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By HARRY V. WARREN* *and* C. E. GORDON BROWN†

THE Dolly Varden Mine is situated in the Kitsault River valley, eighteen miles from the head of the Alice arm, in the Portland Canal mining division of British Columbia. During the years 1919-21 it was operated by the Taylor Engineering Company, Limited, and produced 1,300,000 oz. silver from about 36,000 tons of ore. The ore was transported by narrow-gauge railway to Alice arm, and shipped to the smelter at Anyox for treatment. During recent years, a small quantity of high-grade ore has been extracted by leasers and shipped to the smelter at Tacoma, Wash.

Unfortunately, the bonanza ores which occurred near the surface did not persist to depth, and two hundred feet below the exposures only rare and unimportant patches of rich ore have been found.

Two opinions exist as to the origin of this rich silver ore. One, advanced by V. Dolmage(1, 2),‡ is that the ores are hypogene, and the other by G. Hanson(3, 4, 5), is that the ores are the result of supergene enrichment.

It is true that Dolmage first advanced his view that the ores are primary because they appeared to be analagous to Premier ore, which he had studied in detail and which he considered to be primary. The present authors have had access to excellent suites of material from both mines and consider the comparison well taken, the only essential mineralogical difference being the presence at the Premier mine, in addition to the silver minerals, of gold and electrum.

Although the arguments put forward by Dolmage have, in the opinion of the authors, never been refuted, nevertheless R. P. D. Graham(6), in a reference to the mine published in 1924, describes the ore as of supergene origin, and since then nobody appears to have challenged this statement. Indeed, in 1935, Hanson re-affirmed his earlier conclusion(5).

No apology is offered for reviving this discussion, because the present contribution represents not only a great deal of laboratory work but also eighteen months' study of the deposit in the course of recent mining operations.

The authors support Dolmage and believe that, with the exception of much of the native silver, the rich silver minerals are primary, or hypogene.

General Geology

The Dolly Varden mine is in the central section of the northern half of the 'Kitsault igneous body,' a complex of intrusive, extrusive, and fragmental igneous rocks which are surrounded by sedimentary rocks, principally argillites, the whole being a part of a formation designated by Hanson the 'Hazelton group'(5). The precise age of the Hazelton group is not known, but it is thought to be approximately Jurassic and older than the Coast Range batholithic rocks which, in this area, are considered to be Cretaceous or possibly Upper Jurassic in age, and are exposed from eight to ten miles to the west of the Dolly Varden mine.

Although several dykes, small spurs, and isolated outcrops of granitic rocks, probably satellitic to the batholith, occur about five miles from the Dolly Varden mine, it is impossible to determine the relationship of the batholith to the ore deposits.

The mine is situated on a moderately steep hillside which is cut by longitudinal gullies, following fault lines. Below the main or No. 4 level portal, the hillside falls away very steeply to the Kitsault river, 700 feet below.

The ore deposit is a vein which follows a fault fracture in the country rock, usually known by its colour—purple or green—but here actually a complex of flows and fragmental rocks. The flows are in part andesitic. The fragmental components are coarse to fine breccias with a generally coarse textured, tuffaceous groundmass.

Structural Geology

The Dolly Varden vein represents a replacement of the rocks which, for the most part, form the footwall of a fault fracture. It varies from an inch up to 25 feet in width, has an average strike of N.55°E., and a dip to the northwest of between 45° and 60°. Faults are conspicuous in the developed portion of the vein.

The structural features may be said to fall into four groups, which, commencing with the oldest, are as follows:

(1) A fault, possibly normal, in the plane of the vein and lying along its hanging-wall. It was along this fault that early hydrothermal solutions found their way, and it seems probable that there were later movements and reopenings along it which permitted hypogene enrichments. The hanging-wall of the vein is marked by silicified gouge, which attains a thickness of five feet and even more in places. All the ore occurs below — never above — this impenetrable silicified gouge.

(2) A series of reverse faults. These strike approximately north and south, have displacements up to 130 feet, dip 45° to 55° westerly, and break the vein into a number of short segments (see Figure 2). Also of the same age is at least one horizontal fault whose position can well be seen in Figure 1. This fault has a bearing on the genesis of some of the rich ore and will be referred to in a later section of this paper, where it is termed the 'flat fault'.

(3) A number of diabase dykes. One of these is important because it serves as a useful plane of reference: it is from 10 to 16 feet wide. The other dykes in the mine are much narrower.

(4) A normal fault, known as the 205 fault (see Figures 1 and 2), cuts all the earlier faults and the dyke. It affords a channel for the circulation of meteoric waters.

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‡Numbers within brackets refer to Bibliography at end of paper.

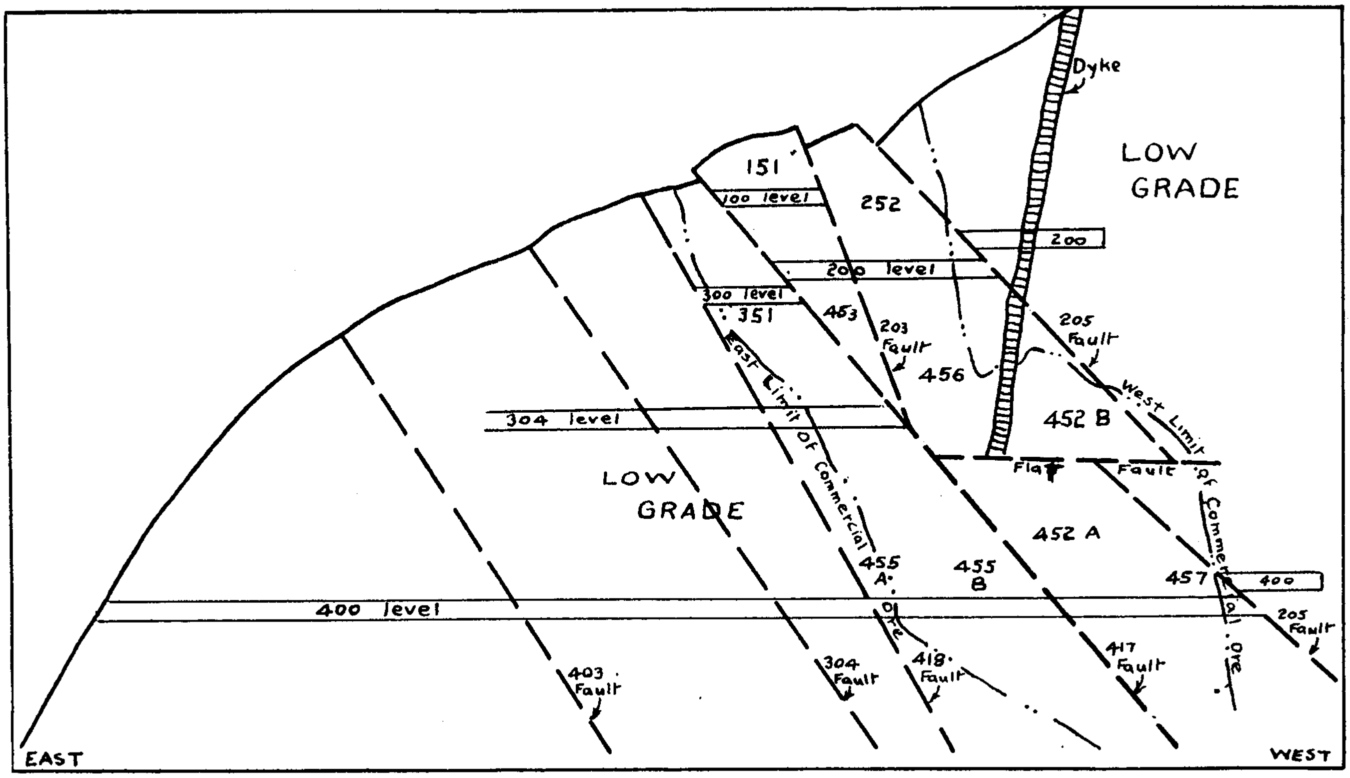

FIGURE 1.—*Projection of vein segments on vertical plane.*

Economic Geology

All the ore in this mine originated in one vein and silver was the only metal recovered. Values decreased rapidly with depth and became uncommercial a short distance below No. 4 level. The following three types of ore have been exploited:

(1) Native silver, in veinlets and masses. These occurred only close to the surface and near the 205 fault.

(2) 'Black' quartz, with no silver minerals visible to the naked eye, was found near the hanging-wall throughout the mine.

(3) 'White' quartz, mineralized chiefly with ruby silver, was mined mainly from the east ends of the ore-shoots.

The outcrop of the vein consists of a barren, oxidized capping from eight to ten feet deep. At the base of the capping there is an abrupt change to unoxidized vein matter. Native silver, the only supergene mineral of importance, occurs in large platy masses and scales immediately below the capping. It is this native silver which is responsible for the first of the three types of ore referred to above.

The following was the tonnage and grade of ore mined from the various stopes during the year 1920, possibly the zenith of achievement of this small but interesting and once much discussed mine:

Summary of Ore Shipments, 1920

Stope	Ore Shipments (Tons)	Average Assay (Oz. Ag/ton)
252	358	23.2
351	5,707	16.4
452A	3,747	27.4
452B	829	36.0
453	255	37.9
454	314	12.6
455A	2,516	26.4
455B	1,961	17.6
455C	433	36.7
456	690	29.5
457	570	25.5

Production statistics for No. 1 glory hole (151 stope) are available only for the month of September, when 330 tons averaging 55 oz. silver per ton were shipped. Thus, during 1920, close to 18,000 tons of rich silver ore were shipped. In addition, much 'high-grade' ore containing 500 oz. silver to the ton or better was sacked and shipped separately to the smelter.

As already indicated, the origin of the ore has been much debated, particularly during the time the mine was under development and in operation. It was then considered that the high-grade silver minerals were the result of the supergene enrichment of low-grade argentiferous galena and tetrahedrite. However, recent laboratory study, and information gained by Gordon Brown during the time the mine was operated under the lease in 1938, point to a high-grade primary mineralization of a low-temperature type, with superimposed supergene enrichment.

Mineralogy

The following minerals have been identified in the Dolly Varden mine: pyrite, chalcopyrite, tetrahedrite, galena, argentite(?), pyrargyrite, sphalerite, native silver, quartz, barite, calcite, jasper, and limonite. The mode of occurrence and probable origin of these minerals are discussed below. Proustite and pearcite(7), arsenopyrite(8), horn-silver (cerargyrite) and stephanite(9), and rhodochrosite or rhodonite(10), have been recorded but were not identified by the writers.

Pyrite

Pyrite occurs abundantly throughout the vein. It was the earliest of the metallic minerals to be deposited and in low-grade portions of the vein it is the only mineral, other than quartz, present in any quantity. As might have been anticipated, a picked sample of pyrite was found to contain negligible amounts of silver. In some parts of the stoped areas, a band of massive, fine-grained pyrite, up to ten feet thick, and barren of silver, lies on the footwall 15 to 20 feet below the hanging-wall. The extent to which pyrite has been replaced by later minerals is not evident in the polished sections studied. However, the fact that much of the pyrite shows sharp boundaries against quartz, but generally has rounded contacts with argentite, pyrargyrite, and other sulphides, indicates that some replacement of pyrite has occurred.

Quartz

Quartz is the most abundant gangue mineral; it comprises from 70 to 85 per cent of the vein. The quartz is solid and glassy in appearance, banding being entirely absent. Thin sections indicate that the quartz and pyrite were first deposited. Then the quartz was brecciated, impregnated with rich silver minerals, and in part recrystallized. Quartz which has been brecciated is usually dark grey in colour and may or may not contain high silver values. Where it does, argentite is always conspicuous under the microscope.

The contacts between quartz and all the other minerals, with the exception of pyrite, show evident rounding of the quartz, indicating that the mineral was attacked, if not replaced, by some action of later mineral-bearing solutions.

Sphalerite

Sphalerite constitutes less than 2 per cent of the deposit in the productive part of the vein. It is one of the early minerals, probably contemporaneous with the quartz and pyrite. It is fine grained and straw-coloured in the upper ore-shoots, but dark coloured and coarser grained in the lower stopes, notably 457.

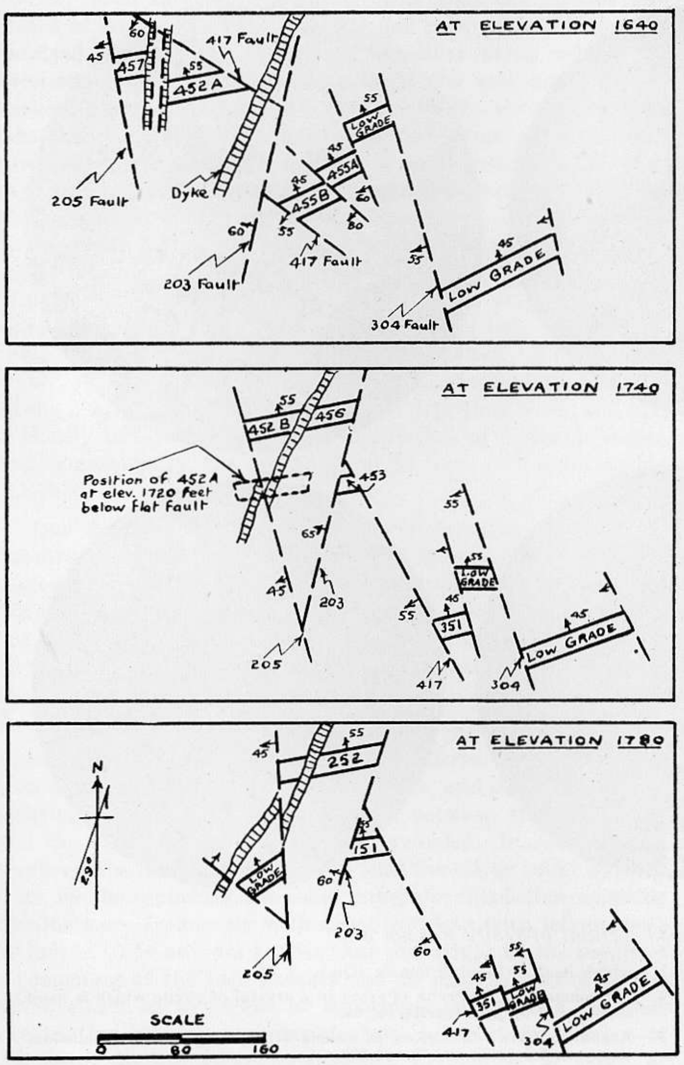

FIGURE 2.—*Plans of vein segments.*

Chalcopyrite

Chalcopyrite is rare. Although more than twenty polished sections of the ore were examined, only one small grain of this mineral was observed. The age relationship of the chalcopyrite to the other minerals remains obscure.

Galena

Galena is present sparingly in the ore as veinlets and irregular masses in quartz. Its relationship to the rich silver minerals will be discussed later, but it is worthy of note that although argentite can, in one or two places, be seen apparently replacing galena along cleavages, the great majority of argentite-galena contacts are mutually rounded and perhaps indicate over-lapping deposition. Despite the richness of the ore in silver, it is noticeable that picked specimens of supposedly pure galena seldom assay more than ten ounces of silver to the ton.

In a low-grade segment of the vein east of the 304 fault, considerable galena is present, associated with sphalerite. The silver values here are low.

Tetrahedrite

Tetrahedrite, like galena, is not abundant but occurs as veinlets and irregular grains and masses in quartz. The sulphide minerals most frequently associated with it are galena and argentite, and these three minerals appear to have been deposited at about the same time. In no place was tetrahedrite found where, by any acceptable interpretation of the facts, it could be said to be in process of alteration to argentite or pyrargyrite. In places, tetrahedrite actually veins and is later than the argentite with which it is in contact. No minerals suggestive of an oxidation zone, such as cerussite, anglesite, or of a secondary sulphide zone, such as chalcocite or covellite, were seen in any of the polished sections. Thus all the observed mineralogical evidence indicates that the galena, argentite, and tetrahedrite are of approximately the same age and that the argentite is not the result of alteration of either tetrahedrite or galena.

Argentite

It is possible that the silver sulphide in this ore is not argentite, but acanthite, the orthorhombic modification of silver sulphide. An X-ray powder analysis would doubtless settle this point. However, as facilities for such an analysis were not available, and as all previous writers on the Dolly Varden have referred to the silver sulphide as argentite, this identification is continued, particularly in view of the fact that in all polished sections examined the mineral appears to be isotropic.

Argentite has three modes of occurrence in this deposit.

(1) As an interstitial mineral, filling the spaces between grains of brecciated quartz. It is this argentite which is usually responsible for giving the high-silver quartz of the ore its characteristic bluish-black colour. Samples of this black quartz were taken from 252 stope, elevation 1809, and from 452 stope, elevation 1693. These two samples, one from close to the surface and the other from well over a hundred feet below, appeared identical to the naked eye except for occasional grains or shreds of native silver in the specimen taken from near the surface. The samples were crushed and, under low-power binoculars, picked as free as possible of minerals other than the black quartz, the argentite being determined under the microscope. The assay results are as follows:

Black quartz from 252 stope, elev. 1,809............576 oz. silver per ton
" " " 452A " , elev. 1,693............295 oz. silver per ton

Even allowing for possible contamination of the upper sample by native silver, it is easy to appreciate the importance of this argentite in 'making' a rich silver ore. Whether or not the difference in silver values as found may be considered as a normal decrease in silver in depth is a moot question. Nevertheless, to any person familiar with the rapid changes in values so often found in rich silver deposits, this explanation must seem plausible. Many microchemical tests were made on these samples of black quartz. In addition to silver, iron was noted, but no arsenic, antimony, or copper were observed in any of the tests. This shows that neither tetrahedrite, nor polybasite, pearcite, or any other of the rich silver minerals often reported in this ore, is associated with the argentite in this black quartz.

(2) Argentite occurs in veinlets associated with galena, tetrahedrite, pyrargyrite, and, more rarely, native silver. The fact that this type of occurrence is more common in the upper than in the lower parts of the vein certainly suggests a secondary origin. However, the mineral relationships seem to rule out such an origin. These relationships, which appear reasonably conclusive to the authors, are: (a) Where in contact with galena, the argentite in some places appears to have assumed definite crystal form; more commonly, the two minerals have mutually rounded boundaries. The fact that in a few of the samples examined argentite occurs along the cleavage planes of galena does indicate that the crystallization of the galena preceded that of the argentite, but does not in any way preclude the argentite being hypogene. (b) Argentite in some specimens is veined by, and therefore in part at least is older than, tetrahedrite; this in itself would surely rule out a supergene origin if the tetrahedrite is accepted as hypogene.

(3) Argentite associated with calcite, barite, and a second generation of quartz, occurs as a filling of vugs. The minerals usually have crystal faces and in many places may have been connected with either of these periods.

It is regrettable that although many random crystal faces were seen on grains of the silver sulphide, no crystals suitable for measurement on the goniometer were found; indeed, not even the crystal forms present are identifiable.

Pyrargyrite

Pyrargyrite is widespread. Its manner of occurrence is similar to that of argentite, except that it is not found as crystals in vugs. Pyrargyrite, where disseminated in quartz, gives the ore a red colour, known to the local miners as 'ruby stain'. Its relation to the other sulphides is identical with that of the argentite. Smooth, mutually rounded boundaries with argentite indicate contemporaneous deposition of the two minerals, and confirming this is the fact that in places the argentite includes islands of pyrargyrite, and close-by pyrargyrite contains islands of argentite. As argentite and tetrahedrite have a similar relationship with galena, it seems obvious that all four minerals were deposited at much the same time. This conclusion is important, because previous writers on the Dolly Varden have contended that the presence of pyrargyrite indicates supergene enrichment. If such were the

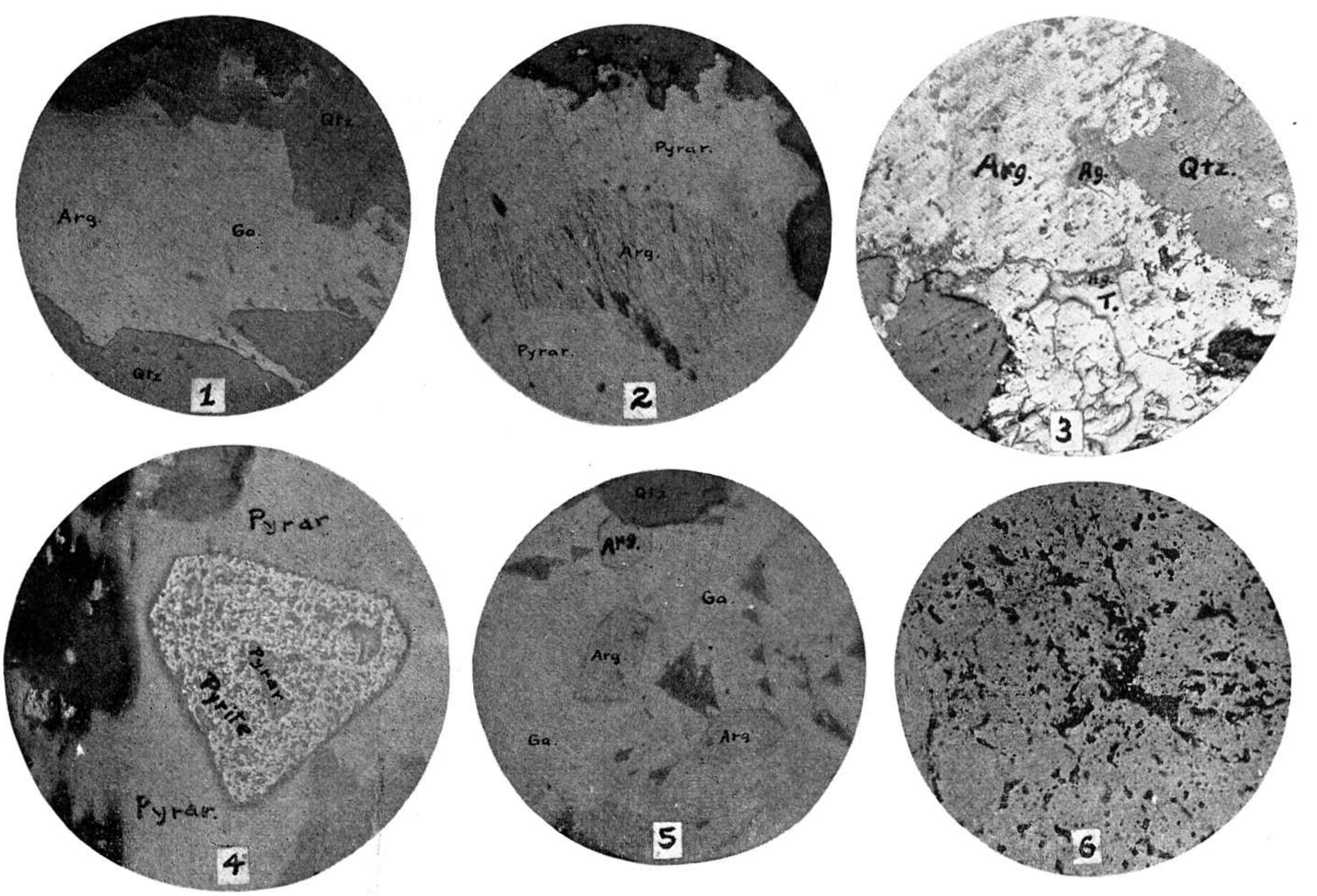

FIGURE 3.—*Photomicrographs of polished sections of Dolly Varden ore.*

1.—Argentite (Arg) and galena (Ga) veining quartz (Qtz). The smooth boundaries between the galena and the argentite probably indicate contemporaneous deposition. × 80.

2.—Argentitie (Arg) inclusion in pyrargyrite (Pyrar) veinlet in quartz (Qtz). Pyrargyrite inclusions in argentite veinlets are to be found nearby. × 80.

3.—Tetrahedrite (T) and native silver (Ag) veining argentite (Arg) which itself is veining quartz (Qtz). × 65.

4.—Inclusions of pyrargyrite (Pyrar) in a crystal of pyrite which is itself surrounded by pyrargyrite. × 65.

5.—Argentite (Arg) inclusions in galena (Ga). Some of the inclusions show crystal outlines (?). × 180.

6.—Thin section showing argentite (dark) in shattered quartz (light). Tetrahedrite occurs similarly. × 65.

case, then the galena and tetrahedrite must likewise be supergene, and for this there is neither mineralogical nor structural evidence. It is therefore concluded that all these minerals must be hypogene.

As may be seen in the accompanying photomicrographs, the mode of occurrence of the pyrargyrite and argentite in the quartz is similar to that of the galena and tetrahedrite, as far as the boundary relations between these minerals and the older quartz and pyrite are concerned.

The pyrite-pyrargyrite relationship is interesting. The pyrite has been fractured and the fractures healed by pyrargyrite in many places. However, as is indicated in several of the polished sections, some replacement of pyrite by pyrargyrite has taken place. One of the photomicrographs shows islands of pyrargyrite in euhedral crystals of pyrite. The explanation of this may well be that the times of crystallization of the pyrite and pyrargyrite were much closer than has heretofore been believed, and that actually a later generation of pyrite, in crystallizing, has merely trapped or included some pyrargyrite, which itself crystallized shortly after.

In short, there is no mineralogical evidence that any pyrargyrite is supergene. It was deposited at much the same time and in much the same manner as were all the other late sulphur-bearing minerals, specifically galena, argentite, and tetrahedrite.

Native Silver

Native silver is undoubtedly in part supergene, as has already been inferred. It seems clear that the masses and scales of silver which have been found immediately below the oxidized capping are the result of silver being taken into solution in the now eroded portion of the vein and then redeposited below the zone of oxidation, in fractures formed by late faulting. Silver is readily deposited from sulphate solutions by ferrous sulphate (11). The latter would be plentiful in ground water resulting from the partial oxidation of pyrite. This supergene native silver was important economically, as it is probable that 40 per cent or even more of the silver produced from the mine occurred in this form. The quantity of native silver rapidly diminished with depth until, at possibly sixty feet below the outcrop, it was found only adjacent to some channel favourable for the circulation of supergene water, such as the 205 fault. The earlier series of faults, such as the 203, 417, and 304, are tight and dry; they were, and are, evidently unfavourable for the circulation of meteoric water, and, consequently, the ore adjacent to them is not noticeably enriched.

One feature of this native silver remains unexplained. Spectroscopic analyses (12) show that it contains appreciable mercury, possibly a quarter of one per cent. Similar analyses (13) of the primary galena, pyrargyrite, and argentite reveal not a trace of mercury. The supergene origin even of this silver must remain vaguely suspect, although admittedly all the other evidence is positive.

To complicate matters further, by no means all the native silver occurs in the manner described above. It may also be seen in veins with tetrahedrite, argentite, and galena. Usually, although not always, the boundaries between these minerals and the native silver are mutually rounded. In some places, however, the boundaries are such that the silver could be later than, and be replacing, the other minerals; this latter condition obtains more frequently with argentite than with tetrahedrite or galena. The authors realize that this might be the result of a reopening of the vein fissures and an introduction of native silver either as hypogene or supergene enrichment. Neither explanation is altogether satisfactory, because the balance of the mineralogical evidence suggests that some, at least, of the native silver in the veins was deposited contemporaneously with the galena, pyrargyrite, and argentite, and is, therefore, hypogene.

Barite

Barite is present in small quantities throughout the vein. It appears as a coating on fracture planes and may have been deposited contemporaneously with the argentite and pyrargyrite in veinlets. Whether or not the barite increases or decreases with depth could not be determined.

Calcite

Calcite occurs as crystals in vugs and is probably a contemporary of the argentite, which has a similar mode of occurrence.

Jasper

Jasper is rare in the ore but occurs in irregular masses in the hanging-wall north of the productive portion of the mine.

Limonite

Limonite is conspicuous in the oxidized zone and in the gouge of the older faults, near the surface.

History of Hypogene Mineralization

The following is considered to be the sequence of events after the formation of the original fault fracture which served as a channel for hydrothermal solutions.

(1) Deposition of quartz, pyrite, and possibly sphalerite. This deposition was accompanied by some replacement, silicification, and sericitization of the green tuffs and this was particularly marked on the footwall side. The hanging-wall, either because it was less permeable or because it was protected by a layer of fault gouge now silicified, was not involved in the replacement. It is noticeable that, in the part of the vein which does not follow the contact and which has green rocks for hanging-wall and footwall, silification has occurred in both walls.

(2) Movement along the hanging-wall. This is indicated by the presence of silicified fault gouge next to the hanging-wall in every segment of the vein. This movement was accompanied by fracturing and brecciation of the vein filling. A noticeable feature, which may well have had a bearing on the formation of the original ore-shoot, is that this layer of silicified gouge and attendant quartz stringers on the hanging-wall is widest in the most productive area. This may mean that fracturing was more intense and sustained here than elsewhere, thus providing for a longer and more concentrated deposition of ore.

(3) Deposition of pyrargyrite, tetrahedrite, and particularly argentite, with quartz. This was the time when the 'black' and 'ruby stained' quartz were deposited.

(4) Further movement, resulting in fractures, followed by a final period of hypogene mineralization when argentite, pyrargyrite, galena, tetrahedrite, native silver, and barite were deposited. This would explain the presence of veinlets of these minerals in the earlier ore minerals.

Post-Hypogene Mineralization History

Subsequent to the hypogene ore formation, stresses, possibly connected with mountain building, caused faulting of the vein. The earliest of these late faults are remarkably clean-cut and show little vertical, but as much as one hundred and thirty feet of horizontal, displacement. The ore-shoot was thus cut into a number of segments or small ore-shoots separated from one another. The intervening country rock has no appreciable silver content.

Subsequent to this horizontal movement, diabase dykes were intruded into fractures which do not displace the vein. The vein matter adjacent to the large diabase dyke near the centre of the original ore-shoot appears to be slightly lower than average grade; the significance, if any, of this is not known.

Following the intrusion of these dykes, a still younger series of faults, the 205 fault being the most important of them, displaced both the dykes and the already faulted ore segments.

After this, meteoric waters gradually attacked the vein segments and, eventually, considerable supergene enrichment took place, some of which was possibly removed by glaciation. Supergene enrichment, which was particularly important just below the zone of oxidation and in the immediate vicinity of the 205 fault, has been important in providing much of the ore of the Dolly Varden mine. This enrichment by native silver has largely obscured the fact that all the other minerals are those normally found in, and now generally recognized to be characteristic of, epithermal silver veins.

As has been seen, the mineralogical evidence indicates overwhelmingly that, with the probable exception of most of the native silver, all of the mineralization is hypogene. However, there is other evidence as to the origin of the ore. This will be mentioned briefly.

Structural Evidence of a Hypogene Origin

If the native silver which has, beyond all reasonable doubt, been established as supergene, is omitted, a study of the remaining native silver, and of the tetrahedrite, pyrargyrite, galena, and argentite, provides structural evidence which indicates that their origin is hypogene. This evidence is as follows:

(1) Always excepting the supergene native silver, it is noticeable that the rich silver minerals are everywhere found below and never above the relatively impermeable silicified fault gouge. Indeed, as has already been mentioned, the better ore-shoots of ruby silver and argentite are found beneath the thicker layers of this gouge, a position difficult to explain on any basis of supergene enrichment.

(2) Because these rich silver minerals bear no relation to the north-south faults, the flat fault, or the 205 fault—except that these faults all cut off various choice segments of ore in a most distressing manner—it is obvious that supergene enrichment, if any, which could have resulted in the deposition of the silver minerals, argentite and pyrargyrite, must have occurred before the post-mineralization faulting. Illustrative of this point are the 452A and 452B stopes. These are in the lower part of the mine and are rich in the silver minerals under discussion.

The vein segments comprising these stopes have no direct vein contact with the present surface. The 452A segment is bounded at the top by the flat fault. The 452B segment is bounded on the west by the 205 fault and on the east by a diabase dyke barren of any mineralization. This dyke is about fifteen feet thick at this place. It is obvious, therefore, that if any supergene enrichment took place it was prior to the displacement of the vein segments along the flat fault and also prior to the intrusion of the dyke. What change in external conditions would explain the fact that there is not the slightest evidence that any rich, silver-bearing sulphide or sulphosalt has been deposited since the flat faulting took place? Moreover, it must be remembered that, not only has there been a period of compression in this area subsequent to the flat faulting, but also a period of tension, as is evidenced by the normal faulting.

It would seem, therefore, that the occurrence of the rich silver minerals is such that a hypogene origin is clearly indicated.

Origin of the Ore

The ore cannot be correlated with any specific intrusion of plutonic rocks. It may be conjectured that an unexposed part of the batholith was the source of the ore solutions. A differentiate from the same magma may have produced the dykes, which, however, are later than the veins. The writers believe that there is a distinct possibility that the ore is Tertiary in age and is consequently not related to any of the plutonic rocks observed in this area.

Neglecting some supergene native silver, reasons to account for the impoverishment of the ore within the comparatively shallow range of 250 to 300 feet are not evident. All that can be said is that it seems probable that the present deposit represents the lower part of a shallow ore-shoot of the bonanza type, and that physical conditions at the time of formation were such as to cause precipitation of ore minerals only over a comparatively limited vertical range.

Summary and Conclusion

Despite the fact that the rich silver ore does bottom at a relatively shallow depth, the writers believe that, except for a large part of the native silver, the rich silver ore is hypogene in origin. All the mineralogical and structural evidence supports this conclusion.

Acknowledgments

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