GEOLOGICAL STUDY ON THE ORE DEPOSITS IN THE LA PAZ DISTRICT, BOLIVIA

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ABSTRACT

There are two types of fissure filling deposits in the La Paz district where is located at the northern portion of a tin bearing mineralization belt along the Eastern Cordillera of Bolivian Andes (Figure 1). One is a meso- and hypothermal deposits of tin and tungsten formed by mineralization in the relation to activity of granitic magma at Triassic to Jurassic ages, and other, polymetallic veins of xenothermal type by mineralization due to subvolcanism or plutonism of acidic magma at Oligocene to Miocene ages. As the former there are ore deposits of the Milluni, Kellhuani, Chojlla and San Antonio mines etc. which are situated in the northern part of the district near La Paz city (Figure 9). They are composed of meso- or hypothermal type quartz veins with some amounts of ore minerals of cassiterite, wolframite, scheelite, arsenopyrite, pyrite, pyrrhotite, and molybdenite etc. Among them cassiterite which is most principal ore mineral occurs in intimate association with coarse grained quartz, and is generally crystallized at early stage of mineralization which is characterized by appearence of halogen bearing minerals such as tourmaline, fluorite and muscovite. It sometimes assembles with pyrite. Wolframite also is an essential ore mineral in Chojlla and San Antonio mines closely associated with quartz and cassiterite. The ore deposits of the Kellhuani mine have been called "Manto type" as reported by Schneider and Lehmann (1977), because they are only found in the layers of Silurian quartzite (Catavi Formation). However, cassiterite from the mine mostly occurs in quartz-tourmaline veinlets along fissure or crack developing in the quartzite layers or sometimes in tourmalinization halo of hydrothermal alteration adjoining to the veinlets in them. Therefore, the deposit of the Kellhuani mine are thought to belong to a hydrothermal fissure filling type.

Meanwhile the polymetallic fissure filling deposits formed by mineralization being related to acidic magmatism at Oligocene to Miocene ages are found as those of the Viloco and Colquiri mines in the southern portion of the district. The ore veins of the Viloco mine occur in quartzite and sandstone of the Silurian system and granodiorite of the Tres Cruces batholith (26 Ma). Beautiful and huge prismatic crystals of cassiterite were found from the Principal section of the mine. The veins consist principally of quartz, tourmaline, siderite, cassiterite, wolframite, arsenopyrite, bismuthinite, pyrite, pyrrhotite, sphalerite, sometimes molybdenite, associated with small amounts of stannite, chalocpyrite, marcasite, jamesonite, galena, bismuthinite and native bismuth etc. As gangue minerals, sericite, chlorite, kaoline and small amounts of monazite besides quartz, tourmaline and siderite are found in the veins. Cassiterite intimately associates with quartz, chlorite and siderite, while wolframite occurs in close assemblage with quartz, arsenopyrite, acicular crystals of tourmaline and bismuthinite. The veins of the Colquiri mine appear in Silurian quartzite and slate, and are composed of sulfide ores consisting of sphalerite, pyrrhotite, pyrite, arsenopyrite, cassiterite, stannite, marcasite, magnetite associated with some amounts of gangue minerals such as quartz, fluorite, gearksutite, topaz, tourmaline, siderite, apatite, vivianite, alunite and creedite. Among them cassiterite occurs as granular or acicular aggregates in intimate association with quartz, sphalerite, pyrrhotite, pyrite and stannite. There is found a band (5 cm wide) of teallite and gearksutite in some veins (San Carlos Ramo 4 etc.). It appears in association with franckeite, cassiterite, fluorite, apatite and alunite.

The ore veins of the Matilde mine which is working as a zinc and lead mine differ to those of other tin mines. They occur mainly in Devonian slate, and consist of sphalerite and siderite associated with galena, marcasite, pyrite and quartz. The veins often show conspicuously characteristic alternated banding or laminating structures of siderite and sphalerite. There are found no tin and tungsten minerals such as cassiterite, stannite, wolframite, franckeite from the mine. It does not make clear whether or not the ore veins of the Matilde mine were produced by mineralization related to Mesozoic granitic magma.

Homogenization temperature of liquid inclusion in quartz from Milluni (Rotschild), Kellhuani, Chojlla and Trinidad mines are 176°-321°C (mean value 261°C), 215°-363°C (294°C), 231°-408°C (311°C) and 217°-427°C (311°C), respectively. Meanwhile salinity in NaCl equivalent concentration of liquid inclusion in quartz from Kellhuani and Trinidad mines are 25.1-26.0 wt% and 23.6-47.1 wt%, respectively. Also homogenization temperature and salinity of liquid inclusion in quartz from the Viloco (Roberto, Broncera, Cinco, Nueva and Doce veins) and Colquiri (San Carlos vein) mines are 263°-494°C, 18.5-55.4 wt% and 205°-383°C (271°C), 1.2-6.4 wt%, respectively. Homogenization temperature of liquid inclusion in quartz from the Matilde mine is 188°-283°C (233°C).

Some sulfur isotope values $\delta^{34}S$ obtained for common sulfide minerals such as pyrite, pyrrhotite, sphalerite and galena from some mines in the La Paz district are $+7.6\sim+7.7$ ‰ for pyrite (Rotschild vein, Milluni) ; $+3.8$‰ for pyrite, $+3.5\sim+5.0$‰ for pyrrhotite and $+2.9$‰ for galena (Chojlla) ; $+13.8$‰ for pyrrhotite (San Antonio) ; $+13.1\sim+14.0$‰ for pyrite, $+14.0\sim+14.6$‰ for sphalerite and $+10.9$‰ for galena (Matilde vein, Matilde).

Introduction

The polymetallic ores such as tin, tungsten, silver, lead, zinc, antimony, and bismuth etc. principally occur from the mines located in the Eastern Cordillera of Andes in Bolivia. They, especially tin deposits are longer distributed along the mountain range of the Cordillera from the north border with Peru to the south end bordered with Argentina as shown in Figure 1. The distribution area of such ore deposits is generally divided into four districts of La Paz, Oruro, Potosi and Quechisla. Among them, the ore deposits in the Oruro and Potosi districts were investigated by us in 1979 and 1980, and in 1981 and 1983, respectively. Also, the ore deposits in the Quechisla district were made studies by us at two times in 1981 and 1983. The results of these studies were already reported in the papers of the Science Reports of the Tohoku University by Sugaki *et al.* (1981a, b, c, d 1983a, b and 1984). The paper of this time is focused on the ore deposits of tin, tungsten, molybdenum, lead and zinc in the La Paz district where corresponds to the most northern portion of the metallogenetic zone in the Cordillera (Figure 2). The field survey of the ore deposits in the district have been intermittently carried out at several times from 1977 to 1983. As shown in Figure 2, there are tin deposits of the Milluni, Kellhuani and Viloco mines, tungsten deposit of the San Antonio mine, molybdenum deposit of the Trinidad mine, tungsten and tin deposit of the Chojlla mine, and tin and zinc deposit of the Colquiri mine etc. They belong to a type of hydrothermal fissure filling deposits occuring in the Paleozoic, mainly Silurian and Ordovician systems, and granitic rocks. Among

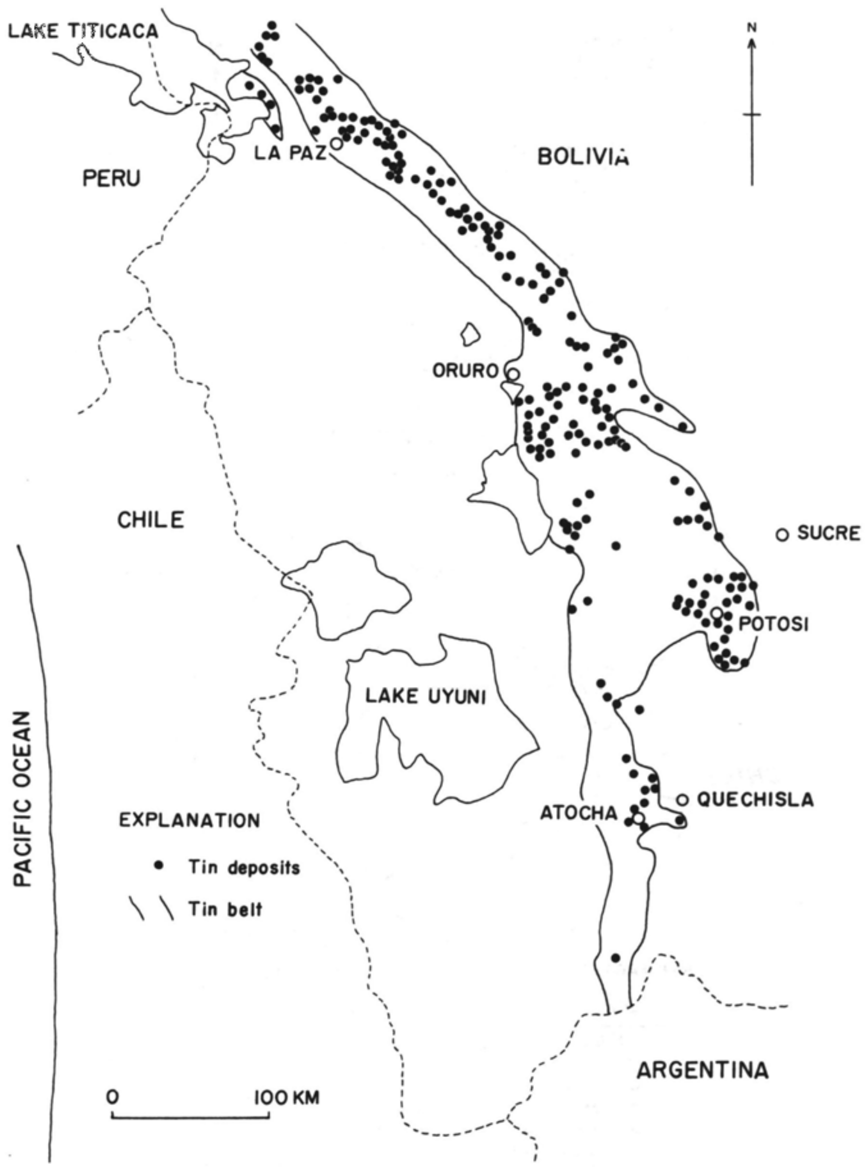

FIGURE 1. TIN MINERALIZATION BELT IN THE EASTERN CORDILLERA OF BOLIVIA (AFTER CLAURE AND MINAYA, 1979).

them, those of the Milluni, Kellhuani, San Antonio, Trinidad and Chojlla mines are thought to have been formed by mineralization related to magmatic activity of granitic pulton at Mesozoic, principally Triassic to Jurassic ages, and correspond to the ore veins of mesothermal and hypothermal types. Meanwhile the veins of the Viloco and Colquiri mines, which are similar to some deposits in the

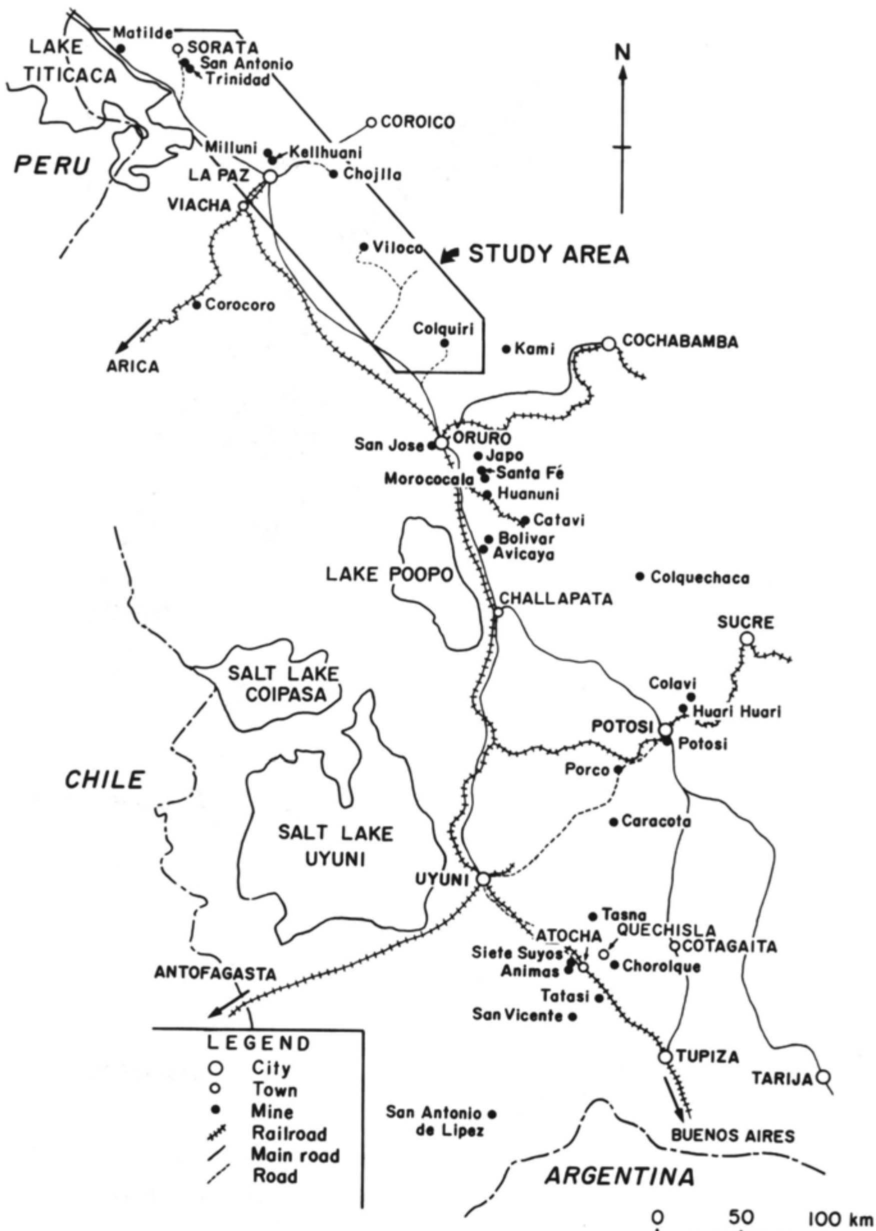

FIGURE 2. MAP SHOWING THE LOCATION OF THE LA PAZ DISTRICT IN BOLIVIA.

Oruro district, belong to a xenothermal type. There are a possibility that they have been produced by a mineralization fluid as post action of acidic magma of plutonic or subvolcanic types generated in Tertiary (Oligocene to Miocene) age.

The metallic ores from the meso- and hypothermal deposits such as Milluni, Kellhuani and Chojlla mines consist of some kinds of ore minerals such as cassiterite, wolframite, scheelite, sphalerite, pyrite, pyrrhotite, arsenopyrite, chalcopyrite, molybdenite, galena, marcasite and native bismuth intimately associated with gangue minerals of quartz, tourmaline, fluorite, muscovite, apatite, siderite and chlorite etc. The assemblages of ore and gangue minerals from this type veins in the district are relatively simple in comparison with those of the xenothermal deposits in other districts, and there are found no stannite, kesterite, franckeite, hocartite, silver sulfosalts, lead-antimony sulfosalts, vivianite, barite, gypsum, alunite and jarosite etc. in the veins.

The deposits of the Matilde mine which is located near the border with Peru, consist principally of sphalerite, galena and siderite, but they are associated with no tin and tungsten minerals such as cassiterite, wolframite and scheelite, though it exists the northern area in the district where are frequently found the tin and tungsten mineralizations of meso- and hypothermal types related to Mesozoic granitic activity. Thus, it does not make clear whether or not the Matilde veins have been produced by such mineralization as mentioned above.

On the other hand, ore minerals from the veins of the Viloco and Colquiri mines which are a xenothermal type are essentially composed of cassiterite, wolframite, pyrite, pyrrhotite, arsenopyrite, sphalerite, galena, stannite, chalcopyrite, bismuthinite, native bismuth, jamesonite, stibnite, closely assembled with many kinds of gangue minerals such as quartz, tourmaline, monazite, topaz, fluorite, apatite, vivianite, creedite, gearksutite, chlorite, sericite, kaolinite, dickite and alunite etc. as being often seen in some xenothermal deposits of the Oruro, Potosi and Quechisla districts. The name Viloco is world-famous because large, euhedral and beautiful crystals of cassiterite have occurred from this mine. The veins of the Viloco mine are composed of cassiterite, wolframite, arsenopyrite, pyrite, bismuthinite and native bismuth associated with quartz, tourmaline and monazite, which are produced by mineralization of relatively higher temperature at early to middle stages, and stannite, chalcopyrite, sphalerite, galena, jamesonite and stibnite with sericite and kaolinite formed by lower temperature mineralization at late stage. Such coexistance of both minerals of high and low temperatures is also found in the veins of the Colquiri mine. Cassiterite, pyrrhotite, sphalerite, arsenopyrite and magnetite with quartz and small amounts of tourmaline and topaz formed at relatively higher temperature coexist with pyrite, stannite, galena, some sphalerite, marcasite, teallite, siderite, fluorite, vivianite, dickite, gearksutite and creedite as low temperature minerals in the veins. It is significant as characteristic of xenothermal type to be found such telescoping ores from both the mines as above.

As stated above, there are two kinds of the ore deposits, meso- and hypothermal, and xenothermal types, formed at different two ages in the district. Geological and mineralogical data on these deposits of both the types are described in this paper.

La Paz, largest city and capital of Bolivia with a population of about 700,000 people, locates roughly a center in the district, and has been used a base of field survey. It of course is traffic center, and has international and domestic airport, railway station, bus center and modern hotels. From La Paz to the mines in the district, we can visit for several hours by car. For example, longest trip from La Paz is a way to Viloco, and we have needed about 8 hours by car. The roads to mines from La Paz are in general good except distinctly curved mountain road to the Viloco and San Antonio mines, but they are unpavement except principal highway from La Paz to Oruro for 230 km. The climate of the La Paz district is obviously divided into dry and rainy seasons. Dry season is from April to October, and rainy season, November to March. Total amounts of rain are only approximately 250 mm at La Paz according to Montes de Oca (1983). However, it almost falls during rainy season, and sometimes floods as cutting off traffic road crossing or going along the river and valley. The humidity generally is as low as 35 to 45% in the dry season and 50 to 60% in the wet season. The temperatures in the district were 0° to -5°C at early morning or night and 20°C at daytime during field survey from July to October.

Topography

The La Paz district topographically belongs to the northern and middle portions of the Eastern Cordillera principally and Altiplano partly in the Andes mountain range of Bolivia. The Eastern Cordillera in the district is formed by steep mountains named White Andes being covered with snow throughout a year as shown in Figure 3. There are often found glacier, moraine hill and U-shaped valley in the Cordillera (Figure 4-B). The principal high mountains in the district are Champi Orco 6,040 m, Illampu 7,010 m (highest mountain in Bolivia; Figure 3-A), Chacha Comani 6,150 m, Condoriri 5,850 m, Huayna Potosi 6,088 m (Figure 3-C), Mururata 5,869 m (Figure 4-A), and Illimani 6,402 m (Figure 3-B), Tres Cruses 5,046 m (Figure 5-A) and Bandani 5,032 m etc. which consist of folded Paleozoic formations and intrusive granitic rocks. These mountains of the Cordillera arranging to the NW-SE direction topographically show a stage of maturity with steep slope (Figure 4-A and B) deeply eroded by valley and river. The rivers found in the district generally run to the northeast or west cutting the mountains. Some rivers such as Keka and Suches running to the west or south flow into Lake Titicaca. The rivers running to the northeast such as the river La Paz, Coroico, Zongo, Challana, Tipuani and Chinijo flow together the river Beni which runs to the north and then flow together the river Amazon. The Cordillera is cut by the Consata and Camata rivers at the north side of Mt. Illampu. The principal rivers in the southern portion of the district run to parallel to the direction of the mountain range of the Cordillera as a result controlled by

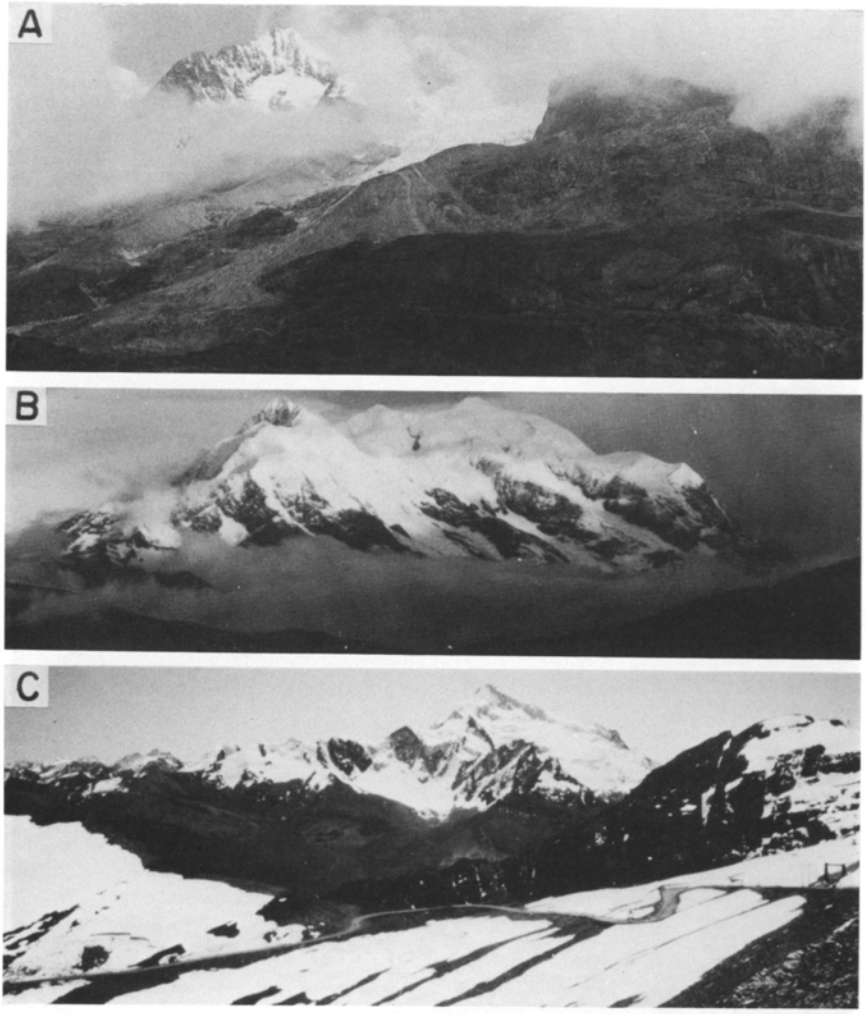

FIGURE 3. HIGH MOUNTAINS OF WHITE ANDES (EASTERN CORDILLERA) IN THE LA PAZ DISTRICT.
A. Mt. Illampu (7,010 m) viewed from the San Antonio mine near Sorata.
B. Mt Illimani (6,402 m) viewed from the La Paz city.
C. Mt. Huayna Potosi (6,088 m) looking from Mt. Chacaltaya (5,395 m).

geological structure.

Altiplano is flat plateau of 3,500 to 4,000 m above sea level developing 200 km or more in east-west width between the Eastern and Western Cordilleras. The boundary between the Cordillera and Altiplano is sharp topographically and parallel to running direction of the mountain range. In the Altiplano there are often found monadnocks consisting of Paleozoic formations. Lake Titicaca (3, 810 m elevation) is in the north eastern part of Altiplano adjoining to the western margin of the Eastern Cordillera. La Paz city (Figure 4-C) is located in the

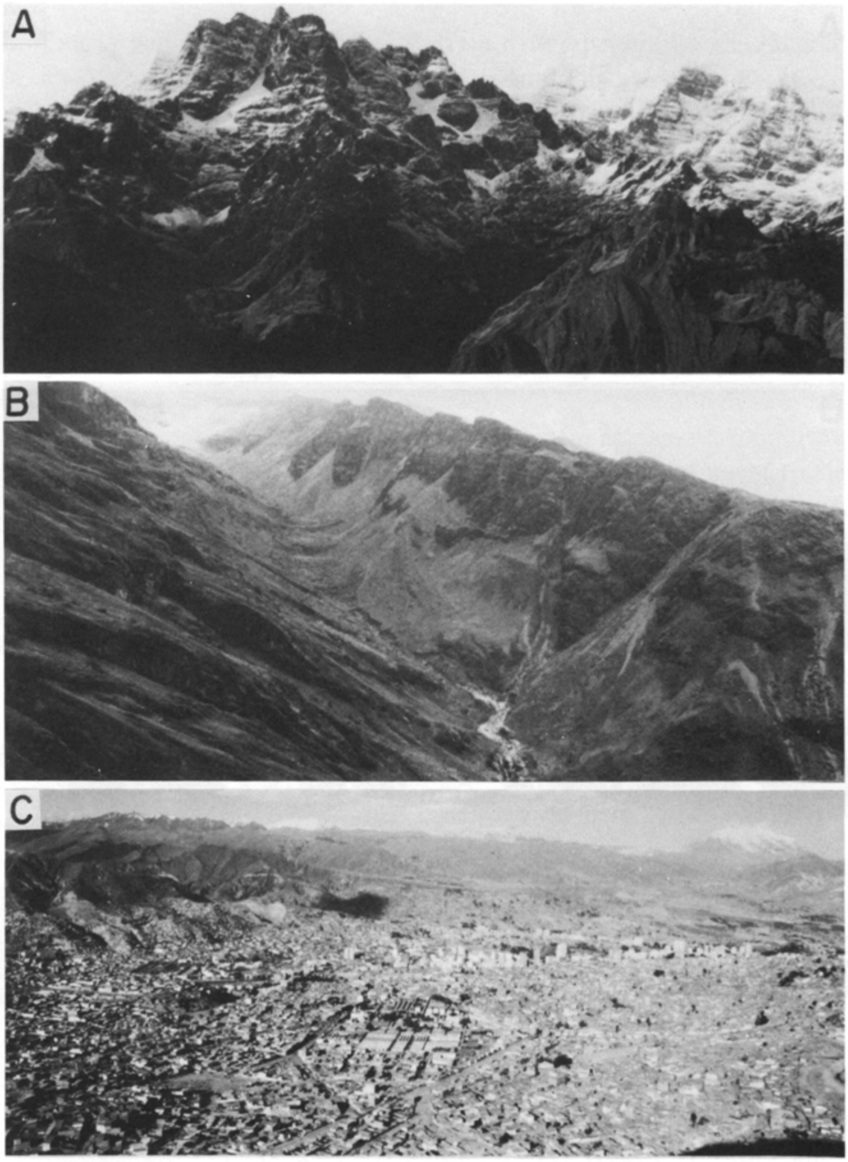

FIGURE 4. SCENERY OF MOUNTAIN RANGES (EASTERN CORDILLERA)

A. Mt. Mururata (5,869 m) looking from the Chojlla mine.

B. U-shaped valley of Mt. Illampu near the San Antonio mine.

C. A view of La Paz city and Mts. Illimani (right) and Taquesi (left) looking from north.

upper valley of the river La Paz originated from the eastern margin of the Altiplano adjacent to the Eastern Cordillera.

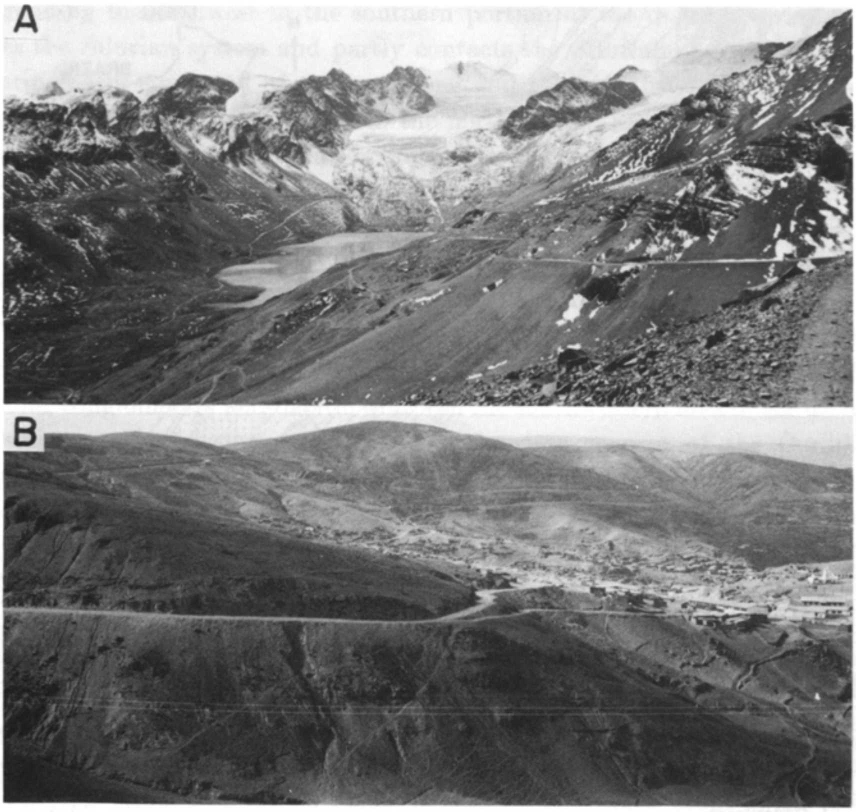

FIGURE 5. MOUNTAIN TOPOGRAPHY OF THE VILOCO AND COLQUIRI MINING AREAS.
A. Steep mountain ranges with gracial landform and its lake at southeast of the Viloco mine.
B. Gentle mountain range near the Colquiri mine.

GEOLOGY

Geology of the La Paz district consists of Ordovician, Silurian, Devonian, Carboniferous and Permian systems of Paleozoic, Cretaceous system of Mesozoic and Tertiary and Quaternary formations of Cenozoic and granitic rocks intruded into the Ordovician and Silurian systems as shown in Figure 6. The topography in the district as mentioned before is in intimate relationship with geology.

1. Paleozoic system

It runs to the NW-SE direction parallel to the trend of the mountain range of the Eastern Cordillera repeating anticlinal and synclinal foldings. They are cut by many faults. The Paleozoic system is principally composed of Ordovician and Silurian formations. The Ordovician system occupies over main portion of the Cordillera, especially in its eastern side, and is principally composed of

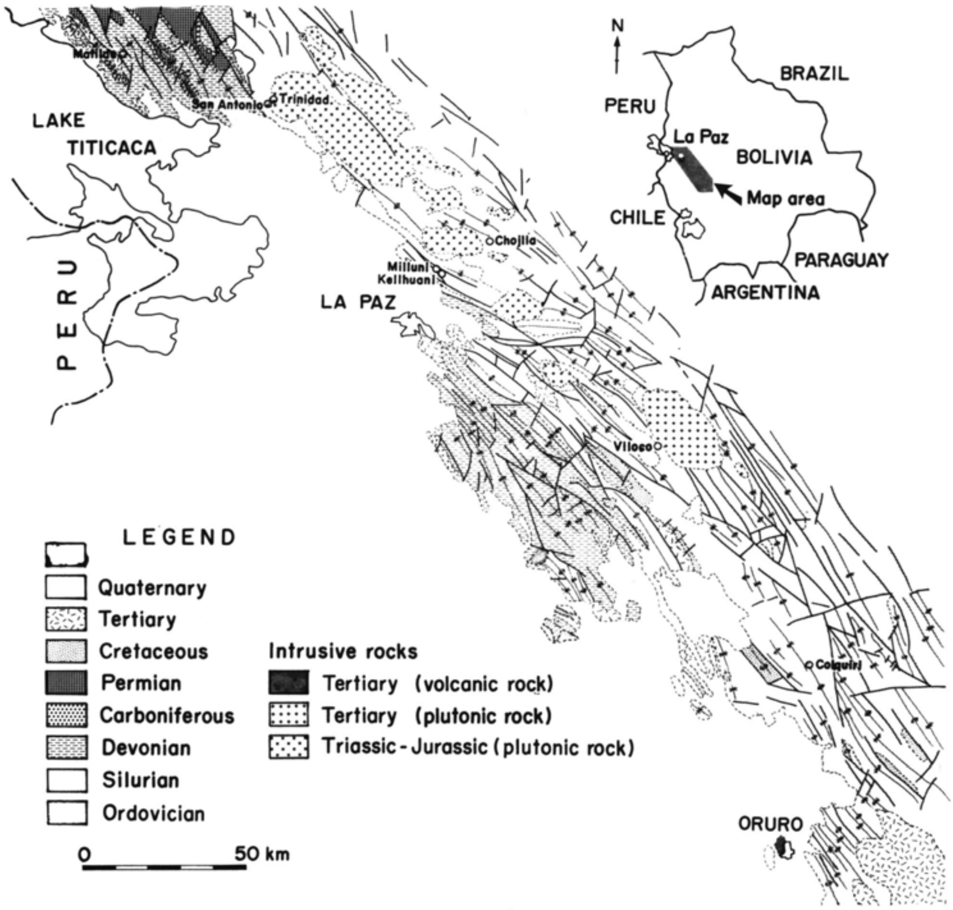

FIGURE 6. GEOLOGICAL OUTLINE OF THE LA PAZ DISTRICT.

quartzite, sandstone, phyllite and black slate. Meanwhile the Silurian system mainly appears in the west side of the Cordillera adjoing to the Ordovician system. It consists of sandstone, phyllite and black slate with quartzite, and is divided into the Cancaniri, Llallagua, Uncia, Catavi and Vilavila Formations. The Devonian, Carboniferous and Permian systems distribute over the low mountain land in the northwestern part of the Eastern Cordillera facing Lake Titicaca or appear locally as a monadnock in Altiplano. Among them, the Devonian system is composed mainly of gray or black slate and fine grained sandstone. Meanwhile the Carboniferous and Permian systems consist of pale gray and coarse grained sandstone, and limestone and coarse grained sandstone, respectively.

2. *Mesozoic system*

The Cretaceous system is sporadically distributed along synclinal folding axes trending to northwest in the southern portion of the district, and directly overlies the Silurian system and partly contacts the Silurian system with fault. It is principally composed of red sandstone and shale. The Cretaceous system also appears locally as narrow zone in the northwestern area near Lake Titicaca covering on the paleozoic formation unconformably. It consists of sandstone, conglomerate, mudstone and limestone. It also appears locally as a monadnock in Altiplano.

3. Cenozoic system

The Tertiary system of Miocene is also found in Altiplano as monadnock and the northwestern area adjacent to Lake Titicaca. It is essentially composed of sandstone, conglomerate and dacitic tuff. In the southwestern area of the district, the Tertiary system occurs sporadically in western margin of the Cordillera overlying unconformably the Silurian and Cretaceous formations. It corresponds to the Morococala Formation which belongs to Pliocene (6 to 9 Ma), and consists mainly of dacitic tuff and lava. The Quaternary system widely consisting of Altiplano is composed of beds of gravel, pebble to cobbel, and sand of several hundred meters in thickness. It is well observed in the valley of La Paz city. Also glacial and alluvial deposits are sporadically exposed as Quaternary sediments in the district.

As mentioned above, the Paleozoic and Mesozoic (Cretaceous) formations are distinctly folded as repeated anticlinal and synclinal structures having axes of NNW-SSE direction as shown in Figure 6. Also many faults occur in the formations, especially the Silurian and Ordovician systems. There are found two kinds of faults in the district; one cut right angle or oblique direction of NE-SW for folding axes, and other, parallel to the axes. They are important as fissures formed ore veins in the district.

4. Igneous rocks

The granitic rocks occur mainly in Silurian and Ordovician systems as batholith sometimes lacolith and stock in the central portion of the Eastern Cordillera in the district, and the distribution of their igneous bodies is shown in Figure 7. They are principally composed of hornblende biotite granodiorite, biotite or two mica granodiorite, biotite, muscovite or two mica granodiorite, and biotite granodiorite or biotite adamellite in Mts. Illampu, Huayna Potosi, Taquesi, and Tres Cruces, respectively. The modal analyses for some granitic rocks collected during our field survey have been carried out. The analytical data are shown in Table 1, and plotted on the quartz-K-feldspar-plagioclase triangular diagram in Figure 8. According to the classification of Bateman *et al.* (1963), the Illampu and Huayna Potosi masses belong to granodiorite family. The Taquesi and Tres Cruses masses have the compositions near boundary

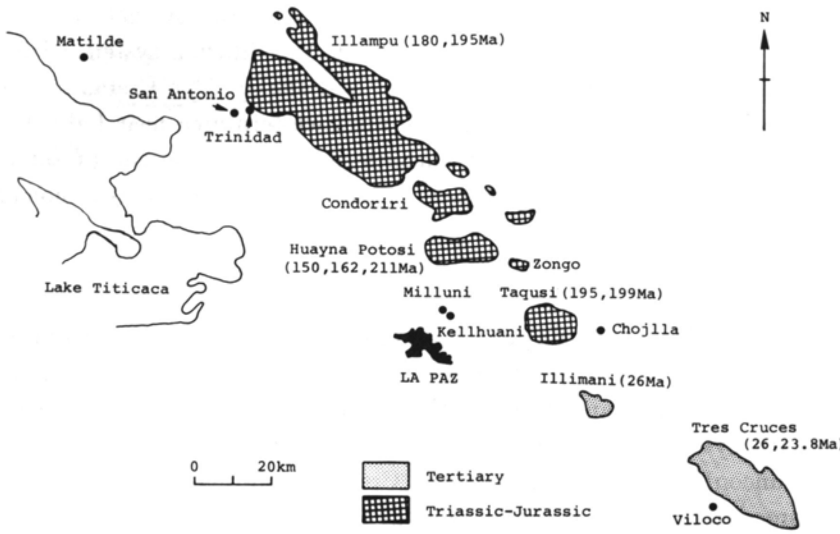

FIGURE 7. DISTRIBUTION OF INTRUSIVE ROCKS AND INVESTIGATED MINES IN THE LA PAZ DISTRICT (AFTER CLAURE AND MINAYA, 1979).
The K-Ar Ages of Intrusions are Shown in Parentheses (After Evernden *et al.*, 1977, Clark and Farrar, 1973).

TABLE 1. MODAL COMPOSITION OF GRANITIC ROCKS IN THE LA PAZ DICTRICT.

	Qz	Kf	Pl	Bt/Ch	Ms	Ho	Ap	Others	Rock type
Illampu									
ILP-04	31.1	11.1	40.4	12.2	-	1.9	0.4	3.0	Ho-Bt-Gd
ILP-06	25.3	14.1	44.4	12.9	tr	2.1	0.3	1.0	Ho-Bt-Gd
Huayna Potosi									
HYP-12	31.1	15.7	38.7	13.6	tr	-	0.7	0.2	Bt-Gd
MIL-08	29.7	13.1	41.4	13.2	tr	-	2.1	0.6	Bt-Gd
MIL-16	33.6	13.9	42.8	6.1	2.4	-	0.9	0.2	Two-Mica-Gd
Taquesi									
CHO-09	37.3	20.0	26.7	-	15.1	-	0.4	0.5	Ms-Ad
CHO-13	41.7	21.6	26.0	2.9	6.1	-	1.1	0.6	Two-Mica-Ad
TAQ-02	39.2	14.7	33.4	11.1	tr	-	0.8	0.7	Bt-Gd
TAQ-03	41.2	12.4	27.8	-	16.7	-	1.5	0.4	Ms-Gd
Tres Cruces									
VIL-05	28.7	17.1	28.1	23.1	tr	-	2.4	0.6	Bt-Ad
VIL-19	26.4	16.8	39.7	16.1	-	-	0.8	0.2	Bt-Gd
CAR-01	27.2	24.4	29.6	17.1	tr	-	1.3	0.4	Bt-Ad
CAR-25	24.4	22.8	33.4	18.3	tr	-	0.8	0.2	Bt-Ad
ATR-06	25.1	21.1	33.4	18.5	-	-	1.1	0.8	Bt-Ad
LAR-02	27.6	26.7	29.0	15.9	tr	-	0.6	0.2	Bt-Ad

Abbreviations; Qz:quartz, Kf:K-feldspar, Pl:plagioclase, Bt/Ch:Biotite/Chlorite, Ms:muscovite, Ho:hornblende, Ap:apatite, Gd:granodiorite, Ad:adamellite

between granodiorite and adamellite families. All the granitic rocks are medium grained and nearly equigranular texture. Among rock forming essential minerals, quartz and K-feldspar are anhedral except large crystal of K-feldspar in the two-mica adamellite. Commonly quartz shows a wavy extinction and K-feldspar has a perthitic and microcline texture. Plagioclase has a conspicuous albite twin and zonal structure, and is partly saussuritized. Biotite is partly altered to

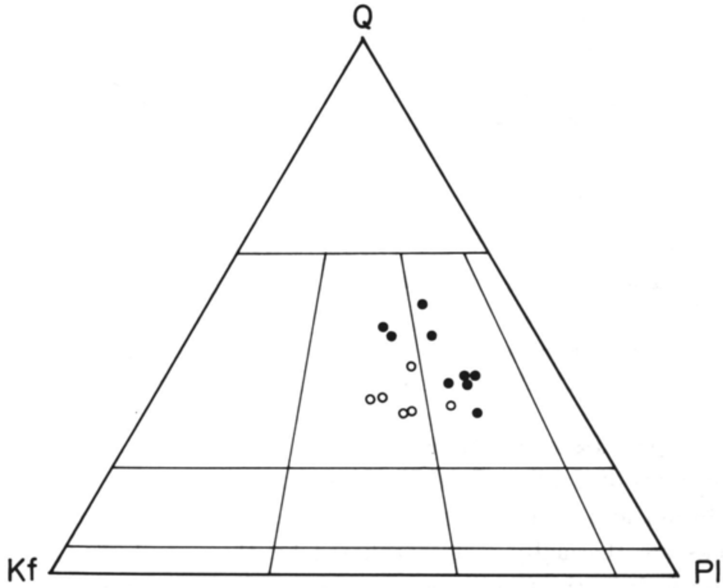

FIGURE 8. MODAL QUARTZ-PLAGIOCLASE-K-FELDSPAR DIAGRAM FOR THE GRANITIC ROCKS IN THE LA PAZ DISTRICT.
Solid Circles Represent Data for the Late Triassic to Jurassic Granitic Rock in the Northern Part (Older Igneous Rocks), and Open Circles, for the Late Oligocene to Miocene Granitic Rocks in Middle and Southern Parts (Younger Igneous Rocks).

chlorite and epidote along the cleavage. The Illampu plutonic rocks are composed mainly of quartz (25 to 31%), K-feldspar (11 to 14%), plagioclase (40 to 44%), biotite (12 to 13%) and hornblende (2%) with minor amounts of apatite (0.3 to 0.4%). Zircon, sphene and opaque minerals are accessory. The Tres Cruces plutonic rocks also have the mineral composition similar to the Illampu older plutonic rocks, except for the presence of hornblende in the latter, but have more abundance of K-feldspar and biotite, and less abundance of plagioclase. The biotite adamellites (CAR-01, CAR-25) sometimes contain mega-crystal of plagioclase 3 to 5 mm in size. The Huayna Potosi plutonic rock is composed mainly of quartz (30 to 34%), K-feldspar (13 to 16%), plagioclase (39 to 43%), biotite (6 to 14%) and/or muscovite (2%), with minor amounts of apatite (0.7 to 2.1%). The biotite granodiorite (MIL-08) and the two-mica granodiorite (MIL-16) sometimes contain mega-crystal of quartz and plagioclase of 3 to 5 mm. The Taquesi plutonic rocks have the mineral composition similar to the Huayna Potosi plutonic rocks, but have more aboundance of quartz, K-feldspar and muscovite and less aboundance of plagioclase and biotite. The biotite granodiorite (TAQ-02) includes mega-crystal of K-feldspar of 3 to 5 mm. The muscovite granodiorite (TAQ-03) sometimes contains mega-crystal of plagioclase of 2 to 5 mm.

The magnetic susceptibility for such granitic rocks as above was measured by

TABLE 2. THE K-Ar AGES OF THE GRANITIC ROCKS IN THE LA PAZ DISTRICT.

Locality	Rock	Mineral	Age (Ma)	Reference
Illampu	granodiorite	biotite	180	Evernden et al. (1977)
	granodiorite	biotite	195	Clark and Farrar (1973)
Huayna Potosi	granite	muscovite	150	Evernden et al. (1977)
	granodiorite	biotite	211	Evernden et al. (1977)
	pegmatite	muscovite	162	Evernden et al. (1977)
Taquesi	granodiorite	biotite	199	Evernden et al. (1977)
	?	biotite	195	Clark and Farrar (1973)
(Chojlla mine)	pegmatite	muscovite	183	Evernden et al. (1977)
Illimani	granite	biotite	26	Evernden et al. (1977)
Tres Cruces	quartz monzonite	biotite	23.8	Clark and Farrar (1973)
	granite	biotite	26	Evernden et al. (1977)

Bison 3101A type. Its values range from 3 to 11×10^{-6} emu/g. They belong to the ilmenite series by Ishihara and Ulriksen (1980).

The Silurian and Ordovician formations around the igneous bodies of the granitic rocks are thermally metamorphosed by them, and change to hornfels. Also, granitic rock in the Chojlla mine corresponding to muscovite or two mica adamellite is intensely altered by greisenization.

The K-Ar ages for biotite and muscovite from the granitic masses of the Illampu, Huayna Potosi, Taquesi, Illimani and Tres Cruces plutons are given in Table 2 making reference to Clark and Farrar (1973), and Evernden *et al.* (1977).

According to the data, the granitic rocks of Illampu (195, 180 Ma), Huayna Potosi (150, 162, 211 Ma), and Taquesi (195, 199 Ma) were formed by igneous activities of the Triassic to Jurassic ages of Mesozoic. Meanwhile the granitic rocks of Illimani (26 Ma) and Tres Cruces (23.8, 26 Ma) belong to the igneous activity of the Oligocene age. The granitic activities of both Mesozoic and Tertiary are in intimate relation with mineralizations produced polymetallic ore deposits of tin, tungsten, molybdenum, lead and zinc etc.

ORE DEPOSITS

1. *Outline of ore deposits*

There are ore deposits such as the Milluni, Kellhuani, Chojlla, Matilde, San Antonio, Trinidad, Viloco and Colquiri mines in the La Paz district as shown in Figure 9. They occur as hydrothermal fissure filling type in the Ordovician, Silurian and Devonian systems or granitic intrusion and are being worked as tin (Milluni, Kellhuani and Viloco), tin-tungsten (Chojlla), tin-zinc (Colquiri) and zinc-lead (Matilde) mines except San Antonio (tungsten) and Trinidad (molybdenum) mines which have been closed now. Among them the ore veins of the Milluni, Kellhuani, Chojlla, San Antonio and Trinidad mines are thought to belong to hypothermal or mesothermal deposits genetically related to magmatic activity of Mesozoic (Triassic to Jurassic) granodiorite or adamellite. Ore and

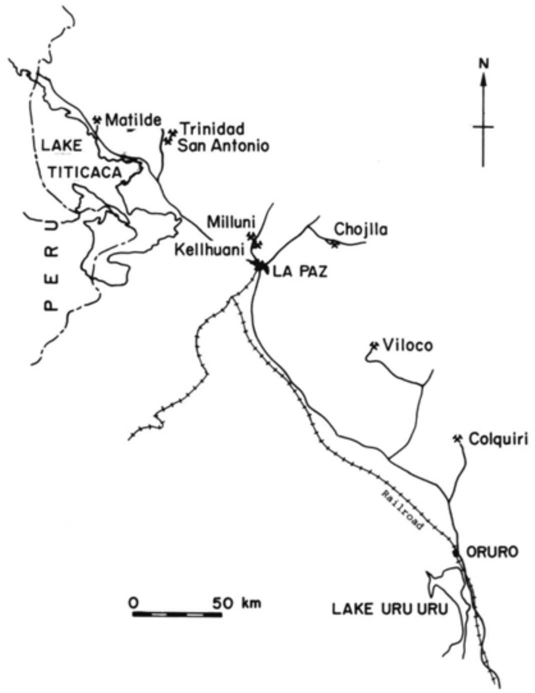

FIGURE 9. LOCATION MAP OF MINES IN THE LA PAZ DISTRICT.

gangue minerals from them are relatively simple in comparison with those of some xenothermal deposits in the Oruro, Potosi and Quechisla districts. As ore minerals, cassiterite, wolframite, sphalerite, galena, pyrite, marcasite, arsenopyrite, pyrrhotite, molybdenite and scheelite etc. occur. However, no stannite, kesterite, franckeite, hocartite, silver sulfosalts and lead-antimony sulfosalts etc. appear. While as gangue minerals, quartz, tourmaline, muscovite and siderite are usually found in association with fluorite, apatite and chlorite etc., but no vivianite, barite, gypsum, alunite and jarosite etc. occur. Also there is found no zonal arrangement of minerals in the deposits as shown often in the xenothermal deposits of the Quechisla district (Sugaki *et al.* 1984). The deposits of the Kellhuani mine has been so-called Manto type by Schneider and Lehmann (1977), but they are a type of hydrothermal fissure filling, according to data obtained by our field study of this time. The ore veins of the Matilde mine, which principally consist of sphalerite and siderite with galena and quartz, differ conspicuously on mineral assemblage and feature of the ore to those of the meso- and hypothermal type of such other mine as stated above. It is unknown whether or not the deposits of the Matilde mine were formed by mineralization related to Mesozoic granitic activity as same as those of the Milluni, Kellhuani and Chojlla mines.

Meanwhile although the ore deposits of the Viloco and Colquiri mines occur in Silurian system and granodiorite, they are considered to have been produced by ore solutions generated from acidic magma of Tertiary, Oligocene to Miocene ages under subvolcanic or plutonic states, and belong to xenothermal type similar to those of the Oruro, Potosi and Quechisla districts. A lot of ore and gangue minerals from the Viloco and Colquiri mines occur as a result of polymetallic and telescopic mineralizations. As ore minerals, there are found cassiterite, wolframite, magnetite, pyrrhotite, arsenopyrite, pyrite, bismuthinite, native bismuth, sphalerite, chalcopyrite, stannite, galena, jamesonite, stibnite and marcasite etc. in association with gangue minerals of quartz, tourmaline, monazite, topaz, fluorite, apatite, vivianite, creedite, gearksutite, chlorite, sericite, kaoline etc. There are found a coexistance of high and low temperature minerals in some veins of both the mines as frequently seen in those of xenothermal deposits in other districts.

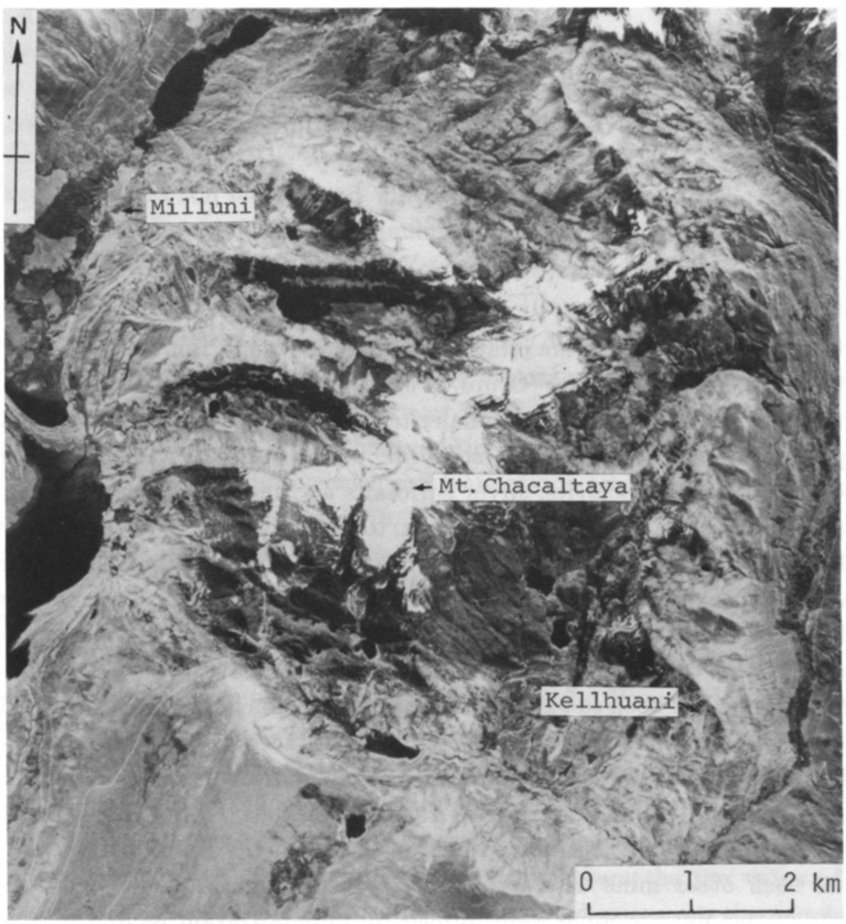

FIGURE 10. AEROPHOTOGRAPH AROUND THE MILLUNI AND KELLHUANI MINING AREA IN THE LA PAZ DISTRICT.

Two types of hydrothormal deposits except Matilde occur in the La Paz district as mentioned above. In the chapter, the ore deposits of the Milluni, Kellhuani, Chojlla, San Antnio, Trinidad, Matilde, Viloco and Colquiri mines in the district are described.

2. Milluni mine

The Milluni mine being at the south foot of Mt. Huayna Potosi (6,088 m) as shown in Figures 10 and 11 is located at 25 km the north of La Paz. The mine which belongs to Compania Minera del Sur Sociedad Anonima has produced crude ore of 8,500 tons per month containing 0.85 to 0.90% Sn in October, 1979 or December, 1982, and concentrate of 150 tons per month with 50% Sn.

The mine is in mountain land of 4,500 to 4,800 m elevations corresponding to the western wing of the Eastern Cordillera of Andes. There are Mts. Huayna Potosi (6,088 m), Charquini (5,392 m), Visuyo (5,221 m) and Chacaltaya (5,395 m)

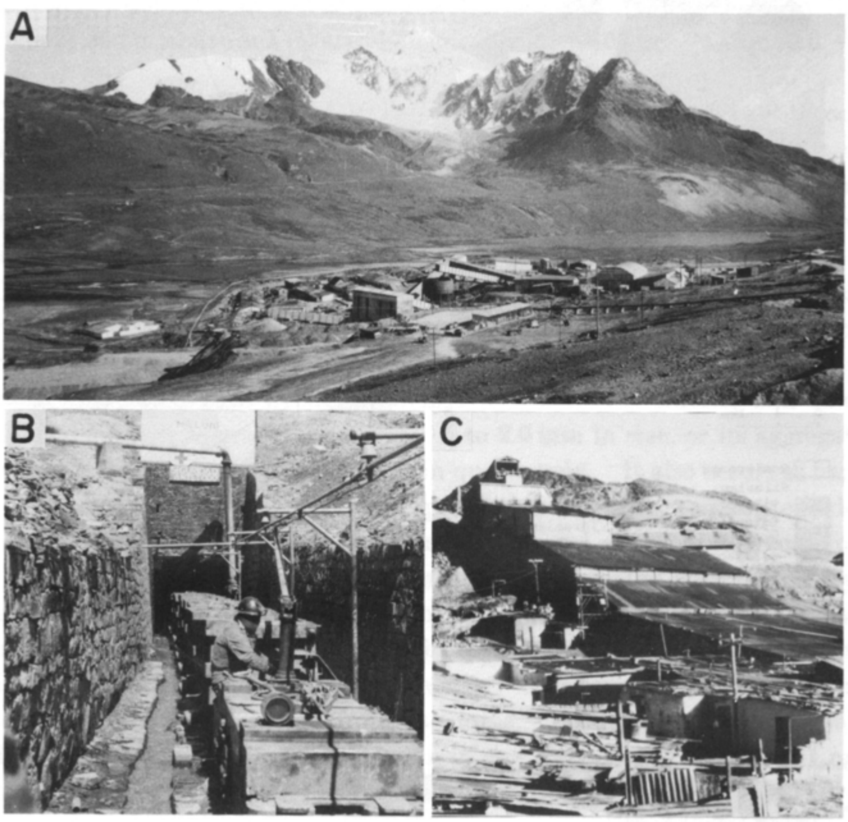

FIGURE 11. SCENERY OF THE MILLUNI MINE.
A. A view of the Milluni mine with a background of Mt. Huayna Potosi looking from south.
B. Entrance of adit of 0 m level (4,350 m) of the mine.
C. Ore dressing plant of the Milluni mine.

etc. around the mine. Also, glacier lake and moraine are often found in the mining area.

According to Lehmann (1977), geology around the mine consists of the Catavi Formation which is composed of quartzite and slate and the Uncia Formation, black slate, of Silurian as shown in Figures 12 and 13. They run to the WNW-ESE direction and dip to N or S, folding with anticlinal and synclinal axes parallel to that direction. Also, as seen in Figure 12 there are also found the Lallagua Formation, quartzite and black slate, and the Cancaniri Formation, diamictite with small amounts of quartzite and slate of lower Silurian, and the Unduavi Formation, quartzite and black slate, of Ordovician in the northern portion of the mine.

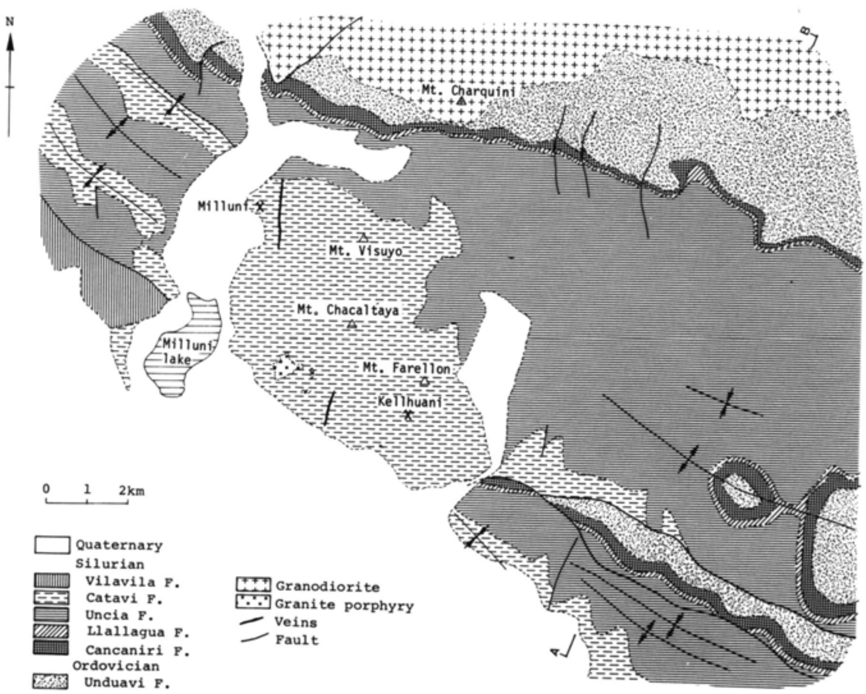

FIGURE 12. GEOLOGICAL MAP OF THE MILLUNI AND KELLHUANI MINING AREA.

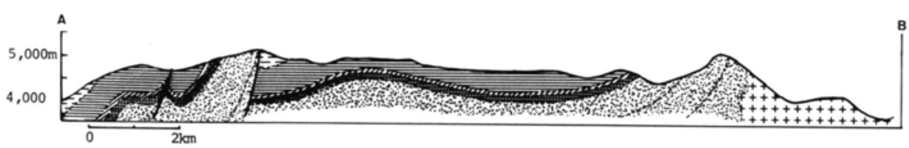

FIGURE 13. GEOLOGICAG SECTION OF THE MILLUNI AND KELLHUANI MINING AREA ALONG A-B DIRECTION IN FIGURE 12.
Symbols are same as those in Figure 12.

Biotite or two mica granodiorite which forms Mt. Huayna Potosi intrudes into the Unduavi and Cancaniri Formations. Granodiorite is a hollocrystalline and equigranular rock, and consists of quartz, orthoclase, plagioclase, biotite and / or muscovite, 0.5 to 3.5 mm in size, with small quantities of apatite and zircon, 0.05 to 0.2 mm in size, as accessory minerals. According to Evernden *et al.* (1977), the K-Ar ages for biotite of granodiorite, and muscovite of pegmatite and granite from Mt. Huayna Potosi are 211, 162 and 150 Ma, respectively.

The ore deposits of the Milluni mine are vein type filled up the fissures running the directions of N5° to 10°E or N30°W developed in black slate of the Catavi Formation of Silurian as shown in Figure 14. There are two mining sections, Cuadro and Compania, divided by Cuarzo fault of the ENE-WSW direction in the mining area. As seen in Figure 14, although many ore veins such as Rotschild, Estructura 1 to 5, Veta 23 and their offset veins are found in the mine, the Rotschild vein among them is being mined principallly at the present. The deposits of the mine are developed from surface to the -167 m level by the + 45 m, 0 m (4,350 m above sea level), −36 m, −72 m, −107 m, −137 m and −167 m levels.

The Rotschild vein striking N10°E to N10°W and dipping 60° to 65°E occurs in slate of the Catavi Formation of Silurian (Figures 15 and 16). It is most principal one which has such scale as 1,500 m in length, 170 m or more in depth and 50 to 150 cm in width. It is essentially composed of quartz associating with some amounts of pyrite, arsenopyrite, cassiterite and siderite etc. (Figure 17-A and B). In the vein slate is frequently found as a gangue rock, and sometimes presents banding structure with vein quartz. Quartz which is most principal mineral of the veins occurs as aggregate of coarse grained crystal, 2 to 7 mm in size, intimately associated with pyrite, arsenopyrite, cassiterite, siderite and chlorite etc. Pyrite appears as granular crystal, 0.5 to 2.0 mm in size, or its aggregate as massive form, dissemination and veinlets in quartz vein. It also occurs as banded form in quartz, closely assembled with quartz, arsenopyrite, cassiterite, siderite and chlorite etc. Siderite which is a common mineral occurs as aggregate of its granular crystals, 0.5 to 1.0 mm in size, intimately associated with quartz, pyrite and cassiterite, and sometimes banded form with quartz and veinlets distinctly cut quartz, pyrite, arsenopyrite and cassiterite. It sometimes accompanies with chlorite and sericite filling up crack in quartz. Cassiterite which is only one as an economic mineral producing from the mine. It appears as coarse grained euhedral or subhedral forms, 0.5 to 3.0 mm in size, in quartz (Figure 17-C), radial aggregate of its needle crystal, 0.5 to 1.5 mm long, in quartz (Figure 17-D), or aggregate of fing grained crystal 0.05 to 0.2 mm in size, with siderite, chlorite and sericite filled up fracture in quartz aggregate. Cassiterite associates with quartz, pyrite, arsenopyrite and siderite commonly, and chalcopyrite and sphalerite rarely. It has 0.0 to 2.3 mole% FeO according to EPMA data. Arsenopyrite is

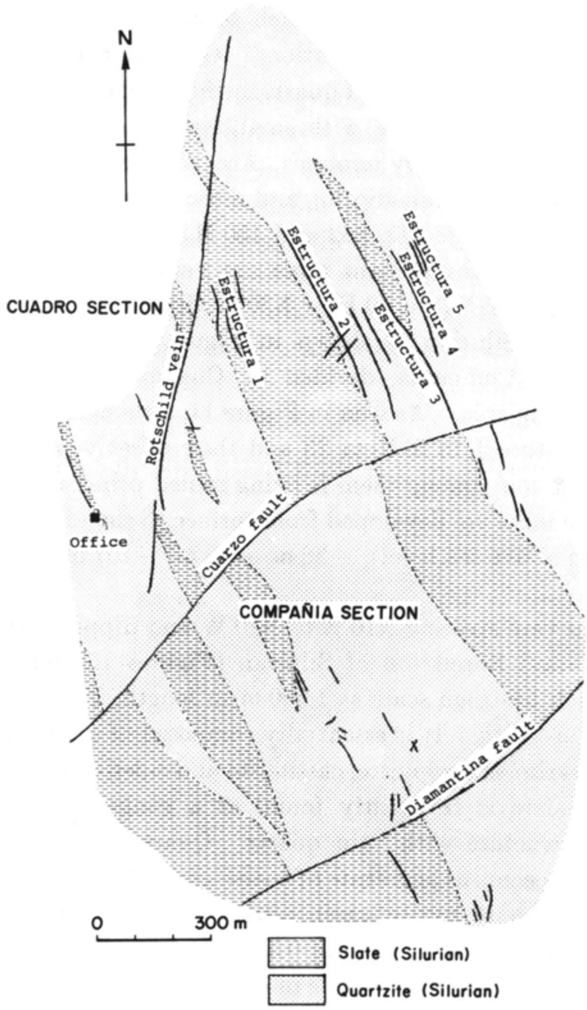

FIGURE 14. GEOLOGICAL MAP AROUND THE MILLUNI MINE.

a common mineral from the mine, and appears as aggregate of its euhedral and subhedral crystals, 0.5 to 3.0 mm in size, intimately associated with pyrite, quartz, siderite and sometimes cassiterite. Chlorite often occurs as common clayey mineral in quartz veins, associating with siderite, quartz, pyrite and sometimes cassiterite. Sphalerite is also found as rare mineral, 0.3 to 1.0 mm in size accompanied by quartz, pyrite, cassiterite and siderite etc. It sometime has fine dots of chalcopyrite microscopically. Chalcopyrite is rarely found as small irregular mass or granular form in association with quartz, pyrite, arsenopyrite, and cassiterite etc. under microscope. Fine grained stannite-like mineral is found in chalcopyrite. However, there is no occurrence of tungsten, silver and antimony minerals such as wolframite, scheelite, silver-antimony and lead-antimony

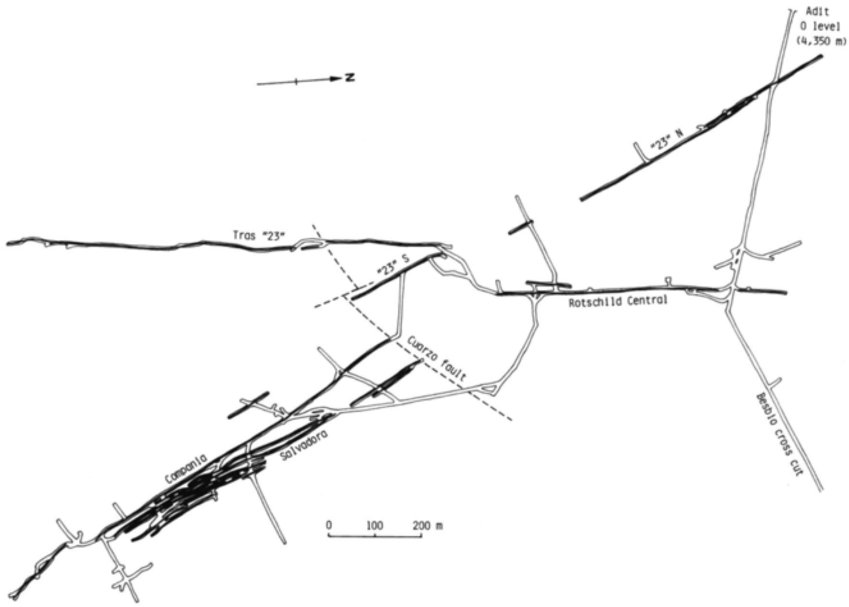

FIGURE 15. VEINS AT THE 0 LEVEL (4,359 m ALTITUDE) OF THE MILLUNI MINE.

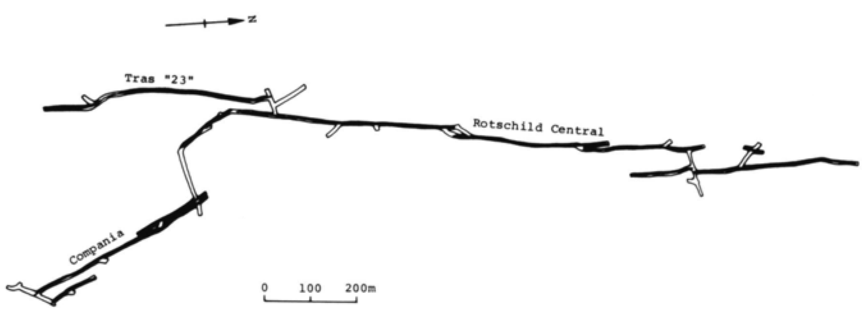

FIGURE 16. ORE VEINS AT THE −107 LEVEL OF THE MILLUNI MINE.

sulfosalts from the mine.

Homogenization temperatures for fluid inclusion in quartz from the Rotschild vein are 176° to 321°C with 260°C as mean value. The values $\delta^{34}S$ for pyrite are $+7.6 \sim +7.7‰$.

3. *Kellhuani mine*

The Kellhuani mine which is at the south wing of Mt. Farellon (5,119 m) is situated at 18 km north of La Paz. It has produced about 9,000 tons per month as crude ore with 0.46% Sn, and 600 to 900 kg per day of a tin concentration contained 59% Sn by table in November of 1982. This mine is being worked by

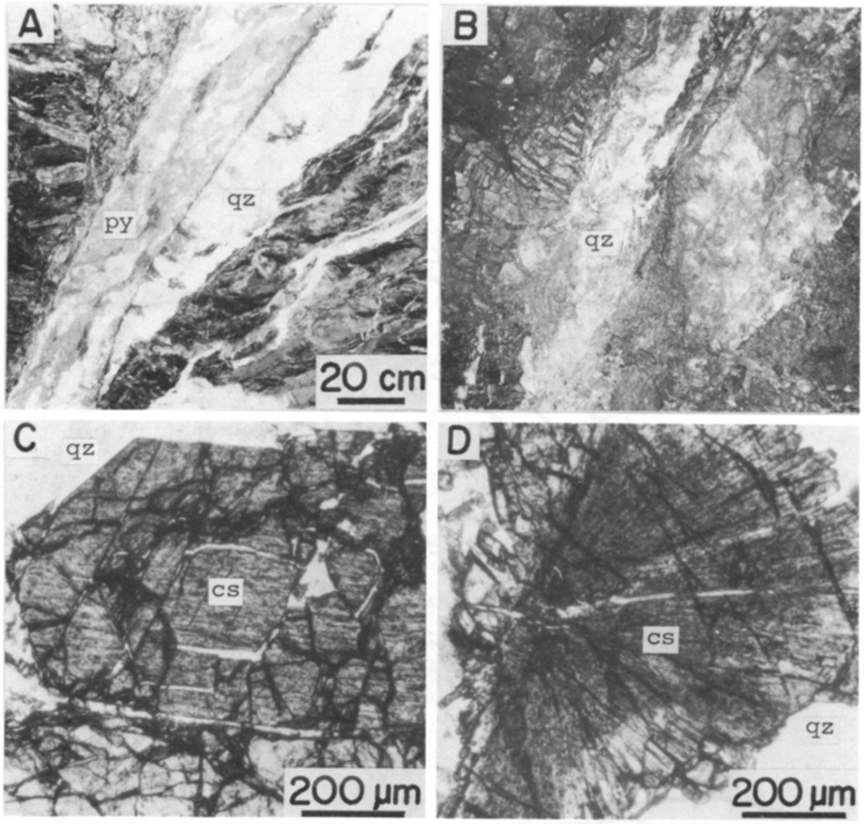

FIGURE 17. PHOTOGRAPHS OF VEINS AND PHOTOMICROGRAPHS OF ORES FOUND IN THE MILLUNI MINE.
C and D ; transmitted light.
A. Cassiterite bearing pyrite-quartz vein, the Rotschild vein, −107 m level.
B. The Rotschild offset vein composed of cassiterite, quartz and pyrite, −107 m level.
C. Euhedral cassiterite (cs) in quartz (qz), the Rotschild vein, −107 level (Sample No. 82121408).
D. Radial aggregate of cassiterite (cs) in quartz (qz), the Rotschild vein, −72 level (82121405).

an associated company of EMUSA (Empresa Minera Unificada S.A.), and the mining is carried out by small scale open pit and underground near surface at steep slope of the southern side of Mt. Farellon in elevation from 4,600 to 4,800 m (Figure 18). Mt. Farellon corresponds to an eastern branch of Mt. Chacaltaya (5, 395 m), and topography of the mining area presents feature of steep sloped mountain of high elevation with U-shaped valley eroded by glacier (Figure 18-A). There are also found some small glacier lakes.

Geology around the mine as seen in Figure 12 consists of the Catavi Formation of Silurian with monoclinic structure striking to the direction of N55°-70°W

FIGURE 18. SCENERY OF THE KELLHUANI MINING AREA.
A. Mt. Farellon (5,119 m) near the Kellhuani mine.
B. A view of the office and ore dressing plant of the Kellhuani mine.

and dipping to 20° to 30°S. It is composed of quartzite, sandstone, slate and alternation of them having several meters to 10 m in thickness. Mts. Chacaltaya and Farellon are formed with the Catavi Formation, while at southern slope of Mt. Chacaltaya granite porphyry occurs as small stock (Figure 12).

Tin ore deposits of the mine develop selectively in quartzite layer of the Catavi Formation. As shown in Figure 19, they have been mined by many adits and pits along a quartzite layer (Figures 20, 21-A and B). The tin ore is only found in the layer of quartzite. Therefore, this deposit has been called "Manto type" as reported by Schneider and Lehmann (1977). There are found seven quartzite layers as Manto type tin deposits in the mine as shown in Figure 19 (Lehmann, 1979; Lehmann and Schneider, 1981). The thickness of the Mantos is as follow: Manto 1, 4.0 m; Manto 2, 1.0 m or less; Manto 3, 1.8 to 2.5 m and Manto 4, 6.0 m etc. Although the deposits are confined to the quartzite layers, cassiterite mostly occurs in quartz-tourmaline veinlets along fissure or crack developing in the quartzite layers (Figure 21-C and D), or sometimes appears in tourmalinization halo of hydrothermal alteration adjoining to the quartz-

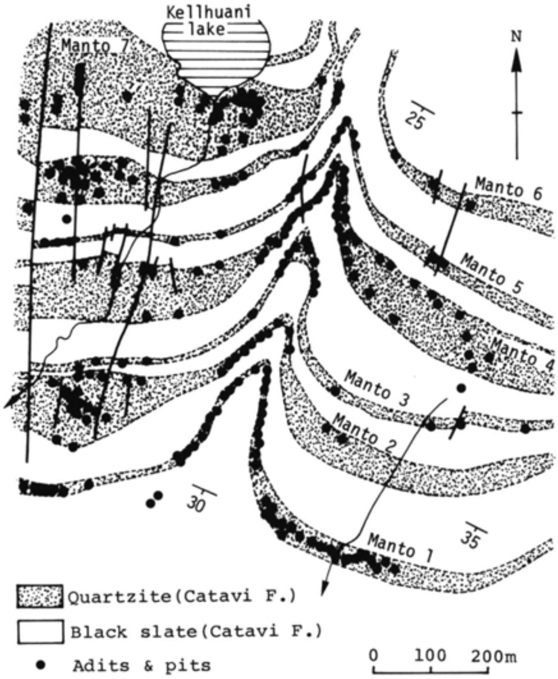

FIGURE 19. QUARTZITE LAYERS CONTAINING TIN ORE OF THE SILURIAN CATAVI FORMATION IN THE KELLHUANI MINE (AFTER LEHMANN, 1979; LEHMANN AND SCHNEIDER, 1981).

tourmaline-cassiterite veinlets in the quartzite layer as seen in Figure 22-A and B. It in general is not observed in the non-altered quartzite microscopically, which corresponds to outside of the quartz-tourmaline-cassiterite veinlets and alteration halo. The alteration halo seen as parallel band adjacent to the quartz-tourmaline veinlet or network is dark gray in color, and has 1 to 2 cm in width, and is composed mainly of aggregate of quartz, 0.3 to 0.7 mm in size, and tourmaline, 0.2 to 0.7 mm long, with small amounts of cassiterite, 0.1 to 0.2 mm in size (Figure 22-C). Therefore, cassiterite as tin ore mineral from the mine is mostly originated from the veinlet or network consisting of quartz and tourmaline essentially or their alteration halo in the quartzite layer subordinately. The veinlets generally consist of quartz, tourmaline, siderite, fluorite and cassiterite etc. Among them, quartz, most principal mineral, occurs as aggregate of coarse grained crystal, 2 to 4 mm in size, in intimate association with tourmaline, siderite, fluorite and cassiterite etc. Tourmaline appears in black colored veinlet, 2 to 10 mm wide, in quartzite, or as aggregate of fine needle crystals in the quartz-cassiterite veinlet as an essential mineral macroscopically. It occurs as prismatic forms, 0.3 to 1.0 mm long, or radial aggregate of long prismatic or needle-like crystal in quartz commonly, and associates with cassiterite, fluorite and siderite. In case of the veinlet consisting of quartz and tourmaline, the latter appears in the outside of the veinlet.

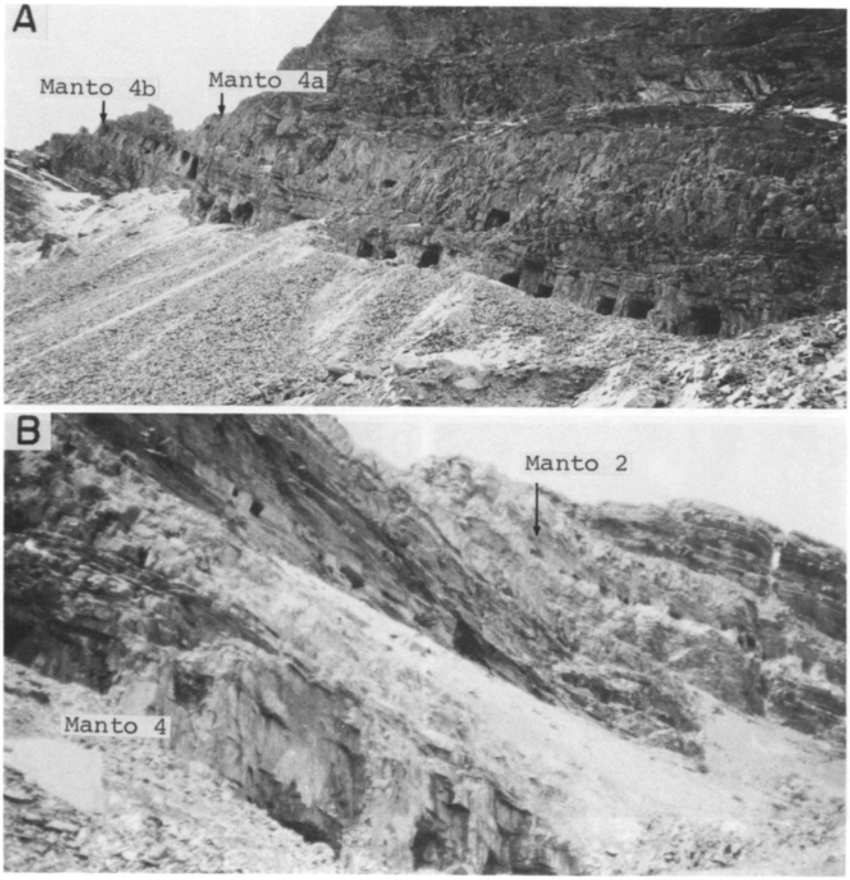

FIGURE 20. MANTOS (QUARTZITE BEDS) IN THE KELLHUANI MINE.
A. Quartzite beds of Mantos 4a and 4b embedded in black slate. There are many adits in the quartzite layers (Mantos).
B. A view of Mantos 2 and 4 in black slate.

Siderite also is a common mineral, and appears as aggregate of granular crystal, 0.5 to 2.0 mm in size, associated with quartz, tourmaline and cassiterite. It sometimes presents occurrence as embedded interspace of crystal aggregate of quartz, and also occurs as its veinlet cut the quartz-tourmaline vein in quartzite. Cassiterite appears in euhedral or subhedral crystals, 0.5 to 1.5 mm in size, and as its aggregate in intimate association with quartz, tourmaline, siderite and fluorite (Figure 22-C). It often presents a twin on (011) microscopically, but in general shows no distinct growth zoning as seen in cassiterite from xenothermal type deposits found in the Oruro, Potosi and Quechisla districts. Cassiterite has 0.0 to 1.9 mole% FeO in composition. Fluorite which is relatively small quantities in comparison with quartz, tourmaline and siderite occurs as subhedral crystal, 0.2 to 0.5 mm in size, or as its aggregate in assemblage with quartz, tourmaline, cassiter-

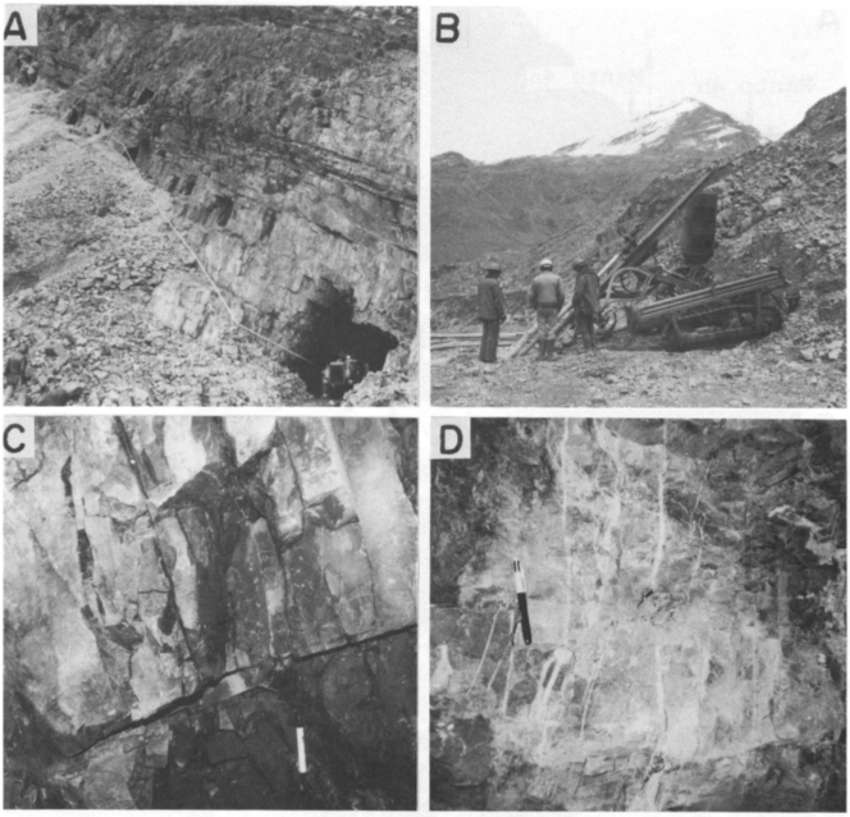

FIGURE 21. ORE DEPOSITS AND MINING OF THE KELLHUANI MINE.
A. Adits and pits in quartzite layer (Manto 4).
B. Open-pit mining in the Kellhuani mine.
C. Cassiterite bearing tourmaline-quartz veinlets (dark gray) in quartzite (gray) of Manto 4.
D. Cassiterite-quartz veinlets (white) in quartzite (gray or dark gray) of Manto 4.

ite and siderite. It sometimes appears in a veinlet, 5 to 10 mm wide, consisting of itself filling up crack or joint in quartzite.

Schneider and Lehmann (1977) have thought that the tin deposits of the Kellhuani mine have formed by remobilization of fossil cassiterite placer in Silurian quartzite. However, as mentioned above, the tin ore contained cassiterite from the mine mostly occurs in the quartz-tourmaline veinlets or their network formed in the fissure, crack and joint of the quartzite layers. Thus, the tin deposits of the mine are considered to have been formed by hydrothermal mineralization filling up the fissure, crack, joint or network-fracture in the quartzite layers which are selectively fractured lithologically as passages for hydrothermal fluids in contrast with slate suffered essentially plastic deformation without fissuring as stated by Lehmann and Schneider (1981). The mineraliza-

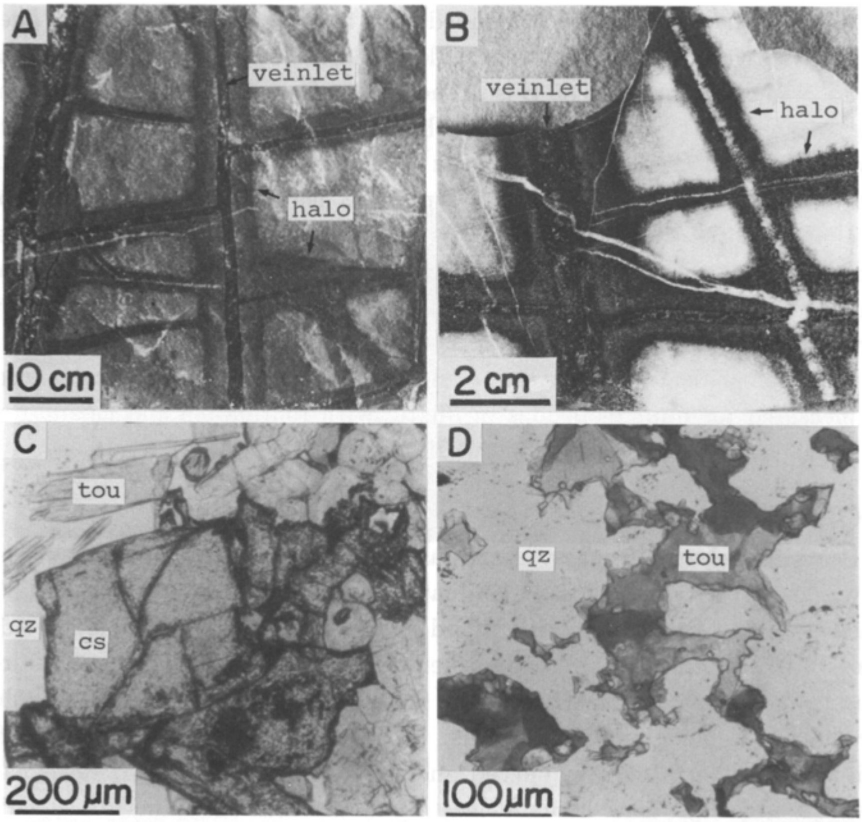

FIGURE 22. PHOTOGRAPHS OF ORE SPECIMENS AND PHOTOMICROGRAPHS OF ORES FROM THE KELLHUANI MINE.

A. Cassiterite-tourmaline-quartz veinlets (black) in quartzite (gray). Dissemination halo (dark gray) of tourmaline is found in quartzite (gray), Manto 1.

B. Cassiterite-tourmaline-quartz veinlets (black), quartz veinlets (white stringer) and turmalinization halo (dark gray) in quartzite (light gray), Manto 1 (82113001).

C. Association of granular cassiterite (cs) and tourmaline (tou) in quartz (qz) veinlet, Manto 4 (82113006).

D. Disseminated tourmaline (tou) filling up interspaces of granular quartz (qz) in alteration halo, Manto 1 (82113001).

tion formed the quartz-tourmaline-cassiterite veinlet or network may be in intimate relation with activity of granite porphyry and granodiorite as described above. As the result, the tin deposits of fissure filling and network types in the mine are confined in the quartzite layers only as named the Manto type. Lehmann and Schneider (1981) also recognized distinct boron anomaly related to detrital tourmaline in the Catavi Formation around the mine. However, there is a possibility that the boron anomaly was formed by tourmalinization of post-magmatic process of Chacaltaya granite porphyry or Huayna Potosi granodiorite. As seen in the figure, they were mined or explored by a lot of adits and pits. At lower part of the mine, Manto 1 is mined at 60 m level in underground. There is found quartz vein having relatively wide thickness, 10 to 15 cm, and running to N15° to 20°E with dip 80° to 85°E is in the level. It consists principally of quartz with some amounts of siderite, pyrite, chlorite and sericite, and small quantities of sphalerite and chalcopyrite. Quartz is massive aggregate of coarse grained crystal, 4.0 mm in size. It sometimes presents feather structure under crossed nicols and occasionally shows in obviously flamboyant extinction. Clayey minerals such as chlorite and sericite occur in the outside of the vein, associating with pyrite. Siderite appears in granular crystal, 0.2 to 0.7 mm in size, with quartz. There are no cassiterite, tourmaline and fluorite from this vein.

The homogenization temperature and salinity in NaCl equivalent concentration measured for fluid inclusions in quartz with tourmaline and cassiterite are 215° to 363°C (mean value 294°C) and 25.1 to 26.0 wt%, respectively.

4. *Chojlla mine*

It is situated at 40 km east of La Paz as direct distance (Figure 9). There is a new highway from La Paz to Unduavi for 30 km going over a hill, 4,800 m elevation, of the Eastern Cordillera and cutting southern steeply sloped side of mountain in eastern wing of the Cordillera faced to the Unduavi river running to the east. But, a road from Unduavi to Chojlla for 30 km along to the Unduavi river mainly is old gravel and curved way, especially a road for 10 km from Florida to Chojlla is narrow, curved and dangerous way faced to steep valley. Thus, it is necessary for 2 hours at least by car to visit the mine from La Paz.

The topography around the mine is steep mountain land from 2,200 m to 3,900 m elevation belonging to the eastern wing of the Eastern Cordillera. Steeply sloped face of the mountain looks out on a rapid stream of the valley. There is the Taquesi river, which is a principal one originating from the ridge of the Eastern Cordillera, running to the east roughly and passing the southern side of the mine. Also the Pongo Pampa river as steeply V-shaped valley erodes deeply the mountain land in the mining area as seen in Figure 23-A, flowing together with the Taquesi river at the south of the mine. As mentioned above, the mine faces to the Pongo Pampa river of the V-shaped valley, and is located at 2,100 to 2,300 m elevation on the southern side of Mt. Livinose (3,208 m).

The mine is now actively working and has produced approximate 20,000 to 25,000 tons per month in 1982 as crude ore with 0.4 to 0.6% as total of tin and tungsten, and about 100 tons per month as concentration containing 67 to 69% Sn and W by table (Figure 23-B and C).

The geology around the mine consists of Ordovician system and granitic pluton intruded into it (Figure 24). The former in the mine area is principally composed of slate with strike of N25°E to N30°W, monoclinally dipping to 30° to 40°E, but it sometimes folds slightly. The latter is muscovite adamellite or

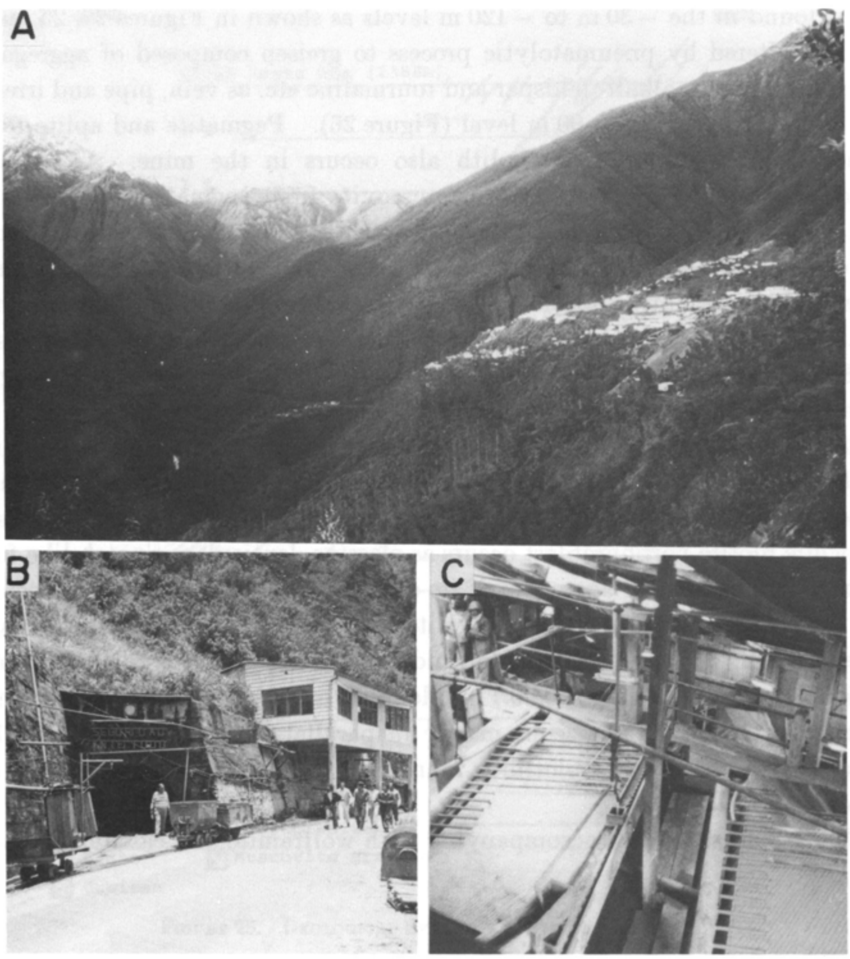

FIGURE 23. SCENERY OF THE CHOJLLA MINE.
A. Mountain deeply eroded by valley in the Chojlla mine.
B. Entrance of main adit of the Carmen level (2,208 m).
C. Ore dressing tables of the Chojlla mine.

sometimes two mica adamellite in the mine area, although pulton of Taquesi appearing at about 12 km southwest of the mine is biotite or muscovite granodiorite. Adamellite is hollocrystalline and equigranular rock consisting of quartz, orthoclase, plagioclase and muscovite, 0.3 to 1.5 mm, sometimes 2.5 mm in size, associated with small amounts of biotite, apatite and zircon. Mode of muscovite adamellite (Table 1, Sample No. CHO 09) collected at the −120 m level is as follows: Qz 37.3%, Kf 20.0%, Pl 26.7%, Ms 15.1%, Ap 0.4% and others 0.5% and its chemical composition is SiO_2 72.59%, TiO_2 0.05%, Al_2O_3 14.06%, Fe_2O_3 0.74%, FeO 0.16%, MnO 0.04%, MgO 0.03%, CaO 1.07%, Na_2O 4.28%, K_2O 3.81%, H_2O_+ 1.60%, H_2O_- 0.91%, P_2O_5 0.05%, Total 99.39%. Adamellite intruded into slate is found in the -30 m to -120 m levels as shown in Figures 24, 25 and 26. It is also altered by pneumatolytic process to greisen composed of aggregate of white mica, quartz, alkali- feldspar and tourmaline etc. as vein, pipe and irregular form as well seen in the -90 m level (Figure 26). Pegmatite and aplite related to intrusion of adamellite batholith also occurs in the mine. According to Evernden *et al.* (1977), K-Ar age for muscovite from pegmatite in the -120 m level of the Chojlla mine is 183 Ma, meanwhile that of biotite from Taquesi granodiorite batholith is 199 Ma. The Ordovician formation suffers contact metamorphism by intrusion of adamellite, and slate becomes to hornfels in the mine. Hornfels is composed of sericite, biotite and quartz with porphyroblasts of andalusite and biotite, as shown in Figure 31-B. As seen in the microphotograph it presents distinctly schistose texture parallel arranging of flaky sericite and quartz. Andalusite appears in lath or roughly prismatic form, 0.1 to 0.2 mm in length, and its twin or aggregate in matrix consisting of sericite, biotite, quartz and some amounts of tourmaline which are arranged parallel to schistosity of slate. Meanwhile biotite porphyroblast occurs as massive, lenticular or patch-like forms, 0.5 to 0.8 mm in size, of aggregate of its crystal, 0.05 to 0.1 mm long, associating with tourmaline in the matrix of sericite and quartz. In low grade metamorphosed hornfels or spotted slate, chloritoid appears in pale green colored prismatic crystal as porphyroblast, 0.07 to 0.1 mm long, in matrix consisting of fine sericite, biotite, quartz and carbonaceous matter in parallel arrangement (Figure 31-A). Also semi-porphyroblast of biotite is found in such low grade metamorphic slate as above.

A lot of quartz veins accompanying with wolframite and cassiterite develop

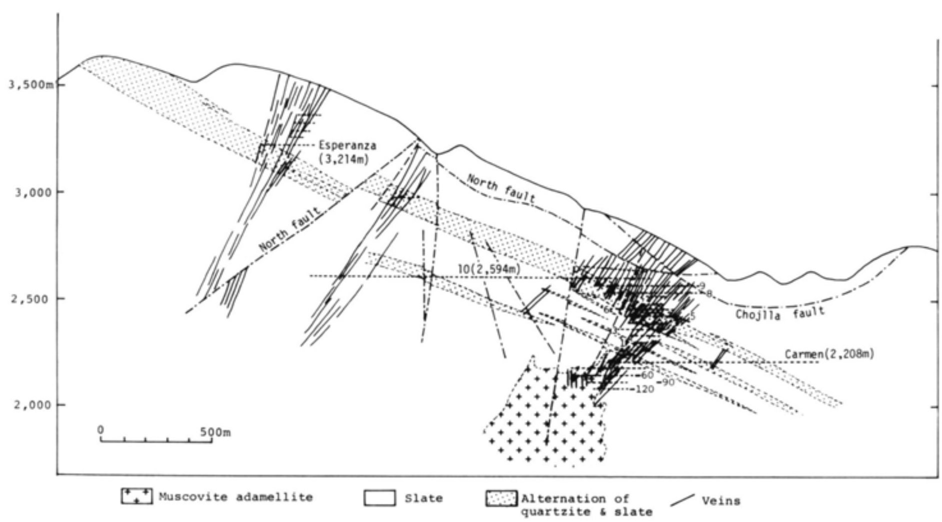

FIGURE 24. GEOLOGICAL CROSS SECTION OF THE CHOJLLA MINE ALONG E-W DIRECTION.

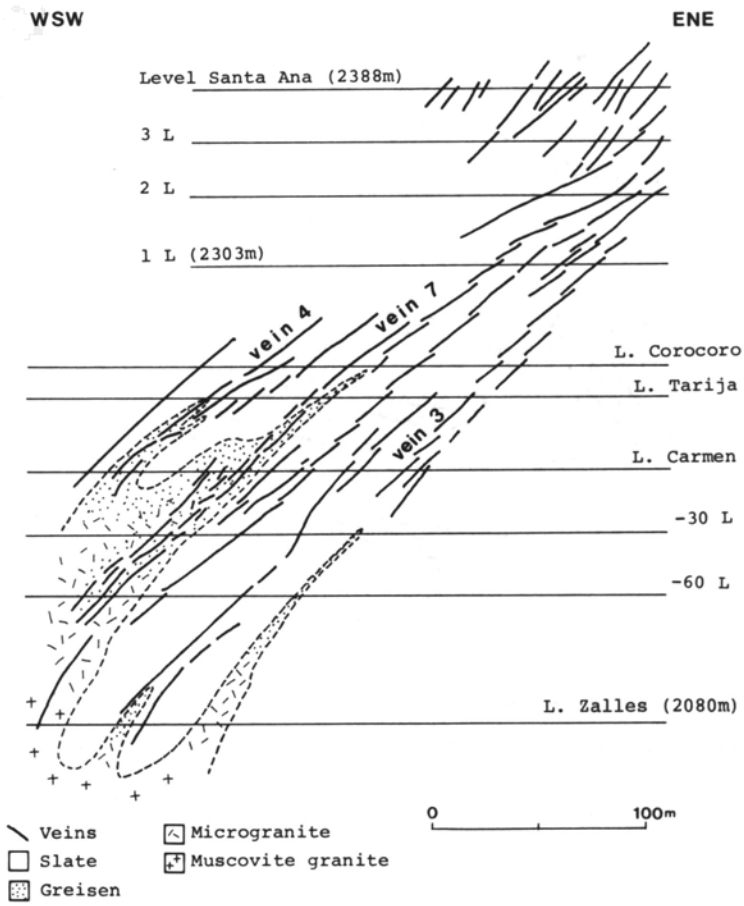

FIGURE 25. GEOLOGICAL SECTION OF THE CHOJLLA MINE.

mainly in Ordovician slate or hornfels and partly in adamellite altered by greisenization (Figure 29-D). They fill up parallel fissures striking to northwest (N30° to 50°W) with dip to 40° to 50°SW as shown in Figures 26, 27 and 28. However the ore veins found in the 190 m level steeply dip to near perpendicular as inserted into adamellite intrusion. The veins are slightly moved by low angle faults roughly parallel to bedding plane of slate. The scale of the ore veins is 100 to 300 m in length, 20 to 150 cm in width and 100 to 450 m in depth. They correspond to tension cracks formed by compressional stress in consequence of an upward motion of the adamellite batholith as stated by Michel and Reutter (1977).

The ore veins are composed mostly of quartz associated with wolframite, cassiterite, fluorite, muscovite, apatite, tourmaline, siderite, arsenopyrite, pyrrhotite, sphalerite, galena, chalcopyrite, scheelite, and very small quantities of stannite, native bismuth and marcasite etc. Among them, quartz is most essential

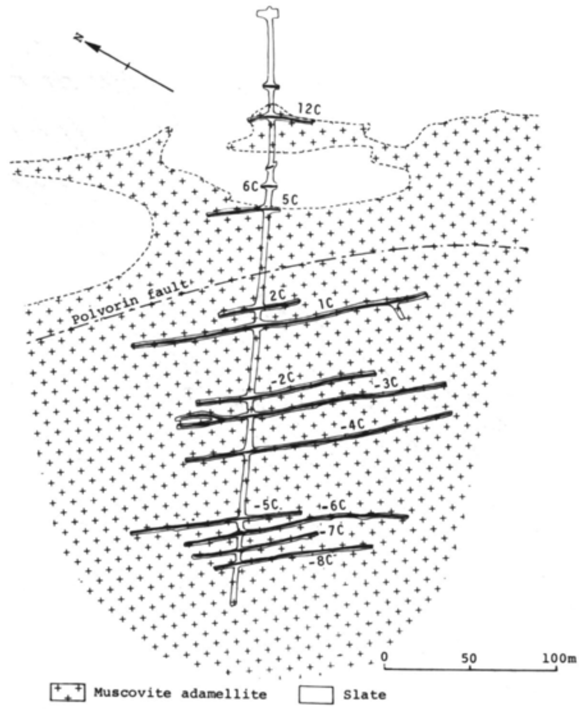

FIGURE 26. GEOLOGY AND VEINS AT THE −90 LEVEL OF THE CHOJLLA MINE.

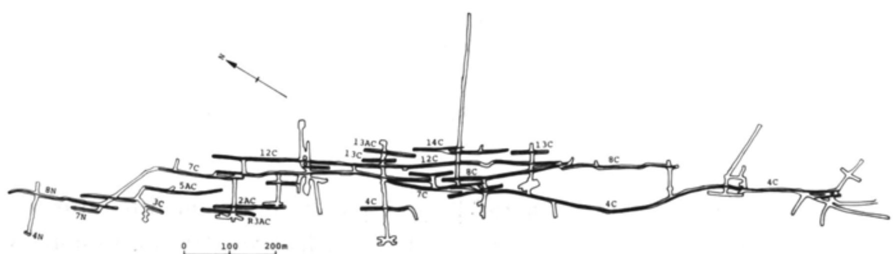

FIGURE 27. ARRANGEMENTS OF VEINS AT THE CARMEN LEVEL (2,208 m ABOVE SEA LEVEL) OF THE CHOJLLA MINE.

mineral forming the ore vein and associates with wolframite, cassiterite, muscovite, apatite, fluorite, siderite, arsenopyrite, pyrrhotite, sphalerite, galena and chalcopyrite etc. Wolframite which is principal economic mineral same as cassiterite occurs in prismatic crystal, 5 to 30 cm long generally (Figure 30-A), sometimes 50 to 130 cm in length, or as its aggergate in quartz, as shown in Figure 29. It commonly assembles with quartz, cassiterite, muscovite, arsenopyrite and apatite etc. Its chemical compositions are generally 54 to 60 mole % $MnWO_4$, but it changes its composition to more wide range from 33 to 72 mole % $MnWO_4$ by

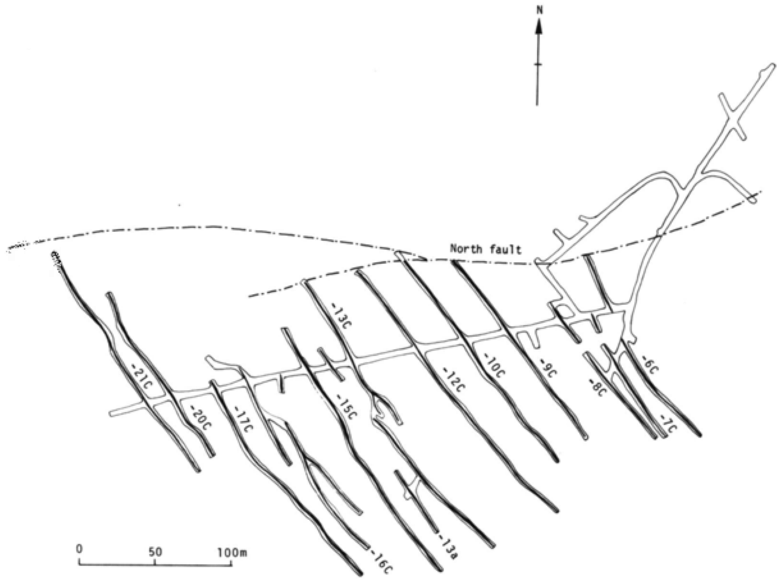

FIGURE 28. VEINS AT THE 10 LEVEL OF THE CHOJLLA MINE.

invasion of film-like or veinlet of quartz or ore fluid along its crack (Figure 31-D). Cassiterite being also important economic mineral appears in euhedral or subhedral crystal, 5 to 50 mm in size, and as its aggregate in quartz, frequently associating with wolframite, muscovite, tourmaline and arsenopyrite (Figure 30-B, C and D). It has a composition near pure SnO_2 containing only 0.1 wt % FeO or less, and its cell constant is a = 4.7347 (3)Å and c = 3.1839 (5)Å. Muscovite occurs in aggregate of flaky crystals, 1 to 5 mm in size, closely assembling with quartz, wolframite and cassiterite etc. It belongs to $2M_1$ polytype. Tourmaline presents needle-like form, 1 to 5 mm long, or long prismatic crystal, 1.5 mm × 30 mm in size in quartz, usually associating with cassiterite and muscovite etc. According to the lattice constant, a = 15.964 (2)Å and c = 7.154 (2)Å obtained from its X-ray powder data, it has composition near schorl. Also the chemical compositions of tourmaline (791017022) analysed by wet method are as follows: SiO_2 34.35%, TiO_2 0.86%, Al_2O_3 32.52%, FeO 11.94%, MnO 0.08%, MgO 1.81%, CaO 1.80%, Na_2O 1.76%, K_2O 0.46%, P_2O_5 0.06%, H_2O_+ 3.33%, H_2O_- 0.20%, F 0.57%, B_2O_3 10.82%, $-(O=F)$ 0.24%, Total 100.32%. The empirical formula calculated on the basis of $O+OH+F=31$ from the analytical data becomes $(Na_{0.57}\ K_{0.10}\ Ca_{0.33})_{1.00}\ (Fe_{1.68}\ Mg_{0.45}\ Mn_{0.01}\ Ti_{0.11}\ Al_{0.23})_{2.48}\ Al_{6.00}\ B_{3.14}\ (Si_{5.78}\ Al_{0.22})_{6.00}\ O_{26.95}\ (OH_{3.74}\ F_{0.30})_{4.04}$, and is close to the ideal formula $XY_3Z_6B_3Si_6O_{27}\ (OH, F)_4$ where X = Na, Ca; Y = Mg, Fe, Mn, Al; Z = Al. Fluorite also appears as irregular form, stringer or band of aggregate of pale blue to green colored crystals, 10 to 30 mm in size, associated with quartz, siderite, cassiterite, muscovite, tourmaline and

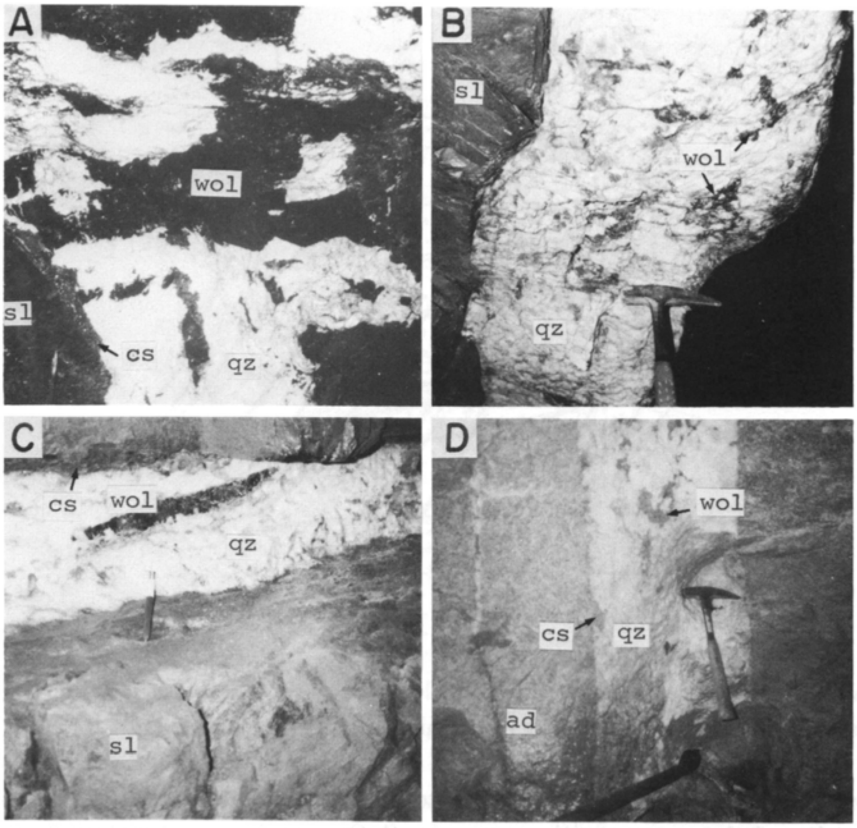

FIGURE 29. PHOTOGRAPHS OF ORE VEINS OF THE CHOJLLA MINE.
A. Wolframite (wol)-cassierite (cs)-quartz (qz) vein in slate (sl), the 2C vein, Tarija level.
B. Wolframite (wol)-quartz (qz) vein in black slate (sl), the 13a vein, 10 level.
C. Aggregate of cassiterite (cs) and prismatic wolframite (wol) in quartz (qz) vein (the 12N vein) embedded in slate (sl), sublevel between 6 and 7 levels.
D. Wolframite (wol)-quartz (qz) vein in muscovite adamellite (ad), the 6C vein, −90 m level.

arsenopyrite etc. (Figure 30-B). Apatite occurs as irregular massive form consisting of aggregate of subhedral or anhedral crystals, 5 to 30 mm in size, associated with quartz, cassiterite, wolframite, tourmaline and arsenopyrite etc. (Figure 30-C). Also the chemical composition of apatite (79101706) from the mine analysed by wet method is TiO_2 0.88%, Al_2O_3 0.06%, Fe_2O_3 0.09%, MnO 2.59%, MgO 0.00%, CaO 51.82%, Na_2O 0.03%, K_2O 0.00%, P_2O_5 42.10%, H_2O_+ 1.01%, H_2O_- 0.00%, F 1.97%, Cl 0.02%, −(O=F, Cl) 0.83%, Total 99.74%. From the analytical data, it corresponds to fluo-hydroxyl apatite essentially without chroline, and its chemical formula calculated on the basis of O+OH+F+Cl=26 is $(Ca_{9.32}\ Na_{0.01}\ Mn_{0.37}\ Fe_{0.01}\ Al_{0.01}\ Ti_{0.11})_{9.83}\ P_{5.98}\ O_{23.82}\ (OH_{1.13}\ F_{1.05}\ Cl_{0.01})_{2.19}$. Its lattice parameters obtained from X-ray powder data are a=9.359Å and c=6.875Å.

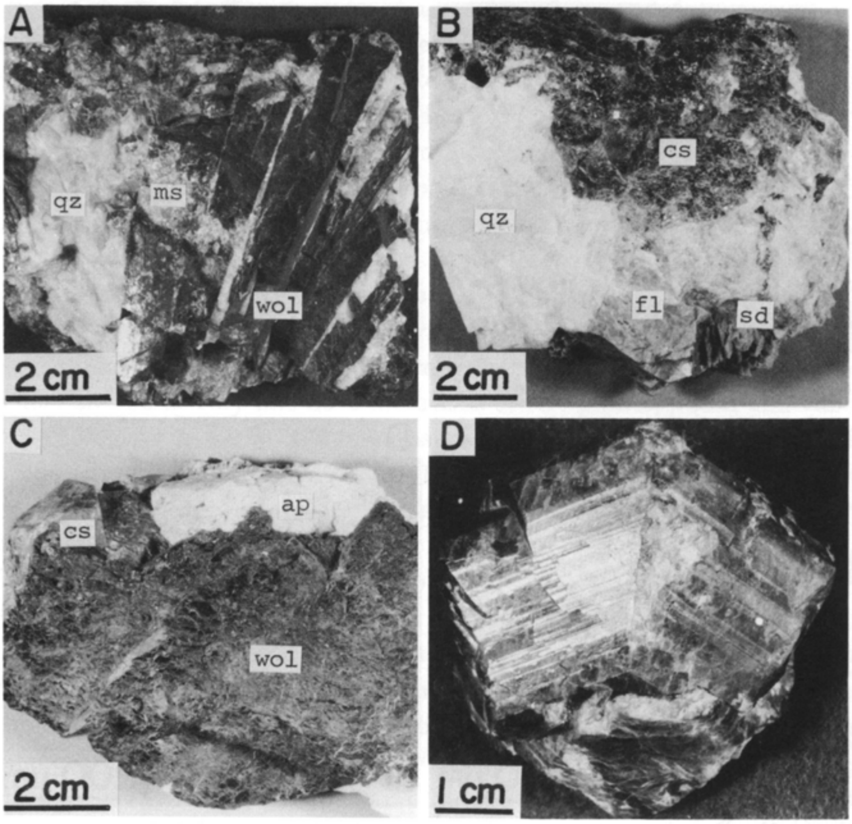

FIGURE 30. ORE SPECIMENS FROM THE CHOJLLA MINE.

A. Prismatic crystal aggregate of wolframite (wol) associating with muscovite (ms) and quartz (qz), the 5C vein, 120 m level (Sample No. 82120327).

B. Association of cassiterite (cs), quartz (qz), flouorite (fl) and siderite (sd), the 2C vein, Tarija level (79101701).

C. Large crystals of cassiterite (cs), wolframite (wol) and apatite (sp), the 2C vein, Tarija level. (79101706).

D. Large single crystal of cassiterite, the 10N vein, sublevel between the 6 and 7 levels (82120231).

Meanwhile siderite is a common mineral from the mine and appears in patch-like or irregular form of aggregate of subhedral or euhedral crystals, 10 to 50 mm in size, in intimate association with quartz, fluorite, muscovite and cassiterite etc. Slight amounts of scheelite are found in spot-like form, 1 to 5 cm in size, as aggregate of its crystal, 2 to 10 mm in size, in quartz sometimes assembled with arsenopyrite, muscovite, wolframite and cassiterite. Its composition is almost pure $CaWO_4$ without powellite molecule.

As sulfide minerals from the mine, arsenopyrite, pyrrhotite, sphalerite, galena and chalcopyrite are found macroscopically. Among them, arsenopyrite is most common mineral and occurs as euhedral or subhedral crystals 5 to 10 mm in size,

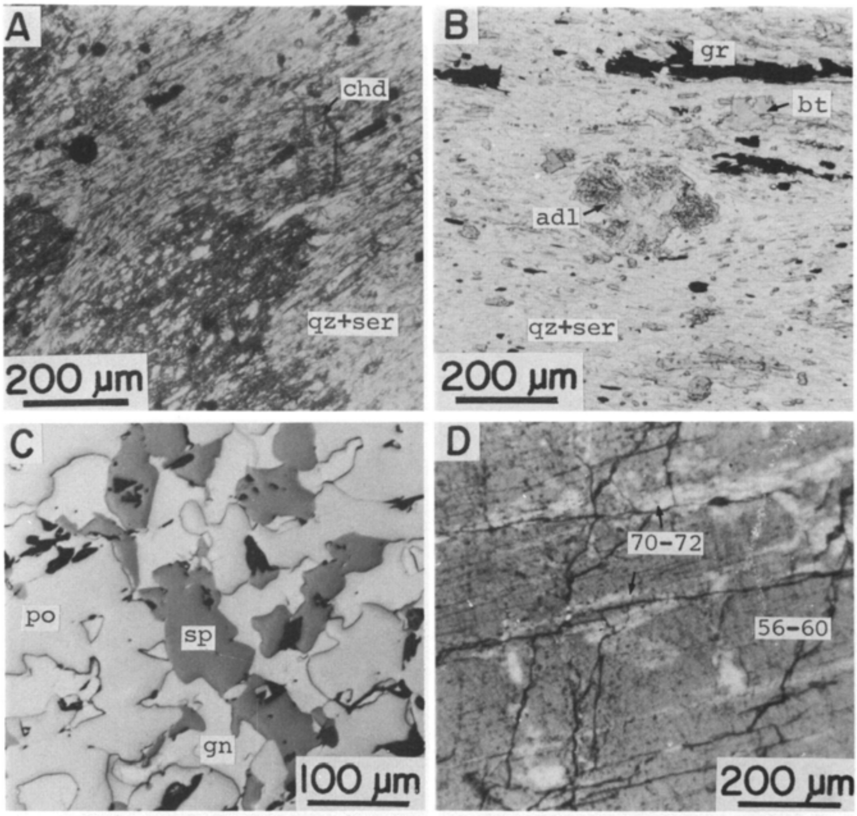

FIGURE 31. PHOTOMICROGRAPHS OF HORNFELS OF SLATE AND ORE MINERALS FROM THE CHOJLLA MINE.

A, B and D; transmitted light, C; reflected light.

A. Weakly metamorphosed slate. Chrolitoid (chd) is formed by thermal metamorphism. Quartz (qz) and sericite (ser) appear. Entrance of adit at the −120 m level (Sample No. 77 CJU09).

B. Hornfels. Prismatic andalusite (adl) with graphite (gr), biotite (bt), sericite (ser) and quartz (qz), 120 m level (77CJU13).

C. Intergrowth of pyrrhotite (po), galena (gn) and sphalerite (sp), the 6C vein, −60 m level (79101719).

D. Internal texture of wolframite, the 2C vein, −90 m level (79101702). Numbers indicate compositions of wolframite in mole % $MnWO_4$.

and often massive or patch-like forms, 3 to 5 cm, of its crystal aggregate in quartz closely assembled with other sulfide minerals described above. Pyrrhotite is also common mineral within sulfides and shows massive form or patch-like shape in quartz, intimately associating with arsenopyrite, sphalerite, galena and chalcopyrite (Figure 31-C). It belongs to a hexagonal form. Sphalerite occurs as massive or patch-like form, several cm to 10 cm in size, of aggregate of its fine crystal, 1 to 3 mm in size, in quartz associated with small quantities of galena, chalcopyrite, arsenopyrite and cassiterite. Sphalerite from the mine contains 6.0 to 6.7 wt % Fe corresponding to 10.4 to 11.6 mole % FeS. Galena sometimes appears in veinlet or stringer, 5 to 30 mm wide, of aggregate of its crystal, 2 to 4 mm in size, embedded interspace of quartz aggregate in intimate association with sphalerite, chalcopyrite, pyrrhotite and arsenopyrite etc. Chalcopyrite similarly occurs as veinlet or network filling up interspace of quartz crystal aggregate, accompanying with galena, sphalerite, pyrrhotite and arsenopyrite etc. in quartz. It occasionally contains small grains of stannite, 5 to 40 microns in size and native bismuth, 5 to 20 microns, microscopically, but it has no sphalerite star. Among the sulfide minerals, arsenopyrite is thought to be crystallized at earlier stage than other sulfide minerals deposited at approximately same period in the mineralization. No sulfosalt minerals such as tetrahedrite, lead-antimony sulfosalts and silver bearing sulfosalts are observed in the ore from the mine.

There are found very fine fluid inclusions of two phases, liquid and vapor, in quartz. Although it is difficult to measure homogenization temperature of the inclusion because of very fine grain, 5 to 10 microns or less in size, the homogenization temperatures obtained for 27 inclusions in quartz are 231° to 408°C (mean value 311°C).

The $\delta^{34}S$ values for pyrite, pyrrhotite and galena are $+3.8$, $+3.5\sim+5.0$ and $+2.9‰$, respectively.

The mineralizations forming such many tin-tungsten bearing quartz veins as described above are thought to be post-magmatic action genetically related to the intrusion of muscovite adamellite batholith (or Taquesi pluton) in intimate accompany by intense greisenization. From the data on geological feature, vein system, ore structure and texture, and mineral assemblages, the veins are deep-seated type which belongs to hypothermal deposits formed under condition of high temperature and pressure.

5. *San Antonio mine*

The San Antonio (old name, Susana) mine is located at 2 km east of Millipaya and about 12 km southeast of Sorata locating at 90 km north of La Paz. It is situated at about 4,300 m altitude in western slope of Mt. Illampu (7,010 m) (Figure 32-A). It has been mined as a tungsten deposit of vein-type.

Geology around the mine is composed mainly of sandstone of Silur-Devonian and granitic rock of the Illampu batholith (Figure 33) which corresponds to hornblende-biotite granodiorite and is equigranular and hollocrystalline rock consisting of biotite, hornblende, quartz, plagioclase and orthoclase, and small amounts of apatite, zircon and rutile etc. Sandstone is strongly affected by contact metamorphism, and recrystallized quartz and sericite are observed. The ore veins develop in hornfels and are principally composed of wolframite, arsenopyrite, quartz, tourmaline and apatite associating with small amounts of chalcopyrite, pyrite and scheelite etc. Wolframite appears as idiomorphic crystals of platy or prismatic forms, 5 to 20 mm in length, assembled with arsenopyrite, tourmaline and quartz, and sometimes scheelite and pyrite. Scheelite is found as granular form, 0.5 to 3 mm in size, enclosed in quartz, and its composition is almost pure $CaWO_4$ with 0.1 to 0.4 mole% MoO_3. It associates with quartz, tourmaline, arsenopyrite and wolframite. Sometimes wolframite is replaced by scheelite along cleavage or crack. Tourmaline appears as aggregate of acicular crystals, 0.01 to 0.1 mm in length, sometimes up to 1 cm (Figure 32-C), assembling with wolframite, scheelite, arsenopyrite, quartz and pyrite. The chemical composition of tourmaline analysed by wet method is SiO_2 34.93, TiO_2 0.73, Al_2O_3 31.95, FeO 6.86, MnO 0.00, MgO 7.21, CaO 1.66, Na_2O 2.26, K_2O 0.37, P_2O_5 0.02, H_2O_+ 3.66, H_2O_- 0.20, F 0.08 B_2O_3 10.63, $-(O=F)$ 0.03, Total 100.53%. The empirical formula obtained from the analytical data is $(Na_{0.72}\ K_{0.08}\ Ca_{0.29})_{1.09}\ (Fe_{0.95}\ Mg_{1.77}\ Ti_{0.09})_{2.81}\ Al_{5.97}\ B_{3.03}\ (Si_{5.76}\ Al_{0.24})_{6.00}\ O_{26.93}\ (OH_{4.03}\ F_{0.04})_{4.07}$. Its cell dimension obtained from X-ray powder data is a=15.954 (8)Å and c=7.210 (5)Å. From these data, it corresponds to dravite. The $\delta^{34}S$ value for pyrrhotite is +13.8‰.

6. Trinidad mine

The Trinidad (old name, Condor Huta) mine (about 4,800 m altitude) is located at 2 km east of the San Antonio mine (Figure 33). It has been mined as a vein-type molybdenum deposit, but closed now. The ore veins are embedded in hornfels as well as the San Antonio mine. They have 5 to 20 cm wide and strike N60°-70°W (Figure 32-B). The principal minerals of veins are molybdenite, quartz, apatite, chlorite, orthoclase associating with minor amounts of tourmaline, pyrrhotite, pyrite, chalocpyrite and calcite. Molybdenite appears as foliated crystal, 0.1 to 1.0 cm in diameter, accompanied with quartz, chlorite and apatite, and sometimes tourmaline, pyrite and pyrrhotite. Its X-ray powder data indicates that it is entirely of a typical $2H_1$ polytype. Pyrite, pyrrhotite and chalcopyrite are found rarely in assemblage with molybdenite, quartz, chlorite and apatite.

The homogenization temperature and salinity in NaCl equivalent concentration for fluid inclusion in quartz are 217° to 427°C (mean value 311°C) and 23.6 to 47.1 wt%, respectively.

7. Matilde mine

The Matilde mine being 10 km east of Carabuco town near eastern shore of Lake Titicaca is located at about 155 km northwest of La Paz. It is also situated at about 50 km southeast from the border between Bolivia and Peru. The mine is now working and has been producing 25,000 and 15,000 tons per month as crude ore containing 7.5% Zn, 1.0% Pb, 150 g/t Ag and 8.0% Zn, 0.80% Pb in 1977 and 1982, respectively. The office of the mine is located at 4,280 m elevation (Figure 34).

Topography around the mine is hill or mountain lands of 3,800 m to 4,700 m

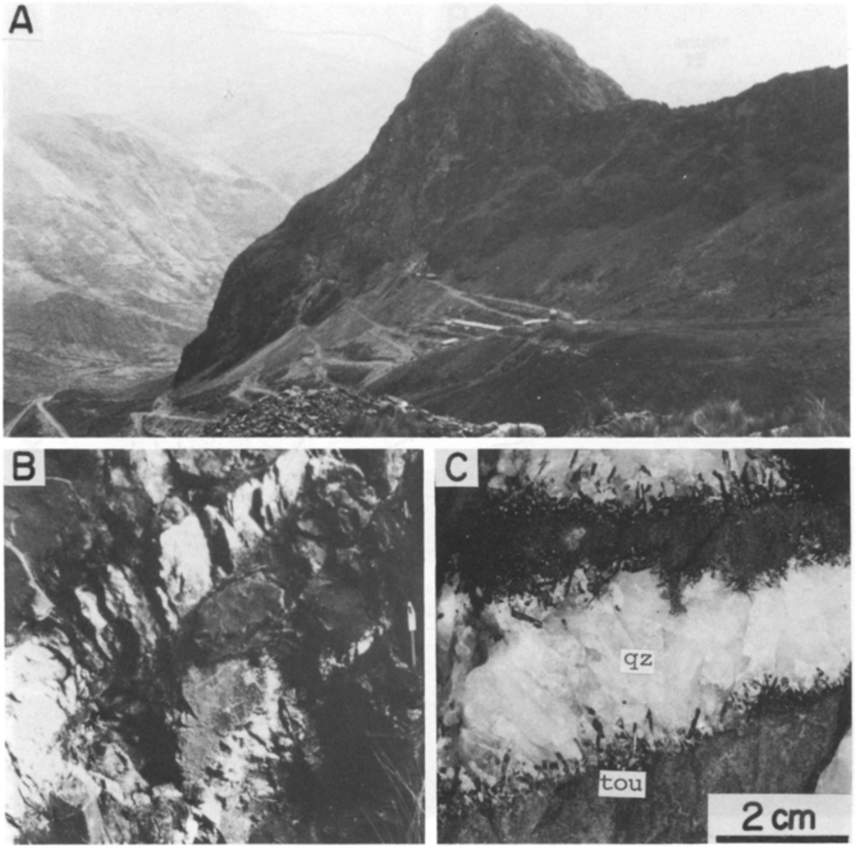

FIGURE 32. SCENERY OF THE SAN ANTONIO MINE AND ORE VEINS OF THE SAN ANTONIO AND TRINIDAD MINES.
A. A distant view of the San Antonio mine looking from the Trinidad mine.
B. Molybdenite-quartz veins (light gray) in hornfels at the Trinidad mine.
C. Aggregate of acicular crystals of tourmaline (tou) in quartz (qz) from the San Antonio mine.

elevation, corresponding to low mountain land in the west side of the Eastern Cordillera of Andes which is cut by the Llica river flowing to northeast. But the mountains in general present gentle slope except some places. A few rivers flowing into Lake Titicaca run generally to west or south, meandering in the hill or mountain lands of the mining area.

According to Rivas (1968), geology around the mine consists of Devonian, Carboniferous and Permian systems of Paleozoic, Cretaceous, Tertiary and Quaternary systems in ascending order as shown in Figure 35. Among them, the Devonian formation appears in wide area as seen in the figure, and is principally composed of gray slate with fissility and light gray fine grained sandstone folded by anticline and syncline axes of the NW-SE direction. The Carboniferous

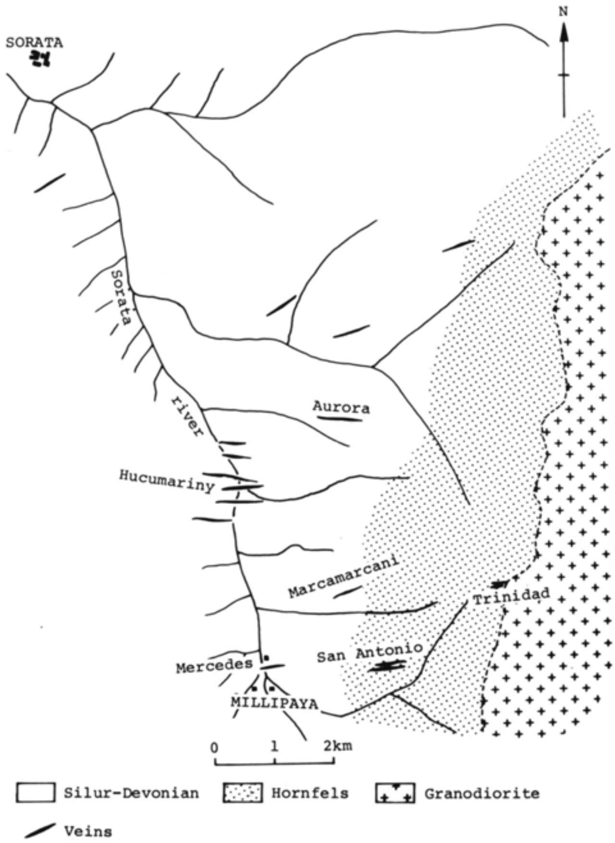

FIGURE 33. GEOLOGICAL MAP AROUND THE SAN ANTONIO AND TRINIDAD MINES (AFTER AHLFELD and SCHNEIDER-SCHERBINA, 1964).

system distributes locally as a belt-like form covered on the Devonian system conformably in the western area, and consists of pale gray coarse grained sandstone inserted green shale. Its sandstone contains a lot of white mica. Meanwhile the Permian formation belonging to the Copacabana Group by Rivas (1968) occurs in western and northern parts of the mining area, overlaying conformably on the Carboniferous system in the western part and sometimes adjoining by fault with the Devonian system at the northern part in the mining area. It is composed of bedding limestone colored pale brown, dark gray and green in lower part, pale brown and coarse grained sandstone with cross laminae in middle and upper parts, and gypsum layer in most upper part of the formation. The Cretaceous system which corresponds to the Moho Group by Rivas (1968) appears locally in western and southern areas as belt-like form covering on the Permian formation unconformably (Figure 34-A). It conists of alternation of shale, quartzite and white colored sandstone inserted gray colored limestone and brown limonite layers in the

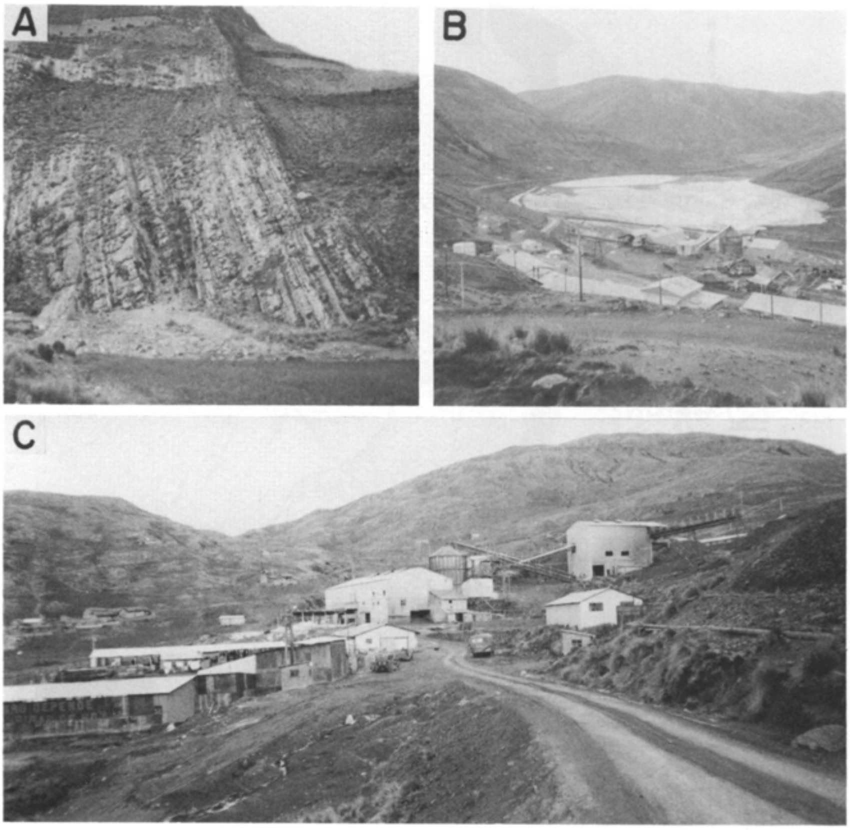

FIGURE 34. SCENERY OF THE MATILDE MINING AREA.
A. Permian formation belonging to the Copacabana Group (left, banding) and Cretaceous system corresponding to the Moho Group (right, dark gray) seen at the west of the Matilde mine.
B. The Matilde mine looking down from the west side.
C. A view of the ore dressing plant of the Matilde mine.

lower and middle horizons of the group, respectively. In its upper part, sandstone is dominant. Tertiary formation of the Corocoro Group is found in the western and southern parts of the area overlaying on the Cretaceous formation unconformably. It is composed mainly of red colored and coarse grained sandstone embedded conglomerate with breccia or fragments of volcanic rocks and sometimes mudstone. As Quaternary sediments, glacier moraine and fluvioglacial deposits consisting of sand and gravel are found in some places near the mine.

As mentioned above, all the systems except Quaternary sediment are distinctly folded by anticline and syncline axes running to the NW-SE direction, and sometimes cut by faults roughly parallel to the direction of folding axes. As shown in Figures 35 and 36 there are conspicuous faults bordering between

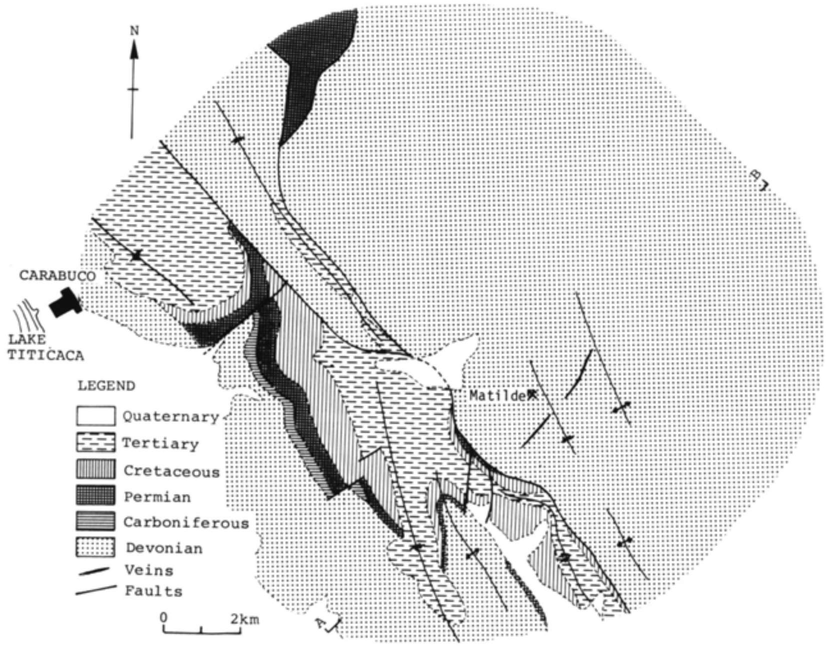

FIGURE 35. GEOLOGICAG MAP OF THE MATILDE MINING AREA.

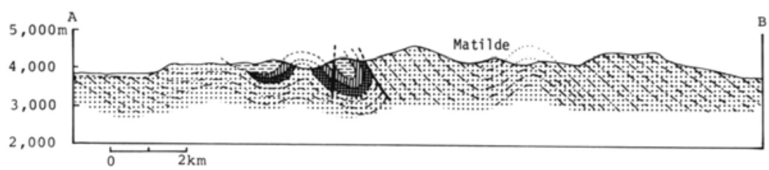

FIGURE 36. GEOLOGICAL SECTION OF THE MATILDE MINING AREA.
Symbols are Same as Fgiure 35.

Devonian system and Permian, Cretaceous or Tertiary systems in the western to southern portions of the area.

The ore deposits of the Matilde mine are zinc and lead veins which are mainly composed of sphalerite, galena, and pyrite as ore minerals with siderite and small amounts of quartz as gangue minerals. There are many ore veins divided into two groups of the NE-SW and NW-SE systems in their strike as shown in Figure 37. As the veins belonging to the NE-SW system, Matilde, Maravillas, Maria Luisa, Santa Ana, Nueva, Santa Rosa 1 and 2, Chica, Gloria and Aurora etc., and also those of the NW-SE system, Grande, Uno and Cuatro Amigos etc. Among them, the Matilde and Maravillas veins are the most principal ones and are vigorously mined at the present. That is, the Matilde vein is developed from outcrop on surface (about 4,600 m elevation) down to the 505 m level by the 50, 100, 125, 170, 205, 245, 270, 285, 325 (main adit, 4,283 m elevation), 365, 385, 400, 425, 456, 460, 465, 490 (Santa Barbara), 495 and 505 m levels with the Senales,

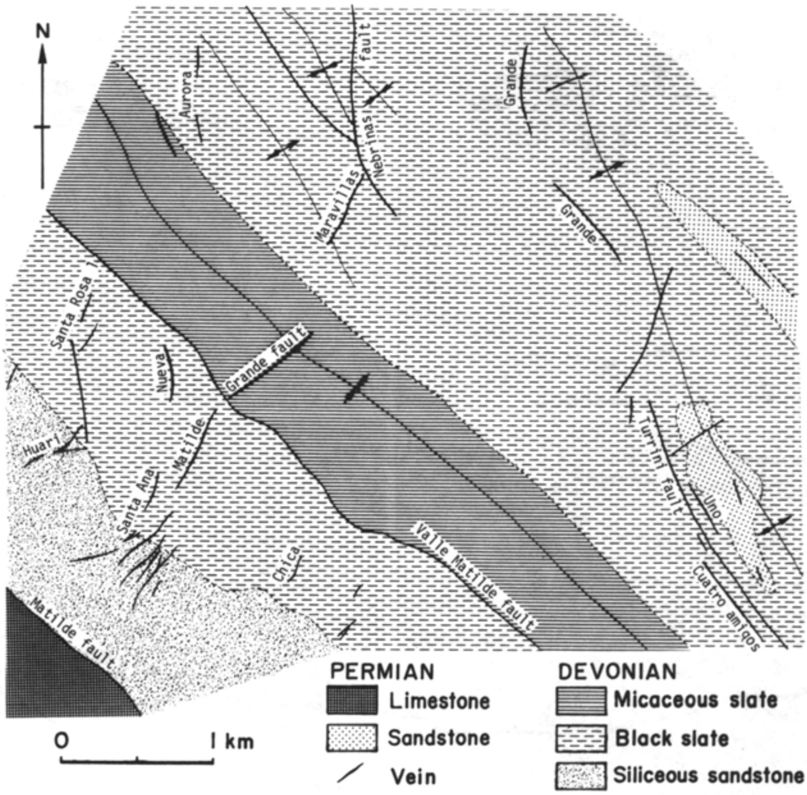

FIGURE 37. GEOLOGICAL MAP IN THE MATILDE MINE.

Enrique and Guillermo shafts (Figures 38 and 39). Meanwhile the Maravillas vein is also exploited from surface (4,470 m elevation) to the 325 m level by the 170, 205, 270, 305 and 325 m levels. The scales of both the Matilde and Maravillas veins having strike N20° to 30°E dipping to 80°W or E sometimes perpendicular are 1,100 and 800 m in length, and 545 and 200 m or more in depth, respectively. Width of both veins is 1.2 to 9.0 m, mean value 2.5 m.

The Matilde vein mainly occurs in Devonian slate. It develops in black slate zone of the Devonian formation, but it disappears in micaceous slate zone as seen in Figure 37. It is principally composed of siderite and sphalerite associated with galena, marcasite and quartz. The ore veins often show conspicuously characteristic alternated banding or laminating structure of siderite and sphalerite, 2 to 20 mm in thickness, as seen in Figure 40-B, C and D. Sphalerite band is aggregate of its granular crystal, 1 to 5 mm in size, associating with siderite in general, and marcasite and quartz occasionally (Figure 41-B). Meanwhile siderite band is mostly composed of aggregate crystals, 2 to 5 mm in size. Also ring ore consisting of sphalerite and siderite is sometimes found in the vein. In the ring

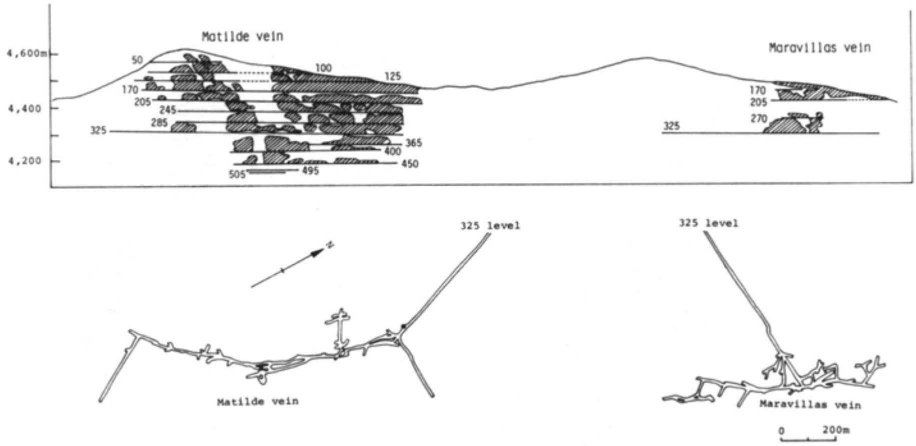

FIGURE 38. ARRANGEMENTS OF MATILDE AND MARAVILLAS VEINS AND THEIR CROSS SECTION IN THE MATILDE MINE.

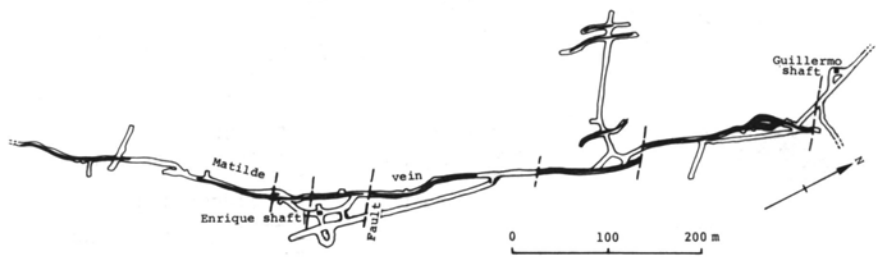

FIGURE 39. MATILDE VEIN AT THE 325 LEVEL OF THE MATILDE MINE.

ore sphalerite appears usually as core, 5.0 to 30 mm in diameter, of ball or ellipsoidal forms, commonly 5 to 10 cm in diameter, presenting the ring structure, and siderite layer, 3 to 15 mm thick, surrounds the core of sphalerite as shown in Figure 40-C and D. As outside rim of the ring structure, sphalerite, 3 to 5 mm thick, commonly encircles the siderite layer. Such the ring structure of ore is formed individually in siderite of the vein, but sometimes it forms a part of the ore shown the banding or laminating structures as stated above. Therefore formation of the ring ore is related intimately to that of the banding ore. Sphalerite besides band and ring core occurs also as brecciated fragments, 1 to 3 cm in size, in siderite of the vein. Occasionally its breccia, 1 cm in size, becomes to the core of the ring ore. Sphalerite banding with siderite has slight amounts of fine pyrrhotite or chalocopyrite dots or lamellae microscopically which may be an exsolution product. According to EPMA data, sphalerite has 6.0 to 7.3 mole% FeS in its composition, but elements of Mn, Cd, Sn and In were undetected in it by EPMA. Meanwhile galena appears in roughly banding form, 3 to 8 mm thick with siderite or as massive form of aggregate of fine grained crystal, 0.5 to 1.0 mm,

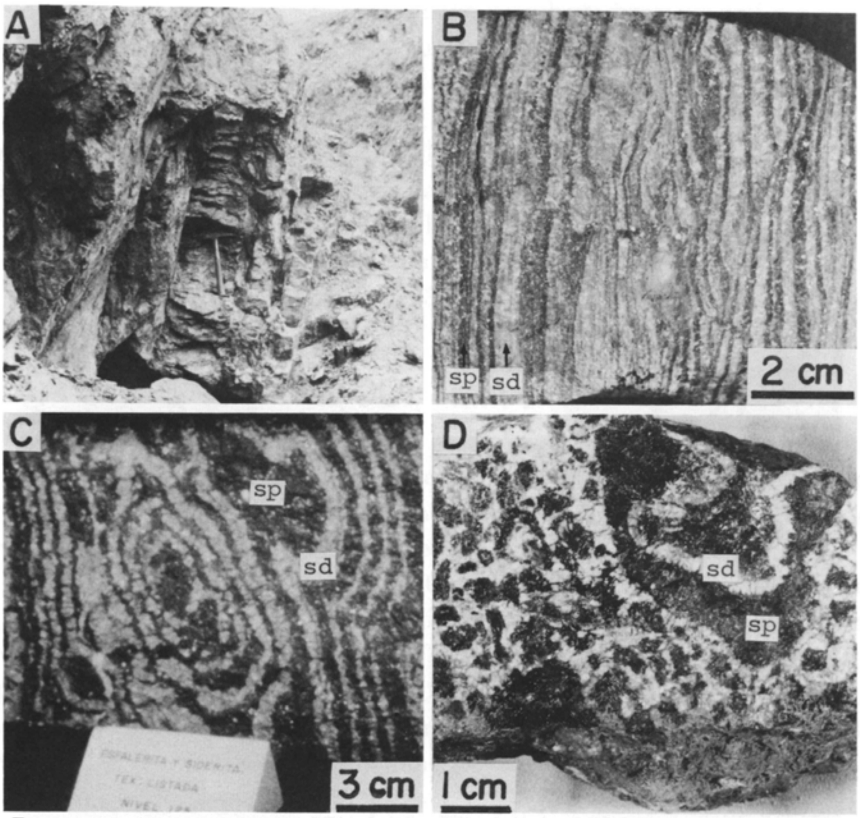

FIGURE 40. ORE VEINS AND SPECIMENS FROM THE MATILDE MINE.
A. Outcrop of galena-siderite-sphalerite vein, Maravillas vein.
B. Banding of sphalerite (sp) and siderite (sd) from the Matilde vein, 490 level (82112901).
C. Ring ore consisting of sphalerite (sp) and siderite (sd), Matilde vein, 125 level.
D. Sphalerite breccia and ring ore of sphalerite (sp) and siderite (sd), Matilde vein, 490 level (82112918).

in siderite. It associates with siderite usually and sphalerite, boulangerite, tetrahedrite and quartz occasionally. Galena often occurs as veinlet, 1 mm wide, or network as cutting siderite band or invading along cleavage of siderite microscopically, and sometimes accompanies intimately with boulangerite. Boulangerite appears as a massive and compact form of aggregate of very fine elongated crystal, 30 to 150 microns long, assembling with galena, sphalerite and siderite. Under ore microscope it intimately associates with galena, presenting form as been replaced by galena as shown in Figure 41-C. Although this mineral is thought to be a new species by some geologists in the mine, it has been confirmed to be boulangerite as the result of microscope examinations and X-ray diffraction. Marcasite which is a common mineral from the mine, but not so much, occurs as

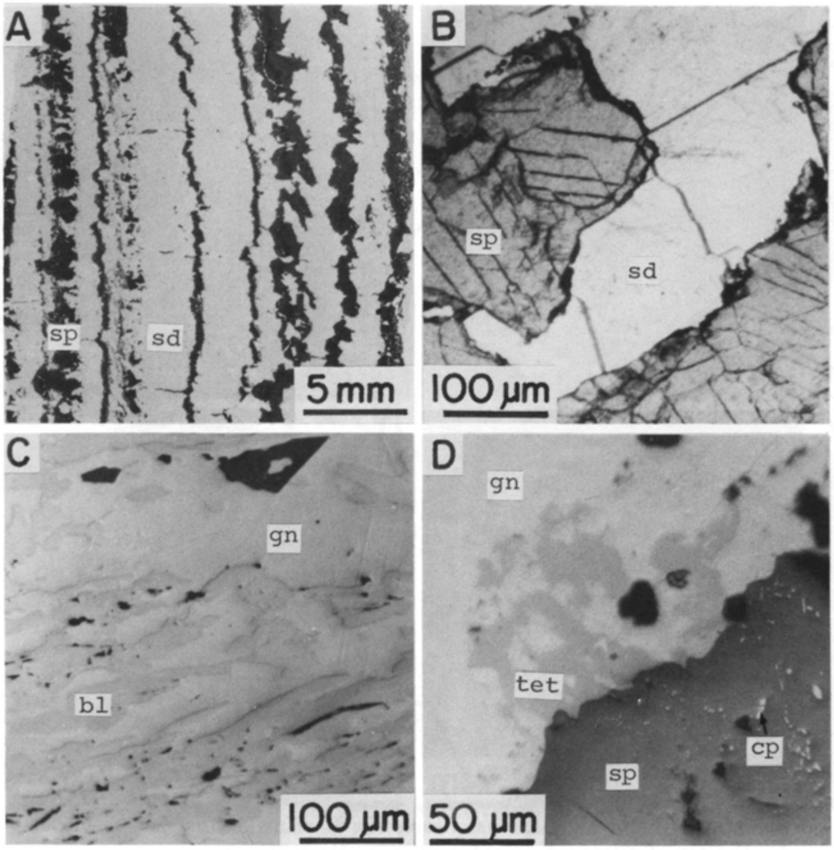

FIGURE 41. PHOTOMICROGRAPHS OF ORES FROM THE MATILDE MINE.

A B : transmitted light and C and D ; reflected light.

A. Laminating bandings of sphalerite (sp) and siderite (sd), Maravillas vein, 270 level (Sample No. 82112917).

B. Association of sphalerite (sp) and siderite (sd) (82112908).

C. Aggregate of boulangerite (bl) and galena (gn), (82112902).

D. Tetrahedrite (tet) in galena (gn) and sphalerite (sp) with chalcopyrite (cp) blebs, Santa Rosa vein, 270 level (82112912).

aggregate of euhedral or subhedral crystals, 0.1 to 0.7 mm in size, showing polysynthetic twin frequently associated with siderite, sphalerite and quartz. It also appears as network or veinlet, 0.1 to 1.0 mm wide, cutting siderite, sphalerite and quartz. Quartz is found as lens, stringer, and spot-like forms in the vein associating with siderite, sphalerite and marcasite, and its veinlet, 2 to 4 mm in width, sometimes cuts the band of sphalerite and siderite. Veinlet of quartz also appears in country rock adjacent to the vein. Quartz and siderite sometimes show undulatory extinction as result suffered stress. Fragments or breccia of slate and sandstone of country rocks are often found in the vein. From data on occurrence and mineral assemblage and paragenesis mentioned above, sphalerite and siderite which form main portion of the vein have been crystallized at early stage of the mineralization, and then quartz, galena, boulangerite and marcasite have been produced at late stage of the mineralization. There are found no tin and tungsten minerals such as cassiterite, stannite, wolframite and franckeite from the mine. Thus, it is not made clear whether or not the deposits of the Matilde mine were formed by mineralization related to Mesozoic granitic magma as same as that of the Milluni, Kellhuani, Chojlla and San Antonio mines.

Homogenization temperature for fluid inclusions in quartz from the Matilde vein is 188° to 283°C (average value 233°C). Also the $\delta^{34}S$ values for pyrite, sphalerite and galena from the Matilde vein are $+13.1 \sim +14.0$, $+14.0 \sim +14.6$ and $+10.9‰$, respectively.

8. Viloco mine

The name Viloco is world-famous because euhedral and large, dark brown to dark yellowish brown colored, semitransparent, beautiful crystals of cassiterite have occurred from this mine (old name, Araca mine).

The Viloco mine is situated about 70 km southeast of La Paz city (Figure 9). The main adit is located at 4,250 m altitude on the foothill of the Tres Cruces range of Cordillera Real (Figure 42). The deposit of the mine is principally composed of fissure filling veins of tin and tungsten ores. The mining is now active and is operated under the Mining Corporation of Bolivia (COMIBOL) (Figure 43). The production of the mine was 5,854 tons per month of crude ores containing 0.88% Sn in 1983. The concentrated ore of tungsten is produced annually less than 40 tons.

The Viloco mining area consists of mountains, valleys, and morainal-dam lakes with great topographic relief from 3,900 m to 5,300 m above sea level. Steeply glaciated valleys and peaks are mostly inaccessible as seen in Figure 42, and moraine deposits locally keep covering the outcrops.

The ore deposits of Viloco are emplaced in both Silurian system and granodiorite of the Tres Cruces batholith. The Silurian in the area is folded in a broad syncline that trends north-northwest. It probably corresponds to the Uncia Formation in the type area, and is divided into four conformable members in ascending order (Figures 44 and 45) as follows. The sandy slate member consists of micaceous black slate frequently intercalating very fine grained layers of sandstone. It has more than 800 m in thickness. The quartzite member is restricted in one horizon, and has a thickness of 40 m. The member is composed of fine grained, grayish white to greenish gray quartzite containing an intercalation of thin sandy slate. The slaty sandstone member has a maximum thickness of 450 m. It is essentially similar to the sandy slate member, but locally rich in fine to medium grained sandstone beds. The top horizon of the area is occupied by the slate member which is distinguished by its lighter color from the lower

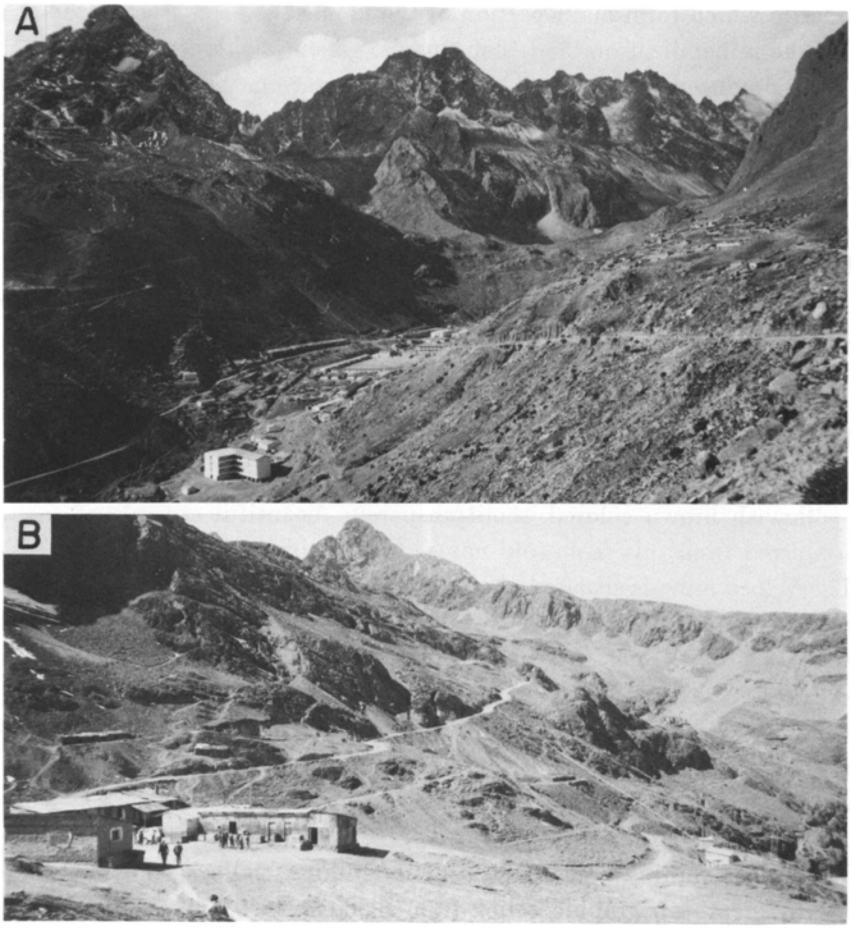

FIGURE 42. TOPOGRAPHY AROUND THE VILOCO MINE.
A and B. Steep mountain range near the Viloco mining town.

members.

The Tres Cruces batholith gives 26 Ma (upper Oligocene) by the K-Ar method, while most granitic batholiths of Cordillera Real give Triassic to Jurassic ages (Evernden *et al.*, 1977). The batholith exposed in the area is composed of comparatively homogeneous, fine grained, biotite granodiorite. Around the granodiorite, the Silurian sediment, especially the sandy slate member, is thermally metamorphosed to biotite hornfels.

Numerous veins are distributed in an area of 4 km × 6 km (Figure 46). Most major veins trend N40°E and N85°E, and they usually associate branching veins trending N70°E and N80°W. Locally barren faults trending N50°W cut the veins. From the lithological point of view, it is noteworthy that the veins have a tendency to localize selectively in competent rocks such as quartzite and slaty

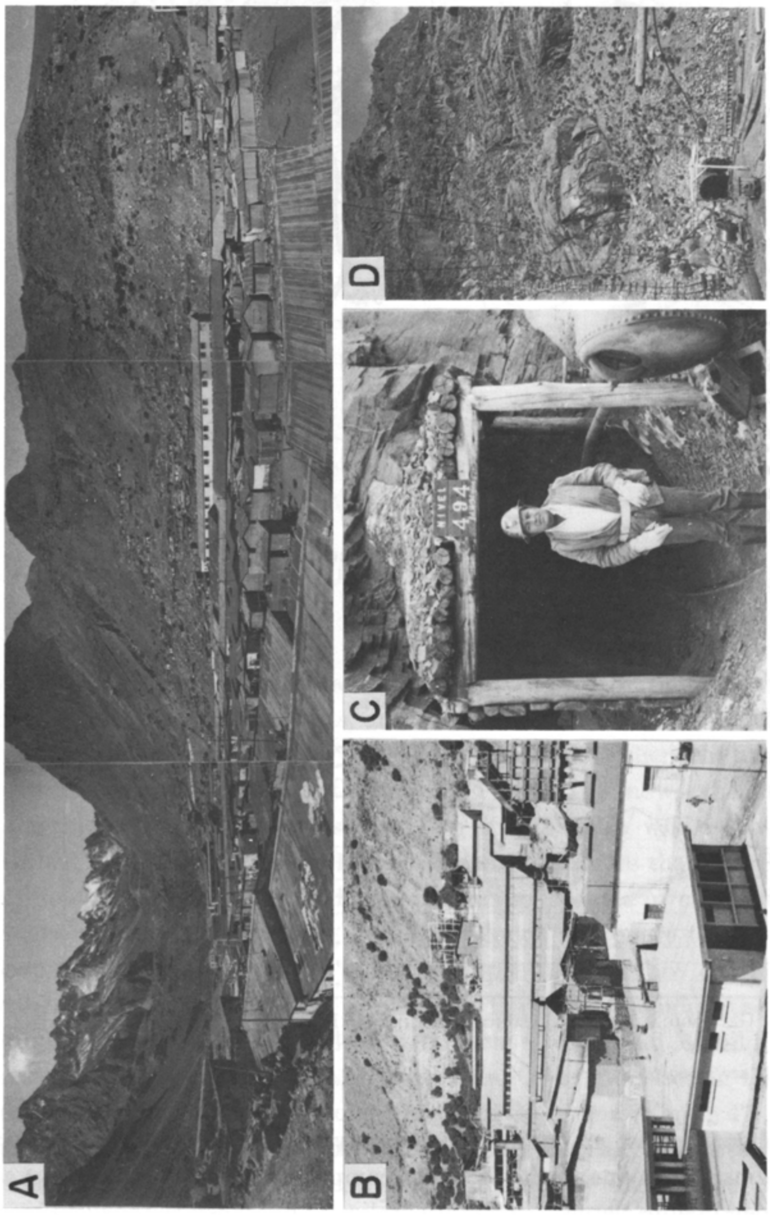

FIGURE 43. SCENERY OF THE VILOCO MINE.
A. A view of the Viloco mining town.
B. Ore dressing plant of the Viloco mine.
C. Entrance of adit of 494 m level, San Antonio section.
D. Entrance of adit of 540 m level, Bonaparte section.

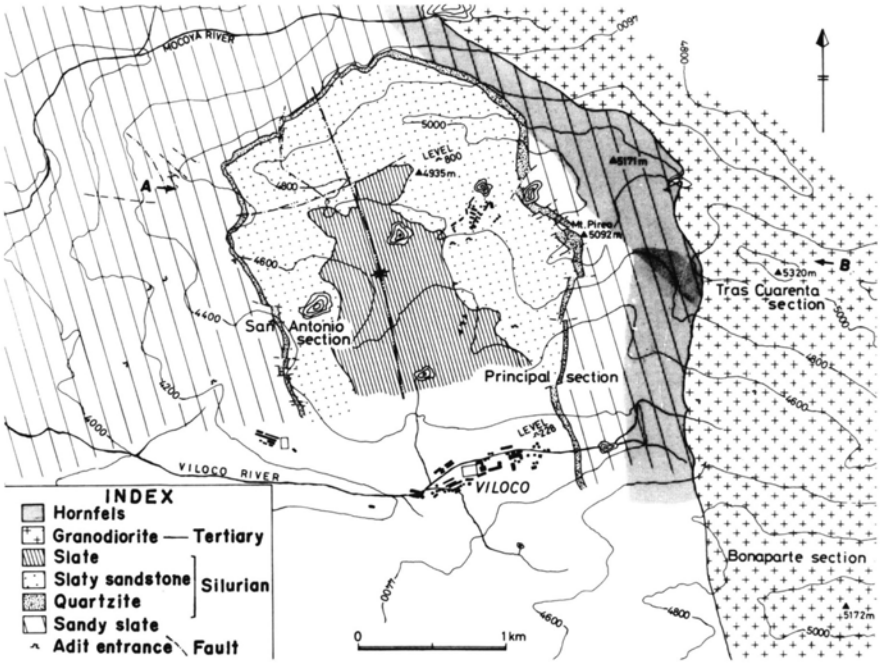

FIGURE 44. GEOLOGICAL MAP OF THE VILOCO MINING AREA (COMPILED FROM BUSTOS AND MURILLO, 1976).

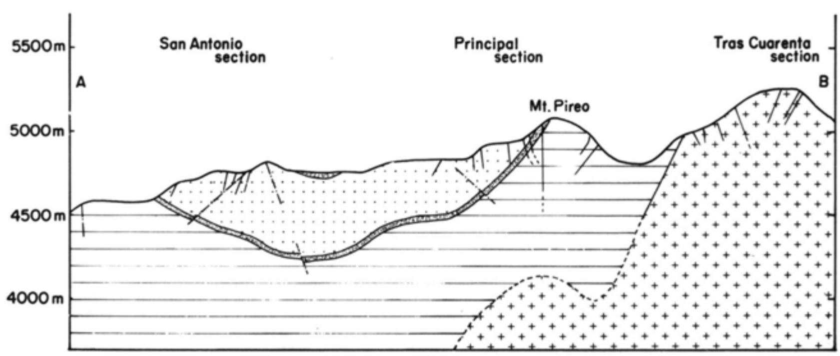

FIGURE 45. GEOLOGICAL SECTION ALONG A-B LINE IN FIGURE 44 (AFTER BUSTOS AND MURILLO, 1976).
Symbols are same to Figure 44.

sandstone members and also granodiorite, but rarely in incompetent beds like slate abundant horizons. It is due to the fact that competent rocks are strong, but are easy to make open fissures permeable for mineralized fluid when they fail to break (Figures 44 and 45).

Veins are concentrated in four swarms and are exploited in four mining sections, namely San Antonio, Principal, Tras Cuarenta, and Bonaparte sections

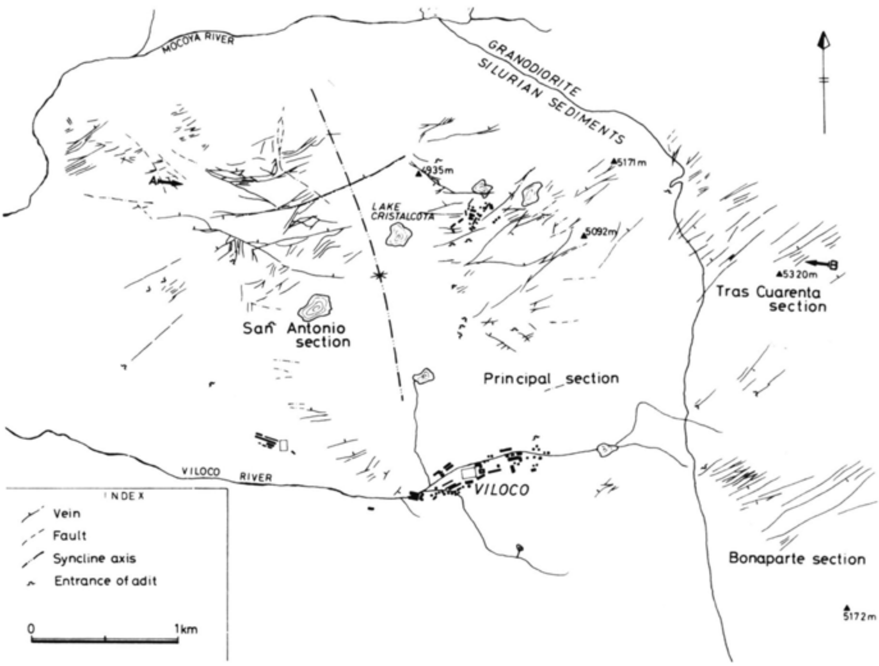

FIGURE 46. VEIN MAP OF THE VILOCO MINING AREA.

(Figure 46).

Principal and San Antonio sections: Vein swarms of the sections are entirely emplaced in Silurian sediments, and are limited in a zone from 400 m to 2,000 m from the granodiorite contact. The Principal section where the champion vein of Ines was exploited to the depth of 750 m (Table 3) is now exhausted. Bonanza of the tin ore was restricted in shape of an inverted corn, where a cassiterite-quartz vein had an average width of 1.5 m and contained more than 5% Sn (Bustos and Murillo, 1976). Beautiful and huge prismatic crystals of cassiterite attaining 8 cm across were found in this section as shown in Figure 47-D. As mentioned above, the quartzite member and its upper member are comfortable for ore localization. Increasing with depth into the lower member, the veins became abruptly narrow to the width less than 15 cm (Bustos and Murillo, 1976). There are some veins such as Martha, Nueva, Uno, Once and Doce in the San Antonio section listed in Table 3. Among them, the Once vein (Figure 47-A) which has a width of 20 to 30 cm, develops along fracture zone of quartzite. It consists of quartz, tourmaline and siderite, and accompanies by small amounts of cassiterite. Tourmaline occurs as veinlet or network of 1 to 2 mm in width, and quartz and siderite veinlets, 1 to 5 mm in width, cut tourmaline veinlets. Also they fill up interspace of brecciated quartzite as shown in Figure 47-B. Cassiterite intimately associates with quartz, and also occurs as veinlet in quartzite (Figure 47-C).

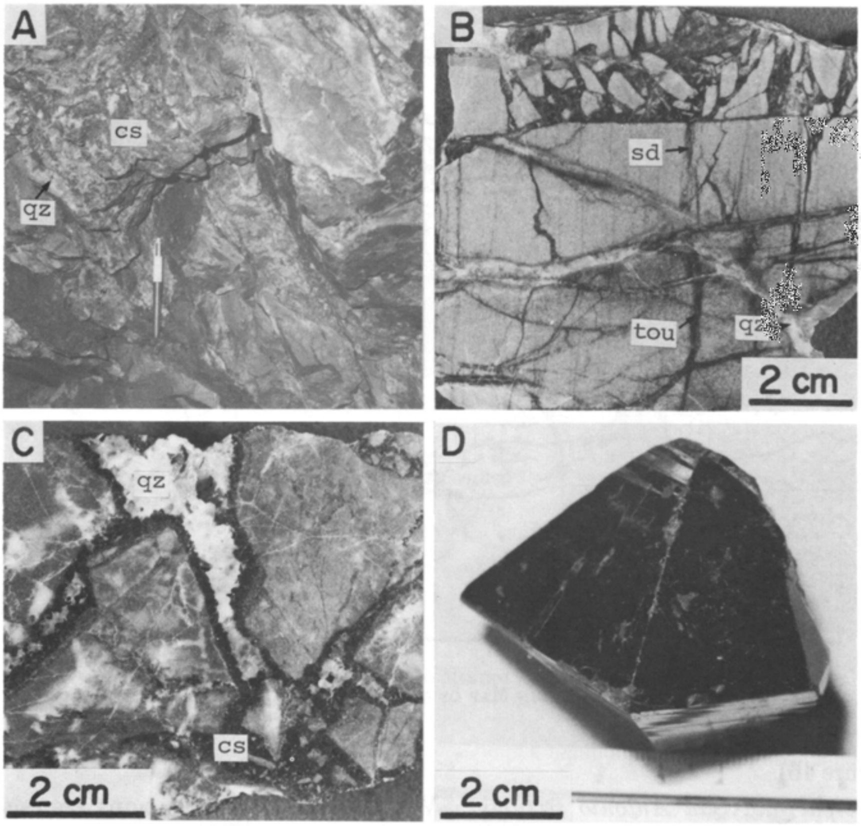

FIGURE 47. VEIN AND ORE SPECIMENS OF THE VILOCO MINE.
A. Cassiterite (cs)-quartz (qz) vein, the Doce vein, sublevel of 494 m level, San Antonio section.
B. Tourmaline (tou)-quartz (qz)-siderite (sd) veinlets filling fissure of quartzite, the Once vein, San Antonio section.
C. Cassiterite (cs)-quartz (qz) banding in the Once vein, San Antonio section.
D. Typical euhedral crystals of cassiterite.

Mineralization of the San Antonio section is similar to that of the Principal section. Arsenopyrite ore is locally abundant within a vein, and accompanies with wolframite and quartz. It frequently contains small but acicular crystals of tourmaline and also an aggregate of bismuthinite and native bismuth. The assemblage of wolframite and arsenopyrite is replaced by cassiterite whose crystals are generally small up to 5 mm across and locally as large as 3 cm long in a druse. Cassiterite shows an intimate association with chlorite and siderite, especially where the former products are deficient in a fissure.

Deposition of pyrrhotite, pyrite, and sphalerite is later than that of cassiterite ores. They accompany minor amount of stannite, marcasite, jamesonite, and galena. Stannite is commonly observed as a reaction rim between cassiterite and

TABLE 3. PRINCIPAL VEINS AND THEIR SCALES IN THE VILOCO MINE.

Section	Vein	Strike	Dip	Length (m)	Depth (m)	Width (m)
Principal	Ines	N45°E	75°NW	700	750	1.0
San Antonio	Martha	EW	78°N	350	350	0.3
	Nueva	EW	70-80°N	750	410	0.7
	Uno	N85°E	70-75°N	800	530	1.0
	Once	N60°E	80°N	120	530	0.8
	Doce	N60°E	45°N	150	490	0.8
Bonaparte	Broncera	N60°E	70-75°N	600	580	0.8
	Cinco	N60°E	70-75°N	450	580	0.5

pyrrhotite or chalcopyrite. No intergrowth of stannite and sphalerite is found. Sphalerite contains very fine blebs of chalcopyrite along grain boundaries. Stringers of well crystallized kaolinite occur along fractures independently.

Tras Cuarenta and Bonaparte sections: Vein swarms of these sections are impregnated mostly in granodiorite, though a few veins of Tras Cuarenta section are in hornfels. In the Tras Cuarenta section, veins are generally narrow ranging from 5 to 30 cm wide and are exploited in a vertical interval of 300 m. Quartz is the main constitute in the veins accompanying with wolframite, arsenopyrite, cassiterite, pyrite and pyrrhotite. Molybdenite-quartz veinlets are rarely found in granodiorite. Wolframite and arsenopyrite contain small but acicular crystals of tourmaline. It is interesting that tin content of veins in granodiorite increases more than that in hornfels. Mineralization of the Bonaparte section is similar to that of Tras Cuarenta, but different in more abundant occurence of pyrrhotite and sphalerite ores. The width of the veins varies from several centimeters to 1 m (Table 3). Major assemblage is composed of quartz, cassiterite, and chlorite. Grain size of cassiterite ranges from 3 to 10 mm across. The assemblage is followed by the deposition of pyrrhotite, sphalerite, chalcopyrite, pyrite, stibnite, galena and siderite, associated with minor amounts of bismuthinite, native bismuth, marcasite, and sericite. Wolframite sometime occurs in quartz, and monazite is found in cassiterite ore from the Cinco vein (470 m level) in the Bonaparte section. Monazite appears as a rounded grain, up to 0.2 mm across, and its images for back-scattered electron and X-ray intensities for Ce, La and P radiations are as given in Figure 48. Also it surely contains detectable amounts of Nd, Pr, Cs, Eu and Gd less than 0.1 wt% by means of an energy dispersive X-ray microanalysis.

The veins are distributed in four sections, however, they can be regarded as a serial product of continuous mineralization related to post magmatic activity of the Tres Cruces granodiorite intrusion, mainly because they have common characteristics on mineral paragenesis and intervein structure with a frequent occurrence of druses. Therefore, mineral sequence of the Viloco mining area is established as a whole as shown in Figure 49. The early stage of mineralization started with acicular tourmaline, followed by the deposition of wolframite, arsenopyrite and

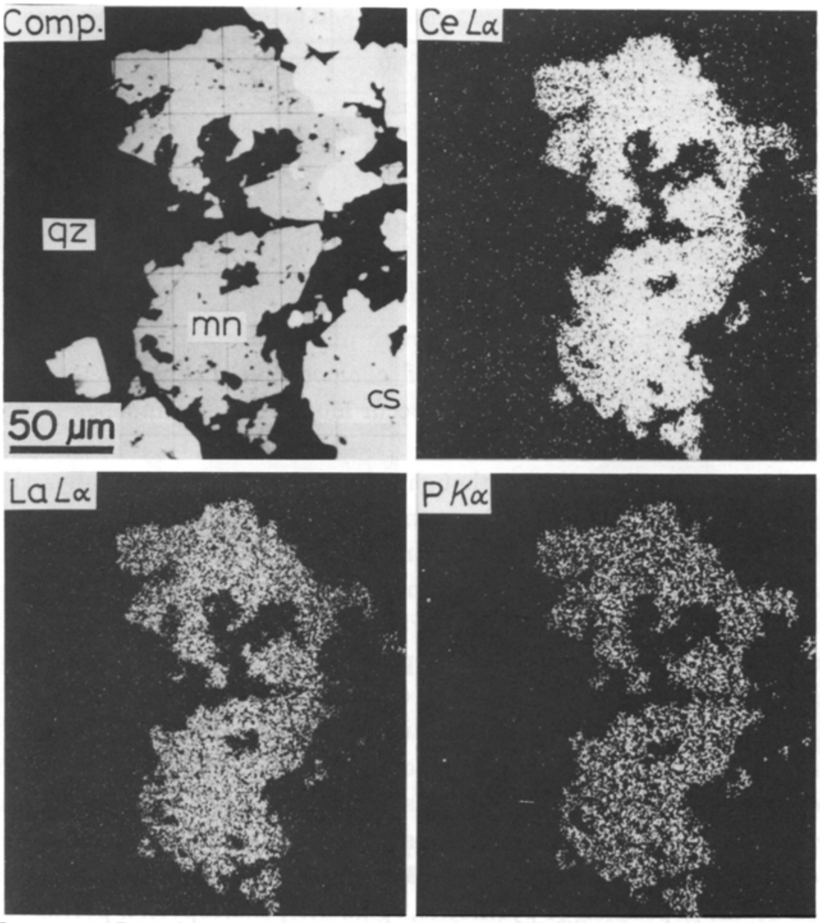

FIGURE 48. BACK-SCATTERED ELECTRON AND X-ray SCANNING IMAGES FOR MONAZITE (mn), CASSITERITE (cs) AND QUARTZ (qz), THE CINCO VEIN, 470 m LEVEL OF THE VILOCO MINE.

quartz. Molybdenite may have been emplaced in this period. A thin layer of pyrite locally covered a top surface of arsenopyrite. The middle stage began with chlorite, followed by abundant cassiterite, locally associated with monazite, and then coated by acicular tourmaline. The late stage is characterized with sulfide deposition such as monoclinic pyrrhotite, chalcopyrite, sphalerite, jamesonite, stibnite, and galena. In this stage, cassiterite was replaced locally and resulted in forming stannite as a reaction rim. Sericite and kaolinite may be regarded as a final products.

There are found three types of fluid inclusions in quartz from the Viloco mine as follows: A, liquid+vapor; B, liquid+vapor+daughter crystal (halite); C, liquid+vapor+some daughter crystals (halite+sylvite). Homogenization temperature and salinity in NaCl equivalent concentration of the fluid inclusions in quartz are 266°-494°C (average value 397°C) and 18.5-26.0 wt% (Roberto vein); 263°-445°C (363°C) and 31.4-47.1 wt% (Broncera vein); 392°-481°C (439°C) and 33.6-55.4 wt% (Cinco vein), respectively. At each stage of mineralizations stated above, inclusion type, homogenization temperature and salinity of fluid inclusion in quartz are C and B types, 500°-400°C and 56-35 wt% (early stage); B and A types, 410°-330°C and 35-30 wt% (middle stage), and A type, 330°-260°C and 26-18 wt% (late stage).

According to analytical data by EPMA, cassiterite has 0.0 to 1.1 wt% FeO. Meanwhile stannite contains small amounts of zinc from 0.6 to 1.4 wt%. Its atomic ratio Zn/(Zn+Fe) corresponding to kesterite (Cu_2ZnSnS_4) mole fraction, is 4 to 11 mole %. Also sphalerite from Broncera vein (540 level), Bonaparte section and Doce vein (494 level), San Antonio section has 3.0 to 18.2 and 15.5 to 19.3 mole% FeS, respectively. Bismuthinite has 0.1 to 0.3 wt% Sb.

9. *Colquiri mine*

The Colquiri mine is one of the enterprises of COMIBOL. It situated at 70 km north of Oruro. The scenery of the mine is shown in Figures 5-B and 50. The monthly production was 41,000 tons of the crude ore containing 0.77% Sn and 4.6% Zn in 1983. The Mineral dresssing plant within the mine treats whole crude ore and produced monthly 716 tons of the concentration containing 24.4% Sn in 1983. In the mine, although there are four sections (Figure 51), the Grande and Triunfo sections develop widely. The working levels in each section are shown in Figure 52.

There are several reports on the Colquiri mine. Campbell (1947) and Mallo

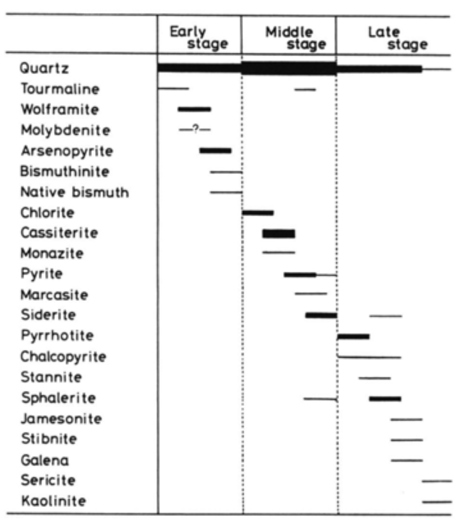

FIGURE 49. MINERAL SEQUENCE FOUND IN THE VEINS OF THE VILOCO MINE.

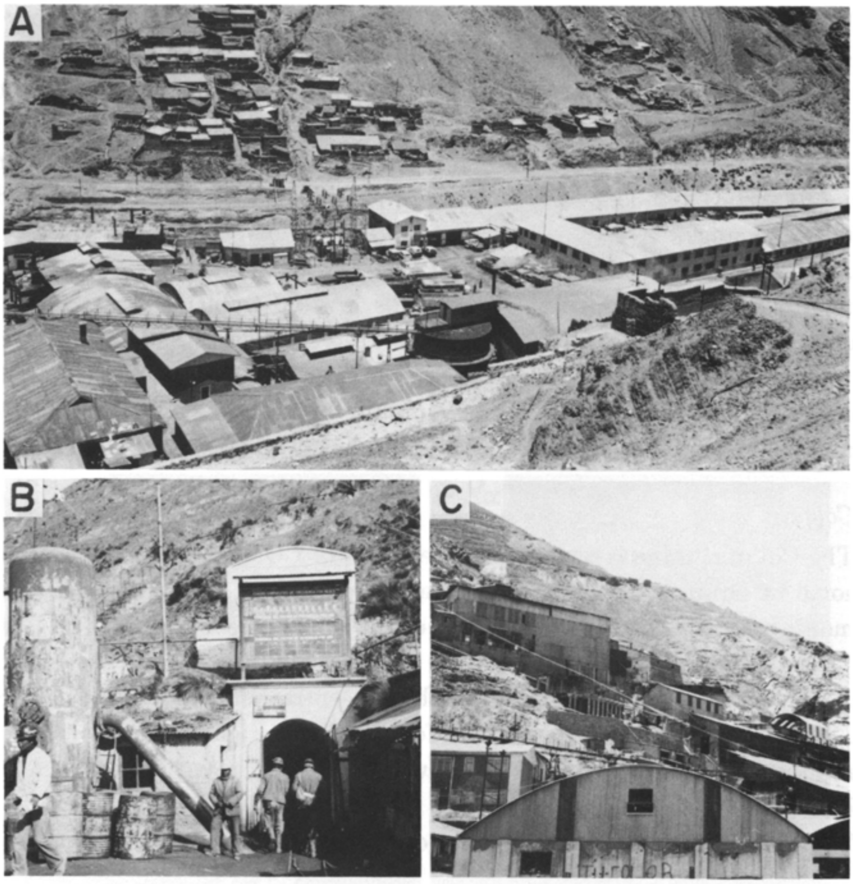

FIGURE 50. SCENERY OF THE COLQUIRI MINE.
A. A view of the Colquiri mining town.
B. Main adit of Incalacaya level.
C. Ore dressing plant of the Colquiri mine.

et al. (1976) have described on geology and mineralogy of ore deposits of the mine. Kelly and Turneaure (1970) and Turneaure (1960, 1971) have mentioned on geothermometry and genesis together with other Bolivian tin and tungsten deposits. Hanus (1977, 1982) have studied on ore minerals and their paragenesis.

The geology around the Colquiri mine are composed of the Llallagua Formation of Silurian. The formation consists of alternation of slate and quartzite, changing from a few cm to 50 cm in thickness. Slate is grayish black in color and shows fine banding which is concordant to the bedding. Quartzite is white to pale gray in color, and presents slightly hard mass within bands. The sediments form NWW trending folds. A syncline axis in the center part and an anticline axis in the northern part are recognized. Remarkable dip faults named Triunfo, Doble Ancho and Ocavi faults from south to north exist. The San Jose fault forming link between the Triunfo and Doble Ancho faults has NS trend.

The ore deposits are of fissure filling type embedded in Silurian slate and quartzite. In the south section, Grande, the ore veins arrange along NNE-SSW direction parallel to the Doble Ancho fault. In the central section, Triunfo, the veins have N-S direction parallel to the San Jose fault. In the northern sections, Unificada and Armas, they have NEE-SWW or NE-SW directions. The arrangement of veins at the 325 level is shown in Figure 53. The prinicipal veins are listed up with their scale in Table 4. As seen in the table the 3 and 2 3/4 veins are largest, and the length is over 1,500 m.

The Rosario vein at 325 and 10 Triunfo level, and the Rosario Ramo D, Rosario Ramo E, Rosario Ramo H veins at the 10 Triunfo level are 20 to 30 cm in width, but in some parts 2 to 3 m. The vein consists principally of sphalerite, pyrrhotite, pyrite, arsenopyrite, cassiterite, stannite, magnetite, marcasite, quartz and siderite with small amounts of galena and chalcopyrite, showing massive form poor in inside structure of the vein. Among minerals as above, sphalerite,

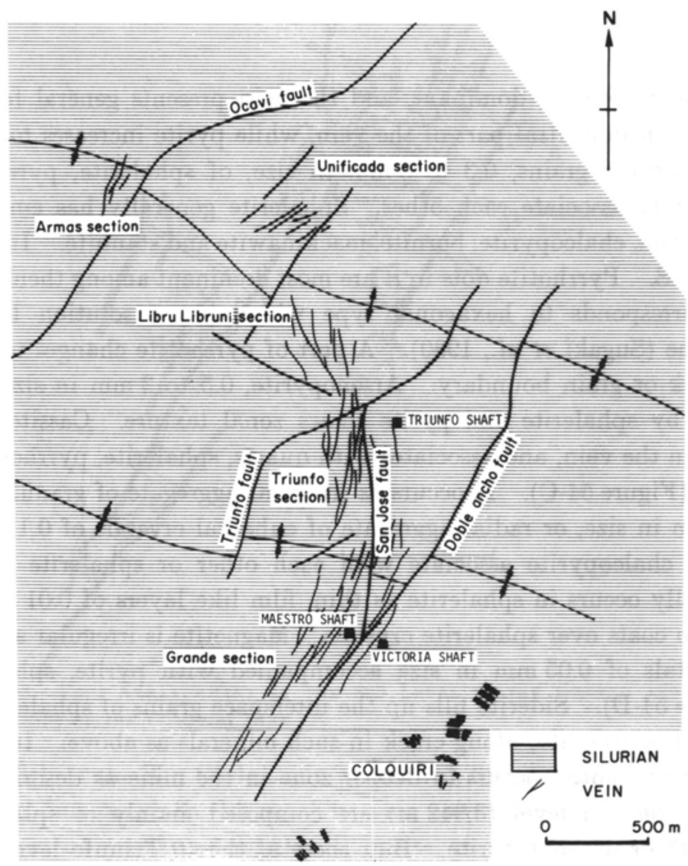

FIGURE 51. GEOLOGICAL MAP OF THE COLQUIRI MINING AREA.

(S)	Section Grande	Section Triunfo	Section Libru Libruni	Section Armas (N)
	Soc. Guillermo (4380m)			
	Soc. Elena (4370m)			
	Soc. Zorro (4345m)			
Level +65;	San Antonio (4337m)			
	Anita; Colquechaca (4338m)			
Level +35;	Doble Ancho (4310m)			Soc. Armas 0 (4310m)
	Level Intermedio (4288m)			Soc. Armas -40 (4270m)
	Soc. Elsa (4283m)		Libru Libruni (4285m)	
Level 0;	Chojna (4274m)			
	Level 30 (4244m)			
	Incalacaya (4210m)			
	Soc. 14 (4186m)			
	Level 100 (4172m)	Soc. Triunfo (4154m)		
	Level 135 (4138m)	Level Triunfo 10 (4146m)		
	San Juanillo (4104m)	Level Triunfo 45 (4109m)		
	Level 205 (4066m)	Level Triunfo 80 (4073m)		
	Level 245 (4029m)			
	Level 285 (3987m)			
	Level 325 (3942m)			
	Level 365 (3908m)			
	Level 405 (3868m)			

FIGURE 52. RELATION BETWEEN LEVELS OF THE GRANDE, TRIUNFO, LIBRU LIBRUNI AND ARMAS SECTIONS IN THE COLQUIRI MINE.

pyrrhotite and pyrite are dominant, and the vein presents general feature that pyrrhotite is rich in central part of the vein, while pyrite increases toward outer part. Xenomorphic grains, 0.3 to 5 mm in size, of sphalerite, pyrrhotite and pyrite intimately associate each other. Sphalerite generally has emulsion like dots of pyrrhotite, chalcopyrite, bornite, mackinawite and stannite. It has 20.7 to 23.5 mole% FeS. Pyrrhotite dots in it are most dominant among them. Massive pyrrhotite corresponds to hexagonal type which has exsolution lamellae of monoclinic one (Sugaki *et al.*, 1980). A part of pyrrhotite changes to marcasite along its crack or grain boundary. Arsenopyrite, 0.5 to 3 mm in size, which is accompanied by sphalerite and pyrite shows zonal texture. Cassiterite partly concentrates in the vein, and associates with quartz, sphalerite, pyrrhotite, pyrite and stannite (Figure 54-C). It occurs as irregular aggregate of granular crystals, 0.05 to 0.1 mm in size, or radial aggregate of euhedral crystals of 0.1 to 0.3 mm. Stannite and chalcopyrite associate with each other or sphalerite intimately. Stannite usually occurs in sphalerite as thin, film like layers of 0.01 to 0.05 mm wide, and also coats over sphalerite crystals. Magnetite is irregular aggregate of granular crystals of 0.05 mm in size accompanied with pyrite, sphaleute and quartz (Figure 54-D). Siderite fills up the interspace grains of sphalerite, pyrite, pyrrhotite and quartz, also along crack in such minerals as above. It is found a tendency that pyrrhotite occurs in deeper zone in the mine as described below. The veins at the 325 level (3,942 m) are composed mainly of sphalerite and pyrrhotite with or without pyrite. But, those at the 10 Triunfo level (4,146 m) consist principally of sphalerite and pyrite with small amounts of pyrrhotite.

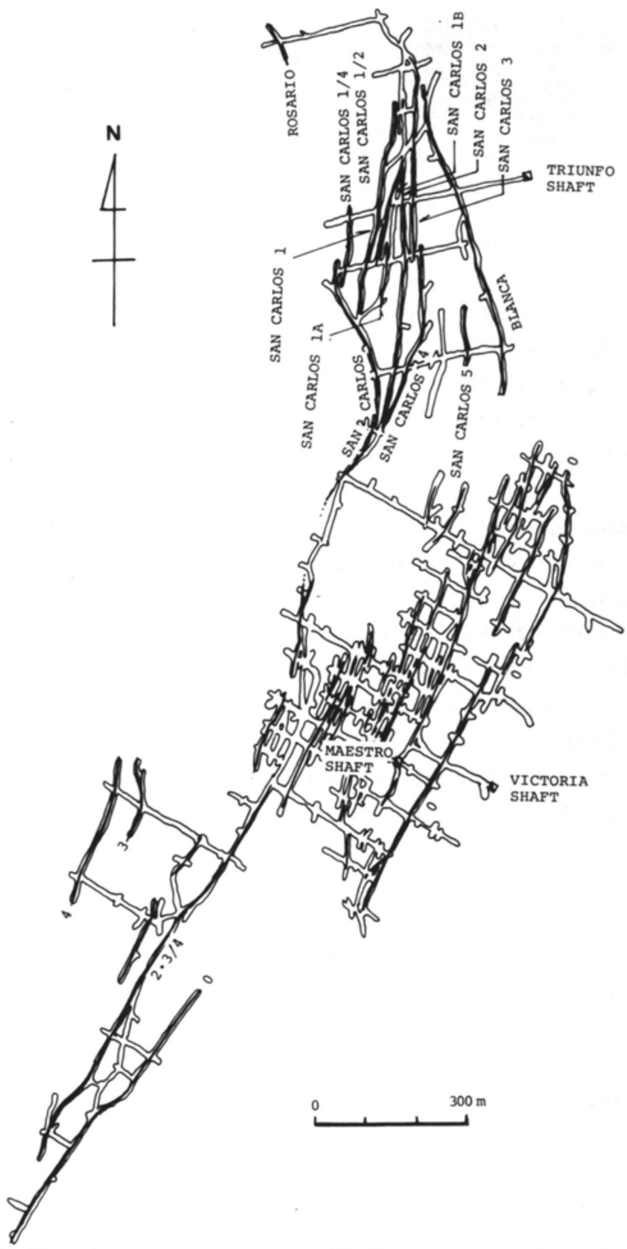

FIGURE 53. VEIN ARRANGEMENT AT THE 325 LEVEL IN THE GRANDE AND TRIUNFO SECTIONS OF THE COLQUIRI MINE.

The width of the San Carlos vein at the 245, 285, and 325 levels ranges from 20 cm to 3 m, but generally 1.5 m. The vein shows same feature as the Rosario vein, and consists mainly of sphalerite, pyrite, pyrrhotite, marcasite, cassiterite, quartz, fluorite and siderite with small amounts of arsenopyrite, stannite, galena,

TABLE 4. PRINCIPAL VEINS AND THEIR SCALES IN THE COLQUIRI MINE.

Vein	Strike	Dip	Length (m)	Depth (m)	Width (m)
San Carlos	N10°W-N10°E	50°W	800	200	1.50
Rosario	N10°W	70°W	400	120	1.50
Blanca	N20°W	75°W	1250	120+	1.50
3	N30°E	75°W	1500	380	0.8-1.0
2 3/4	N30°E	75°W	1500	460	1.50
0	N40°E	80°W	700	160+	1.20

topaz, tourmaline and dickite. Among them, sphalerite and pyrite are dominant. The former has 14.4 to 19.7 mole% FeS. Marcasite widely replaces pyrrhotite along its crack or grain boundary. Euhedral crystals of cassiterite, 1 to 5 mm in size, sometimes concentrate in association with sphalerite, quartz, fluorite and small amounts of topaz and tourmaline. Dickite occurs as veinlets of a few cm wide in the vein at latest stage of the mineralization.

The San Carlos Ramo 4 vein at the 245 level consists of sphalerite-pyrrhotite band, 30 cm or more in width, teallite-gearksutite band, 5 cm wide and vivianite band, 1 to 2 cm wide. They show parallel banding. Teallite-gearksutite zone which shows banding structure in the vein consists mainly of teallite, franckeite, cassiterite, gearksutite, fluorite, apatite and alunite. Teallite occurs as a band of 5 mm to 1 cm in width, and shows lath shape aggregate of 1 to 10 mm in length (Figure 54-A). It accompanies by stringer crystals of franckeite, 0.01 to 0.1 mm in length and cassiterite showing euhedral shape, 0.05 to 0.1 mm in size. Fine grained cassiterite of 10 to 5 microns in size occurs as irregular aggregate with franckeite. Small amounts of sphalerite, pyrite and apatite are sometimes found in teallite band. Gearksutite concentrates central part of the vein, and accompanies with fluorite. Alunite is usually found in druse of gearksutite in the vein. Creedite occurs from the 3 vein at the 205 level as a druse mineral. Crystals of creedite, commonly a few millimeters in size, often up to 2 cm (Figure 54-B), show prismatic form with pyramid. Creedite from the Colquiri mine have been described by Herzenberg (1949), Frenzel (1953) and Cook (1975). The chemical composition obtained by a wet method for creedite from the 3 vein at the 205 level is SiO_2 0.00, TiO_2 0.02, Al_2O_3 22.61, FeO 0.00, MnO 0.00, MgO 0.00, CaO 33.81, Na_2O 0.00, K_2O 0.06, P_2O_5 0.02, H_2O_+ 13.05, H_2O_- 0.03, SO_3 14.48, F 26.54, $-(O=F)$ 11.17%, total 99.45%. Its empirical formula $(Ca_{2.981}\ K_{0.006})_{2.99}\ Al_{2.19}\ (OH_{3.170}\ F_{6.907})_{10.08}\ (SO_4)_{0.90}\ 2H_2O$ on the basis of $O+OH+F=16$ is richer in Al_2O_3 and poor in SO_4 compared with the ideal formula $Ca_3Al_2\ (OH, F)_{10}\ (SO_4)2H_2O$, but agrees well with the formula of creedite from Colorado by Fleischer (1952). Cell constant of creedite obtained from X-ray powder data is a = 13.953 (2)Å, b = 8.607 (1)Å, c = 9.985 (1)Å and β = 94.36 (1)Å.

Fluid inclusions in quartz from the San Carlos vein give filling temperatures ranging from 205° to 385°C, and their salinities range from 1.2 to 6.4 wt% in NaCl

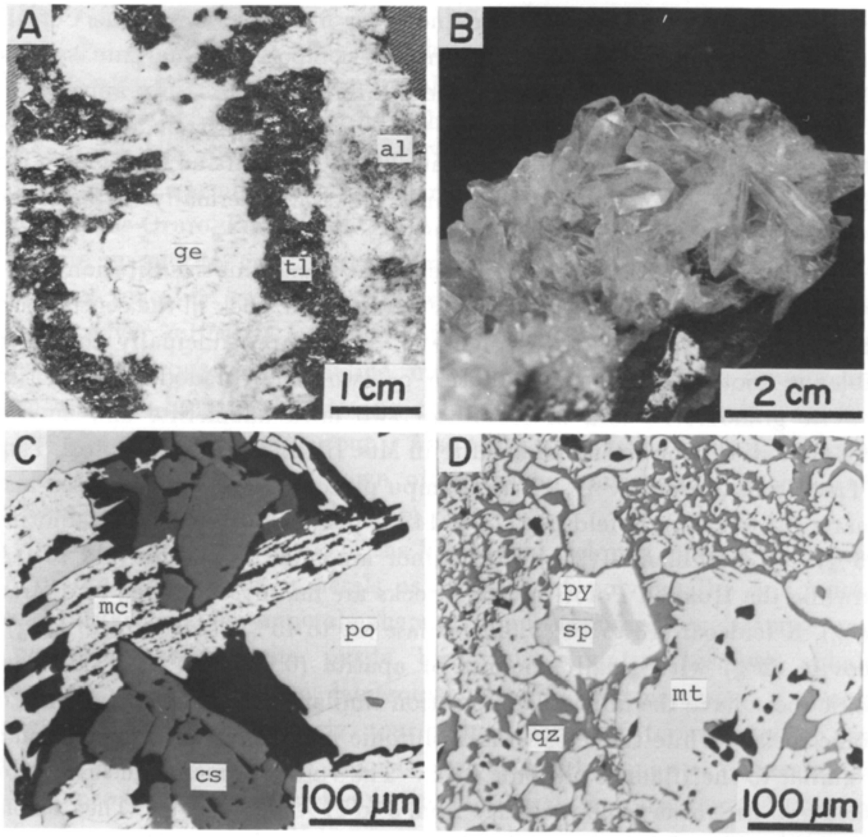

FIGURE 54. PHOTOGRAPHS OF SPECIMENS AND MICROSCOPIC INTERGROWTH OBSERVED IN ORES FROM THE COLQUIRI MINE.

A. Teallite (tl)-gearksutite (ge)-alunite (al) vein, the San Carlos Ramo 4 vein, (Sample No. 77090609).

B. Euhedral creedite crystals, the 3 vein, 205 level (83101037).

C. Association of cassiterite (cs), pyrrhotite (po) and marcasite (mc), the Rosario vein, 325 level (83101018).

D. Magnetite (mt), pyrite (py) including sphalerite (sp) in quartz (qz), the Rosario vein, 325 level (83101010).

equivalent.

SUMMARY

1. Geology of the La Paz district where corresponds to the northern portion of the Eastern Cordillera in Bolivian Andes consists of principally Paleozoic system, locally Cretaceous, Tertiary and Quaternary systems as shown in Figure 6. Granitic rocks intrude into the Ordovician and Silurian systems. Paleozoic system runs to the NW-SE direction parallel to the trend of the mountain range of the Eastern Cordillera repeating anticlinal and synclinal foldings. It is cut by many faults. The Paleozoic system is composed mainly of Ordovician and

Silurian formations. The former occupies over main portion of the Cordillera, especially in its eastern side, and is essentially composed of quartzite, sandstone, phyllite and black slate. Meanwhile the Silurian system mainly appears in the west side of the Cordillera adjoing to the Ordovician system. It consists of sandstone, phyllite and slate with quartzite. The Silurian and Ordovician formations around the igneous bodies of granitic rocks are thermally metamorphosed and change to hornfels.

2. As intrusive rocks, granitic rocks are found in the Silurian and Ordovician systems as batholith, sometimes lacolith and stock in the central portion of the Cordillera in the district (Figure 7). They are principally composed of hornblende biotite granodiorite, biotite or two mica granodiorite, biotite or muscovite granodiorite and muscovite or two mica adamellite and another is biotite granodiorite or biotite adamellite in Mts. Illampu, Huayna Potosi, Taquesi and Tres Cruces, respectively. The Illampu plutonic rocks are composed mainly of quartz (25 to 31%), K-feldspar (11 to 14%), plagioclase (40 to 44%), biotite (12 to 13%) and hornblende (2%) with minor amounts of apatite (0.3 to 0.4%). Meanwhile the Huayna Potosi plutonic rocks are mainly composed of quartz (30 to 34%), K-feldspar (13 to 16%), plagioclase (39 to 43%), biotite (6 to 14%) and muscovite (2%) with small amounts of apatite (0.7 to 2.1%). The Taquesi plutonic rocks have the mineral composition similar to that of the Huayna Potosi plutonic rock. While the Tres Cruses plutonic rocks have the mineral composition similar to the Illampu plutonic rock. The values of magnetic susceptibility for such granitic rocks as above range from 3 to 11×10^{-6} emu/g. They belong to the ilmenite series (Ishihara and Ulriksen, 1980).

3. The K-Ar ages for biotite and muscovite from the granitic masses of the Illampu, Huayna Potosi, Taquesi, Illimani and Tres Cruces plutons are given in Table 2. According to these data, the granitic rocks of Illampu (180, 195 Ma), Huayna Potosi (150, 162, 211 Ma) and Taquesi (195, 199 Ma) were formed by igneous acitivities of the Triassic to Jurassic ages of Mesozoic. Meanwhile the granitic rocks of Illimani (26 Ma) and Tres Cruces (23.8, 26 Ma) belong to the igneous activity of the Oligocene age. The granitic activities of both the Mesozoic and Tertiary ages are though to be in intimate relation with mineralizations produced polymetallic ore deposits of tin, tungsten, molybdenum, lead and zinc etc. in the Eastern Cordillera of the district.

4. There are two types of ore deposits (Figure 9) in Paleozoic formations or granitic rocks of the La Paz district. One is meso- and hypothermal fissure filling deposits formed by mineralization as post-action of Mesozoic (Triassic to Jurassic) age, and other, ore veins produced telescopically by ore solutions generated from acidic magma of Tertiary, Oligocene to Miocene ages under xenothermal condition. As the former, the veins of the Milluni (tin), Kellhuani (tin), Chojlla (tin and tungsten), San Antonio (tungsten) and Trinidad (molybdenum) mines are,

and the latter, the veins of the Viloco (tin and tungsten) and Colquiri (tin and Zinc) mines. It does not make clear whether or not the veins of the Matilde (zinc and lead) mine were formed by mineralization due to Mesozoic granitic activity.

5. The veins of meso- and hypothermal type such as those of the Milluni, Kellhuani, Chojlla, San Antonio and Trinidad mines generally consist of ores of simple mineral assemblage in comparision with those of some xenothermal deposits in the Oruro, Potosi and Quechisla districts. As ore minerals, cassiterite, wolframite, sphalerite, galena, pyrite, marcasite, arsenopyrite, pyrrhotite, molybdenite and scheelite etc. occur. However, no stannite, kesterite, franckeite, hocartite, silver sulfosalts and lead-antimony sulfosalts etc. appear. While as gangue minerals quartz, tourmaline, muscovite and siderite are usually seen in association with fluorite, apatite and chlorite etc., but no vivianite, barite, gypsum, alunite and jarosite etc. occur. Also there is found no zonal arrangement of minerals in the deposits as shown often in the xenothermal deposits of the Quechisla district (Sugaki *et al.* 1984).

Meanwhile the ore deposits of the Viloco and Colquiri mines are composed of a lot of ore and gangue minerals as a result of polymetallic and telescopic mineralizations. As ore minerals, there are found cassiterite, wolframite, magnetite, pyrrhotite, arsenopyrite, pyrite, bismuthinite, native bismuth, sphalerite, chalcopyrite, stannite, galena, jamesonite, stibnite and marcasite in association with gangue minerals of quartz, tourmaline, monazite, topaz, fluorite, apatite, vivianite, creedite, gearksutite, chlorite, sericite and kaoline etc. There are found a coexistance of high and low temperature minerals in some veins of both mines.

6. Ore deposits of the Milluni mine are fissure filling vein type developed in black slate of the Catavi formation of Silurian. There are many ore veins in the mine. Among them, the Rotschild vein which is being mined principally has strike of N10°E to N10°W and dip of 60° to 65°W. It consists mainly of quartz acompanied with some amounts of pyrite, arsenopyrite, cassiterite and siderite. Cassiterite usually occurs as coarse grained euhedral or subhedral forms associating with quartz, pyrite, arsenopyrite and siderite, and rarely chalcopyrite and sphalerite. It has 0.0 to 2.3 mole % FeO. Pyrite and arsenopyrite appear as aggregate of granular crystals intimately associating with quartz, siderite and sometimes cassiterite. Small amount of sphalerite and chalcopyrite is rarely found as granular forms accompanied with quartz, pyrite, arsenopyrite, cassiterite and siderite. No silver or antimony bearing sulfosalt minerals are found in the mine. Homogenization temperatures of fluid inclusion in quartz are 176° to 321°C. The $\delta^{34}S$ value for pyrite are +7.6 to 7.7‰.

7. Tin deposits of the Kellhuani mine develop selectively in quartzite layer of the Catavi Formation of Silurian. The tin ore is only found in the layer of quartzite. Therefore, this deposit has been called "Manto type" as reported by Schneider and Lehmann (1977). There are found seven quartzite layers as Manto

type tin deposits in the mine. Although the deposits are confined to the quartzite layers, cassiterite mostly occurs in quartz-tourmaline veinlets along fissure or crack developing in the quartzite layers or sometimes appears in tourmalinization halo of hydrothermal alteration adjoining to the quartz-tourmaline-cassiterite veinlets in the quartzite layer. The veinlets generally consist of quartz, tourmaline, siderite, fluorite and cassiterite etc. Among them cassiterite appears in euhedral or subhedral crystals, 0.5 to 1.5 mm in size, and as their aggregate in intimate association with quartz, tourmaline, siderite and fluorite. It often presents a twin on (011) microscopically, but in general shows no distinct growth zoning. Cassiterite contains 0.0 to 1.9 mole% FeO. The homogenization temperature and salinity in NaCl equivalent concentration measured for fluid inclusion in quartz with tourmaline and cassiterite are 215° to 363°C (mean value 294°C) and 25.1 to 26.0 wt%, respectively. The mineralization formed the quartz-tourmaline-cassiterite veinlet or network is thought to be in intimate relation with activities of granite porphyry and granodiorite of the Mesozoic age.

8. Ore deposits of the Chojlla mine develop mainly in Ordovician slate and hornfels, and partly in adamellite which is affected by greisenization. Ore veins fill up fissures having strike N30° to 50°W and dip 40° to 50°SW, and are mostly composed of quartz accompanied with wolframite, cassiterite, fluorite, muscovite, apatite, tourmaline, siderite, arsenopyrite, pyrrhotite, sphalerite, galena, chalcopyrite, scheelite and very slight amounts of stannite, native bismuth and marcasite. Cassiterite occurs as very coarse grained euhedral or subhedral forms associating with wolframite, muscovite, tourmaline and arsenopyrite. It has a composition near pure SnO_2 (less than 1.1 wt% FeO) and its cell parameters are a=4.7347, b=3.1839Å. Wolframite (33 to 72 mole% $MnWO_4$) occurs as prismatic crystal assembling with quartz, cassiterite, muscovite, arsenopyrite and apatite. Chemical compositions of tourmaline and apatite obtained by wet chemical analysis are $(Na_{0.57}\ K_{0.10}\ Ca_{0.33})_{1.00}\ (Fe_{1.68}\ Mg_{0.45}\ Mn_{0.01}\ Ti_{0.11}\ Al_{0.23})_{2.48}\ Al_{6.00}\ B_{3.14}\ (Si_{5.78}\ Al_{0.22})_{6.00}\ O_{26.95}\ (OH_{3.74}\ F_{0.30})_{4.04}$ and $(Ca_{9.32}\ Na_{0.01}\ Fe_{0.01}\ Mn_{0.37}\ Al_{0.01}\ Ti_{0.11})_{9.83}\ P_{5.98}\ O_{23.82}\ (OH_{1.13}\ F_{1.05}\ Cl_{0.01})_{2.19}$ as empirical formulae, respectively. The cell parameters of tourmaline are a=15.964 and c=7.154 Å, and those of apatite are a=9.359 and c=6.875 Å. Sulfide minerals such as arsenopyrite, pyrrhotite, sphalerite, galena and chalcopyrite are found as aggregate of granular forms in intimate association with each others and accompaning with quartz, cassiterite and wolframite. But, silver or antimony bearing sulfosalt minerals are not found in the ore from the mine. Homogenization temperatures of fluid inclusion in quartz are 231° to 408°C. The δ^{34}S values of sulfide minerals such as pyrrhotite, pyrite and galena are in the range from +2.9 to +5.0‰.

9. Ore deposits of San Antonio mine develop in hornfels metamorphosed from Silur-Devonian sandstone by intrusion of Illampu granodiorite are composed mainly of wolframite, arsenopyrite, pyrrhotite, quartz, tourmaline and apatite

associated with small amounts of chalcopyrite, pyrite and scheelite etc. Wolframite and scheelite occurs in intimate association with arsenopyrite, tourmaline, quartz, and sometimes pyrite. Tourmaline appears as aggregate of acicular crystals assembled with wolframite, scheelite, arsenopyrite and pyrite, and its chemical composition is $(Na_{0.72}\ K_{0.08}\ Ca_{0.29})_{1.09}\ (Mg_{1.77}\ Fe_{0.95}\ Ti_{0.09})_{2.81}\ Al_{5.97}\ B_{3.03}\ (Si_{5.76}\ Al_{0.24})_{6.00}\ O_{26.93}\ (OH_{4.03}\ F_{0.04})_{4.07}$. The δ^{34} S value for pyrrhotite is +13.8 ‰.

10. Ore veins of the Trinidad mine embedded in hornfels as same as those of the San Antonio mine have 5 to 20 cm wide and strike N60°-70°W, and mainly consist of molybdenite, quartz, apatite, chlorite, orthoclase and small amounts of tourmaline, pyrrhotite, pyrite, chalcopyrite and calcite. Molybedenite appears as foliated crystals associating with quartz, chlorite, apatite, tourmaline, pyrite and pyrrhotite. X-ray powder data for molybdenite indicate that it is $2H_1$ polytype. The homogenization temperature and salinity of fluid incusion in quartz are 217° to 427°C and 23.6 to 47.1 wt% in NaCl equivalent concentration, respectively.

11. The zinc and lead veins, 1.2 to 9.0 m wide of the Matilde mine mainly occur in Devonian slate. They are essentially composed of siderite and sphalerite with galena, marcasite and quartz. The ore has simple mineral assemblage and often shows conspicuously characteristic alternated banding or laminating structures of siderite and sphalerite. There is sometimes found ring ore, 5 to 10 cm across, consisting of sphalerite and siderite in the vein. Homogenization temperature for fluid inclusion in quartz from Matilde vein is 188° to 283°C (mean value 233°C). The δ^{34}S values for pyrite, sphalerite and galena from the Matilde vein are +13.1 to 14.0, +14.0 to 14.6 and +10.9‰, respectively. They are more rich in heavy sulfur than those of xenothermal type tin deposits in other districts in Boliva.

12. Tin and tungstan deposits of the Viloco mine is a fissure filling type. The ore veins occur in Silurian system and granodiorite of the Tres Cruces batholith. The Silurian system is divided into four members consisting of sandy slate, quartzite, slaty sandstone and slate in ascending order. The Tres Cruces batholith, whose age is 23.8 to 26.0 Ma, composed of biotite granodiorite at the Viloco area. Around the granodiorite, the Silurian sediments are thermally metamorphosed to biotite hornfels. Ore minerals such as cassiterite, wolframite, arsenopyrite, pyrite, monoclinic pyrrhotite, chalcopyrite and sphalerite, assembled with small amounts of molybdenite, bismuthinite, native bismuth, marcasite, stannite, jamesonite, stibnite and galena occur in association with quartz, tourmaline, chlorite, monazite, siderite, sericite and kaolinite. Among them, cassiterite whose grain size ranges generally from 3 mm to 10 mm, sometimes up to 8 cm, associates with quartz and chlorite and rarely monazite and siderite. It contains 0.0 to 1.0 wt% FeO. Stannite appears as a reaction rim between cassiterite and pyrrhotite or chalcopyrite. It contains 0.6 to 1.6 wt% of Zn, which correspond to

4 to 11 mole% kesterite. Bismuthinite has 0.1 to 0.3 wt% Sb. Sphalerite of the middle stage contains 14.8 to 19.3 mole % of FeS and that of late stage ranges from 3.0 to 8.8%. Filling temperature and salinity of the fluid inclusion in quartz range 500-400°C and 56-35 wt% in equivalent NaCl (early stage of the mineralization), 410-330°C, 35-30 wt% (middle stage) and 330-260°C, 26-18 wt% (late stage), respectively.

13. The ore deposits of the Colquiri mine are of fissure filling type embedded in slate and quartzite of the Llallagua Formation of Silurian. Ore minerals such as sphalerite, pyrrhotite, pyrite, arsenopyrite, cassiterite, stannite, galena, chalcopyrite, magnetite, marcasite, teallite and franckeite occur in association with quartz, siderite, fluorite, topaz, tourmaline, gearksutite, apatite, alunite creedite and dickite. Among them, sphalerite, pyrrhotite and pyrite are dominant, and the amount of pyrrhotite increases toward deeper level, reversely pyrite increases to the upper level. Sphalerite generally has emulsion dots of pyrrhotite, chalcopyrite, bornite, mackinawite and stannite, and its iron content ranges from 14.4 to 23.6 mole % FeS. Cassiterite partly concentrates in the vein associating with quartz, sphalerite, pyrrhotite pyrite and stannite. Teallite-gearksutite vein found at the San Carlos Ramo 4 vein consists mainly of teallite, franckeite, cassiterite, gearksutite, fluorite, apatite and alunite. Pyrrhotite from the San Carlos vein is a hexagonal type with exsolution lamellae of monoclinic one and its composition is 47.34 to 47. 40 at% Fe. Creedite occurs from the 3 vein as a druse mineral, whose empirical formula is $(Ca_{2.981}\ K_{0.006})_{2.99}\ Al_{2.19}\ (OH_{3.17}\ F_{6.907})_{10.08}\ (SO_4)_{0.90}\ 2H_2O$ on the basis of $O+OH+F=16$. Fluid inclusion in quartz gives filling temperatures ranging 205 to 385°C, and salinities of 1.2 to 6.4 wt% in NaCl equivalent. The value of $\delta^{34}S$ for sphalerite ranges from +0.2 to +2.3‰.

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