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to carbon tetrachloride to phenanthrene to anthracene, and since the difference in internal pressures between n-octane and solute is greater than between carbon tetrachloride and solute, we expect the deviation from ideality in octane to be greater. To give some idea as to the magnitude of internal pressures in non-polar liquids, the internal pressure of n-octane is about 2000 atmospheres/cm^2, and for super-cooled phenanthrene (liquid) at 25° it is 3550 atmospheres/cm^2.

The data of Henstock and of Hillyer and Vestling were all made by the analytic method, and they check reasonably well with the data obtained by the synthetic method. The synthetic method was checked by the writers for the solubility of phenanthrene in carbon tetrachloride at 25° by the analytic method, and the results were in very close agreement.

Carbon tetrachloride was chosen as solvent because its molecule is very nearly a perfectly spherical molecule as well as non-polar, and therefore it would apparently satisfy the requirements of regular solutions. N-octane was chosen because its molar volume is very close to that of liquid phenanthrene, n-octane having a molar volume of 158 cc., and phenanthrene 163 cc. at 25°. Also, no measurements of solubility in octane have been made before, and therefore the data are increasingly important.

STRUCTURAL GEOLOGY AT LLALLAGUA, BOLIVIA

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Location

Llallagua is located about 75 kilometers southeast of Oruro, Bolivia near the center of the Bolivian "Tin Belt." This "Tin Belt" is an area 800 kilometers long and 150 kilometers wide. It is situated where the axis of the eastern range of the Andes turns from northwest-southeast to north-south. (see fig. 1)

General Geologic Setting

In the northern part of the belt the tin ores are associated with monzonitic batholiths which intrude the Paleozoic and later sedimentary rocks. In the southern two thirds of the area the deposits are in and near quartz-latite and dacite volcanic necks and dikes. It has been shown by chemical and microscopic analyses that these different igneous rocks quite probably belong to the same magmatic province.

The northern tin deposits are of the "normal" cassiterite vein type, i. e., of hypothermal origin, associated with granitic rocks which have been greisenized near the lodes. The deposits in and near the volcanic necks are unusual when compared with most of the other tin occurrences of the world, for they are of mesothermal to epithermal origin. There is good physiographic evidence that the surface at the time of their formation — probably Miocene or Pliocene — was no more than 200 meters above the present surface. Some of these deposits are unusual also in having rich silver ores intimately associated with the tin. Llallagua is interesting in that it is thought to be a near-surface but high-temperature deposit in the midst of the low-temperature region.

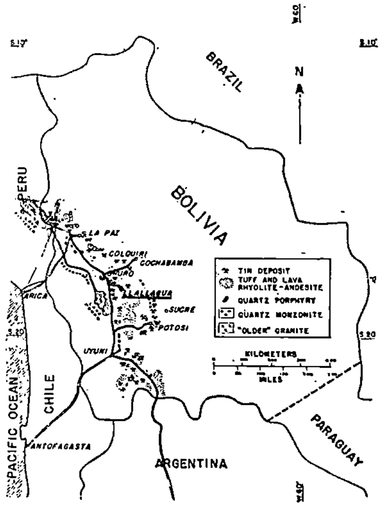


FIGURE 1. — TIN BELT OF BOLIVIA

Koeberlin,[1] Kittl,[2] and Ahlfeld[3] agree that there is a general gradation from deposits of tin, through those of tin and silver, to those of silver-lead-zinc which accompanies the gradation from the monzonite intrusives in the north to the quartz-latite and dacite volcanic necks and dikes in the south. The irregularities in this mineral-type gradation, such as that at Llallagua, Koeberlin explains by suggesting that the actual surrounding rock was probably not so important in the development of high or low temperature veins as the persistence in depth of the trunk fracture of fault which served as the channelway for the ascending mineralizing solutions. Even the monzonite would have to be cool enough to fracture before veins could form, but if the channelway were persistent enough, easy access to the source of the ore solutions would be permitted. It seems likely to the writer that another, perhaps more important, factor which may have influenced the development of an irregularity in the mineral-type gradation such as that found at Llallagua is the relative proximity of the typothetical, underlying source magma. In other words, Llallagua may be above an unusually high place on the roof of the supposed magma chamber.

Local Geology

The producing tin veins at Llallagua are almost entirely confined to a mass of quartz-latite porphyry which in plan at the surface has the shape of an ellipse with major and minor axes of 1500 meters and 1000 meters respectively. (fig. 2) In cross section this

[1] Koeberlin, F. R.: Geologic features of Bolivia's tin-bearing veins, Eng. & Min. Jour., vol. 121, 1926, pp. 636–642.

[2] Kittl, E.: Estudios sobre los campos de existencia de la cassiterita en Bolivia, Revista Minera de Bolivia, vol. 3, 1928, pp. 97–118, 225–244, 257–280.

[3] Ahlfeld, F.: The Bolivian tin belt, Econ. Geol., vol. 31, 1936, pp. 48–72.

mass of porphyry is roughly funnel-shaped. Although there are minor irregularities, the contacts dip inward at about 70 degrees. The major axis of the ellipse is parallel to and about 500 meters to the west of the axis of a northwest-trending anticline. The west limb of this anticline dips from 60 to 90 degrees to the west while the east limb is overturned in places so that the dips of the beds vary from 90 degrees to 30 degrees to the west.

The oldest sedimentary rock exposed in the district — that which outcrops along the axis of the anticline — is a dark gray, massive rock which locally shows spheroidal weathering. It was called "greywacke" in the field, but under the microscope Turneaure[4] found it to be an impure, sericitic quartzite. Its entire thickness is not exposed, although in places about 800 meters is shown.

Overlying the greywacke with a slight angular unconformity is the Llallagua formation which consists of buff-colored, well-cemented, medium- to coarse-grained sandstone in beds 10 to 50 meters thick interbedded with thin brownish shales. The thickness of the formation varies from 110 meters to 400 meters in the area adjacent to Llallagua and has an average of about 250 meters.

Comformably overlying the Llallagua is the Pampa shale which usually shows at least 1000 meters' thickness of light to dark gray, nonfossiliferous shale with occasional thin beds of buff-colored sandstone.

The next overlying formation is a light tan, thinly-bedded sandstone about 40 meters thick which carries a few brachiopods. F. R. Koeberlin, in a private report to the old Cia. Estanifera de Llallagua written in 1919, described these fossils as of Devonian age.

The next and youngest sedimentary formation exposed in the area near the mine is about 100 meters of reddish-brown conglomerate and sandstone which may have a slight unconformity with the underlying Devonian(?) sandstone. It outcrops only along the axis of a syncline which is roughly parallel to the anticline described above. These redbeds are similar to those near Potosi which are said to carry a Cretaceous fauna.

As mentioned above, the quartz-latite porphyry neck roughly has the shape of a funnel as shown throughout the 700 meters of vertical extent exposed by the mine workings. Near its contacts the latite contains abundant fragments of the sedimentary greywacke which adjoins it throughout most of its exposure. A study of most of the exposed contacts in the mine and on the surface showed no evidence of a chilled border, and only a very feeble contact metamorphism — at the most only about five centimeters of "baked" hornstone. These three features suggest the possibility that the latite is a volcanic neck. There is no evidence at Llallagua to contradict the assumption that the latite is of the same age as other Bolivian volcanic vents which are known to be late Tertiary. There are a number of

[4] Turneaure, F. S.: Tin deposits of Llallagua, Bolivia, Econ. Geol., vol. 30, 1935, pp. 14–66, 170–190.

dikes of quartz-latite, most of them intruding the sedimentary rocks near the prolongation of the major axis of the main intrusive and parallel to it.

Many of the ridges in the neighborhood of Llallagua are capped by a horizontal bed of tuff about 30 meters thick. This tuff can be traced almost to Oruro. It lies on the late Tertiary plateau surface which has been dissected by the present drainage system. It is later in age than the latite as will be shown below, but it is probably of the same volcanic epoch.

Fracture Pattern in the Mine

The veins have in general a northeast trend, but they fall into two groups as shown in figure 2. The majority of them strike about N25E and dip steeply in either direction, while a few of them strike about N70E. The picture given by figure 2 is slightly misleading, for many of the N25E veins are too small and noncontinuous to be shown on a map of that scale. All the veins have abnormal segments, many of which strike N20W. The wider, more persistent veins are easy to follow in the mine, but many narrower ones form an intricate, interlacing, branching system. All of these fractures are of pre-ore age, for all have been mineralized.

There is some post-mineral faulting indicated by offsets of the mineralized fractures and by ore breccia. The main post-mineral faults are parallel to the short N20W segments of the veins, but some of the N70E veins have slight evidences of post-ore movement such as ore breccia. Such an occurrence may indicate continued before, during, and after mineralization.

Most of the N25E veins are nearly vertical, have tight filling, and are not persistent either along the strike or down the dip. They are, in fact, typical tension fractures. Some of the N70E fractures, especially those few which show slight post-mineral movement, and all of the N20W post-mineral faults show slickensides, tough leathery gouge, and brecciation. All of these features indicate movement, perhaps due to shearing stresses. Such a pattern (see figure 2) shows no relation to the boundaries of the porphyry, and probably is not due to the cooling and shrinking of the igneous mass.

There is a similarity between the pattern of the veins and that developed experimentally by Dr. W. J. Mead who subjected a rubber sheet, coated with paraffin made brittle by chilling, to a shear couple. Dr. Mead, in describing the results of the experiment says [5] "The first fractures to appear at any one locality on the rubber sheet are usually tension cracks inclined about 45 degrees to the direction of shearing movement. These are at right angles to the direction of maximum elongation and appear as vertical open cracks. They are followed immediately by two sets of vertical faults with horizontal displacement, one set striking parallel to the direction of

[5] Mead, W. J.: Notes on the mechanics of geologic structures, Jour. Geol., vol. 28, 1920, pp. 512–513.

movement and the other parallel to the free edges of the rubber sheet. These represent two directions of non-distortion, or two shear planes developed by the shearing movement in which direction of relief is in the plane of the paraffin layer."

Dr. F. S. Turneaure (op. cit.) first suggested the similarity between the vein pattern at Llallagua and that developed by Dr.

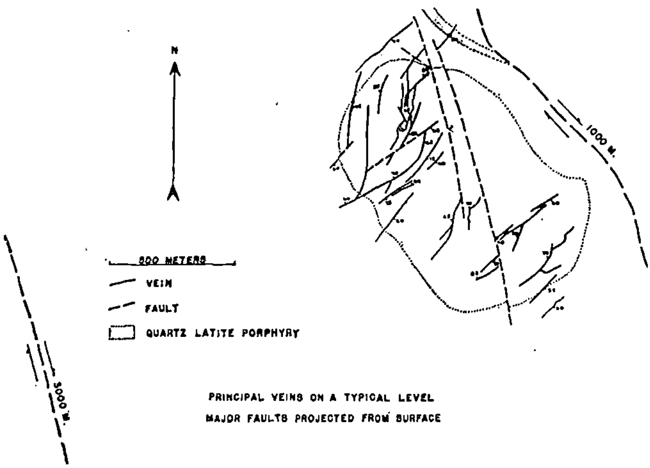


FIGURE 2. — FRACTURE PATTERN IN MINE

Mead. In studying his maps of the mine and of the surface immediately above the mine, he came to the conclusion that the fact of tensional failure indicated by the N25E veins suggests that a shear couple may have acted at an angle of 45 degrees to their strike. He further concluded that the N70E veins, some of which show evidences of shearing, are representative of those faults described by Mead as "parallel to the direction of movement." Although he recognized that the N70E veins are characterized by abrupt changes in strike which seem to deny the existence of any great lateral movement, he apparently did not have sufficient data on the district as a whole to consider the possibility that a N20W direction, which is also at 45 degrees to the N25E trend of the tension cracks, might represent the direction of the major shear. He considered that while the N20W structures have the required strike to constitute one of the sets of shear planes developed in the experiment, they are poorly developed in the mine area except in the short segments of the major veins and in the faults running through the center of the porphyry (fig. 2). Since these faults involve post-ore movement, he thought that they might be of much later, perhaps independent origin.

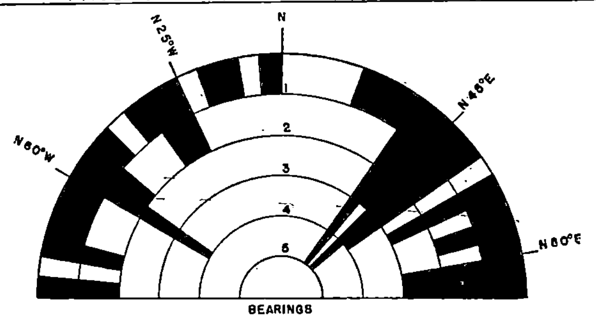
Fault Pattern of the District

During 1933 and 1934 the writer had the opportunity to spend a year in mapping the surface around Llallagua; the following discussion is based on that study. In figure 2, two major faults mapped by the writer have been projected to Turneaure's plan of the principal veins on a typical mine level. The broken lines indicating these major faults may be seen crossing the plan in a northwesterly direction, one in the northeast corner, the other in the southwest corner of the plan. Due to the fact that more than 75% of the surface area mapped is outcrop, the actual movements along these two fault planes has been worked out quite closely. In calculating the movement of the one crossing the northeast corner of figure 2, it was possible to correlate across it two earlier faults and a dike as well as three sedimentary beds. The displacement was found to be 995 meters almost exactly in a horizontal plane. This fault has tough leathery gouge and causes an overlap of the sedimentary beds. It is unlikely to be due to tension. The other major fault, which dips about 70 degrees to the west, has a displacement of approximately 2800 meters along a line inclined about 20 degrees to the horizontal. If these faults are related to the shear which caused the vein fractures, their direction is quite likely to be that of the main shearing movement, for they are the major faults of the district. The "thousand meter" fault is definitely later in age than the porphyry since it offsets a dike of the same rock and age as the main body of the porphyry. In attempting to decide whether or not these major faults are related to the stresses which formed the vein pattern, the main problem was to decide the relative ages of the various faults and whether or not some or all of them are later than the veins. From relations established in many places in the district, they are all known to be later than the porphyry.

Figure 3 is a diagram showing the number of faults, for which the relative ages are known, whose bearings fall in each five degree segment of the compass. It can be seen that there are certain concentrations in various parts of the diagram. There is a northeast group, an approximately east-west group, and two northwest groups. These four groups are found to have the following averages: N45E, N80E, N25W, and N60W. Most of the N60W group have low-angle dips; a number of them cause overlapping of the sedimentary beds which they offset. They may represent a compression type of which only two were developed in Dr. Mead's experiment (op. cit.). These two were in the form of "thrust faults striking approximately at right angles to the tension cracks and inclined approximately 45 degrees, dipping in either direction." The N45E group is composed of steeply dipping faults most of which cause a gap between the faulted segments of the sedimentary beds which they offset, and are probably due to tension. The faults of the N80E group have no distinguishing features except that they are fairly persistent. Although the N25W group is not large in numbers, the faults of this group are the most persistent of the region and cause the greatest displacements. The "thousand meter" fault, for instance, was traced for nine kilometers, the entire length of the area mapped, and appeared to continue in both directions. The average displacement along the eight faults of this group is about 800 meters.

While there is considerable variation in strike among the faults which have been grouped together, it is felt that there is a definite grouping with no more variation than would be expected in view of the fact that the faults in question traverse a series of nonhomogeneous sedimentary rocks. Actually, a study of the photographs illustrating Dr. Mead's article show that there is almost as much variation in the experimental case with homogeneous paraffin as in

FAULTS OF KNOWN RELATIVE AGES



GROUP	TOTAL NUMBER	YOUNGER THAN N 25° W	OLDER THAN N 25° W
N 60° W	12	1	11
N 45° E	20	4	16
N 60° E	15	5	10

FIGURE 3. — FAULT PATTERN OF DISTRICT

the case of the vein pattern at Llallagua. Those faults which are most consistent in strike are those of the N25W group which parallel the axis of the anticline and consequently stay in the same formation for long distances.

Since the faults of the N20W group in the mine are known to be in part post-mineral, a table has been made giving the number of faults of each other group which are known to be older or younger than one or more of the N25W group. This table is shown in the lower part of figure 3. From the table it can be seen that although most of the faults of the other groups are older than one or more of the N25W group, there are faults in each of the other groups which are known to be younger than at least one of the N25W classification. This fact suggests that if a shear couple were at work, it continued for some time with an overlapping of the development of the different groups of faults. This idea is not inconsistent with Dr. Mead's observations. It may indicate that the stress was active before, during, and after mineralization.

In considering whether or not the majority of the N25W structures developed after the mineralization, the writer was impressed by a point made by Dr. Turneaure. He says in regard to a typical case (op. cit., p. 22), "Pre-mineral fracturing is clearly illustrated. . . . ; the . . . vein shows an abrupt change in strike, but detailed mapping reveals barren clays as the southeasterly continuation of one segment and pyritic seams as the northeasterly continuation of the other." The point which comes to mind is that the development work in the mine naturally follows ore, so that the northwest-southeast "barren clays" may be much more persistent than the mine openings would indicate. It is only to be expected that fractures in this direction, if they should be parallel to the direction of main shearing stress, would be tighter and less susceptible to mineralization than the northeast-striking tension cracks. Another point in regard to the age of these faults is that all the various groups of faults mentioned are older than the volcanic tuff. They all pass beneath the tuff without disturbing it. In one case a N60W fault has such a relationship with the tuff although it is known to offset a N25W fault which in turn offsets earlier northeast faults one of which cuts a latite dike. This occurrence indicates three ages of faulting, one of them of considerable magnitude, between the time of the intrusion of the porphyry and that of the deposition of the tuff. These relations prove that the tuff is later than the porphyry and may suggest that it is later than the mineralization. If the tuff is of the same general volcanic epoch as the latite neck, it seems reasonable to postulate a process of formation for the various ages of faulting whereby one continuous progressive shear can account for all the features rather than suppose three complete readjustments in the conditions during the comparatively short geologic time between the intrusion of the latite and the deposition of the tuff.

Conclusion

In conclusion, it has been shown that the fault system of the Llallagua district and the fracture pattern shown by the veins of the Llallagua tin deposit probably were both developed within the comparatively short geologic time between the intrusion of the porphyry which contains most of the tin veins and the deposition of the related volcanic tuff. Although there is some difference in the trends of the two systems, there is probably no more variation than would be expected in the development of failure cracks and shear planes in a series of nonhomogeneous rocks when subjected to shearing stress.

It is postulated that the main direction of shear was probably about N25W with the west side moving relatively to the north as indicated by the arrows on the major faults in figure 2. The numerous N25E veins are thought to be the result of the filling of tension cracks roughly at an angle of 45 degrees to the direction of maximum shear. The more persistent, but less numerous N70E veins, some of which have a gouge selvage and brecciation indicating movement, are thought to correspond to the second set of shear faults noted by Dr. Mead in his experiment. The N20W segments of the veins are thought to be due to the filling of the early openings along the direction of maximum shear, while the post-mineral faults, notably those striking N20W, and to lesser degree some of the N70E structures, are thought to be due to the continued application of the same stress. The low-dipping N60W group of faults evident in the district as a whole probably are of the compression type mentioned by Dr. Mead as being approximately perpendicular in strike to the tension cracks. It seems likely that the faults of the district and the fractures filled by the veins in the tin deposit were both caused by the same progressive shearing stress acting in an almost horizontal plane.

PERIOD OF OSCILLATION OF A THYRATRON CIRCUIT

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In the course of a series of experiments requiring a constant rate of interruption of continuous radio signals, considerable trouble was experienced with strays generated by mechanical methods of interruption. At the suggestion of Dr. H. E. Hartig of the University of Minnesota, a circuit was used in which a thyratron tube with a condenser-resistance unit in its plate circuit produced periodic discharges across the condenser. The present paper deals with the theory of the interrupting circuit which is shown in detail in Figure 1. To use this circuit for interrupting an oscillator, the resistor in the plate circuit of the thyratron is connected to the grid circuit of the oscillator.

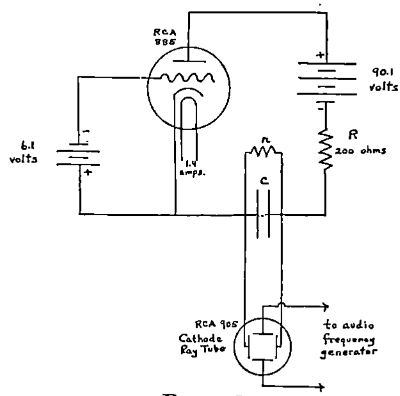

FIGURE 1

The 885 thyratron is similar to an ordinary triode in structure but is filled with neon gas under low pressure. The gas ionizes when the plate voltage becomes sufficiently great. By actual measurement it was found that with a grid bias of — 6.1 volts and a heater current of 1.4 amperes, ionization would occur when the plate voltage reached 54 volts and deionization when the voltage dropped to 17 volts. When ionized, the