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GEOLOGY AND ORE DEPOSITS OF THE COLLBRAN CONTACT OF THE SUAN MINING CONCESSION, KOREA.¹

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INTRODUCTION.

In the Suan Mining Concession granitic intrusions have intensely metamorphosed a series of sedimentary rocks and resulted in the formation of deposits of copper, bismuth and gold. Some of the phenomena associated with the intrusion, metamorphism, and ore deposition are considered in this paper.

¹ Published with the permission of the Seoul Mining Company.

The general location of the Suan Mining District is in Central Korea (Fig. 1), about fifty-five miles east-south-east of the city of Pyeng Yang, Korea, approximately in latitude $38^{\circ} 48'$ north, and longitude $120^{\circ} 20'$ east. The Suan Mining Concession held

FIG. 1. Map of Korea showing the general location of the Suan Mining Concession and the principal towns.

by the Seoul Mining Company (recently seized) covers an area of 40 by 60 Korean *li*, about 260 square miles. The camps are reached by government and company roads from Pyeng Yang. The generally rugged nature of the topography of the concession is indicated in Plate I., *A*. The maximum difference of elevation on the concession is about 3,500 feet. The climate blends the characteristics of semi-tropical and north temperate conditions.

There is a rather heavy rainfall in the summer; while spring, autumn, and winter are comparable with those seasons in Ohio.

GENERAL GEOLOGY.

The general geologic features of the district are, briefly: a series of sedimentary rocks intruded by a granite batholith. The contact principally concerned (Fig. 2) is irregularly elliptical in outline with a periphery of about 21 miles, not taking into ac-

FIG. 2. Suan granite and the Collbran contact. The position of placers, and prospects are indicated.

count the irregularities. The major axis of the ellipse extends in an east-south-east direction. The invasion of the granite has uplifted and pushed aside the overlying and surrounding rocks with tremendous force. Erosion has exposed the mass, showing a rim of the upturned edges of the sedimentary rocks around the granite. In the immediate vicinity of the granite the sediments

have been metamorphosed more or less profoundly into hornfels, schist, marble, and other metamorphic types. In some of these metamorphosed rocks ore deposits containing copper, bismuth, and gold have been found. The granite core forms the highest part of the concession, and hence the drainage is roughly radial from the center of the massif. Streams crossing the contact between the granite and the sedimentary rocks, where gold values are present at the contact, carry the metal downstream across the upturned edges of the sedimentary rocks which form excellent natural riffles. The Koreans have worked these placers for the old Korean Household Department for centuries.

Sedimentary Rocks.—There are at least two sedimentary series on the Suan Concession. If the gneiss of the western part of the concession be of sedimentary origin, there are three series. This Siroo Pong San gneiss (the name being derived from the mountain where it is extensively developed) is the oldest rock on the concession; and over it and complexly folded into it are certain schists and a thin quartzite. These latter rocks are the oldest definitely sedimentary series of the area.

The second series, which detailed study would doubtless show to comprise two series, is composed of limestones, slates, and quartzites. The intricacy of the structure in the immediate neighborhood of the Collbran contact is such that no definite

FIG. 3. Showing the contact north of the Tul Mi Chung.

FIG. 4. Diagrammatic section through a part of the Tul Mi Chung mine.

sequence can be decided upon except from general field relations. Fossils are lacking; the batholith cuts across the sediments irregularly (see Fig. 2), and the Hol Kol limestone invariably underlies the Suan slates. This is shown in section in Figs. 3 and 4.

In general the field relations show the Hol Kol limestone to be closer to the batholith than the Suan slates.

Assuming then that the oldest sediments are the nearest to the intrusion, all being upturned about its edges, we have in order from oldest to youngest: Hol Kol limestones, Suan slates, quartzite (with a little conglomerate), Tul Mi Chung limestone, and Tong Am limestone. The Suan mine and the Tul Mi Chung mine are in the Hol Kol limestone. This is the only limestone surficially in contact with the granite. The Hol Kol limestone is in part pure calcite, in part magnesian (but this point needs to be definitely established by analyses), and in no place is it very siliceous or argillaceous, though "blue limestone" is abundant. Near the contact, the limestone is usually a marble, characteristically saccharoidal.

Igneous Rocks.—In order of age the igneous rocks are as follows: the dolerite from its metamorphosed appearance in the field and under the microscope is considered to be older than the main granite intrusion; originally it was a gabbro composed almost entirely of augite, plagioclase at least as calcic as oligoclase, and ilmenite. Almost all of the augite has been altered to hornblende (uralite), and the plagioclase to chlorite, quartz, and other alteration products. The ilmenite has been partially altered to leucoxene.

Near the western part of the contact are certain dikes and stocks. The Tong Am quartz-diorite dikes, closely related to the "Weigall granite" referred to later, are doubtless one of the last phases of the intrusion of the Suan granite. These dikes, strangely enough, have exercised the strongest metamorphic influences observed on the concession. They carried large amounts of mineralizers and metallic sulphides including molybdenite in considerable amount. Molybdenite was not seen elsewhere except in very small amount at Peh Wha.

Certain other granites and diorites of this western part seem to be older than the Suan granite, which is the main intrusive.

Weigall Granite.—The "Weigall granite,"² the so-called "sye-

² So named after Mr. A. R. Weigall, who first (in 1913) identified the rock as being closely associated with the ores in the lower level of the No. 2 cross-cut tunnel at Tul Mi Chung.

nite," occurs in large and small dikes in the workings of the Tul Mi Chung mine (see Fig. 4). There it is without doubt closely connected with the origin of the ores. Microscopic study shows the rock to vary from a quartz monzonite through a quartz diorite to a mica diorite. The average composition is probably that of a quartz-biotite diorite. It is probably an offshoot of the parent magma of the Suan granite intruded shortly after the main mass, but before any great cooling had taken place. Locally through alteration the rock has developed a dirty white or buff color. The biotite was the last of the minerals to succumb to this alteration, and in some places a limey-looking rock with numerous black or brown mica flakes in it marks this stage of the alteration. The alteration has occurred along and out from cracks and small faults in the formation (Fig. 5); and it has

FIG. 5. Vein of calcite in quartz-diorite in the Tul Mi Chung mine.

proceeded so far in many places that the product cannot be recognized as having been derived from the diorite without tracing the intermediate stages. At present the writer can only advance the hypothesis, which seems to be supported by all the evidence available, that the alteration of this igneous rock has been caused by the circulation of hot water through fissures, and presumably given off by the main Suan granite, or possibly, in part, by the "Weigall granite" itself during cooling. These waters were of first importance in the deposition of the Tul Mi Chung ores. In fact, it seems not improbable that a part of the ore has been deposited in a highly altered phase of the diorite.

Suan and Other Granites.—The Hol Kol granite and the Tul Mi Chung quartz-porphyry and tourmaline granite are stocks

which were intruded soon after the main granite. Tourmaline indicates the presence of mineralizers. They are in all probability differentiation products of the parent magma, occurring significantly close to ore deposits. The Chil Sing Dei granite (later granite, Fig. 2) is of the same type as regards origin, but is entirely surrounded by the Suan granite. The possibility must not be overlooked, however, that the Chil Sing Dei granite may have been the primary stock subsequent to the solidification of which the Suan granite may have been intruded. Certain aplite dikes were both precursors and followers of the great intrusion. They do not appear in connection with ores except at Sang Dai, the eastern prospect of the contact (see Fig. 2). The Suan granite itself appears in two principal masses, one being the Unjinsan massif batholith which occupies an area of about thirty square miles; and the other the granite boss of An Ka Roo Kai (Fig. 2) occupying an area of about $\frac{1}{4}$ square mile. The general shape of the intrusion (Fig. 2) is elliptical, five by eight miles. The long axis extends in a west-north-west, east-south-east direction, which seems to be the general orogenic axial direction of the region. At no place has the writer observed the contact to dip toward the granite, but a local bulge may have caused such a condition to develop in some restricted localities. The average dip of the contact varies from 30° to vertical. About 60° is most common, but great variations occur (see Fig. 6).

The Suan granite is porphyritic in texture, about 5 per cent. being phenocrysts of orthoclase from $\frac{1}{4}$ inch to 3 inches in size and the remainder a rather coarsely granitoid ground-mass. The phenocrysts are very commonly in the form of Carlsbad twins which in places weather out so as to show the characteristic form of this combination. The phenocrysts are never free from small inclusions of biotite, quartz, and hornblende.

The ground-mass of the Suan granite is made up essentially of plagioclase, orthoclase, quartz, hornblende and biotite. The comparatively large amount of plagioclase and of ferro-magnesian minerals indicate that this is not a true granite, but that it has dioritic affinities. Its true name should be a tonalite-

porphyry; but the term granite has here been used. The plagioclase is oligoclase with an average composition close to $\text{Ab}_{82}\text{An}_{18}$ as determined microscopically; but the composition varies slightly in different parts of the intrusion. The accessory minerals noted were titanite, apatite, magnetite, and zircon.

About the periphery of the granite, dikes of basalt varying from a few inches to seven feet in width, and from a few hun-

FIG. 6. Diagram showing present and hypothetical former section at the Suan mine. The actual structure is more complicated than shown in figure.

dred feet to half a mile in length, are of frequent occurrence. There is also a small area of basalt of slightly more than an acre in extent in the Morachi Valley southwest of Hol Kol. This basalt is the youngest igneous rock of the contact area. It is doubtless older, however, than the basalt of the lava plains of Korea, one of which lies a number of miles to the southeast of the concession. The basalt cuts both granite and sediments, and seems to have been intruded shortly after the solidification of the granite.

Metamorphic Rocks.—The metamorphic rocks are the granite gneiss of the Siroo Pong San massif with its associated schists and quartzite, all products of regional metamorphism; the hornfels, schist and marble, and garnet-epidote-actinolite, diopside-phlogopite-garnet, diopside-vesuvianite, wollastonite-tremolite

(?), collbranite (a highly ferriferous pyroxene), and similar complicated mineral aggregates, in many places highly metalliferous, were formed by the contact metamorphism of the Suan granite.

Geological Record.

Certain red conglomerates exposed some distance southwest of the concession, along the railway from Pyeng Yang to Seoul, may, because of the lack of fossils, be correlated tentatively with the red Yung Ning sandstone and quartzite of the Liaotung Peninsula, determined by Blackwelder³ to be of Cambrian (basal) age, and also correlated by him with the Man-t'o (lower Cambrian) of Shantung and Shansi provinces, China. They have been identified by the present writer in Chili province. If this suggested correlation be correct, there can be no doubt that the sedimentary rocks of the Suan Concession are of pre-Cambrian age. They are provisionally classified as follows:

Siroo Pong San granite gneiss	Archean.
Schist and quartzite of Siroo Pong San region ..	Early Proterozoic.
Hol Kol limestone, Suan slates, Tul Mi Chung quartzites, etc.	Later Proterozoic (possibly Nankow ⁴).
Suan granite intrusion with formation of ore- deposits	Close of Mesozoic.

Paleozoic sediments, now completely removed from the area of the concession, are to be found about Pyeng Yang; hence, it seems certain that these Paleozoic rocks once extended over the area described, but they have been removed by prolonged erosion.

The Siroo Pong San massif seems to be a dome beneath the center of which one may suspect there is another batholith similar to the Suan granite, but not yet exposed by erosion. Carbonated springs and certain zinc and lead veins are suggestive of this hypothesis. No granite similar to the Suan granite is to be seen in Korea in this latitude. The "Korea granite" of von

³ Willis and Blackwelder, "Research in China," Carnegie Institution of Washington, 1903-4.

⁴ *Loc. cit.*; Geology of Shansi Province.

Richthofen, so abundant in Korea, is non-porphyrific, and is chemically different, being more acid than the Suan granite.

ECONOMIC GEOLOGY.

Geologic Relations.—In general the dip of the sedimentary rocks along the Collbran contact is quaquaversal. Near Tul Mi Chung there is an important exception to this rule (Fig. 4). This condition seems to have been developed by the great opposition to the Unjinsan uplift by the Siroo Pong San massif in the western part of the concession, which also was being uplifted probably at the same time. Here the contact is very steep, in some places vertical, and the slate dipping toward the granite has had its edges resorbed by the granite (Fig. 4). Contact metamorphism has profoundly altered some of the rocks bordering the granite. During an early stage of the metamorphism silicates were developed, and at a later stage the sulphides and metallic gold-silver alloy were deposited.

The part which weathering has played in the formation of the ore deposits of the Suan Concession is somewhat problematical. There is very little secondary concentration at the Suan mine. In the western ore-body a small amount of secondary chalcocite was observed. The second period of deposition of chalcopyrite may be due to the action of surface waters. On the other hand, at the Tul Mi Chung mine, secondary concentration is very evident. The lack of secondary concentration at Hol Kol is no doubt largely due to the rapid run-off caused by the steepness of the slopes. Surface leaching penetrated several fathoms, but even stains of malachite do not occur at depths of over 100 feet in the eastern ore-bodies. Chalcocite films were seen at a depth of about 200 feet in the western ore, where topographic and structural conditions are more favorable for the retention of rain-water.

Ore Deposits (Suan Mine).

Form and Structure.—At the Suan mine at Hol Kol there are two distinct types of ore in two distinct groups of ore-bodies, known as the western and the eastern groups respectively. The

western group includes the locally known "western ore-body"; and the eastern group the locally known "central ore-body" and the "eastern ore-body" with its "north split" and "south split."

The ore-bodies of the western group are tabular or lenticular in form and occur on the great fault zone which extends along the west side of the Hol Kol valley (Fig. 7). The ore-bodies of the eastern group are far more irregular, and occur in a series of interlocking fault zones which make up one large zone about parallel to the contact and approximately at right angles to the west fault (Fig. 8). In this zone the last movement was down-

FIG. 7. Diagram of the western group of ore-bodies, showing the mineralized zone at the Suan mine, looking south.

FIG. 8. Diagram of the eastern group of ore-bodies, showing mineralized zone at the Suan mine.

ward about 30° towards the south, and was probably caused by a settling of the granite in cooling. As a whole the zone dips 60° – 80° toward the contact in the upper levels, but is about vertical in the lower levels of the mine. The western zone dips 50° – 60° to the south, and extends into the granite; while the eastern one runs about parallel to the contact. Distinctive minerals of the western group are tetrahedrite and dolomite, which

occur with the other ore and gangue minerals. Sphalerite and galena may also belong to this category, as they were not certainly recognized in the eastern group. Tetrahedrite and dolomite are never found in the eastern group.

Genesis.—It is clear from both structural and mineralogical evidences that the ores of the two groups have originated differently from the same magma. The ore of the western group was deposited from gold-silver-copper-iron-zinc-lead-antimony-bismuth-magnesium-bearing solutions working up and laterally along the fault zone from the granite into the limestone. The deposits are in the limestone hanging-wall, none having been found in the hornfels foot-wall. Certain silicates, such as diopside and phlogopite, had been developed prior to the deposition of the sulphides. The ores replaced the calcite in preference to these silicates, and filled fractures. Minute veinlets of chalcopryite constitute the last stage of the mineralization.

In the eastern group, gold-silver-copper-iron-bismuth-bearing

FIG. 9. Drawing to scale from hand specimen, showing selective replacement of calcite rather than diopside by chalcopryite.

solutions, emanating from the granite, passed upwards along the complicated channels of the fault zone. Calcite was most easily replaced (see Fig. 9), but phlogopite and diopside (see Plate

I., B) were also extensively replaced. The solutions altered the wall rock to a much greater extent than in the case of the western group. The presence of pyrrhotite as an important sulphide of the eastern group must also be emphasized.

Paragenesis.—Briefly, the order in which the sulphides and gangue minerals of the second period of mineralization of the two groups of ore-bodies seems to have been as shown in the following table. The observations were made at depths of between 150 and 400 feet below the present land surface.

WESTERN GROUP.

Primary.

1. Tetrahedrite.
2. Tetrahedrite, sphalerite, and galena.
3. Chalcopyrite, bismuthinite, and gold-silver alloy; bornite.
4. Dolomite.
5. 2d chalcopyrite.
6. Calcite and quartz.

Secondary.

1. Chalcocite.

EASTERN GROUP.

Primary.

1. Pyrite.
2. Pyrrhotite, chalcopyrite, and bornite.
3. Chalcopyrite, bismuthinite, and gold-silver alloy.
4. Gold-silver alloy and bismuthinite.
5. 2d chalcopyrite.
6. Calcite (and a little quartz).

Secondary.

1. Chalcopyrite.

Overlapping is indicating by repeating the mineral species, so that the metallic content of the depositing solutions is evident for each period. The mineralization proceeded more or less uniformly, and the table does not mean to convey the idea that there was necessarily an abrupt change in the solutions at the tabular divisions. The mineralization of the eastern ore-group of the Suan mine seems to be characteristic of the whole Collbran

contact, with the probable exception of some of the Tul Mi Chung ore, which the writer did not examine in detail. It contains abundant galena and hematite, and has been modified by meteoric waters.

SPECIAL CONSIDERATIONS OF A THEORETICAL NATURE.

Mechanics of the Intrusion.

The method by which so vast a body of rock as the Suan granite could have dispossessed the overlying rocks of their posi-

FIG. 10. Sketches to scale from drifts at Peh Wha prospect, Suan concession, at a distance of about 200 feet from the contact.

tion is of great speculative interest. Field observation shows that it was largely by forcing aside the surrounding and overlying rocks. Shortenings actually measured in the field were to $\frac{1}{3}$, to $\frac{1}{4}$, to $\frac{1}{6}$, and to $\frac{1}{10}$ of the original length of the strata (see Figs. 10 and 11).

If the shortening be assumed to have been the same on each side of the granite, there would be $2\frac{1}{2}$ miles to account for. As a matter of fact, there would be a little more, on account of the turning up of the edges of the country-rock due to the dragging wedge-like action of the inclined sides of the batholith. Assume that there are three miles to be accounted for on each side of the intrusion. Three miles could be accounted for in:

- about $\frac{1}{3}$ mile for a shortening to 1:10,
- about $\frac{1}{2}$ mile for a shortening to 1:6,

about 1 mile for a shortening to 1:3,
 about 1½ miles for a shortening to 1:2,

in which the shortening expresses the ratio of final to original lengths. It appears from the actual measurements taken that, even allowing 50 per cent. for such deformation as antedated the intrusion, there is ample room with a shortening of 1:2 to account for the space occupied by the granite in a reasonable dis-

FIG. 11. Reduction from a direct tracing from rock showing the deformation at about 200 feet from the contact with the Suan granite. The crooked lines indicate bedding.

tance on the hypothesis of deformation alone. Allowing 50 per cent. for such ancient deformation, we would assume the very low shortening of 2:3. It would then require six miles to account for three miles shortening. This seems to be a fair average distance, as observed in the field, over which deformation extends from the granite. However, as shown by the above measurements, the greater part of the three miles shortening is easily to be accounted in the first three miles from the contact.

In addition to this evidence favoring deformation of the country as the principle method of advance of the magma, there is most decisive evidence that resorption, or solution of the enclosing rocks took place.

Process of Resorption.

Along the Collbran contact at certain places there is very definite record of resorption having been active at the time of the intrusion of the magma. Fig. 4 illustrates the conditions at the best exposures showing this phenomenon. It was noted in the field that the limestones along the contact showed none of this, but that it was confined to the hornfels and slate areas. It was also noted, however, that in the granite, as far as half a mile from the contact, were in some places patches of pure garnet, in appearance like grossularite, up to an acre in extent; and it may be that these are the results of intense action on limestone blocks, and that silicification most readily explains the occurrences. Unaltered limestone blocks were also seen in the granite.

Unfortunately the writer has not had facilities for the careful microscopic and chemical work necessary to go into this matter of resorption closely. He can record only what he saw in the field.

The hornfels, toward the intrusive, becomes coarser and coarser in grain. The biotite and (or) phlogopite flakes increase in size, but finally disappear and give place to a highly siliceous "augen"; in its place appears a much smaller amount of biotite of different habit, and orthoclase. The augen containing almost invariably small amounts of black tourmaline, euhedral orthoclase and quartz which tend to form with crystal faces seem to have grown into bands and bodies, coalescing until the whole rock took on the general aspect of the granite.

Blocks of the hornfels can be seen in all possible stages from those practically unchanged and plainly showing bedding, to a mass indistinguishable from the granite. In this change there is a pronounced lightening of the color of the substance changed, which seems to be due to a lessening of the ferro-magnesian mineral content and a strong development of quartz and especially orthoclase.

Some of the blocks do not take on the characteristics of the granite, but remain as permanent darker inclusions. Macroscopically and microscopically they have all the characteristics

of an igneous rock, even to containing porphyritic crystals of orthoclase. Without observing their origin, one would call them fragments of some igneous rock taken up by the magma in its journey. Such blocks are infrequent; most of them become part of the magma and indistinguishable from it. Veinlets of quartz and orthoclase penetrated the hornfels in some places, forming an intricate network. In such places the rock between the veinlets, in a distance of six inches to two feet, has become highly feldspathic, gradually taking on the aspect of the granite. An interesting point is the apparent disappearance of ferro-magnesian mineral matter and the appearance of feldspars.

Detail History of the Mineralization.

Under this heading the writer confines himself to the mineralization of the Suan mine, where more complete observations and more careful study of thin sections have been made than elsewhere. The conclusions derived from the Suan mine, however, apply to the remainder of the contact.

The country rock is a fairly pure limestone, possibly in part magnesian and siliceous, of fine-grained original texture. Contact metamorphism of the pure limestone produced a marble with the grains some 125,000 times the size of those of the original limestone. Intense deformation caused the grains of the marble to bend or flow.

In many places along the contact, notably at the Suan mine, extensive silicification of the limestone occurred during the period of static metamorphism. The actual occurrence shows that large quantities of silicates occur in such relations as to suggest very strongly that silica, alumina, and iron have been introduced from an outside source. In particular, there is a mass of many hundreds of tons of almost solid phlogopite in connection with the "central ore-body." To the writer it is unreasonable to assume such enormous quantities of phlogopite, a mineral of the approximate constitution⁵ SiO_2 —40 per cent., Al_2O_3

⁵ Dana's "Textbook of Mineralogy," phlogopite. Analysis of the material from the mine would make the elucidation of this problem more certain, especially as regards the fluorine content of the phlogopite.

—15 per cent., MgO —27 per cent., K_2O —9 per cent., H_2O —4 per cent., F —say 1 per cent., to have been formed in a limestone of whatever constitution without the accession of chemical substances from outside sources. While silica and alumina, as well as magnesia, might be derived from the limestone, the first two being concentrated by the removal of carbonate to suit the required composition of the phlogopite, it seems improbable to expect potassia and fluorine to follow the same rule. In the case under observation, situated on and near a trunk zone of mineralization (and later metallization), it seems much more reasonable to assume that practically all of the calcium carbonate was removed and replaced by phlogopite.

In another part of the mine, Level No. 4, East, may be seen prismatic crystals of phlogopite, up to 1 cm. in diameter, which have replaced calcite. Here is definite proof that the silicate may replace the carbonate. It may be asked: Where did the silica, magnesia, alumina, potassia, water, and fluorine come from? The two are associated with an undetermined brown mineral, possibly ankerite, and a little chalcopyrite of later age.

Again, a large part of the eastern ore has as its principal gangue, diopside. It occurs in great quantity, in small and large (Plate III., *A*) radial aggregates, in some places penetrating calcite (see Plate II., *A*), and in many places composing by far the major part, certainly 90 per cent. of the rock. While it is conceivable that certain constituents might have been driven off from the original rock in such a way as to leave silica, lime, and magnesia in the exact proportions to form diopside, it could not have been so done without a lessening of the volume of the rock. There is no evidence of such shrinkage. In fact, the evidence is most decisive that the diopside was formed in a perfectly quiet rock. Radial diopside crystals extended into calcite of large crystallographic dimensions (now replaced in many places by chalcopyrite), and the writer has numerous slides showing the same uniform growth in smaller individuals. Fig. 9, Plates IV., *A* and *B*, also show diopside crystals well developed, and broken after their growth had ceased. It is necessary to con-

clude, then, for those large masses of almost pure diopside, that either the composition of the original rock was close to that of diopside, or, since all evidence indicates that the original rock was a limestone, carbon dioxide has been removed together with alkali earth oxide, and that silica has been brought in in such proportions as to form the stable diopside.

Similarly, deformation of the phlogopite, individuals not uncommonly being two inches across, was entirely after its formation. The mineral was formed under quiescent conditions, and there is no evidence of change of volume of the rock during the formation of the mineral.

There occurs very commonly in the marble walls of the ore-bodies of the mine, and in massive form in the western group, a black acicular mineral in characteristic stellar aggregates (see Plate III., *B*). This mineral has been referred to by Koto⁷ as ilvaite. In the unfortunate lack of a chemical analysis the identification of this mineral is doubtful. The writer believes, however, from microscopic evidence, and from that of mineral association, that the mineral is not ilvaite, but a highly ferriferous pyroxene of the hedenbergite type. There is a definite possibility that this mineral may be very close to the iron end of the isomorphous $(\text{Ca}, \text{Fe})(\text{SiO}_3)_2$ series; if not indeed the terminal pyroxene, ferrous metasilicate, FeSiO_3 . He therefore proposes the name "collbranite," after Mr. H. Collbran and his son, Mr. A. H. Collbran, who have made the Suan mine a producer. This mineral will hereinafter be referred to as "collbranite" (Plate III., *B*). The occurrence of collbranite corroborates in all particulars the history of the diopside and phlogopite.

The garnet was also formed before the general disturbance which preceded the advent of the sulfid-bearing solutions.

Thus there is established the following major events in the history of the genesis of the ores of the Suan mine: (1) A period of great deformation of the original country rock; (2) a prolonged period of quiescence, during which recrystallization and the development of large amounts of metamorphic minerals took

⁷ B. Koto, *Journal of the College of Science*, Imperial University, Tokyo, May, 1910.

FIG. 12.

FIG. 13.

Diagrams of pressure temperature and rate of mineralization changes covering the geologic episode of the intrusion of the Suan granite, as now recorded in the western and eastern group of ore-bodies of the Suan mine.

place, with the accession of water, silica, fluorine, alumina, some sulphur, and probably some iron; (3) initiation of stresses impressed from without the country rock, and under pressure greater than that required for flow in calcite and less than that required for flow of diopside; (4) immediately following the deformation the circulation of ore-bearing solutions.

In Figs. 12 and 13 are brought together these facts with some others in a diagrammatic form, showing their probable and hypothetical relations to the heat, pressure, and rate of metallization induced by the Suan granite, for the ore-bodies. Pressure, temperature, and time-rate of mineralization (not amount of mineralization) are plotted as against time. Present data are insufficient to assign definite scales to the curves, but it is believed that they show the correct relations of events. The irregularities of the curves represent an incident in geologic time, in which the normally nearly horizontal curves of pressure and temperature, together with the normally zero curve of total mineralization are greatly disturbed by the advent of the Suan granite intrusion. A curve of recrystallization might have been added, which would have had a maximum at about the time of the maximum temperature.

By recrystallization is meant in this paper those readjustments of crystalline shape and (or) composition taking place in a rock without accessions of foreign material, other than that of catalyzers or solvents, which leave essentially unchanged the original chemical constitution of the rock, but material may be removed from the rock. By mineralization is meant in this paper those changes in the chemical constitution of a rock which involve accessions to the original material (in absolute quantity) of the rock. It is with the changes of mineralization thus defined that the curves figured in Figs. 12 and 13 deal.

Examination along the Collbran contact has shown that the mineralization falls naturally into two epochs and four groups, somewhat overlapping especially in the case of the first and second. This grouping is based on the time of appearance of the minerals and consequently their association. The grouping is

therefore a fundamental one in the paragenesis of the minerals. With each group more or less characteristic substances seem to have been received from outside sources—the magma. According to these substances the groups have been named.

For the western group at the Suan mine the paragenesis of the minerals is as follows:

Epoch.	Group.	Mineral formed.	Substances received from the magma, or by its direct influence.
Silication.	{	Oxide group. {	Magnetite. Fe_2O_3 .
		Quartz. SiO_2 .	
		Garnet (X). Al_2O_3 .	
		Collbranite (X). FeS_2 .	
		Pyrite.	
	{	Mineralizer group. {	Phlogopite (X). H_2O .
		Diopside (X). F.	
		Collbranite. SiO_2 .	
		Garnet. Al_2O_3 .	
		(In many other places Fe_2O_3 along the contact, vesuvianite is a prominent mineral here.)	
Metallization.	{	Sulfide group. {	Tetrahedrite (X). CuS .
		Chalcopyrite (X). Sn_2S_3 .	
		Bornite. FeS_2 (or Fe_2S_3).	
		Sphalerite. ZnS .	
		Bismuthinite. Bi_2S_3 .	
		Galena. PbS .	
		Gold-silver alloy. Au-Ag .	
		Chalcopyrite 2d.	
	{	Carbonate group. {	Dolomite (X). MgO .
		Calcite. CaO .	
		Quartz. CO_2 .	
		Sericite (in small amount). SiO_2 .	
		Chlorite. H_2O .	

(X) Indicates the minerals most abundant.

The origin of the magnesia and the potassia of the phlogopite is not referred to in the above table pending chemical analyses of the phlogopite.

Starting with the definitely established fact that the second group was formed during a period of quiescence, we may reason as follows, the diagram in Fig. 12 being based on this reasoning:

The first indication of the approach of the magma in the region of the present ore-deposit was probably a slight reduction

of pressure⁸ due to the arching of the rocks overlying the rising mass. This is shown in the diagram by a downward bend of the pressure curve which had been approximately horizontal for an indefinite period of time. It is assumed that the pressure of the overburden was not equal to that of the maximum strength of the rocks at this horizon. At that time the temperature, likewise approximately constant for an indefinite time, had not risen.

When the forerunners of the magma appeared and the active pressing apart of the sediments began, the pressure rose rather promptly to the maximum possible, that of the maximum strength or resisting power of the sediments. That the pressure persisted at this constant throughout most of the time of the enlargement of the intrusion is shown by the great amount of flowage of the surrounding rocks. The temperature, lagging a little on account of the time necessary for conduction, rose rather promptly to a maximum, but began to fall as soon as that part of the magma near the wall of the batholithic cavity became approximately stationary, that is, when the accession of heat from the magma became less than the amount of heat conducted away by the surrounding rocks. The temperature after having fallen from the maximum became a constant value determined by the crystallizing or freezing temperature of the eutectic. If we assume that there was a considerable amount of latent heat of crystallization the temperature probably then for some little time held a constant value lower than the maximum; during which time the pressure fell if there was contraction during crystallization or remained about constant if there was expansion during crystallization. It is probable that reduction of temperature of solid parts about offset the expansion due to crystallization.

Study of the contact zone shows that there was introduction of the oxide group during the time of the intrusion, and during part of the time of quiescence. But the appearance of the mineralizer group, though beginning before quiescence, attained its greatest development in the period of quiet crystallization of the magma. This part of the episode of intrusion was probably as

⁸ For a discussion of the probable pressure, see under the next section.

long as all the other parts except the final cooling of the solidified mass put together. In the diagram it is probably not extended long enough. Water, fluorine, silica, alumina, were all given off by the magma in great abundance, and caught by the lime and magnesia of the limestone. It is not improbable that iron, magnesia, and potassium were also given off in the same way. The fault zone of the two groups of ore-bodies (see Figs. 6, 7 and 8) formed a channel of escape for these solutions.

At the close of the epoch of crystallization in the country rock the metal-bearing solutions appeared. They must have come at the close of the crystallization of the magma, if we may carry further the reasoning that the main part of the silicate mineralization was during the crystallization of the magma; for there is no evidence that further mineralization of the mineralizer type (production of silicates) took place after the metallization, or even during it. There seems to have been a very sharp break in the paragenesis at this point.

The cessation of silicification and the beginning of metallization was marked also by readjustments of the rocks. This part of the history is not as well marked in the western group as in the eastern one, for reasons which will be explained in the discussion of the eastern group. This readjustment is interpreted for the western group as having been due to the shrinkage of the batholith, or its solid portions, after solidification.

At that time the sulphide-bearing solutions appeared from sources lower than the present deposits, but certainly in the magma, for the western group deposits extend along the fault for some distance into the granite itself, first attacking the calcite, then phlogopite and diopside, replaced in part the rock along and near the fault zone (see Fig. 7), and filled fissures and crevices as these opened.

The order in detail of the deposition of the sulphides and metals seems to have been:

- (1) Tetrahedrite.
- (2) Tetrahedrite, sphalerite, and galena.
- (3) Chalcopyrite, bornite, and bismuthinite.

(4) Gold-silver alloy (89 per cent. Au).

(5) Chalcopyrite 2d, cutting across the others.

The current theory that quartz, solidifying last from the magma from silicic acid, causes the liberation of large quantities of water, free to gather and take away metals in a sort of "mother liquor," seems to be strikingly corroborated here.

Following the deposition of the sulphide group, dolomite, calcite, and quartz were deposited in veins and cementing breccias caused by more movement in the fault zone, presumably by the contraction of the cooling solid granite. Minor amounts of sericite and considerable chlorite were developed by the alteration of older minerals, but dolomite is far larger in quantity than all the others together. Whether the dolomite represents a true magmatic product, or whether it was selectively deposited by hot waters of whatever origin after having been dissolved from the surrounding limestone can not be settled without further study; but the writer believes that the magnesia and the carbon dioxide were in large part at least derived from the magma along with quartz in the last stages of its cooling. A little chalcopyrite followed part of the dolomite.

In conclusion for the western group, the time-rate of the mineralization was very slow in the early stages of the intrusion, increased slowly during the crystallization of the magma (but in this period there was the greatest *quantity* of mineralization), rose to a sharp and pronounced maximum at the close of the crystallization of the magma, and was followed by a rather rapid falling off to zero (or nearly so) after the magma had become solid.

With the eastern group the series of events was somewhat different (Fig. 12), and it is thought that the eastern type is more general for the larger profitable deposits. It is almost certainly the type for the Tul Mi Chung mine. A normal, undisturbed condition is shown in Fig. 12, diagramming pressure, temperature, and rate of mineralization of the western group, but, although in general outline the same, the curves in Fig. 13 suffer change on account of the intrusion of a second granite, a small stock close to the ore-deposits, the Hol Kol granite.

The pronounced deformation closed the period of quiet silication in which grew diopside and phlogopite in great abundance, and is interpreted as having been caused by the intrusion of this stock of the Hol Kol granite, which field relations show clearly to be later than the Suan granite. The Hol Kol granite, from microscopic observations, seems to be somewhat more acid than the Suan granite, is of finer grain, and contains many miarolitic cavities lined with orthoclase and quartz crystals. This is interpreted as indicating the presence of abundant mineralizers, which is in accord with the development of fluorite and abundant asbestos (replacing calcite usually), and amphibole, this latter usually in positions crystallographically parallel to the older diopside (see Plate II., *A*). Plates IV., *A* and *B* show typical examples of diopside crystals, broken after large growth, about which chalcopyrite, bismuthinite, and metallic gold-silver alloy were deposited after the deformation of the crystals. Plate II., *B* shows chalcopyrite and bornite replacing diopside and phlogopite in the eastern ore of the Suan mine, thus again demonstrating the later age of the sulphides.

The sequence of events, referred to in Fig. 13, is as follows: (1) a slight lessening of pressure due to arching over the approaching magma; (2) a sharp rise in pressure to the maximum possible for the enclosing rocks; that is, till they readily flowed, closely followed by a rapid rise in temperature; (3) constant pressure during the enlargement of the magmatic cavity and part of the period of crystallization (on the assumption that there was no great increase of volume of the igneous rock during crystallization), accompanied by a gradual fall of temperature till one was reached in accord with the temperature of freezing of the eutectic established. This period (probably not shown long enough in the diagram in comparison with the rest of the figure) was the period of silication, marked at first by the appearance of magnetite, specular hematite, quartz (these three not in large amount, however), pyrite, both iron and calcium garnet (the latter predominating), collbranite,⁹ and possibly spinel. Later

⁹ See an earlier part of this paper for definition of the species collbranite.

came the more important silication, represented particularly by large quantities of diopside and phlogopite. Garnet, epidote, quartz, asbestos, wollastonite (?), and an undetermined brown mineral were not unimportant. Fluorite, actinolite and vesuvianite (these two are especially prominent at the prospects Sang Dai, for actinolite, and Peh Wha, for vesuvianite), tremolite (?), and minor amounts of the sulfides. (4) Next appeared the Hol Kol granite, raising the pressure and temperature. The readjustments necessary for the accommodation of this stock are recorded, as explained above. Quickly following the advent of the Hol Kol granite came (5), the period of intense mineralization—this time metallization instead of silication. The order of the sulphides was as follows:

1. Pyrite, in small amount.
2. Pyrrhotite, chalcopyrite, and bornite. The order in these three cannot be certain without metallographic work, but pyrrhotite seems to have been the first and chalcopyrite seems to have begun before the bornite.
3. Chalcopyrite, bismuthinite, gold-silver alloy; probably also overlapping bornite.
4. Bismuthinite and gold-silver alloy.
5. Second chalcopyrite.

Under 2 and 3 the greatest quantity of mineralization took place. Chalcopyrite and bornite¹⁰ are *par excellence* the sulphides of the eastern group. The second chalcopyrite is small in amount, cutting earlier sulphides and the first chalcopyrite in tiny stringers. (6) Calcite, quartz, chlorite, asbestos, and sericite appeared as additions or as alterations under the influence of magmatic water of reduced metal and sulphur content. (7) The deposition of calcite and a little quartz is going on to-day in scattered open cavities. For calcite the scalenohedron form ("dog-tooth spar") favors the upper levels of the mine; but the flat e-rhombohedron favors the lower levels, and hence is probably

¹⁰ Under the microscope a border of slightly darker bornite was noted around larger and older masses of the same mineral. The occurrence is not understood but possibly may represent a compound of the chalcopyrite-chalcocite series.

more stable at higher pressures than the spar. These occurrences seem to be distinctly post-intrusive.

In conclusion for the eastern group, it may be said that the time-rate of the mineralization was very slow in the early stages of the intrusion. It increased slowly during the crystallization of the magma (during which time, however, was the greatest absolute amount of mineralization—silication), but was suddenly interrupted with the advent of the Hol Kol granite stock. With the cooling of this stock and the further cooling of the main Suan granite batholith, the time-rate turned to a strong maximum, during which period the metallic sulphides and metallic gold and silver were introduced. This was followed by a rapid falling off of the rate of mineralization to zero (or nearly so) after the magma became solid.

LIST AND CLASSIFICATION OF MINERALS OBSERVED.

The chart on page 29 is a complete list and classification of the minerals observed in the metamorphosed country rock along the Collbran contact.

SUMMARY.

A region of pre-Cambrian slates, limestones, and quartzite, together with earlier igneous rocks, has been intruded by a batholith of porphyritic granite (tonalite) approximately roughly elliptical in shape and occupying an area, as now exposed, of some 30 square miles. Strong contact metamorphism of the rocks close to the granite took place, involving recrystallization of minerals *in situ* and mineralization with accession of material from the magma. During an early stage in the development of the contact metamorphism notable additions of silica, alumina, ferric oxide, potassia (?), fluorine, boron, and to a lesser extent metallic sulphides took place; mineralization probably being assisted greatly by the solvent and catalyzing action of water, fluorine, and boron. Following this early stage of silication certain crustal disturbances, caused both by the injection of subsidiary stocks and dikes from the magma which in part had already solidified and also by readjustments in the magma itself.

Epoch of Metallization.	Sulphide Group.	<ol style="list-style-type: none"> 1. Pyrite (in cubes). 2. Pyrrhotite. 3. Chalcopyrite. 4. Bornite. 5. Tetrahedrite. 6. Bismuthinite. 7. Sphalerite. 8. Galena. 9. Molybdenite. 10. Undet. gray mineral (sulphide?). 11. Hematite, blue. 12. Gold-silver alloy.
	Carbonate Group.	<ol style="list-style-type: none"> 1. Calcite. 2. Dolomite. 3. Siderite. 4. Ankerite (?) (probably formed here). 5. Quartz. 6. Sericite. 7. Chlorite.
Epoch of Deep-seated Hydration. (Hydroxyl Group.)		
		<ol style="list-style-type: none"> 1. Quartz. 2. Chalcedony. 3. Chlorite. 4. Epidote. 5. Sericite. 6. Serpentine. 7. Asbestos.¹¹ 8. "Mountain leather." 9. Zeolites. 10. Amphibole (here or under mineralizer group, q.v.).¹²
Epoch of Weathering.	Deeper Group.	<ol style="list-style-type: none"> 1. Chalcopyrite. 2. "Copper-pitch." 3. Chalcocite. 4. Undet. white sulfide. 5. Calcite. 6. Quartz.
	Surficial Group.	<ol style="list-style-type: none"> 1. Cuprite. 2. Metallic copper. 3. Azurite. 4. Malachite. 5. A manganese oxide (?). 6. Undet. yellow mineral. 7. Limonite (from pyrite).

¹¹ There are in all probability two minerals covered by the term asbestos; but clearly some asbestic mineral was formed both in the epoch of silication and in the epoch of deep-seated hydration.

¹² The time of the origin of the amphibole (see Plate II., A) is uncertain. The writer inclines to the opinion that it was formed in the last part of the epoch of silication.

EXPLANATION TO PLATE I.

FIG. A. General view of Camp at Hol Kol, Korea, looking north down the valley towards Suktari.

FIG. B. Chalcopyrite (black) replacing phlogophite and diopside, Suan Mine.

A.

B.

A.

B.

EXPLANATION TO PLATE II.

FIG. A. Cross-section of pyroxene (diopside) aggregate piercing calcite. The forms (100), (010), and (110) are shown. Note the crystallographically parallel amphibole in several places developed later than the pyroxene. Section about parallel to c. $\times 70$.

FIG. B. Chalcopyrite and bornite (black) replacing diopside. Note intricacy of contacts. There is no sign of change of volume. Suan Mine.

EXPLANATION TO PLATE III.

FIG. A. Characteristic radial aggregate of coarse diopside crystals from Eastern ore-body of the Suan Mine. $\times 1\frac{1}{2}$.

FIG. B. Highly ferruginous pyroxene in marble from the Suan Mine, described as collbranite.

A.

B.

A.

B.

EXPLANATION TO PLATE IV.

FIG. A. Fragment of diopside crystal from the eastern ore-body of the Suan Mine showing later crushing and splitting along cleavage planes parallel to the basal pinacoid. Later, chalcopyrite (light gray), bismuthinite (white spots), and metallic gold-silver alloy (too small to show) were deposited in crevices and along sides of the crystal. This specimen illustrates two stages of mineralization: (1) growth of large crystals under static conditions, followed by deformation, and (2) the introduction of metal-bearing solutions. $\times 3$.

FIG. B. Crystal of diopside showing static metamorphism, with possible introduction of silica and iron-bearing solutions, followed by deformation and metallic mineralization. $\times 3$.

A short period of intense mineralization followed these crustal disturbances which had caused fracturing and deformation. At this time metallic sulphides and the gold and silver alloy were deposited, the latter occurring in sufficient quantity to make the average value of the ore about ten dollars a short ton. Along different parts of the contact different metals appear in different relative proportions, but copper, bismuth, and gold are always present. Subsequently erosion has exposed the deposits; but secondary concentration has by no means been equally developed in all places. The depth at which the deposits were formed was probably about 20,000 feet, at a pressure of about 1,500 atmospheres to the square inch; but this estimate may be subject to great revision.