralization. The Andean region was uplifted and peneplained. Later, during continental Cretaceous sedimentation, two marine transgressions occurred. The calcareous sandstone resulting from the first transgression is of local extent. It has been replaced by cassiterite to form the *manto* type deposit at Calavi in the province of Potosi.
2. The Andean cycle starts with the red beds of the Cretaceous to Eocene, which are highly folded and overlying more highly folded dark gray rocks of the Paleozoic basement. Continental sedimentation continued especially in the Altiplano. Andean uplift began in the early Tertiary and has continued up to the present (into the Recent era). The principal stages of mountain building in the Andean zone, including the Altiplano, took place during the Miocene and Pliocene. Emplaced in the Miocene were the Tres Cruces and the Kari Kari batholiths which are responsible for a second period of mineralization in which important deposits of tin and other elements were formed. The strongest Andean uplift was that of the Middle Pliocene, which built the high Cordilleras now undergoing erosion. This

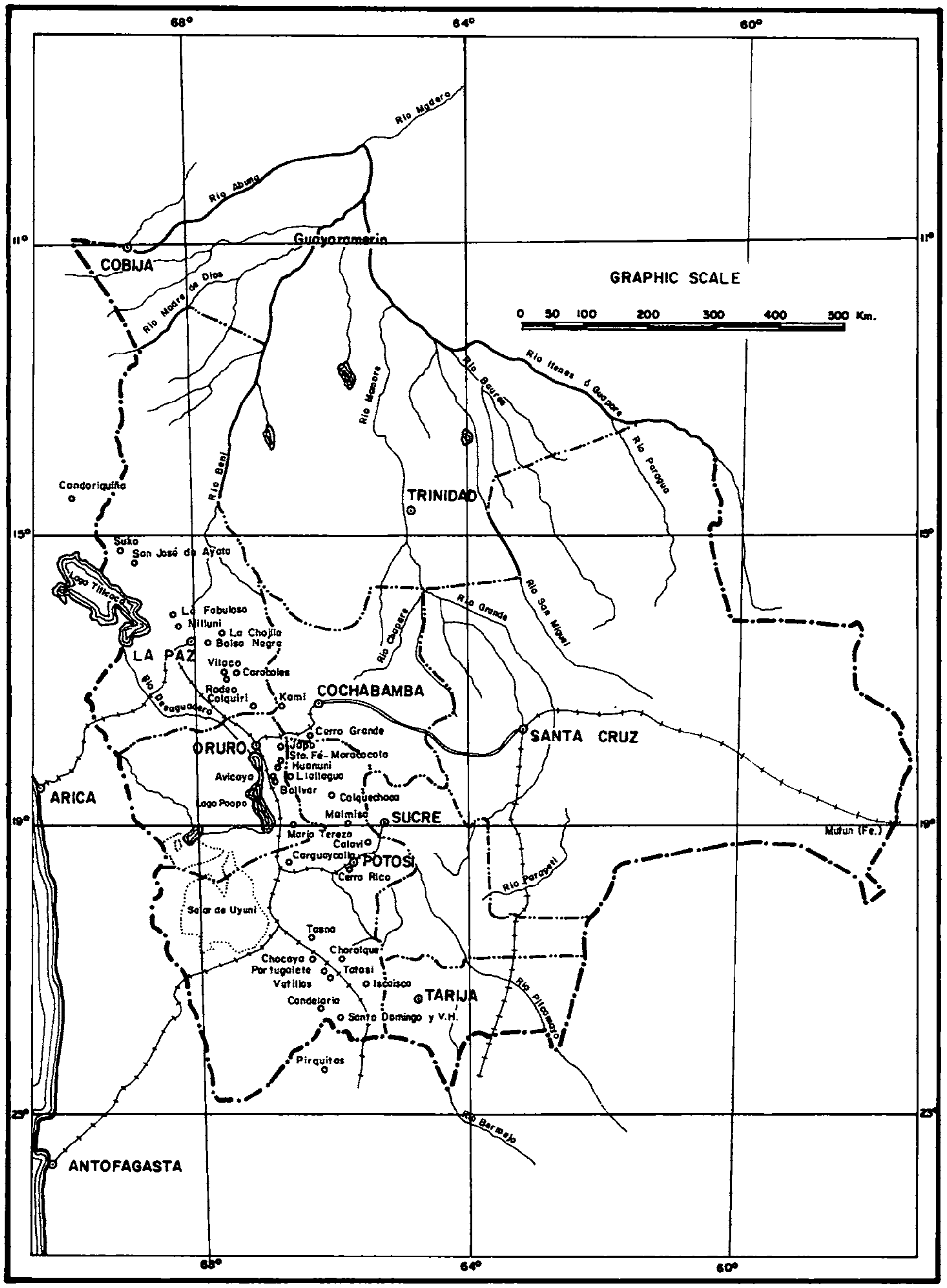

Fig. 1. Location of principal tin deposits of Bolivia.

activity uncovered its granite nucleus, and exposed cassiterite veins at its peaks. In the central and southern parts of the country mineralized subvolcanic bodies and volcanic cones were formed in the Pliocene. Pliocene glacial action and the effects of permanent snow cover formed some morainic and placer deposits.

TIN PROVINCE

This metalliferous province *par excellence* occurs as a narrow belt in folded metamorphic and sedimentary terrains of the Oriental Andean Block (Fig. 1). The mineralization is intimately related to the calc-alkaline magmatic activity which took place after the Hercynian (upper Paleozoic) and the Andean (Tertiary) folding phases.

Near the Peruvian border (parallel 14° 30′ south) in the north there are granitic intrusive bodies of Triassic-Jurassic to Paleocene age. Farther south are Cretaceous and Miocene intrusions, which are located along anticlinal axes and are bounded by longitudinal faults. These bodies are arranged like a rosary up to the parallel 17° south, and form the nucleus of the Cordillera Oriental, where tin and tungsten deposits are abundant.

More to the south it is likely that various batholiths exist at different depths below the belt. Surficial manifestations of these large igneous complexes are (a) the Miocene intrusion of the Kari-Kari (b) the porphyritic subvolcanic bodies and (c) the dikes of Miocene and Pliocene age. In most of them the abundance of tin, tin-silver, tin-zinc and other complex mineralization is highly notable. This mineralization continues south into the volcanic Lipez area, located close to Argentina (parallel 22° south).

In the tin belt the intensity of mineralization is greatest between Oruro and Potosi. At both the northern and southern ends of the great Cordilleran warp, mineralization progressivly diminishes and disappears at Condoriquina, Peru, and Pirquitas, Argentina. The belt is relatively narrow. Its eastern boundary coincides with the eastern boundary of the Cordillera with the central valleys, where the calc-alkaline intrusions are missing. To the west it merges with the Altiplano copper belt, where tin intermingles with other minerals.

The mineralization is related to the main orogenic and magmatic processes. According to radiometric age determinations of the granites, tin mineralization has evolved over an interval extending from late Paleozoic to late Tertiary. Six epochs of mineralization are recognized, the most important of which are the Triassic-Jurassic and Miocene in the high snow covered Andean Cordillera, and the Miocene to Pliocene in the central and southern part of the belt.

High Oriental Cordillera (northern part)

In the northern part of the Bolivian cordillera, one can distinguish four mountain chains interrupted by deep river gorges, which follow transversal faults of fold axes. These mountain ranges from north to south are called the Cordillera de Apolobamba, Munecas, Real and Tes Cruces-Santa Vera Cruz. These are intruded by granitic plutons of various ages which are responsible for the various metallogenetic epochs and pulsations.

The associated mineral deposits, as a general rule, are located mainly in the metamorphic rocks near the contacts, and also in the batholiths themselves. The mineralization is cassiterite-wolframite in a quartz gangue accompanied by some pyrite, pyrrhotite and bismuthinite, and a little sphalerite, galena and chalcopyrite. Chlorite and tourmaline alteration is common.

Various authors have proposed a depth of formation of 5,000 m for the plutonic deposits, which were initially exposed in the Pliocene. The batholiths are asymmetrical with their western contact almost vertical due to faulting and their eastern contact gently inclined. The oxidation zone is shallow, and cassiterite enrichment has taken place in its upper portions. During the oxidation processes sulfides were removed by meteoric waters. Cassiterite, more resistant to the natural leaching processes, remained, producing tin enrichment through volume loss.

Central and Southern Oriental Cordillera

The snow covered peaks of the Cordillera end in the south and the mountains decrease in altitude and widen into rounded hills. Isolated high points underlain by metamorphic rocks exposed by downcutting rivers or volcanic cones rising above the Paleozoic Block are mineralized by tin and other metals.

One can note that the central and southern parts of the Cordillera were the locations of widespread subsurface and volcanic magmatic intensity, which are probably the manifestations of underlying batholithic activity. The prophyritic stocks are mushroom shaped, with wide circular surface areas (1 to 3 square kilometer), and narrow roots which change at depth into dikes and circular conduits a few meters in diameter.

There are about 100 of these bodies scattered at random, some along north-south, east-west or diagonal lines, probably reflecting megafractures recently detected via satellite, others along regional faults, and axes of anticlines. Very seldom do they occur along synclinal axes. Some stocks are flanked by sheets or remnants of lava flows of ignimbritic or tuffaceous rocks. Others have detrital and volcanic sediments on their slopes and some horizons have flora remains, as relics of the low plains intervolcanic forests (Potosi, Chocaya). The porphyritic volcanic rocks are of dacitic calc-alkaline composition similar to the plutons in the north.

The veins, not only of cassiterite and wolframite but also of Sn-Ag, Sn-Zn, etc., are sometimes confined to the stocks but also occur in metamorphic rocks surrounding and underlying the intrusives.

To finish the geological panorama we can say that two high plateaus were formed in the central part of the Cordillera by ignimbrites of late Pliocene age. These are known as the "Morococala" and "Livichuco or Los Frailes" plateaus. The flat-lying rocks are barren and could overlie undiscovered mineralization.

The Central and Southern Cordillera exhibits a mixed stanniferous mineralogy. Besides cassiterite it produces franckeite and teallite (San José, Chocaya, Carguaicollo, Monserrat), stannite (Colquiri, Fabulosa) and souxite (Bolivar). The alteration zones contain principally sericite, quartz, clay minerals and tourmaline. Topaz was found in Morococala and chlorite is typical of Colquiri and Caracoles.

In the volcanic deposits the mineral zoning is less ordered compared to that of the high Cordillera, and superimposition of tin, silver, lead, zinc, arsenic, iron, and other metals is more prominent. Sometimes lead and silver mineralization gives way at depth to minerals of tin (Chocaya, Tatasi, etc.).

Various reports have suggested that 500 to 1,000 meters of suprastructure have been removed from the subvolcanics or the old volcanic centers. At the same time it is suggested that the vertical extensions of these veins are greater than the veins of the high Cordillera, that is 600 meters, as compared with a maximum of 400 meters for the Cordilleran deposits.

The oxidation zones in these volcanic deposits have very irregular boundaries. These zones may extend up to 400 meters, creating "pacos" with cassiterite, limonite, jarosite, cerussite and silver sulphosalts which were originally exploited. There are many new theories regarding the genesis of these long lived deposits. The following have been postulated: hydrothermal regeneration, metasomatism of pyrite to pyrrhotite, origin of cassiterite starting from biotite, granitization, etc. All in all it is evident that the mineralization and the volcanism have the same magmatic source, and that recurrent hydrothermal processes, that were generated during various periods of tectonic movement caused reôpening of old fissures, the brecciation of original mineralization and its cementation with new minerals, sometimes of higher temperature than the earlier ones, were the most important ore forming agencies.

Due to Bolivia's tectonic complexity, and especially to its peculiar mineralogy, it has become a geological laboratory of great interest, open to all researchers of the world.

Descriptions of some deposits

The following is a description of most representative tin deposits, considered geographically from north to south.

In the first range of the High Cordillera, the Apolobamba, little investigation has been done and no igneous outcrops are known, although granitic apophyses may lie hidden beneath its perpetual snow. The zone is auriferous and its large morrains (20 kilometers in length and 1 kilometer in width), containing Paleozoic sedimentary fragments, and its narrow alluvial plains carry very low values of tin (0.06 % Sn). In the most northerly part, Sayhuani, there are several, thick veins of quartz with minor presence of cassiterite (0.08 % Sn).

In the Munecas range, the rivers dropping into the Beni basin have deeply eroded the igneous body at their headwaters below Charazani. This body is quartz-biotite monzonite with a noteworthy and extensive metamorphic aureole of Devonian slates and quartzites. Many faults cut these rocks.

In the immediate vicinity of the monzonite body and in the metamorphic halo there are two deposits of mesothermal origin which are described below:

Suka (3,600 m in altitude)

In Devonian slates, outcropping in a ravine there are five zones of silica and iron alteration containing *manto* type deposits in quartzites ranging in width from 0.15 and 0.60 meters in thickness. There are also faults zones where cassiterite is found in massive form showing a yellow color. Selected samples have returned up to 10 % Sn and 0.03 to 0.04 % WO_3.

San Jose De Ayata (4,100 m)

The deposits here occur in concordant veins in slates. At present 6 parallel veins 0.10 to 0.60 meters in thickness are being worked. The ore consists of light brown, fine grained cassiterite, pyrite, little quartz, calcite and chalcopyrite. In the outcrops there is a limited amount of scheelite. The ore contains 4% Sn.

The third range is the Cordillera Real, distinguished by its alpine splendour. In eastern contact zone of the granite, the Sorata batholith, with the metamorphic rocks there is a zone of pegmatites containing large crystals of quartz, cassiterite and white mica. In the central part of the range cassiterite is found in *mantos* and fractures along the anticlinal axes (Chucura batholith). The southern part of the range formed by the Tatasi and Illimani batholiths, the latter overshadowing La Paz, is characterized by a predominence of wolframite and by a scarcity of cassiterite deposits.

Fabulosa (4,600 m)

This is a zone of pegmatites partly emplaced in granite and partly in slates. The slates due to the strong metamorphism have been converted to phyllites containing andalusite. The granite is coarse grained with abundant muscovite. The pegmatites are low grade (1% Sn). The cassiterite is coarse grained changing laterally to veins of milky quartz with abundant muscovite and sulfides, molybdenite, chalcopyrite, pyrrhotite, arsenopyrite, pyrite and dark sphalerite rich in stannite (this last mineral at present is being mined).

Chojilla (2,200 to 3,500 m)

In an outcrop on a steeply dipping slope are slates, chloritic and sericitic schists, andalusite hornfels, granodiorites, adamellites, micropegmatites and tourmalined topazic greisen. The mine lies at the contact of the greisen with hornfels, and the best ore is in slates. The quartz veins carry wolframite and some cassiterite, and appear as *en echelon* structures concordant in strike and discordant in dip with the stratification. There is a group of 25 veins and 75 branches which average less than 1 meter in thickness. The width of the veins diminishes at the upper levels. The veins are banded and are composed of a thin outer crust of cassiterite succeeded by a thicker wolframite rich section with a core of quartz flecked with sulfides. The vertical extension is about 500 meters.

Beneath the snow capped peak of Illimani the Rio La Paz has opened a great canyon that separates the Cordillera Real from the Cordillera Tres Cruces. The Cordillera Tres Cruces is prolifically mineralized. The lithologic and structural controls are surprising, the veins having developed in fractures in white quartzites and in the flanks of folds, as well as in granodiorite. Chlorite is the main alteration mineral. The vertical range of the ore shoots is less than 400 meters. COMIBOL works two such deposits: one almost at the extreme north, Viloco, in contact metamorphic rocks and the other, Caracoles, at the southern border, in the granodiorite itself.

Viloco (4,600 m)

The deposit is located in a 200 meter wide, north-south striking syncline of metamorphic Silurian lutites very near the contact with biotitic granodiorite (Fig. 2). Quartzites on both flanks of the syncline are mineralized. These rocks are cut by transversal faults perpendicular to the igneous contact. The veins were emplaced in these faults. Economic mineralization consists only of large, black, well polished cassiterite crystals, considered to be the most beautiful in the world, and highly prized by foreign collectors.

The mineralization begins up in the upper part of a hill with a little molybdenite, sometimes as flakes disseminated in the granodiorite, then continues near the contact,

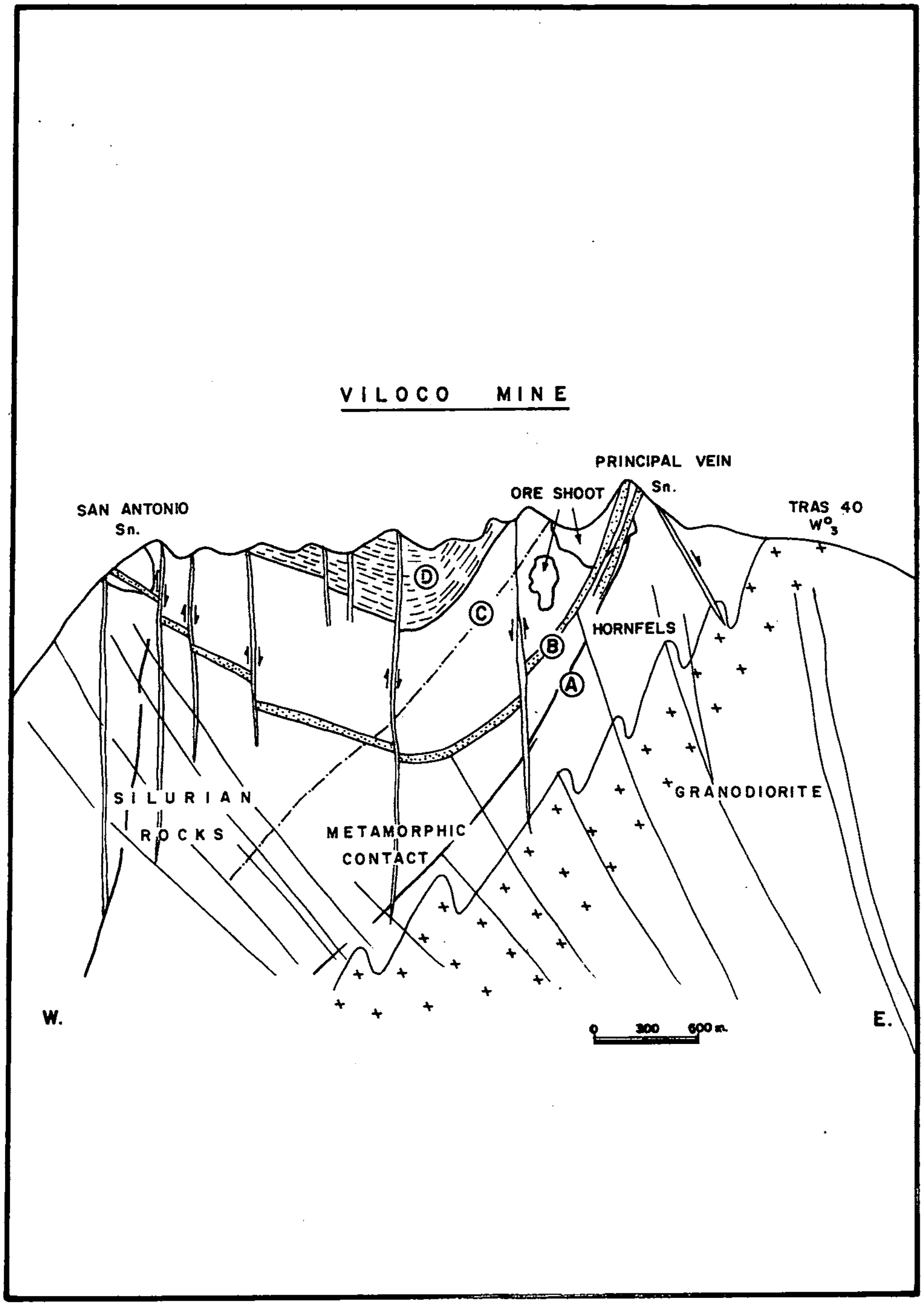

Fig. 2. Geological cross section at Viloco Mine.

with veins of wolframite, scheelite, tourmaline, quartz, pyrrhotite, jamesonite, arsenopyrite, siderite and principally cassiterite and finally degenerate to marmatite at the edges of the mineralized zone. The veins pinch out 300 to 400 meters below surface. Presently cassiterite veins in tension fractures in the granite are being developed (Bonaparte section).

Caracoles (4,800 to 5,200 m)

The mineralised veins occur in the less eroded portion of the granodiorite itself (Fig. 3). Some veins are frequently curving and irregular in tension fissures in the igneous rock, but the principal veins are mineralized faults (Pepita, Ali, etc.). All have strikes perpendicular to the boundary of the elongated batholiths. The mineralization consists of quartz, fine grained cassiterite, pyrite, bismuthinite; with a little apatite, wolframite and ankerite. Chlorite alteration is most conspicuous. Tourmalinization and sericitization are less intense. On the western border of the batholith between Viloco and Caracoles there are large veins that cut the metamorphic rocks at right angles to the contact: the Ferreccio-San Luis of Chojnacota, San Francisco of Laramcota and Copacabana of Mallachuma.

The last part of the section Tres Cruces is the high Santa Vera Cruz Cordillera. Here a considerable number of quartz-cassiterite-tourmaline veins are distributed throughout the metamorphosed Devonian shales surrounding a small granite body outcropping as a small high "serranía". These veins are of pneumatolitic origin with brecciated structures rich in sulfides and low in tin.

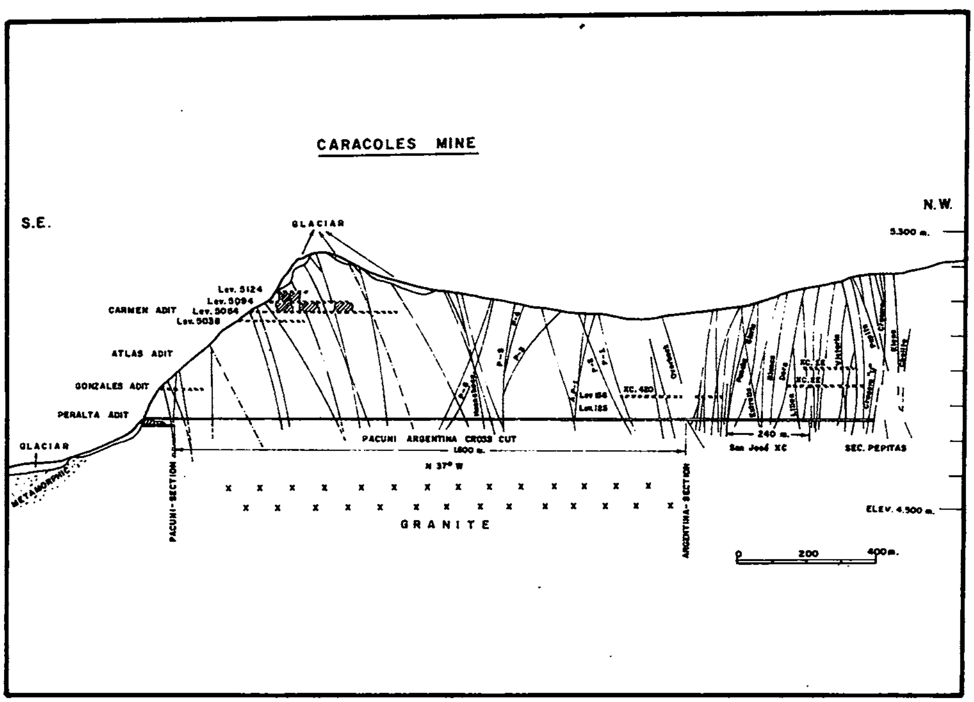

Fig. 3. Geological cross section of Caracoles Mines.

Farther south the high and snow covered Cordillera disappears, but the tin belt carries on in two directions: one through, Amutara, Chicote and Kami hills to the Cerro Grande—Berenguela district near Cochabamba, the other through the important and isolated Colquiri deposit, which lies along the axes of the Cordilleras to the north. South of Colquiri the subvolcanic and volcanic deposits of the provinces of Oruro and Potosi, located in isolated hills, begin.

Colquiri (4,200 m)

At Colquiri weakly metamorphosed Silurian lutites and sandstones are gently folded into northwest-southeast striking synclines and anticlines which have been eroded into rolling hills. Various transversal faults displace the structures and control the mineralization. The principal veins are related to the Doble Ancho fault which is 3,000 meters in length.

In detail, the mineralized zones are composite structures composed of alternating veins, veinlets and country rocks. The zones reach a maximum width of 30 meters. The deposit has been mined to 500 meters depth, at which point the tin content diminishes relative to zinc. The upper part of the mineralized zone was originally worked for argentiferous galena. In the footwall of these parallel structures is the "9 de Abril" vein, 0.8 m. in thickness, and carrying abundant pyrite with 2% Sn.

At the east side of the mine, the main vein is displaced by a transversal fault. This vein is called the San Carlos vein and is a marmatite filled structure measuring 2 to 8 meters wide with 10% Zn and 1.1% Sn. Two stages of mineralization are recognized, a first consisting of marmatite, cassiterite, fluorite, pyrrhotite, galena, calcite, chalcopyrite and stannite and the second with siderite, magnetite, pyrite and marcasite. The first stage of mineralization has been brecciated as a result of minor tectonic movements taking place between the two mineralizing phases.

Oruro (3,700 m.).

The national center of Oruro rises as an island over the arid plains of the Altiplano in a series of rounded volcanic hills, overlying a "basement" of dark and non-fossiliferous Silurian shales. The volcanism, now exposed as a number of deeply eroded mushroom shaped latite stocks, has pierced a regional anticline, giving rise to a very strong alteration zone. The contacts of these stocks with the enclosing shales are brecciated and irregular. The accompanying vein mineralization has assumed a classic curvature, due to the combined influence of the brecciation and contact irregularity. In the shales the veins split and fray and decrease in grade.

The mineralization has developed in two principal phases. Pyrite was formed first (85% of the fill), then quartz and cassiterite. Later subsidence reopened the fissures giving rise to deposition of Cu, Pb, Sb sulfides and sulphostannites, followed by a little sphalerite, stannite, freibergite, sulfoantimonites of lead (jamesonite, zinckenite, boulangerite and others), franckeite, galena and barite. Kaolinite, dickite and alunite formed last. The silver zone was superimposed on the tin zone, and is larger in lateral and vertical extent.

Huanuni (3,950 m.)

This deposit has recently entered its best days, having become Bolivia's richest tin producer with large reserves of high grade ore. The deposit is located in an asymmetric anticline whose axis strikes N 20° W and dips 65° E. The core of the anticline is composed of Silurian quartzites with slates and lutites also of Silurian age occupying its flanks. Most of the veins occur near the core on the more gently dipping eastern flank. Highly altered porphyritic dikes up to 25 meters wide outcrop east of the veins. The Huanuni veins are very irregular in strike and dip and are generally with short vertical dimensions. Many veins decrease in grade with depth and either change in mineral composition or pinch out, giving way to new structures at greater depth. The Grande vein, normal to anticlinal axis, is 600 meters in length and 320 meters in depth. In the upper part it attained widths of up to 14 meters of cellular quartz, limonite and jarosite, with grades of 1 to 1.5 % Sn. The primary mineralization consists of cassiterite, pyrite, some marmatite, chalcopyrite, fluorite and some jamesonite, boulangerite, franckeite and cylindrite.

Japo, Santa Fe and Morococala (4,500 m.).

In Oruro province and east of the city, the Central Cordillera becomes a high plateau composed of extensive horizontal ash flows, and ignimbrites out of which rise a few igneous hills. Silurian rocks occur in windows exposed in depressions in the plateau. At the north edge of the volcanic plateau and related to the first igneous hill is located the district of Japo. Santa Fe and Morococala lie 15 kilometers farther south, in windows in the volcanics. All three mines occur along the axes of two narrow and parallel anticlines. A sericitized and silicified quartz biotite porphyry stock at Japo, intruded near the axis, is barren. The veins are in fractures transverse to the axis and are best formed in graywackes and quartzites in the core of the anticline. The veins upon entering the lutites become faulted, narrow and eventually fade out.

The principal mineralized structure at Japo, the Gomez vein crosses greywackes in the core of the anticline and passes into quartzite in the flanks. Its strike length is 750 meters and it has been worked to 100 meters depth. Mining is presently concentrated in the quartzite of the western flank. The veins cross transversally the thick quartzite, where several crosscuts are being developed. The veins vary from 0.2 to 1.3 m. wide with average width of 0.35 m. Average grade over 0.8 m. is 1.31 % Sn. The main vein filling is pyrite, partly derived from pyrrhotite. Highly corroded, fine grained cassiterite is irregularly distributed throughout the pyrite.

In contrast to Japo, the veins at Santa Fe and Morococala occupy two diagonal shear zones striking NNW-SSE at Santa Fe and NNE-SSW at Morococala. Wall rocks again are greywackes. The veins are emplaced in *en echelon* fashion in both the vertical and horizontal dimensions and are difficult to correlate. One of the features of these deposits is the existence of pipe-shaped ore shoots (clavos) containing disseminated mineralization in breccias. Veinlets and impregnation of microcrystalline cassiterite apparently formed at the intersection of two sets of shear zones, where movement was most intense. These bodies plunge almost vertically and their outlines are very irregular and elongated generally in the NW-SE direction. At the lower levels of Santa Fe, some narrow dikes of highly tectonized and sericitized quartz rich igneous rock have been found. The greywacke at Morococala has been metamorphosed and carries tourmaline, apatite, andalusite and sillimanite, minerals indicative of contact metamorphism due probably to the presence of buried intrusions at shallow depth.

Llallagua (3,900 m.).

Llallagua (Plate 1) is the richest and biggest tin lode concentration in the world. It is located at the central part of the tin belt, on the closure of a narrow regional anticline, whose east flank has been overturned. The core of the anticline is composed of greywacke, and the flanks of quartzites overlain by a thick sequence of lutites. An elliptical shaped acid igneous body has intruded the greywacke with development of extensive brecciation at its contacts. The body occupies an area of 2 square kilometers and the veins of cassiterite are mainly contained in fissures within it (Fig. 4).

Thirty principal veins and 400 branches aligned normal to the axis of the anticline have been encountered in the stock. Also found in the stock are two post-mineral faults parallel to the fold axis and cutting the long axis of the stock. The veins are banded and drusy, in groups with opposing dips. They occur in clusters which, from north to south, decreases in depth and are arranged in the form of a pipe organ whose individual components, measuring 400 m. in length, 500 m. in depth and 1.0 m. in thickness, are stepped progressively upward. Both the veins and old fills have been reworked up to three times. Cassiterite bearing breccias are frequent. Abundant branches, veinlets and stringers interspersed with the principal veins, allow exploitation by block caving. The mineralization is not considered porphyritic owing to the fact that cassiterite is not disseminated.

Cassiterite is the only mineral recovered. It is accompanied by quartz, bismuthinite, wolframite, monazite, apatite, pyrrhotite, pyrite, marcasite, arsenopyrite, stannite, sphalerite, siderite, vivianite, wavellite, and other phosphates. Mineralization varies from pneumatolitic through hypothermal to epithermal, making Llallagua an exceptional deposit. Except for four veins, the San José, Salvadora, Inca and Bismarck, the mineralization either does not outcrop or appears on surface only as fractures filled with iron minerals and limited cassiterite. Only the intermediate levels of the mine were exploitable, due to the fact that the veins grade upwards into pyrite and marcasite and downwards into pyrite and quartz.

Colquechaca (4,600 m)

In common with many of the volcanic deposits Colquechaca has developed in an anticline, in this case, composed of Ordovician, Silurian and Cretaceous sediments. It appears as a roughly circular volcanic pile, 6 km in diameter, composed of thick dacite flows interbedded with breccias and other pyroclastic material. A volcanic dome, Cerro Yanakaka, has formed near the present top of the pile. Radial porphyritic dikes are common. Old longitudinal faults in the sediments and reflected in the volcanics have been reactivated. In two of these closely spaced and NW-SE striking faults located at the center of the volcanic pile the two principal vein deposits, the Descubridora and the Embudo-Gallofa, have been formed.

The tin zone at Colquechaca is represented by the Descubridora vein which divides the extrusive body into a northeastern tin-bearing marmatite zone and a southwestern pyrite-cassiterite zone carrying appreciable silver and minor copper and bismuth. The Embudo-Gallofa vein is silver bearing and carries zinc, tin, lead, antimony, bismuth and copper in addition to complex silver minerals. Two weaker intersecting vein sets striking N 15° E and NE–SE are mineralized with sphalerite, galena, cassiterite, pyrite, silver minerals and complex lead and zinc sulfosalts. The veins are generally narrow and although consistent structurally, contains only small ore shoots which are capriciously distributed and difficult to locate, a factor which limits exploitation on a great scale. Colquechaca, noted for its polymetallic mineralization, is of considerable interest to mineralogists due to the presence of about twenty rare silver minerals associated with sphalerite. Colquechaca silver is now confined to museum and private collections, the last remnants of its colonial splendour.

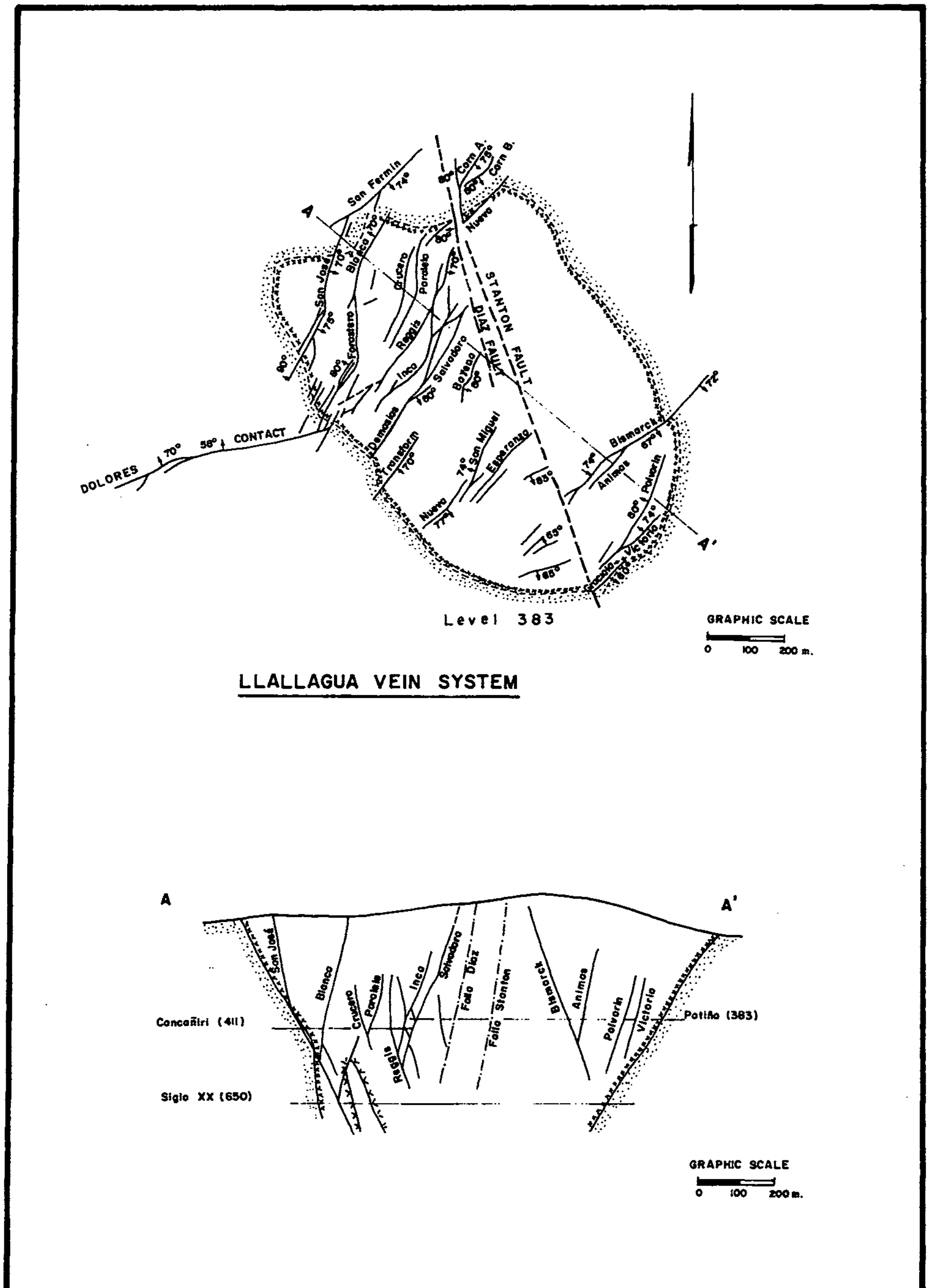

Fig. 4. Structural sketch map and cross section showing the Llallagua vein system.

Cerro Rico De Potosi (4,000 m)

The immortal Potosi is a hill full of legends but empty of minerals (Plate 2). A llama was lost from a Spanish herd and the Indian Hualpa, its shepherd, climbed a hill looking for it. Night fell, and he lit a fire to keep warm. At daybreak he found a puddle of metal silver by the fire and so discovered the greatest silver deposit of the world. It is said that the noble metal extracted from the hill during the colonial time would provide a silver bridge from Potosi of Spain. Beginning in the Republican epoch, at the end of the past century, attention was given to tin minerals. Old working places were reopened and 300 mining companies incorporated. 3,000 adits were driven into the slope of the mountain. During the present century the multiple land holdings were gradually consolidated and in 1952 nationalization placed most of the hill and all of the underground workings under government control. The igneous body is elliptically shaped, oriented north-south and has an area of 2 square kilometers. It stands as a conical hill 700 meters over the city where almost every backyard is a tin concentration plant. At depth the stock contracts into a narrow feeder dike, thus producing the classic "mushroom" shape. Drifting and crosscutting are currently underway in the Ordovician slates below the stock, where the veins are formal (regular) and promise a significant reserve that will be utilized in the new Russian built volatilization plant at Palca. Three vein sets lie about and within the intrusive, one each on the eastern and western rims, dipping inward and a third in the middle part of the stock, dipping vertically. All strike north-south. The individual veins of each set intersect and form conjugate patterns.

Mineralization has taken place in two stages, the first characterized by abundant pyrite, quartz, cassiterite, arsenopyrite, stannite, wolframite, and bismuthinite; the second by silver minerals (freibergite, pyrargyrite, miargyrite, jamesonite), chalcopyrite, sphalerite and alunite. Potosí, mined since 1545, is the most outstanding example of the mineral wealth of Bolivia.

Colavi (4,100 m)

Colavi is of particular interest, since it is the only large *manto* type deposit in Bolivia. The deposit is located in a small basin or trench filled with Cretaceous clastic continental sediments, enclosed by fossiliferous shales and sandstones of Ordovician age. The basin is fault bounded and disrupted by transverse fracturing and is complicated structurally by intrusions of three distinct lithologies, emplaced mainly in the form of sills.

The *manto* mineralization is restricted to a horizon of calcareous sandstone up to 6 meters thick, tilted gently west and occupying an area 2 kilometers wide and 6 kilometers long. Within this horizon there are 3 to 4 patchy layers of cassiterite impregnation, the upper of which, 1 to 1.5 meters in thickness, is the most continuous and of greatest economical value (1% Sn). The cassiterite occur as an incomplete metasomatic replacement in the calcareous part of the sandstone and is light yellow with greenish tint. It is very fine grained, ranging from 5 to 15 microns in size. The cassiterite is accompanied by abundant pyrite, some ankerite, siderite and some barite and opal. Quartz is absent and a little tetrahedrite is present.

Volcanism and mineralization is consanguineous, the mineralization formed first and was succeeded by intrusion of dacite sills which displaced it. Later cassiterite veins occur in the dacites.

Plate 1. Surface subsidence at Llallagua due to underground mining activities.

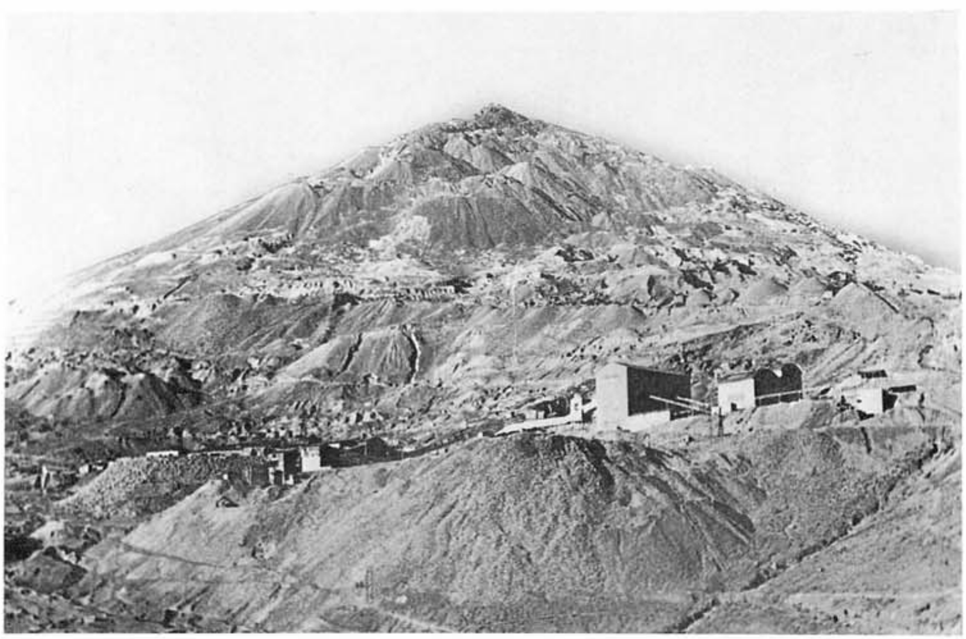

Plate 2. The immortal Potosi Hill, full of dumps and depleted of ore mineral.

Tasna (4,500 m)

Tasna rises from the Altiplano as a high and bulky NW–SE striking hill, shaped like a sleeping elephant, with abrupt flanks polished by mountain glaciation. Ordovician slates are folded in a series of anticlines and synclines, with complex plunges and are faulted longitudinally. Part of the broad summit of the hill is underlain by hornfels and exhibits at three or four places small bodies and dikes of silicified quartz porphyry. In the metamorphic zones near the contact with the igneous rocks, wolframite predominates ocer cassiterite and bismuthinite are found in veins. On the flanks of the hill, especially on the south side outside of the hornfels zone, the mineralization is differentiated with tin and bismuth occurring separately. The veins are perpendicular to the axes of the folds and are located in the cores of anticlines.

The tin bearing structures are parallel and widely separated. They consist of very irregular, curved and branching ore shoots, a few of which reach lengths of 200 m and widths of 100 m. Their thicknesses vary from 0.2 to 0.7 meters. Vein filling is massive, sometimes vuggy with quartz, cassiterite, scaly hematite, siderite and calcite. The cassiterite is light yellow and very fine grained (needle tin).

In the Rosario and Farellon sections of the mine on the eastern and western sides of the hill respectively, the veins hold the greatest concentration of bismuth in the world.

Chocaya (4,000 m)

The Chocaya mineralized zone occupies a great collapse caldera in a composite volcano. This zone is composed of intermingled lavic and pyroclastic and sedimentary material, spilled onto a folded Paleozoic basement. The caldera has been filled with a later effusion of green dacitic lava.

Two large east-west striking faults, Siete Suyos in the north and Gran Chocaya in the south, transcend the western flank at the caldera. These faults enclosed the general mineralized area. Within this area the veins and alteration zones occur. These veins are set at acute angles to the major faults, and strike N 30° E and dip south east.

The Colorado vein, the richest tin lode in the country, is accompanied on both walls with veins of lead, silver, and at the ends with zinc. Some veins (Animas, Arturo, San Patricio, Esperanza) exhibit vertical zoning passing from tin-silver near surface, through lead and silver in their central portions, into high grade tin at depth. The presence of the deeper tin zone has recently been detected by deep drilling.

Chorolque (4,800 m)

Chorolque is located at the inflection point of the regional folding, that is, the point where the axes of the folded Paleozoic bends from south-north to north 45° West. It also occurs at the intersection of two regional NS and EW striking faults apparent on satellite photographs.

The Chorolque volcanic event seems to have commenced in the late Tertiary with pyroclastic activity that began with deposition of a tuff layer upon which the volcanic cone was later constructed. This volcanic subsequently cooled down and fractured and the mineralization was settled in the cracks. A little before the Quaternary the volcanism culminated in the ejection of an ignimbrite sheet which is now preserved in the Allita basin. Much of the cone itself has been stripped by glacial action and carved into an immense pyramid that is the principal landmark in southern Bolivia. Glacially produced talus sheets still mantle the northern part of the pyramid.

The conduit, a hard, tough, tourmalinized quartz porphyry plug which gradually contract with depth, the surrounding effusives and the sedimentary basement which is partly converted to hornfels have been broken by strong east-west fault sets which converge at depth along the flanks of the plug. These faults are mineralized and the mineralization is longitudinally and vertically zoned with bismuth occurring on the western end outside the plug in lavas and ignimbrites, tin in the plug itself and tungsten in slates on the eastern end of the plug. The cassiterite mineralization in the plug gives way to stannite in the enclosing hornfels and dies out at depth as the veins grade into massive barren quartz.

Tatasi (4,120 m)

This mine has been a lead-silver producer since colonial times. It lies in a deeply eroded stratovolcano extruded onto an anticlinorium of Paleozoic rocks containing remnants of two Cretaceous synclines. The volcanics rounded cake consists of abundant pyroclastic material intruded by a neck of porphyritic dacite and invaded by radial and annular dikes. The volcanic activity terminated with an outpouring of green and red lavas and the formation, in the central part of the area, of volcanic domes.

Vein mineralization has developed in reactivated basement faults, with dip-slip movements within the volcanics, which cross the complex as a wide zone of east-west fracturing connecting the active Tatasi mining camp with the abandoned colonial silver mining center, Portugalete. In the fracture zone pyrite-cassiterite occurs at the intersections of northeast and northwest striking veins, while argentiferous sphalerite occupies the extremities of the veins. Potentially economic concentrations of tin appear in these silver rich sections at depth.

Vetillas (3,950 m)

The principal feature of the Vetillas deposit is a cylindrical body of breccia "La Caldera o El Hueco", apparently a shallow seated "pipe" filled with volcanic fragments but some distance removed from the manifestations of volcanic activity. The volcanism is expressed in this area by stocks and dikes. Two parallel veins the "Chica" and the "Ancha", separated by a second body of breccia and located on the flank of the "Hueco" have been explored to a depth of 150 meters.

Vein mineralization consists of dark, fine grained cassiterite and pyrite, followed by stannite, galena, franckeite, greenockite (in green crystals), barite and alunite. Kaolinite selvages border the veins. In the zone of oxidation secondary cassiterite formed after franckeite was concentrated in fissures and vugs. This zone has now been exploited in its entirety. Presently mine workings have reached below the breccia pockets, where the veins are narrow but regular.

Santo Domingo and Victor Hugo (4,600 m)

Located in a high plateau of Ordovician rocks in the south of the country and west of Tupiza, are two stanniferous veins outcrop, constituting the Santo Domingo and Victor Hugo mines. These deposits are a curiosity inside an antimony province. The veins extend for 2 kilometers striking N 55 W and dipping 75° NE and are composed of pyrite, finely disseminated cassiterite, teallite, sphalerite and galena. The ore averages 2% Sn.

About 100 kilometers farther south, in Jujuy province, Argentina, lies the tin-silver Pirquitas deposit.

Candelaria (4,700 m)

In the eastern part of Lipez provinces in the extreme south western corner of the country, volcanic activity and hydrothermal alteration has been intense. Several dissected stratovolcanos of great size rise above a platform composed mainly of Lower Tertiary rocks but with some subordinate Cretaceous and Ordovician exposures. Mineralization is vein type lead-silver, zinc, antimony and copper-bismuth. The silver was mined on a substantial scale during the colonial era.

The Candelaria mine is located on Cerro Poderoso within Santa Isabel dacite stock. The Linares adit 1,200 meters long, follows a vertically dipping N 70° W striking vein, 0.2 to 0.7 meters wide, containing pyrite, sphalerite, jamesonite, tetrahedrite and stannite. Near the summit of the hill veinlets of very fine grained light yellow cassiterite outcrop. Candelaria is the southern most tin deposit in the country.

CONCLUSIONS

In the High Cordilleras, the granites were intruded into elevated and folded Paleozoic blocks bounded east and west by major longitudinal faults. The stocks of the central and southern part of the country, though they appear to be distributed haphazardly, follow alignments related to megafractures, regional faults, or anticlinal axes.

The lithological control is granite or granodiorite in the High Cordilleras and rhyolite, latite or dacite in the stocks of central and southern part of the country. Generally quartzite is the preferred rock in contact metamorphic zones. Anticlines, sometimes asymmetric or overturned, also exercise a structural control.

Veins mainly fill faults or fractures, which exhibit one or two periods of reactivation Mineralization similarly shows evidence of pulsative deposition. The veins are perpendicular to the axes of the folds, and in some cases they fill shear fractures.

The depth of economic mineralization seldom exceeds 500 meters. In the granite it is shallower, normally reaching only 300 meters. Beneath the upward flare of the porphyritic stocks, the veins penetrate sediments, sometimes losing their cassiterite content and passing into quartz and sphalerite. Lead-silver mineralization near surface gives way to complex tin ore at depth. Vein structures are arranged in *en echelon* fashion and tend to converge at depth. Some structures are curved, following contacts between igneous rocks and sediments which are sometimes brecciated.

There are generally two phases of mineralization in the High Cordillera: the first consists of high temperature deposition of cassiterite and wolframite, and the second of copper, bismuth and other metallic sulfides. In the stocks of central and southern Bolivia, the second phase is silver rich, and the mineralization is generally more complex with addition of sulfosalts of zinc, lead, silver, tin and other metals. In general the more acidic rocks produce less contaminated tin ore, sometimes only cassiterite with quartz. In the less acid the rocks, the ore is characterized by more complex mineralogy.

The gangue minerals in the high Cordilleras are pyrite, pyrrhotite, chalcopyrite, arsenopyrite, and quartz. In central Bolivia, apatite and phosphates also appear. Chlorite and tourmaline are the dominant alteration minerals in the north with sericite being less common. Sericite, tourmaline, kaolinite and a little topaz are characteristic of the center and tourmaline, alunite and some sericite, of the south.

Oxidation in the north is shallow. Leaching by meteoric waters of the upper part of the veins with subsequent enrichment of cassiterite is prominent. In the central and southern part, oxidation is deeper, having reached 400 meters and formed "pacos" composed of cassiterite, limonite, jarosite, cerussite and some silver minerals.

Mineral zoning of the High Cordilleras is regular and regional. High temperature minerals occur in the summits of the granites and in the metamorphic contacts. Wolframite appears first, followed by tin, then succeeded outward by lead, silver and antimony. In the subvolcanic deposits zoning in less orderly and less evident.

The tin belt is vital to Bolivia since it accounts for more than 80 % of the country's current metallic mineral production.

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