TIN DEPOSITS OF CARGUAICOLLO, BOLIVIA.

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ABSTRACT. The tin-silver veins of Carguaicollo, in the Department of Potosí, are noteworthy because the principal ore mineral is teallite, a relatively uncommon sulphide of tin and lead. They occur in a dacite porphyry which intrudes folded sediments and which, except near the mines, is covered by later barren tuffs and lavas. Extensive hydrothermal alteration has converted the wall rock into quartz, sericite and serpentine, with less chlorite and carbonate.

Besides the dominant teallite are the other tin minerals, franckeite and cassiterite. Wurtzite and sphalerite are abundant; pyrite and marcasite somewhat less common. The silver occurs mostly with sphalerite and wurtzite, though some is found with teallite. Other minerals present are galena, arsenopyrite, proustite, quartz, chalcedony, siderite, and alunite.

Teallite, earliest of the vein minerals, was extensively replaced by an aggregate of wurtzite and sphalerite, and by pyrite and marcasite. Cassiterite is late in the sequence and with galena forms a fine intergrowth replacing teallite.

On the basis of predominant sulphides present, most of the veins may be divided into two groups: (1) teallite-wurtzite-sphalerite and (2) wurtzite-sphalerite-pyrite veins. Non-metallic minerals are distinctly subordinate.

Within the main zone most veins strike nearly north, but a few strike N. 40°-60° W. The veins dip 45°-80° either easterly or westerly. The vein width averages 10-15 and rarely exceeds 50 centimeters. Though narrow some veins are rather persistent.

In the zone of oxidation the zinc is largely removed and the teallite veins are locally changed to a fine-grained mass of cassiterite, anglesite, jarosite, and limonite.

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THE Carguaicollo tin deposits are in the Department of Potosí about 20 kilometers by automobile road east of Rio Marquez, a station on the Antofagasta-Bolivia Railway. The mines are situated along a ridge at the headwaters of the Coroma River, a small stream which drains to the west, reaching the Altiplano near Rio Marquez (Text Fig. 1). Cerro Tigui, just east of the ridge, stands out as a prominent peak, with a steep western face which is visible from the railroad. The mine camp, which has a reported elevation of 4200 meters, is at the north end of the ridge and on the east side of a local divide.

Tin and subordinate silver are the economically important metals of the veins. The deposits are of unusual interest because the principal ore mineral is teallite, a sulphide of tin and lead.

According to vague reports, the Carguaicollo veins were worked for silver in the Colonial period and again about 1890. Not until 1910 were they prospected for tin when a little cassiterite concentrate is said to have been produced. The teallite ores were first mined about 1924. After being idle for several years, the mines were reopened in 1932, and by 1936 the monthly production averaged about 35 metric tons of picked teallite ore, a complex product containing tin, lead, zinc, and silver.

The veins were examined previously by Ahlfeld.¹

PHYSIOGRAPHY AND GENERAL GEOLOGY.

Carguaicollo lies within the volcanic plateau of Central Bolivia, not far from the western margin. The plateau in this area is characterized by moderate relief, but it is cut in places by several streams and elsewhere is interrupted by low mesas and isolated peaks reflecting, in part, faulting of the flat-lying volcanics.

At Caraguaicollo erosion has removed the volcanic rocks within a small area and has exposed a dacite porphyry intrusive cutting sedimentary beds, probably Paleozoic. The latter

are restricted to a narrow belt not more than 150 meters in width, bordering the dacite porphyry on the west. It is clear that the dacite porphyry has invaded the sedimentary rocks but the contact, revealed for only a few meters in two or three narrow ravines, gives no indication of the form of the intrusive mass. The surface exposure of dacite porphyry is about seven square kilometers.

Except along the west side, the intrusive is bordered by volcanics but the actual contact is almost entirely covered by surface débris. However, at the places where the contact could be studied in detail, the tuffs and lavas show no sign of contact metamorphism, the dacite porphyry has no fine-grained margin, and zones of alteration which are conspicuous in the intrusive end abruptly at the contact. Therefore, it is concluded that the dacite porphyry is definitely older and that the volcanics rest upon a former erosion surface.

The productive veins of the district are found only in the dacite porphyry and most of them are limited to a broad zone of alteration described below. The tuffs and lavas are not known to be ore-bearing in the area under review.

Andesite porphyry is exposed in Cerro Amarillo, a rather prominent peak situated in the Coroma valley below Carguacollo southwest of the area shown on the map. The porphyry is entirely surrounded by the tuffs and lava flows, but the contacts are obscure and its relative age could not be determined. It is probably an intrusive.

Sedimentary Rocks.

The oldest rocks of the district are thin-bedded, easily-weathered shales that are light gray or, more rarely, red in color. Locally in the creek beds the rock is bleached white.

These beds strike N. 15°-40°W. and dip commonly about 80° NE. The strike of the contact between the shale and the intrusive dacite porphyry is approximately the same but exposures are too limited to indicate the dip.

Igneous Rocks.

Dacite Porphyry. The oldest igneous rock appears to be the dacite porphyry intrusive which contains the veins. On fresh fracture the rock is gray to pale green and over large areas appears to have a fairly uniform grain. Feldspar, biotite and a little quartz can be recognized in hand specimens.
Examination of thin sections of the fresh rock discloses a porphyry with phenocrysts commonly 1.5-2.0 mm. and exceptionally 7 mm. in greatest dimension; the groundmass has an average grain size of .01-.02 mm. Some sections, however, show a seriate porphyritic texture.

The phenocrysts comprise quartz, plagioclase and biotite. The groundmass is made up of the same minerals with accessory zircon, sphene, apatite, pyroxene, and iron oxide. Plagioclase phenocrysts range from calcic oligoclase to calcic andesine, whereas plagioclase in the groundmass is more sodic.

Broad areas of the dacite porphyry are hydrothermally altered to a light-colored, bleached, somewhat pyritized rock, the most important area extending from the Tigua mine camp south to Cerrillos, a distance of 1600 meters. This includes most of the Cerro San Pedro ridge west of the principal veins. To the south the alteration gradually fades out, but to the north it continues beneath the volcanics for an unknown distance. In addition, smaller areas and narrow belts of altered dacite porphyry are found throughout the exposed area of the intrusive. Productive veins are found only in altered dacite porphyry but the microscope shows that some porphyry rather remote from known veins is as greatly altered as that nearer to them.

Thin sections of the least altered rock show incipient replacement of the plagioclase and biotite chiefly by carbonate, sericite, serpentine and chlorite. In the more completely altered parts of the intrusive the rock is dominantly quartz, sericite and serpentine with less chlorite and scant zoisite and carbonate.

*Andesite porphyry.* The andesite porphyry at Cerro Amarillo is, where unaltered, a massive, somewhat purplish rock in which biotite and abundant feldspar phenocrysts are evident in a fine-grained groundmass.

Over most of the area where it is exposed the andesite porphyry is altered and of light color. Seams and masses of iron oxide are characteristic of the altered rock, but no ore has been found within it.

Thin sections show that phenocrysts are chiefly oligoclase-andesine (about An 30) with less abundant biotite and hornblende. The groundmass is even grained and holocrystalline; most grains have a lower index than balsam, and, hence, are probably more sodic plagioclase than the phenocrysts.
Volcanic Series. Overlying the dacite porphyry intrusive in the Carguaicollo region is a series of volcanic rocks made up principally of two members, a gray tuff and a brown tuff, with possibly a third member represented by an andesite flow of restricted occurrence.

The gray tuff is exposed at the base of the volcanic series along the Corona valley where it is 100 meters or more in thickness. It is light purple and weathers to purplish gray or pale gray. The tuff contains an abundance of large, angular fragments, both igneous and sedimentary, in some places comprising as much as 50 per cent of the rock mass. In these places the rock is more accurately called a breccia. In one place the top of the gray tuff has been converted by silicification to chert-like breccia, some of which shows a mixture of brilliant red and white colors.

The brown tuff which caps ridges along the Corona valley is similar to the gray except that it is a little darker in color, has a little higher percentage of large angular fragments, and is more massive and resistant to weathering.

Under the microscope both tuffs are found to consist chiefly of broken fragments of quartz, plagioclase (oligoclase-andesine), and biotite, and less orthoclase in a very fine-grained to glassy matrix. The gray tuff contains less biotite than the brown tuff and is more altered. Both may be classified as dacite or quartz latite.

The purple andesite is a fine-grained porphyry, and on the weathered surface it is pitted owing to the leaching out of the hornblende phenocrysts. This andesite was not studied in detail but it crops out on two low peaks southwest of the dacite area and may represent a flow of local extent overlying the gray tuff.

ORE DEPOSITS.

Introduction.

The Carguaicollo tin property includes vein deposits and placers, the latter contributing but a small part to the total production.

The veins are in the altered dacite porphyry and contain tin and silver. The most abundant tin mineral is teallite and the silver is present in wurtzite and sphalerite, though the teallite also contains a little silver.
The placer deposit, along the Coroma River, is said to extend for about six kilometers and to have produced high-grade cassiterite concentrate, assaying 68 per cent tin.

**General Description of the Veins.**

The veins, which are located in Carguacolico ridge, are confined to a zone 150–300 meters wide and about 1600 meters long. At one place the vein zone has been prospected at a depth of 200 meters.

Within the main zone most veins strike nearly north but a few strike N. 40°–60° W. Traced to the south the zone spreads out considerably and the strike of the veins gradually changes from north to N. 20° E. Veins of different strikes are of the same age, however, and there is no important offset of one group by another. The veins dip 45°–85° either easterly or westerly. Outside of the principal area, the most important vein is that of San Pedro ridge. This vein strikes N. 20° W. and can be traced by means of scattered workings for 200 meters.

The vein width averages 10–15 cm. and rarely exceeds 50 cm. Most of the veins pinch and swell. They feather out in short distances but where one stringer dies out, another generally takes its place forming an "en echelon" pattern, and a zone of veins two to three meters wide which is reasonably persistent. Some veins, though narrow in width, are remarkably persistent for this region, and one of 10 cm. in the Tigua adit can be traced for 90 meters. The older adits have been confined mostly to the eastern half of the vein zone where presumably patches of good silver ore were encountered. Recent developments have been concentrated on the teallite veins which are found at the extremities of the mineralized zone and a little west of the principal silver workings.

A coarse banding of the veins is apparent in many exposures underground; and a fine banding is shown by the hand specimens. Vugs, often strung out parallel with the vein walls, are another striking feature of the veins and accentuate the banded character. These facts suggest that filling was the dominant manner of vein formation but as will be pointed out below the mineralization was complex and replacement accompanied and followed filling.

On the basis of the predominant sulphides present most of
Teallite (T) laths replaced by cassiterite (Cs) and galena (Gn). Minor amounts of wurtzite (W) and arsenopyrite (Asp). X40.

Teallite (T) replaced by galena (Gn) and cassiterite (Cs). Pyrite rim (Py) antecedent to (Gn) and (Cs) along former teallite lath. X85.
Pyrite-marcasite (Py-Mc) pseudomorphs after teallite. Some teallite was bent before being replaced. Matrix is chiefly quartz (Q). X35.

Hexagonal grains of wurtzite (W) partly surrounded by later pyrite (Py). X130.
the veins may be divided into two groups: (1) teallite-wurtzite-sphalerite veins, and (2) wurtzite-sphalerite-pyrite veins. In nearly all the veins non-metallic gangue minerals are distinctly subordinate. The teallite veins account for most of the tin production whereas veins of the second group have been most extensively worked for silver. However, as the teallite veins contain considerable silver and the silver-bearing veins contain scattered patches of teallite or franckeite, it is impossible to draw a sharp line between the two types.

**Teallite-Wurtzite-Sphalerite Veins.**

The teallite ore is derived largely from the Catalina vein (Santa Rosa, Principal, and No. 1 adits) at the extreme north end of the mineralized zone but some is produced also from a vein worked through adits No. 2 and No. 3 at the south end. Veins in the western part of the mineralized zone appear to be more productive of teallite than those in the eastern half of the zone. Small pockets of teallite ore, however, are found elsewhere in the district, and on the south slope of Cerro Tigua specimens of partly oxidized teallite ore were obtained from narrow veins exposed in two shallow trenches.

The Catalina vein strikes N. 5° E. and dips 70° NW. When examined it was being worked through a vertical interval of 33 meters above the lowest level which was possibly 100 meters below the surface. The vein was not traced from the lowest level to the surface, however, because the upper levels are caved and no outcrops were found on the ridge that could be definitely correlated with the Catalina vein. The vein is closely paralleled by a prominent strike fault which is later than the ore. To the north, the extension of the vein is represented only by the fault and elsewhere over short distances the sulphide filling gives way to barren gouge.

The teallite veins consist chiefly of wurtzite, sphalerite, teallite, pyrite and marcasite. Wurtzite, the hexagonal form of zinc sulphide, is more abundant than sphalerite, the isometric form; but in any hand specimen containing one, more or less of the other is usually present. Pyrite is more common than marcasite. Galena is a rather widespread mineral but is not abundant. Cassiterite and arsenopyrite are erratic in distribution. In a few places in the veins very small quantities of franckeite accompany or take the place of teallite.
Non-metallic gangue minerals are present in small quantity and consist mostly of quartz and siderite with a little chalcedony.

Seemingly pure bands of either teallite, zinc sulphides (wurtzite and sphalerite), iron sulphides (pyrite and marcasite), or siderite are found, upon microscopic examination, to contain minor to fairly large amounts of other minerals finely distributed. Other bands in the teallite veins are composed of large amounts of all of these minerals with complicated interrelations.

In a typical vein the ore shoot has an average width of approximately 20 cm. Beyond the ore shoot, there is an increase in the proportion of siderite or of zinc and iron sulphides and in places between ore shoots the teallite and zinc sulphides give way almost entirely to pyrite and marcasite. In the teallite vein at the south end of the area, this same change is shown in depth, and in the lowest adit the vein increases to 50 cm. in width, but consists almost entirely of pyrite and marcasite.

_**Wurtzite-Sphalerite-Pyrite Veins.**_

Many of the veins of the wurtzite-sphalerite-pyrite type were worked for silver in the early days. The most productive veins of this class are in the eastern half of the vein zone and in the central section from north to south. In the Tigua, Gallofa and Mercedes adits and in the nearby shallow workings the vein zone has been developed over a length of 800 meters. The extent and abundance of the old workings indicate that the veins were thoroughly prospected and probably a considerable amount of silver ore was produced.

To the north and south of the adits mentioned, the silver belt is not well defined and the workings are more scattered. Silver veins are reported in the oxide zone above the Catalina (teallite) vein as well as to the west of it.

In general the silver veins are uniform but very narrow, rarely exceeding 15 cm. in width. Most of them maintain a northerly strike and steep dip. In one adit four parallel veins were worked within a distance of 25 meters, measured across the strike.

The mineralogy of the silver-bearing veins is somewhat similar to that of the teallite veins but the proportions of the minerals present are different. A typical vein is composed
chiefly of massive pyrite, wurtzite, and sphalerite. As in the teallite veins, wurtzite is more abundant than sphalerite.

Fig. 2a  Hypogene Mineral Sequence in the Tin Veins

quartz

teallite

franckeite

pyrite + marcasite

wurtzite + sphalerite

arsenopyrite

galena

cassiterite

marcasite

siderite

Fig. 2a. Hypogene mineral sequence in the tin veins.

quartz

teallite

franckeite

arsenopyrite

pyrite + marcasite

wurtzite + sphalerite

marcasite

cassiterite

galena

siderite

proustite

chalcedony

Fig. 2b. Hypogene mineral sequence in the silver veins.

Minor amounts of marcasite, teallite, franckeite, cassiterite, galena, arsenopyrite and ruby silver are present, none of which is so widespread as pyrite, wurtzite, or sphalerite. A little
siderite, quartz, and chalcedony, and, rarely, alunite are the only gangue minerals.

The Palermo adit, which prospected the zone some 200 meters beneath the Mercedes adit where silver veins had been worked, encountered narrow pyritic veins, suggesting that the mineralization as a whole becomes more pyritic in depth.

The Vein Minerals and their Sequence.

The textures of these ores are somewhat like those of Llallagua and, seemingly, have been developed in the same way. Teallite and frankelite, early soft minerals, have been largely replaced by later minerals such as pyrite, wurtzite, and cassiterite yielding complex textures difficult to interpret. The approximate order of deposition is shown graphically in Text Figs. 2a and 2b, the sequence in the tin veins being slightly different from that in the silver veins.

Teallite (PbS·SnS$_2$) Teallite is an early abundant mineral. It occurs in bands 1 to 5 cm. wide made up of coarse laths or plates commonly near the walls of veins. It occurs also as residual grains in bands of other minerals near the center of veins (Pl. 3 Fig. 2). In places the teallite plates are curved, deformed, and fractured.

Teallite was an easy victim of attack by hypogene solutions. Convincing evidence is furnished by the laths or plates which are found in all stages of replacement by wurtzite, sphalerite, cassiterite, galena, pyrite, and marcasite. The solutions performing the replacement take advantage of the prominent basal cleavage of teallite (Pl. 1 Figs. 1, 2) and the lath-like shape is often preserved with great fidelity (Pl. 2, Fig. 1) even where the original mineral has been nearly or quite destroyed. Teallite is replaced by galena and cassiterite in a striking pattern somewhat like graphic granite (Pl. 1, Fig. 2).

In some veins there is a thin marginal layer of wurtzite, pyrite, or siderite between the thick teallite band and the wall rock, but polished sections of specimens from such places show that all these minerals are commonly later in sequence than teallite.

Spectrographic test of one specimen of clean teallite showed a large amount of silver present but no zinc. Microchemical

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tests on other specimens revealed no zinc. The absence of zinc in the specimens tested may cast some doubt on the existence of pufahlite (zinc-teallite) previously reported by Ahfeld in these ores.

Wurtzite and sphalerite. Wurtzite is the most abundant mineral in the veins and is almost invariably accompanied by sphalerite. According to Short, wurtzite appears as if isotropic in polished sections. This is true, but in numerous thin sections made for this study, wurtzite is clearly anisotropic.

Wurtzite occurs in bands up to 5 cm. wide. Some of these are vuggy and exhibit good hexagonal crystals (Pl. 2, Fig. 2); other bands are made up of radial aggregates or flamboyant sheaf-like clumps or rosettes of grains. Though these bands are dominantly wurtzite and sphalerite they contain small quantities of other minerals. Some bands containing numerous residual particles of teallite and franckeite were formed seemingly by the wholesale replacement of these tin minerals. Other bands of zinc sulphides, relatively pure, appear to have been formed by open space filling.

Wurtzite replaces teallite along the cleavage and in places wipes out the teallite completely but preserves the shape of the bladelike teallite unit. Wurtzite is an early mineral especially in the tin veins but commonly somewhat later than teallite. It is veined or replaced by pyrite, marcasite, siderite, galena and quartz, but some was deposited late and replaces galena. Minor amounts of it were probably deposited throughout much of the mineralization period.

The age relations of wurtzite and sphalerite are not uniform. In some places wurtzite grains are surrounded by rims of sphalerite; in other places the situation is reversed.

Pyrite and marcasite. Some silver-rich veins are composed of bands of massive pyrite and marcasite with less wurtzite and minor amounts of other minerals. Pyrite occurs, also, in straight or reniform bands, and scattered grains in veins that are dominantly wurtzite or teallite. Cubes and pyritohedrons of pyrite line some of the vugs, and pyrite is the commonest mineral disseminated in the wall rock near veins. Pyrite


forms rims or frames around teallite units and remains after the teallite is completely replaced by cassiterite and galena (Pl. 1, Fig. 2).

Pyrite and marcasite usually accompany each other, though pyrite is more abundant and a little more widespread than marcasite. Marcasite is commonest as very irregular grains, clumps of grains, and veinlets in pyrite. Some pyrite and marcasite are later than teallite and replace it along the cleavage and form pseudomorphs after teallite (Pl. 2, Fig. 1). In places the former teallite cleavage is shown by alternate thin straight bands of marcasite of different shades of yellow or of slightly different orientation. Some of the pseudomorphs after teallite consist of pyrite in the center and marcasite on the edges, the marcasite seemingly having replaced pyrite.

*Cassiterite.* Hypogene cassiterite is not abundant in either the tin or the silver veins. Though cassiterite is in many tin veins elsewhere an early mineral, at Carguácillo it was deposited late in the sequence. It occurs chiefly as needles (Pl. 3, Fig. 1), often in pinwheel-like clusters and as irregular grains, many of which are closely associated with galena where these two minerals have replaced teallite. Cassiterite cuts marcasite veinlets in galena cleavage cracks, replaces pyrite that is interstitial to teallite, and forms frames around arsenopyrite. A little cassiterite is disseminated in the walls near the veins.

Fine grained supergene cassiterite in small amount was detected in the oxidized ore. It replaces teallite and is accompanied by anglesite, jarosite, plumbojarosite, and limonite. Its supergene occurrence here as an oxidation product of tin-bearing sulphide is no support for the hypothesis of supergene cassiterite in ores of hypogene cassiterite.

*Franckeite.* (5PbS . 2SnS₂ . Sb₂S₃) Franckeite is present in silver ores as well as in tin ores but is not abundant in either. It occurs in very small wisps and feathery grains in wurtzite, sphalerite and galena. It is replaced by wurtzite, proustite, and probably by cassiterite.

*Galena.* Galena is a late and widespread mineral in both tin and silver veins but is nowhere abundant. It is almost invariably accompanied by cassiterite and appears to have been formed at the same time as much of the cassiterite by replacement of teallite. The distribution of galena bears no relation to the silver.

*Arsenopyrite.* Arsenopyrite in small quantity is widespread
in both teallite and silver veins. It occurs in very small euhedrons, usually wholly enclosed in wurtzite but in places at or near the border of teallite in relationships that strongly suggest that it is later than teallite (Pl. 1, Fig. 1). Arsenopyrite is cut by veinlets of pyrite and is both earlier and later than wurtzite.

**Proustite.** Proustite, which was seen only under the microscope, is present as small irregular grains most commonly at the grain boundaries of other minerals. Proustite is invariably accompanied by tin minerals. In the main the silver exceeds the amount accounted for by the proustite. Indeed, analyses show that silver is present in teallite and zinc sulphides where no silver minerals could be detected in polished sections.

**Quartz.** Quartz is the most abundant and widely distributed of the gangue minerals though all gangue minerals are subordinate to the metallic minerals in these veins. Persistent throughout the vein-forming period, quartz occurs in many textures, but most commonly it is medium to coarse grained and anhedral. Rarely it is exceedingly fine grained to fibrous and closely associated with a little chalcedony. In many sections euhedrons of quartz are scattered through the ore minerals or are bunched in vugs. Great differences in grain size may be seen in the same section, which in some places is caused by two generations of quartz. It has uniform to flamboyant extinction and is commonly clear but in a few places shows solid inclusions, the only identifiable ones being needle cassiterite.

**Siderite.** Although siderite is not very common, it is more abundant in tin veins than in silver veins. It occurs as fine grained, thin, reniform masses, coarse, flamboyant grains, and in good crystals lining vugs. Siderite is commonly a late mineral and in some places is present in two generations.

**Oxidation.**

Siderite and iron sulphides are converted to limonite or other iron oxides of light yellow to dark red color. In some outcrops the iron oxide shows a boxwork structure, but it was impossible to correlate this with a specific type of sulphide vein.

The zinc sulphide is easily dissolved during weathering. Analyses indicate that most of the zinc was removed from the
Galena (Gn) replaced by needle cassiterite (Cs). X150.

Remnants of teallite (T) in a band of pyrite-marcasite (Py-Mc). Wurtzite (W) and siderite (S) replaced by pyrite-marcasite. X30.
oxide zone but that most of the silver, formerly present in zinc sulphide, remained. The condition of the silver in the oxidized zone is not known, for no silver minerals were observed.

The effect of oxidizing solutions on teallite is of special interest. It is far more resistant than the associated sulphides and, in places, it persists as partly weathered residual flakes and platy aggregates surrounded by oxidation products of other sulphides. Under the microscope such partly altered teallite is seen to be replaced along the cleavage chiefly by anglesite, jarosite, plumbojarosite, and exceedingly fine-grained pale yellow cassiterite.

In only one section of oxidized ore was cassiterite seen which was clearly hypogene and residual. Here it occurred in sheaf-like bundles of needles embedded chiefly in jarosite. No sulphides were left in the section. Needle tin of exactly the same type and texture was seen in sections of unoxidized ore, but the cassiterite was surrounded by hypogene sulphides.

At several places in the Caraguaicollo district old dumps of oxidized teallite ore have been worked, and one owner reported that a test run of concentrates from 1000 sacks of material assayed 64 per cent tin, which indicates that the metal is present in cassiterite. Part of this may well be residual hypogene cassiterite, but much of it is probably supergene cassiterite.

**Origin.**

Not only is the mineral assemblage at Caraguaicollo unusual, but the sequence of deposition deserves attention, especially with respect to the time-temperature relationship. Certain minerals of the deposit, like pyrite, sphalerite, galena, quartz and sericite, have a wide range of persistence as stable varieties, whereas others possess a more definite temperature connotation. Arsenopyrite and, notably, cassiterite are commonly regarded as stable at relatively high temperature, whereas marcasite, alunite, proustite and probably wurtzite seem to be characteristic of lower-temperature deposits. The significance of teallite and franckeite is not so well established, as both minerals, in quantity, are confined to a small group of deposits of the Bolivian province. A statistical survey of the mineralogy of the Bolivian deposits, however, indicates that simple tin ores rich in teallite and franckeite belong at the low temperature end of the tin series. While the two minerals may
not be strictly of the low-temperature group, they clearly repre-
sent a less intense phase of deposition than cassiterite. Thus
the abundance of teallite at Carguaicollo, together with alunite,
marcasite, wurtzite and proustite, means that the main period
of deposition took place at relatively low temperature. But
the presence of cassiterite in the same ore points to a high-
temperature phase of deposition and a mild degree of that kind
of anomaly called telescopying.

The combination of minerals of low and high temperature is
of added interest in the sequence of deposition, which is so
clearly indicated by the unusual textures. By reference to the
microphotographs, particularly Plate 1, Figs. 1 and 2, it will
be seen how convincing is the evidence that the teallite ante-
dated the aggregate of minerals now included within its initial
crystal boundaries; and conspicuous among these later min-
erals that replaced the teallite is cassiterite. It seems nec-
essary to conclude, therefore, that in so far as these two min-
erals are concerned, the high-temperature mineral, cassiterite,
formed later than the low-temperature mineral, teallite. An
analogous interpretation presumptively applies to the teallite-
pyrite relation, as seen in Plate 2, Fig. 1, though the broader
temperature range of pyrite compared with cassiterite makes
this example less convincing than the teallite-cassiterite pair.
Association of galena with cassiterite in the pseudomorphs
after teallite does not embarrass the conclusion that the cas-
siterite is of high-temperature significance; important occur-
rences are known where the environment indicates that galena
formed at fairly elevated temperature, like the pyrometaso-
matic lead deposits and the lead-tourmaline veins.

By the conventional view, high-temperature minerals should
be early and low-temperature minerals late in the sequence, but
Graton has long advocated that hypogene "mineralization ordi-
narily proceeds on an ascending temperature scale, not a
descending one." His position is indicated in the following
generalization:

"Temperature of the solutions ordinarily declines from source
to outlet . . . although any given portion of the solution is con-
stantly losing heat as it ascends, the channelway wall at any given

Also Graton, 1940, for Bolivian tin deposits in general, Econ. Geol., 35
p. 296.
level and the deposit there formed are generally and for the most part subjected to rising temperature through continued flow of the solution . . .”

If the temperature significance of the several diagnostic minerals at Carguaicollo be accepted as approximately correct, and if, in particular, cassiterite be assigned a higher-temperature connotation than teallite, then it would appear that the association of high temperature and early deposition does not hold for this district, but that, instead, deposition occurred on a rising temperature scale. It will be recalled, also, that Turneaure encountered a similar sequence in the great and complex Llallagua deposits, where the early soft mineral, franckeite, was found strongly replaced, pseudomorphously, by minerals of higher-temperature significance, such as pyrrhotite, wolframite and arsenopyrite, as well as by pyrite-marcasite aggregates almost identical with those of Carguaicollo.

As reasoning, Graton’s hypothesis sounds unassailable; but when actually applied to given ore occurrences, support by the textural indications of timing is not uniformly so self-evident. At Carguaicollo, however, as well as at Llallagua, there are indications of deposition under rising temperature; both deposits lend support to Graton’s hypothesis.

The nature of the solutions with respect to alkalinity-acidity balance also deserves brief comment. Taken as a whole, the mineral assemblage tends to approximate in this respect the conditions “normal” in hypogene sulphide ores. The dominant alteration to sericite in the vein walls and the nature of many of the vein minerals are taken to indicate that the solutions, in the main, were of alkaline reaction.

But there are some hints that as deposition proceeded, there was a trend toward neutrality or even mild acidity. The evidence for this change is found in the scanty development of the sulphate mineral, alunite, and in the abundant deposition of marcasite and wurtzite, minerals which seem to be most stable in an environment neither highly alkaline nor highly acid. The pyrite-marcasite aggregates, closely resembling those so commonly developed from franckeite at Llallagua, are strikingly

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* The depth zones in ore deposition, Econ. Geol. 28, 521, 1933. The same idea is expressed in Graton’s paper on the ore fluid, Econ. Geol. 35, pp. 197-358, 1940; also in his paper with Bowditch on Cerro de Pasco, from which comes the quotation at the beginning of the paragraph, Econ. Geol., 31, p. 688, 1936.

† The depth zones in ore deposition, Econ. Geol. 28, pp. 44-45, 55-56, 1933.
similar to the product of known acid attack on pyrrhotite, as, for instance, in supergene alteration; and at Llallagua there was clear evidence that at least some of the franckeite was replaced by pyrrhotite before this, in turn, was converted to the hypogene pyrite-marcasite aggregates.

The mineralogical criteria thus imply rather than definitely prove a mild degree of acidity developed late in the depositional program. This change, furthermore, seems consistent with the thermal history outlined above and the moderate pressures likely to prevail in these relatively shallow and easily permeable deposits. If temperature rose during the mineral forming process while the pressure remained low, there would be, according to Graton, a tendency both toward the reaction producing $\text{H}_2\text{SO}_4$ and towards boiling, which tends to localize the acid forming constituents.

As with the question of the trend of temperature during mineralization, so with the change in composition of the solutions, we prefer to point out the possibilities rather than to urge definite conclusions.

There remains to be considered the precise genetic classification appropriate for the Carguaicollo deposit. The vuggy character of the ore, the banding and the finely crystalline druses point to deposition at shallow depth. This is entirely compatible with the narrow, well-defined veins and the texture of the associated intrusive, the dacite porphyry. The deposit belongs, therefore, in the near-surface zone, but it is not readily placed in a systematic genetic scheme such as the Lindgren classification. Lindgren, who had personal experience with several of the Bolivian tin occurrences, placed Llallagua and the mines farther to the north in the hypothermal class, while putting Potosí, Oruro and others to the south, including Carguaicollo, in the mesothermal category in the latest (1933) edition of his Mineral Deposits. Since that time, the useful and, we believe, valid class of xenothermal deposits has been established by Buddington, who includes in it the Llallagua deposits and certain tin deposits elsewhere. Moreover, in certain other directions, there has been some tendency toward a rearrangement of the groups established by Lindgren.

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9 Papers already cited.
10 High-temperature mineral associations at shallow to moderate depths, Econ. Geol. 30, pp. 205-222, 1935.
We adopt the xenothermal classification for Llallagua with its abundance of distinctly low-temperature and high-temperature minerals. Carguaicollo is surely of lower intensity, on the whole, than Llallagua and perhaps best classified as a tin-silver deposit of the epithermal class. Its somewhat conflicting characters, however, give it a suggestion of the xenothermal.

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