GEOLOGICAL STUDY ON THE POLYMETALLIC ORE DEPOSITS IN THE POTOSI DISTRICT, BOLIVIA

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Abstract

The Potosi district located at central portion in the metallic mineralization belt of the eastern cordillera of bolivian Andes is composed of the Ordovician, Silurian, Cretaceous and Tertiary systems with some igneous intrusions, such as granite and dacite etc. There are many polymetallic ore deposits of hydrothermal fissure filling type in the district. They occur in Ordovician slate, and Miocene dacitic pyroclastics such as tuff and tuff breccia, and dacite stock, and are composed of polymetallic ore minerals such as sphalerite, pyrite, galena, cassiterite, wolframite, chalcopyrite, stannite, tetrahedrite, stibnite, bismuthinite, fizelyite, semseyite, pyrargyrite and boulangerite etc. and gangue minerals such as tourmaline, quartz, alunite, kaoline, sericite and siderite etc. The ore veins form banding as seen in the Potosi mine. In this case cassiterite occurs as thin crustified band crystallized after principal pyrite mineralization at early stage. It associates intimately with pyrite, sphalerite, chalcopyrite, stannite and arsenopyrite etc. Silver bearing minerals such as fizelyite, pyrargyrite, semseyite, boulangerite, tetrahedrite appear in close association with galena, sphalerite, pyrite and jamesonite etc., and are produced in general at the middle stage of the mineralization. Stibnite from the Caracota mine occurs in massive form, granular aggregate and acicular crystals. It is quite noteworthy that the paragenesis of stibnite and ferberite is found in a druse of quartz in the vein. In this case, acicular crystals of stibnite overgrow on tabular crystals of ferberite, and sometimes stibnite needles stick vertically into a crystal face of ferberite.

Ore deposits of the Colavi mine, which are quite different with hydrothermal fissure filling type as mentioned above, develop as stratabound (Manto) form in the Cretaceous formation consisting of red sandstone and dacitic tuff. There are found six ore beds dipping gently in about 80 m thick of sandstone of the Conufillos Member of Cretaceous in the mine. They have a thickness from 0.8 to 1.0 m, and are mainly composed of pyrite and cassiterite with quartz, siderite, kaoline and barite etc. Cassiterite appears as pale brown colored powder or aggregate of very fine grain of submicroscopic size, less than 1.0 μm. Although the genesis on them is not made clear whether such Manto type tin deposits are syngenetic or not, there may be a possibility that they are sedimentary tin deposits formed at the Cretaceous age.

Introduction

Mineral resources are very important in Bolivia economically. The mining for metallic ores is the most principal industry in this country. The production of metallic ores such as tin, tungsten, lead, zinc, copper, silver, antimony, bismuth and cadmium for 7 years from 1975 to 1981 are given in Table 1. These metallic ores of Bolivia are mainly produced from the mines located in the eastern

TABLE 1. PRODUCTIONS OF METALLIC ORES FROM BOLIVIA (Tons in metals).

	1975	1976	1977	1978	1979	1980	1981
Tin	31,952	30,315	33,740	30,881	27,648	27,271	29,780
Zinc	48,774	53,014	63,508	59,619	46,141	50,260	47,029
Lead	17,967	19,200	18,937	18,039	15,359	17,225	16,757
Antimony	16,089	17,015	16,341	13,336	13,019	15,465	15,301
Cpper	6,218	5,101	3,191	2,833	1,797	1,882	2,637
Tungsten	2,311	3,132	3,063	3,073	3,114	3,359	3,449
Bismuth	622	612	651	307	10	11	11
Silver	160	169	181	195	179	190	212
Cadmium	-	-	135	108	156	-	-

(Ministerio de Mineria y Metalurgia, Bolivia)

FIGURE 1. LOCATION MAP OF PRINCIPAL CITIES AND RAILWAYS IN BOLIVIA.

cordillera of Andes range. In the many cases, they intimately associate with each other, and form polymetallic ores which contain a lot of metals such as tin, tungsten, zinc, lead, antimony, bismuth, gold and silver etc. Such polymetallic ores occur from hydrothermal ore deposits formed in the eastern cordillera. The

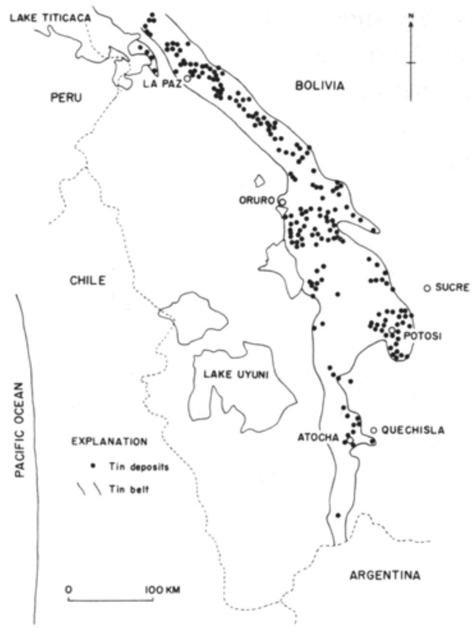

FIGURE 2. TIN MINERALIZATION ZONE FOUND IN EASTERN CORDILLERA OF BOLIVIAN ANDES (After Claure and Minaya, 1979).

distribution area of the ore deposits is in general divided into the four districts of La Paz, Oruro, Potosi and Quechisla (Atocha) (Figure 1). They, especially tin deposits, are widely distributed along the mountain range of the eastern cordillera from the north border with Peru to the south end bordered with Argentina as shown in Figure 2. The ore deposits in the Oruro district were investigated by us in 1979 and 1980. The results of our investigations were reported in some publications such as Sugaki *et al.* (1981a, b, c, d). The investigations of this time were focussed on the polymetallic ore deposits in the Potosi district and the field studies were carried out in 1981 and 1983.

The ore deposits in the Potosi district except Colavi Manto type deposit are formed by polymetallic mineralizations of hydrothermal solutions originated by acidic igneous activities. Some deposits in the district, especially those of Potosi mine, belong to so-called bolivian type tin deposits which correspond to a xenothermal type formed under wide range conditions from high to low temperatures at shallow depth as same as those in the Oruro district as described by Sugaki *et al.* (1981a, b). The metallic ores from such ore deposits are telescopic, and consist of many kinds of ore minerals such as cassiterite, wolframite, stannite, sphalerite, wurtzite, galena, stibnite, jamesonite, bournonite, boulangerite, bismuthinite, arsenopyrite, chalcopyrite, pyrite, marcasite, tetrahedrite, semseyite, pyrargyrite, etc. To make clear the process and conditions of ore formation on such ore deposits, it is very significant to make study on the occurrence, assemblages and paragenesis of ore and gangue minerals, ore textures, sequences of mineralizations, fissure pattern, hydrothermal rock alterations, and relations between mineralizations and igneous activities etc. This investigation has been done for the purpose making clear geological and mineralogical problems as stated above, consequently genesis of polymetallic hydrothermal deposits in the eastern Andes of Bolivia.

In the Potosi district there are the metallic mines of Unificada del Cerro de Potosi (Potosi, tin and silver), Porco (zinc and lead), Kumurana (tin and silver), Caracota (antimony) and Colavi (tin) etc. as shown in Figures 3 and 4. This district occupies area of about 80 km north-south and about 50 km east-west. Potosi city, a population of about 80,000, which is the center in the district stands at 3,900 m elevation. Potosi was an old city founded by the Spaniards on April 10th, 1545, after they had discovered Indian mine working at Cerro Rico, the hill at whose foot it stands. Huge amounts of silver were once produced from the hill. Early in the 17th century Potosi had a population of 150,000. It is located 420

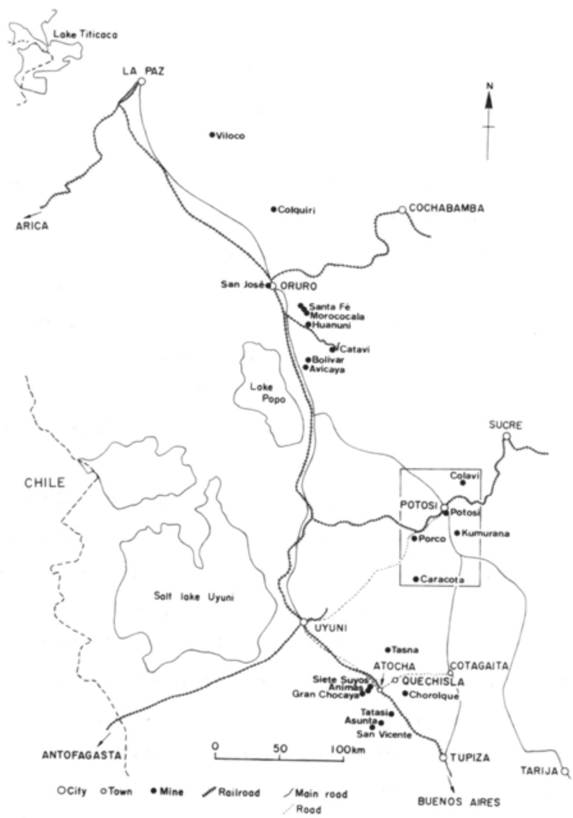

FIGURE 3. MAP SHOWING THE LOCATION OF THE POTOSI DISTRICT INVESTIGATED.

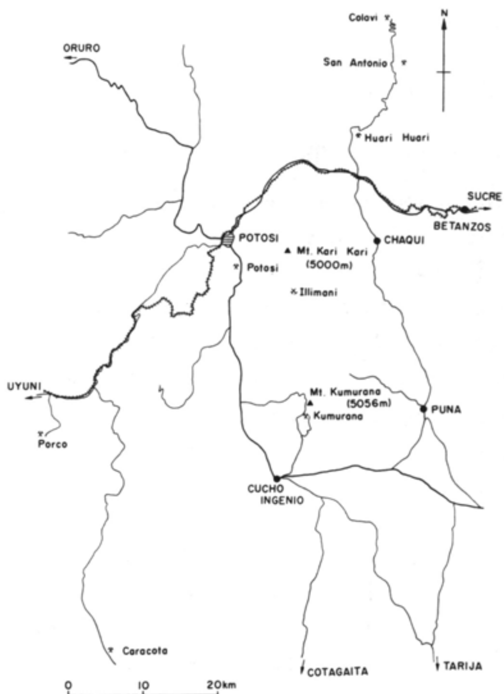

FIGURE 4. LOCATION MAP OF MINES IN THE POTOSI DISTRICT.

km (direct distance) south-east of La Paz. We can use train, bus and airplane when visiting Potosi from La Paz. Railroad distance from La Paz to Potosi via Oruro is 625 km. Also, it needs for 12 hours (570 km) from La Paz to Potosi via Oruro by bus. Potosi occupies traffic important position. Many main roads develop from Potosi to Sucre, Oruro, Uyuni and Tarija etc. But, they are no pavement except the road between La Paz and Oruro (240 km). There are many bus systems between Potosi and these cities; to Sucre, the official capital of Bolivia, 175 km about 5 hours by bus, and to Oruro about 6 to 7 hours by bus.

The climate of the Potosi district is annually divided into dry and rainy (wet) seasons of which distinction is obvious. Dry season is from April to October, and rainy season, November to March. Total amounts of rain are only 370 to 670 mm per year in the Potosi district. However, it almost falls during the rainy season (40–140 mm per month) and often floods as cutting off traffic road. Therefore field works had to be done during winter time, dry season (0–20 mm per month, especially 0–3 mm in July or August). Daily temperature change also is very hard from −6°C (night or morning) to 17°C (daytime) at the Potosi district in July and August.

Field survey at elevations of 4000 m or above usually was very difficult because of dilute oxygen, and the underground of the mines sometimes becomes more oxygen-lack state so that we can not use gas lighter for smoking.

The geological and mineralogical data obtained by the field survey on the ore deposits in the Potosi district in 1981 and 1983 are described in this paper.

TOPOGAPHY

The Potosi district is located at a central portion of the eastern cordillera of Andes in Bolivia, and consists in mountain lands which have elevations from 3,500 m to 5,000 m. Topography of the district is roughly divided into 3 sections of southern, middle and northern areas. The southern area of the district is generally composed of steep sloped mountains (Figure 5-A) of 4,000 to 5,000 m elevation, eroded by well developed valleys running to north, mostly consisting of the Ordovician system. Meanwhile the middle area including Potosi city consists of gentle sloped hills of 3,500 to 4,800 m elevation, which are formed by the younger formations of Cretaceous and Tertiary, except a few steep mountains of igneous intrusions such as Cerro Rico de Potosi (4824 m) and Cerro Kumurana (5056 m) etc. There is found a feature of eroded old caldera basin (Figures 5-B, 6-A and B) as pointed out by Francis *et al.* (1981) showing an oval-like form, 40 km in north-south length and 25 km in east-west, in the middle area. Kari Kari massif occupies a central portion of the caldera. At western side of Potosi city, a fine landscape of mesa topography is seen as a result covered unconformably with dacitic ignimbrite of the Los Frailes or Tollocci Formations (Rivas and Carrasco, 1968) of Miocene on the Cretaceous and Ordovician systems (Figure 6-C and D). And the plateau feature extends to the western part of the area because of development of the Los Frailes and Tollocci Formations.

The northern area which is composed of the Cretaceous and Ordovician systems is mountain lands (Figure 5-B and C) of 3,400 to 4,500 m elevation, eroded steeply by valleys as same as those of the southern area.

GEOLOGY

A geological map in the Potosi district is shown in Figure 7. It is based on the map of Rivas and Carrasco (1968), and Murillo *et al.* (1968). As seen in Figures 7 and 8, geology of the district is composed of the formations of Paleozoic (mostly Ordovician and partly Silurian), Mesozoic (Cretaceous), Tertiary (Miocene), and Quaternary. There are also found intrusive igneous rocks such as dacite, quartz porphyry and granite etc. in the district.

The Ordovician system develops in northern and southern areas of the district. It consists of mostly slate and partly quartzite. Slate is black or dark gray in color and shows obvious bedding with distinctly slaty cleavage (Figure 9-A). It has quartz, 2 to 5 μm in size, sericite and carbonaceous matter etc. in clayey matrix under microscope. Quartzite is massive, hard and compact, and shows pale gray in color and no bedding. It is composed mostly of aggregate of

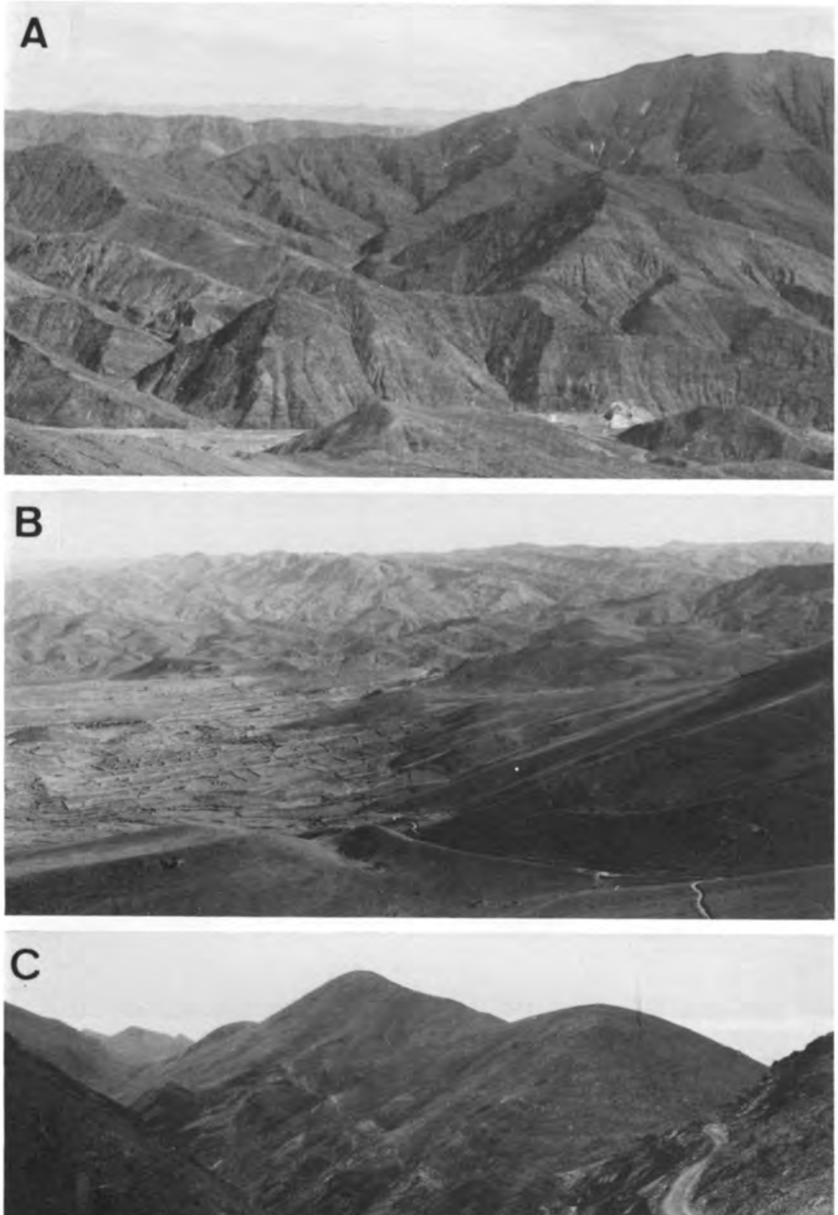

FIGURE 5. TOPOGRAPHY IN THE POTOSI DISTRICT.
A : Mountain range of Ordovician system near the Caracota mine. B : Slope of Kari Kari massif (right side) and Ordovician mountain range (upper part). C : Ordovician mountain range near the Huari Huari mine.

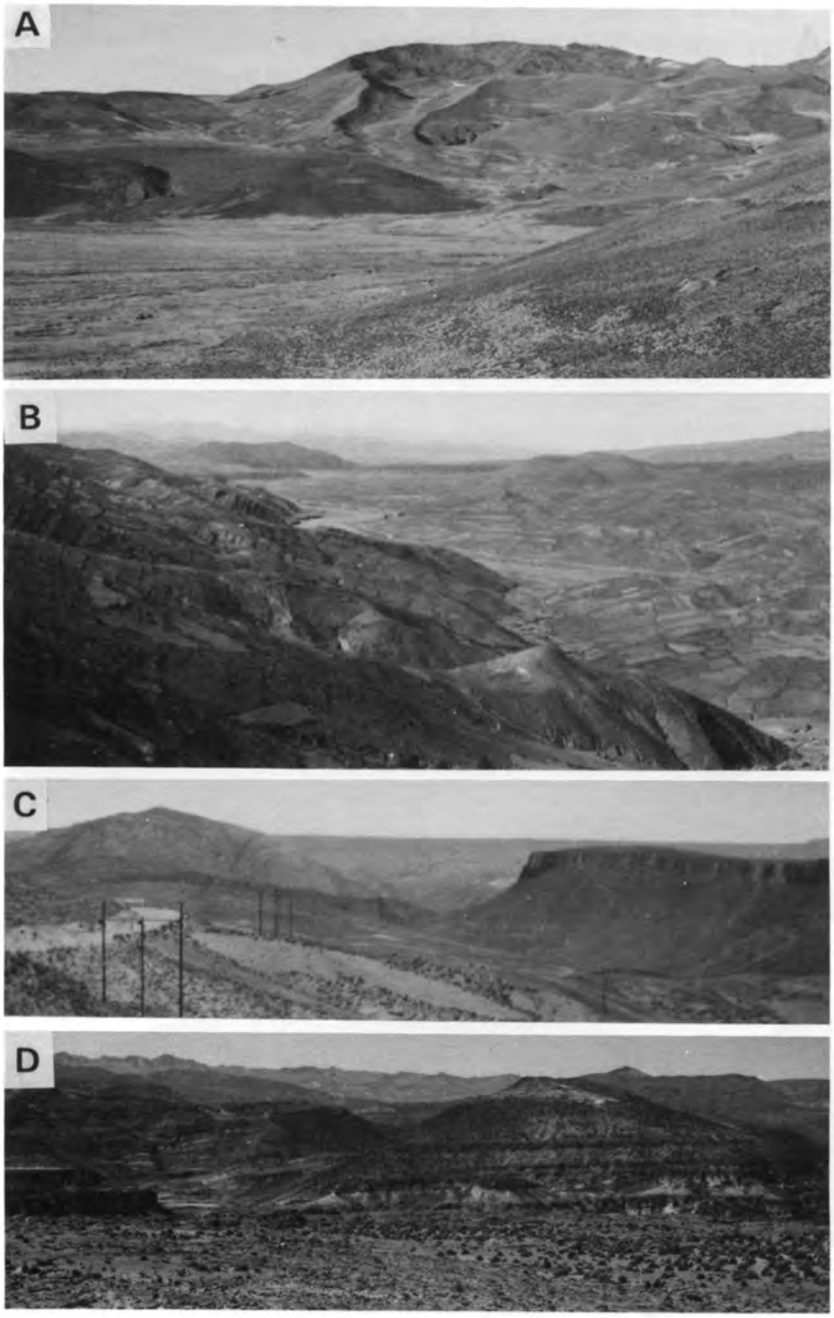

FIGURE 6. TOPOGRAPHY OF THE MIDDLE AREA IN THE POTOSI DISTRICT.
A : Kari Kari massif. B : A view of Kari Kari mountains (left side) and eroded Ordovician range. C, D : Distant view of flat plane of Tertiary system near the Porco mine.

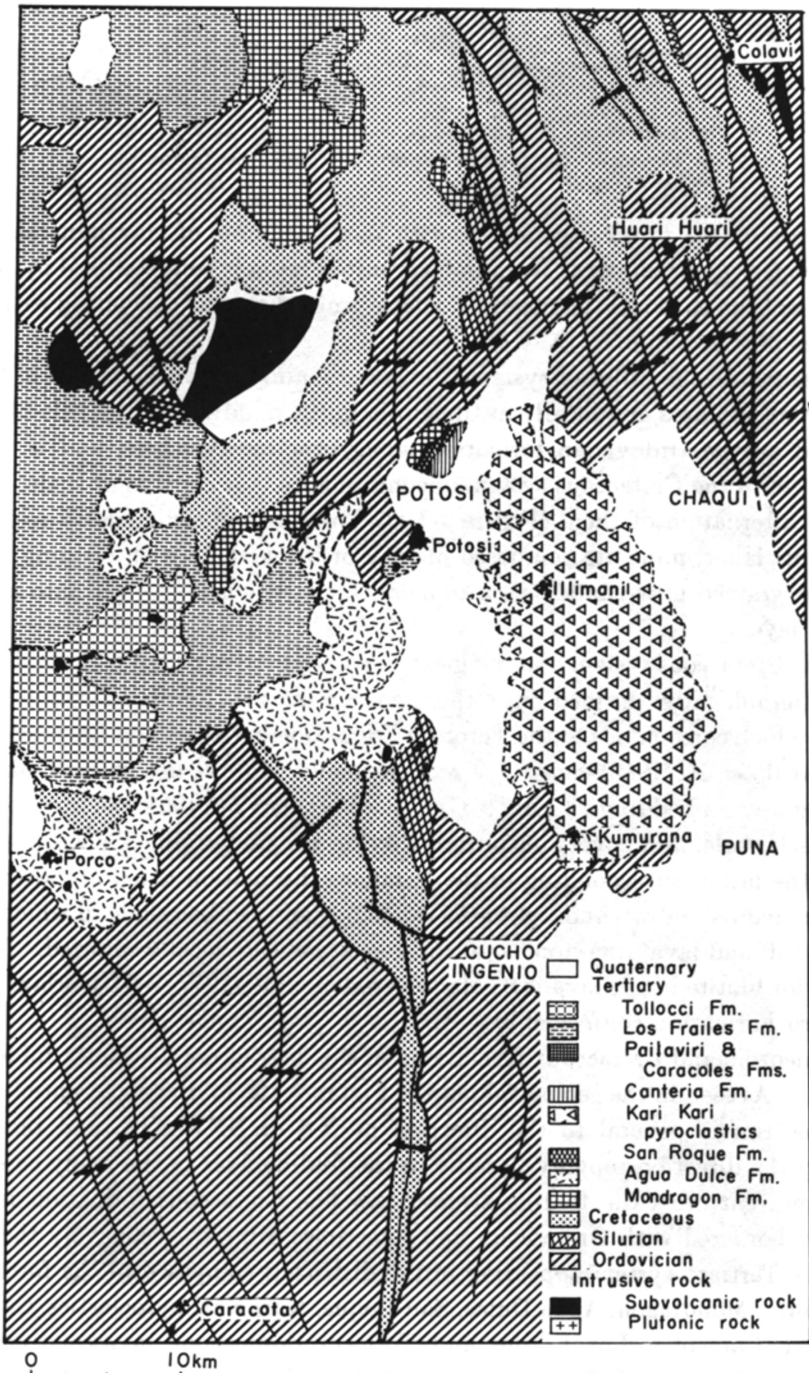

FIGURE 7. GEOLOGICAL MAP OF THE POTOSI DISTRICT.

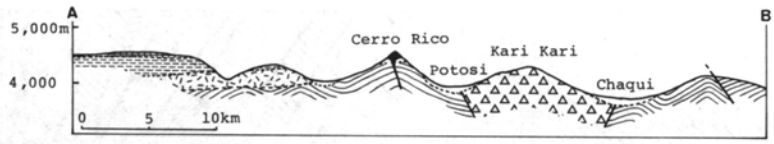

FIGURE 8. GEOLOGICAL SECTION OF THE POTOSI DISTRICT.

quartz grains, 0.1 to 0.2 mm in size, with small amounts of clay minerals under microscope. Quartzite near Kumurana granite pluton is recrystallized by contact metamorphism as mozaic aggregate of coarse grained quartz associating with small amounts of tourmaline.

Meanwhile the Silurian system is exposed mainly at northern part of Colavi in the northern area and locally at Chaguilla in the middle area as a belt-like form overlaid on the Ordovician formation along syncline structure, and is usually covered with the Cretaceous system unconformably. It consists of shale, quartzite and alternation of them (Figure 9-B). The Silurian sedimentary rocks near the Huari Huari mine are composed of gray or black shale with bedding fissility and fine grained gray sandstone, 2 to 5 cm thick, which is inserted into shale as several layers.

The Cretaceous system occurring extensively in the northern and middle areas is stratigraphically divided into the two formations, lower and upper. The former which corresponds to the Torotoro Formation by Rivas and Carrasco (1968) and Murillo *et al.* (1968) consists of red, green and white coarse grained sandstone showing a cross bedding (Figure 9-C). It sometimes has dark red conglomerate and black shale, and covers unconformably on the underlying Paleozoic system. While the latter corresponding to the Miraflores Formation is mainly alternation of green, reddish brown and light gray sandstone and reddish shale in which white dacitic tuff and lava, limestone and calcareous shale are locally inserted. The K-Ar age for biotite in the lava is 83 Ma (Evernden *et al.*, 1977). It overlays on the Torotoro Formation conformably.

Paleozoic and Cretaceous formations in the district are distinctly folded and faulted. As seen in the geological map of Figure 7, the folding axes, anticline and syncline, run in general to the direction of N-S or NNW-SSE, and the faults develop the direction roughly parallel to the folding axes in the many cases, but sometimes cut cross the folding structures. The Cretaceous formation is occasionally bordered with Ordovician and sometimes Silurian systems by the fault.

The Tertiary system appearing in the district is composed of the formations as follows: Mondragon, Agua Dulce, San Roque, Kari Kari pyroclastics, Canteria, Pailaviri, Caracoles, Los Frailes and Tollocci Formations in ascending order (Rivas and Carrasco, 1968; Murillo *et al.* 1968). They belong to the Miocene age. Among them, the Mondragon Formation occurs at northern or werstern parts of Potosi and in the northern area of the district, and is composed of brown coarse

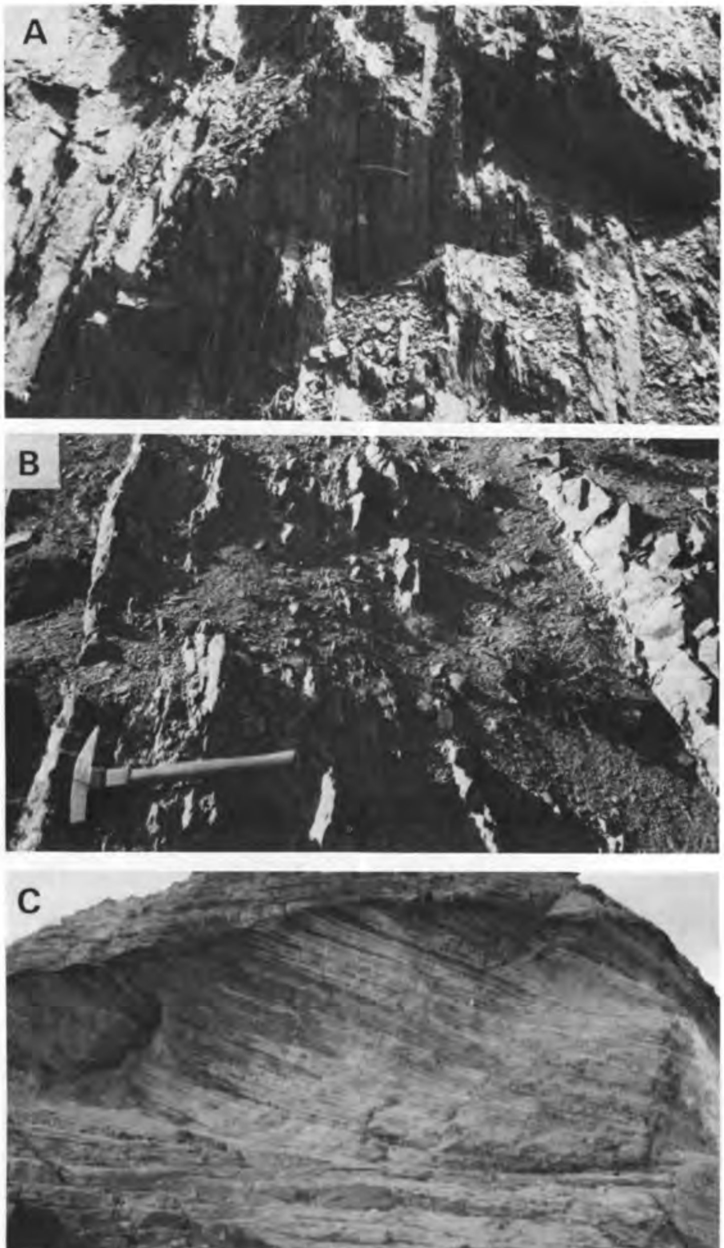

FIGURE 9. OCCURRENCE OF SOME PALEOZOIC AND MESOZOIC FORMATIONS.
A : Ordovician slate at 4 km west from Potosi city. B : Silurian shale with thin layers of sandstone near the Huari Huari mine. C : Cretaceous sandstone showing cross bedding at Yoccalla.

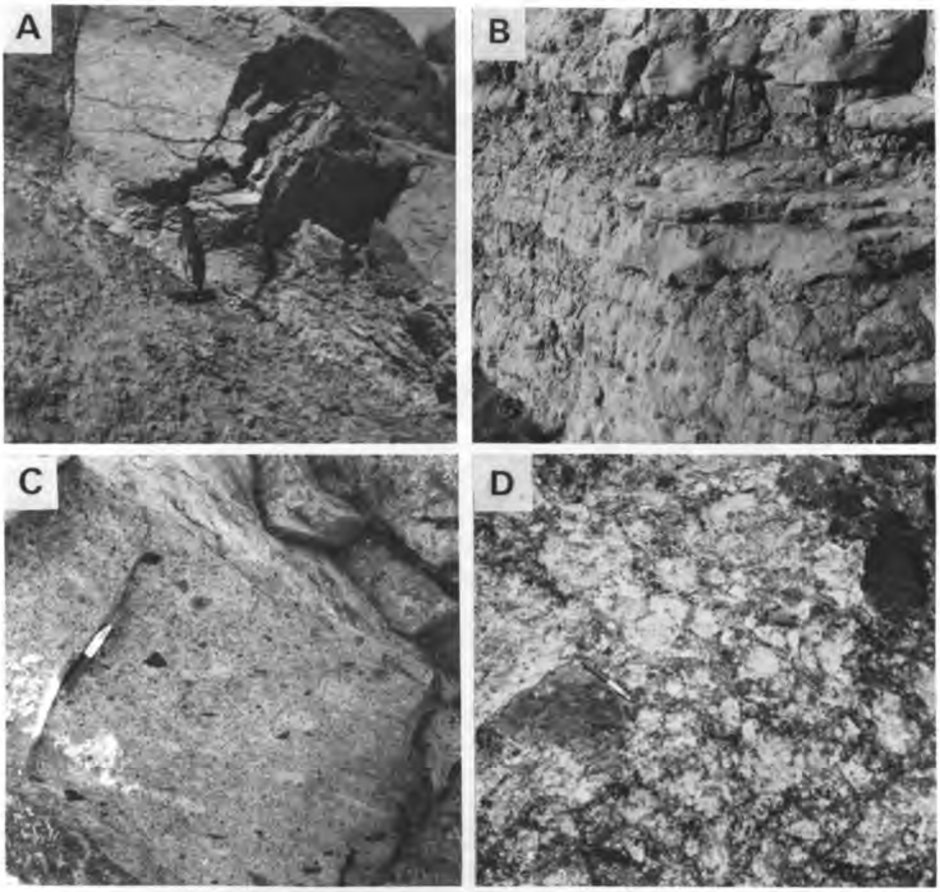

FIGURE 10. OCCURRENCE OF SOME TERTIARY FORMATIONS.
A : Dacitic tuff breccia of the Agua Dulce Formation covering Cretaceous shale near the Porco mine. B : Sandy tuff of the San Roque Formation at 1 km north of Potosi city. C : Dacitic tuff breccia of Kari Kari pyroclastics at the Illimani mine. D : Dacitic agglomerate of the Canteria Formation at 2 km northeast of Potosi city.

grained sandstone, conglomerate and their alternation. Sandstone has sometimes pebble, and shows cross bedding. It overlays unconformably on the Cretaceous and Paleozoic systems. According to Evernden *et al.* (1977), K-Ar age of biotite from volcanics of the Mondragon Formation is 21.1 Ma. The Agua Dulce Formation distributes at western and southern sides of Potosi and around Porco etc., and consists of brown, red or gray colored tuff, tuff breccia and lava of andesitic and dacitic rocks. Locally tuffaceous sandstone, shale and conglomerate are found. Small crystals of biotite, hornblende, plagioclase, garnet and quartz etc. are recognized in matrix of the pyroclastics. The formation near Porco is mainly composed of tuff breccia (Figure 10-A). K-Ar ages for biotite and feldspar from a sample of garnet-bearing andesite lavas are 20.3 and 20.0 Ma, respectively

(Evernden *et al.*, 1977). Also, according to Grant *et al.* (1979b) K-Ar ages for biotite from rhyodacite tuff of the Agua Dulce Formation are 20.9 to 21.3 Ma. The San Roque Formation appears locally at north-east side of Potosi, and is composed of brownish gray sandstone, conglomerate, dacitic tuff and their alternation (Figure 10-B). Among them, dacitic tuff has fine biotite crystals, and its pumice is sometimes welded. Kari Kari pyroclastics forming Kari Kari massif in the middle area is composed of dacitic tuff and tuff breccia with Paleozoic slate, quartzite, sandstone and andesite etc. as rock fragments (Figure 10-C). It is equivalent to Kari Kari pyroclastic flows by Francis *et al.* (1981). In marginal zone of the Kari Kari massif, dacitic welded tuff is sometimes recognized. Dacitic tuff of the Kari Kari pyroclastics has quartz, orthoclase, plagioclase, biotite and garnet, 1 to 3 mm in size, as phenocrysts, and microcrystal aggregate of plagioclase and quartz, and small amounts of biotite and glass are found in its matrix (Figure 11-A). K-Ar ages for biotite from latite and rhyodacite porphyry of the Kari Kari pyroclastics are 20.1 Ma (Evernden *et al.*, 1977) and 20.6 to 22.3 Ma (Grant *et al.*, 1979b), respectively. The dacitic pyroclastics was erupted before the formation of the Kari Kari caldera. The caldera was formed by callapse due to the eruption of voluminous pyroclastic flows. Meanwhile the Canteria Formation overlaying conformably on the San Roque Formation distributes in its east side, and consists of massive dacitic tuff breccia and agglomerate including pebble of dacite, andesite, red sandstone and slate, 2 to 20 cm, sometimes 30 to 40 cm in size (Figure 10-D). A lot of crystals of biotite, feldspar and garnet are recognized in matrix of the pyroclastics. K-Ar ages for biotite from rhyodacite tuff of the

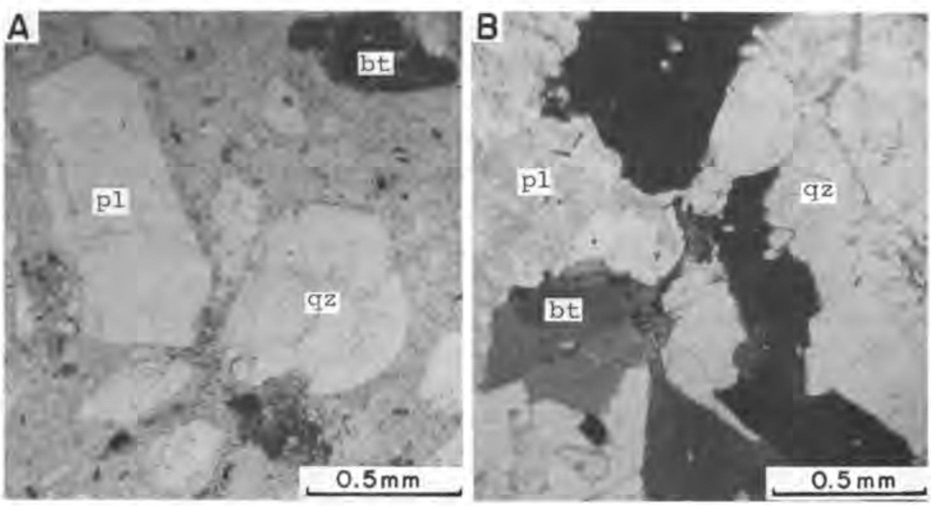

FIGURE 11. PHOTOMICROGRAPHS OF KARI KARI PYROCLASTICS AND KUMURANA PLUTONIC ROCK.
A : Kari Kari pyroclastics (dacitic tuff breccia), pl : plagioclase, qz : quartz, bt : biotite.
B : Kumurana plutonic rock (granite) composed of quartz (qz), plagioclase (pl), biotite (bt), hornblende and potassium feldspar.

Canteria Formation are 21.1 to 21.9 Ma (Grant *et al.*, 1979b). The Pailaviri Formation is found only in area of the Potosi mine (Empresa Minera Unificada del Cerro de Potosi), especially underground of the mine, and consists principally of dacitic tuff breccia containing a large amount of rock fragments of Paleozoic black slate. The Caracores Formation occurs locally near main adit (0 level) of the Potosi mine at surface and upper level in its underground, and is mainly composed of grayish white dacitic fine tuff overlaid concordantly on the Pailaviri Formation. The Los Frailes Formation distributes extensively in the western parts of the middle and northern areas of the district. It is dacitic ignimbrite which consists of hard lava, tuff, and tuff breccia. They are generally alternated showing horizontally obvious bedding. Phenocrysts of quartz, biotite, and feldspar are usually found in dacite lava and tuff. This formation covers discordantly on the lower Tertiary, Cretaceous and Paleozoic systems. K-Ar ages for biotite from dacite ignimbrite of the Los Frailes Formation are 7.4 and 7.5 Ma (Grant *et al.*, 1979b). It corresponds to the Morococara Formation in the Oruro didtrict (Sugaki *et al.*, 1981a) and is suffered quite no ore mineralization. The Tollocci Formation is the youngest one of the Tertiary system in the Potosi district. It consists of dacitic lava and welded tuff with quartz, biotite and feldspar phenocrysts, 1 to 5 mm in size.

As Quaternary sediments, glacier and moraine deposits as gravel, sand and mud etc. are found in basin of the Kari Kari caldera. Also gravel and sand as the Alluvium is found in narrow area along rivers in the district and in the basin of the Kari Kari caldera. Some alluvial tin is being taken by dredger in the river at Tarapaya near Potosi.

As intrusive rocks, dykes, sheets and stocks of dacite intrude into the Los

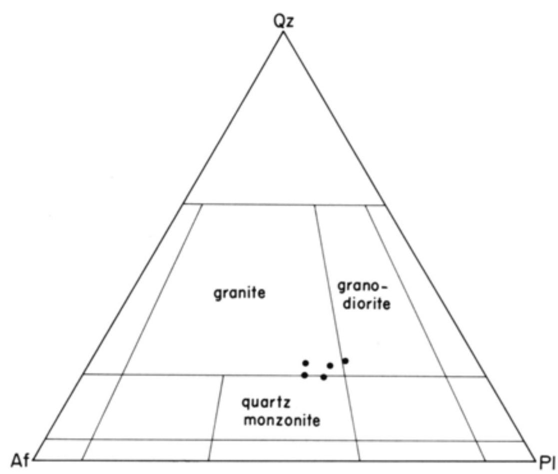

FIGURE 12. MODAL COMPOSITION OF KUMURANA PLUTONIC ROCK SHOWN IN THE Qz-Af-Pl DIAGRAM.

TABLE 2. K-AR AGES OF THE PYROCLASTICS AND LAVA OF TERTIARY AND CRETACEOUS FORMATIONS, AND INTRUSIVE ROCKS IN THE POTOSI DISTRICT.

Rock type	Material	Ma	Reference
Los Frailes Fm. Dacite ignimbrite	Biotite	7.4- 7.5	Grant et al.(1979a)
Cerro Rico stock			
Altered porphyry	Whole	13.2-14.1	Grant et al.(1979a)
Altered porphyry	Whole	13.3-13.8	Grant et al.(1979b)
Canteria Fm. Rhyodacitic tuff	Biotite	21.1-21.9	Grant et al.(1979a)
Plutonic rock			
Granodiorite	Biotite	20.5-20.8	Evernden et al.(1977)
Granodiorite	Biotite	21.2	Grant et al.(1979a)
Kari Kari Pyroclastics			
Rhyodacite porphyry	Biotite	20.6-22.3	Grant et al.(1979)
Latite	Biotite	20.1	Evernden et al.(1977)
Agua Dulce Fm.			
Lava	Biotite	20.3	Evernden et al.(1977)
Lava	K-feldspar	20.0	Evernden et al.(1977)
Rhyodacitic tuff	Biotite	20.9-21.3	Grant et al.(1979a)
Cretaceous			
Miraflores Fm. Lava	Biotite	83	Evernden et al.(1977)

Frailes, Pailaviri, Caracoles and Agua Dulce Formations of the Miocene series and the Cretaceous system. The dacitic stock of Cerro Rico de Potosi has domed at north-western edge of the Kari Kari caldera, and was intensely altered by late-stage hydrothermal activity. K-Ar ages for whole rock of Cerro Rico altered porphyry (dacite) are 13.2 to 14.1 Ma according to data by Grant *et al*., (1979b). Kumurana plutonic rock is found in the Kari Kari pyroclastics and the Ordovician quartzite, and gives contact metamorphism to them. It is an equigranular and holocrystalline rock consisting of quartz, orthoclase, plagioclase, biotite and hornblende etc., 0.5 to 3.0 mm in size (Figure 11-B). Its modal compositions are quartz: 15-20%, orthoclase: 21-28%, plagioclase: 33-40%, biotite: 14-20%, and hornblende: 2-8%, and most of them belong to granite family as shown in Qz-Af-Pl diagram of Figure 12. K-Ar ages for biotite from granodiorite (granite) of Kari Kari pluton are 20.5 to 20.8 Ma (Evernden *et al*., 1977) and 21.1 Ma (Grant *et al*., 1979b).

The K-Ar ages for some formations of the Cretaceous and Tertiary systems and intrusive rocks in the Potosi district measured by Evernden *et al*. (1977) and Grant *et al*. (1979a, b) are listed up in Table 2.

ORE DEPOSITS

1. *Outline of ore deposits*

The Potosi district is the most principal mining area of Bolivia from the 16th century. It is located in central portion of tin mineralization belt in the eastern cordillera of Bolivia as shown in Figure 2. This district extends over the tin, antimony and lead-zinc zones of the metallogenic belts in Bolivia as seen in Figure 13, and there are many metallic mines of tin, silver, antimony, lead and zinc etc. in the district. Among them, the mines of Potosi (tin and silver), Huari Huari (zinc, tin and silver), Porco (silver, lead and zinc), Caracota (antimony), Kumurana (tin) and Colavi (tin) etc. are working now. They except Colavi mine are hydrothermal deposits filling fissures developed in the formations of Ordovician (slate and quartzite) and Miocene (andesitic and dacitic pyroclastics), and altered dacite stocks. Their mineralizations were carried out at stage of the late Miocene, and produced polymetallic ores consisting of cassiterite, wolframite, stannite, pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, stibnite, jamesonite, fizelyite, semseyite and pyrargyrite etc. with gangue minerals such as quartz, tourmaline, alunite, sericite and kaoline etc. While the Colavi mine is "Manto" type (stratabound) tin deposit found in the Torotoro Formation of the Createceous system. Very fine grained cassiterite, pyrite and quartz are essential minerals in ores from the Colavi mine. In this paper, the ore deposists of Potosi, Huari Huari, Porco, Caracota, Kumurana and Colavi mines etc. are described as below.

2. *Empresa Minera Unificada del Cerro de Potosi (Potosi mine)*

The Potosi mine is situated at northern foot of Cerro Rico de Potosi (4824 m elevation) which rises at southern outside of Potosi city (Figures 14 and 15). The Cerro Rico de Potosi, a symbol of Potosi city is the richest hill in Bolivia, which contains immense amounts of silver and tin. The ore deposits of the Cerro Rico de Potosi was discovered by Diego Huallpa in 1544, and mined first in 1545. By 1572 an extremely high grade ore in the upper part of the hill was largely exhausted. The silver content of this high grade ore has been reported as from 1,500 to 9,000 ounces per ton (4.25 to 23.5% Ag). In 1580 the hill reached its peak production of 13,000,000 pesos per year. The formation of large mining companies began in 1852 and lower grade silver ores in deeper levels were mined. However, in 1852 low silver prices forced many of mines to change from silver to tin (Evans, 1940). At the present, the lower zone than the 0 (Pailaviri) level (4205 m above sea level) is being mainly mined for tin ore by Empresa Minera Unificada del Cerro de Potosi which belongs to Corporacion Minera de Bolivia (COMIBOL). The upper zone, vigorously mined out during a few hundred years for silver and tin ores, in the hill is being still worked by many small private companies which rent the claim mining the remains of ore bodies from COMIBOL. The ore deposits in the hill are developed for 1,150 m in depth from submit of Cerro Rico to the -16th level (3674 m above sea level) which is submerged now. The crude ore productions were 344,878 tons with 0.54% Sn in 1979 and 387,305 tons with 0.46% Sn in 1980. Also those for a half year from January to June in 1981 were 201,547 tons with 0.51% Sn.

The crude ores are sent to an ore dressing plant in same area as the mine

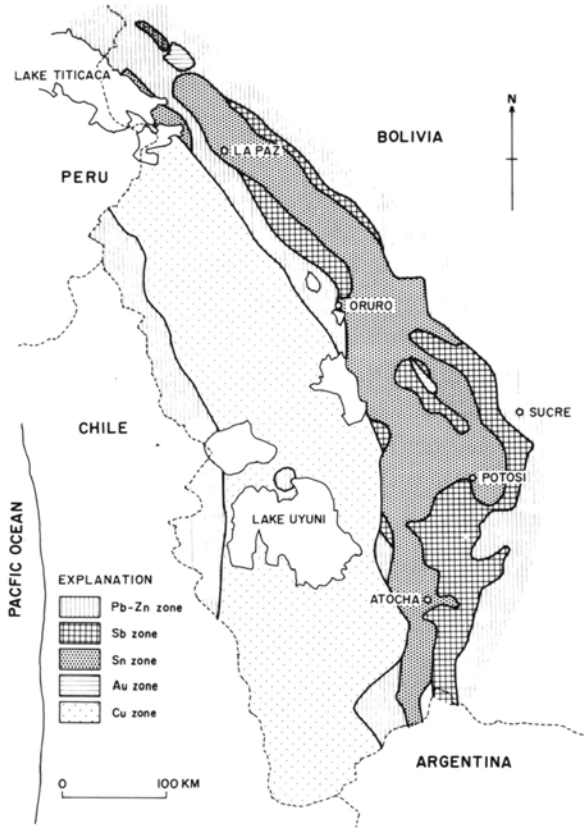

FIGURE 13. METALLOGENIC BELTS IN BOLIVIA (After Claure and Minaya, 1979).

offices. Its capacity has 1,500 to 2,000 tons per day in crude ore, and semiconcentrate for volatilizing smelter of 3,500 to 4,000 tons per month containing 2.5 to 3.3% Sn was produced in 1981. The workers of the Potosi mine (COMIBOL) are about 2,000 persons, but about 8,000 persons in addition to them are working at a lot of small private companies by which upper mineralized zone of Cerro Rico is being mined. Main adit of the mine is the 0 (Pailaviri) level (Figure 15-C), and two main shafts, Central and Keller, carry out an important role on transport of the ores from underground.

Geology of this mine consists of the Ordovician and Miocene formations and Cerro Rico dacite stock. The Ordovician formation is composed mostly of slate with small quantities of sandstone and quartzite. It generally strikes north-west and dips gently southwest, but is locally crumpled. The Miocene formations covering nearly flat on Ordovician slate with unconformity consist of conglomerate, dacitic tuff and tuff breccia (Pailaviri Formation), and dacitic fine tuff with shale (Caracoles Formation) in ascending order. The Cerro Rico dacite stock intrudes into Ordovician slate, dacitic tuff, tuff breccia, and fine tuff of the Miocene formations as shown in Figure 16. As seen in the figure, the form of the stock presents a funnel- or mushroom-like shape changing to a pipe and dyke at lower part (Figures 17 and 18). Dacite of the Cerro Rico stock has quartz, 3 to 5 mm in size, orthoclase and biotite, 0.5 to 1.0 mm as phenocrysts, but is altered hydrothermally to occur sericite, kaoline, chlorite and secondary quartz etc. after orthoclase, biotite and groundmass although primary quartz phenocryst remains. Also pyritization is often found in the rock. It is very difficult to observe fresh dacite at underground of the mine because of extensive hydrothermal alteration. Such rock shows gray or grayish white colored massive form.

Ore deposits of the Potosi mine are composed of hydrothermal veins filled up innumerable fissures formed in dacite stock, Miocene dacite tuff and tuff breccia, and Ordovician slate. Although the veins usually develop in Ordovician basement and dacite intrusion, they also occur well in dacitic fine tuff of the Caracoles

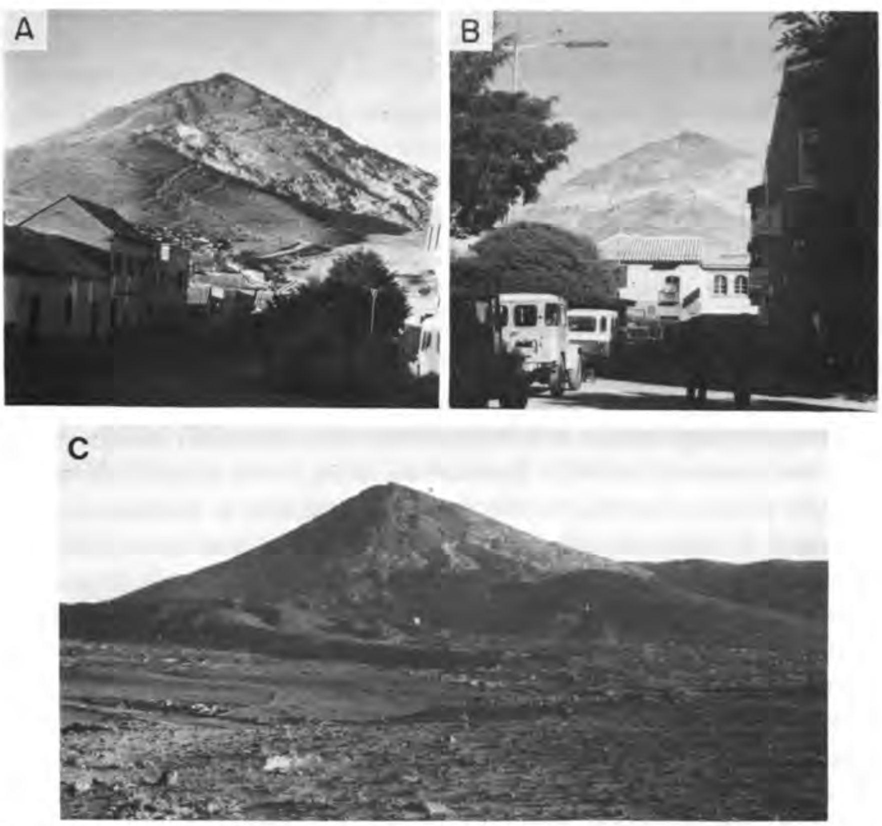

FIGURE 14. CERRO RICO DE POTOSI.
A and B: Cerro Rico de Potosi seeing from Potosi city. C: Cerro Rico de Potosi viewing from 8 km northeast of Potosi city.

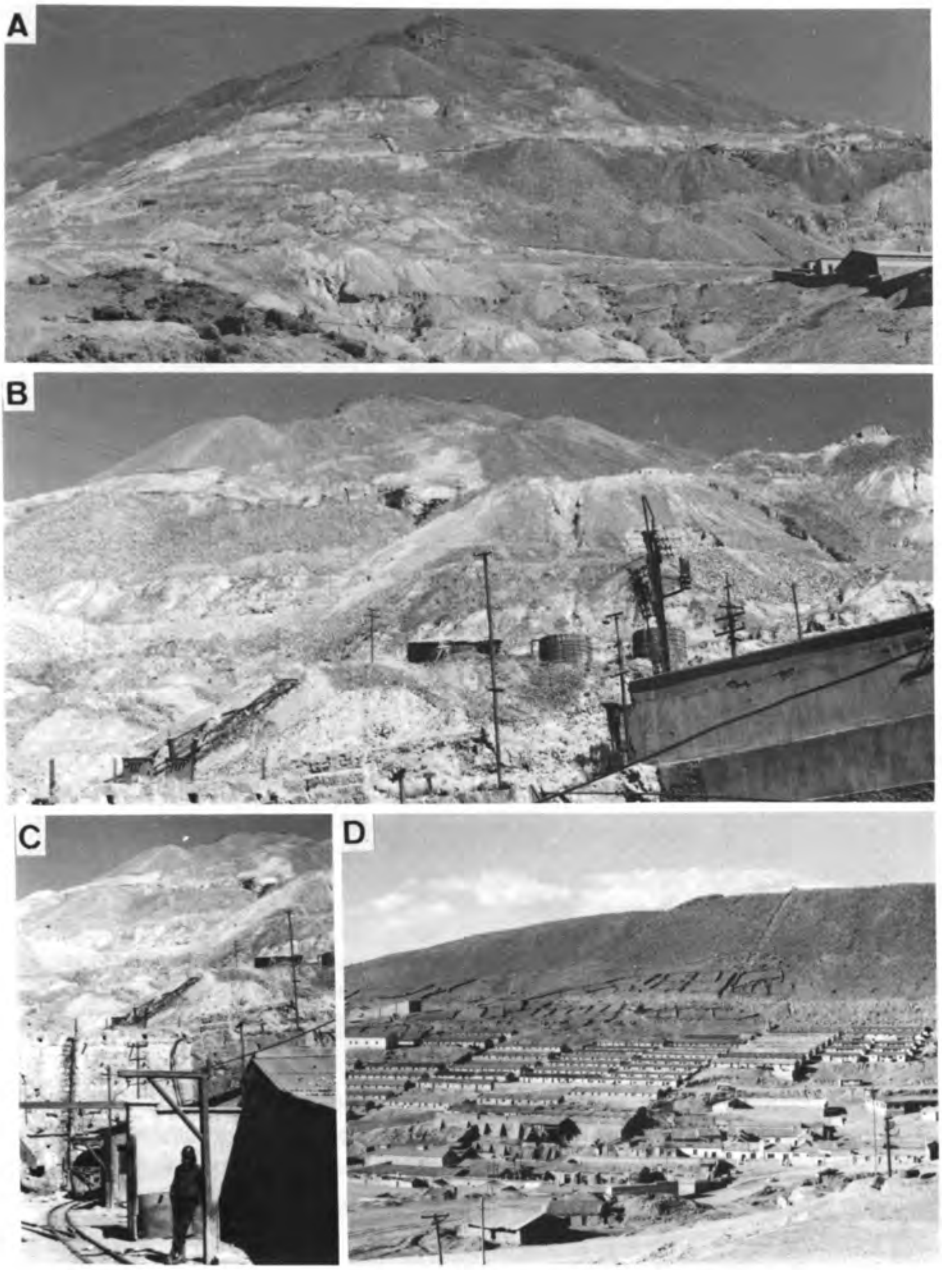

FIGURE 15. SCENERY OF THE POTOSI MINE.
A and B: Cerro Rico de Potosi looking at from north. C: The main adit of the 0 (Pailaviri) level. D: The mining town in Potosi city.

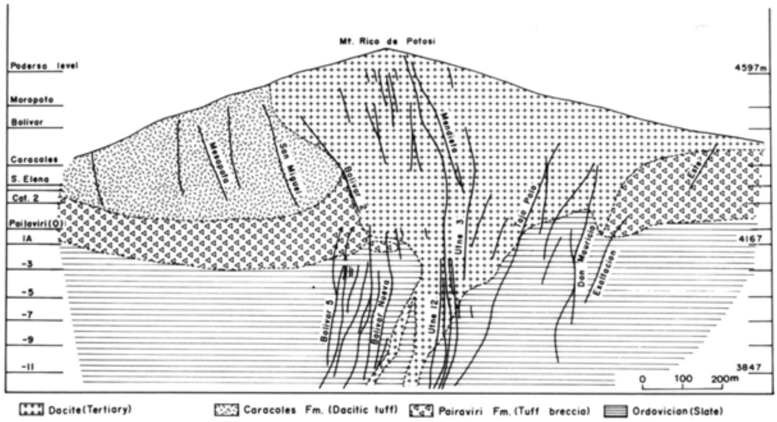

FIGURE 16. GEOLOGICAL SECTION OF THE POTOSI MINE.

TABLE 3. MAIN VEINS AND THEIR SCALES IN THE POTOSI MINE.

Veins	Strike	Dip	Length (m)	Depth (m)	Width (m)
Bolivar	N35°E	70°W	500	420	0.25
Bolivar 1 Ramo 1	N10-20°E	80°E	150	60+	0.3
Bolivar 2	N25°E	80°E	400	400	0.2
Bolivar 4	N20°E	85°E	500	200	0.2
Bolivar 5	N30°E	75°W	300	420	0.4
Bolivar 6	N25°E	80°E	600	300	0.2
Bolivar Nueva	N25°E	80°E	500	450	0.2
Utne 2	N40°E	85°W	400	450	0.4
Utne 3	N45°E	85°W	300	420	0.4
Utne 4	N40°E	65°W	950	450	0.5
Tajo Polo 1	N-S	75°W	500	370	0.8
Rica 2	N40°E	90°	450	250	0.3
Rica 2A	N25°E	90°	450	290	0.3
Mendieta 2	N60°E	85°W	460	400	0.3
Don Mauricio	N20-30°E	75-80°E	650	490	0.5

Formation rather than in tuff breccia of the Pailaviri Formation. Our underground survey was carried out on the ore veins in the 0 level or below such as the -7th and -8th levels because working places of the mine are limited lower levels than the 0 level at the present. The arrangement of the veins in the 0 (Pailaviri) level and -7th level is shown in Figures 19 and 20, respectively. Although they run as roughly parallel veins, there are found the fractures of two systems: one is NNE-SSW or N-S direction and other, NE-SW strike. In the 0 level, the veins principally occur in Pailaviri tuff breccia and altered dacite as shown in Figure 17. Among them, the veins in Pailaviri tuff breccia tend to have NNE-SSW or N-S direction, meanwhile those in the dacite pipe are dominant NE-SW strike. There is a possibility that the fractures of NNE-SSW (N15°-30°E) or N-S (N0°-10°

FIGURE 17. GEOLOGICAL PLAN AT THE 0 LEVEL, POTOSI MINE.

E or W) system may be formed by shear, but the NE-SW (N40°-50°E) fissures, by tension. At the -7th level, the veins are also divided into two systems as same as those at the 0 level as shown in Figure 20. The dacite intrusive changes its form to dyke in the -7th level. The strike, dip, length and width of principal ore veins observed by us are given in Table 3.

These ore veins, usually 10 to 50 cm, sometimes 1.0 to 2.0 m in width, consist of pyrite, sphalerite, galena, cassiterite, arsenopyrite, marcasite, wurtzite, chalcopyrite and small amounts of wolframite, stannite, stibnite, tetrahedrite, and some silver minerals etc. in intimate association with gangue minerals of quartz, tourmaline, alunite, kaoline, sericite, phosphophyllite and siderite etc. Among

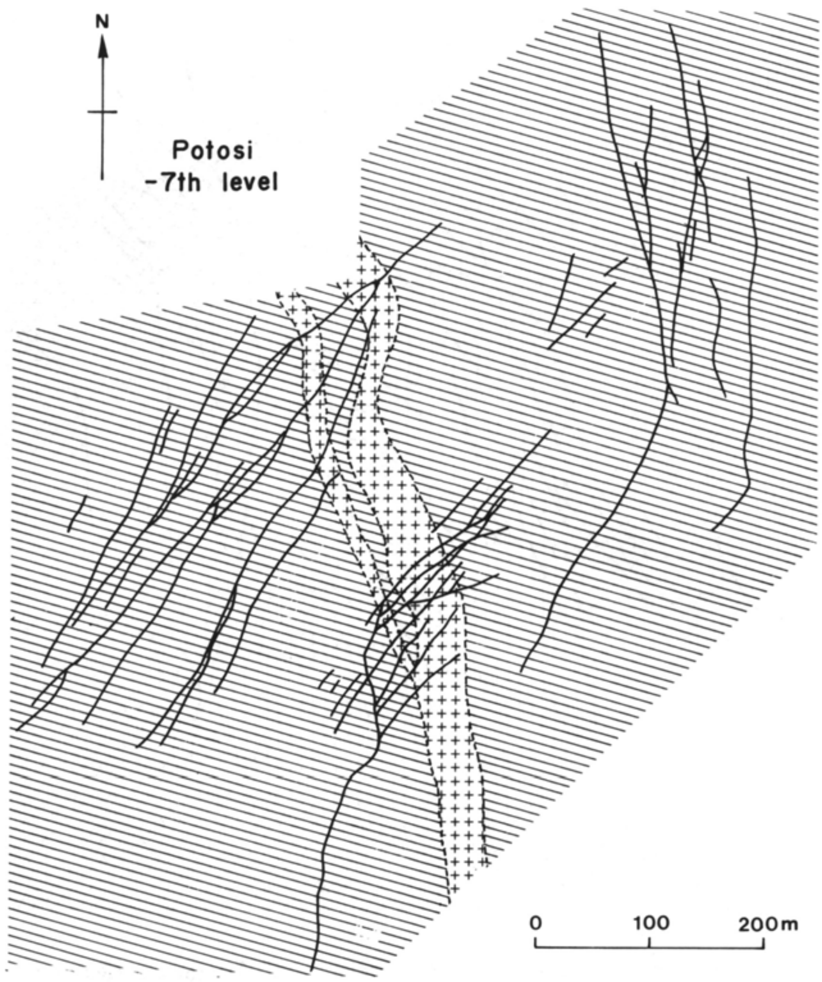

FIGURE 18. GEOLOGICAL PLAN AT THE-7TH LEVEL, POTOSI MINE.

them, the essential minerals are pyrite, sphalerite, cassiterite, arsenopyrite, galena, quartz, alunite, kaoline and siderite etc. The veins usually show banding structure (Figure 21-A, B, C and D). In the case, pyrite and sometimes sphalerite with quartz, 5 to 20 cm wide, commonly occur as band in both sides of outer part (zone) of the vein, meanwhile alunite, kaoline and sometimes sericite, 5 to 10 cm in width, appear in inner (central) zone. Cassiterite is often found as thin band, 2 to 5 mm wide, between pyrite of the outer zone and quartz, alunite or kaoline of the inner zone besides often associating intimately with pyrite, sphalerite and quartz in the outside zone. The banded cassiterite is aggregate of euhedral and subhedral crystals, 0.1 to 0.3 mm in size, which have yellow to brown in inter-reflecting color and commonly present growth zoning and twinning under the microscope. On the other hand, it also occurs in intimate assemblage with pyrite, sphalerite and quartz in the outer zone as seen in the Bolivar vein. Under microscope, cassiterite is found in close association with pyrite, sphalerite, quartz, and occasionally chalcopyrite. It also appears as euhedral or subhedral form or its aggregate of very fine grains, 1 to 10 μm, in aggregate of sphalerite, stannite and arsenopyrite as seen in ore from the Don Mauricio vein (Figure 22-A). Sphalerite, 0.2 to 1.0 mm, sometimes 3.0 mm in size, overgrows on cassiterite

FIGURE 19. VEIN ARRANGEMENT AT THE 0 (PAILAVIRI) LEVEL, POTOSI MINE.

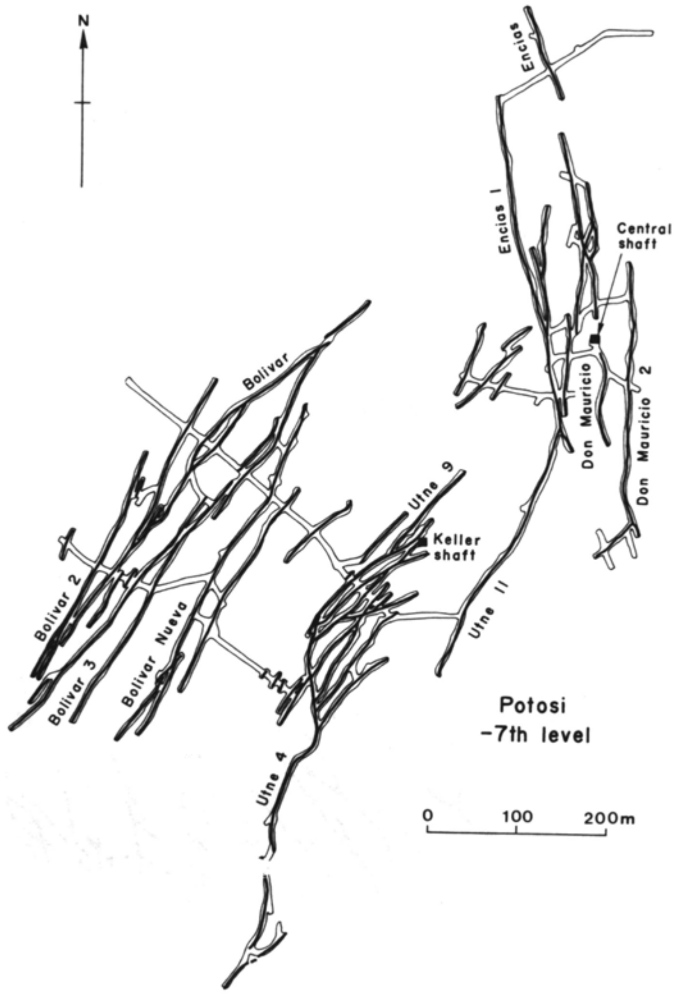

FIGURE 20. VEIN ARRANGEMENT AT THE-7TH LEVEL, POTOSI MINE.

crystal (Figure 22-B). Stannite appears frequently along grain boundary between cassiterite and sphalerite. Wolframite sometimes occurs as euhedral platy crystal, 5 to 10 mm in size, in association with quartz, pyrite, chalcopyrite and stannite at inside adjacent to the cassiterite band. Its composition is 4.6 to 7.1 mole % $MnWO_4$. Bismuthinite is occasionally found in sphalerite associating with cassiterite. Marcasite and wurtzite are formed along the boundary between such ore minerals as above and alunite. Cassiterite, pyrite, sphalerite and quartz are often cut by alunite veinlet.

The silver bearing minerals such as fizelyite, pyrargyrite, semseyite, boulangerite, tetrahedrite and galena etc. are found in ores from the Don Mauricio vein at the 0 level. They are in microscopic size except semseyite and tetrahedrite.

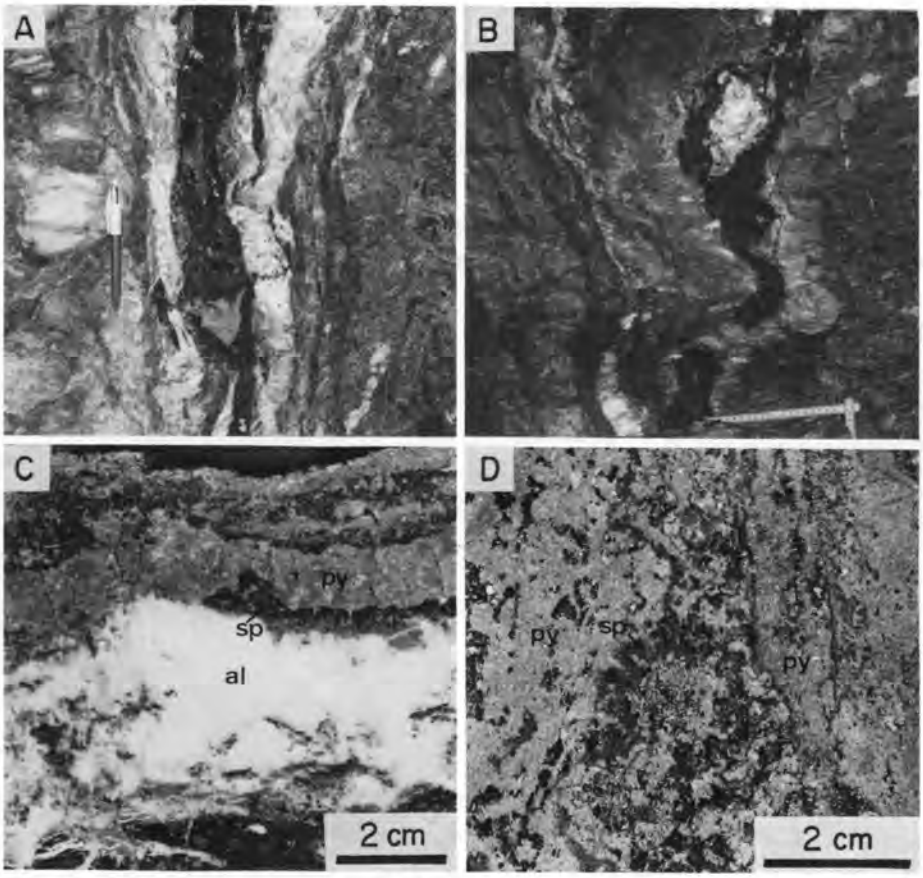

FIGURE 21. ORE VEINS IN THE POTOSI MINE.
A: Pyrite-sphalerite-cassiterite (black) -alunite (white) vein, Bolivar 1 vein, 0 level. B: Pryite-sphalerite-cassiterite (black) vein, Bolivar 1 vein, (white) level. C: Pyrite (py) and sphalerite (sp) zones with cassiterite and alunite (al) zone from outside to inside of the vein, Bolivar 1 vein, 0 level (Sample No 8172009). D: Pyrite (py)-stannite-arsenopyrite-sphalerite (sp) ore, Don Mauricio vein, 0 level (8172032).

Among them, fizelyite shows characteristically polysynthetic twin under the microscope, and occurs in aggregate of fine grains, 10 to 50 μm in size, in intimate association with galena, pyrargyrite, sphalerite, semseyite, jamesonite, boulangerite, and pyrite (Figure 22-C). Pyrargyrite occasionally appears as irregular form, 10 μm or less in size, along the boundary between galena and fizelyite. Tetrahedrite fills up in the interspace of pyrite aggregate assembled with sphalerite and chalcopyrite, meanwhile it also occurs as an euhedral crystal, 1 to 5 mm in size, in druse of pyrite in the vein. Under the microscope, tetrahedrite intimately associates with stannite, bournonite, sphalerite, chalcopyrite and galena which embed in the interspace of aggregate of pyrite, arsenopyrite and quartz. In such ore as above, stannite is always found in close assemblage with pyrite, chalcopyrite, bournonite and cassiterite (Figure 22-D). Large amounts of semseyite appears as an essential ore mineral from the Don Mauricio vein in the 0 level. It is aggregate of granular crystals, 2 to 4 mm in size, and closely assembles with pyrite, sphalerite, galena, jamesonite, fizelyite and quartz etc. under the microscope. Such silver bearing ores contain no cassiterite.

Among gangue minerals, alunite and kaoline commonly occur intimately association with each other in central portion of the vein, but they sometimes

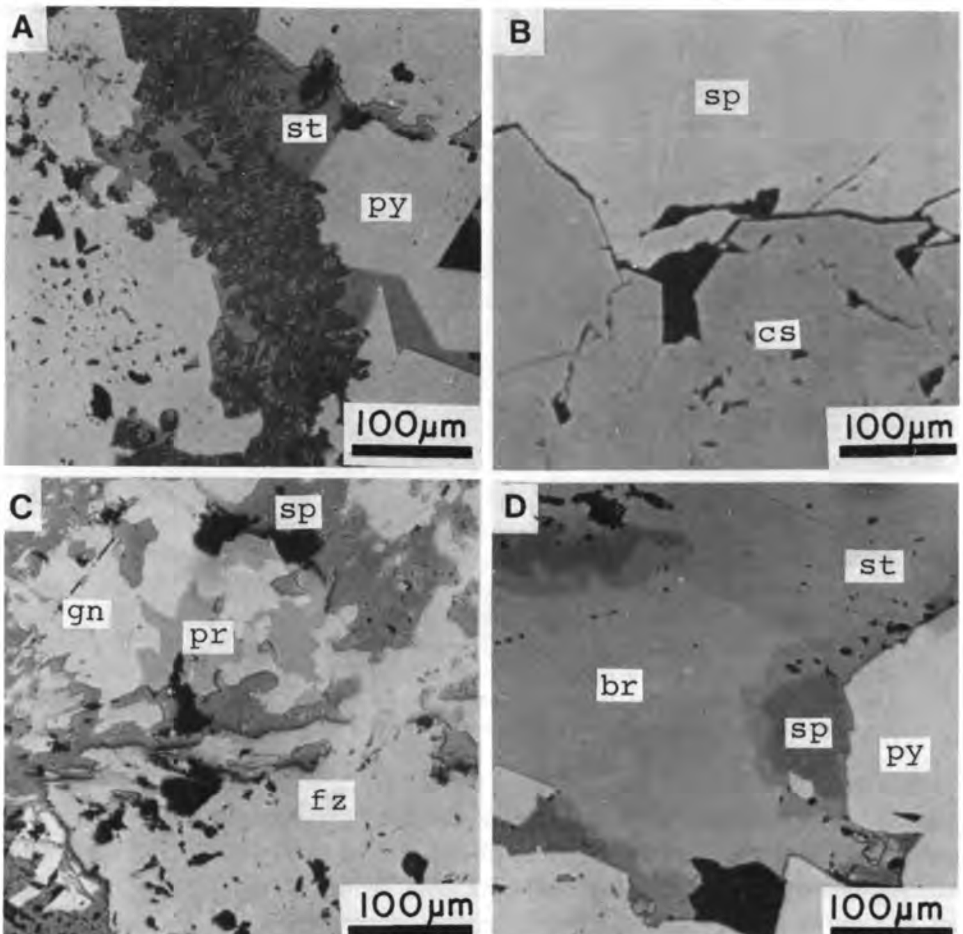

FIGURE 22. PHOTOMICROGRAPHS OF ORES FROM THE POTOSI MINE.
A : Fine grained idiomorphic cassiterite (dark gray) included in stannite (st) and pyrite (py), Don Mauricio vein, 0 level (8172029). B : Idiomorphic cassiterite (cs) overgrown by coarse grained sphalerite (sp), Bolivar 1 vein, 0 level (8172001). C : Intimate association of fizelyite (fz), galena (gn), pyrargyrite (pr) and sphalerite (sp), Don Mauricio vein, 0 level (8172018). D : Stannite (st) associated with pyrite (py) sphalerite (sp) and bournonite (br), Don Mauricio vein, 0 level (8172019).

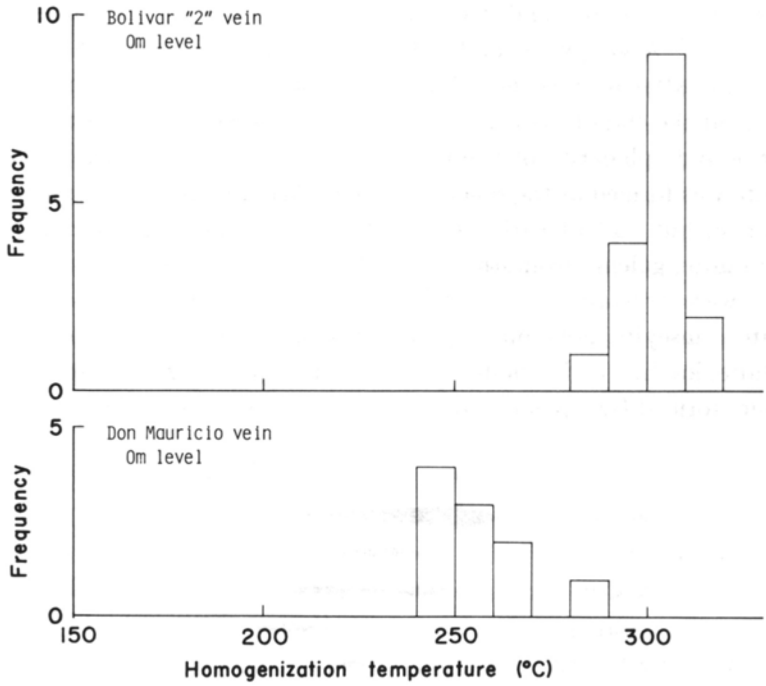

FIGURE 23. HOMOGENIZATION TEMPERATURE OF FLUID INCLUSIONS IN QUARTZ FROM THE POTOSI MINE.

occupy the oustide in the vein as veinlet of late stage mineralization as seen in the Bolivar 1 vein of the 0 level (Figure 21-A). They also appear as veinlet penetrating pyrite and sphalerite zone in the vein. Sericite occurs in assemblage with kaoline and alunite. Carbonate minerals such as siderite and calcite etc. also appear as a veinlet of the latest stage.

Fluid inclusions are frequently observed in quartz, sphalerite and cassiterite from the ore veins under the microscope. The filling temperatures of the fluid inclusion in quartz with cassiterite from the Bolivar 2 vein (specimen No. 8172038) and quartz with pyrite and chalcopyrite from the Don Mauricio vein (specimen No. 8172030) of the 0 level were measured by heating stage (TH-600, Linkam Company). The homogenized temperatures obtained by the experiments are 280° to 320°C for quartz of specimen No. 8172038 and 240° to 290°C for quartz of specimen No. 8172030 as shown in Figure 23. Also salinities obtained from freezing temperatures of fluid inclusions in the two specimens as above are 13.0 to 13.3 equivalent wt % NaCl for specimen No. 8172038 and 4.8 to 10.8 equivalent wt % NaCl for specimen No. 8172030.

From the data on occurrence, structure, mineral assemblage and arrangement of the veins and mineral paragenesis in the ores, the sequence of crystallization of the ore and gangue minerals from the mine is shown in Figure 24. As indicated in the figure, tourmaline and some quartz are formed at the earliest stage of mineralization. Also, pyrite and sphalerite were mostly crystallized at early mineralization after tourmaline. Cassiterite was produced in the crustified band after pyrite at the end of the early stage, although some cassiterite occurs together with pyrite and sphalerite of the early stage and stannite of the middle stage. Wolframite was formed at the relatively later stage than prinicipal mineralization of cassiterite, but end of early stage. At the middle stage of mineralization, quartz, stannite, galena, bismuthinite, chalcopyrite, arsenopyrite with pyrite and sphalerite were crystallized, and then sulfosalt minerals such as tetrahedrite, bournonite, semseyite, jamesonite, pyrargyrite, and fizelyite etc. were also produced. Alunite, kaoline and sericite which are principal gangue minerals as same as quartz were formed by the mineralization of the late stage as shown in the figure.

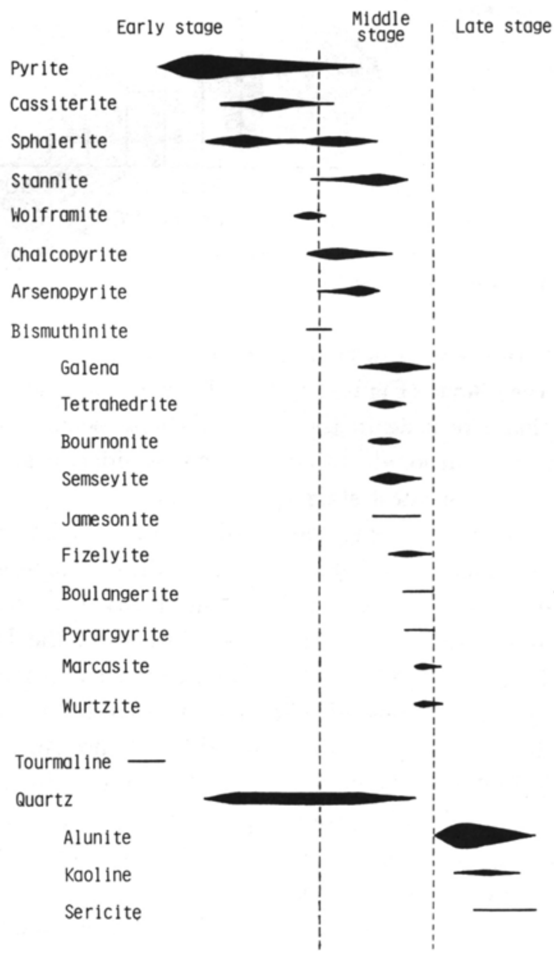

FIGURE 24. MINERALIZATION SEQUENCE OF MINERALS FROM THE POTOSI MINE.

3. Porco mine

The Porco mine is situated at 30 km southwest of Potosi city, and located at 2 km southeast of Porco town. It is very old and famous mine because of production of high grade silver ores as same as old Potosi mine. The mine belongs to Compania Minera del Sur S.A. of a private mining company. The production is about 10,000 tons per month in crude ore containing 11% Zn. The workers of the mine are 300 persons among whom 185 persons are working at underground.

Geology around the mine consists of dacite and its tuff corresponding to the Agua Dulce Formation in the Potosi area (Mendieta *et al.*, 1963). They are conspicuously altered by hydrothermal mineralization, and change its color to light gray or grayish white. There are also found two dacite stocks at Cerro Huayna Porco (Figure 25-A) and Cerro Apa Porco.

The ore deposits of the mine are composed of several veins filled up the fissure developing in the altered dacite and its tuff (Ahlfeld and Schneider-Scherbina, 1964). San Antonio vein which is principal one among them runs to the direction N10° to 30°E dipping to 70° to 85°E (Figure 26). It has 500 to 1,500 m in length, 300 m in vertical depth, and 120 to 200 cm in width. The vein is accompanied by pyrite, sphalerite, galena and quartz etc. macroscopically. Sphalerite occurs as massive, or stringer accompanied by pyrite and sometimes galena in the vein, and often disseminates with pyrite into the country rock. There is frequently found druse structure of pyrite and sphalerite in the vein. Galena commonly assembles with sphalerite and pyrite. Small amounts of chalcopyrite and arsenopyrite occur with pyrite. The San Antonio vein is divided into the branches of Oriente (Figure 25-B), Misericordia and Santos (Figure 26) in southern end. It is being developed by the levels of Santa Cruz (4,000 m elevation), San Jose (4,350 m), Dolores (4,285 m), San Cayetano (main adit, 4,105 m) and -60 m (4,045 m). The galena rich ore from the M-Uestra Grande vein of Cerro Huayna Porco section sometimes contains very high grade of silver, 2,300 g/t Ag. Rajo Zuniga vein (Figure 25-C) which was mined out by open pit, 100 m long and 20 m wide, consists of cassiterite, wolframite, galena, silver minerals and pyrite in altered dacite. Its strike and dip are N30°E and 75° to 80°E, respectively, and its width is approximately 1.0 to 1.5 m.

4. Huari Huari mine

The Huari Huari mine belongs to the New Jasey Zinc Cooperation, and is operated by the Consur South America. The mine (19°27′ S, 65°35′ W) is situated at 25 km northeast of Potosi. The monthly production is 4,600 tons of a crude ore containing 8.20% Zn, 0.41% Sn and 100 g/ton Ag in June, 1983. The crude ore is sent to the ore dressing plant near Don Diego. The workers are 200 persons and

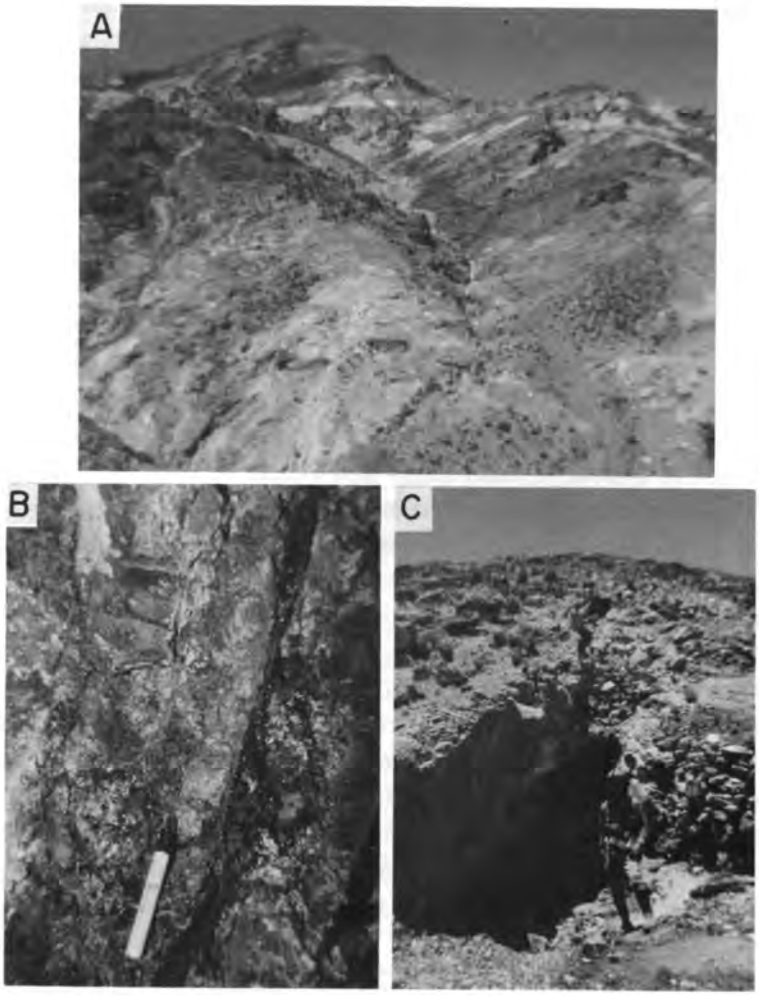

FIGURE 25. SCENERY AND ORE VEIN OF THE PORCO MINE.
A : A view of Mt. Huayna Porco. B : Pyrite-sphalerite-galena vein, Oriente branch of San Antonio vein, Dolores level. C : Open pit of Rajo Zuniga Vein.

123 persons within them in underground.

The geology around the mine is composed mainly of Ordovician black slate and sandstone, Silurian slate, and Cretaceous sandstone (Figure 27). The Ordovician formation is folded, and an anticline axis of NW is found near the ore deposits. As shown in Figure 27, there are two large faults of NS and a fault of NNE linked with them. Small igneous bodies of dacite and others are exposed in the south area of the mine. They are assumed to be intrusive rocks in the Miocene.

The ore deposits are of a fissure filling type along the fault fracture running

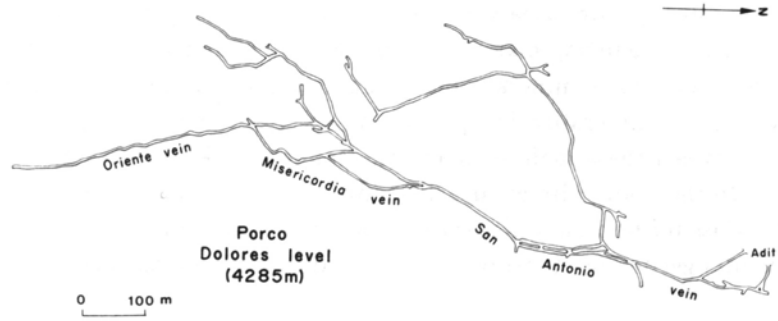

FIGURE 26. ORE VEINS AT THE DOLORES LEVEL IN THE CERRO APA PORCO SECTION, PORCO MINE.

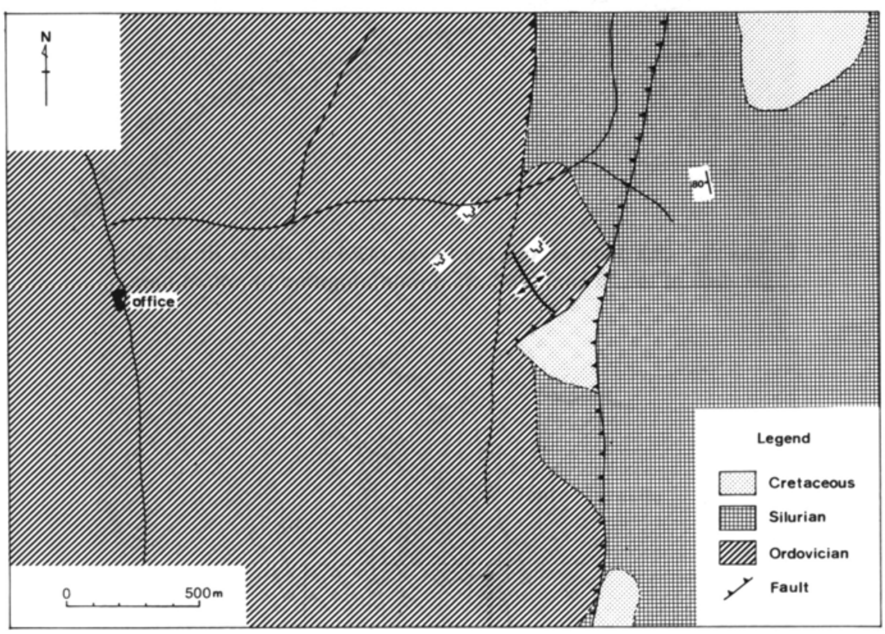

FIGURE 27. GEOLOGICAL MAP OF THE HUARI HUARI MINE.

a direction of NNE as mentioned above. There exists a vein named as Anton Bravo. Its country rock is mainly Ordovician slate and sandstone, and partly Silurian slate. The recognized length of the vein along its strike is 110 m at the Carluncho level (4146 m above sea level), 470m at the San Antonio level(4067 m), 660 m at the San Jose level (3965 m), 920 m at the Esperanza level (3911 m), 620 m at the 110 level (3858 m), 600 m at the 55 level (3802 m) and 390 m at the 0 level (3745 m). Its depth is about 450 m. It dips 80° W at the northern part, but 75° to 85° E at the southern part. Its width is usually 20 to 60 cm, but occasionally over 2 m. The vein at the 110 level is shown in Figure 28.

The ore minerals are large amounts of pyrite and sphalerite associating with small amounts of galena, marcasite, jamesonite, boulangerite, cassiterite and pyrargyrite. As gangue minerals quartz, kaoline and siderite etc. are found. In the early stage of mineralization pyrite and sphalerite occur with quartz. The boundary between these main ores and the country rock is not sharp because of existing hydrothermally altered and disseminated zone of about 1 m or more along the vein. Cassiterite occurs in sphalerite as small grains of about 10 μm in size. Galena, boulangerite and pyrargyrite are found in intimate association with each

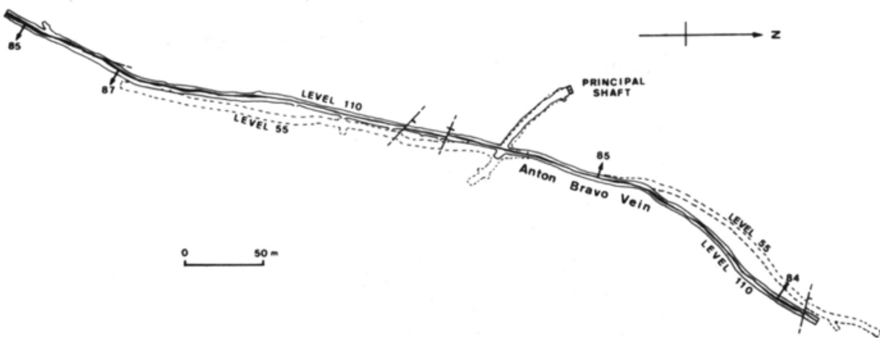

FIGURE 28. ORE VEIN AT THE 110 LEVEL (3858 m), HUARI HUARI MINE.
The drift of the 55 level (3802 m) is shown together by dotted lines.

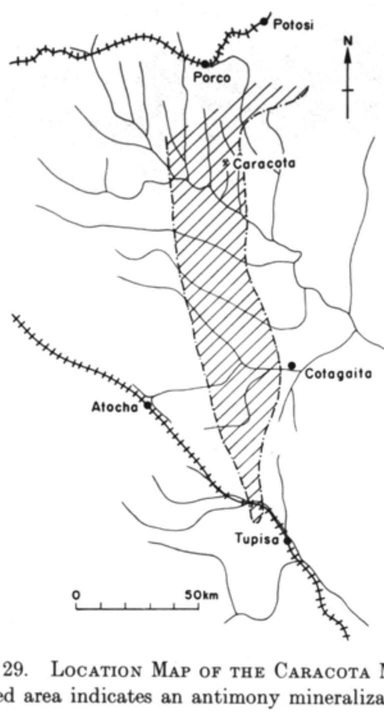

FIGURE 29. LOCATION MAP OF THE CARACOTA MINE.
Shaded area indicates an antimony mineralization belt.

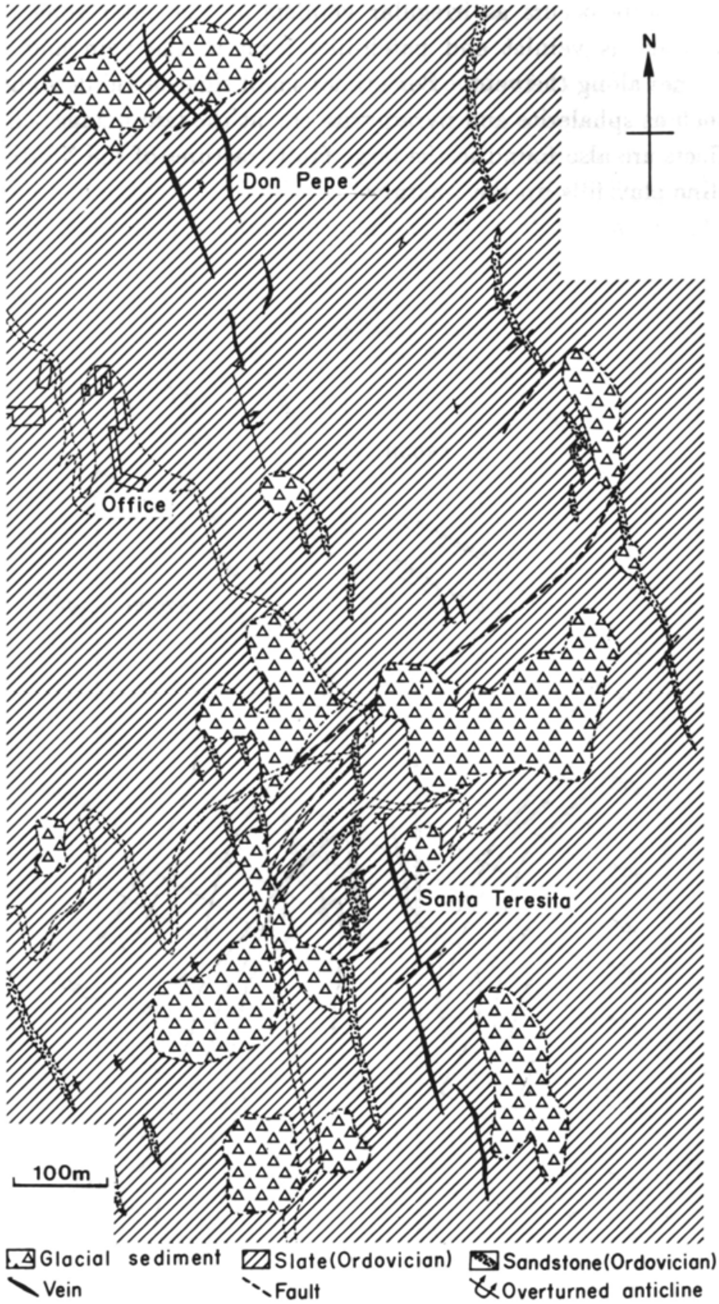

FIGURE 30. SURFACE GEOLOGY OF THE CARACOTA MINE.
Some veins crop out along NNW trending fault.

other. Jamesonite occurs as irregular veinlets at the outer zone in the vein. Kaoline appears as veinlet and patch-like form in the vein and also in the alteration zones along the vein. Sometimes small siderite veinlets cut all the ore minerals such as sphalerite and pyrargyrite etc. at the latest stage. Some hydrothermal effects are also found in the large fault fractures of the NS direction, and white kaoline clay fills up the fractures.

Figure 31. Panel Diagram Showing Vein Pattern in the Don Pepe Section, Caracota Mine.

5. Caracota mine

The Caracota mine is situated at 70 km south of Potosi (Figure 4). This mine is owned and operated by the private mining company, Empresa Minera Unificada S.A. (EMUSA). It is now active and representative mine in the antimony belt extending from Porco to Tupiza (Figure 29). The production was approximately 800 tons per month containing 3.5% Sb and 45 g/t Ag in 1981.

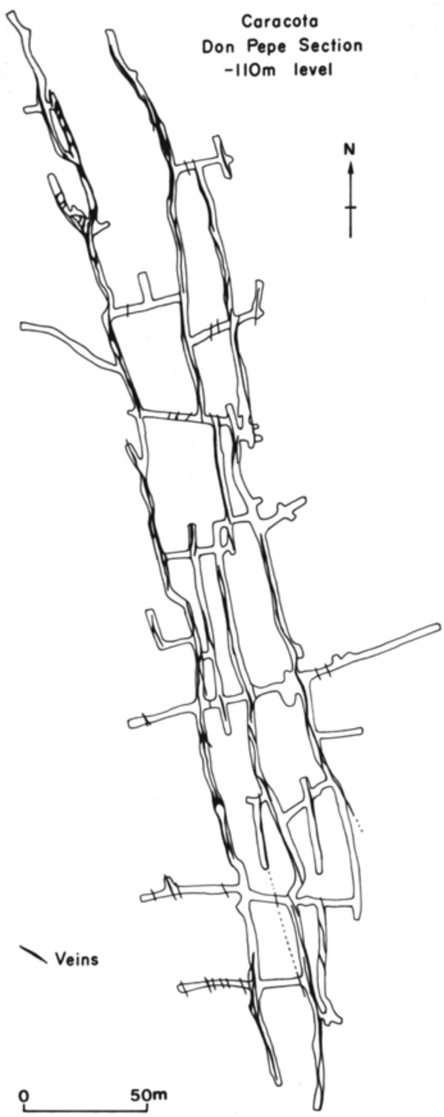

FIGURE 32. VEINS AT THE LEVEL-110 m (3,630 m above sea level), DON PEPE SECTION, CARACOTA MINE.

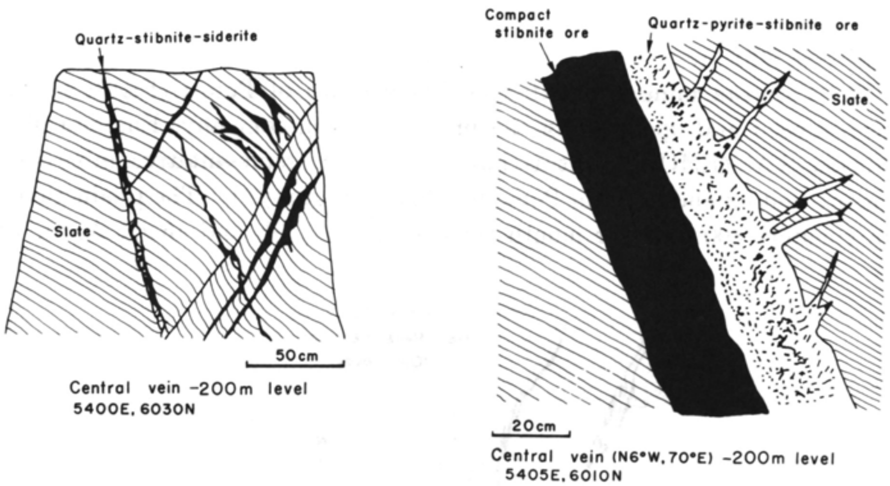

FIGURE 33. SKETCHES SHOWING VEIN FEATURES IN THE DON PEPE SECTION, CARACOTA MINE.

The content of gold was 5 to 7 g/t within a vein.

Two vein swarms are exploited at Don Pepe section in north and Santa Terecita section in south (Figure 30). Both veins occur in fractures along NNW trending faults which develop at the eastern wing of an anticline axis. Host rock is entirely composed of folded Ordovician slate intercalated with thin sandstone bed. No igneous rock is found in the mining area nor in the antimony belt.

In the Don Pepe section, more than ten veins have been detected and exploited in eleven levels as shown in Figure 31. Three main veins, called East, Central and West veins, extend more than 500 m toward the strike direction of N10°-15°W, and dip 65° to 75°E (Figure 32). They are principally simple lodes and narrow less than 50 cm in width (Figures 33 and 34-C, D). Stibnite, quartz and pyrite are main constituents, and minor amounts of dioctahedral chlorite, siderite, ferberite, sphalerite, zinckenite, and native gold are also found in a vein (Figure 35-A, B).

Massive stibnite shows granular texture of fine grains, 10 to 200 μm in size, however, acicular stibnite attains 5 mm in length. Chemical composition of stibnite is very close to theoretical one containing less than 0.1 wt % of bismuth or lead.

It is quite nothworthy that the paragenesis of ferberite and stibnite is found in a druse of quartz in the vein (Figure 35-C, D). Acicular crystals of stibnite overgrow on tabular or prismatic euhedral crystals of ferberite, and sometimes an edge of stibnite needles sticks vertically into a crystal face of ferberite under a microscope. This fact clearly suggests that stibnite grew at later time of ferberite crystallization. Ferberite contains 1.1 to 4.0% of huebnerite molecule. Native gold, 50 to 100 μm in size, occurs as either with stibnite or isolatively within

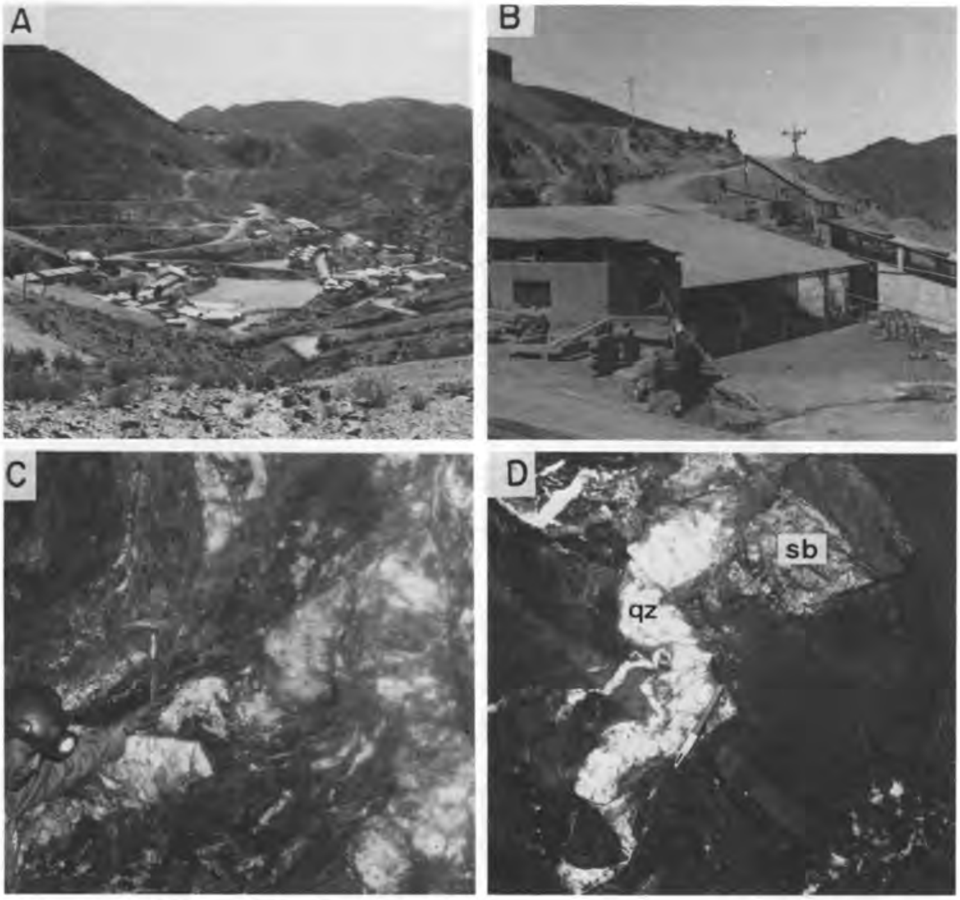

FIGURE 34. SCENERY AND ORE VEINS OF THE CARACOTA MINE.
A : A distant view of the Caracota mine. B : The mine office of Caracota. C : Stibnite-quartz vein, Central vein, 240 level, Don Pepe section. D : Stibnite(sb)-quartz (qz) vein, Central vein, 200 level, Don Pepe section.

quartz grains. Average of nine analyses of native gold is $Au_{0.98}Ag_{0.02}$. Quartz successively deposits throughout all the mineralization of the veins, however, earlier quartz is massive and milky white in color and later one frequently takes radiated masses with transparent pyramids. Abundant fluid inclusions are found in later quartz, and their homogenization temperatures take a wide range from 158° to 342°C as shown in Figure 36. Most are two phase aqueous inclusions but subordinate amounts of three phase inclusions containing CO_2 are sometimes found. The mineral sequence is schematically determined as shown in Figure 37.

From the data of paragenetic relations such as stibnite and ferberite association and homogenization temperatures, it is interesting that even an antimony deposit as described represents a xenothermal mineralization feature in Bolivia.

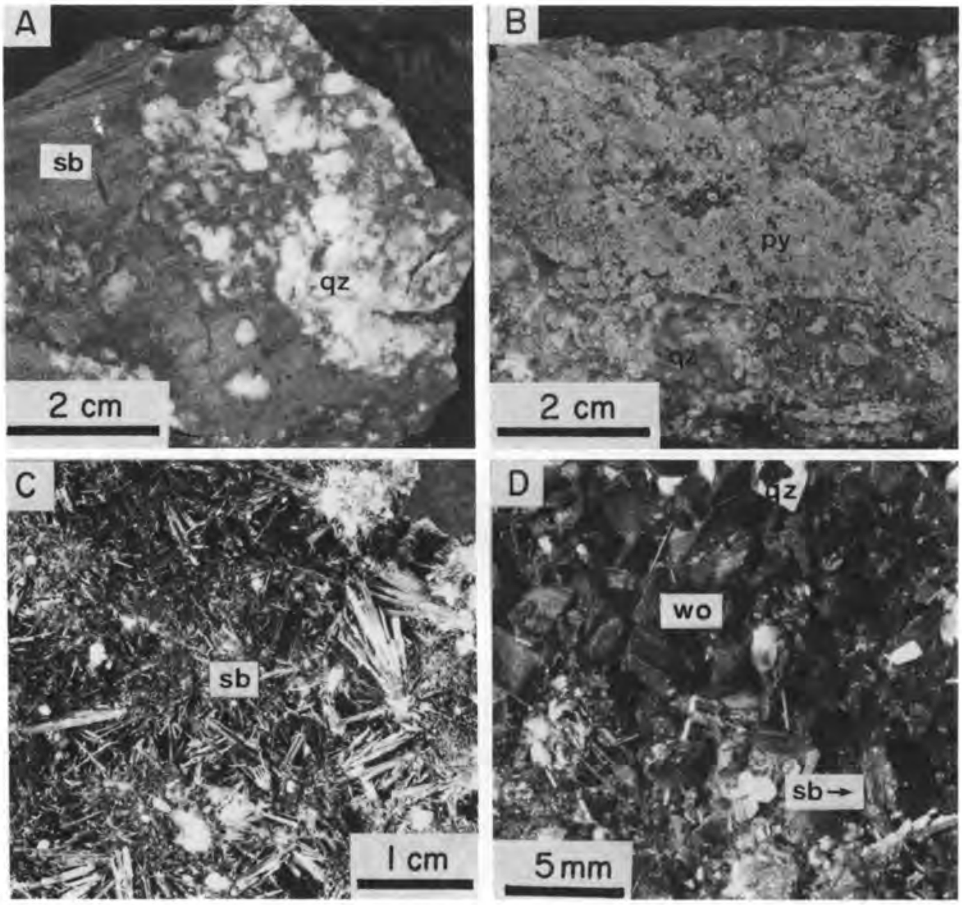

FIGURE 35. PHOTOGRAPHS OF VEIN MINERALS FROM THE CARACOTA MINE.
A: Stibnite (sb) associated with quartz (qz), Central vein, 200 level, Don Pepe section (8172320). B: Stibnite (sb) associated with quartz (qz) and pyrite (py), Este vein, 110 level, Don Pepe section (8172312). C: Acicular crystals of stibnite (sb), EMUSA vein, 130 level, Don Pepe section (8172338). D: Wolframite (wo) associated with stibnite (sb) and quartz (qz), Central vein, 110 level, Don Pepe section (8172336).

6. Kumurana mine

The Kumurana mine is located at 30 km south of Potosi city (Figure 4) and southern end of the Kari Kari caldera (Figures 5-B and 6-A, B). This is small mine operating discontinuously by private mining company, and working at Porvenier and 0 levels (Figure 38-A, B).

Geology around the mine is mainly composed of Ordovician system, Kari Kari pyroclastics and plutonic intrusion in Tertiary (Figure 7). The Ordovician system is composed of slate and quartzite. Dacitic tuff breccia of Kari Kari pyroclastics has biotite, garnet, quartz and plagioclase as phenocrysts and fragments, and slate and quartzite fragments of Ordovician in the volcanic matrix (Figures 10-C and 11-A). Plutonic rock which corresponds to granite is composed of biotite, hornblende, quartz, orthoclase and plagioclase as principal constituent minerals (Figure 11-B). At near intrusive rock, Ordovician slate and quartzite are weakly affected by contact metamorphism, and recrystallized quartz and muscovite, and small amounts of tourmaline are formed.

Ore veins as Amarilla, Maria, Llike Amalia etc. are mainly found in intrusive granite (Figure 38-B). They tend to become thin and low grade in the Ordovician system. High grade tin ores, about 2.0 wt % Sn, occur along the intersections of these veins. Granite near the veins is strongly altered by tourmalinization. Ores from this mine are principally composed of cassiterite, sphalerite, pyrrhotite, chalcopyrite, quartz and tourmaline associated with minor amounts of bismuthinite, stannite and marcasite etc. Cassiterite shows euhedral to subhedral crystal from 0.1 to 0.3 mm in size microscopically. It usually associates with

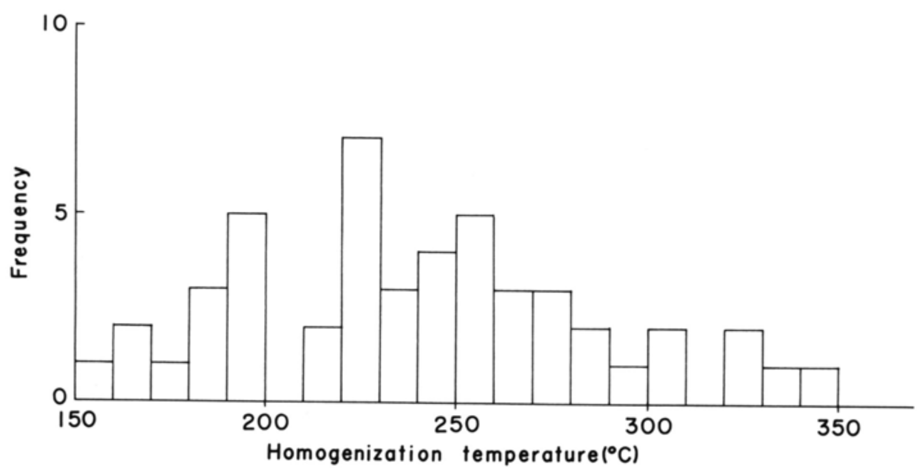

FIGURE 36. HISTGRAM OF HOMOGENIZATION TEMPERATURE OF FLUID INCLUSIONS IN QUARTZ FROM THE DON PEPE SECTION, CARACOTA MINE.

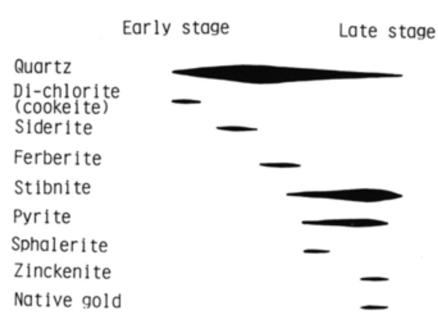

FIGURE 37. MINERALIZATION SEQUENCE OF MINERALS FROM THE DON PEPE SECTION, CARACOTA MINE.

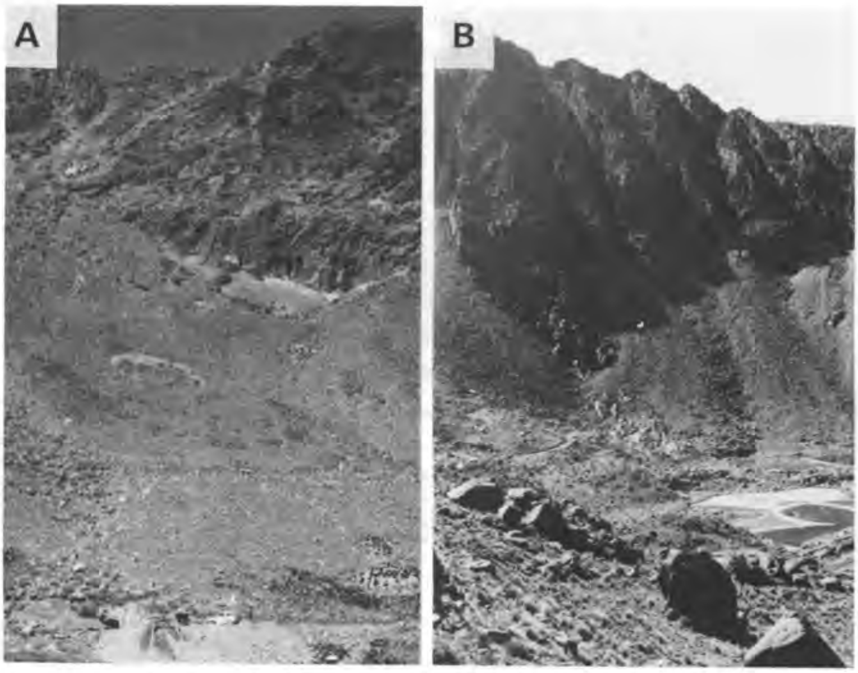

FIGURE 38. SCENERY OF THE KUMURANA MINE.
A : The adit of the 0 level. B : Granite intrusive.

quartz, pyrrhotite, and sphalerite, and is replaced by stannite and chalcopyrite. Chalcopyrite accompanied by pyrrhotite, sphalerite, bismuthinite and stannite has sphalerite stars as exsolution products. Pyrrhotite and chalcopyrite are often replaced by marcasite of late stage.

7. Khomer Khocha and Illimani mines

The Khomer Khocha mine (4,473 m elevation) located at about 500 m northwest of the Kumurana mine was worked as a vein-type silver mine, but it has been now closed. Ore vein, 30 to 40 cm in width, has a strike of N5°E and dips to 60° E. It is embedded in Kari Kari pyroclastics as dacitic rocks and Ordovician slate, and composed of quartz, galena, sphalerite, pyrite and jamesonite etc. Andorite-like sulfosalt as silver bearing mineral is found in association with galena, jamesonite, sphalerite, pyrite and quartz microscopically.

The Illimani mine (about 4,600 m altitude) is located at 12 km southeast of Potosi city and situated in the middle part of the Kari Kari caldera. It has been operated as a vein-type silver-lead-zinc mine, but it has been now closed. High grade ores containing 42% Pb and 0.7% Ag, and 28 to 36% Zn occurred from the mine (Murillo *et al.*, 1968). The ore veins, 10 to 30 cm wide, having strike N5°E and dip 80°E, develop in the Kari Kari pyroclastics which consists of hard welded dacitic tuff breccia with biotite, quartz, garnet, plagioclase and orthoclase as fragments of phenocrysts in matrix. It is hydrothermally altered by tourmalinization and kaolinization near the veins. The principal minerals from the mine are galena, sphalerite, pyrite, tetrahedrite, quartz, siderite and rhodochrosite with small amounts of chalcopyrite, bournonite and jamesonite. As silver mineral, tetrahedrite, 0.5 to 3 mm in size, containing 15 to 16 wt % Ag is mainly found in association with galena, pyrite and bournonite, and also occurs in galena as fine grain, about 10 to 30 μm in size.

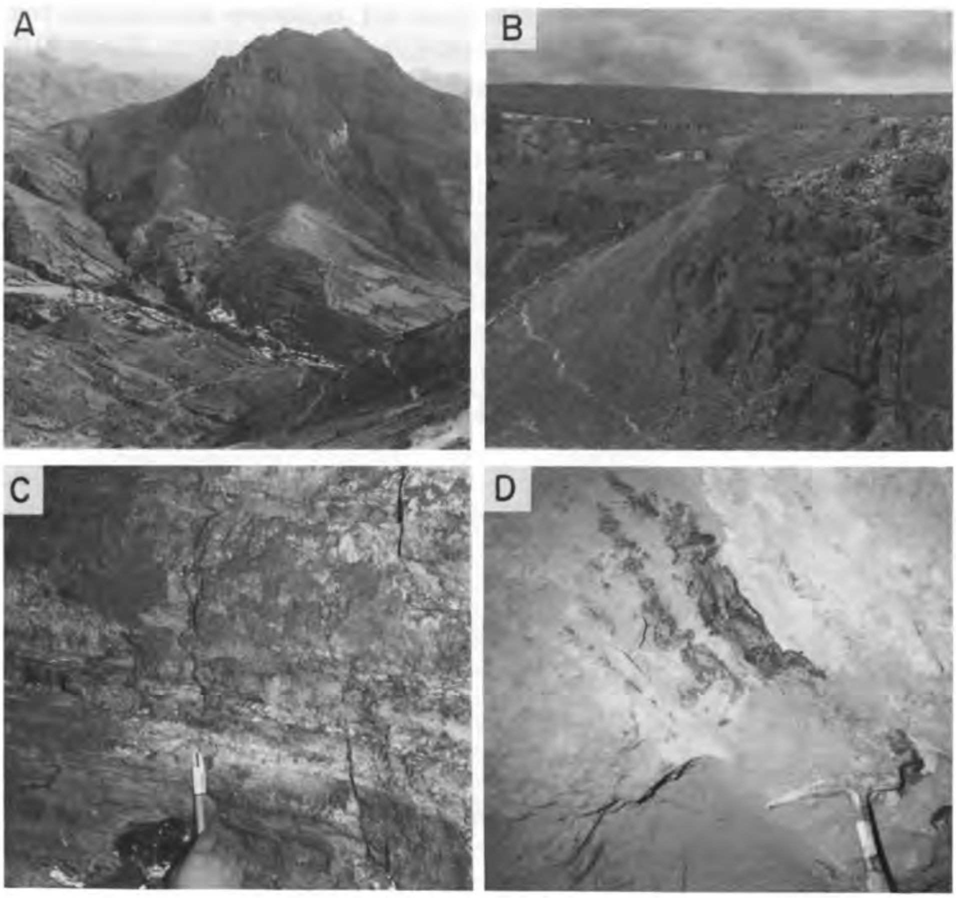

FIGURE 39. SCENERY AND ORE BED OF THE COLAVI MINE.
A : A view of the Colavi mine. B : Many small adits arranged along bedding of Cretaceous sediments. C : Tin ore beds composed of pyrite, cassitarite and kaoline concordantly embedded in Cretaceous sandstone, Manto Uno. D : Cassiterite (dark gray) and kaoline (light gray) beds in Manto Cristina.

8. Colavi mine

The Colavi mine (Figure 39-A) belonging to COMIBOL is located at 35 km northeast of Potosi. The production from this mine was about 5,700 tons containing 0.7 wt % Sn as crude ore in June of 1981. Semiconcentrated ore of about 2 to 3 wt % Sn obtained by hand picking and screening the crude ore was 650 to 1,000 tons per month. Workers in the mine are 330 persons, and within them the miners for underground, 180 men. Ore deposits of this mine known as a "Manto" type tin deposit in Bolivia, develop as the stratabound form (Figure 39-B, C, D) in the Cretaceous formation consisting of red sandstone and dacitic tuff. Geology around the Colavi mine (Turneare, 1960) as shown in Figure 40 is composed of Ordovician slate, Silurian sandstone and Cretaceous formation which corresponds to the Torotoro Formation. Some dacitic intrusive rocks are found in

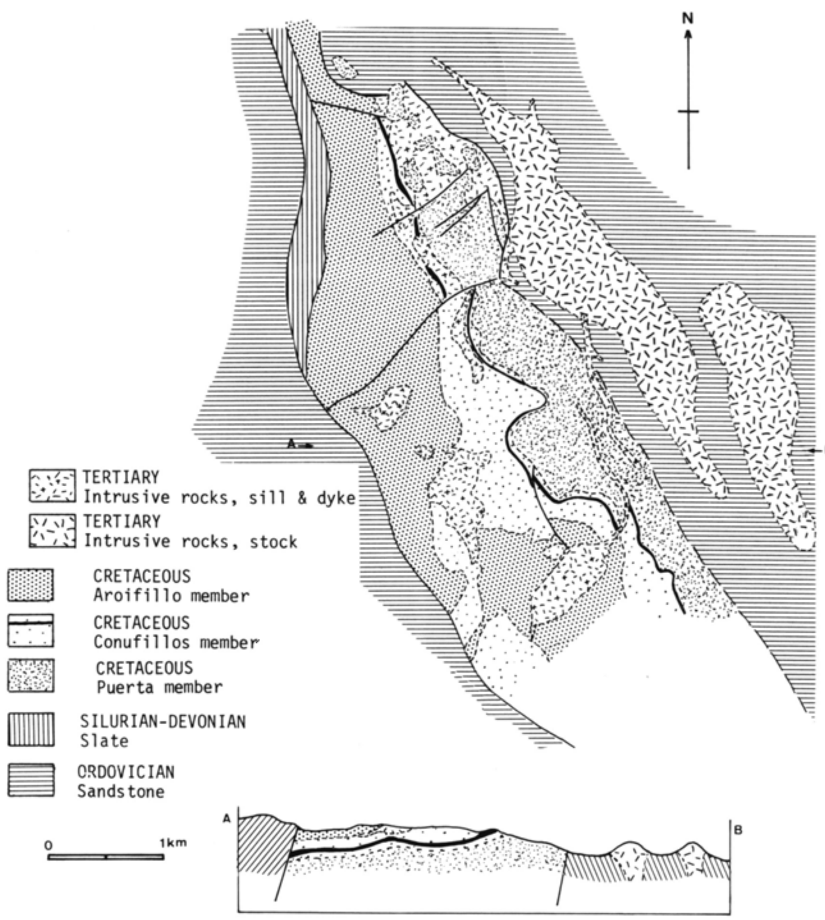

FIGURE 40. GEOLOGICAL MAP OF THE COLAVI MINE (After Turneare, 1960).

Ordovician and Cretaceous systems as stock, sill or dyke. The Cretaceous formation is divided into three members as follows: Puerta Member composed of coarse grained sandstone with red to brown colors, Conufillos Member of sandstone and dacitic tuff, and Aroifillo Member of red shale. The Manto type tin deposits are included in the Conufillos Member as seen in cross section of Figure 40. Six ore beds so-called "Manto" have been found in about 80 m thick of sandstone of the Colavi mining district, and are named Manto Tres, Manto Dos, Manto Uno, Manto Cristina, Kara Manto, Kachi Manto in ascending order as shown in Figure 41. They have thickness from 0.8 to 1 m, and are being mined at six levels of Cervantes (4019 m elevation), Porvenir (3983 m), Zenteno (3944 m), Banini (3904 m), Ayacucho (3849 m) and Garcia (3906 m). These ore beds have general strike of N0° to 20°W and dip to 20°-30°W (Figure 42), and are concordant to sandstone or dacitic tuff in the Cretaceous formation as seen in Figure 40.

Ore minerals are mainly composed of pyrite, hematite, and cassiterite as shown in Figure 43-A, B and C. However, sphalerite and galena are very rare. Gangue minerals such as quartz, siderite and kaoline are usually found. Sometimes, big crystal of barite with about 10 cm in size occurs in sandstone at 20 cm above the Manto Dos. Cassiterite usually appears as pale brown colored powder or aggregate of very fine grain of submicroscopic size, less 1.0 μm, but sometimes can be recognized its crystal form under the microscope as shown in Figure 43-C. Pyrite occurs as a main constituent mineral and shows often idiomorphic crystal, usually 2 to 3 mm, rarely 2 to 5 cm in size of octahedral form (Figure 43-B, D). It has growth zoing in general as seen in Figure 43-D. Hematite appears as aggregate of thin platy crystals, 1 to 3 mm in size, in intimate association with pyrite

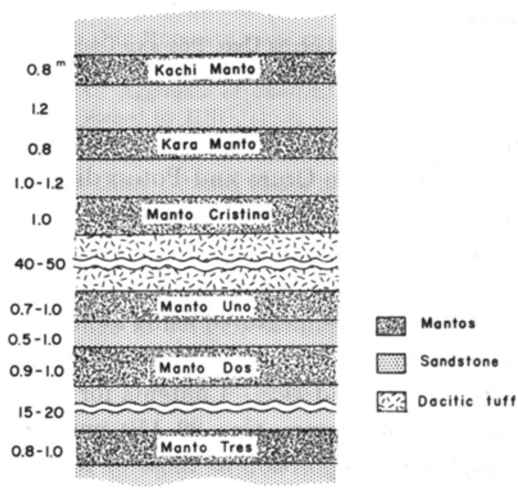

Figure 41. Schematic Section Showing of "Mantos" in the Colavi Mine.

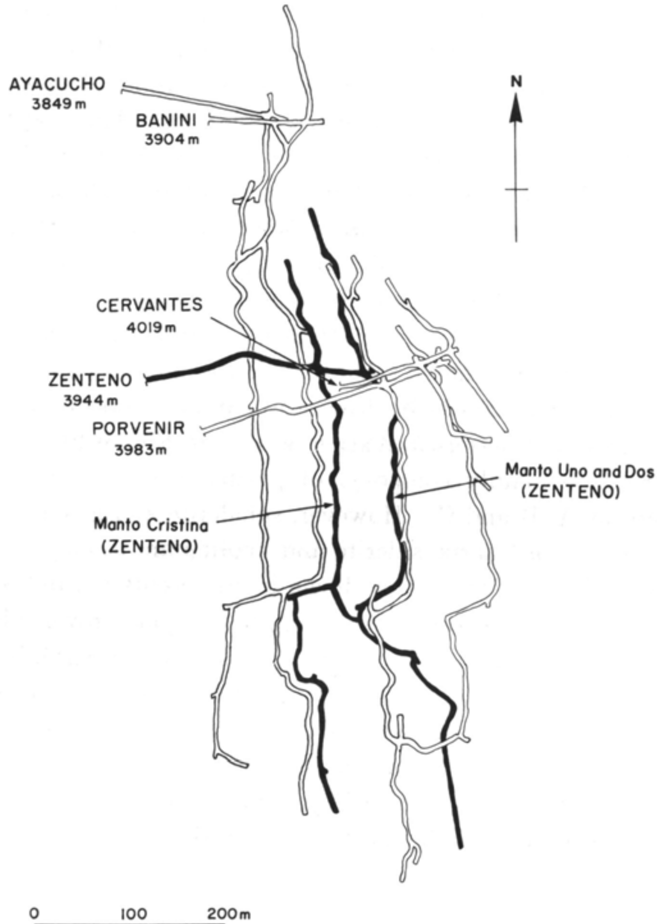

FIGURE 42. ORE BEDS (MANTOS UNO, DOS AND CRISTINA) AT THE ZENTENO LEVEL, COLAVI MINE.

and sometimes barite. Polymetallic sulfide or sulfosalt minerals commonly found in the vein-type tin deposits of the Oruro and Potosi districts do not occur from this mine. There also is no description on silver, bismuth and antimony bearing minerals from the mine.

Amounts of minor elements such as Cu, Zn, Mn, Co, and Ni in pyrite from the Mantos Uno, Dos, and Cristina were measured using atomic absorption spectrometer. Their results are given in Table 4 compared with those of pyrite occurring in sandstone betweem Mantos Uno and Dos. Contents for elements are Cu : 1.0–41 ppm, Zn : 0.6–35 ppm, Mn : 6–39 ppm, Co : 22–150 ppm and Ni : 27–418 ppm. Amounts of Co are roughly in proporition to those of Ni. Carstens (1941, 1942) and Hegemann (1948) suggested that sedimentary pyrite has lower Co content than 100 ppm and higher Ni content than 500 ppm, and that Co/Ni values of

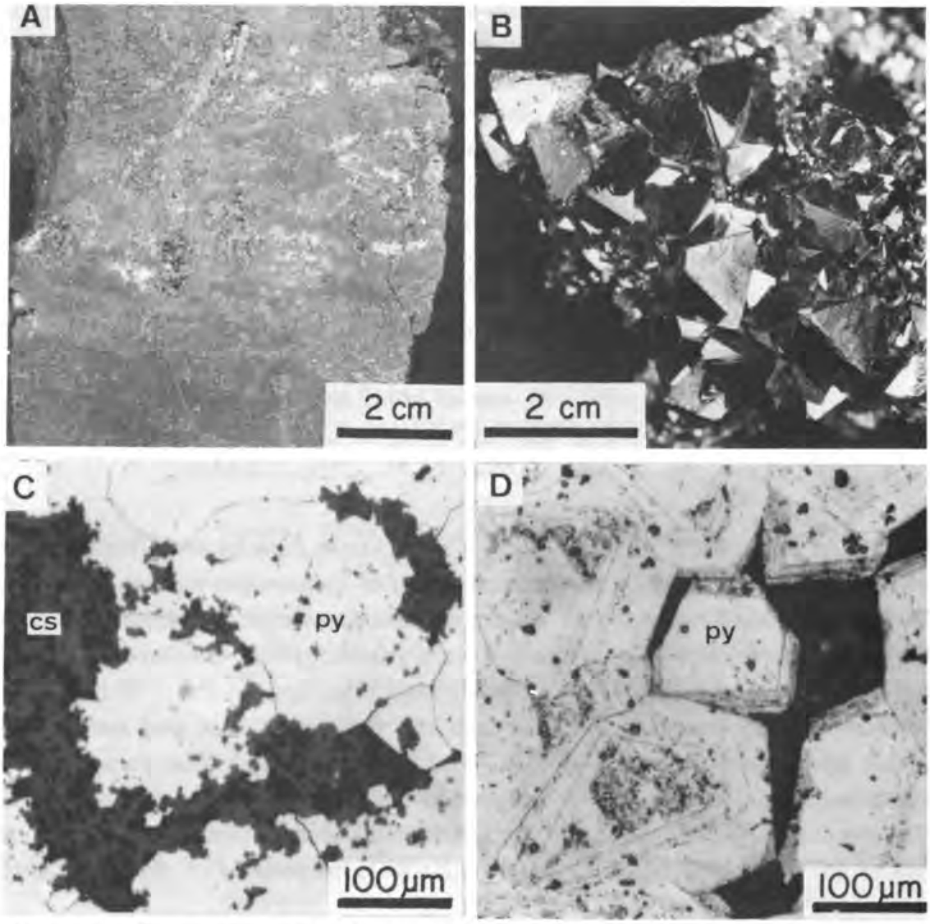

FIGURE 43. PHOTOGRAPHS OF ORE MINERALS FROM THE COLAVI MINE.
A: Aggregate of pyrite including fine grained cassiterite (8172113). B: Euhedral pyrite (py) crystal (8172128). C: Aggregate of cassiterite (cs) and pyrite (py) (8172143). D: Zonal structure in pyrite etched by HNO_3 (1 : 1) (8172128).

sedimentary pyrite are less than 1.0 and those of hydrothermal one, more than 1.0. These values of pyrite from the Colavi mine are from 0.13 to 1.45. From the data, its origin can not make clear whether it is sedimentary or not. However, there is a possibility that the tin bearing pyritic ore beds of the Colavi mine have been formed at the Cretaceous age as syngenetic deposits.

ORE MINERALS

The ore and gangue minerals from the mines in the Potosi district are given in Table 5. Also the kinds and amounts of minerals from each mine are shown in Table 6, in which size of circles indicates amount of the minerals. Pyrite and sphalerite are most common ore minerals as found from all the mines. Cassiterite

TABLE 4. CONTENTS OF MINOR ELEMENTS IN PYRITE FROM THE COLAVI MINE.

	Concentration in ppm Cu	Zn	Mn	Co	Ni	Co/Ni
In Manto Uno						
(1)	17	35	13	51	83	0.62
(2)	41	15	4.4	55	418	0.13
(3)	1.0	31	3.1	40	27	1.45
(4)	2.2	0.6	39	76	70	1.08
(5)	3.0	2.9	4.4	22	115	0.19
(6)	15	22	12	150	240	0.62
(7)	3.1	22	26	91	182	0.50
(8)	8.6	21	27	24	68	0.35
In Mato Dos						
(1)	1.5	9.2	7.4	95	70	1.36
In Manto Cristina						
(1)	1.8	9.7	6.1	127	95	1.35
(2)	25	21	1.6	93	228	0.41
In sandstone between Mantos Uno and Dos						
(1)	1.6	10	5.8	36	72	0.50
(2)	1.5	4.6	5.3	47	40	1.16

also occurs from most of the mines except the Khomer Khocha and Illimani mines, but grain size of cassiterite varies from 2 mm of megascopic size as it from the Potosi and Kumurana mines to 1.0 μm of submicroscopic one from the Colavi mine. Cassiterite is closely associated with quartz, pyrite, sphalerite, and sometimes assembles to stannite, arsenopyrite and chalcopyrite etc. Wolframite is found in the ores from the Potosi, Porco and Caracota mines, and assembles to quartz, pyrite, chalcopyrite, stannite, and cassiterite etc. The paragenesis of wolframite and stibnite are found within druse of quartz in the ore vein of the Caracota mine. Wolframite from the Potosi and Caracota mines has the compositions of 4.6 to 7.1 and 1.1 to 4.0 mole % $MnWO_4$, respectively. Pyrite from the

TABLE 5. ORE AND GANGUE MINERALS FOUND FROM THE MINES IN THE POTOSI DISTRICT.

Mineral name	Chemical formula	Mineral name	Chemical formula
Pyrite	FeS_2	Andorite	$AgPbSb_3S_6$
Marcasite	FeS_2	Fizelyite	$Ag_3Pb_7Sb_{11}S_{25}$
Arsenopyrite	$FeAsS$	Electrum	(Au,Ag)
Pyrrhotite	$Fe_{1-x}S$	Cassiterite	SnO_2
Chalcopyrite	$CuFeS_2$	Hydrocassiterite	$(Sn,Fe)(O,OH)_2$
Galena	PbS	Wolframite	$(Fe,Mn)WO_4$
Spahlerite	ZnS	Hematite	Fe_2O_3
Wurtzite	ZnS	Quartz	SiO_2
Stibnite	Sb_2S_3	Siderite	$FeCO_3$
Stannite	Cu_2FeSnS_4	Calcite	$CaCO_3$
Tetrahedrite	$(Cu,Ag,Fe,Zn)_{12}Sb_4S_{13}$	Rhodochrosite	$MnCO_3$
Bismuthinite	Bi_2S_3	Barite	$BaSO_4$
Pyrargyrite	Ag_3SbS_3	Alunite	$(K,Na)Al_3(SO_4)_2(OH)_6$
Bournonite	$CuPbSbS_3$	Phosphophyllite	$Zn_2(Fe,Mn)(PO_4)_2\cdot 4H_2O$
Jamesonite	$FePb_4Sb_6S_{14}$	Tourmaline	$NaFe_3Al_6B_3Si_6O_{27}(OH)_4$
Semseyite	$Pb_9Sb_8S_{21}$	Kaolinite	$Al_2Si_2O_5(OH)_2$
Boulangerite	$Pb_5Sb_4S_{11}$	Sericite	$KAl_2Si_3AlO_{10}(OH)_2$
Zinckenite	$Pb_9Sb_{22}S_{42}$		

Colavi mine is an idiomorphic octahedral form, commonly 2 to 3 mm, rarely 2 to 5 cm in size. Stannite is a microscopic mineral, and occurs in granular forms associated with cassiterite, pyrite, sphalerite, bournonite and wolframite etc. from the Potosi mine. Pyrrhotite and chalcopyrite are essential minerals in the ore from the Kumurana and assemble to quartz, sphalerite, bismuthinite and cassiterite. The chalcopyrite has fine star-like crystals of sphalerite as exsolution products under the microscope. Bismuthinite occurs in the ores from the Potosi and Kumurana mines, and associates with quartz, sphalerite and cassiterite. Marcasite and wurtzite generally are products of the late stage mineralization in the Potosi, Huari Huari and Kumurana mines. Sulfosalt minerals such as tetrahedrite, jamesonite, pyrargyrite, bournonite, boulangerite, zinckenite, semseyite, andorite and fizelyite etc. are found in the ores from the Potosi, Huari Huari, Khomer Khocha and Illimani mines. They are in general found as products of

TABLE 6. MINERALS OCCURRING FROM EACH MINE IN THE POTOSI DISTRICT AND THEIR AMOUNTS.

Minerals \ Mines	Potosi	Porco	Huari Huari	Caracota	Kumurana	Khomer Khocha	Illimani	Colavi
Tourmaline	○				○		∘	
Quartz	◯	◯	◯	◯	◯	◯	◯	◯
Cassiterite	○	○	○	∘	○			◯
Wolframite	○	○		∘				
Hematite								◯
Pyrite	◯	◯	◯	◯		◯	◯	◯
Marcasite	∘		∘		○			
Arsenopyrite	○	○						
Pyrrhotite					◯			
Chalcopyrite	○	○			◯		∘	
Galena	○	◯	∘			◯	◯	∘
Sphalerite	◯	◯	◯	∘	◯	◯	◯	∘
Wurtzite	∘							
Stibnite	∘			◯				
Stannite	○							
Tetrahedrite	○						◯	
Bismuthinite	∘				○			
Pyrargyrite	∘		∘					
Fizelyite	∘							
Bournonite	○						○	
Jamesonite	∘		○			○	∘	
Semseyite	○							
Boulangerite	∘		○					
Siderite			○	○			◯	○
Barite								○
Alunite	◯							
Phosphophyllite	∘							
Kaoline	○		◯				◯	◯
Sericite	∘		○					

the middle stage mineralization. Among them, tetrahedrite, pyrargyrite, andorite, fizelyite, semseyite, boulangerite and zinckenite etc. are essential minerals of silver ores from mines as above. As gangue minerals, quartz occurs as a principal mineral in intimate association with ore minerals from all of the mines in the Potosi district. Tourmaline is formed as a product of high temperature mineralization at early stage in the ore veins and country rocks near the veins as found in the Potosi, Kumurana and Illimani mines, and associates intimately with quartz. Meanwhile kaoline, sericite, alunite and siderite also are essential gangue minerals at late stage of mineralization in the Potosi, Huari Huari and Illimani mines. They often cut such ore minerals as pyrite, sphalerite, cassiterite and arsenopyrite. Barite occurs as a common gangue mineral from the Colavi mine, and sometimes appears as large platy crystal, 10 cm in size. Phosphophyllite, which is very rare hydrous phosphate mineral, is found only in druse of the ore vein in the Potosi mine.

Summary

1. Geology of the Potosi district is composed of the formations of Ordovician and Silurian, Cretaceous, Miocene, and Quaternary. The Ordovician formation consists of mostly slate and partly quartzite distinctly folded and faulted, and the Silurian one, shale, quartzite, and their alternation. The Cretaceous system is divided into two formations, lower and upper. The former (Torotoro Formation) consists of red, green and white sandstone, while the latter (Miraflores Formation), alternation of green, brown and gray sandstone, mudstone and shale. The Miocene system is composed of the Mondragon, Agua Dulce, San Roque, Kari Kari pyroclastics, Canteria, Pailaviri, Caracoles, Los Frailes and Tollocci Formations in ascending succession.

2. As intrusive rocks, sheets and dykes of dacite intruded into the Cretaceous formation, dacite stocks as Cerro Rico, and Kumurana granite are found. The dacite stock of Cerro Rico is intensely altered by late stage hydrothermal actions. K-Ar ages of Kumurana granite (Granodiorite according to Evernden *et al.*, 1977 and Grant *et al.*, 1979b) are from 20.5 to 21.2 Ma. Also, those of altered Cerro Rico stock are 13.2 to 14.1 Ma as given in Table 2.

3. There are many metallic mines of silver, tin, zinc, lead and antimony etc. in the Potosi district. Among them, the mines of Potosi (Empresa Minera Unificada del Cerro de Potosi, tin and silver), Porco (zinc, lead and silver), Huari Huari (zinc and tin), Caracota (antimony), Kumurana (tin) and Colavi (tin) are working now. They except Colavi are hydrothermal deposits filled up in the fissures developed in the formations of Ordovician and Miocene and altered dacite stock. Meanwhile the Colavi mine is Manto type tin deposits found in the Cretaceous Torotoro Formation, especially the Conufillos Member.

4. The mineralizations which produced the veins occurred at late Miocene,

and as a result the polymetallic ores consisting of cassiterite, wolframite, stannite, pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, tetrahedrite, stibnite, jamesonite, fizelyite, semseyite, and pyrargyrite etc. with gangue minerals of quartz, tourmaline, alunite, sericite and kaoline etc. were formed.

5. The ore deposits of the Potosi mine are composed of hydrothermal veins filled up many fissures in Ordovician slate, dacitic tuff (Caracoles Formation) and tuff breccia (Pailaviri Formation) and dacite stock. These veins, commonly 10 to 50 cm in width, consist of pyrite, sphalerite, cassiterite, arsenopyrite, galena, marcasite, wurtzite and small amounts of wolframite, stannite, stibnite, tetrahedrite, bismuthinite, fizelyite, pyrargyrite, semseyite, and boulangerite etc. in intimate association with gangue minerals of quartz, tourmaline, alunite, kaoline, sericite and siderite etc. Among them, essential minerals are pyrite, sphalerite, cassiterite, arsenopyrite, galena, quartz, alunite, kaoline and sericite. The veins usually show banding structure. In this case pyrite and sometimes sphalerite with quartz, 5 to 20 cm in width, commonly occur as band in both sides of the outer zone of the vein, meanwhile alunite, kaoline and sometimes sericite, 5 to 10 cm in width, occupy inner zone of the vein. Cassiterite appears as thin symmetric bands, 2 to 5 mm wide, between outside pyrite and inside quartz, alunite and kaoline in the vein. Large amounts of semseyite occur as principal ore mineral form the Don Mauricio vein. It closely assembles with pyrite, sphalerite, galena, tetrahedrite, jamesonite, fizelyite, and quartz etc., but no cassiterite.

6. The mineralization sequence of ore and gangue minerals from the Potosi mine is shown in Figure 24. That is, tourmaline and some quartz were formed at the earliest stage of mineralization. Pyrite and sphalerite were mostly crystal lized during early stage continued after mineralization of tourmaline. Cassiterite was produced in the crustified band after main pyrite. On the other hand, wolframite was formed at relatively later stage than principal mineralization of cassiterite. At the middle stage of mineralization, some quartz, stannite, galena, bismuthinite, chalcopyrite, arsenopyrite, tetrahedrite, sulfosalt minerals such as bournonite, semseyite, jamesonite, pyrargyrite, fizelyite etc. were produced. Alunite, kaoline and sericite which are principal gangue minerals were formed by mineralization of the late stage.

7. The ore deposits of Porco mine are composed of several veins developing in the altered dacite and its tuff which belong to the Agua Dulce Formation of Miocene. San Antonio vein, most principal one in the mine, has such scale as 1,500 m long, 300 m deep and 1.2 to 2.0 m wide, and consists of pyrite, sphalerite, galena and quartz etc. The galena rich ore from the M-Uestra Grande vein sometimes contains very high grade of silver, 2,300 g/t Ag. Rajo Zuniga vein which was mined out by open pit consists of cassiterite, wolframite, galena and pyrite etc.

8. The fissure filling vein of the Huari Huari mine having strike NNE, dip 80°

W or E, 400 to 900 m long, 20 to 200 cm wide and 450 m in depth, develops in Ordovician slate and sandstone, and partly Silurian slate. As ore and gangue minerals from the mine, sphalerite, pyrite with small amounts of galena, marcasite, jamesonite, bourlangerite, cassiterite and pyrargyrite, and quartz, kaoline and siderite etc. are found. Cassiterite occurs in sphalerite as small grains, about 10 μm in size, and galena, boulangerite and pyrargyrite associate with each other. Jamesonite appears as irregular veinlets at the outer zone in the vein. The production of the crude ores from the mine containing 8.20% Zn, 0.41% Sn and 100 g/t Ag is 4,600 tons per month.

9. The ore veins, less than 50 cm in width, of the Caracota mine which is working for antimony ore (3.5% Sb) consist of stibnite, quartz and pyrite as principal constituents with small amounts of chlorite, siderite, ferberite, cassiterite, sphalerite zinckenite, and native gold. In massive antimony ore, stibnite occurs in aggregate of irregular grain, 10 to 200 μm in size, and acicular crystals, 5 mm in length, with quartz. It is quite noteworthy that the paragenesis of ferberite and stibnite is found in a druse of quartz in the vein. In this case, acicular crystals of stibnite overgrow on tabular or prismatic crystals of ferberite.

10. The ore veins, such as Amarilla, Maria and Llike Amalia, of the Kumurana mine are found in Kumurana granite and Ordovician slate and quartzite. The tin ore, about 2.0% Sn, consists of cassiterite, sphalerite, pyrrhotite, chalcopyrite, quartz and tourmaline associating with small amounts of bismuthinite, stannite and marcasite etc. Chalcopyrite has sphalerite stars as exsolution products.

11. Ore deposits of the Khomer Khocha mine are veins having strike N5°E, dip 60°E and 30 to 40 cm in width, embedded in the Kari Kari pyroclastics of dacitic rocks and Ordovician slate, and composed of quartz, galena, sphalerite, pyrite, jamesonite and andorite-like mineral etc.

The ore vein of the Illimani mine having strike N5°E, dip 80°E and 10 to 30 cm wide, develops in the Kari Kari pyroclastics of welded dacitic tuff which is hydrothermally altered by tourmalinization and kaolinization near the vein. The principal minerals from the mine are galena, sphalerite, pyrite, tetrahedrite, quartz, siderite and rhodochrosite with small amounts of chalcopyrite, bournonite, and jamesonite. As silver bearing mineral tetrahedrite containing 15 to 16 wt % Ag is found in association with galena, sphalerite, pyrite and bournonite. High grade ore contains 42% Pb, 28 to 36% Zn and 0.7% Ag.

12. Manto type tin deposits, which consist of six ore beds, of the Colavi mine occur in sandstone, about 80 m thick, of the Conufillos Member of the Cretaceous Torotoro Formation. The ores are composed of pyrite, cassiterite, hematite, quartz, kaoline, sericite and barite etc. Cassiserite commonly appears as brownish powder or very fine grained aggregate in submicroscopic size less than 1.0 μm. It is not clear whether this Manto type deposits are syngenetic or not,

but there is a possibility that the tin bearing pyritic ore beds may be sedimentary deposits.

13. From the vein-type deposits found in the Potosi district, many ore and gangue minerals occur as mentioned above. It is noticeable that such high temperature minerals as cassiterite, wolframite and tourmaline coexist with low temperature minerals as stibnite, jamesonite, silver bearing minerals, wurtzite, marcasite, alunite, kaoline, sericite and siderite etc. in the same vein, that is telescoping. In general, such high temperature minerals as above are crystallized at earlier stage with quartz, pyrite and sometimes sphalerite, while the low temperature minerals are formed at later stage during mineralization. Hydrothermal solution which formed the ore veins are supposed to have become to acidic at late stage from occurrence of wurtzite, marcasite, alunite and kaoline etc. as same as reported about the ore veins in the Oruro district.

14. The mineralization which produced polymetallic ores as mentioned above was generated by Miocene igneous activities due to such shallow depth intrusion as dacite stock. The telescoping ores in which high and low temperature minerals coexist suggest that the ore deposits in the Potosi district except Colavi were produced under xenothermal condition similar to polymetallic deposits in the other districts of eastern cordillera of Bolivia.

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References

Ahlfeld, F. and Schneider-Scherbina, A., 1964, Los yacimientos minerals y de hidrocarburos de Bolivia. Dept. Nacional de Geologia, La Paz.

Carstens, C.W., 1941, Uber sedimenare Schewefelkies Vorkommen. Kgl. Norsk. Vidensk. Selskab.

Forh., 14.
Carstens, C.W., 1942, Ein neuer Beitrag zur geochemischen Charakteristik norwegischer Schwefelkieserze. Kgl. Norsk. Vidensk. Selskab. Forh., 15.
Claure, H.V. and Minaya, E.R., 1979, Mineralizacion de los Andes Bolivianos en relacion con la Placa de Nazca. Servicio Geol. Bolivia, La Paz.
Evans, D.L., 1940, Structure and mineral zoning of the Pailaviri section, Potosi, Bolivia. Econ. Geol., **35**, 737-756.
Evernden, J.F., Kriz, S.J. and Cherroni, M.C., 1977, Potassium-argon ages of some Bolivian rocks. Econ. Geol., **72**, 1042-1061.
Francis, P.W., Baker, M.C.W. and Halls, C., 1981, The Kari Kari caldera, Bolivia, and the Cerro Rico stock. Jour. Volcanology Geothermal Res., **10**, 113-124.
Grant, J.N., Halls, C., Avila, W. and Snelling, N.J., 1979a, Potassium-argon ages of some Bolivian rocks, a discussion. Econ. Geol., **74**, 702-703.
Grant, J.N., Halls, C., Avila, W. and Snelling, N.J., 1979b, Potassium-argon ages of igneous rocks and mineralization in part of the Bolivian tin belt. Econ. Geol., **74**, 838-851.
Hegemann, F., 1948, Uber sedimentare Lagerstatten mit submariner vulkanichen Stoffzufuhr. Fortscher. Min., **27**, 54-55.
Mendieta, G., Blanco, F., Soliz, N., Claure, M., Davila, J., Vargas, E., Sanchez, V. and Caro, E., 1963, Cuadrangulo de Cucho Ingenio. Servicio Geol. Bolivia.
Mariaca, O., Valasquez, J., Donoso, J., Blanco, F., Zapata, H. Suarez, M., Oquendo, A. and Ruiz, L., 1967, Cuadrangulo de Tinguipaya. Servicio Geol. Bolivia.
Murillo, J., Cordero, G. and Bustos, A., 1968, Geologia y yacimientos minerales de la region de Potosi, II. Servicio Geol. Bolivia, Bol. 11, La Paz.
Rivas, S. and Carrasco, R., 1968, Geologia y yacimientos minerales de la reqion de Potosi, I. Servicio Geol. Bolivia, Bol. 11, La Paz.
Sugaki, A., Ueno, H., Kitakaze, A., Hayashi, K., Shima, H., Sanjines, O.V. and Saavedra, A.M., 1981a, Geological and mineralogical investigation on polymetallic hydrothermal deposits in Andes Area of Bolivia, Report of Overseas Scientific Survey, Sendai.
Sugaki, A., Ueno, H., Shimada, N., Kitakaze, A., Hayashi, K., Shima, H., Sanjines, O.V. and Saavedra, A.M., 1981b, Geological study on polymetallic hydrothermal deposits in the Oruro district, Bolivia. Sci. Rept. Tohoku Univ., ser. 3, **15**, 1-52.
Sugaki, A., Ueno, H. and Saavedra, A.M., 1981c, Mineralization and mineral zoning in the Avicaya and Bolivar mining district, Bolivia. Sci. Rept. Tohoku Univ. ser. 3, **15**, 53-63.
Sugaki, A., Kitakaze, A. and Sanjines, O.V., 1981d, Study on the ore minerals from Bolivian Tin deposits (I), Cassiterite and stannite from the mines in the Oruro district. Sci. Rept. Tohoku Univ., ser. 3, **15**, 65-77.
Turneaure, F.S., 1960, A comparative study of major ore deposits of central Bolivia. Econ. Geol., **55**, 217-254, 576-606.
Turneaure, F.S., 1971, The Bolivian tin-silver province. Econ. Geol., **66**, 215-225.