GEOLOGICAL STUDY ON POLYMETALLIC HYDROTHERMAL DEPOSITS IN THE ORURO DISTRICT, BOLIVIA

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Abstract

There are two kinds of tin mineralization in the eastern cordillera of Bolivian Andes. One was generated by granitic plutonism during late Triassic to Jurassic (150 to 221 Ma). The other was induced by igneous activity of acidic hypabyssal rocks in the Miocene age (13 to 26 Ma). The former mineralization produced hypothermal quartz veins with cassiterite and wolframite, and the latter is polymetallic mineralization formed quartz or pyrite and cassiterite veins associated with a number of ore minerals such as stannite, stibnite, jamesonite, franckeite, zinckenite, cylindrite and andorite etc. The polymetallic veins in the Oruro district were developed in folded Silurian formations, and are being now mined by the San José, Japo, Santa Fé, Morococala, Huanuni, Catavi, Bolivar and Avicaya mines etc. in the district. Cassiterite which is most principal ore mineral occurs in intimate association with quartz (Huanuni and Avicaya mines) and pyrite (San José and Morococala mines) which were crystallized at earlier stage of mineralization, meanwhile sulfosalt minerals as above were formed at later stage. The mineralization is also characterized by the appearance of halogen bearing minerals of fluorite and tourmaline etc., phosphate minerals of apatite, vivianite and phosphophyllite etc., and sulfate minerals of alunite, jarosite and barite as primary ascending minerals. They can be divided into four types by the mode of occurrence of igneous rocks and ore deposits, the distance between them and grade of surface erosion etc. as shown in Figure 39. Mineral zoning according to the distance from a intrusive stock sometimes occurs as seen in the Avicaya and Bolivar mining area. Also, the telescopic ores coexisting together with both high and low temperature minerals occur in general. From such evidences as the intimate relation between mineral zoning and appearance of the telescopic ores, the ore deposits in the Oruro district are thought to belong to one of typical xenothermal veins.

Introduction

Mineral resources are very important in Bolivia economically. Mining is most principal industry in the country, and the production of metallic ores such as tin, tungsten, silver, antimony, zinc, lead, bismuth and copper etc. were as given in Table 1. Among them, tin is the most principal one and is produced from many mines in Bolivia. These mines produced tin distribute over a belt developed in the eastern cordillera of Bolivian Andes as mentioned later. The tin belt has 8,000 km long from north to south with 30 km to 130 km in width along mountain

TABLE 1. PRODUCTION OF METALLIC ORES
(Metal Contents: Tons)

	1975	1976	1977	1978	1979
Tin	31,952	30,315	33,740	30,881	27,781
Zinc	48,774	53,014	63,508	59,619	46,804
Lead	17,967	19,200	18,937	18,039	15,395
Antimony	16,089	17,015	16,341	13,336	14,420
Copper	6,218	5,101	3,191	2,883	1,856
Tungsten	2,311	3,132	3,063	3,073	3,130
Bismuth	622	612	651	307	10
Silver	160	169	181	195	182
Cadmium			135	108	156

(Ministerio de Mineria y metalurgia, Bolivia)

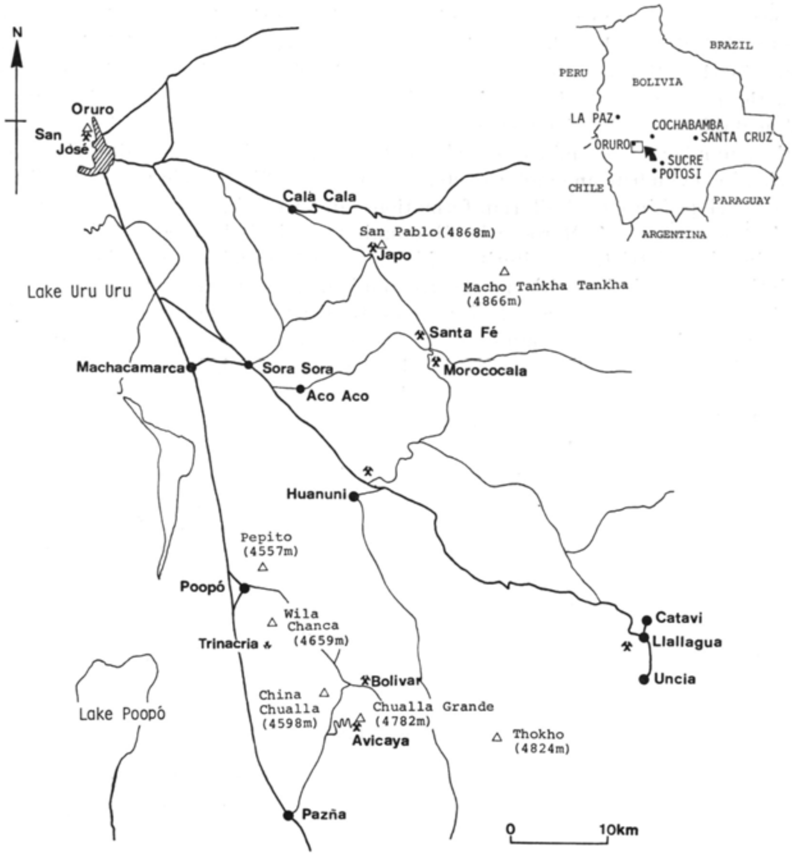

FIGURE 1. MAP OF THE ORURO DISTRICT.

range. Such many tin ore deposits were formed by mineralization related to activity of acidic magma. The major part of the deposits are so-called as Bolivian type tin deposits which correspond to xenothermal type produced at temperatures of wide range from high to low temperatures under condition of shallow depth reratively. Tin ores from these deposits are telescopic and consist of various kind of ore minerals such as cassiterite, wolframite, stannite, stibnite, pyrite, pyrrhotite, sphalerite, galena, arsenopyrite, jamesonite, franckeite and cylindrite etc. They are thought to have been formed by polymetallic mineralizations of hydrothermal solution which was originated to acidic igneous activities. To make a study of the process and conditions of formation on such polymetallic mineralizations of Bolivian type tin deposits, it is very significant to make clear the genesis of hydrothermal ore deposis. Therefore, the study on polymetallic tin deposits in Bolivian Andes range, especially the Oruro district was carried out by the authors for 3 years from 1977 to 1979.

In the Oruro district, there are many tin mines such as San José, Japo, Santa Fé, Morococala, Huanuni, Poopó, Trinacria, Catavi, Bolivar, Avicaya, Totoral and Martha etc. as shown in Figure 1. The field survey on geology of the Oruro district, especially on rock facies of Paleozoic formation, geological structure and occurrence of igneous rocks and underground survey on the ore deposits of these mines were carried out. The area in which the field survey has done is approximately 100 km in north-south length and 60 km in east-west width. Oruro city which is 200 km south from La Paz, capital of Bolivia, is located at northwestern corner in the field. The ore deposits investigated by us in this time were those of the San José, Japo, Santa Fé, Morococala, Huanuni, Trinacria, Catavi, Bolivar and Avicaya. Among them, the mines except Trinacria and Avicaya belong to Corporacion Minera de Bolivia (COMIBOL) which is under the control of Bolivian government, especially Ministerio de Mineria y Metalurgia. Meanwhile the Avicaya mine is being worked by the International Mining Company. The general geology, ore deposits, ore minerals and mineralization in the Oruro district are described in this paper.

TOPOGRAPHY

Bolivia is divided from topographic feature into Andes mountain range and eastern platform districts. The Andes range in Bolivia consists of western cordillera, Altiplano, and eastern cordillera lying from north to south as shown in Figure 2. The western cordillera ranging along border between Bolivia and Chile is mainly composed of Cenozoic volcanoes, 5,000 m to 6,500 m in height. Meanwhile eastern cordillera is formed by steep mountains named White Andes to be covered with snow thoroughout a year as shown in Figure 3. There are often found glacier, moraine hill and U-shaped valley. The principal high mountains are Chaupi Orco 6,040 m, Illampu 6,920 m (highest in Bolivia), Chachacomani 6,533 m, Condriri 6,150 m, Huayna Potosi 6,200 m, Mururata 6,000 m, and Illimani 6,882 m etc. consisting of folded Paleozoic formations and intrusive acidic rocks. Altiplano is plateau of 3,500 m to 4,000 m high above the sea level developed 200 km or more

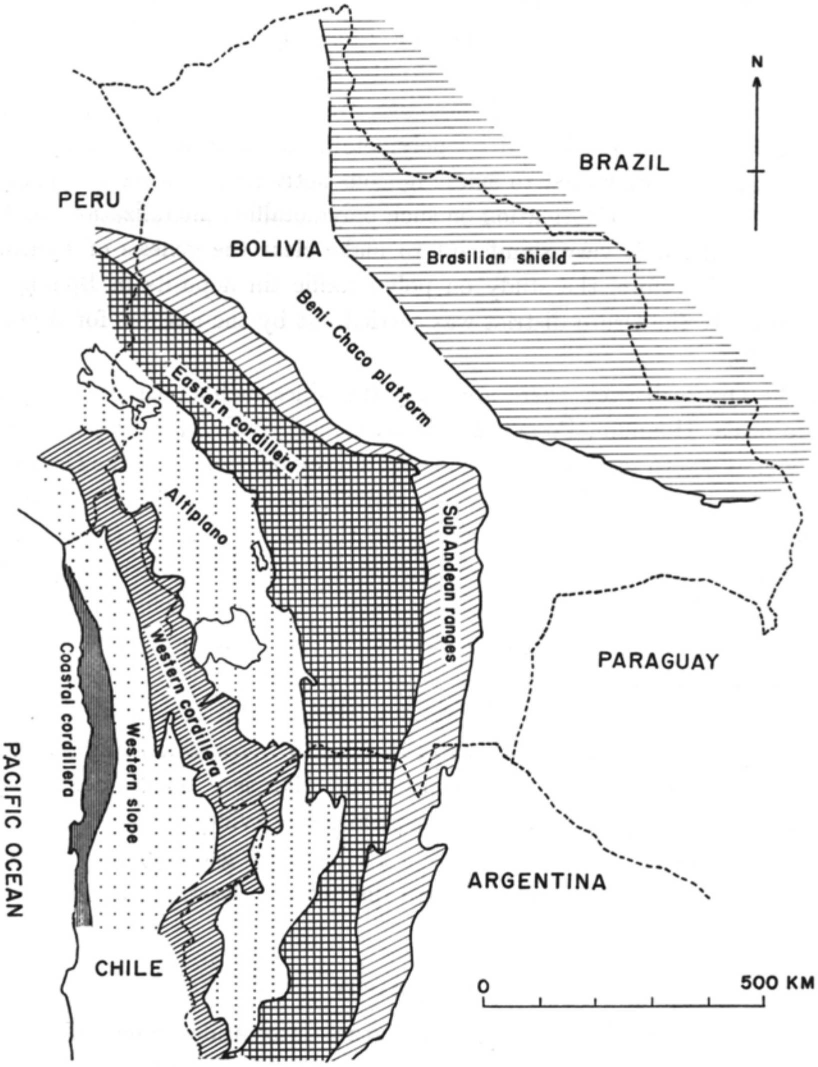

FIGURE 2. MORPHO-TECTONIC MAP OF BOLOVIA.

in east-west width between eastern and western cordilleras from Peru to Argentina through Bolivia (Figure 4). There are several basins such as Titicaca, Oruro and Uyuni in Altiplano together with lakes of Titicaca (Figure 4-C), Poopó and Uyuni, respectively. The platform occupied vast area in eastern Bolivia can be divided into Beni-Chaco platform and Brazilian shield continuing to borders with Brazil and Paraguay. They are plateau less than 700 m high above the sea level, corresponding to the upper stream area of Rivers Amazon and La Plata which meander extreamely in this area. Also the sub-Andean range between eastern cordillera of

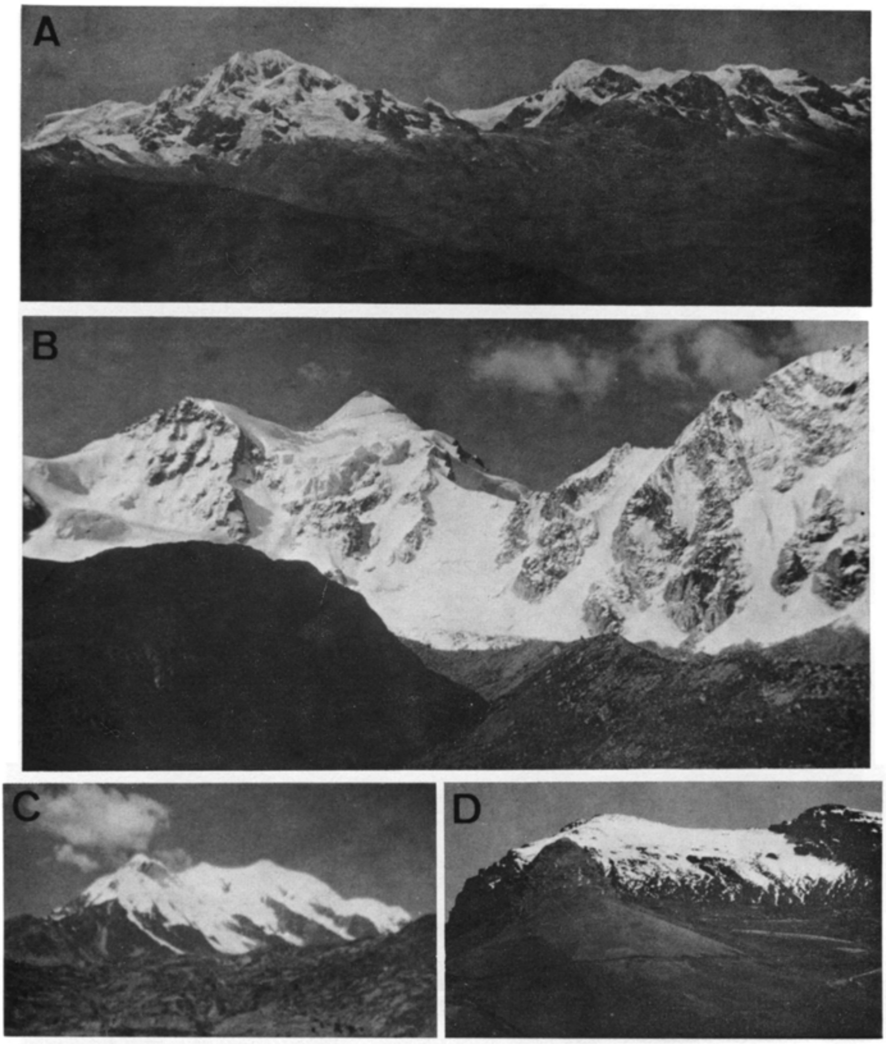

FIGURE 3. VIEW OF THE EASTERN CORDILLERA.
A: Mt. Illampu (6,920 m), B: Mt. Huayna Potosi (6,200 m), C: Mt. Illimani (6,882 m), D: Mt. Chakaltaya (5,395 m).

Andes and Beni-Chaco platform is hilly country of 1,000 m to 2,500 m high, being foot region of the Andes range.

The rivers cut the northern part of the eastern cordillera flow to east and join with the River Amazon finally. Also the rivers running to east in the middle and southern parts of the cordillera meet with the River La Plata which flows into the Atlantic Ocean. However, the rivers in Altiplano are small scale and are fed into lakes. Amount of water of them is not so much, so the lakes except Titicaca become to salt lake.

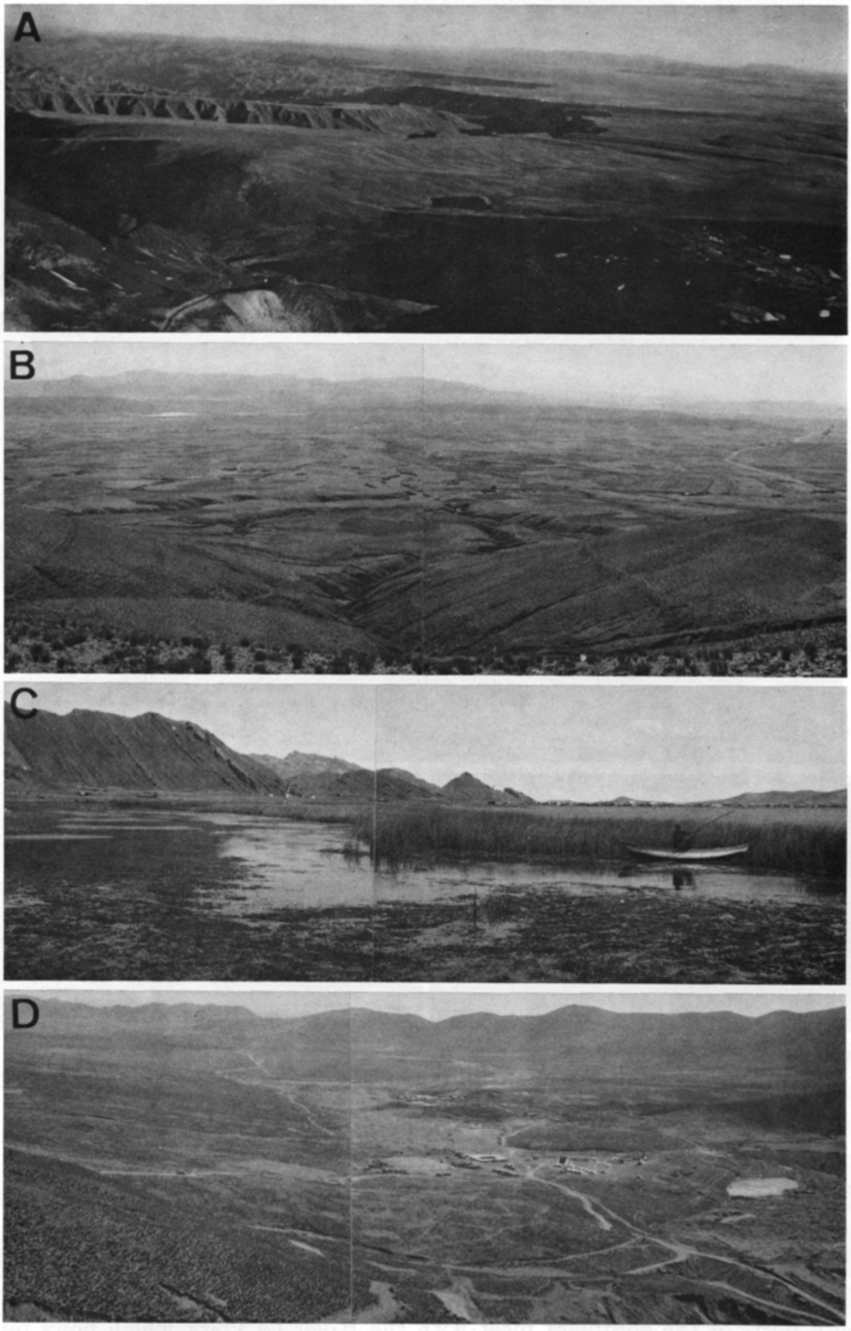

FIGURE 4. VIEW OF THE ALTIPLANO.
A: A view of the Altiplano from the foot of Mt. Chakaltaya toward southwest. B: View of the Altiplano from near Lajo toward northeast C: Lake Titicaca, D: A view from Mt. Chualla Grande toward Pazña.

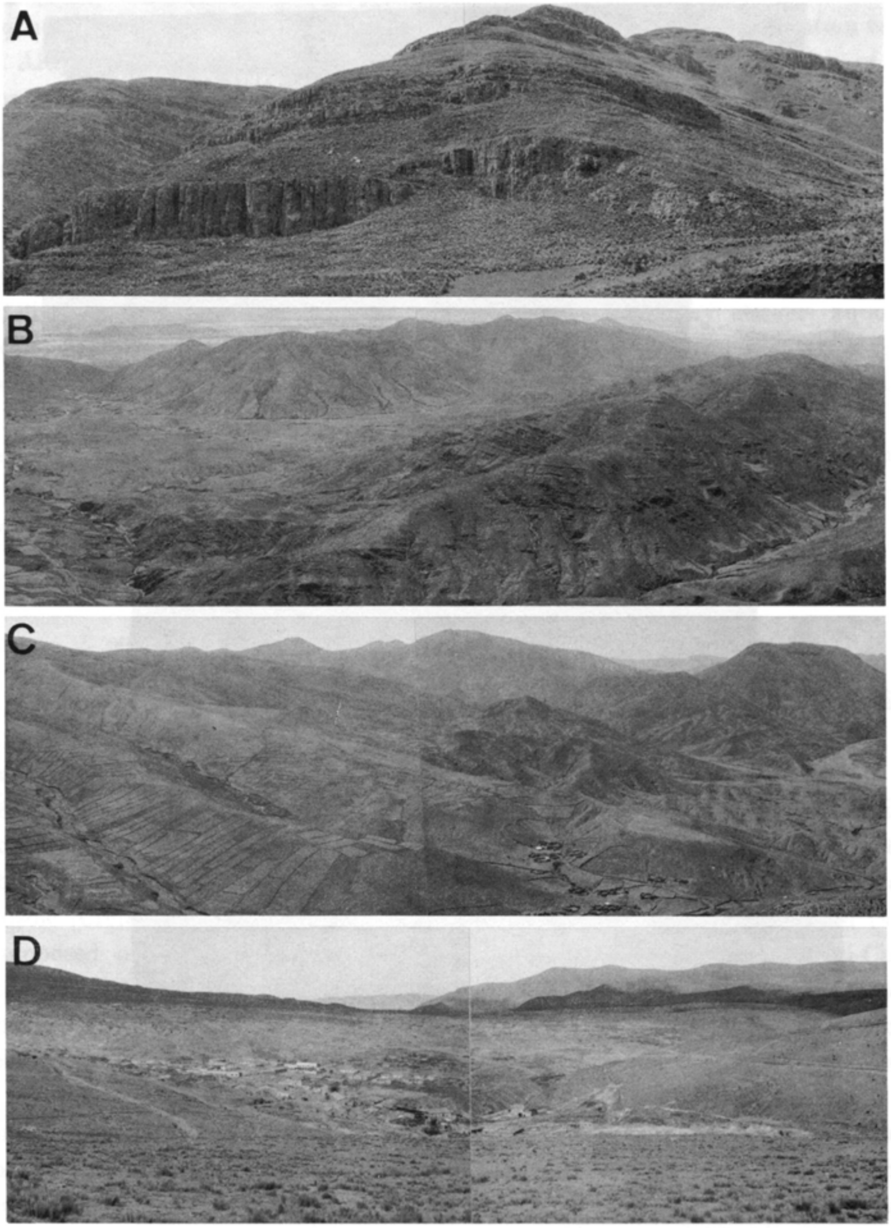

FIGURE 5. TOPOGRAPHIC PHOTOGRAPHS IN THE ORURO DISTRICT.
A: Mountain range 3 km east of Poopó, B: A view from Mt. Taipi Chanca, C: Mountain range near the Huanuni mine, D: Gentle slope hill around the Santa Fé mine.

The Oruro district, which is mainly described in this paper as below, locates western margine of middle portion in the eastern cordillera and is bordered with Altiplano (3,800 m) which has the Oruro basin and Poopó salt lake (3,686 m). There

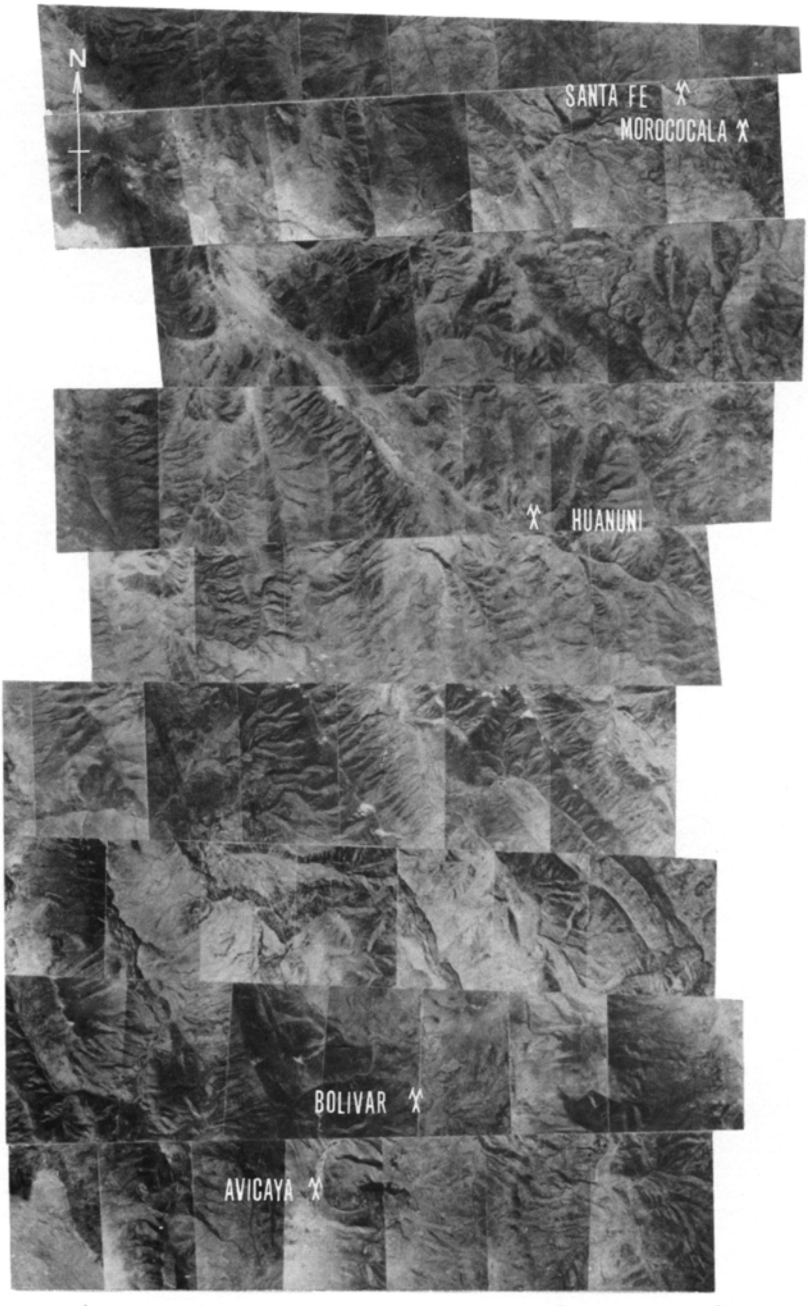

FIGURE 6. AEROPHOTOGRAPH OF THE ORURO DISTRICT.

is fairly steep mountain range consisting of folded Paleozoic formations of 4,500 m to 5,000 m high above the sea level in the district (Figure 5) and it lies the direction from northwest to southeast (Figure 6). The boundary between the mountain range and Altiplano is very clear topographically parallel to running direction of the mountain range. There is found a conspicious relationship between topography and geological structure being mentioned below. Principal rivers and valleys in this area also run parallel to the direction of the mountain range as a result controlled by geological structure.

The climate of Bolivia belongs to tropic latitudinally, but there is wide range of climate from tropical to frigid zones because change of topographic feature in Bolivia is extreamely distinct. Also there are dry and rainy seasons annually of which distinction is obvious. Dry season is from April to November, while rainy season, December to March. Total amount of rain is only 400 to 700 mm per year in La Paz and Oruro districts. However, it almost falls during the rainy season and often floods as cut off a trafic road. Thus, field works have to carry out during dry season in winter time. Daily temperature change also is serious from –5°C (morning and night) to 20°C (daytime) at La Paz and Oruro districts.

GEOLOGY

1. *Outline of geology*

Geology of Bolivia is composed of Precambrian, Paleozoic, Mesozoic, Tertiary and Quaternary formations, and igneous rocks of Mesozoic and Tertiary ages, as shown in Figure 7 (Ahlfeld and Bransa, 1960, Betollo *et al.*, 1973 Pareja *et al.*, 1978). As seen in this figure, Altiplano consists of Quaternary and Tertiary (Miocene and Pleiocene) formations mostly and Mesozoic (Cretaceous) formation partly, and the eastern cordillera is formed by Paleozoic rocks mainly and Mesozoic (Cretaceous) and Tertiary (Pleistocene) partly. Also, sub-Andean range is composed of Tertiary mainly, and Mesozoic and Paleozoic partly. Beni-Chaco platform and Brazilian shield are principally formed by Quaternary sediments and Precambrian rocks, respectively. The stratigraphic relation of them is roughly displayed in a cross section of Figure 8. The basement of Paleozoic formation in the eastern cordillera is thought to be Precambrian rocks. Although there are found the formation of all Paleozoic ages from Cambrian to Permian, the area being ore deposits is mostly formed by Ordovician and Silurian formations which mainly consist of quartzite, graywacke and slate, and alternation of them. They were conspicuously deformed by Variscan (Hercynian) and Andes orogenies (tectonics), and consequently folded and faulted distinctly. There are a lot of parallel folding axes of anticline and syncline running to NW-SE as found in the Oruro district. Also, faults parallel to the folding axes develop remarkably. Altiplano and eastern cordillera are usually bordered by such faults. The geological structures and rock facies of the formation and igneous intrusions are generally reflected by topography in the eastern cordillera, that is, mountain range lying

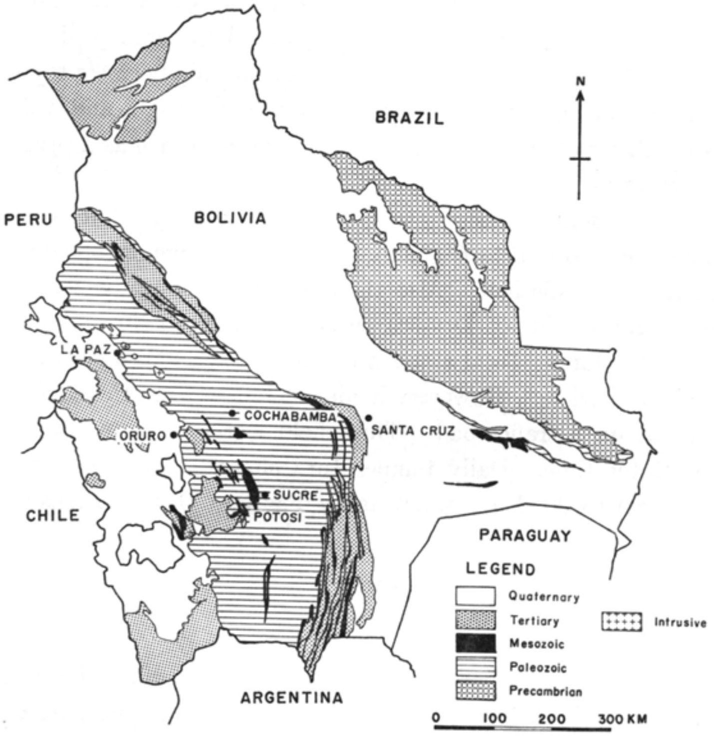

FIGURE 7. GEOLOGICAL OUTLINE OF BOLIVIA (After Betello *et al.*, 1973, Pareja *et al.*, 1978).

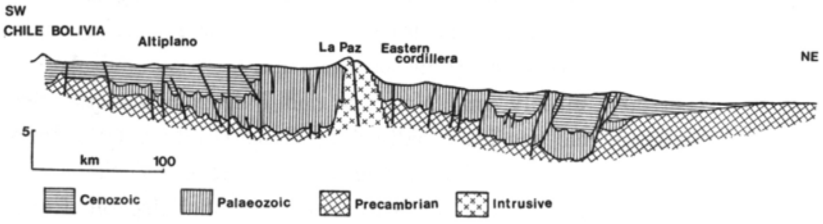

FIGURE 8. SCHEMATIC CROSS SECTION THROUGH CENTRAL BOLIVIA (After Martines and Tamasi, 1978).

parallel to folding axes and main faults of Paleozoic formations; rivers and valleys along to faults; mountain slope and feature indicating rock character of some formation and igneous intrusion. Therefore, an aerial photograph for surface topography is very useful to obtain an information on geology and its structures. Aerophotograph of the Oruro district is shown in Figure 6.

In the eastern cordillera, there are found some igneous intrusions such as granodiorite, adamellite, adamellite porphyry and quartz porphyry etc. Among them, plutonic rocks of granodiorite and adamellite occur mostly in the northern part of the eastern cordillera as batholith and lacolith, meanwhile the intrusive rocks found in the middle and southern parts of the cordillera are hypabyssal type appearing in stock, dyke and neck etc. except Karikari plutonic rock, granodiorite, near Potosi. The plutonic rocks from Mts. Illampu and Huayna Potosi located in the nothern part of the eastern cordillera belong to granodiorite family (hornblend biotite granodiorite). Also igneous rocks from Chualla Grande near the Avicaya mine in the Oruro district is adamellite porphyry. All the igenous intrusions as above belong to ilmenite series. Porphyry in stock and neck is often altered hydrothermally so it is very difficult to identify an original rock. The chronological study on these igneous rocks was made by Ahlfeld *et al.* (1960, 1964), Everden *et al.* (1977) and Grant *et al.* (1979). The distribution of igenous rocks

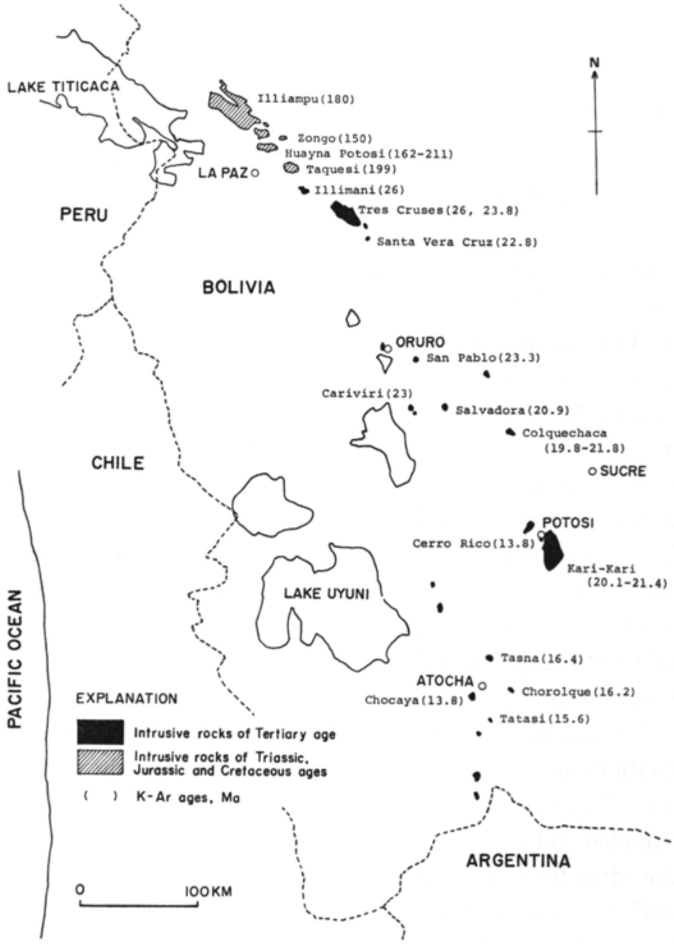

Figure 9. Igneous Rock Bodies in Bolivia and Their Potassium-Argon Ages (Compiled from the data by Ahlfeld *et al.*, 1960, 1964, Everden *et al.*, 1977 and Grant *et al.*, 1979).

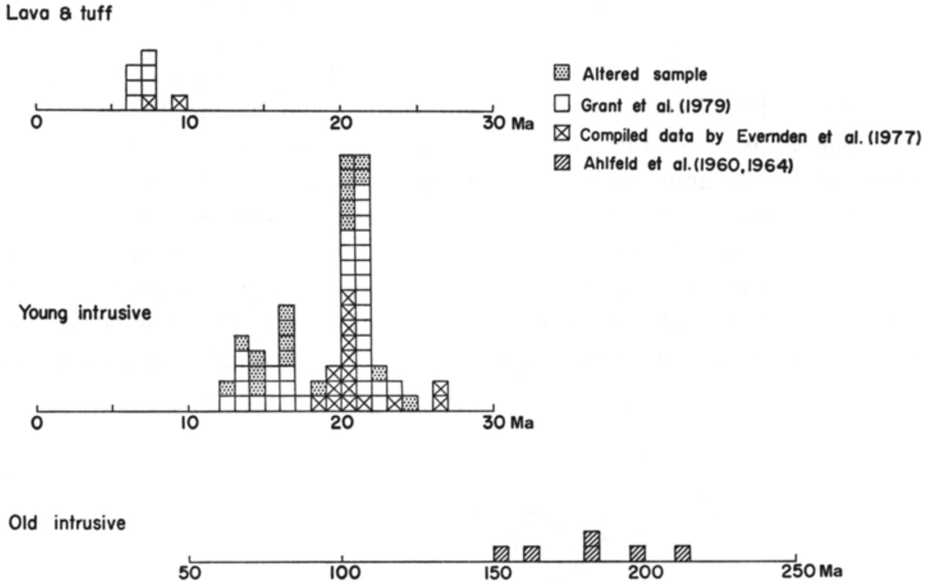

FIGURE 10. POTASSIUM-ARGON AGES OBTAINED FROM THE IGNEOUS ROCKS IN BOLIVIA.

and these K-Ar ages obtained by them are compiled in Figure 9. According to them, ages of acidic plutonic rock occurred in the northern part of the eastern cordillera are 150 Ma to 211 Ma as shown in Figure 10. These correspond to age from late Triassic to Jurassic. On the other hand, the igneous rocks exposed in the southern part from Mt Illimani have absolute ages from 13 Ma to 26 Ma corresponding to from late Oligocene to Miocene. Also, dacite lava and tuff (Morococala Formation) overlaid uncomformably on Paleozoic formation in northeastern part of the Oruro district show values of 6 Ma to 9 Ma indicating to Pliocene. The mineralization produced metallic ore deposits are intimately associated with both igneous activities of Jurassic and Miocene.

Geology of Altiplano is composed of formation of Mesozoic (Cretaceous), Tertiary and Quaternary including Cenozoic volcanic rocks (Ahlfeld and Bransa, 1960). Formations of Cretaceous are mostly red sandstone and slate and their alternation. Meanwhile those of Tertiary mainly consist of Corocoro, Mauri and Taraco Formations in succession of older age, which belong to from Oligocene to Pliocene. The Corocoro Formation is very important in mineral resoruces, and is still more divided into three sub-formations. Chakarilla sub-formation among them has the stratiformed copper deposits composed of chalcocite and native copper, so-called Corocoro type in banded red sandstone with plant fossils. According to the data of K-Ar method by Everden (1966), age of the Chacarilla sub-formation is 9.1 Ma.

2. *Geology of the Oruro district*

The western margin of the eastern cordillera in the Oruro district consists of folded Paleozoic formations, Tertiary volcanic system and Quaternary sediments. Among them, Paleozoic system is divided into four formations of Cancañiri, Llallagua, Uncia and Catavi in acending order which belong to Silurian. These formations are mainly composed of sandstone, quartzite, slate and their alternation, and have 4,000 m or more in the total thickness. While the Morococala Formation of Tertiary volcanic system occurs widely in the northeast area of the district

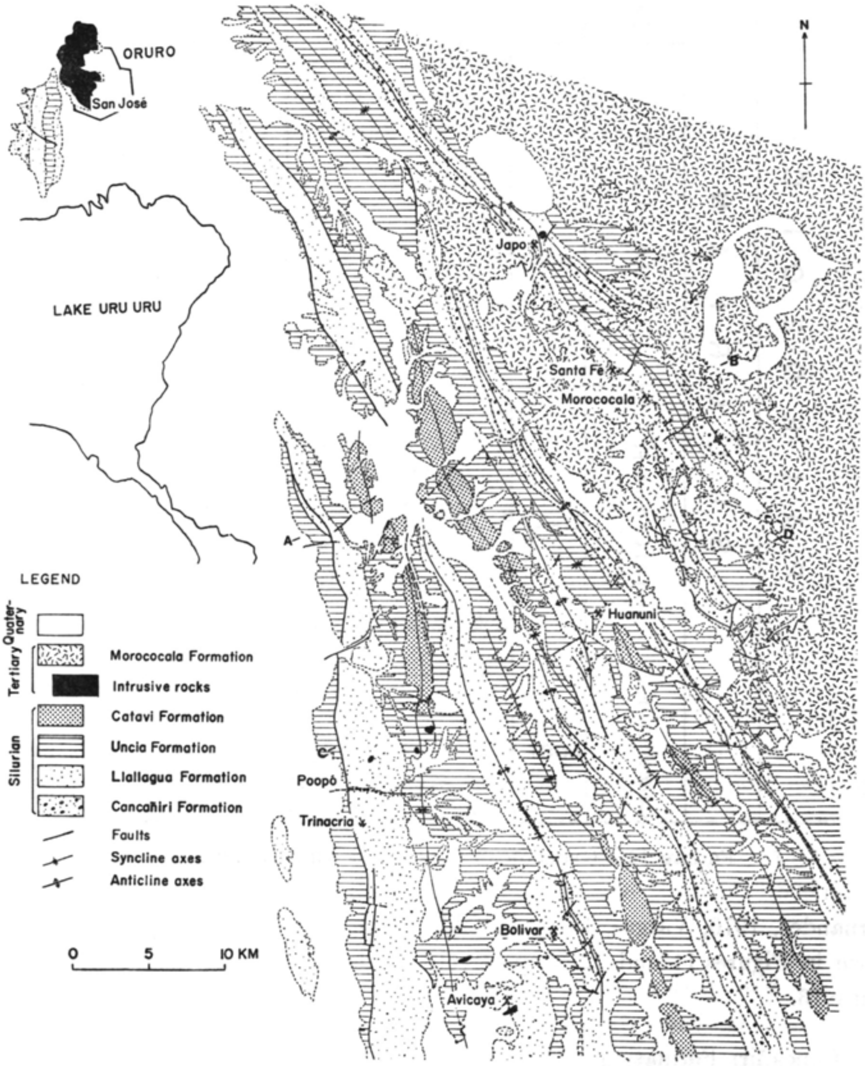

FIGURE 11. GEOLOGICAL MAP OF THE ORURO DISTRICT.

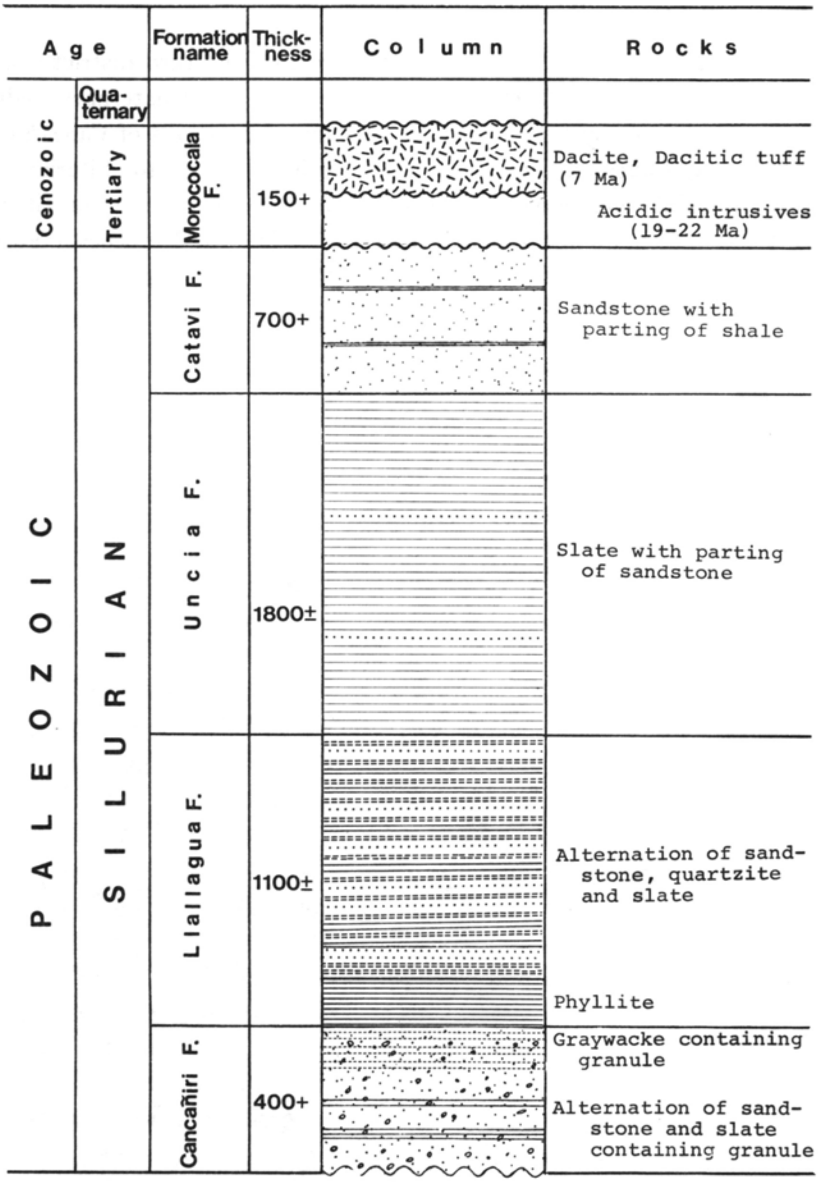

FIGURE 12. GEOLOGICAL COLUMN OF THE ORURO DISTRICT.

(Fernandes, 1970, Vargas, 1970, Ahlfeld, 1972). Geological map and column are shown in Figures 11 and 12, respectively. Also the geological section is given in Figure 13.

2.1. Cancañiri Formation

This formation which is the lowest member in the district is exposed along

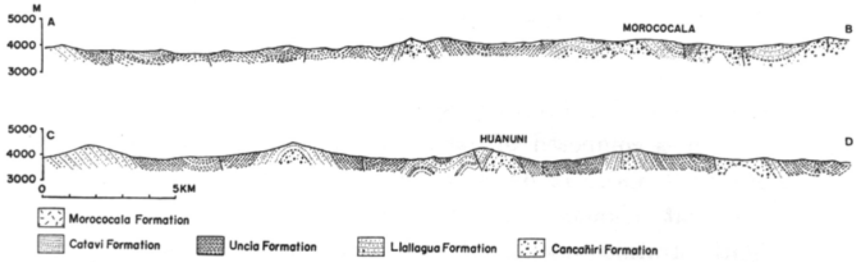

Figure 13. Geological Sections of the Oruro District.
Location of the sections are shown in Figure 11.

anticline axes elongated NNW to SSE in the central part of the district as seen in Figure 10. It consists of sandstone, graywacke or slate containing both granules or subangular fragments of shale and quartzite of a few centimeters in size. Thin sandstone lenses are sometimes embedded in slate. The thickness of the formation exceeds 400 m.

2.2. Llallagua Formation

The Llallagua Formation exposes distinctly with the Uncia Formation in western and southern part of the district, and often forms steeper slope and cliff of mountain (Figures 14-A, B, and 15-A). It consists of phyllite, thick member of alternation of sandstone, slate and/or quartzite, and slate etc. Phyllite is found in lowest portion of this formation, and its thickness is within 100 m, but sometimes thinning out. The alternation of sandstone, slate and quartzite is a most principal member in the formation as shown in Figure 16, and overlies phyllite layer. Slate becomes to predominant at upper part of the formation. Quartzite and sandstone are light gray to yellowish gray in color, while slate is grayish. The total thickness is approximate, 1,100 m. This formation becomes to principal country rocks of many ore veins in the district.

2.3. Uncia Formation

This formation overlying conformably the Llallagua Formation widely appears in all the area as seen in Figure 11. It mostly consists of slate with a few parting of sandstone (Figure 15-B). Slate being grayish black in color has well developed slaty cleavage parallel to its bedding plane. This formation is weak for erosion and forms topographic feature of gentle mountain slope in comparison with that of the Llallagua Formation. The total thickness of the formation is about 1,800 m.

2.4. Catavi Formation

This formation is the most upper formation of Silurian system, and comformably covers the Uncia Formation. It almost appears at synclinal basin, and consists of medium grained sandstone with thin slate inserted (Figure 15-C). Sandstone changes its color from gray to brown by grade of weathering. Typical localities of the formation are Aco Aco and Cerro Llallagua to Cerro Sumiragi etc. The formation has the thickness in excess of 700 m.

2.5. Morococala Formation (Tertiary system)

This formation is composed of dacite lava and dacitic tuff which belong to Pliocene (6 Ma to 9 Ma). It overlies unconformably Paleozoic formation and generally forms flat highland. Lower part of the formation is pale gray massive or slightly stratified dacitic tuff with small amounts of accidental fragment, and upper part is brownish gray dacite lava with columnar joints and flow structure (Figure 15-D). Dacite has quartz, plagioclase, biotite and small amounts of hornblende as phenocrysts of 0.2 mm to 3 mm in size. Its groundmass is mostly glassy sometimes showing pearlitic texture. The thickness of the formation is 150 m or more.

2.6. Quaternary sediments

In the Oruro district, there are glacial and alluvial deposits exposed sporadically, and white chemical sediments such as halite, calcite and gypsum in Uru Uru and Poopó lakes (Retting *et al.*, 1980). The formers are important as an alluvian tin deposit as being dredged at Avicaya and Martha.

2.7. Igneous rocks

Igneous rocks which are found in the Oruro district occur in stock, dyke and neck of adamellite porphyry and quartz porphyry etc. intruded into Paleozoic formation. They are divided into three types as follows:

Adamellite porphyry (*Avicaya type*): It occurs in stocks intruded into the Llallagua Formation at Chualla Grande in Avicaya area. Adamellite porphyry is holocrystalline but porphyritic, and composed of quartz, plagioclase, orthoclase and biotite phenocrysts of 0.5 to 2 mm in size and groundmass of equi-microgranular quartz, orthoclase, plagioclase and biotite of 0.1 mm or less in size. Plagioclase and biotite phenocrysts are often altered to sericite and chlorite along its cleavage, respectively. Quartz phenocryst is euhedral but sometimes corroded form. This stock is also suffered hydrothermal alteration such as sericitization, tourmalinization and silicification by mineralization produced tin bearing ore veins of Avicaya mine. Also, adamellite porphyry appears as dyke of 1 m to 10 m wide, cut the Llallagua Formation in the Avicaya mine. Its rock facies is very similar to the Chualla Grande stock and is considered to be branchs of the stock. On the other hand, a stock of porphyry intruded into the Uncia Formation is found at the top of Mt. China Chualla (4,598 m) which is about 4 km, northeast of Chualla Grande. It consists of a lot of quartz and small amounts of orthoclase, plagioclase and biotite as phenocrysts of 2 mm to 3 mm in size. It is strongly altered by hydrothermal sericitization, silicification and tourmalinization etc. Sometimes, the later is distinctly in some parts of the stock as changing its color to

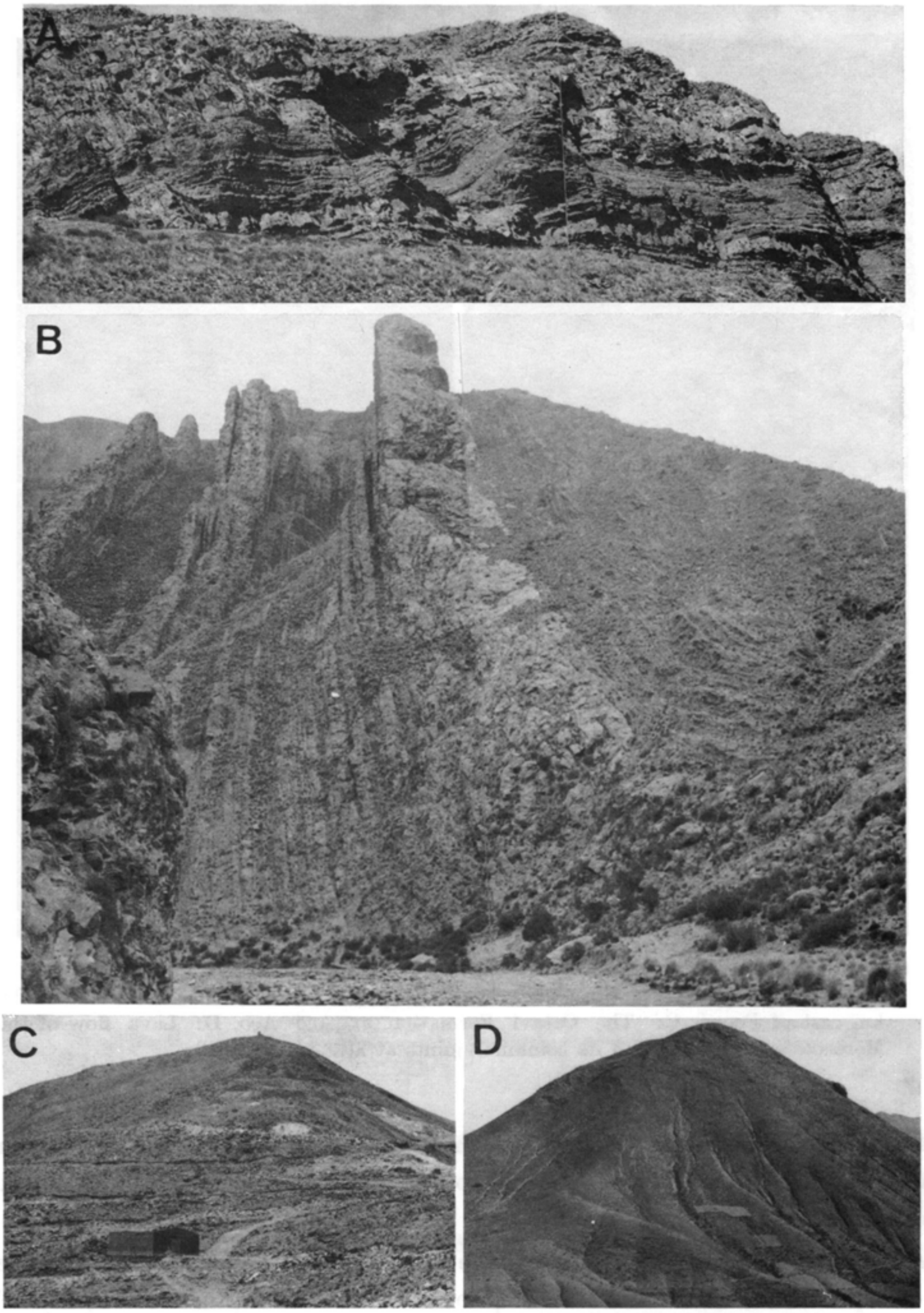

FIGURE 14. TOPOGRAPHY CHARACTERIZED BY GEOLOGICAL FACTORS.
A: Sandstone of the Llallagua Formation, east of Poopó, B: Folding Sandstone and slate of the Lallagua Formation, 4 km east of Aco Aco, C: San Pedro quartz porphyry stock of the Catavi mine, D: Quartz porphyry stock of Mt. Pan de Azucal near Poopó.

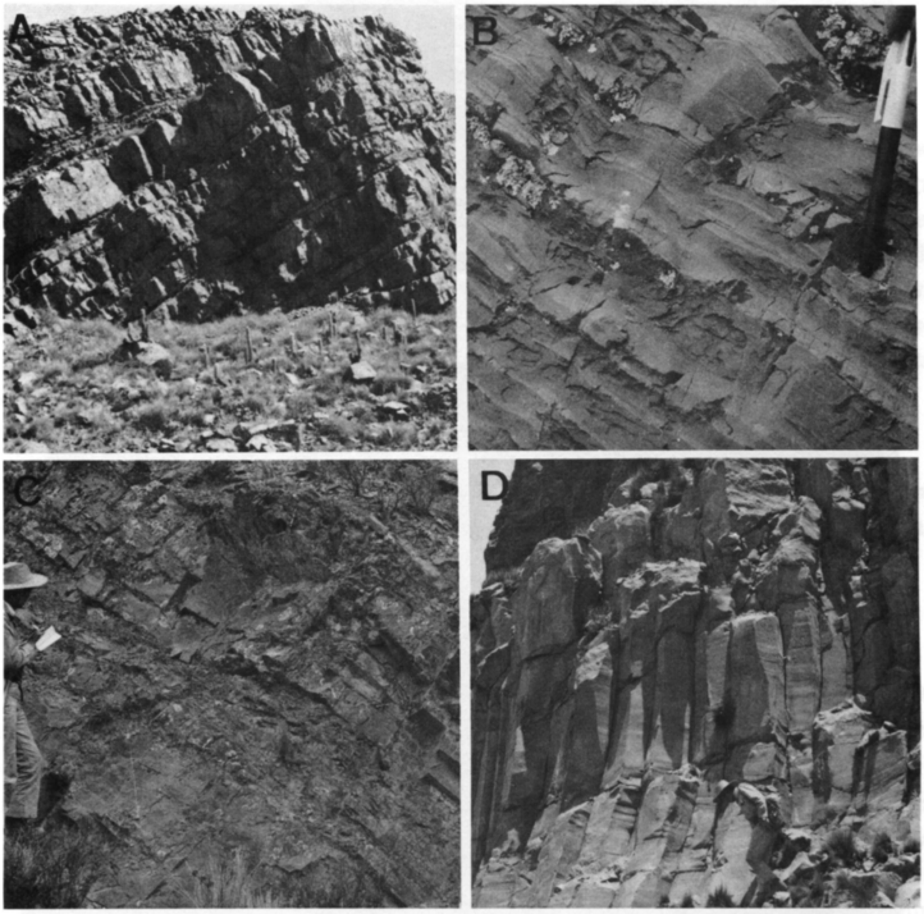

FIGURE 15. OUTCROP OF SEDIMENTARY FORMATIONS.
A: The Llallagua Formation, 1.5 km east of Poopó, B: The Uncia Formation, 2.0 km east of Poopó, C: The Catavi Formation at Aco Aco, D: Lava flow of the Morococala Formation and its columnar joints at Mt. Agua Castilla.

black just like basic rock. Owing to such alterations, it is difficult to determine rock name although the stock is thought to belong to quartz porphyry or adamellite porphyry.

Quartz porphyry: It occurs in stock, dyke and neck at Catavi and San José mines, and Taipi Chanca, Pan de Azucal, Pepito and San Pablo (Figure 14-C, D). At Catavi mine, it forms a stock intruded into the Cancañiri Formation, and has quartz, plagioclase and biotite as phenocryst, 1 mm to 2 mm in size. Its K-Ar age is 9.4 Ma (Thormann *et al.* 1966). The stock becomes most principal country rock of ore veins and is mostly suffered by hydrothermal alteration. Plagioclase and

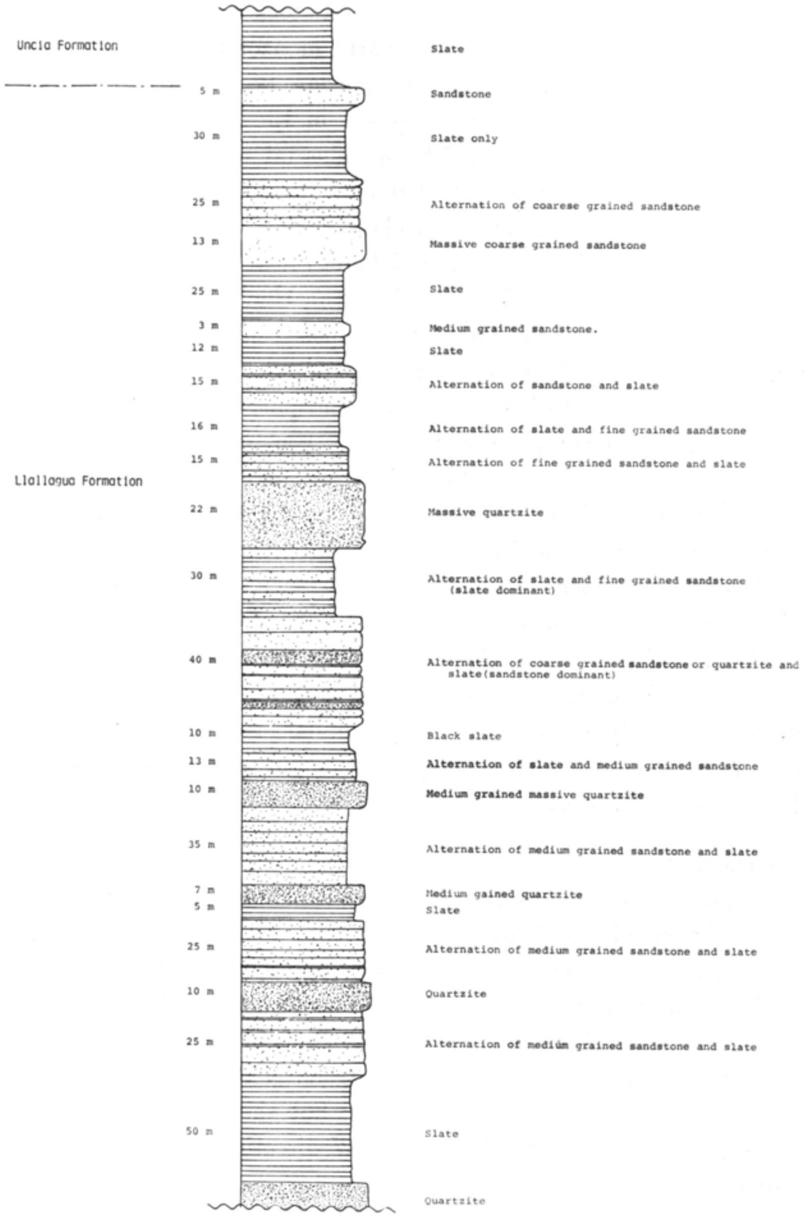

FIGURE 16. COLUMNAR STRATIGRAPHIC SECTION OF THE LLALLAGUA FORMATION.

biotite are altered to sericite and chlorite, respectively. Tourmalinization is observed partly in the stock.

Quartz porphyry in San José mine near Oruro city is conspicuously altered by hydrothermal solution, as it is very difficult to observe fresh facies of porphyry in mining area. It appears in irregular formed stock and dyke intruded into the Uncia Formation, and associates with quartz monzonite porphyry and explosive breccia rock. They form complex acidic igneous body. According to observation about relatively fresh porphyry exposed in the northwestern part of the igneous body, quartz porphyry consists of euhedral to subhedral quartz, altered plagioclase and biotite as phenocryst of 0.3 mm to 3 mm in size, and groundmass containning small grained quartz, plagioclase, orthoclase and biotite.

Quartz porphyry of Taipi Chanca and Pepito near Poopó, and San Pablo near Japo occur in stock and neck intruded into the Uncia and Llallagua Formations. But, Pan de Azucal body near Poopó is composed of many small dykes of quartz porphyry. There is found idiomorphic to hypidiomorphic quartz, 0.2 mm to 2 mm in size, plagioclase 0.5 mm to 1.5 mm, potash feldspar, 0.5 mm, and biotite, 0.5 mm as a phenocryst of quartz porphyry. While constituents of groundmass are chiefly fine grained quartz and potash feldspar and small amounts of biotite. Among these igneous bodies as above, Pan de Azucal and San Pablo bodies are altered hydrothermally as been found chlorite and sericite as products of alteration.
Dacite: Two dykes of dacite penetrated the Llallagua Formation are found near Huanuni. One is 2.0 km east of Huanuni, east slope of Cerro Convento, and another, 1.2 km northwest of Huanuni. The former dyke has about 10 m wide and over 2 km long in scale and contains plagioclase, quartz and biotite as phenocryst in glassy groundmass. These dyke rocks are very similar to dacite lava flow of the Morococala Formation. Therefore, they are thought to correspond to volcanic neck or original pass of Morococala dacite lava.

2.8. Geological structures

As mentioned above, the eastern cordillera is mainly formed by Paleozoic formation remarkably folded and faulted by Hercynian and Andean orogenies. In the Oruro district, there are roughly six anticlines and synclines which have a trend of NNW. While many faults are found in folding structure of Paleozoic formation. They are two kinds as follows; one cut at right angle or oblique direction of NE-SW for folding axes and another, parallel to the trend NNW of the folding axes. The former extends only within a few kilometers, but the later continues over 30 km long. Among them, the faults of the NE-SW direction are important as fracture system for ore veins.

Hot spring which may be considered as one of post-igneous actions in Miocene are found at three points; 3 km east of Poopó, 6 km northeast of Pasña, and Urmiri. The temperature at the outlet is approximate 60°C. These hot springs are situated at the distance within a few kilometers from Miocene igneous bodies and limited in the Llallagua Formation only. It is also noteworthy that they are located along the faults of the east-west direction.

ORE DEPOSITS

1. *Outline of ore deposits*

Various kind of metallic ore deposits are found in the eastern cordillera. Among them tin deposits are most important economically, and there are a lot of tin mines ranged from north to south of Bolivia in the eastern cordillera as a belt-like zone (Ahlfeld, 1967, Turneaure, 1971, Grant *et al.* 1980) as seen in Figure 17. As mentioned above, igneous intrusive rocks have intimte relationship with metallic ore deposits, especially tin mineralization. Most of igneous intrusions are in the tin belt as shown in Figure 18. Also the ore deposits together with tin and tungsten occur in local along to the center of the belt as seen in this figure. In this case, tin-tungsten deposits exist near igneous intrusion bodies as seen in the northern part of the eastern cordillera. Chojlla tin-tungsten deposit is a typical example of this type (Michel and Kuetter, 1977).

There are also found many metallic ore deposits such as antimony, zinc, lead, copper, silver, bismuth and gold etc. besides tin and tungsten in Bolivian Andes. The ore deposits of tin with tungsten, antimony, lead, zinc and copper are ranged

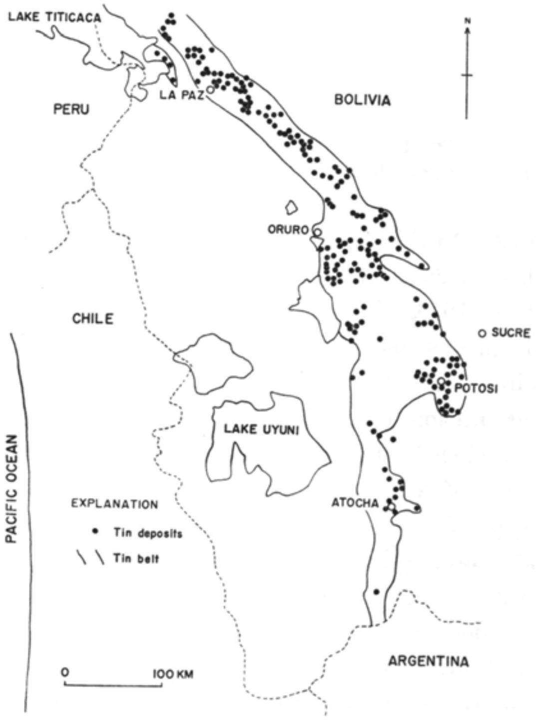

FIGURE 17. TIN BELT SHOWING THE DISTRIBUTION OF TIN MINERALIZATION IN BOLIVIA (After Claure and Minaya, 1979).

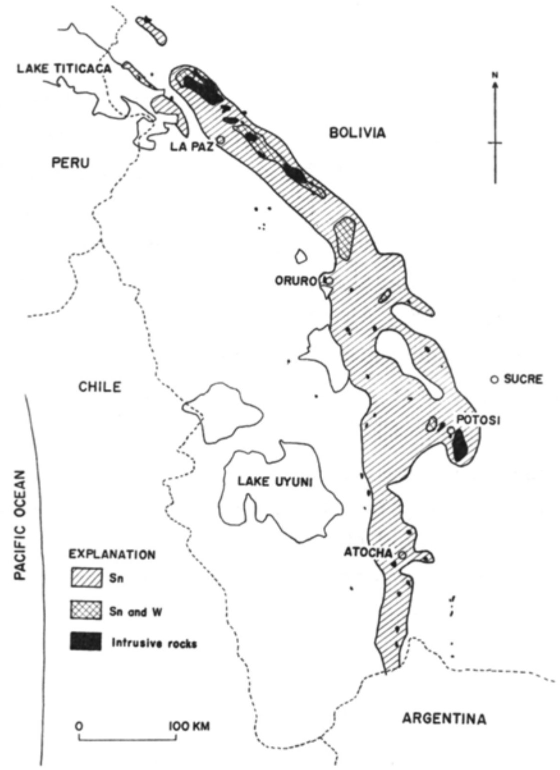

Figure 18. Tin Belt, Tin-Tungsten District and Intrusive Rocks in Bolivia (After Claure and Minaya, 1979).

as shown in Figure 19. In this figure, there is roughly found a zoning of mineralization from the tin belt of center to lead and zinc via antimony zone in the eatern cordillera (Clark *et al.*, 1976, Sillitoe, 1976, Claure and Minaya, 1979). From the fact that principal igneous intrusions of acidic rocks occur in central portion of tin belt, it is possible that the zoning mentioned above may be formed by hydrothermal mineralization induced due to magmatic action by which acidic igneous rocks were produced. The ore deposits belong to hydrothermal fissure filling (vein) type. The area of Altiplano correspond to the zone of copper deposits so-called as Corocoro type of which ore deposits are thought as sedimentary, telethermal or underground water origin. These copper deposits consisting of native copper and chalcocite as ore minerals occur in bedded form in Chacarilla red sandstone of upper Miocene. The formation of the copper deposits in Altiplano is no relation with the tin mineralization genetically.

As mentioned above, there are two stage of igneous activities in the eastern cordillera. That is Jurassic to late Triassic and Miocene ages. The tin mineralization were acompanied by the both igneous activities intimately. The intrusive rocks of Jurassic igneous activity which was induced by Variscan orogeny, occur mostly in the northern part of the eastern cordillera. They are acidic plutons such as granodiorite and adamellite etc. forming batholith and lacolith as described above, and tin and tungsten deposits intimately associated with the activity of them are a deep-seated pneumatolytic and hydrothermal vein type produced at high temperature and pressure. These deposits are found in La Paz area (Turneaure and Walker, 1947), and the ore veins of the Chojlla mine is a typical example (Michel and Kuetter, 1977). They are composed of coarse grained quartz, cassiterite and

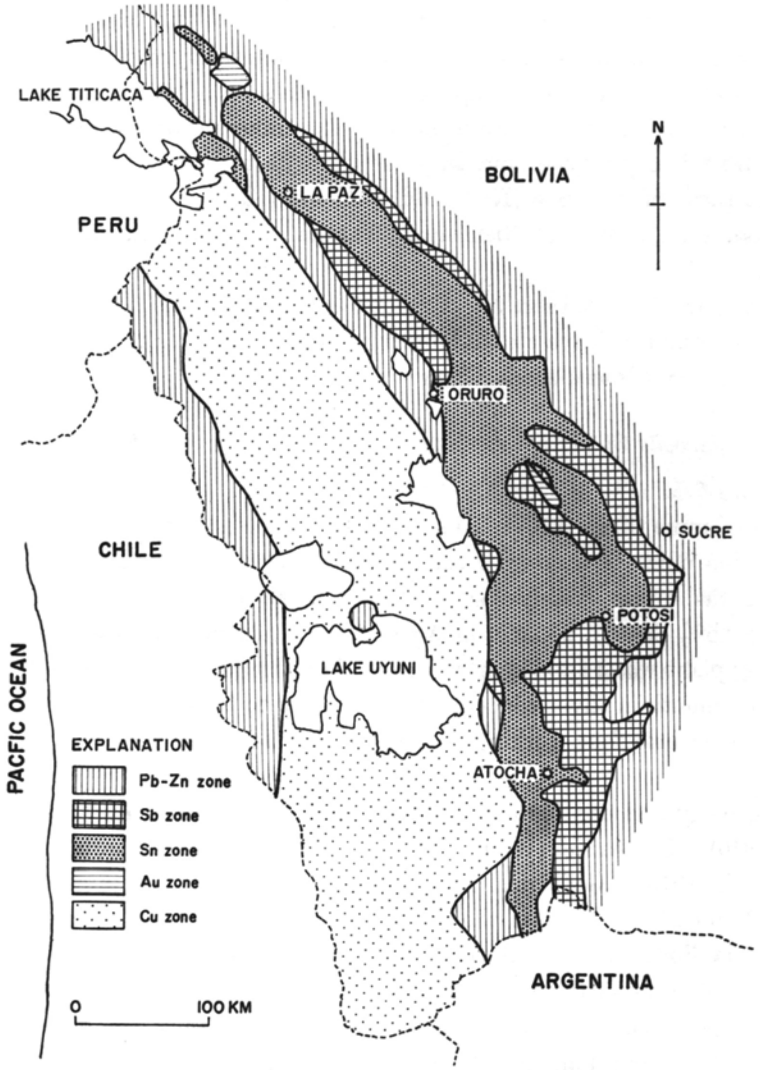

FIGURE 19. METALLOGENIC BELTS IN BOLIVIA (After Claure and Minaya, 1979).

wolframite with small amounts of pyrrhotite, sphalerite and arsenopyrite etc. On the other hand, intrusive igneous rocks generated by the Andes orogeny of Miocene are adamellite porphyry and quartz porphyry etc. occurred in stock, dyke and neck etc. The tin deposits associated with such igneous activity in mountain range from middle to southern portions of the eastern cordillera are shallow-depth veins of sub-volcanic type. The ores from them are consisted of a lot of minerals such as cassiterite, wolframite, stannite, sphalerite, wurtzite, galena, pyrrhotite, pyrite, marcasite, arsenopyrite, stibnite, jamesonite, zinckenite, franckeite and cylindrite etc. in ore minerals, and quartz, tourmaline, apatite, fluorite, vivianite, phosphophyllite, siderite, calcite, barite, kaoline, sericite, chlorite, alunite and jarosite etc. in gangue minerals. It is characteristic of the ores that high temperature formed minerals such as cassiterite, wolframite, pyrrhotite and tourmaline etc. occur together with low temperature minerals such as marcasite, wurtzite, stibnite, barite and alunite at same place. The mineralizations formed such ores as above are telescopic type, and they are thought to belong to xenothermal type as same as those of Akenobe (Kato, 1920), Ikuno (Kato, 1920, Yamaguchi, 1939), Ashio (Nakamura, 1954) and Nishizawa (Watanabe, 1916, Watanabe, 1940) mines in Japan.

In the Oruro district, there are San José, Japo, Santa Fé, Morococala, Huanuni, Catavi, Bolivar and Avicaya etc. as working mines at the present. The ore deposits of these mines are described as below.

2. *The ore deposits of the Oruro district*

2.1. San José Mine

San José mine (Figure 20-A, B) is in a residual hill, 6×2 km west of Oruro city, and the mine office is located 2 km northwest from Oruro railroad station. Its production was approximately 25,000 tons to 28,000 tons per month in a crude ore containing 0.5% Sn and 230 g /ton Ag in 1979. Amount of concentrate from the ore dressing plant was 14 tons per month in tin concentrate with 19 to 23% Sn and 3,800 kg per month in silver concentrate with 4,200 to 5,000 g/ton Ag in 1979. The mine is divided into four working sections of San José, La Cororada, Itos and Socavon.

The geology and ore deposits of this mine were described by Campbell (1942), Chace (1940), Turneaure (1960), Ahlfeld and Schneider-Scherbina (1964) and Sillitoe *et al.* (1975). Geological map and section of San José mine are shown in Figures 22 and 23. As seen in the figure, the area of the mine is consisted of slate of the Uncia Formation in Silurian and quartz porphyry and quartz monzonite porphyry of Miocene intrusion. There is often found intrusive or explosive breccia in dykes, pipes, veinlets and irregular forms. It is mainly composed of sericite altered porphyry and Paleozoic black slate of 2 to 10 cm in size. The area is locally covered by Pliocene dacite lava corresponding to the Morococala Formation.

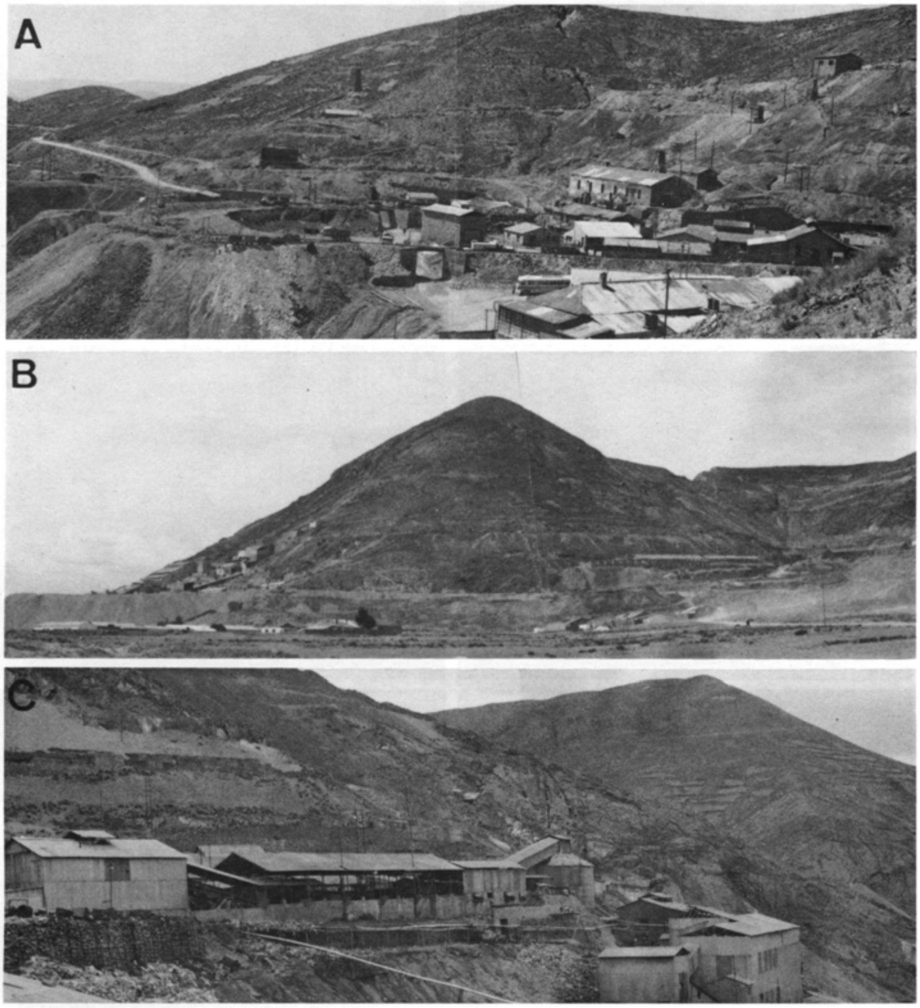

FIGURE 20. SCENERY OF THE SAN JOSE AND HUANUNI MINES.
A: San José section of the San José mine, B: Itos section of the San José mine, C: Scenery of the Huanuni mine.

The porphyry occurs in stock and dyke, and its largest intrusive in the mine area is the San Pedro stock (Figure 20-A), but the major part of the mineralization occurs in the smaller San José and Itos stocks which have quartz, plagioclase, alkali feldspar and biotite as principal phenocryst. The stocks of San José and Itos and intrusive breccia are distinctly altered hydrothermally. The common alteration of them is sericitization with quartz, sericite and pyrite, together locally with alunite and kaoline.

The ore deposits of the San José mine are a fissure filling type developed

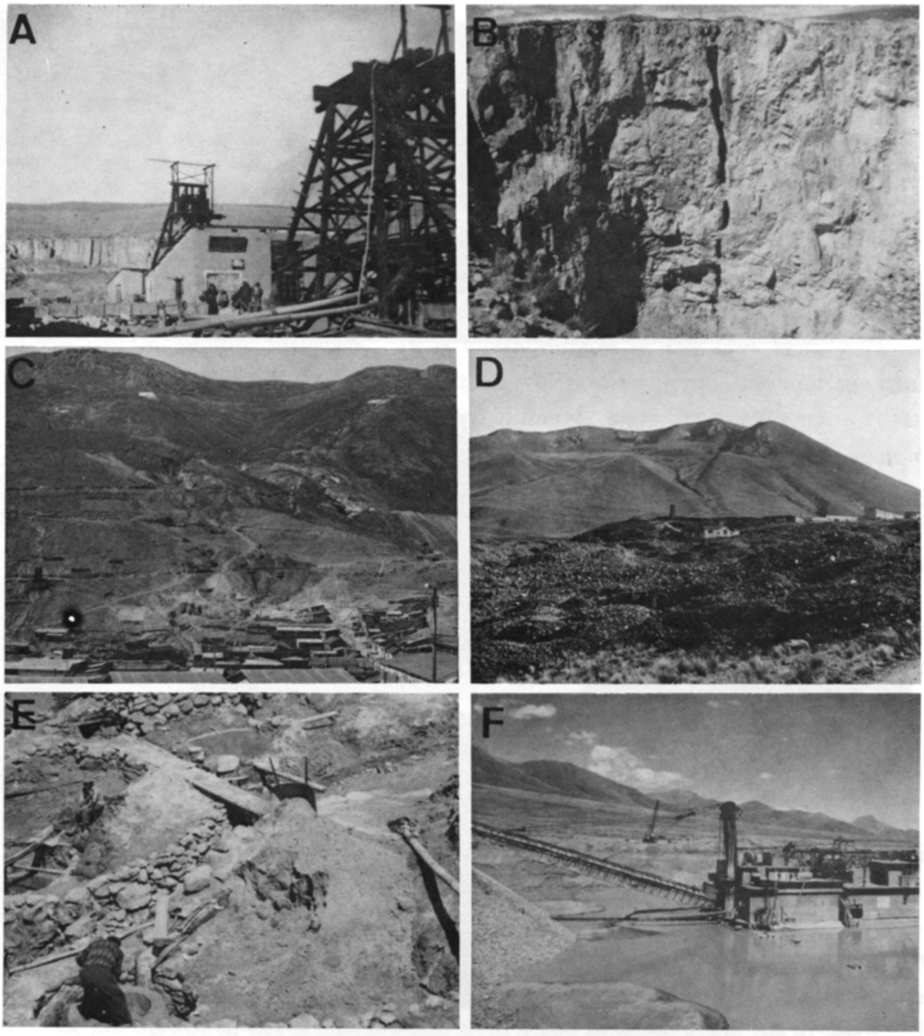

FIGURE 21. SCENERY OF THE SANTA FE, MOROCACALA, BOLIVAR, AVICAYA AND CATAVI MINES.

A: The Antia and Gustavo shafts in the Santa Fé mine, B: The Grande open pit of the Morococala mine, C: Scenery of the Bolviar mine, D: A distant view of the Avicaya mine, E: Small scale operation for alluvian tin around the Catavi mine, F: The dredging for the alluvian tin near the Avicaya mine.

mainly in quartz porphyry and Silurian slate. The ore veins tend to have northwest and northeast strikes mainly, but some lodes trend to north-south and east-west partly. They are known to be about 700 m deep or more from surface as shown in Figure 23. Among a number of veins, the veins such as San Ishidro, Aguilar, San José, Bronce, D and J etc. were investigated in this study. Their arrangement at –340 m level is shown in Figure 24, and their scale is given in

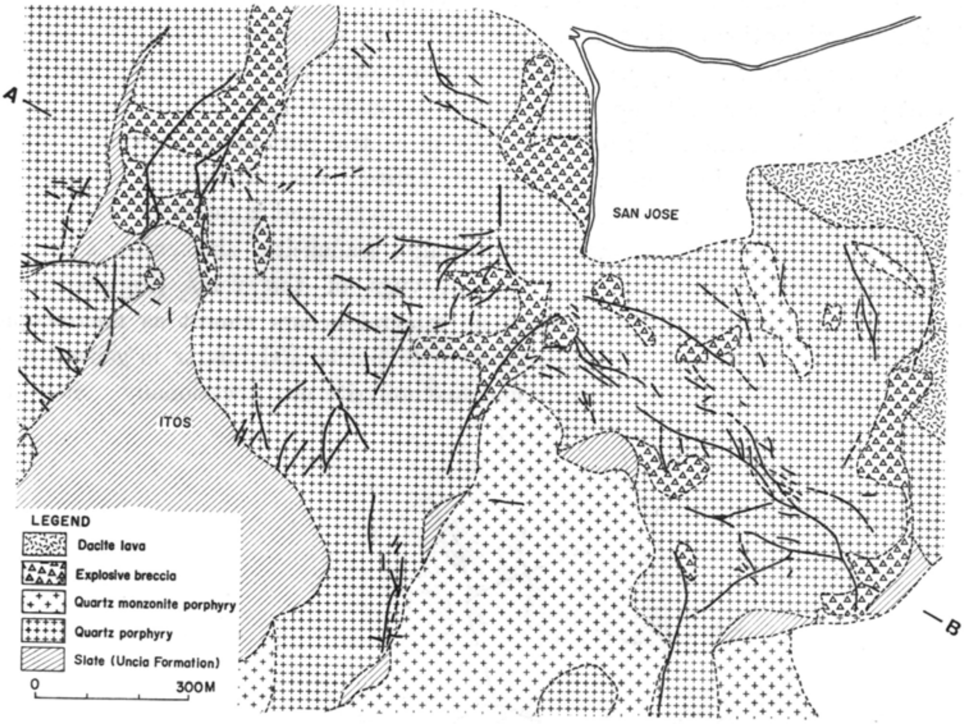

FIGURE 22. GEOLOGICAL MAP OF THE SAN JOSE MINE.

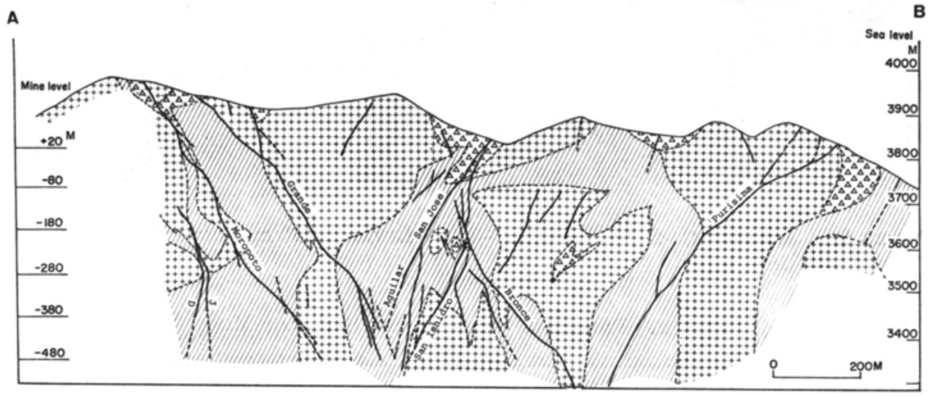

FIGURE 23. GEOLOGICAL SECTION OF THE SAN JOSE MINE.
Symbols are same as in Figure 22.

Table 2. The veins usually form simple banding consisted of pyrite, jamesonite, franckeite and quartz macroscopically as shown in Figure 25-A. In this case, pyrite is most common minerals, and occupies always outside zone in the vein with jamesonite and franckeite etc. It also forms pyrite mono-mineral veins which

contains some amounts of cassiterite microscopically. Jamesonite occurs generally in the central portion of the vein (Figure 26-A), but sometimes cuts pyrite zone of the vein as veinlet and appears along to a boundary between pyrite zone and country rock. Franckeite appears in fairly amounts (Figure 26-B), but smaller than that of jamesonite. It occurs usually in central part of pyrite vein. When jamesonite occurs in central portion of pyrite vein, franckeite occurs as synmetrical bands, 2 cm to 10 cm wide, between pyrite and jamesonite. There are often found drusy mineral such as jamesonite, franckeite, zinckenite, andorite, cassiterite, pyrite, marcasite and quartz in vugs of the veins (Figure 26-C). Cassiterite which is a principal economic mineral occurs almost as microscopic grains, 0.01 to 0.03 mm in size, associated with pyrite and quartz in general and with franckeite, jamesonite, stannite and arsenopyrite etc. occasionally. Stannite

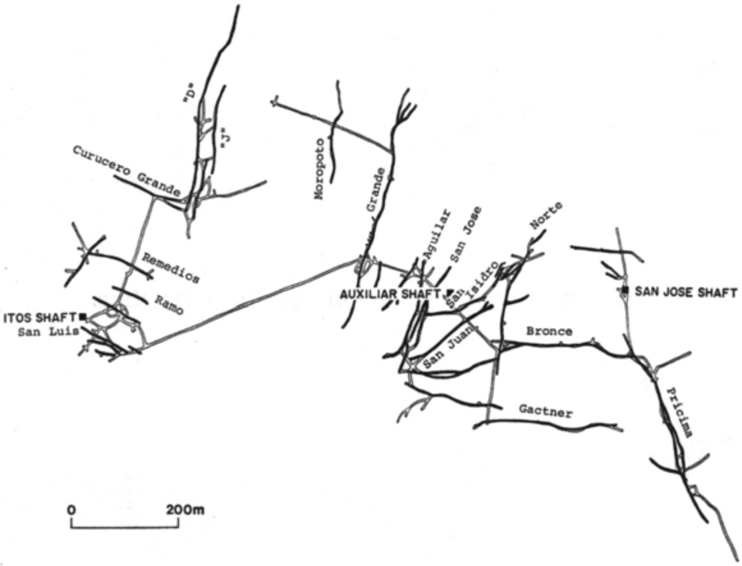

FIGURE 24. ARRANGEMENTS OF VEINS AT –340 m LEVEL (3,470 m, above the sea level) OF THE SAN JOSE MINE.

TABLE 2. PRINCIPAL VEINS OF THE SAN JOSE MINE

Vein name	Strike	Length (m)	Dip	Depth (m)	Width (cm)
J	N0-10°E	250	75-80°E	300	10-20
D	N5-25°E	400	70-75°W	350	50+
Moropoto	N10°E	400	60°E	700	100+
Grande	N20°E	450	60°E	700	100-200
Aguilar	N35°E	200	85°W	250	10
San Jose	N10°E	200	55-80°W	500	20-30
San Ishidro	N70-90°E	150	60-70°N	300	20-60
Bronce	N70-90°E	450	70°S	400	50+
Pricima	N15°E	400	80°W	600	50+

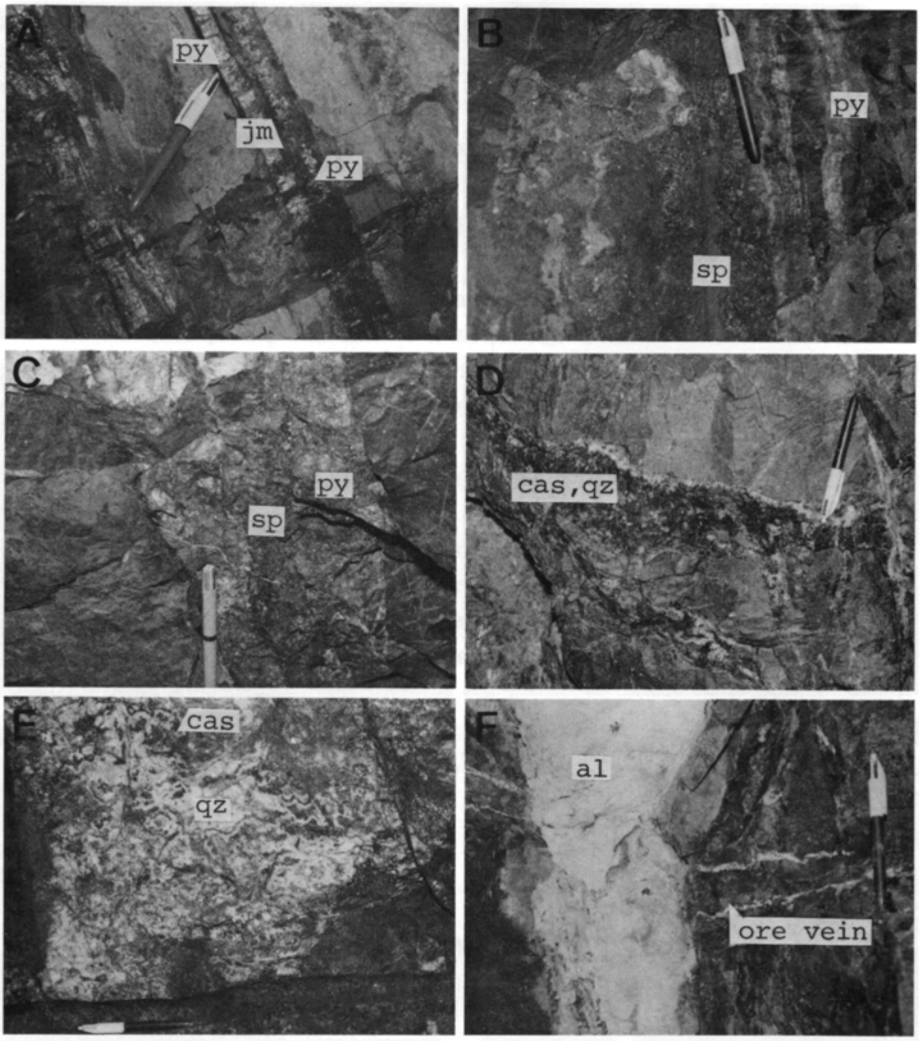

FIGURE 25. VEINS IN SAN JOSE, MOROCOCALA, HUANUNI AND AVICAYA MINES.
A: Pyrite-jamesonite vein. J vein, –340+35 m level of the San José mine. B: Pyrite-sphalerite-quartz vein. San Francisco vein, –190 m level of the Morococala mine, C: Pyrite-sphalerite-quartz vein. Crucera vein, –190 m level of the Morococala mine, D: Cassiterite-quartz vein. Nothaft W vein, –160 m level of the Huanuni mine. E: Quartz-cassiterite-pyrite vein. Salvadora vein, Porvenir level of the Avicaya mine, F: Alunite vein cuts sulfide vein. Loa level of the Avicaya mine.
py: pyrite, sp: sphalerite, jm: jamesonite, cas: cassiterite, qz: quartz, al: alunite.

appears microscopically in intimate association with pyrite, jamesonite, franckeite and cassiterite, and uncommonly assembles with zinckenite, sphalerite and chalcopyrite etc. According to analytical data by the microprobe, it contains approximate 20% in kesterite molecule. Franckeite, which is important as tin and silver minerals, closely accompanies pyrite, jamesonite, cassiterite, stannite and

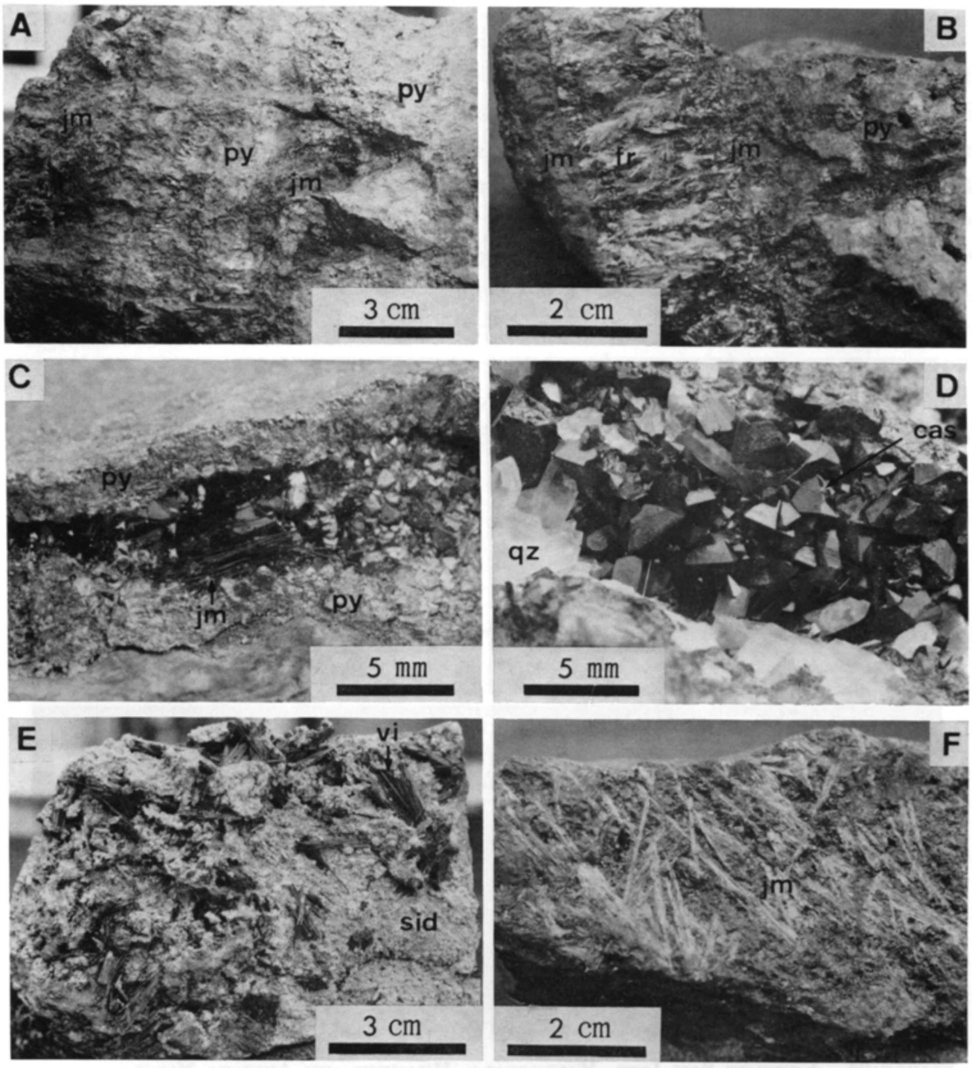

FIGURE 26. OCCURRENCE OF MINERALS FROM THE SAN JOSE HUANUNI AND BOLIVAR MINES. A: Pyrite and jamesonite from J vein, –340+40 m level of the San José mine, B: Pyrite, franckeite and jamesonite from D vein, –340+20 m level of the San José mine, C: Acicular crystals of jamesonite in vug from San Ishiro vein, –380 m level of the San José mine, D: Cassiterite and quartz from Nothaft W vein, –160 m level of the Huanuni mine, E: Vivianite and siderite crystals from Huanuni mine, F: Aggregate of acicular crystals of jamesonite from Bolivar vein, –40 m level of the Bolivar mine. py: pyrite, fr: franckeite, jm: jamesonite, cas: cassiterite, qz: quartz, vi: vivianite, sid: siderite.

arsenopyrite etc. under ore microscope. The ore and gangue minerals from the San José mine are listed up in Table 4. From data obtained by macroscopic and microscopic examinations on occurrence and mineral paragenesis of ores, it is thought that most of cassiterite produced reratively earlier stage and franckeite crystallized middle stage of mineralization, meanwhile jamesonite formed in range from the middle to late stage.

2.2. Japo Mine

The Japo mine which belongs to COMIBOL is located at 30 km southeast of Oruro. The production from this mine is 6,241 tons with 1.15% Sn as a crude ore in August of 1979. It is now working at three levels of Leonor (0 m; 4,490 m above the sea level), –30 m and –70 m.

Geology and ore deposits of the mine were described by Ahlfeld and Schneider-Scherbina (1964) and Sillitoe *et al.* (1975). Geology of this area consists of Cancañiri, Llallagua and Uncia Formations in Silurian, and Morococala Formation in Pliocene. The ore deposits of the mine are situated at the west wing of an anticline axis running to NNW direction. General strike of country rock is N25°–30°W and dip to SW 45°–60°. The ore deposits consists of numbers of small veinlets, 5 mm is 20 cm wide, generally 5 mm to 3 cm, and several meter to 20 m long. The veins exist along joints and tensional fractures in Cancañiri and Llallagua Formations, remarkably develope in quartzite of lower part of Llallagua Formation as shown in Figure 27, but a few veins are found in sandstone and slate of upper part of the Llallagua Formation and graywacke and sandstone of the Cancañiri Formation.

Vein shaped ore bodies which can be mined consist of aggregate of such small veinlets developed in quartzite of lower Llallagua Formation, and have about 200

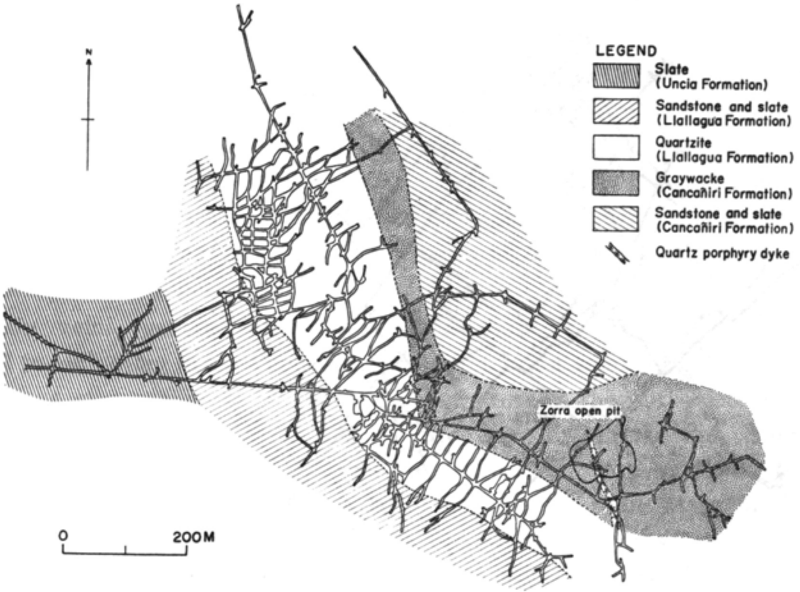

FIGURE 27. GEOLOGY AND ORE VEINS AT LEONOR LEVEL (4,490 m above the sea level) OF THE JAPO MINE.

m in width and 1,000 m in length at Leonor level. Outcrops of such ore bodies are now being mined at Porvenir and Zorra open pits, 50 m×50 m, 50m×60 m in area respectively. Veins consist of mainly quartz and pyrite associating with microcrystalline cassiterite.

Mt. San Pablo situated at 2 km north of Japo mine is a stock, 1.0×1.5 km in size, of quartz porphyry which is partly altered by hydrothermal silicification and sericitization. Sillitoe *et al.* (1975) reported that the mineralization of the porphyry tin type was found in the stock.

2.3. Santa Fé Mine

The Santa Fé mine is situated at 10 km southeast of Japo mine mentioned above. This mine also belongs to COMIBOL, and the production from the mine is 2,787 tons having 0.68% Sn as a crude ore in August, 1979. The mine has two shafts named Gustavo and Anita (Figure 21-A) and is developed down to –170 m level (0 m level is 4,358 m above the sea level).

Geology of the Santa Fé mine is composed of the Cancañiri Formation of Silurian and the Morococala Formation of Pliocene. However, the former is widely covered with dacite lave and tuff of Morococala Formation uncofmrably around the mine. Thus, it appears narrow limited area only about 50–200 m×300 m. The Cancañiri Formation is important as a country rock of ore veins, but there is found neither hydrothermal alteration nor ore deposit in the Morococala Formation.

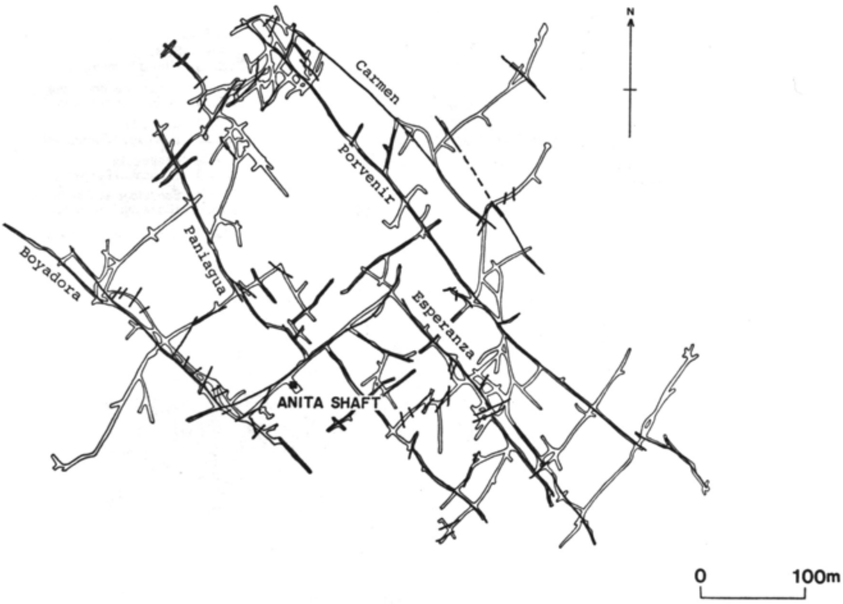

FIGURE 28. VEINS AT –170 m LEVEL (4,180 m above the sea level) OF THE SANTA FE MINE.

Ore deposits of the Santa Fé mine are formed in sandstone of the Cancañiri Formation which occurs the west wing of anticline. Main veins named Nueva, Boyadora, Paniagua, Esperanza, Porvenir and Carmen etc. have general strike N40°W and dip 60°–80°SW. Among them, Boyadora vein is longest one, extend to about 1,000 m along its strike, but its depth is 200 m only. There are some veins crossed perpendicular to the principal veins. Vein pattern at –170 m level is shown in Figure 28. The upper part of the veins becomes to network, and the shape of such ore bodies shows in irregular pipe and funnel forms, about 80×50×100 m in size. This fact suggests that the fractures filled up by ores were formed at very shallow place from surface. Such network bodies are mined from surface as Fortuna open pit. At –170 m level, Boyadora vein which has narrow width up to 10 cm only consists mainly quartz, pyrite, sphalerite and cassiterite. The amount of cassiterite and sphalerite tends to decrease toward to north of the vein. Cassiterite is very fine grains less than several μm in size, as can be recognized under microscope only, and intimately associates with sphalerite, pyrite and quartz etc. In addition to such minerals as above, stannite, jamesonite, franckeite, chalcopyrite, galena, marcasite, fluorite, apatite and sericite etc. are found from this mine.

2.4. Morococala Mine

The Morococala mine is located only 3 km southeast of the Santa Fé mine. This mine is now working and produced 3,090 tons of crude ore whose grade is 0.59% Sn in August of 1979. Three shafts named Maestero, San Miguel and Auxilier are operating and ore bodies are developed down to –211 m level (0 m level is 4,422 m above the sea level) by using them.

Geology around the Morococala mine consists of the Cancañiri Formation and Morococala Formation. Ore deposits are only found in the area where the Morococala Formation was eroded out and the Cancañiri Formation appeared (Ahlfeld and Schneider-Scherbina, 1964). The area of the Cancañiri Formation is of 600 m north to south and 500 m east to west as shown in Figure 29. The Cancañiri Formation around the mine consists of quartzite in the lower part and graywacke in the upper part.

Main veins, general strike N30°–40°E and dip 70°–90°SE, were formed parallel to each other in the Cancañiri Formation, but a vein named Crucera crossing to them as seen in Figure 30. As principal veins in the northeast vein system, Bruce, Esperanza, Explotadre, Morococala, San Francisco, Sin Nombre, San Miguel and San Antonio etc. are found in Figure 30. Among them, Bruce and San Francisco veins continue 500 m in stirke and more than 200 m in depth, and principally consist of fine grained pyrite, sphalerite and cassiterite etc. (Figure 25-B,C). Also, Crucera vein has the same scale as that of Bruce with 30 to 50 cm wide in –190 or –211 m levels, and consists of mainly quartz, sphalerite, galena and pyrite, and microcrystalline cassiterite which is accompanied by pyrite intimately.

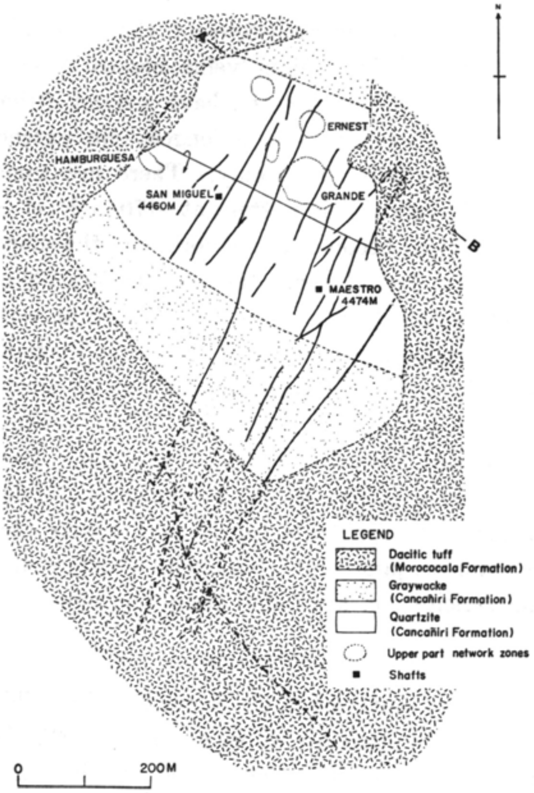

Figure 29. Geological Map and Vein Pattern of the Morococala Mine.

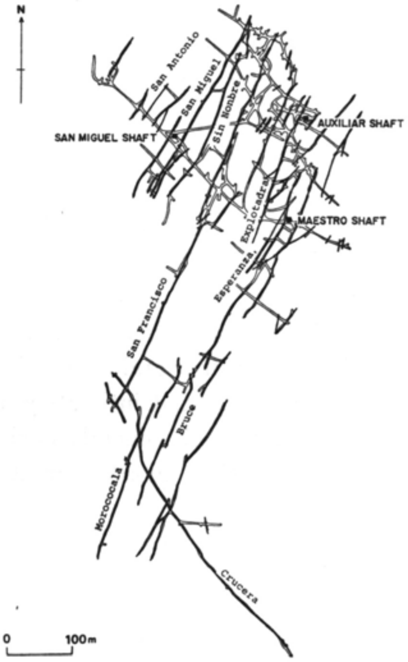

Figure 30. Veins at –190 m Level (4,290 m above the sea level) of the Morococala Mine.

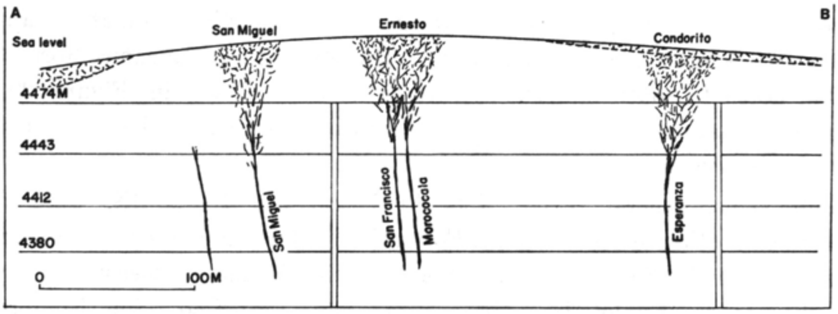

Figure 31. Section of the Morococala Mine, Showing the Upper Part Network Zone.
Location of the section is shown in Figure 29.

The vein is occasionally cut at right angle by a vein of stibnite formed at latest stage of mineralization. The shape and fissure pattern of ore deposits are very similar to those of the Santa Fé mine. Upper part of the ore deposits becomes to funnel-shaped network bodies as shown in Figure 31. Although these network bodies were already mined out as Grande and Hamburguesa open pits, Ernest open pit is now working. Grande open pit was the largest, 80×40 m in area, and 70 m in depth (Figure 21-B). Wall rocks of open pit are strongly altered, and disseminated microcrystalline cassiterite is found in such zone with its veinlets.

2.5. Huanuni Mine

The Huanuni mine (Figure 20-C) is now one of the largest tin mines in Bolivia, and is situated 50 km southeast of Oruro. Its productions are 1,000 tons per day as a crude ore with 1.3% Sn. Geology of this mine consists of the Llallagua and Uncia Formations of Silurian and the Morococala Formation of Pliocene as shown in Figure 32. The Llallagua Formation consists of quartzite in the lower part and sandstone and slate in the upper part, and the Uncia Formation is composed of slate. While the Morococala Formation mostly consists of massive dacitic tuff covered on the Silurian formations uncomformably. Two dacite dykes cut the Llallagua Formation near the Huanuni mine. No plutonic and hypabyssal rocks are found in this area.

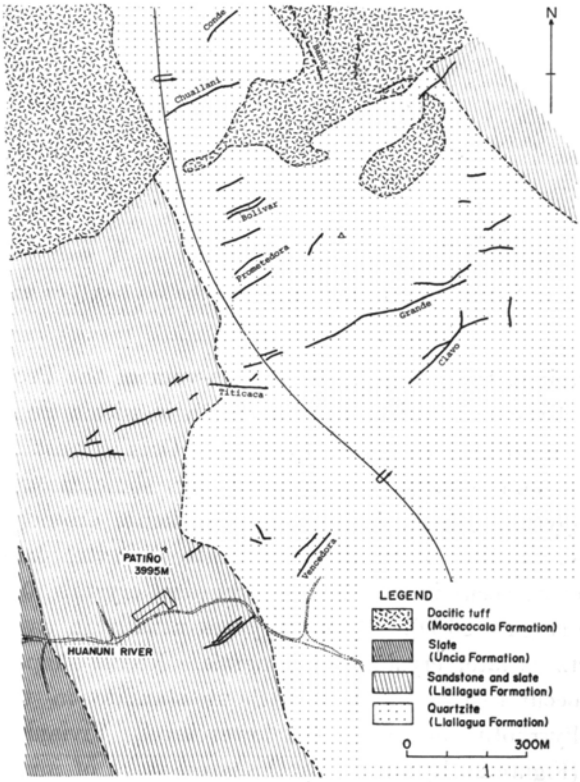

FIGURE 32. GEOLOGICAL MAP AND VEIN PATTERN OF THE HUANUNI MINE.

Veins are mainly embedded in the Llallagua Formation. The number of veins found in the mine is over thirty, and the general trend of veins is NEE and NNE direction as seen in Figure 33. Veins have mainly branches, but do not continue so long. For example, the Ramo 20–60 branch-vein of the Prometedora vein at –120 m level has 100 cm in width, but its length is within 20 m only. The ore grade of the vein is so high as 0.4 to 4.3% Sn. Ores consist mainly of coarse grained cassiterite and quartz accompanied by some amounts of stannite, sphalerite, chalcopyrite, galena, jamesonite, franckeite, arsenopyrite, pyrrhotite, marcasite, apatite, fluorite, tourmaline, vivianite, siderite, kaoline and sericite etc. Cassiterite often occur in euhedral or subhedral crystals, 0.5 to 3 cm in size, and its aggregate (Figure 26-D). Pyrite appears usually in association with cassiterite and quartz as later crystallized minerals. Needle shaped jamesonite and platy franckeite occur together with or without stannite in the later stage of mineralization. Pyrrhotite occurs at the lower level. Vivianite appears as large beautiful crystal (Figure 26-E) formed by the latest stage of mineralization. Fluid inclusions, 20 to 30 μm in size, found in quartz from the Nothaft zone at –120 m level

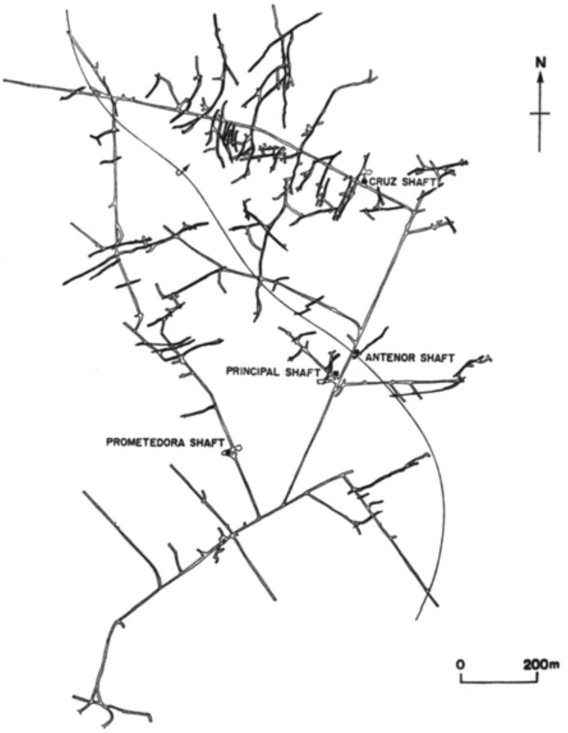

Figure 33. Veins at Patino Level (4,000 m above the sea level) of the Huanuni Mine.

are two phases, gas and liquid, under microscope and their filling temperatures were from 300° to 320°C.

2.6. Catavi Mine

The Catavi mine which belongs to COMIBOL is 80 km southeast of Oruro. This mine is also called the Lallagua or Patiño mines, but the formal name of this mine is "Siglo XX". The production during 1978 is 4,375 tons as metal tin, although it was 40,000 tons of metal tin in 1940. The mine is being worked at levels of 0 m (4,516 m above the sea level), 250 m, 383 m (Patiño), 411 m (Cancañiri),

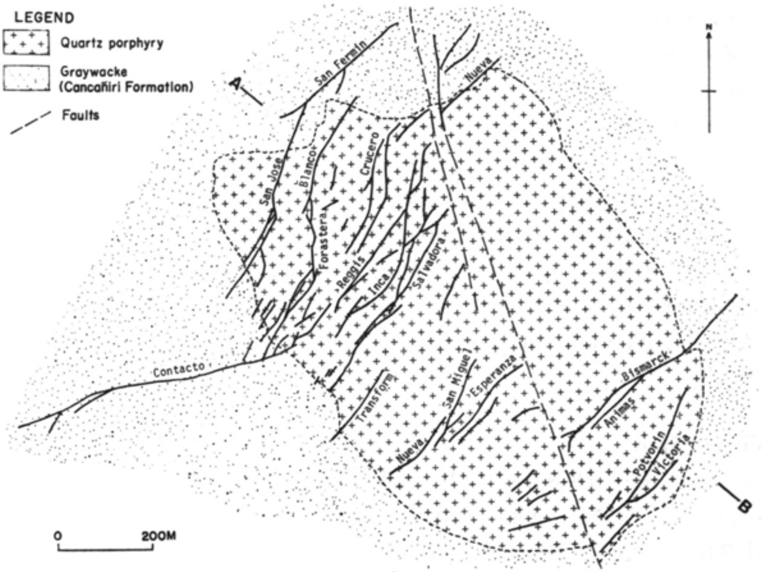

Figure 34. Geological Plan of the Cancaniri Level (411 m level, 4,105 m above the sea level) of the Catavi Mine. (After Turneaure, 1960)

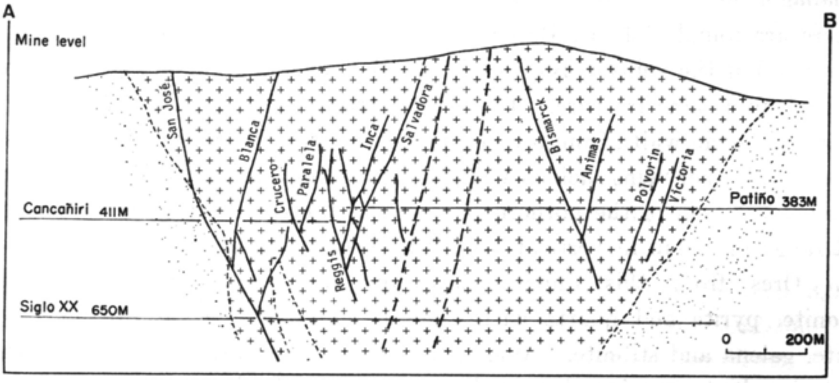

Figure 35. Geological Section of the Catavi Mine (After Turneaure, 1960)
Location of the section and symbols are shown in Figure 34.

500 m, 600 m, 650 m (Siglo XX), 720 m and 800 m levels etc. Geology of the mine is composed of graywacke of the Cancañiri Formation of Silurian system and quartz porphyry of the Salvadora stock intruded into the formation as shown in Figures 34 and 35 (Turneaure, 1935, 1960, Ahlfeld and Schneider-Sherbina, 1964). The stock has breccia rock in its marginal zone and sometimes change to rhyolitic or dacitic facies. The K-Ar ages of the stock are 9.4 Ma (Thormann *et al.*, 1966, Everden *et al.*, 1977) and 21 Ma (Grant *et al.*, 1979). The stock has been distinctly suffered by hydrothermal alteration such as silicification, kaolinization and sericitization etc. Also the tourmalinization is partly observed in the stock. Ore veins exist mostly in the stock, but some of them continue into the Canañiri Formation from the stock as shown in Figure 34. All veins have strike NE or NEE, and dip 60° to 80°E or W. In general, veins range in width from a few centimeter to 2 m, average 50 cm to 80 cm, including impregnated zone. Depth extension of veins along dip direction end to be over their strike length. The principal ores from the mine consist essentially of cassiterite, quartz and pyrite associated with some amounts of marcasite, arsenopyrite, pyrrhotite, wolframite, bismuthinite, sphalerite, tourmaline, siderite, kaoline and phosphate minerals such as vivianite, paravauxite and vauxite etc. Now, open pit mining is being planned about network veinlet zone of uppermost part in the stock. There is tin placer in alluvial sediments near Llallagua town. The alluvial cassiterite is now dredged by primitive hand method (Figure 21-E).

2.7. Bolivar Mine

The Bolivar mine (Figure 21-C) which is one of the enterprises of COMIBOL is 8 km northeast of Pasña. The monthly production is both 750 tons of a crude ore contained 3.0 to 3.5 % Sn and 350 tons of hand picking ore with about 10% Sn. Geology of the Bolivar mine is composed of slate and quartzite of the Llallagua Formation, and slate of the Uncia Formation. Ore veins are mainly embedded in the Llallagua Formation and partly in the Uncia Formation. As shown in Figure 36, there are found Bolivar, Ramo Bolivar, Ponabanba, Santa Rosa and Nane as main veins, but the veins of Bolivar, Ramo Bolivar and Nane are thought to have been filled up a same fracture. They have strike N50°E to N70°E and dip 45° to 70°N, and range in width from few centimeters to 2 m. Besides them as above, there are also found other veins such as Venus and Rosario veins in the southwestern part, and San Jorge vein in the nothern part in the Bolivar mine area. The veins are mined range of 430 m in vertical from 0 level (4,015 m above the sea level) to 14 levels. Ores from this mine consist of commonly sphalerite, cassiterite, jamesonite, pyrite and quartz with some amounts of arsenopyrite, chalcopyrite, stannite, galena and stibnite. Among them, sphalerite corresponding to marmatite is most abundant ore mineral generally accompanied by jamesonite, cassiterite and pyrite. Jamesonite also is a principal mineral of Bolivar vein and occurs massive

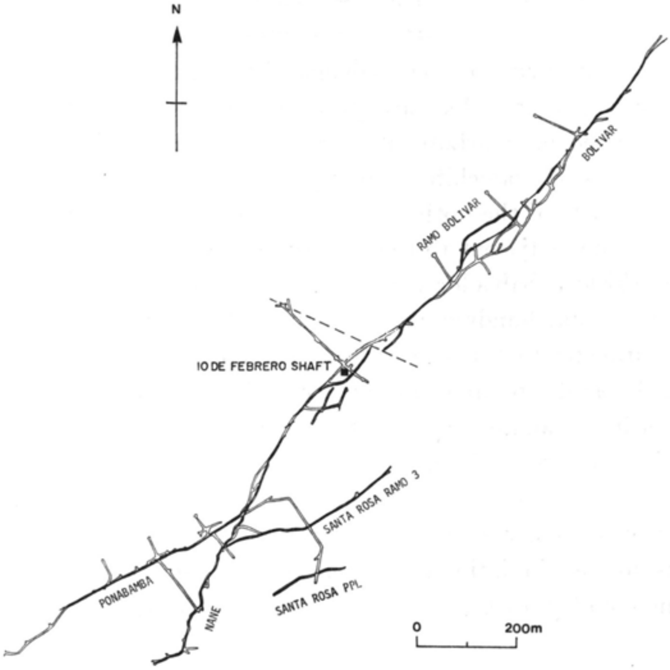

FIGURE 36. VEINS AT 0 m LEVEL (4,105 m above the sea level) OF THE BOLIVAR MINE.

aggregate consisting of needle shaped crystals about 0.5 mm long accomanied by sphalerite, cassiterite and pyrite (Figure 26-F). Cassiterite is found in very small grains with jamesonite, sphalerite, pyrite and quartz. The grains of cassiterite included in jamesonite is 10 μm or less in size. There is found no franckeite from this mine. So-called franckeite from this mine was identified to be jamesonite by X-ray and EPMA examinations. Also, galena and stibnite appears in fairly amounts from Bolivar and San Jorge veins being nothern side in the mining area. Quartz is common gangue mineral. The zonal arrangement of ore minerals is found in the area including Bolivar, Martha, Totoral and Avicaya mines.

2.8. Avicaya Mine

The Avicaya mine is 6 km northeast of Pasña, and is worked as a branch of the International Mining Company. The monthly production is 50 tons of concentration with 30% Sn. There are two mining sections in the Avicaya mine; Chualla and Minchin sections. The Chualla section has eighteen levels between 4,261 m and 4,590 m, while the Minchin section, fourteen levels between 3,928 m to 4,259 m. The geology of the mine consists of quartzite and sandstone with slate of the Llallagua Formation (Ahlfeld and Schneider-Scherbina, 1964, Cabero, 1979). There are found three igneous rocks around the Avicaya mine; Chualla Grande of adamellite porphyry, China Chualla stock of quartz porphyry and dyke rocks of adamellite porphyry. These stocks have intruded to the Silurian formation and given the thermal effect for the surrounding sedimentary rocks. Veins mainly occur in quartzite of the Llallagua Formation. Veins of San Francisco, Ramo San Francisco and Dike are principal ore bodies in the Chualla section, especially developed in quartzite at –200 m level distinctly. They also continue into the dyke rocks of adamellite porphyry at the same level, but become narrow in the dyke. The parts of the nothern extension of these same veins are working by Totoral private mine adjacent to the Avicaya mine. Veins in the Minchin section are Porvenir, Cristna, Salvadora, Herrera and Secondary veins (Figure 37). The veins continue several hundred meters along both strike and dip directions with from a few centimeter to 1.5 m in width. The common ore consists of medium or coarse grained cassiterite and quartz, sometimes associated with arsenopyrite, pyrite, marcasite, stannite, pyrrhotite, galena, tourmaline, siderite, vivianite, alunite and jarosite etc. Alunite of the latest stage of mineralization sometimes cut in dyke-form the ore veins (Figure 25-F). The strong tourmalinization is characteristic of the early stage mineralization in the Avicaya mine, and a lot of tourmaline is formed in intimate association with quartz and cassiterite in the veins, and in country rocks of Silurian sedimentary rocks, dykes and stocks.

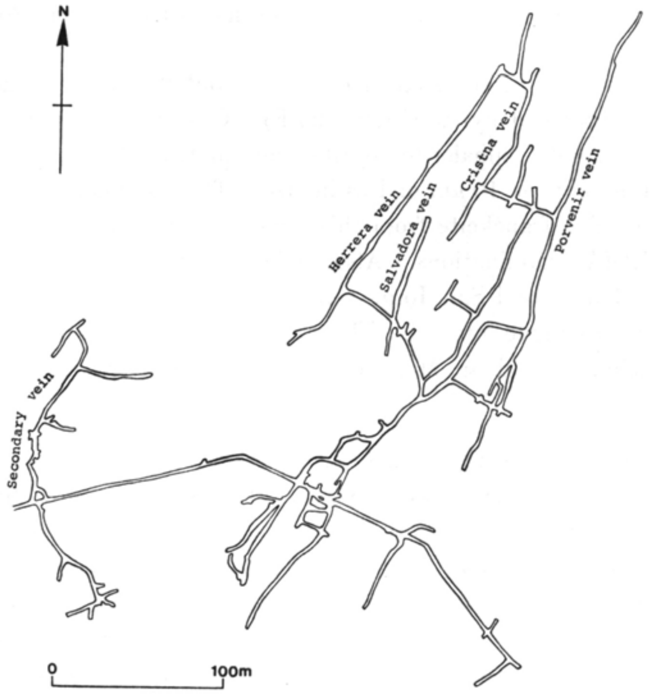

FIGURE 37. VEINS AT THE PORVENIR LEVEL (4,006 m above the sea level) OF THE MINCHIN SECTION IN THE AVICAYA MINE.

Stannite appears with cassiterite, pyrite, chalcopyrite, sphalerite and occasionally marcasite. It has kesterite molecule from 1.4% to 19.3%. FeS contents in sphalerite is a limited range from 18.5 to 22.1 mole %. Vivianite rarely occurs together with siderite in vug as latest products of the mineralization. Fluid inclusion in quartz and cassiterite from the ore veins of the Chualla section were studied by microscope with heating stage. Fluid inclusions in quartz are divided into three groups; the liquid rich two phase inclusion, the gas rich two phase inclusion and three phase inclusion with crystal. On the other hand those in cassiterite almost are a liquid rich two phase inclusion. The filling temperatures of the liquid rich two phase inclusions in both minerals range from 200° to 350°C.

There are tin bearing glacier and alluvial deposits in the Avicaya mining area. Such deposits contain gravel and sand of cassiterite, and the grade is approximate 0.01 to 0.03% Sn. They are now being dredged by the Estalsa mine as shown in Figure 21-F.

2.9. Trinacria Mine (Poopó)

This mine being 3 km south of Poopó town is located on west slope of steep mountain faced to the Poopó lake. Geology of the mine consists of slate, quartzite and sandstone of the Llallagua Formation having strike N10°W and dip 35°–50°E. Ore vein, 2 to 15 cm in width, with strike N30°E and dip 50°SE is found in slate. Ores from the mine are composed of pyrite, quartz and cassiterite, with some amounts of cylindrite, franckeite, jamesonite, arsenopyrite, stannite, galena, sphalerite, stibnite, siderite and alunite. Among them cylindrite is characteristic and occurs in the central portion of the vein as massive aggregate of about 15 cm wide in intimately association with sphalerite, franckeite and jamesonite etc. The mine is not working at the present time.

ORE MINERALS

The ore and gangue minerals occurred from the mines in the Oruro district are given in Table 3. Also, the kinds and amounts of minerals from each mine are shown in Table 4. In the table, size of circles indicates amount of the minerals. Quartz, cassiterite and pyrite occur from all the mines, but their quality and grain size are different. Especially, grain size of cassiterite varies as follows; that is, cassiterite from the Santa Fé, Morococala and Bolivar is microscopic size less than 5 μm; San José and Japo, fine and medium grains, 0.01– 0.3 mm in size and Huanuni and Avicaya; coarse grain, 0.1–5 mm in size. Cassiterite is closely associated with quartz and pyrite, and sometimes assembles to galena, arsenopyrite and stannite etc. It intimately associates with sphalerite and pyrite as seen in the ores from the Santa Fé and Morococala mines. Cassiterite from the San José mine also assembles to pyrite and sulfosalt minerals such as jamesonite, franckeite and sometimes zinckenite.

TABLE 3. ORE AND GANGUE MINERALS FOUND FROM THE MINES IN THE ORURO DISTRICT

Mineral name	Chemical formula	Mineral name	Chemical formula
Pyrite	FeS_2	Semseyite	$Pb_9Sb_8S_{21}$
Marcasite	FeS_2	Boulangerite	$Pb_5Sb_4S_{11}$
Arsenopyrite	$FeAsS$	Zinckenite	$Pb_9Sb_{11}S_{42}$
Pyrrhotite	$Fe_{1-x}S$	Meneghinite	$CuPb_{13}Sb_7S_{24}$
Chalcopyrite	$CuFeS_2$		
Galena	PbS	Cassiterite	SnO_2
Sphalerite	ZnS	Hydrocassiterite	$(Sn,Fe)(O,OH)_2$
Wurtzite	ZnS	Wolframite	$(Fe,Mn)WO_4$
Stibnite	Sb_2S_3	Hematite	Fe_2O_3
Stannite	Cu_2FeSnS_4	Quartz	SiO_2
Kesterite	Cu_2ZnSnS_4	Siderite	$FeCO_3$
Tetrahedrite	$(Cu,Ag,Fe,Zn)_{12}Sb_4S_{13}$	Fluorite	CaF_2
Bismuthinite	Bi_2S_3	Sellaite	MgF_2
Native bismuth	Bi	Barite	$BaSO_4$
Cylindrite	$FePb_3Sb_2Sn_4S_{14}$	Anglesite	$PbSO_4$
Franckeite	$FePb_6Sb_2Sn_2S_{14}$	Alunite	$(K,Na)Al_3(SO_4)_2(OH)_6$
Incaite	$FePb_4Sb_2Sn_4S_{14}$	Jarosite	$KFe_3(SO_4)_2(OH)_6$
Teallite	$PbSnS_2$	Apatite	$Ca_{10}(F,OH)_2(PO_4)_2$
Stephanite	Ag_5SbS_4	Vivianite	$Fe_3(PO_4)_28H_2O$
Pyrargyrite	Ag_3SbS_3	Phosphophyllite	$Zn_2(Fe,Mn)(PO_4)_24H_2O$
Miargyrite	$AgSbS_2$	Wavellite	$Al_3(PO_4)_2(OH)_35H_2O$
Andorite	$PbAgSb_3S_6$	Monazite	$(Ce,La,Y,Th)PO_4$
Freieslebenite	$AgPbSbS_3$	Tourmaline	$NaFe_3Al_6B_3Si_6O_{27}(OH)_4$
Chalcostibite	$CuSbS_2$	Topaz	$Al_2SiO_4(F,OH)_2$
Bournonite	$CuPbSbS_3$	Kaoline	$Al_2Si_2O_5(OH)_2$
Jamesonite	$FePb_4Sb_6S_{14}$	Sericite	$KAl_2Si_3AlO_{10}(OH)_2$
Plagionite	$Pb_5Sb_8S_7$		

Stannite is found in the ores from the San José, Avicaya and Huanuni mines etc. It occurs generally microscopically in irregular form. From the San José mine, it occurs in intimate ssociation with franckeite, pyrite, cassiterite, arsenopyrite and jamesonite, and sometimes with zinckenite and chalcopyrite. Stannite from the Avicaya and Huanuni mines usually occurs together with cassiterite and quartz. Sphalerite, arsenopyrite and galena are commonly found in the Santa Fé, Morococala and Bolivar mines etc., and they associate with pyrite, cassiterite and other ore minerals. Marcasite is a common mineral generally crystallized at late stage of mineralization, but its amount is slight.

Sulfosalt minerals such as jamesonite, franckeite, andorite and zinckenite occur from the San José, Santa Fé, Huanuni and Bolivar mines. Jamesonite is very common mineral in the San José and Bolivar mines. It usually occurs as aggregate of acicular crystals, and megascopically shows lead gray in color. It from the San José mine occurs sometimes as euhedral or needle-like crystal in vug of the pyritic vein together with crystals of pyrite, quartz and zinckenite. Jamesonite commonly associates with franckeite and stannite in the San José, Huanuni and Santa Fé mines, and with sphalerite in the Bolivar mine. Franckeite which is one of characteristic minerals in Bolivian type tin deposits occurs from the San José, Huanuni, and Santa Fé mines. It is usually aggregate of foliated platy crystals with lead gray in color, and commonly occurs together with jamesonite, stannite and pyrite, sometimes with arsenopyrite, sphalerite and cassiterite. Especially, franckeite from the San José mine intimtely assembles with sulfide minerals such as pyrite, jamesonite, sphalerite, stannite, arsenopyrite and rarely chalcopyrite.

Table 4. Minerals Occurred from the Mines and Their Amounts

MINES MINERALS	SAN JOSE	JAPO	SANTA FE	MOROCOCALA	HUANUNI	CATAVI	AVICAYA	BOLIVAR	TRINACRIA
Tourmaline					○	∘	○		
Quartz	○	∘	○	○	◯	○	◯	○	○
Cassiterite	○	○	○	○	◯	○	◯	○	○
Wolframite						∘			
Pyrite	◯	◯	◯	◯	∘	○	○	○	○
Jamesonite	○		∘		∘			◯	
Franckeite	○		∘		∘	∘			∘
Cylindrite									∘
Andorite	∘								
Zinckenite	∘								
Stannite	○		∘		∘	∘	∘	∘	∘
Chalcopyrite	∘		∘		∘		∘	∘	
Sphalerite	∘	∘	○	○	∘	○	∘	○	○
Galena	○		∘	○	∘		∘	○	∘
Pyrrhotite	○					∘	○		
Arsenopyrite	○		∘	∘	∘	∘	∘		
Marcasite	∘		∘	∘	∘	∘	∘	∘	
Stibnite				∘					∘
Bismuthinite						∘			
Fluorite			∘		∘		∘		
Apatite	∘		∘	∘	∘	∘	∘		
Siderite				∘	∘	∘	∘	∘	∘
Alunite	∘						∘		
Vivianite				∘	∘		∘		
Jarosite							∘		
Kaolinite	∘				∘		∘		
Sericite			∘	∘	∘				

Massive ore colored in lead gray, which is composed of aggregate of acicular crystal up to 5 cm long, occurs in fairly amounts from the Bolivar mine. The crystal was named franckeite, but it was proved to be jamesonite by X-ray and EPMA studies. Cylindrite occurs from the Trinacria mine near Poopó town, and intimately associates with sphalerite, franckeit, stannite and pyrite etc.

Apatite is common gangue mineral associated with quartz and cassiterite. It from Huanuni mine occurs as an euhedral crystal of 0.5 to 5 cm in size. Vivianite and siderite crystallized at late stage of mineralization occur as euhedral crystal in vug at central portion of some veins of the Huanuni and Morococala mines.

As listed up in Table 3 and 4, a number of minerals occur from the mines in the Oruro district. The ores composed of them contain many kinds of metals such as tin, tungsten, silver, lead, zinc, bismuth, antimony, manganese and iron etc. Occurrence of such polymetallic ores is characteristic of the deposits in the district (Ahlfeld, 1936, Kelly and Tourneaure, 1970). Appearance of complex sulfosalt minerals such as franckeite, cylindrite, incaite, andorite, freieselebenite, bournonite, jamesonite, stannite, kesterite and tetrahedrite is peculiar as polymetallic type mineralization in the district. In addition to ore minerals as above, occurrence of phosphate minerals such as apatite, vivianite and phosphophyllite, halogen bearing minerals such as fluorite and tourmaline and sulfate minerals as barite, alunite and jarosite also is significant as a characteristic mineralization in the district.

Mineralization of Ore Deposits

As mentioned above, there are two kinds of tin mineralization in the eastern cordillera. One was generated by plutonism formed granitic batholith during late Triassic to Jurassic related with Variscan (Hercynian) orogeny. Other was induced by igneous activity of acidic hypabyssal rocks such as adamellite porphyry and quartz porphyry in Miocene age related with Andes orogeny. The former produced deep seated quartz vein with cassiterite, wolframite and small amounts of sulfide minerals, corresponding to a common hypothermal tin-tungsten bearing quartz vein as often found in the granitic region. On the other hand, the latter formed cassiterite-pyrite-quartz veins associating with minerals contained many metals of tin, tungsten, silver, and some amounts of antimony, zinc and lead etc. They are extensively developed from the middle to southern area of the eastern cordillera, in which the Oruro district studied by the present authors has a lot of typical such deposits. A number of minerals such as listed up in Table 4 were found from these deposits. Occurrence of such many minerals is characteristic of this type deposits, and it is notable that both minerals of high and low temperatures coexist together with intimate association in ores. That is, in the minerals formed by mineralization at high temperature, there are cassiterite, wolframite, pyrrhotite, arsenopyrite, stannite, apatite and tourmaline etc. meanwhile as low temperature minerals, stibnite, wurtzite, marcasite, andorite, franckeite, jamesonite, siderite, barite, vivianite, kaoline, sericite, alunite and jarosite etc. From data on mineral assemblages and ore textures, it is thought that they were rapidly precipitated during a finite time in limited zone from ascending ore solution generated by action of acidic magma. Such process called telescoping is also a peculiarity of this type deposits. Sequence of mineralization formed such ores and veins is important to make clear ore genesis. Its general idea summarized about those of all the mines in the Oruro district is shown in Figure 38. There are two types of tin ores, quartz and pyritic ores. As seen in Figure 38, cassiterite is mainly associated with quartz

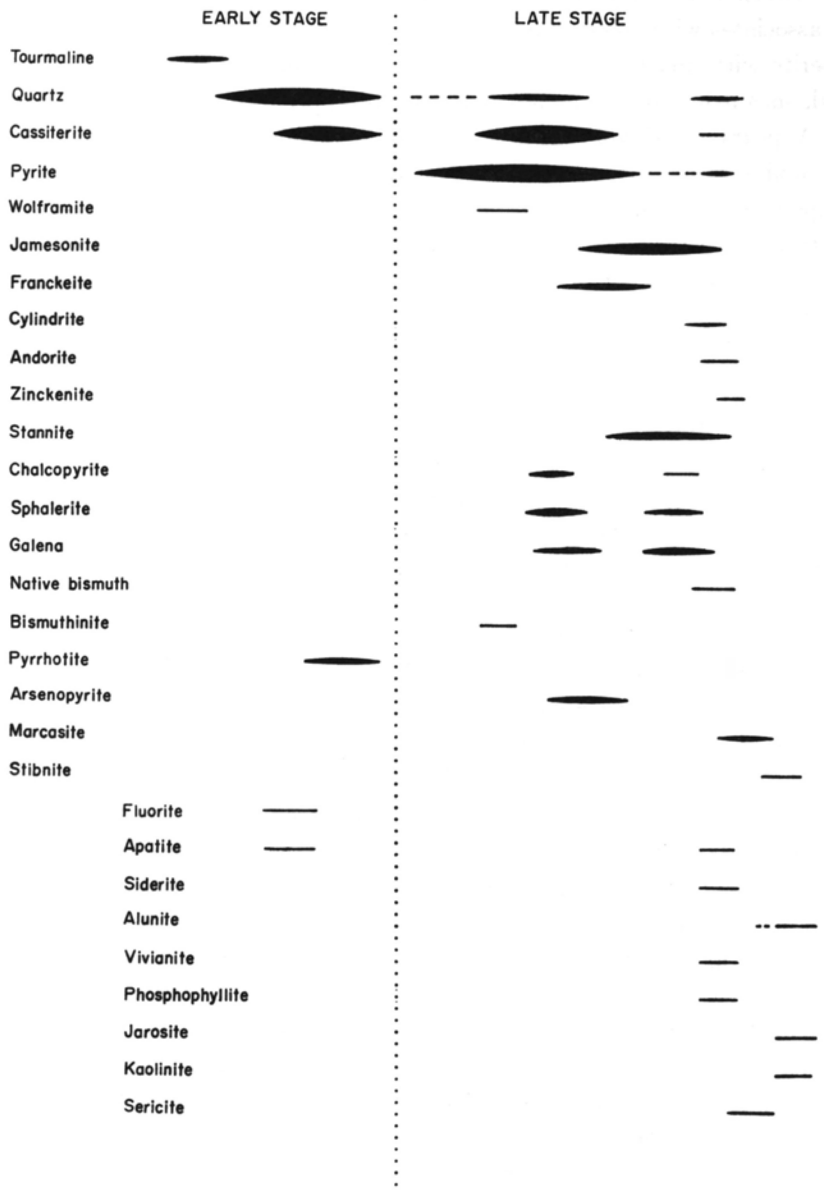

FIGURE 38. MINERALIZATION SEQUENCE COMPILED BY DATA OBTAINED FROM ALL THE MINES IN THE ORURO DISTRICT.

and pyrite. Therefore, quartz and pyrite mineralizations are important for tin ores. Quartz assembled with cassiterite is found in the Huanuni and Avicaya mines, and on the other hand pyrite with cassiterite occurs from the San José, Santa Fé and Morococala mines. According to Figure 38, main quartz mineralization associated with cassiterite is earlier stage than that of pyrite with cassiterite, but the relationship between both mineralization is not made clear sufficiently. Because pyrite often associates with some amounts of quartz, these relation become to complicate. Cassiterite with quartz formed by the early mineralizations occurs in coarse grained crystal, meanwhile it accompanied by pyrite appears as fine grain as microscopic size. Appearance of wolframite is rare, but it associates with quartz, cassiterite, pyrite and bismuthinite etc. in the ore from the Catavi mine. Stannite is also accompanied with both type ores of pyrite and quartz, but crystallization time of stannite is later than that of quartz and pyrite. The characteristic of this type deposits is to occur a lot of sulfosalt minerals such as jamesonite, franckeite, cylindrite, zinckenite, boulangerite, bournonite and andorite etc. They are generally produced during late stage mineralization as shown in Figure 38. In this type deposits, it is also characteristic of appearance of phosphate minerals such as apatite, vivianite and phosphophyllite and halogen bearing minerals such as tourmaline and fluorite. The hydrothermal solution are thought to become acidic at late stage of the mineralization, because some minerals which are considered to produce from acidic aqueous solution at low temperature and pressure such as wurtzite, marcasite, kaoline, alunite and jarosite etc. occur frequently in fairly amount. Besides cassiterite, stannite, franckeite and cylindrite, tin minerals such as mawsonite and stannoidite are not yet found until now. Copper minerals such as chalcopyrite and bornite appear, but amount of them is very small. These fact is quite different with such ore deposits of same type in Japan as Akenobe, Ikuno, Ashio and Nishizawa mines from which chalcopyrite and bornite occur as principal ore minrals. Somewhat similarly, sphalerite and galena are smaller amounts than those from same type mines in Japan as mentioned above, but they are found fairly more amounts than chalcopyrite in the Oruro district.

The mineralization of the Oruro district are in intimate association with igneous intrusion in Miocene age as mentioned above. The tin bearing deposits are often formed in or around a stock and neck of porphyry. They are divided into four types by the occurrence of igneous rocks, the distance between intrusive rocks and ore deposits and the grade of erosion as shown in Figure 39. The ore veins of A type in Figure 39 occur mostly in stock or neck of igneous rocks, and the ore deposits of the San José and Catavi mines belong to this type. Upper part of the Catavi mine becomes network of veinlets, and was mined by open pit. The deposits of the Japo, Santa Fé and Morococala mines, as shown in Figure 39-B, arrange around stock or neck of porphyry which is hydrothermally altered and contains tin veins of small scale. The veins in these mines are mostly thin in width, and the

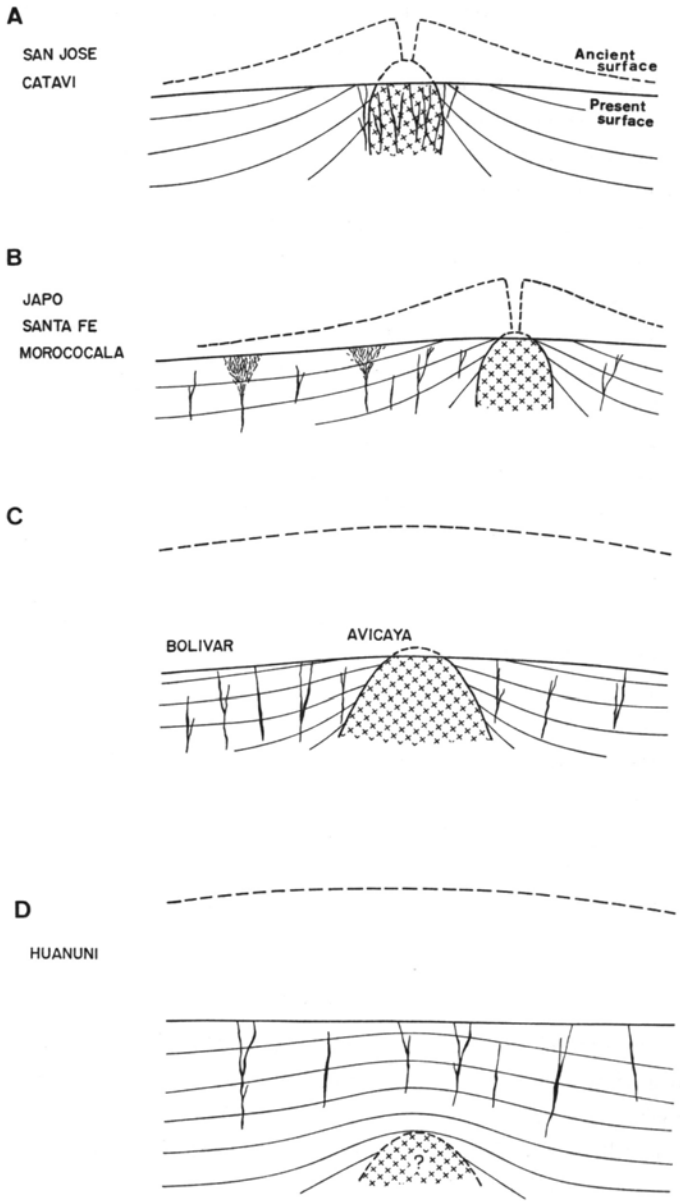

FIGURE 39. SCHEMATIC MODEL OF THE TIN DEPOSITS IN THE ORURO DISTRICT.

upper part of some of them changes to funnel and pipe-shaped network bodies as seen in the figure. The network fissures formed funnel shaped ore bodies are thought to occur at shallow place near surface. The deposits of C type, for example, the Avicaya and Bolivar mines, develope around stock of porphyry which intrudes such depth as can form coarse grained hypabyssal rock (adamellite porphyry) roughly similar to plutonic rock. They were naturally produced more deeper place than that of type A and B. In the case of type C, the mineral zoning is found in the Avicaya and Bolivar mining area. Ore veins of type D correspond to those of the Huanuni mine. There is neither stock nor neck, but the intrusive body is possible to be latent as stock as supposed in the figure. The veins of this type are possible to have been formed at relatively deeper place than those of the types A and B.

The area of the Avicaya and Bolivar mines is divided into three mineralization zonesby the distance from the Chualla Grande stock. The most inner zone in which the veins of the Avicaya, Totoral and Martha mines, near the Chualla Grande stock are ore formed is characteristic of coarse grained cassiterite, pyrrhotite, tourmaline and large amount of quartz. In the middle zone in which is most principal veins of the Bolivar mine, fine grained cassiterite, pyrite, sphalerite and jamesonite occur as peculiar minerals. The outer zone in which a part of veins in the Bolivar mine and some veins in the northwestern part in the area occur, is characterized by appearance of a lot of galena, stibnite and silver minerals. This zonning of the mineralization will be described in more detail in the other paper of this Report. There is another stock of China Chualla, but it is no relation with the mineral zoning mentioned above. These evidence suggests that the ore solutions were originated from the Chualla Grande stock or by the igneous activity related to this stock and that the distance from the Chualla Grande stock controls mineral distribution due to differences of the physical and chemical conditions of ore solutions.

As described above, there are many evidences characterizing xenothermal mineralization such as polymetallic mineralization, telescoping ores, mineral zoning intimate relationship with igneous activity, especially with sub-volcanic magmatism. Therefore, the ore deposits in the Oruro district are thought to be the typical model of xenothermal deposits as have been said already.

SUMMARY

1) The geology of the eastern cordillera in Bolivian Andes is composed of Paleozoic (Cambrian to Permian) formations mainly, and Mesozoic (Cretaceous) and Tertiary (Pliocene) formations partly. The area of tin-bearing metallic mineralization in the cordillera consists of Ordvician and Silurian formations which are principally composed of quartzite, sandstone, graywacke and slate, and their alternation. They were conspicuously deformed by Variscan and Andes orogenies, and consequently folded and faulted distinctly.

2) There are also found igneous intrusions such as granodiorite, adamellite porphyry and quartz porphyry etc. Among them, plutonic rocks of granodiorite and adamellite generally occur in the nothern part of the eastern cordillera as batholith and lacolith, meanwhile the intrusive rocks found in the middle and southern parts of the cordillera are mostly hypabyssal type such as adamellite

porphyry and quartz porphyry except Karikari plutonic rock near Potosi, and appear in stock, dyke and neck etc.

3) K-Ar ages of acidic plutonic rocks occurred in the nothern part of the eastern cordillera are from 150 Ma to 221 Ma, corresponding to from late Triassic to Jurassic. On the other hand, the igneous rocks in the middle and southern parts of the cordillera have K-Ar ages from 13 Ma to 26 Ma, corresponding to from late Oligocene to Miocene. Also, dacite lava and tuff of the Morococala Formation show absolute ages of 6 Ma to 9 Ma, indicating to Pliocene.

4) The mineralizations produced metallic ore deposits found in th eastern cordillera have been carried out in two ages of Jurassic and Miocene accompanied by igneous actions of granitic rock and porphyry, respectively. The older mineralization has formed deep seated veins which belong to pneumatolytic and hypothermal types. Meanwhile the younger has occurred polymetallic shallow seated veins with telescoping ores of the xenothermal type.

5) The geology of the Oruro district consists of the Cancañiri, Llallagua, Uncia and Catavi Formations of the Silurian system. They are composed of quartzite, slate, graywacke and their alternation, and were folded and faulted distinctly. Also they were intruded by neck and stock of adamellite and quartz porphyries, during Miocene age (13 to 26 Ma). There is also found the Morococala Formation (Pliocene, 6 to 9 Ma) consisting dacite lava and tuff which have uncomformable relation with the underlying Silurian formations.

6) The tin deposits of the San José, Japo, Santa Fé, Morococala, Huanuni, Catavi, Avicaya and Bolivar mines in the Oruro district occur as polymetallic veins with such a number of minerals as pyrite, cassiterite, wolframite, stannite, jamesonite, franckeite, cylindrite, zinckenite, stibnite, pyrrhotite, sphalerite, andorite, bismuthinite, native bismuth, quartz, tourmaline, siderite, fluorite, apatite, sericite, alunite, jarosite, kaoline, vivianite and phosphophyllite etc. Their mineralization are in intimate association with stock and neck of porphyry in the Miocene age.

7) These ore deposits are divided into four types according to the mode of occurrence of related igneous rock, the distance between intrusive rock and ore deposits and the grade of erosion, as shown in Figure 39. In type C of the figure, there is found mineral zoning as seen in Avicaya and Bolivar area. Also veinlet pattern and funnel shaped ore bodies of type B as seen in the Santa Fé and Morococala mines suggested that their fractures were formed at shallow depth near surface.

8) A number of minerals occurs from these mines in the Oruro district as listed up in Table 3 and mineralization sequence of them is shown in Figure 38. Cassiterite occurs in intimate association with quartz (Huanuni and Avicaya mines) and pyrite (San José, Santa Fé and Morococala mines), which were crystallized at earlier stage of mineralization. On the other hand, sulfosalt minerals such as

jamesonite, franckeite, zinckenite, cylindrite and andorite etc. were formed at later stage comparatively.

9) The mineralization formed these deposits is also characterized by appearance of phosphate minerals such as apatite, vivianite and phosphophyllite etc. and halogen bearing minerals such as tourmaline and fluorite. Also appearance of wurtzite, marcasite, kaoline, alunite and jarosite suggests that an ascending solution at late stage of mineralization was acidic and low temperature.

10) It indicates telescopic process that high temperature minerals such as cassiterite, wolframite, tourmaline, pyrrhotite and arsenopyrite etc. coexist with low temperature minerals such as stibnite, jamesonite, wurtzite, marcasite, siderite, barite and alunite etc., in limited vertical zone of the veins. There are many evidences characterizing the xenothermal mineralization such as polymetallic crystallization, telescopic ores, mineral zoning and intimate relationship with igneous activity, especially with sub-volcanic magmatism. Therefore, the ore deposits in the Oruro district are thought to be a typical model of xenothermal deposits.

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