GEOLOGY OF THE COLQUIRI TIN MINE,
BOLIVIA

by

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CONTENTS

Ms
Page

Abstract - - - - -	-1
Introduction - - - - -	-2
General Outline of Bolivian Geography & Geology - - -	-2
History - - - - -	-6
Location - - - - -	6
Scope of Present Work - - - - -	-6
Past Work - - - - -	-7
Acknowledgments - - - - -	-8
Physical Conditions - - - - -	8
Climate, Vegetation, and Water Supply - - - - -	8
Topography - - - - -	9
General Geology - - - - -	-10
Sedimentary Rocks - - - - -	10
Igneous Rocks - - - - -	11
Structure - - - - -	13
Folding - - - - -	13
Faulting - - - - -	14
Mineralogy - - - - -	17
Supergene Minerals - - - - -	18
Hypogene Minerals - - - - -	19
Early Stage Minerals - - - - -	19
Late Stage Minerals - - - - -	19
Paragenesis of Hypogene Minerals - - - - -	27
Ore Deposits - - - - -	28
Mines - - - - -	28
Production - - - - -	30
Oxidized Ores - - - - -	31
Primary Ores - - - - -	-32
Vein Structure - - - - -	32
Vein Texture and Mineral Arrangement - - - - -	34
Distribution of the Tin - - - - -	-35
Guides for Exploration and Development - - - - -	36
Location, Size, etc., of Ore Bodies - - - - -	37
Grade of Ore and Reserves - - - - -	37
Future Possibilities - - - - -	38
Origin - - - - -	38
General Character of Deposit - - - - -	38
Source of Mineralizing Solutions - - - - -	39
Nature of Mineralizing Solutions - - - - -	39
Temperature of Formation of Deposit - - - - -	41
Depth of Formation of Deposit - - - - -	42
Classification of Deposit - - - - -	43

Contents, Cont. - p. 2

Ms
Page

Mining - - - - -	43
Exploration and Development - - - - -	43
Mining Method - - - - -	45
Critieisms and Suggestions - - - - -	46
Sampling as a Guide to Mining Operations - - - - -	47
Power - - - - -	48
Labor and Supplies - - - - -	48
Milling - - - - -	48
Bibliography - - - - -	51

LIST OF ILLUSTRATIONS

<u>Plate No.</u>	<u>Description</u>	<u>After Page No.</u>
1	Index Map showing Location of District, Scale: - 1 : 10,000,000	6
2	Photographs of Surface Features.	8
3	Photographs of Surface Features.	8
4	Photographs of Surface Features.	8
5	Photographs of Surface Features.	8
6	Map of Colquiri District, Scale: - 1 : 20,000	9
7	Generalized Section across Colquiri Dis- trict, Scale: - 1 : 75,000	13
8	Microphotographs of Mineral Relationships.	27
9	Microphotographs of Mineral Relationships.	27
10	Microphotographs of Mineral Relationships.	27
11	Microphotographs of Mineral Relationships.	27
12	Areal Geologic Map, Sheets 1 and 2, Scale: - 1 : 1000	In pocket
13	Composite Level Map, Scale: - 1 : 1000	In pocket
14	Longitudinal Section, Scale: - 1 : 7500	28
15	Geologic Map of Chojna Level, Scale: - 1 : 1000	In pocket
16	Geologic Map of Incalacaya Level, Scale: - 1 : 1000	In pocket
17	Geologic Map of San Juanillo Level, Scale: - 1 : 1000	In pocket
18	Geologic Cross Section A - A', Scale: - 1 : 1000	In pocket
19	Geologic Cross Section B - B', Scale: - 1 : 1000	In pocket
20	Geologic Cross Section C - C', Scale: - 1 : 1000	In pocket
21	Geologic Cross Section D - D', Scale: - 1 : 1000	In pocket

List of Illustrations, Cont. - p. 2

<u>Plate No.</u>	<u>Description</u>	<u>After Page No.</u>
22	Geologic Cross Section F - F', Scale: - 1 : 1000	In pocket
23	Geologic Cross Section G - G', Scale: - 1 : 1000	In pocket
24	Longitudinal Projection of Main Vein showing Lines of Equal Tin Value (after H. J. DeWijs (2)), Scale: - 1 : 5000	35
25	Map showing Vein Structure and Tin Distribution on Doble Ancho Level (after H. J. De Wijs (2))	35
26	Standard Arrangement for Chutes and Manways in Horizontal Cut and Fill Stopes, Scale: - 1 : 200	45

ABSTRACT

The Colquiri tin mine, studied by the writer in 1941, lies at an elevation of 4200 meters in the Central Andean Cordillera 148 kilometers southeast of La Paz, the Bolivian capital. The region is one of high relief and is composed of slightly metamorphosed Devonian shales and sandstones which are cut by hydrothermally altered Tertiary dikes. The sedimentary rocks have been moderately folded and faulted. The mineralized area is one of doming in the sediments, with mineralization following steeply dipping normal faults of the gravity type. Cassiterite, the ore mineral, was one of the earliest minerals to be deposited; it occurs in a gangue consisting chiefly of fluorite, massive simple sulphides, siderite, and serpentine. Most of the ore in the district occurs as shoots in a large vein which has been explored for 3000 meters along the strike and to a depth of 300 meters. The vein branches downward and laterally, splitting accompanying changes in dip and strike; tin deposition is directly related to the intensity of fracturing. Early minerals in the deposit were formed at high temperature, whereas later minerals formed at intermediate to low temperatures. Deposition occurred at moderate depth, and the deposit may be classified as lower intensity hypothermal.

INTRODUCTION

General Outline of Bolivian Geography and Geology (3)

Bolivia, with an area of approximately 1,200,000 sq. km. (463,000 sq. mi.) and a population of more than 3,000,000, lies in the interior of South America between 10° and 23°30' South Latitude, and 57°30' and 69° West Longitude. The Andean Ranges and high plateau ("altiplano"), with nine-tenths of the population, constitute approximately one-third of Bolivian territory; the eastern lowlands, parts of the Amazon and La Plata drainage basins, make up the remaining two-thirds.

From west to east the following physiographic provinces may be differentiated: Western Andes, interior basins of the Altiplano, Central and Eastern Andes, and the eastern lowlands of the Beni and Chaco.

The Western Andes constitute a natural frontier between Bolivia and the neighboring republics of Chile and Peru, and the water shed between the Pacific Ocean and the Altiplano. They form a table land of volcanic ash and tuffs, with an average elevation of 4000 m., upon which volcanic cones have been built up to a height of 1000 m. to 2000 m.

The Altiplano consists of a series of basins and alluvial plains, 3600 m. to 3800 m. in elevation, with island-like groups of mountains composed chiefly of Paleozoic sediments and Tertiary volcanics projecting above the

general level. It resembles the Great Basin country of Utah and Nevada.

In northern Bolivia the high cordillera on the eastern side of the Altiplano is narrow, and drops off sharply to the Beni Plains; here only the Central Cordillera is distinguished. This narrow section is about 200 km. long with its southern end at approximately 17° South Latitude. It is separated into several ranges by deep transverse valleys. The area is very rugged and has many high peaks (Illimani - 6500 m., Illampu - 6400 m.); it forms the most magnificent mountain scenery in Bolivia. Geologically it consists of granitic batholiths and stocks (Tertiary) intruded into folded Paleozoic sediments.

Southward the Andean Cordillera east of the inter-andean basin broadens considerably with the appearance of numerous chains of mountains with diverse directions. The Eastern Cordillera may be distinguished as marginal mountain chains between the main Central Cordillera and the lowlands. Geologically the broad zone of the Central and Eastern Cordilleras consists of folded sediments, for the most part Paleozoic, and Tertiary volcanics of intermediate to acid composition. The igneous rocks occur as shallow seated intrusives and flows; there are few deep seated intrusives. Andean folding was most intense in the Central Cordillera. Intensity of folding decreased to the east through the Eastern Cordillera to the lowlands.

Folding in the Altiplano area is rather weak.

The summit areas of the Central Cordillera are at around 4500 m. elevation. Ranges of the Eastern Cordillera are generally lower than those of the Central Cordillera and are composed of folded sedimentary rocks.

Not much is known about the geology of the Eastern Lowlands because this level area is masked by Recent deposits. Some areas of pre-Cambrian rocks are exposed in the eastern part.

Most of the Bolivian Paleozoic strata are shallow water marine deposits. Cambrian is sparingly present. Silurian deposits (Lower Silurian is equivalent to the Ordovician of North America) are widespread in the Eastern Andes. The Devonian is extensively developed throughout the Central and Eastern Andes and the Eastern part of the Altiplano. Carboniferous is present in small amounts near Lake Titicaca, in the northern part of the Altiplano, and in the Eastern Andes. Lower Carboniferous (Mississippian of North America) is represented by continental deposits, but Upper Carboniferous is marine. Permian strata are present near Lake Titicaca and in the Eastern Andean zone. Some of these beds are tillites and fluvioglacial deposits.

The continental sedimentation of the Permian continued into the Triassic; but not much Triassic material is present. There is no evidence of Jurassic strata. Land-formed Lower Cretaceous deposits are overlain by Upper

Cretaceous beds which are in part marine. The terrestrial deposition of Upper Cretaceous time increased in intensity into the Tertiary. Continental Tertiary deposits are extensively developed, especially in the Eastern Andean zone and the northern part of the Altiplano. Much of the material deposited during the Tertiary is of volcanic origin. Quaternary lake deposits were laid down in part of the basin area.

History

The Colquiri District was discovered during Spanish colonial times and was worked for silver (at shallow depths) intermittently until the early part of the present century, when Bolivian tin became of economic interest. The oxidized ores were worked for tin and deeper exploration was begun. By the mid-thirties a sizeable tin deposit had been partially developed on the principal property and the construction of a concentrating mill had been planned. The Hochschild organization took over the operation of the property about 1937 and rushed mill construction and mine development. The mill went into production at the end of 1938 and by 1941 the property was the second largest tin producer in Bolivia.

Location

The Colquiri District is located in the department of La Paz, 148 km. (92 miles) southeast of the city of La Paz, and 63 km. (39 miles) north of the city of Oruro (see Plate I).

It is reached by 58 km. of all-weather mountainous automobile road from Soledad, a station on the Antofagasta Bolivia Railroad 30 km. north of Oruro.

Scope of Present Work

Field work for this report was done from December, 1940, to June, 1941, while the writer was geologist for Cia. de Minas de Colquiri, a branch of Cia. Minera de

INDEX MAP SHOWING LOCATION OF DISTRICT - Scale: 0 250 Km.
 PLATE I

Oruro, one of the affiliated companies of Mauricio Hochschild, S. A. M. I. This work consisted of checking previous geologic mapping and bringing the geologic mapping up to date. A suite of ore specimens was collected and brought to the University of Arizona for study.

Laboratory study of specimens, maps, and field notes was done during 1941-43 and the second semester of 1945-46, while the writer was a graduate student at the University of Arizona.

Past Work

The topographic map of the mine area and the level maps were prepared in 1935-36 by Lowell Moon, an American geologist, and Carlos Oroza Ferreira, a Bolivian mining engineer. At this time Moon mapped the surface geology and the geology of the accessible underground workings, and Oroza studied the property, presenting the results as his engineer's thesis at the Oruro (Bolivia) School of Mines (1). About 1937 Hydra, a Dutchman, spent some time as resident geologist at the property. In June of 1938 Gerald Kirwan, an American, was appointed resident geologist and spent about a year at the mine; he brought the geologic mapping partially up to date. In addition to the work mentioned above, the mine has been examined and reported upon by several consulting engineers and geologists. Only one of these reports, that of H. J. DeWijs (2) was available to the writer.

Acknowledgments

The writer is indebted to the late W. V. DeCamp, then manager of mines for Mauricio Hochschild, S. A. M. I., for permission to collect data and specimens with the object of using them in the preparation of a thesis. The staff of Cia. Minas de Colquiri cooperated with me in my work at the mine. Dr. B. S. Butler and Dr. M. N. Short of the Geology Department of the University of Arizona offered many suggestions and guidance in the thesis preparation; their help is gratefully acknowledged. Acknowledgment is due Professors H. E. Krumlauf and J. B. Cunningham of the College of Mines and Metallurgy of the University of Arizona for helpful discussion and suggestions regarding mining and milling.

PHYSICAL CONDITIONS

Climate, Vegetation, and Water Supply

The climate is temperate and semi-arid. Although the area lies in the tropics (Latitude South 17° 24', Longitude West 67° 07'), the high altitude (4000 to 4500 meters - 13,000 to 15,000 feet) makes it rather cool. The daily variation in temperature is great, and the nights are cold, frequently with frost. In mid-day the sun is intense, but it is always cool in the shade. Annual precipitation is about 10 inches, most of it coming in the summer months of November to April. The winter season is remarkably clear and dry.

EXPLANATION OF PLATE 2

- a. View looking northwest from the Main Vein outcrop to the glacial peaks of the Quimsa Cruz Range. Note the sparse vegetation.
- b. Alpacas grazing in the summit areas near the Colquiri Mine.
- c. Indian women digging potatoes near Incalacaya Camp.

Plate 2

a. Market at Incalacaya Camp. Practically all food has to be imported from the lower country to the east.

a. Market at Incalacaya Camp. Practically all food has to be imported from the lower country to the east.

b. Pia Pia Canyon. The portal of the San Juanillo haulage adit is just above the "x" near the center of the photograph. The Main Vein outcrop is in the background.

c. View down Pia Pia Canyon from near Incalacaya Camp.

EXPLANATION OF PLATE 4

a. View showing the general type of topography down drainage (north-east) from the Colquiri Mine. Incalacaya, the main camp in the head of Pia Pia Canyon, is near the lower center of the picture.

b. View looking southwest along the Main Vein outcrop from its central part. The vein dips to the right.

c. View of the Main Vein outcrop near the Anita Adit. The vein dips to the left.

Plate 4

EXPLANATION OF PLATE 5

a. Incalacaya Camp. The row of houses in the foreground is for the American mine staff. Office, shop, and warehouse are situated in the left center. The group of houses on the hill in the background are for Bolivian workmen. The large building at the right center houses the Diesel-electric installation.

b. View south along the Main Vein outcrop from near the Doble Ancho adit. The large excavation in the foreground is a glory hole where waste for stope filling is quarried.

c. San Juanillo Mill.

The only vegetation in the area is sparse coarse grass and moss. Practically no agriculture is possible at this altitude. Practically all fuel, except "taquia" (llama excrement), and food has to be imported (see Plates 2 and 3, a).

Streams in the area are intermittent, in part because of light rainfall and in part because of nearness to the continental divide. Wells sunk in stream gravels produce a little water even in the dry season, but not enough to supply a large camp. Water for the camp and mining and milling operations is pumped from Mamuta, about 8 km. down Pia Pia Canyon from the mine (see Plate 6); the lift is 450 meters.

Topography

The Colquiri District lies in the Central Cordillera of the Andes a few kilometers east of the watershed between the Amazon drainage on the east and the interior drainage of the Bolivian high plateau on the west.

The district is near the north end of the wide zone in the Central and Eastern Cordilleras. Northwest from the mine it is only 30 km. to the southeastern end of the Quimsa Cruz Range (see Plate 2, a), which is the backbone of the Central Andean Cordillera southeast of La Paz. The Quimsa Cruz Range is relatively narrow (30 km.) and high (peaks to 5800 m. - 19,000 ft.). Southeast of the Quimsa Cruz Range the Central Cordillera widens but is not

so high (peaks to 4500 m., Plate 2, b). At the latitude of Oruro, 60 km. south of the mine, the Central and Eastern Cordilleras are nearly 150 km. wide.

The district lies at an elevation of 4000 to 4450 meters. The Main Vein outcrop is at about 4400 m., the mine camp at 4200 m., and the mill at 4050 m. This is due to the fact that the vein crops out across the head of the canyon in which the camp and mill are located (see Plate 3, b and c). Plate 6 is a generalized topographic and geologic map of the district.

The area is one of steep slopes and high relief (see Plate 3, c and Plate 4, a). Maximum relief is about 500 meters. The region is still in the youthful stage of the fluvial erosion cycle. Valleys are narrow V-shaped, and in many places cliffs have developed, especially where the slope of the valley side is opposed to the dip of the beds (see Plate 3, b).

GENERAL GEOLOGY

Sedimentary Rocks

The region is composed of Paleozoic sedimentary rocks consisting of slightly metamorphosed shales, sandy shales, and sandstones. Since secondary cleavage is lacking, the more clayey beds are argillites. The sandy beds have not been metamorphosed enough to be quartzites.

All the sedimentary rocks are medium dark gray in color and weather to a lighter color. Bedding is from thin

(several inches) to medium (1.5 ft.); the sandier the rock the thicker the beds. In hand specimen the argillite is blocky; it shows a fine banding parallel to the bedding, but has very little tendency to split along these bands. The banding is due to sandy layers up to 1 mm. thick and spaced up to 5 mm. apart. Under the microscope the argillite is seen to consist of kaolin, quartz, and a little sericite. It shows banding caused by the concentration of dark constituents; the darker bands have less quartz and more organic matter. The sandstone is fine grained, but coarser than the sandy beds in the argillite. The proportion of sandy beds seems to increase somewhat in going up the stratigraphic section.

The age of these strata is uncertain because of the lack of fossils. They are thought to be Devonian because they resemble rocks at Viacha (4), 150 km. to the northwest, and Llallagua (5), 115 km. to the south-southeast, the Devonian age of which has been reasonably well established.

Igneous Rocks

The only igneous rocks known in the area occur as dikes. The dikes are not numerous, are from less than 1 ft. to about 5 ft. wide, and steeply dipping. In places they strike across the Main Vein, in which the chief tin ore bodies of this district occur, at a fairly high angle; in other places vein mineralization appears to have come in

along or around a dike.

The dike rock is light gray in color and is so highly altered hydrothermally that its original character is obscure. It is fine grained and gives a strong odor of clay when breathed upon. It has a few faint greenish spots and occasional small quartz phenocrysts, which have led some observers to call the dikes porphyry. It is very soft and breaks easily into more or less equidimensional blocks. Ahlfeld (3) remarks that it might be a dacite. Under the microscope the rock is seen to consist of very fine-grained kaolin, chlorite, quartz, and sericite, with a few larger quartz grains. The alteration products, kaolin, chlorite, and sericite, are those which would be expected to have formed by hydrothermal alteration of a rock of intermediate to basic composition. Some suggestion of the original texture is preserved in the form of lath-shaped areas of kaolin and sericite which have the same arrangement as the plagioclase feldspar of a diabase. This texture, together with the alteration products, suggests that the rock may be an altered diabase.

Granodiorite intrusive rocks are common in the Quimsa Cruz Range, northwest of the mine. Since Colquiri lies on the extension of the axial zone of these granodioritic intrusives, it is possible that the deposit may be nearer to plutonic rocks than would appear at first glance. Some of the snow covered peaks of the Quimsa Cruz Range are

shown in Plate 2, a.

The igneous activity with which the dikes and mineralization of the district are associated took place during the Tertiary; it is assigned to the Miocene or Pliocene (7 and 3).

STRUCTURE

Folding

The sedimentary rocks of the region have been folded along northwesterly trending axes. In general the folds are open and the beds have only a moderately steep dip. But toward the center of the structure where stratigraphically lower horizons are exposed, some of the main anticlines show close folding with contorted beds and, in some places, overturning. The axis of a closely folded anticline is crossed about 2.5 km. southeast of the mine camp. Most of the folds are more or less plunging, causing higher stratigraphic horizons to wrap around the nose of domed areas. In the immediate mine area the plunge of the main fold axes is to the northwest. The mineralized area is one of doming in the sediments. Within the major folds are minor superimposed flexures. Plate 7 is a generalized cross section of the district.

The main deposit lies in a synclinal area of rather gently dipping beds between the closely folded anticline to the southeast (mentioned above) and the Colquiri Canyon Anticline. Colquiri Canyon is along the southwest limb of

GENERALIZED SECTION ACROSS COLQUIRI DISTRICT
DISTANCES AND ELEVATIONS APPROXIMATE
VERTICAL SCALE EXAGGERATED

an open anticline; the beds strike west-northwest and dip about 40° southerly. The general strike of the beds in the mine area is northwesterly, with dips to the northeast of usually less than 30° . Minor local warps are superimposed upon this general attitude. In several places in the mine southwesterly dips may be observed. At the north end of the mine (coordinates N 2750 to 2900, W 1200 to 1350) there is a small area where the beds strike northerly and dip easterly; while at the extreme south end of the mine (N 1850 to 2000) the beds strike northerly and dip westward. Only the attitude of the beds at some distance from the vein zone is uniform; dips and strikes near the vein are very erratic due to the influence of faulting.

Faulting

The faulting in the area may be divided into pre-mineral and post-mineral.

Pre-mineral faulting is of two types: that which occurred in conjunction with the folding of the sedimentary beds; and normal faulting of gravity type caused by differential subsidence of the area. Faults which were formed as the direct result of folding are common in the axial part of anticlines and tend to strike nearly parallel to the strike of the beds. Both normal and reverse types of small displacement were observed, and the presence of large bedding faults in zones of closely folded beds is suspected. Some of the faults of this group,

especially the normal ones, may have been caused by differential subsidence, and formed after folding.

The most significant pre-mineral faults are those which are now occupied by veins. These strike nearly normal to the general strike of bedding in the area and are steeply dipping. The amount of movement along these faults cannot be determined because of the lack of suitable markers, but it must have been considerable as indicated by the extent and persistence of the fractures. The fracture occupied by the main Colquiri vein shows a tendency to flatten at depth, pinch out to the south, and split up to the north as the Colquiri anticline is approached. In Colquiri Canyon, north-northeast of the main vein, veins are numerous but small; movement appears to have been taken up by several small faults rather than by one large one. This feature probably bears some relationship to the nearness to a main anticlinal axis. With the possible exception of bedding faults along anticlinal axes, the pre-mineral normal faults which were mineralized are the largest in the area.

Post-mineral faulting consists of steeply dipping faults crossing and offsetting the vein, and of renewed movement along the fractures occupied by the vein. Slickensides on fault surfaces of both these types are always more or less in the direction of the dip (2).

The cross faults are numerous near the ends of the

main vein zone. Their general dip is northward, and their downthrow side is usually the one toward the central part of the main vein. For this reason most of those at the south end of the main vein are normal, and those at the north end reverse. The largest cross fault observed, the Anita, has a dip slip displacement of 40 to 45 m., which offsets the vein 16 m. horizontally on the Incalacaya Level (see Plate 16). Displacement of the vein along other cross faults is smaller.

Probably the greatest amount of post-mineral faulting movement occurred along the vein itself; this is suggested by the crushing of certain vein material, and the presence of gouge along the walls and at some places within the vein. The post-mineral faulting is attributed to a continuation (or renewal) of the same stresses which provided fractures for mineralization. At least some of the post-mineral faults were initiated before mineralization ceased as shown by the presence of minor amounts of late stage minerals along them.

The large pre-mineral normal faults and the smaller post-mineral faults are apparently the result of shearing stresses set up by subsidence, common in the later stages of magmatic activity, and perhaps caused by contraction due to crystallization of the magma. The details of this system of fractures might be reasonably explained by postulating differential settling along the main vein fracture,

with the greatest movement in the central part. The cross faults, in the main post-mineral, which occur near the ends of the main vein fracture system, would be adjustments to stresses set up by the differential movement. The fact that the down throw side of the cross faults is generally the side toward the central part of the main fracture seems to support this. Why the cross faults at the north end dip away from the central part, and why some of them are normal (see Plate 15) is not apparent.

MINERALOGY

The following minerals occur in the Colquiri Mine:

Sulphides

Galena
Sphalerite
Pyrrhotite
Chalcopyrite
Pyrite
Marcasite
Arsenopyrite
Stannite

Tourmaline *
Sericite
Biotite
Serpentine
Kaolin

Phosphates

Vivianite

Fluorides

Fluorite

Sulphates

Selenite

Oxides

Quartz
Magnetite
Cassiterite
Limonite

Unknown mineral

Carbonates

Siderite

Silicates

Topaz *

* Reported by others but not observed by writer.

Supergene Minerals

Limonite ($\text{Fe}_2\text{O}_3 \cdot n \text{H}_2\text{O}$) is the chief mineral of the oxidized part of the veins. It is porous and may include up to several percent of cassiterite, a mineral which is unaltered by oxidation. The limonite is the residual iron resulting from the oxidation of the sulphides.

Selenite ($\text{CaSO}_4 \cdot 2 \text{H}_2\text{O}$) crystals up to 1.5 inches long were found on some of the dumps. The mineral was formed in the oxide zone from aqueous solutions resulting from the breakdown of fluorite and the sulphides.

Vivianite ($\text{Fe}_3\text{P}_2\text{O}_8 \cdot 8 \text{H}_2\text{O}$). - A few crystals were found on the dumps and must have been formed by secondary processes in the oxide zone. The source of the phosphorous is not known.

Kaolin ($\text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2 \cdot 2 \text{H}_2\text{O}$). - A small amount of the kaolin minerals occurs in the oxide zone. Although part of it is residual hydrothermal material, some of it formed in the oxide zone by the breakdown of silicate minerals and wall rock.

Silver Mineral. - Since the ores of the oxide zone were originally worked for silver, one or more supergene silver minerals formed through the breakdown of argentiferous galena must have been present, but have not been recognized. It is probable that there was some enrichment of silver in the lower part of the oxidized zone.

Lead Mineral. - Lead released by the oxidation of the galena in the primary ore undoubtedly went to form a lead mineral stable in the oxide zone; however, galena was more resistant to oxidation than the other sulphide minerals. Owing to the small amount of galena present, appreciable quantities of supergene lead minerals did not form. Because of this fact and the inaccessibility of the workings in the oxidized zone, no supergene lead mineral was recognized.

Hypogene Minerals

The hypogene minerals may be subdivided as follows:

I. Early Stage Minerals

(a) Cassiterite - Fluorite Group

Biotite
Cassiterite
Fluorite
Topaz
Tourmaline

(b) Massive Sulphide Group

Pyrrhotite
Arsenopyrite
Pyrite
Quartz
Stannite
Chalcopyrite
Sphalerite
Galena

II. Late Stage Minerals

Siderite
Magnetite
Sericite
Serpentine
Pyrite
Marcasite
Unknown Mineral
Kaolin

The early stage minerals are high temperature oxides, fluorides and silicates. They were deposited chiefly as fillings in the original fractures.

The first members of the massive sulphide group to be deposited are also generally considered as high temperature minerals, while later members indicate decreasing temperature. The deposition of the first members of the group has overlapped the deposition of the cassiterite-fluorite group; pyrrhotite, especially, is closely associated with cassiterite and fluorite. The massive sulphide group was deposited chiefly by replacement of wall rock and fluorite, and later members replaced earlier members of the same group.

After the deposition of the early stage minerals, there was a marked renewal of movement along the vein fractures causing reopening with crushing and brecciation of earlier minerals. This movement continued at intervals during the deposition of the late stage minerals so that the resulting material is conspicuously banded. Both filling and replacement were important in the deposition of this group of minerals. Taken as a group the late stage minerals have a much lower temperature of formation than the early stage ones.

Biotite ($\text{H}_2\text{K}(\text{Mg},\text{Fe})_3\text{Al}(\text{SiO}_4)_3$) is present in small amounts associated with cassiterite. It is green and rather fine grained. Because it frequently occurs coating

the walls of cassiterite-fluorite stringers, it is thought to have started to deposit before cassiterite and is the earliest mineral to form in the deposit (see Plate 8, a). Winchell (6) states that biotite in its alteration to chlorite often changes from brown to green, but that the green mineral is considered still a mica since its birefringence is strong as in the brown original. This explanation may apply to the green mica in the Colquiri deposits; however, the green mica appears perfectly fresh and not as though it had formed by alteration.

Cassiterite (SnO_2), the only ore mineral of the deposit, occurs as euhedral and subhedral dark brown to honey colored crystals up to 1 cm. long; larger crystals are occasionally seen. The crystals are zoned and intergrown. It occurs along walls of the main vein and branches, in stringers along the footwall or hanging wall of the main vein, and in areas with massive vein minerals (see Plate 9, a and b). It is usually associated with fluorite (see Plate 8, b and e), and pyrrhotite (see Plate 8, c). Cassiterite areas are cut by stringers of siderite (see Plate 8, d) and serpentine.

Fluorite (CaF_2) is medium to coarse grained and white, bluish white, or greenish white in color. It is usually found in areas of massive vein minerals along with cassiterite, pyrrhotite, pyrite, and serpentine (see Plate 8, b, e, and f).

Topaz ($(\text{AlF})_2\text{SiO}_2$) and Tourmaline ($\text{H}_9\text{Al}_3(\text{B.OH})_2\text{Si}_4\text{O}_{19}$) have been reported from the Colquiri deposit. DeWij's (2) states that they occur in close association with the cassiterite. Oroza (1) also mentions them. These minerals apparently occur in very small amounts.

Pyrrhotite (FeS_{1+}) was the earliest sulphide to be deposited; it is abundant in the massive sulphide ore and is associated with cassiterite (Plate 8, c), fluorite, and pyrite. It is slightly magnetic and is extensively replaced by pyrite (Plate 9, c) and other sulphides (Plate 9, d).

Arsenopyrite (FeAsS) was among the earliest sulphides to be deposited (Plate 9, a). It is present in only small amounts and is associated with pyrrhotite and pyrite.

Pyrite (FeS_2) is the most abundant metallic mineral and sulphide in the deposit, and was among the earliest sulphides to be deposited. Much of the pyrite replaced pyrrhotite, as is shown by the presence of pyrrhotite remnants in the pyrite (Plate 9, c). In structure the pyrite may be massive, porous, or concentric. The massive variety is thought to have formed by replacement of pyrrhotite; porous and concentric varieties may be the result of deposition by filling. Pyrite is widespread in the deposit; it occurs alone or associated with cassiterite (Plate 9, b), pyrrhotite and other sulphides (Plate 9, f), or with late stage non-metallic minerals. Minor late stage pyrite

occurs as bands in siderite (Plate 9, e).

Quartz (SiO_2). - The scarcity of quartz in the ore is an outstanding feature of the Colquiri Mine. Very small amounts of quartz are associated with the early stage minerals. Quartz partially replaced by sphalerite was observed (Plate 10, a).

Stannite ($\text{Cu}_2\text{S.FeS.SnS}_2$) is present in small amounts in the massive sulphide ore associated with chalcopryrite and sphalerite. Its tin content is not recovered in milling.

Chalcopryrite (CuFeS_2), formed chiefly by replacement of pyrite and pyrrhotite, is present in small amounts in the massive sulphide ore (Plate 10, b).

Sphalerite (ZnS), the black high-iron variety, is moderately abundant in the massive sulphide ore; after pyrite and pyrrhotite it is the most abundant early sulphide (marcasite is more abundant, but later). It may be observed veining earlier minerals and replacing earlier sulphides (Plates 9, d and 10, b). Much of the sphalerite contains small specks of pyrrhotite (Plate 9, d) and chalcopryrite (Plate 10, b).

Galena (PbS) is present in small amounts associated with sphalerite (Plate 10, c and 9, d), with which it was deposited in part contemporaneously; it may be replaced by later minerals (Plate 10, f). The galena is of interest in the Colquiri deposit because it was the source of the

silver in the primary ore; a sample of pure galena from the Doble Ancho Level assayed 185.7 ounces of silver per short ton.

Siderite (FeCO_3) is the most abundant non-metallic mineral in the deposit. Some of it, probably the earlier to form, occurs intimately intergrown with magnetite (Plate 10, d and e), and replacement of magnetite may have been an important process in its formation. Siderite occurs closely associated with cassiterite (Plate 8, d) and fluorite (Plate 8, f), partly because they were brittle and partly because they were deposited along vein walls; when reopening occurred these areas were highly fractured. It also fills cracks in early minerals. Banded structure in siderite is very common and is attributed to deposition by filling. In places siderite contains bands of late stage pyrite (Plate 9, e); it is also closely associated with marcasite (Plates 10, f and 11, a).

Magnetite ($\text{Fe}_2\text{O}_3 \cdot \text{FeO}$) occurs in minor amounts associated with siderite (Plate 10, d). Veinlets of magnetite and siderite are commonly observed cutting across pyrite and other earlier minerals (Plate 10, e). The presence of magnetite with late stage minerals is of interest because it seems to indicate a change in the composition or a rise in the temperature of the mineralizing solutions. This is probably related to the reopening of the veins in some way.

Sericite ($2\text{H}_2\text{O} \cdot \text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$) is present in small amounts. It occurs as rims around the cassiterite crystals (Plate 11, b) and replacing fluorite (Plate 11, c). Its general occurrence is similar to that of serpentine and for this reason these two minerals are thought to have been deposited at about the same time; serpentine is more abundant.

Serpentine ($3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$) was deposited in cracks in the earlier minerals. Like siderite it is concentrated in areas of the brittle minerals, cassiterite and fluorite (Plates 8, e and 11, d). Its microscopic texture varies from fairly coarse fan-like aggregates to very fine grained massive areas. Much of it shows a banded structure attributed to deposition by filling (Plate 11, e). Serpentine was selectively replaced by marcasite (Plate 11, d).

Pyrite (FeS_2) of the late stage occurs as discontinuous bands (up to 5 mm. wide) of euhedral and subhedral crystals in banded siderite (Plate 9, e); the pyrite bands are from 1 cm. to 5 cm. apart. Late stage pyrite is not very widespread in its development.

Marcasite (FeS_2) is very abundant and occurs closely associated with early stage pyrite, around crystals of which it forms alteration rims (Plate 9, f), and with siderite (Plates 10, f and 11, a), in which it often occurs as bladed crystals. Serpentine was very amenable to replacement by marcasite, and most serpentine areas contain

bladed crystals of marcasite and associated siderite (Plate 11, d).

Unknown Mineral. - A mineral which has not been identified is present in small quantities. It is a white porcelain-like mineral, very fine grained, H.-about 3.5, G.- 2.58. Before the blowpipe it is fusible, alkaline after ignition, and gives off a small amount of acid water in a closed tube. It gives chemical tests for Al, Ca, and F. Optically it is biaxial negative with a large axial angle. Birefringence is medium and indices of refraction are below 1.450. It occurs as white bands (up to several inches wide) in the center of the vein on top of banded siderite and serpentine, and fills cracks in earlier minerals (Plate 11, f).

Kaolin ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$) is the last hypogene mineral to be deposited. It occurs in small amounts as coatings on earlier minerals.

Paragenesis of Hypogene Minerals

The order of formation of the hypogene minerals may be shown graphically as follows:

Early Stage Minerals

Biotite	_____
Cassiterite	_____
Fluorite	_____
Topaz	?_?
Tourmaline	?_?
Pyrrhotite	_____
Arsenopyrite	?_?
Pyrite	_____
Quartz	_____
Stannite	_____
Chalcopyrite	_____
Sphalerite	_____
Galena	_____

Late Stage Minerals

Siderite	_____
Magnetite	_____
Sericite	_____
Serpentine	_____
Pyrite	_____
Marcasite	_____
Unknown	_____
Kaolin	_____

EXPLANATION OF PLATE 8

- a. Green biotite (Bi.) rim around argillite fragment (dark); this area is surrounded by siderite (light). Thin section, crossed nicols, X 20.
- b. Cassiterite - fluorite intergrowth. (The cassiterite is the mineral with high relief.) Thin section, plain light, X 45.
- c. Pyrrhotite crystal (light) corroded (replaced) by cassiterite. Polished section, X 160.
- d. Siderite (Sid.) veining cassiterite crystal. Thin section, plain light, X 80.
- e. Cassiterite crystal (high relief) veined by fluorite; serpentine (gray, low relief) replacing fluorite. Thin section, plain light, X 80.
- f. Fluorite (light) replaced and veined by siderite (Sid.) and serpentine (Ser.). Thin section, plain light, X 80.

EXPLANATION OF PLATE 9

- a. Arsenopyrite (light) veining cassiterite (gray, high relief), and veined by siderite. Polished section, X 85.
- b. Pyrite (light) veining cassiterite (gray, high relief) and replaced by siderite. Polished section, X 60.
- c. Pyrrhotite (Py.) remnants in pyrite (P.). Polished section, X 85.
- d. Galena (Gn.) and sphalerite (Sl.) veining pyrrhotite. Note the specks of pyrrhotite in the sphalerite. Polished section, X 80.
- e. Banded siderite and late stage pyrite (light.). Polished section, X 80.
- f. Pyrite (P.) replaced by marcasite (light); siderite (gray) associated with the marcasite. Polished section, X 85.

EXPLANATION OF PLATE 10

- a. Sphalerite replacing quartz (dark). The specks in the sphalerite are pyrrhotite. Polished section, X 135.
- b. Chalcopyrite (Ccp.) and sphalerite (Sl.) with siderite (Sid.). A few specks of chalcopyrite in the sphalerite. Polished section, X 135.
- c. Galena (light) and sphalerite (gray). (The wormy structure is due to reticulation in the film.) Polished section, X 85.
- d. Intergrowth of magnetite (light) and siderite. Polished section, X 285.
- e. Magnetite - siderite intergrowth veining pyrite (light, high relief). Polished section, X 80.
- f. Marcasite (Mr.) and siderite (Sid.) replacing galena along cleavage. (The wormy structure is due to reticulation of the film.) Polished section, X 50.

EXPLANATION OF PLATE 11

- a. Marcasite needles (light) associated with siderite (gray) in sphalerite (S1). Polished section, X 160.
- b. Sericite rims (light) around cassiterite (Cs.) crystals. The interstitial mineral is siderite (Sid.). Thin section, crossed nicols, X 20.
- c. Spherulitic sericite (light) replacing fluorite. Thin section, X 80.
- d. Serpentine (Ser.) replacing fluorite (F.) and replaced by marcasite (black). Thin section, plain light, X 20.
- e. Banded siderite (light), magnetite (dark) and serpentine (Ser.). Thin section, plain light, X 20.
- f. Unknown mineral (white) and siderite (gray) veining sulphides. Thin section, plain light, X 80.

ORE DEPOSITS

Mines

Silver Mines. - During the time the district was being worked for silver (prior to 1900), many mines were active; at that time each "socavon" (tunnel) was a separate mine. The outcrop of the Main Vein and the smaller veins outcropping in Colquiri Canyon had dozens of "socavones", now inaccessible. Just south of the village of Colquiri are the outcrops of several veins which were worked for silver. The ore in the principal one of these, Socavon Inca, is reported to have been high in galena.

Tin Mines. -

Colquiri Group. - The main Colquiri Mine had been the only active mine in the district for about 7 years prior to the time the field work was done. The workings of this mine are those on the Main Vein, which is reached by adits from various points in the head of Pia Pia Canyon. The Main Vein, which strikes N 30°E and dips 64° westerly, has been developed by 8 levels over a vertical interval of 275 m. (306 m. inclined) (Plates 13 and 14). At a depth of about 100 m. the vein is strong and continuous for about 1500 m. along the strike; this is shown on the Doble Ancho and Chojna levels (Plates 25 and 15), the two most extensive levels of the mine. The vein zone has been explored over a distance of 3000 m. (Socavon Guillermo to Triunfo, Plate 14). Up to June of 1941, 370 m. had been opened up

PLATE 14

EXPLANATION

- DRIFT
- + ADIT
- RAISE OR SHAFT
- /// MINED
- RESERVE

C.M.C.
LONGITUDINAL
SECTION

SCALE: 0 75 150 MTS.

JAN. 1, 1941

Canyon north

on the bottom level, the San Juanillo, along the strike of the vein in the central part of the developed area.

Along the northern extension of the Main Vein, in Colquiri Canyon, there are numerous smaller veins (refer to Plate 12). With the exception of the Triunfo Section, none of the workings on these veins are very extensive, and they were chiefly on oxide ore. Many of these workings were separate mines before they were consolidated as Cia. de Minas de Colquiri. Apparently little or no work had been done in this area since the mid-1920's.

The Triunfo workings are on one principal vein, Veta Colorado, which strikes north-northwest and dips about 55° westerly, and various hanging wall branches. The workings extend about 300 m. along the strike and over a vertical range of about 150 m., the lower 50 m. of which is below the level of the canyon bottom. These workings had gone into primary ore but were inaccessible.

Ocavi Mine. - This mine is about 3 km. north-northwest of Incalacaya, the Colquiri Mine camp, in Colquiri Canyon (Plate 6). It was worked more or less continuously on a small scale for tin from 1897 to 1934. The workings are on several small northerly striking veins; they have a horizontal extent of about 200 m. and a vertical extent of nearly 100 m.

There are many old dumps on the north side of Colquiri Canyon north of the Triunfo and Ocavi workings. None of

these workings were accessible and no data concerning them available.

Production

Silver. - No data are available on silver production. In comparison with the famous Bolivian silver camps of Potosi, Colquechaca and Oruro, it was very small.

Tin. - Early tin production in the district came from numerous small mines and was chiefly from oxide ores ("pacos"). No data are available prior to the consolidation of most of the small mines as Cia. de Minas de Colquiri, nor for several years thereafter.

Colquiri Mine - In the early 1930's all work was concentrated on the main vein with the object of developing enough ore to justify a mill. Consequently there was no regular production until the mill started operating in the fall of 1938. Production for the years 1938 to 1941 was approximately as follows:

1938	-	-	-	-	-	-	-	500	metric	tons	fine	tin
1939	-	-	-	-	-	-	-	4000	"	"	"	"
1940	-	-	-	-	-	-	-	5200	"	"	"	"
1941	-	-	-	-	-	-	-	6000	"	"	"	"

Ocavi Mine - This mine was a small producer from about 1897 to 1934. No exact data are available, but judging from the extent of the workings and the grade of the unmined pillars, I would estimate that ore containing 1300 to 1500 metric tons of tin had been mined. Of this amount of tin less than half was recovered by milling, thus giving a production of perhaps 600 metric tons of fine tin.

Oxidized Ores

The oxidized zone was first worked for silver. With the start of tin mining the ores of this zone were preferred because they were easier to mine and treat than the deeper and harder primary ores. However, the oxides were soon exhausted and at present all of the ore being mined is primary.

Oxidation in the district is shallow because of the relatively rapid rate of erosion. The maximum depth observed was about 50 meters near the south end of the main vein. The minimum depth observed was less than 10 meters in some of the smaller veins on the south side of Colquiri Canyon. The depth of oxidation varies inversely as the steepness of the slopes on which the veins crop out. The lower limit of oxidation in the veins seems to parallel the surface at an average depth of about 25 meters; it is deeper under the higher and more gently sloping parts of the outcrop area than in gulches and on steep slopes.

The oxidized ores are reddish to yellowish brown limonitic material in which cassiterite is present as residual grains.

At some places in the gullies below the southcentral part of the main vein outcrop, a veneer of mineralized breccia up to several meters thick covers sizeable areas. It consists of fragments of oxidized vein material, sandstone and argillite cemented by limonite. It may have

been formed by the oxidation in place of a rubble containing unoxidized vein minerals.

Primary Ores

Tin is the only metal recovered from the primary ores. The mined ore contains about 3.5 percent Sn (4.44 percent cassiterite), of which a little over 0.1 percent is present in the soluble form (in the stannite). The ore is dark gray in color due to the included argillite; closer inspection shows sulphides to be abundant. Cassiterite is frequently visible in the larger fragments. The soft brittle non-metallic vein minerals occur as fines.

Vein Structure. - (Refer to Plates 15 to 23 inclusive.) In its central part the Main Vein strikes N 33°E (nearly at right angles to the strike of the enclosing sedimentary rocks); its average dip in the upper 200 meters is approximately 63° northwesterly. Deeper, in general below the 100 Level, the dip of the vein flattens to 45° to 55°; there is some suggestion that the flattening might be related to a decrease in the proportion of sandy beds in the argillite. Northward along the strike from its central part the dip flattens and the general strike swings westward, in places as much as 15°, as a result of the flattening of the dip; the average dip is about 55°, with the dip between the outcrop and the lowest developed levels remaining fairly constant. Southward from its central part especially on the footwall side of the Anita Fault, the

strike swings slightly (5° to 10°) eastward as a result of a slight steepening of the dip.

Downward the vein splits, branches taking off from the footwall side where the dip flattens. In plan the vein splits northward, but the relation of splitting to changes in strike is not so marked as its relation to changes in dip. De Wijs (2) observes that this structural change in the north is coincident with an increase in the proportion of sandstone beds. South of the Anita Fault on the Doble Ancho and Chojna levels there is some splitting up of the vein, but mine openings are not extensive enough to determine its extent and character. To the south the vein dies out by gradual pinching. To the north it dies out by splitting up, with individual branches narrowing and disappearing; the fractures do not appear to continue much beyond the point where the mineralization dies out. Why the vein should die out at one end by splitting and at the other by pinching is not understood.

The width of the vein where simple varies from 5 m. to 20 m., with an average of about 10 m. At the northern end of the mine where the vein has branched, the vein zone is up to 100 m. wide, and consists of three well defined branches, with several additional ones locally developed. Individual branches vary from 2 m. to 12 m. wide and are separated by from 3 m. to 50 m. of wall rock, which in some places is more or less mineralized. Extreme footwall

and hanging wall branches tend to be much narrower than intermediate branches.

The following generalizations may be drawn:

- (1) The pattern of the vein down the dip may be predicted from its pattern along the strike.
- (2) Branching accompanied changes in dip and strike.

Vein Texture and Mineral Arrangement. - Within the vein banding is the most conspicuous feature; it is characteristic of the late stage minerals. Coarse banding is caused by bands of late stage minerals up to several meters wide which occur alongside of and within areas of massive early stage minerals. The most common place for such bands is along the hanging wall of a vein branch, but there are places where they occur along the footwall or within a vein; in a few cases the entire vein may be composed of late stage minerals and be completely barren of tin. Finer banding is caused by variations in the proportion of component minerals (for example the banded structure of the siderite - magnetite mixture, Plate 11, e), variations in the color and texture of a single mineral (for example siderite), and alternating layers of different minerals.

Another common textural feature of the vein is the brecciation of early stage minerals and their cementation by late stage minerals. Practically no masses of cassiterite and fluorite can be found that are not crisscrossed by siderite and (or) serpentine veinlets. Areas in which

partially replaced fragments of early stage minerals (pyrite, fluorite, etc.) occur in a groundmass of serpentine, marcasite, and siderite represent the more extreme development of this process.

Some of the pyrite deposit occurs as compact nodules with a concentric structure in a groundmass of porous sooty pyrite. In some places nearly the entire volume of a vein branch may be composed of this material plus a little cassiterite.

Distribution of the Tin

Cassiterite was deposited along early fractures chiefly by filling; the most favorable place for its deposition was in areas of lateral or vertical branching in the vein. Plate 25 shows that the high tin content on the Doble Ancho Level is related to the splitting up of the vein. Plate 24 shows the general distribution of tin in the main vein. Comparison of this tin distribution chart with the level maps (Plates 15, 16, and 17) and the cross sections (Plates 18 to 23) further establishes the relationship between high tin content and intensity of fracturing. Since cassiterite was deposited by filling fractures, the total number of open and connected (accessible) fractures in a given area was a prime factor in determining the amount of cassiterite deposited. A single vein, even though wide, contains less tin than several parallel veins, even though small.

ELEV. 4500 M.

S.S.W.

N.N.E.

ELEV. 4000 M.

N. 2000

	Centimeter x percent tin	tons fine tin per square meter
	0 - 100	0.000 0.033
	100 - 500	0.033 0.165
	500 - 2000	0.165 0.660
	2000 - 8000	0.660 2.640
	8000 or more	2.640 or more
	Anita fault	
	Minor post-mineral faults.	

C. M. COLQUIRI

LONGITUDINAL PROJECTION
of main vein

Showing lines of equal tin-value.
The tin-value is expressed in
centimeters (width) x percent tin.
Only channel samples in X-cuts,
assaying over 10% Sn were taken
into account.

SCALE 0 50 100 mts

Note: Only channel samples in cross-cuts assaying over 1% Sn were taken into account.

The low grade area in the central upper part of the vein is in a place where the vein is simple and regular. Relief of the fracturing stresses here was concentrated along a single break and must have caused the formation of a considerable amount of gouge which prevented access of early tin-depositing solutions. Where the fracturing stresses were relieved by the formation of several breaks, gouge formation was less in any one place; the fractures were therefore cleaner and more accessible and are the locus of important cassiterite deposition. Other things being equal, steeper fractures appear to have been more accessible to the tin-depositing solutions than flatter ones, and the footwall side of the vein zone more accessible than the hanging wall side; however, there are numerous exceptions to this generalization.

In some cases mineral associations can be used as a guide in prospecting for cassiterite. In general the cassiterite occurs in close association with other early stage minerals, especially fluorite and pyrrhotite. Any vein or part of vein in which fluorite and pyrrhotite are abundant should be closely examined for cassiterite.

Guides for Exploration and Development. - (Summary)

- (1) Areas in which vein branching occurs are more favorable than elsewhere; these are found where there are changes in dip or strike of the main vein.
- (2) Fluorite and pyrrhotite are good guides to cassiterite.

Location, Size, etc., of Ore Bodies. - Ore bodies are most frequently found along vein walls. In some cases the entire vein may be mineable, in others only a streak along one or both walls. The footwall is a slightly more favorable location for good ore than the hanging wall.

Some ore bodies may be up to 8 m. wide and extend for as much as 150 m. horizontally and nearly as much vertically. Some have low grade areas in them, and others are comparatively small bodies of mineable material within areas too low grade to work. In many places there may be several ore bodies located so as to fall one behind another in longitudinal projection; this is especially common in the northern part of the mine where there are numerous branches in the vein zone.

In many places along the footwall of the vein zone, and in some places in the footwall at some distance from the vein, there are thin stringers of cassiterite and fluorite with little or no sulphides; some of these are numerous enough to be mineable. The easternmost vein on the San Juanillo Level (Plate 17) is of this type.

Grade of Ore and Reserves. - Although mine run ore contains only about 3.5 percent Sn, channel samples up to 1 m. long assaying as much as 30 percent Sn are common in some of the stopes. Masses of nearly pure cassiterite are occasionally found; these are usually small but one was sizeable enough to justify separate mining, the mate-

rial being sacked in the stope and exported to the United States without further treatment.

About 4,500,000 metric tons of ore containing 2.3 percent Sn had been developed by the end of 1940.

Future Possibilities. - The northward extension of the vein zone on levels 100 to San Juanillo and the southward extension on all levels below the Chojna should be developed. Exploration and development should be continued downward by shaft from the San Juanillo Level. Deeper work probably will not develop areas so productive as some of those on the upper levels, but there is no indication that the deposit has been bottomed. Peak production had not been reached in 1941. It is my opinion that there are good chances for developing 2,000,000 to 3,000,000 metric tons of additional reserves with no great difficulty.

Origin

General Character of Deposit. - Geographically the Colquiri District is situated between areas characterized by distinct types of Late Tertiary tin deposits; the normal hypothermal tin veins of the Quimsa Cruz Range to the north, and the complex (mesothermal) tin-silver veins of central Bolivia to the south; Colquiri more nearly approaches the normal hypothermal type both geographically and geologically.

The Colquiri deposit is characterized by cassiterite and fluorite with abundant simple sulphides, and abundant

late stage minerals (siderite and serpentine). Quartz and tourmaline are rare; wolframite is absent from the main deposit, although sparingly present in the district. Wall rock alteration is not intense. Both filling and replacement were important in vein formation. The deposit differs from the hypothermal veins of the Quimsa Cruz region in abundance of sulphides, absence or small amount of quartz, tourmaline, and wolframite, less wall rock alteration, and in showing no close areal relation to granodiorite intrusives.

Source of Mineralizing Solutions. - Mineralizing solutions were undoubtedly of magmatic origin. The location of the district on the southeastward axial extension of the Quimsa Cruz intrusive belt suggests that the solutions may be genetically related to similar intrusives.

Nature of Mineralizing Solutions. - In his discussion of the bearing of fumarolic incrustations on ore deposition, Zeis (8) observes that hydrogen sulphide, sulphur, and steam react at elevated temperatures in the following manner:

He states that as the temperature falls, these equilibria are displaced from right to left. The above reactions show that at high temperature sulphur would be present in the

oxidized condition, and not as hydrogen sulphide. In a study of the fumaroles of the Katmai Region, Allen and Zeis (9) found that hydrogen sulphide and sulphur are most likely to be associated with steam escaping from relatively low temperature vents (100° - 200°C). This suggests that hydrogen sulphide is not stable at temperatures much in excess of 200°C .

Early Stage solutions contained abundant Sn, F, and Ca, in addition to the metals Fe, Zn, Cu, and Pb. Iron deposition was low at first, as no magnetite (or similar mineral) was deposited, but it had increased when sulphide deposition began. The solutions which deposited the mica, cassiterite, and fluorite were oxidizing for the metals and for sulphur, and were probably acid; they were above the temperature at which sulphur could exist as hydrogen sulphide. With falling temperature hydrogen sulphide was generated and the precipitation of Fe, Zn, Sn, Cu, and Pb as sulphides commenced; precipitation of the sulphides of these metals was in part by replacement of earlier sulphides. At this stage the solutions were reducing for the metals, and were probably alkaline.

Late Stage. - With the beginning of late stage mineralization the composition of the solutions had changed; the principal changes were the depletion of the metals, Sn, Cu, Zn, and Pb, and of fluorine and marked increase in the amount of CO_2 . Minor changes were an increase in the

amount of Mg and SiO_2 and a possible decrease in the amount of Ca. The presence of CO_2 appears to have been an important factor in temporarily bringing about the return of oxidizing conditions for iron (shown by the presence of magnetite associated with early siderite). But in the main conditions were probably reducing for the metals, and the solutions were probably alkaline. However, the deposition of abundant marcasite suggests that the alkalinity was decreasing, and the presence of the very late fluorine-bearing unknown mineral indicates that end stage solutions were acid.

Temperature of Formation of Deposit. - The temperature of formation of any mineral deposit is best indicated by the mineral assemblage contained. The Colquiri minerals indicate that early mineralization took place in the hypothermal temperature range, and that later mineralization took place in the mesothermal temperature range. The cassiterite-fluorite-biotite assemblage is indicative of high temperature, and most certainly formed at temperatures considerably in excess of 200°C . During the high temperature stage of mineralization, minerals deposited were oxides, fluorides, and silicates; iron was present in the ferric state.

The remainder of the minerals in the deposit indicate decreasing temperature. The group of simple sulphides (pyrrhotite, arsenopyrite, pyrite, chalcopyrite, stannite,

sphalerite, and galena) were probably deposited below 200°C. The logical division between hypothermal and mesothermal temperature ranges would seem to be between the oxide-fluoride-silicate mineral assemblage and the simple sulphide assemblage in which iron combined with oxygen was present in the ferrous state.

The deposition of magnetite early in the late stage of mineralization might indicate an increase in the temperature of the mineralizing solutions. It might also be due wholly or in part to the abundance of CO₂ in the solutions which temporarily brought about oxidizing conditions, probably in accord with the following reaction:

Depth of Formation of Deposit. - The depth at which the deposit formed is best indicated by the texture of the minerals and the structure of the vein. The minerals are fairly coarse grained, thus indicating constant conditions of deposition such as would be expected at considerable depth. There is no apparent change in mineralogy over the 1000 ft. interval which has been developed; from this it may be inferred that the mineralogy was essentially the same for 1000 ft. above the present outcrop and 1000 ft. below the lowest level. The distribution of the cassiterite and fluorite suggests that filling was important at the time of their deposition. Replacement became increasingly important during simple (massive) sulphide deposition.

Banding of late stage minerals indicates that filling again became important during the late stage mineralization.

The structure of the vein suggests fracturing at intermediate depth. The fracturing definitely took place in the zone of brecciation where an increase of volume was possible and open spaces could exist, even though the rock is not particularly competent. There is little or no development of sheeting along the fractures, or an echelon arrangement of individual fractures. However, shattering of the rock and upward branching of the fractures is not apparent, and there was a good deal of gouge formed; these features indicate considerable cover.

The region is one of high relief and rapid erosion; this suggests removal of considerable cover.

In view of the above evidence, an estimate of 6000 ft. to 10,000 ft. as the depth of formation of the deposit seems reasonable.

Classification of Deposit. - The Colquiri deposit was formed at high to intermediate temperature at moderate depth. It might be classified as lower intensity hypothermal.

MINING

Exploration and Development

Topographic and geologic conditions were such that the development of much of the upper 300 m. of the vein by adits was possible. The mine has been laid out by estab-

lishing levels at vertical intervals of approximately 30 m. (actual interval between levels varies from 28 m. to 34 m.). Adits have been driven to the vein on all levels above the Chojna, the Incalacaya Level, and the San Juanillo Level. The strike of the vein is approximately parallel to the general trend of the contours, but the dip of the vein is opposite to that of the surface. For this reason deeper levels require longer adits; the lowest adit, the San Juanillo, cut the vein 1283 m. from the portal at a depth of 274 m. The lower limit of economical development by adits has been reached, and deeper development will have to be by shaft. There is a three-compartment inclined shaft, about 3 m. x 9 m., between the Chojna and San Juanillo levels.

The system of exploration as originally planned at the time that systematic development of the property was begun in the early 1930's, consisted of drifting in the country rock on the footwall side of the vein and completely cross-cutting the vein zone at 25 m. intervals. Much of the work was more or less in accord with this plan as shown by the composite map (Plate 13). In more recent times, especially on the lower levels, there has been a tendency to drift on the best ore and cross-cut occasionally to outline the vein zone.

Blocks of ore are developed by driving so-called "stope drifts" between the cross-cuts on the better streaks

of ore, and raising at 25 m. intervals; these raises are afterwards used to bring fill into the stopes.

Mining Method. - The cut-and-fill system of stoping with some modifications is the mining method used at Colquiri. Stopes are started from the stope drifts mentioned above. Since the ore is generally high grade, no pillar is left above the drifts to support the fill in the stopes. Where the ore body is narrow, hitches are cut in the walls and stulls are placed across the drift at a height of about 2 m. above the track level. The stope is started from a floor of lagging laid on these stulls. Where the ore body is wider than the drift, the drift is first widened to the width of the ore. Then three-piece sets are put in over the track and the sides and top lagged. The open space behind the lagging is filled with waste and stoping proceeds upward. Ore bodies up to 8 meters wide, the maximum width thus far encountered, are being mined in this way. Local bad spots in the back are temporarily supported by "T-bone" stulls (a two-piece set consisting of a post and a head block). In stoping the ore is blasted down directly on top of the waste fill. Fill raises and manways are 25 m. apart; chutes are 8 m. apart (refer to Plate 26). In some cases horizontal cut-and-fill stoping has been modified to inclined cut-and-fill stoping to facilitate filling. Waste rock for fill is obtained from a glory hole on the outcrop. Trimming of waste and ore in

NOTE.- MEASUREMENTS IN METERS.

DRAWN BY: P.R. MERRIS.

DATE: 18-III-40

TRACED BY: E. LARREA V.

CHECKED:

APPROVED:

SCALE: 1:200

CIA. DE MINAS DE COLQUIRI

COLQUIRI-BOLIVIA

STANDARD ARRGT FOR CHUTES & MANWAYS IN HORIZONTAL CUT & FILL STOPE.

PLATE 26

8059

most of the mine is by hand. Ore is hauled to the mill by trolley locomotive; the distance from the main ore pass in the mine to the mill is 2000 m. Daily production in June, 1941, was from 600 to 700 metric tons.

Criticisms and Suggestions. - In many places it would probably pay to blast down the ore on a plank floor to prevent loss of high grade cassiterite fines in the fill.

In starting a wide stope no provision is ever made for coming up under it from the level below with another stope; ore pillars must be left. While it is not customary to lay a sill floor in cut-and-fill stoping, this procedure might be justified in case of very high grade ore such as is sometimes encountered.

In many parts of the vein zone ore occurs in closely spaced streaks essentially parallel in strike and dip to the general mineralized trend (refer to Plate 16 north of cross-section line D), and the stopes are too close together here for safe mining without leaving an excessive amount of ore as pillars. In some cases the intervening waste material is argillite, while in others it is low grade vein matter. Argillite waste could easily be sorted from the ore on a picking belt under water sprays. In places where closely spaced ore bodies are separated by argillite waste, as on the Incalacaya Level (Plate 16) between cross-section line D and the shaft, it might prove advantageous to mine the entire block as a unit, perhaps by shrinkage

stopping or caving, and sort out the coarse waste on a picking belt. Some experimenting should be done along such lines.

Usually where there are parallel ore bodies lying over one another in an inclined vein zone, it is considered better practice to mine the upper (or hanging wall) ones first, abandon those workings, and start farther back toward the footwall. However, at Colquiri ore bodies in all parts of the vein zone are being mined at the same time. As the stoped out area increases, trouble in keeping the workings open is likely to result, and ore will be lost that could have been recovered had the vein zone been worked systematically from hanging wall to footwall.

Sampling as a Guide to Mining Operations. - In the Colquiri Mine an intensive system of sampling has been well developed. The stope backs are channel sampled at 2 m. intervals after every cut, and up to date sample maps given to the shift bosses. Samples above the cut-off are painted white so that the width of the stope can be varied, and low grade material left as fill or larger low grade areas left as pillars. The walls of stopes are drilled at 2 m. intervals to a depth of 6 ft. and the cuttings for each 2 ft. interval assayed. This sampling procedure often justifies widening the stope. Drift backs are channel sampled at 2 m. intervals, and faces after every round so as to tell whether to dump the muck from the next round as ore

or waste. Cross-cuts in the vein zone are sampled on both walls. The length of all channels varies with the material sampled; the channel is broken whenever the type of material changes. However, 1.5 m. is the maximum length of any cut.

Power. - The hydroelectric plant for the mine is 65 km. distant over rough mountain country. Seasonal variation of water supply and difficulties caused by sanding up of flumes, etc., made the power supply so precarious that an emergency and supplementary diesel-electric plant was being installed.

Labor and Supplies. - The labor supply is very unskilled as judged by American standards; many workmen are ignorant Indians who cannot even speak Spanish. The only advantage of the labor supply is that it is cheap. Supplies are more expensive than in the United States due chiefly to high transportation costs. Supplies, rather than labor, is the more expensive item in the production costs; they amount to 60 percent or more of the total.

MILLING

Tin is the only metal commercially recovered and cassiterite (SnO_2) the only mineral of direct commercial interest. Because of its high specific gravity (7), cassiterite is amenable to gravity concentration and the milling process is based on this principle. Mineralogically the mill heads are composed of 4.4 percent of

cassiterite, and approximately 33.6 percent of sulphides and 62 percent of non-metallic vein minerals and argillite wall rock.

Of the 3.5 percent Sn contained in the heads, 0.15 percent is present in stannite ($\text{Cu}_2\text{FeSnS}_4$) which is not recovered in the concentrates. Tin present in stannite is referred to as soluble tin. In bodies of massive sulphide ore stannite is locally abundant and may represent a considerable proportion of the tin shown in the assays. In such cases the assays might be over the cut-off of 1 meter percent Sn even though the recoverable tin value was much lower than this. For this reason sulphide material should be examined for cassiterite before being dumped as ore. This was not being done and was probably a factor in lowering the apparent tin recovery in milling.

Of the 33.6 percent of sulphides contained in the mill heads, iron sulphides (pyrite, pyrrhotite, and marcasite) constitute about 28.5 percent. The remaining 5.1 percent is made up of sphalerite (2.8 percent), chalcopyrite (1.2 percent), stannite (0.6 percent), arsenopyrite (0.3 percent), and galena (0.2 percent). The average specific gravity of the sulphide assemblage is about 4.8 to 4.9. The non-metallic vein minerals are siderite (sp. gr. 3.8) and fluorite (sp. gr. 3.2); the argillite (slate) wall rock has a specific gravity of 2.7. The weighted average specific gravity of this assemblage is about 3.2.

From a comparison of the specific gravities of these two assemblages, it is apparent that the impurities in the gravity concentrates will be sulphides.

The first step in gravity concentration of the ore is rougher jigging of plus 1 mm. material. Jigg concentrates are then ground finer in tube mills and tabled, with further grinding between stages. The concentrates are partially cleaned of sulphides at intervals by bulk flotation. The final concentrates contain at least 62 percent Sn.

In June, 1941, about 600 metric tons of ore were being milled per day. Percent recovery was about 80 percent, and the ratio of concentration was about 20 to 1. It was proposed to increase the milling capacity to 1000 metric tons daily by the installation of a sink-float unit.

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EXPLANATION

- ROAD
- DUMP
- PROSPECT
- BUILDING
- SHAFT
- OPEN CUT
- ADIT, WITH NAME
- ELSA
- CROSS SECTION
- INTERMITTENT STREAM
- SED. ROCK, MOSTLY ARGILLITE
- ALTERED DIKE
- VEIN, OBSERVED, INFERRED
- FAULT, OBSERVED, INFERRED
- ARGILLITE BEDDING
- SANDSTONE BEDDING

C.M.C.
AREAL GEOLOGIC MAP
scale, 0 25 50 100 mts.
contour interval, 10 mts.
GEOLOGY BY L. MOON, 1935

PLATE 12, Sheet 1

- SAN ANTONIO
- DOBLE ANCHO
- CHOJÑA
- 30 LEVEL
- INCALACAYA
- 100 LEVEL
- 135 LEVEL
- SAN JUANILLO

ANITA
4335 mts

ELSA
4283 mts

C.M.C.
COMPOSITE LEVEL MAP
scale: 0 50 100 mts.

PLATE 13

- EXPLANATION**
- SEDIMENTARY ROCK (mostly argillite)
  - ALTERED DIKE
  - VEIN, observed, inferred
    - > 50% sulphides
    - < 50% sulphides
  - NARROW STRINGERS and/or IRREGULAR MINERALIZATION
  - FAULT, observed, inferred
  - GOUGE or BRECCIA ZONE
  - ARGILLITE BEDDING
  - SANDSTONE BEDDING
  - SAMPLES
    - > 2% Sn
    - 1% to 2% Sn

REFERENCE LINE

PLATE 15

C.M.C.
GEOLOGIC MAP
CHOJŇA LEVEL
scale: 0 25 50 mts.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulphides
  - < 50% sulphides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
  - > 2% Sn
  - 1% to 2% Sn

C.M.C.
GEOLOGIC MAP
INCALACAYA LEVEL
scale: 0 25 50 mts.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulfides
  - < 50% sulfides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
  - or : > 2% Sn
  - : 1% to 2% Sn
  - : < 1% Sn

PLATE 18

X-SECT. A-A'

C. M. C.

GEOLOGIC CROSS SECTION
N 57°W THROUGH N2701 W1494

Incalocay X-C-13 N

Scale: 0 5 10 20 MTS.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulfides
  - < 50% sulfides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
  - or : > 2% Sn
  - : 1% to 2% Sn
  - : < 1% Sn

PLATE 19

X- SECT. B - B'

C. M. C.

GEOLOGIC CROSS SECTION

N57W THROUGH N2556 W 1591

Incalacaya X-C#6N

Scale: 0 5 10 20 MTS.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulfides
  - < 50% sulfides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
  - or : > 2% Sn
  - : 1% to 2% Sn
  - : < 1% Sn

PLATE 20

X-SECT. C-C'

C. M. C.

GEOLOGIC CROSS SECTION
N 57°W THROUGH N 247°W

Incalecayo XC + 2N

Scale: 0 5 10 20 MTS.

EXPLANATION

- SEDIMENTARY ROCK (mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulfides
  - < 50% sulfides
- NARROW STRINGERS and (or) IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
  - or : > 2% Sn
  - : 1% to 2% Sn
  - : < 1% Sn

PLATE 21

X-SECT. D-D'

C. M. C.
 GEOLOGIC CROSS SECTION
 N 57° W THROUGH N 2384 W 1703
 Incolocoye X-C # 215
 Scale: 0 5 10 20 MTS.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
- > 50% sulfides
< 50% sulfides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING
- SAMPLES
- or • : > 2% Sn
 H : 1% to 2% Sn
 || : < 1% Sn

PLATE 22

X-SECT. F-F'

C. M. C.

GEOLOGIC CROSS SECTION

N 57°W THROUGH N.2277, W.1775

Incolacova 7± S.

Scale: 0 5 10 20 MTS.

EXPLANATION

- SEDIMENTARY ROCK
(mostly argillite)
- ALTERED DIKE
- VEIN, observed, inferred
  - > 50% sulfides
  - < 50% sulfides
- NARROW STRINGERS and (or)
IRREGULAR MINERALIZATION
- FAULT, observed, inferred
- GOUGE or BRECCIA ZONE
- ARGILLITE BEDDING
- SANDSTONE BEDDING

SAMPLES

- or • : > 2% Sn
- : 1% to 2% Sn
- || : < 1% Sn

PLATE 23

X-SECT. G-G'

C. M. C.

GEOLOGIC CROSS SECTION
N. 57° W. THROUGH N. 211° W. 1864

Inocleays X-C #151 S.

Scale: 0 5 10 20 MTS.