THE GEOLOGY OF THE SULLIVAN MINE

by

ALAN MACDONALD

Geology 9

1929-30

CONTENTS.

V THE SULLIVAN MINE

VI MINERALOGY

THE GEOLOGY OF THE SULLIVAN MINE.

INTRODUCTION.

The Sullivan Mine is 2½ miles north of Kimberley by road. A branch line of the Crowsnest Branch connects Kimberley with Cranbrook, lying 19 miles by rail to the south-east.

Since 1914 the Sullivan Mine has been the largest producer of lead in Canada. The tonnage in 1914 was 36,000 t; for first half of 1928 it was 783,403 tons. The total shipment of all ores up to June 30, 1928 is 7,714,699 tons. The ore is hauled to the concentrator at Kimberley which has a daily capacity of 6,000 tons.

There is little available data concerning the geology of the Sullivan Mine. This paper is based principally on "Geology of Cranbrook Map - Area, British Columbia, by Stuart J. Schofield", published by the Geological Survey of Canada in 1915.

TOPOGRAPHY AND GENERAL GEOLOGY OF THE CRANBROOK AREA.

The Cranbrook area covers 2535 square miles in south-eastern British Columbia - bordered on the south by the international boundary and on the east by the Rocky Mountain Trench. It includes the central part of the Purcell Range. There is a marked accordance of mountain summits, probably due to glaciation, which has modified the topography of the whole area considerably. Many of the peaks are over 9000 feet high. The Kootenay River system drains the entire area.

The Purcell Range is composed of the Purcell unfossiliferous sediments of Precambrian (Beltian) age, deposited in the western part of the Rocky Mountain geosyncline. These sedimentary deposits have been intruded by small bodies of granite and porphyritic granite - probably genetically related to the West Kootenay granite batholith - and by the Purcell lavas. There are also a few sedimentary formations later than the Beltian, and of course, glacial and post-glacial drifts, clays and sands.

The following is Schofield's stratigraphic section of the Purcell Series:

Erosion surface.

Pre-Cambrian.	Gateway	2000 +	feet
	Purcell Lava	300	"
	Siyeh	4000	"
	Kitchener	4500	"
	Creston	5000	"
	Aldridge	8000 ±	"

Base unexposed.

Only the Aldridge formation will be described, since it contains the Sullivan deposits. This, the oldest of the series, is exposed in three large areas of the Cranbrook sheet. The strata of the most northerly area form a northward plunging anticline and contain the Sullivan Mine.

The Aldridge formation consists of fine-grained homogeneous quartzites, purer quartzites, and argillites, with decidedly subordinate amounts of conglomerate and sandstone. The argillaceous members have abundant crystals of muscovite and biotite with lesser quantities of garnets and striated felspar crystals.

There has been but slight metamorphism of this formation, although there is a belt of garnetiferous mica schist on Matthew Creek, which passes gradually on either side to the normal argillaceous quartzites.

The Aldridge formation shows the effects of orogenic movements, as it consists in general of a series of anticlines and synclines striking approximately north and south. Most of the folds are gentle but in the vicinity of St.Mary River (about 15 to 20 miles south-west of the Sullivan Mine) the major folds are modified by minor overturned anticlines.

The other formations of the Purcell Series are all sedimentary except for the Purcell lava and sills. The latter represent an intrusion of gabbro accompanied by an outpouring of basalt over the land surface. The sediments are mainly continental. The Purcell sills occur chiefly in the Aldridge formation and vary in composition from hypersthene gabbro to a very acid granite or granophyre, and in texture from fine-grained to porphyritic. The lavas and sills are thought to be of the same age.

STRUCTURAL GEOLOGY OF THE CRANBROOK AREA.

The region is one of structural complexity - consisting of abundant folds, faults, fissures, and joints, of different ages. The folds lie in a north and south direction. The large anticline of the Aldridge formation in the north, cut by the eastwardly flowing St. Mary's River, has already been mentioned. Its structure is quite complex. Folding (Jurassic) was followed by two systems of normal faulting - a north-east south-west system (probably post-Jurassic), and a north-west south-east system (probably post-Cretaceous).

ECONOMIC GEOLOGY OF THE CRANBROOK AREA.

The Cranbrook area is rich in mineral deposits. As early as 1905 it was the largest producer of lead in Canada. At that time, the North Star and St. Eugene Mines were the leading producers, and when they began to decline the Sullivan came to the fore as an even greater producer.

The silver-lead deposits are by far the most important and they occur almost invariably in the more quartzitic phases of the Aldridge formation. They appear both as fissure veins and as replacement deposits, and consist usually of an intimate fine-grained mixture of pyrite, pyrrhotite, and galena. In the Sullivan Mine there is also much sphalerite. Other types of deposits are gold-quartz, gold-copper, iron, placer gold, and clay.

THE SULLIVAN MINE.

Location.

The location of the Sullivan Mine in the Cranbrook Map-area has already been given. It is on the southern slope of Sullivan Hill at an elevation of 4600 feet above sea-level.

With reference to the main geological structure it is situated on the eastern limb of the large anticline already mentioned.

History.

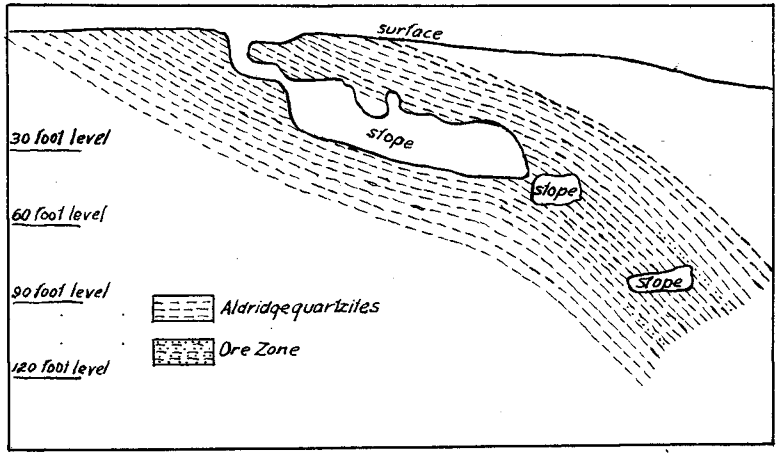
The outcrop was located in 1892 by Pat Sullivan. However, no systematic development work was done and no ore was shipped until 1900. Because of serious metallurgical difficulties, a smelter erected at Marysville to treat the ore was shut down in 1907 after four years unprofitable operation. The ownership passed through many hands before being finally acquired in 1910 by the Consolidated Mining and Smelting Company of Canada, Ltd. From this time on the mine has been a steady and growing producer.

Owing to the fact that most of the ore is a fine-grained intimate mixture of sulphides, it took many years of experimental work to discover a suitable method of treatment. It cannot be smelted without losing the zinc, and all attempts at wet concentration were failures; tabling will not separate the iron and zinc sulphides because of the small difference in their specific gravities. Magnetic separation was satisfactory in laboratory experiments but proved a disappointment when attempted ina 600-ton capacity mill. Finally, selective flotation was introduced in 1920 and has proved to be very successful.

The Ore-Bodies.

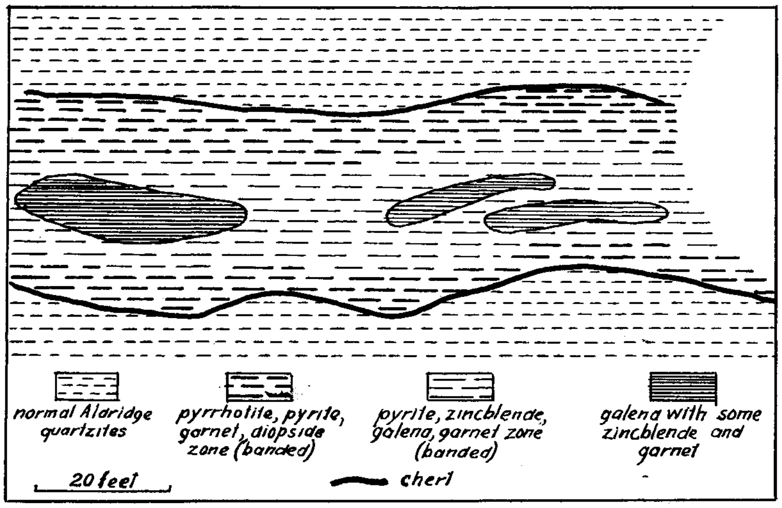
The ore-bodies are replacement deposits in the argillaceous quartzites and argillites of the Aldridge formation. The argillaceous phases of this formation are thin-bedded,

Figure I.



Diagrammatic Cross Section of Sullivan Mine.

Figure II.



Diagrammatic Longitudinal Section of Sullivan Ore-body.

while the purer quartzites are heavy-bedded. The formation has been intruded by many gabbro sills but none have been found near the mines.

The deposits conform in dip and strike with the country rock; the dip varies from 10° to 60° to the east and averages 23°; the strike is approximately north and south. (See figures I and II). In places the ore is 24o feet thick at right angles to the dip. In the upper workings, close folding subsequent to mineralization has increased the real width of the deposit. This disturbance also caused fissuring and in places a readjustment of the ore boundaries as well as a rearrangement of the minerals themselves. There has been no serious faulting - the greatest displacement being 150 feet and of little effect on the deposit. The main fractures trend north and south.

Development has proceeded in two zones, named simply the North and South Zones, which are quite similar as regards value and form, both having produced ores of fairly high grade. Between these two valuable zones is one of iron sulphides with a maximum length of 800 feet, composed of pyrite above and grading into massive pyrrhotite below. This middle section contains several rich ore-pockets which are thoughtto be non-commercial.

The deposits are very noticeably zoned. In the central portions there are large masses of galena with a little sphalerite, surrounded by a fine-grained intimate mixture of sphalerite and galena. The lead ore-shoots are found singly, or as two parallel shoots separated by one of poorer grade. (See figure II). Exteriorly, this inner zone gradually passes into a zone of pyrite, pyrrhotite, and blende. Most of the ore mined is composed of galena, blends, pyrite, and pyrrhotite. However, in the same working face it is not unusual to find pure galena, sphalerite, and pyrrhotite, [redacted], as well as the usual intimate mixture of all four. Towards the periphery the minerals gradually diminish in amount and finally give way either to a fine-grained chert or to the normal country rock where it shows an argillaseous slaty character. The chert if more characteristic of the footwall than of the hanging wall and grades into the normal quartzites. As can be seen, the walls are not well defined - their boundaries are commercial rather than structural - except where the country rock consists of thin-bedded slaty quartzites. These beds apparently offered greater resistance to replacement.

Gangue Minerals.

The deposits are remarkable for their small gangue content. According to Schofield, gangue in the inner zone is practically absent, consisting essentially of a few idiomorphic crystals of a pink manganese-bearing garnet. In the next zone garnets are much more plentiful and almost colorless, and are accompanied by a few grains of actinolite or possibly diopside. The cherty zone has no gangue minerals. The normal quartzite, Schofield reports, is barren of all contact minerals such as garnet, diopside, and actinolite (with one exception). According to Young the chief gangue minerals in the ore are quartz and calcite.

Composition of the Ore.

The average composition of the ore is

Lead	10% to 11%
Zinc	12% to 13%
Silver	3 to 4 ounces per ton
Iron	32% to 33%
Sulphur	30% to 32%
"Insoluble"	4% to 6%

The sphalerite is of the variety known as marmatite, represented by the formula $FeS.5ZnS$.

Fracture.

The typical ore fractures readily to give irregularly-shaped rhomboids. There is distinct evidence to show the development of two cleats, one of which is subordinate, intersecting nearly at right angles. The ore is brittle rather than tough and grinds readily. Fractured surfaces reveal the intimate fine-grained mixture of minerals, and quite often conspicuous bands and streaks.

MINERALOGY.

Polished sections of the typical Sullivan ore were studied under the microscope. The minerals identified in these sections will be discussed first.

Galena. PbS.

Galena is the most important mineral of the Sullivan deposit. A study of the sections shows that it is the youngest of the important ore minerals. In figure XII an irregular veinlet is seen to run through a groundmass of sphalerite containing minute irregular crystals of pyrrhotite and a few particles of galena. This veinlet also shows "islands" of pyrrhotite and sphalerite. Figure VI shows angular particles of galena and pyrrhotite in sphalerite. From this it would appear that at least a small amount of galena was deposited simultaneously with sphalerite and pyrrhotite. Where these three minerals occur in about equal amounts and equally disseminated, the boundaries of the galena particles are quite rounded, with, however, not infrequent short straight edges or sharp corners, which in only a few cases appear to be caused by growth of crystal faces. Where the galena occurs as veinlets, there sometimes seems to be a greater tendency to form such edges and corners.

Sphalerite. ZnS. $(FeS.5ZnS)$

The sphalerite occurs as the iron-rich variety, marmatite, which appears black to the naked eye on the polished surface. Where it predominates in amount over pyrrhotite, the latter occurs in irregularly-shaped crystals, as shown in figure VI. Some of these crystals are lath-shaped which suggests that they lie along cleavage planes or crystal boundaries of the sphalerite. Etching makes this more evident. Where pyrrhotite is the abundant mineral, the sphalerite occurs in similarly-shaped crystals, except that no lath-shaped ones are seen, due no doubt to the fact that pyrrhotite possesses no well-developed cleavage. (See figure IV) The presence of the lath-shaped

🟨	Pyrrhotite	Pyrite	🟥
🟫	Sphalerite	Quartz	🟦
🟪	Galena	Gangue	🟨⬜⬛

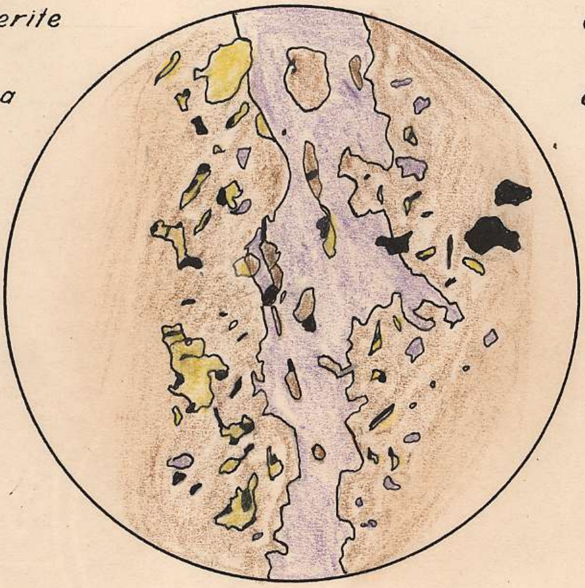


Figure III.

Galena Veinlet Cutting Sphalerite. X38

Figure IV.

Sphalerite in Pyrrhotite. X54

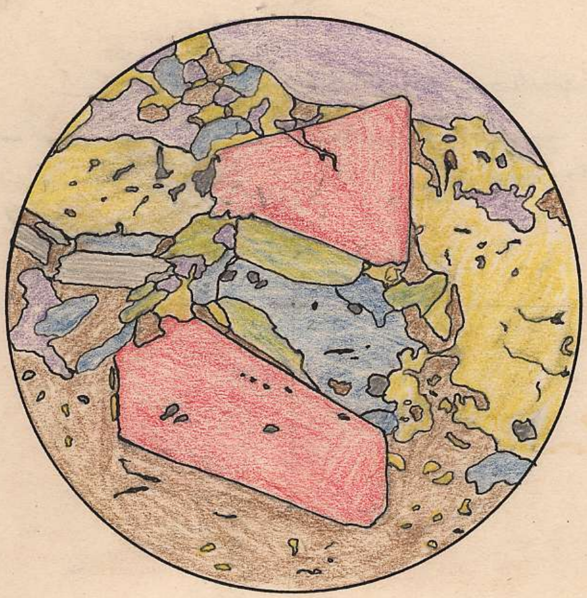


Figure V.

Euhedral Crystals of Pyrite. X23

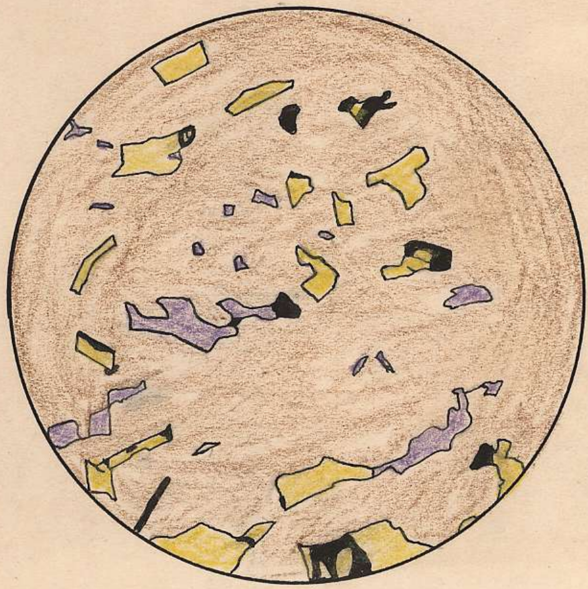


Figure VI.

Pyrrhotite and Galena in Sphalerite. X 178

Where galena is abundant (as in the stringer of fig 3
[illegible] the quartz? seems either to be later or to difficult
to replace

~~where qu & galena are both abundant~~

Where qu & sphal. is abundant they are in contact
with ragged boundaries

pyrrhotite crystals would indicate "unmixing", which in turn is supposedly a result of contemporaneous deposition.

Pyrrhotite. FeS.

The relation of pyrrhotite to galena and sphalerite has been discussed.

Pyrite. FeS_2

In one of the sections examined several euhedral and comparatively large crystals of pyrite were seen. Figure V shows two such crystals embedded in a groundmass of galena, pyrrhotite, and sphalerite, together with gangue minerals. Evidently pyrite formed before the other minerals and was not replaceable by them. Schwartz found distinctly rounded pyrite crystals in a fine groundmass of galena and sphalerite.

Quartz. SiO_2

A small amount of quartz was found in one of the specimens, chiefly in contact with sphalerite, and showing very ragged boundaries. It is rarely found in the sulphide zone and is probably a recrystallized residue of the replaced quartzites.

The following minerals were not identified in any of the specimens examined. The descriptions are taken largely from "Geology and Mineralogy of the Sullivan Mine" by R. M. Logie.

Chalcopyrite. $CuFeS_2$

Chalcopyrite occurs in very subordinate amounts. Because of this, its age relations are obscured. Schwartz suggests that it is probably contemporaneous with pyrrhotite and sphalerite.

Arsenopyrite. $FeAsS$.

Schofield noted that arsenopyrite occurred "in the form of crystals embedded in a mixture of pyrite, pyrrhotite, and zinc blende."

Jamesonite. $Pb_2Sb_2S_5$

Jamesonite is believed to be secondary in origin, as Schofield observes that it may be forming at the present time. It occurs in small stringers of calcite cutting the ore-body.

Cassiterite. SnO_2

Cassiterite is present in amounts almost great enough to make its extraction profitable. Its relation to the other minerals has not been described.

Silver Minerals.

The mode of occurrence of silver in the ore is not definitely known, but it is believed to be primary and associated with galena. Secondary native silver is found at the top of the ore-body.

Garnet.

The garnets are present as almost colorless or pink idiomorphic crystals and are scattered throughout the deposit. They are very scarce and pink in the inner zone, being more numerous and nearly colorless toward the periphery of the ore-body. It was one of the first formed minerals, for Logie shows sphalerite penetrating a garnet crystal.

Actinolite and Diopside.

Schofield mentions that small amounts of actinolite or possibly diopside occur with the garnet in the outer zones of the deposit. They are believed to have been present before the main sulphide mass was precipitated.

Calcite.

Calcite occurs both as a primary and secondary mineral. Logie says "There is some secondary calcite occurring at the top of the ore-body in small stringers and veinlets cutting the main mass of the sulphides. Some of the primary calcite seems to be post-mineral in age but this relation is confused in many cases. In some specimens thecalcite is found along the cleavage of the galena; while in others, remnants of the calcite are found in galena. This relationship is much like that of sphalerite and pyrrhotite and points to contemporaneity of deposition."

GENESIS.

A study of the geology of the Sullivan Mine, together with microscopic examination of the ores, indicates that there were three main periods of mineralization.

I. During the first main period, the minerals introduced were: diopside, actinolite, and garnet, with some arsenopyrite and pyrite. Toward the close of this period there was alteration of some garnet and biotite to form pennine.

II. The second period was the most important, as it brought in the main mass of sulphides. The sphalerite and pyrrhotite were deposited before the galena, as we have seen that the latter mineral replaced the others. A small amount of galena was contemporaneous with sphalerite and pyrrhotite.

III. This period of mineralization was one of secondary processes, brought about by weathering and circulation of ground water. These processes, of course, are still at work.

The minerals formed were: jamesonite, marcasite, native silver, and some calcite.

The order of formation of the minerals seems to have been:

1. Garnet, diopside, pyrite, arsenopyrite.
2. Quartz, pyrite, pyrrhotite, sphalerite.
3. Galena, calcite.
4. Marcasite, calcite, jamesonite, native silver.

It might be well here to enter into some discussion concerning the formation of the ore-bodies. We have already decided that the Sullivan deposits were formed by replacement. It has been suggested, however, that all the minerals were introduced at one time in the form of a sill, in a manner similar to the intrusion of a rock magma.

This theory has fatal objections. In the first place, the original source of the liquid mineral mass must be accounted for by magmatic differentiation. It is conceivable that there could have been such a concentration before injection, but the chief minerals of the Sullivan deposit - especially galena and sphalerite - are certainly not the kind of minerals that are found in deposits which are known to have been formed by magmatic segregation. Again, minerals characteristic of such deposits, e.g., magnetite, chromite, and chalcopyrite, are either entirely or practically absent. However, pyrite, and especially pyrrhotite, are known to be formed in appreciable amounts by magmatic segregation. It would be difficult to explain, also, the very marked banding of the ores, if one accepts the idea that the minerals have displaced, rather than replaced, the country rock.

The replacement theory offers a plausible explanation of the banding, which is especially marked with sphalerite and galena. The sphalerite, on being injected, replaced those beds most susceptible to replacement. When the galena came in, it found the remaining quartzite beds more easy to replace than the layers of sphalerite.

There is one problem that is difficult to explain, though, if we accept the replacement theory. The North and South ore-zones are separated by a great mass of iron sulphides. This being so, how can one explain why the galena, which is apparently of later age than this mass, was able to pass through it to reach the upper ore-zone, without replacing it to any appreciable extent, when it has already shown its ability to replace pyrrhotite in the lower zone? We must either suppose that the galena was present first rather than last, or assume that for some reason the present iron sulphide zone was at that time much more pervious to mineralizing solutions than was the rest of the ore-body and allowed them practically unretarded advance.

One purpose for the examination of polished sections of ores is to determine the relative ages of the minerals. Certain criteria are interpreted to indicate that one mineral has replaced another; but all geologists are not agreed as to just what deductions should be made from certain observed facts. For instance, Bastin[1] and Schwartz differ in the inter-

[1] Bastin, E.S. Supergene Processes at Neihart, Mont.

pretation of crystal boundaries. Bastin cites as evidence for replacement "Exceedingly ragged contacts between minerals, irregular even under high magnification." Schwartz considers that rounded "corroded" crystal boundaries are definite evidence of replacement. Again, some think that if a mineral lies in thin plates along the cleavage planes of another, then the former mineral has replaced the latter. Lindgren(1) believes that in some cases at least, such an occurrence represents contemporaneous deposition due to unmixing; a process by which one mineral, present in solid solution in another, is ejected from it during crystallization at a high temperature.

In the study of the Sullivan ores, it seemed evident that the galena replaced the pyrrhotite and sphalerite, because the galena developed in many places, what appeared to be definite crystal faces. Pyrrhotite and sphalerite did not show such faces. The galena showed, however, more rounded edges and curved corners than straight edges and sharp corners. All edges were extremely well defined and altogether devoid of raggedness. Conclusive evidence of replacement would be available if an "island" of pyrrhotite or sphalerite in galena was shown to be oriented crystallographically similar to the "mainland". An unsuccessful attempt was made to prove, by etching, that the "islands" in figure III were formerly part of the "mainland." The sphalerite was not sufficiently affected by the etching agents.

The origin of the mineralizing solutionsis believed to

---

(1) Lindgren,W. Mineral Deposits. P.213.

have been an igneous intrusion not yet exposed. There are many small cross-cutting bodies of granite and granite-porphyry in the district which are thought to be subordinate or "cupola" stocks of the West Kootenay batholith.

Schofield compares the occurrence of the Cneur-D'Alene deposits with the Sullivan. The former are contact metamorphic deposits, and apparently formed under more extreme conditions. A monzonite intrusion in the Coeur-D'Alene district accounts for the ore-bodies there, and it is quite possible that the Sullivan deposits originated from a similar intrusion.

The Aldridge formation must have been tilted, and was probably also folded to its present position, prior to the deposition of the ore. Assuming that there is an unexposed igneous intrusion, it would seem that it cut or very nearly cut the Aldridge formation at depth, and injected the mineral-bearing solutions along bedding planes of the quartzite. Since there seems to have been four periods of mineralization, it is reasonable to assume that there were at least four periods of igneous intrusion that were responsible for the entry of minerals.

The fact that the galena showed extremely few pits in the polished sections would indicate that the solutions were introduced under very high pressure to form a very compact ore. The ore-bodies are considered to be of the deep vein zone type.

CONCLUSION.

The Sullivan is a remarkable deposit. It is the only mine in the world where great amounts of galena are associated with much pyrrhotite. Galena normally occurs in large amounts as a mineral formed under intermediate or low conditions of temperature and pressure, while pyrrhotite usually occurs under high temperature conditions. Since the galena was deposited later than the main sulphides, it is quite possible that it was introduced under less extreme conditions. We have seen, nevertheless, that the galena probably crystallized under high pressure. The remarkably low gangue content has already been commented on. It should be noted, too, that these very extensive deposits have replaced quartzite, which is known to be comparatively resistant to replacement.