# ON the ORIGIN of the SULLIVAN OREBODY KIMBERLEY, B.C.

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### INTRODUCTION

The Sullivan orebody is one of the great base-metal sulphide deposits of the world and in some respects it is one of the finest examples of a group of sulphide-rich deposits that are increasingly referred to as being of the conformable or strata-bound type. This tendency for many geologists to emphasize the characteristic of conformability of the sulphide bodies with the sedimentary and volcanic units that enclose or are interlayered with them appears to derive from a conviction that the genesis of these deposits is in some way significantly different from other sulphide rich deposits in which parallelism with the enclosing lithic units is slight or essentially absent.

For a time, many massive sulphide deposits were thought by most geologists to have been emplaced largely through the medium of metal-bearing thermal waters derived from a deep-seated magma source that was undergoing differentiation. As the metal-bearing fluids rose, they deposited their metallic burdens wherever suitable structures and physico-chemical conditions were encountered. Not all geologists, however, have been satisfied with the hydrothermal theory as an explanation for the origin of these massive sulphide deposits, principally because none of the chemical mechanisms postulated for collecting and transporting the metals in the thermal waters appeared to be adequate for the task at hand. It is only natural then that some geologists would become attracted to the sulphide-rich group of conformable metalliferous deposits and that they would become intrigued with the possibility that the observed conformability between the sulphide units and the lithic units might arise from a direct and interrelated set of phenomena. That is, the deposition of the sulphide was contemporaneous with the deposition of the associated lithic material. Vigorous and aggressive support for this concept of origin for these deposits appears to have developed at about the same time in South Africa and Australia during the late forties and early fifties arising from research into the Origin of the Rhodesian copper belt deposits and the great silver-lead-zinc lodes at Broken Hill, Australia. Shortly after this, more impetus was given to this movement by the work of Kraume (1955) at Rammelsburg and by Ehrenberg, Pilger and Schröder (1954) at Meggen, Germany. The latter geologists have presented strongly stated cases for a marine hydrothermal syngenetic origin for these deposits.

Canadian geologists are notably exploration-minded and therefore have followed and participated very actively in discussions of these problems. Their concern over these matters increased greatly following the discoveries of the Manitouwadge orebodies in Ontario; the numerous base-metal deposits in the Bathurst area of New Brunswick; and the important ore discoveries of this type in the Mattagami Lake area of Quebec. As the intensity of argument increased, it is not surprising that geologists who are antagonistic to the views of the hydrothermalists would question the official position of the Sullivan geological staff that the Sullivan orebody was formed principally by some process involving selective replacement of favourable argillaceous beds by metalliferous hydrothermal solutions derived from a body of differentiating magma at depth.

The Sullivan geological staff through the visits and writings of geologists dealing with other strata-bound base-metal deposits have been keenly aware of this challenge to their position on the origin of the Sullivan orebody almost from its inception and accordingly have been active in trying to discover new evidence that would help to clarify the points at issue. In addition, we have cooperated with government and university geological groups on several investigations that were beyond the ability of the department to undertako on its own. The results of some of these studies have been published nnd it is hoped that reports on the others will appear soon because they are all valuable scientific contributions toward a better understanding of Sullivan geology. Perhaps it should be mentioned here that the Sullivan geological staff is and has been a large one for over two decades and it would not be correct to construe from the above statements that all of its members are or were of one mind on the question of the origin of the deposit.

## SCOPE AND ACKNOWLEDGEMENTS

When the original request for this paper was made, it was suggested that emphasis should be largely on evidence from the field and underground rather than on evidence derived from laboratory studies. In the main, the writer has followed this suggestion.

In preparing this paper the writer has drawn freely from all the published and private reports dealing with the geology of the Sullivan that were available to him and of necessity will be passing on ideas and observations that have come from such a wide variety of sources thet it would be impossible for him to acknowledge them all. However, he does wish to acknowledge a very great indebtedness in this regard to the present and former members of the Sullivan geological staff.

It is impossible within the limits of the space available to review thoroughly the details of the regional and local geology, which have an important bearing on the problem. Good up-to-date accounts of the essential aspects of Sullivan geology have been available for some years and many of the critical points relating to the origin of the deposit have been dealt with in them. The writer therefore, presumes that most readers are personally well acquainted with the published accounts and so proposes to give, with the aid of illustrations, some highlights on the regional and local geology that he considers to be significant in regard to the question of origin. But he hastens to point out that he does not know of any evidence that unequivocally establishes that any one of the hypotheses suggested is the correct one. Nevertheless, if it is necessary or desirable to take a position on the question, he believes that the weight of evidence at this time favours an epigenetic hydrothermal replacement origin over those invoking a syngenetic origin.

## PREVIOUS HYPOTHESES

Almost all of the early workers believed that the Sullivan orebody is an epigenetic hydrothermal replacement deposit. The private or published accounts of S.J. Schofield (1915), G. M. Schwartz (1927), H. M. A. Rice (1937), A. G. Pentland (1943), C. O. Swanson and H. C. Gunning (1945, 1948), to mention only some of the authors whose writings are readily accessible, clearly indicate this. Most, if not all stated that they believed that the ore is related to one or another phase of local igneous activity and so their disagreements, if any, were over dating rather than over processes of formation. For example, Rice (1937) believed that the deposit was formed by processes arising from the injection of the local granitic intrusions. At that time, all the granitic intrusions in the region were thought to have formed during Late Cretaceous or Early Tertiary time. Swanson and Gunning (1945) on the other hand, considered that the evidence arising from their investigations favored relating the formation of the orebody to a period of Precambrian igneous events one manifestation of which was the injection of the Moyie doleritic intrusions. Inasmuch as the ore was found to disrupt and replace some of the sills and dikes of the Moyie intrusive suite, they considered the ore to be younger but consanguineous possibly representing a late differentiate of a deep seated parental magma. It is of interest to note that many years after this suggestion was made, scientists of the Geological Survey of Canada (Leech, 1962) clearly established that the Aldridge formation is intruded and highly metamorphosed by a Late Precambrian granite that outcrops a few miles to the southwest.

Moro recent writers on this broad group of deposits have not been as concerned over the question of dating as they have over the question of the processes involved in forming these deposits, and the following will serve to illustrate two of the current modes of thinking on this subject:

Sullivan (1957) suggested that the metals in the Sullivan Mine are derived from 'euxenitic shales' and their concentration into the present orebody was effected during a period of local granitization. He does not appear, however, to have been prepared to relate the time of granitization to a known period of local igneous or tectonic activity as he did not specify a time for the emplacement of the ore in its present position.

Stanton (Stanton and Russel 1959, Stanton 1960) suggests that the metals in most conformable base-metal deposits have been introduced into a sedimentary basin by processes arising from and associated with a period of contemporaneous volcanism. The metals, presumably derived from the volcanic rocks and their exhalation products, became dispersed in the sea water and subsequently were precipitated, largely by biogenic agencies. The metals therefore could be deposited subaqueously during a period of accumulation, compaction and diagenesis of the associated sediments. He then suggested that the present form and textures of the minerals in these deposits may have developed at a later date by a regrouping of the minerals in response to subsequent changes in environment. Although Stanton does not include the Sullivan specifically with the conformable deposits that he believes formed in the above way, he does mention that it has many charecteristics that are similar to them.

In conclusion, it would appear that the most pressing questions regarding the origin of the Sullivan orebody at this time are:

(1) What was the original source of the metals?

(2) How were they collected, transported and finally deposited?

(3) Have they been significantly remobilized and redistributed since they were first deposited in the upper limits of the crust or in their present site?

(4) How well do the inferred processes for its formation fit the observed geological facts?

Let us now examine some aspects of the regional and local geology as well as something of the orebody itself to determine whether any insight into these questions can be achieved.

## REGIONAL SETTING

The Sullivan orebody is enclosed in Lower Purcell sediments of late Precambrian age and it lies on the east limb of a segment of the large north-plunging Purcell 'geanticline' (Reesor 1957, Leech 1961). The age of the strata in this large structure ranges from Late Precambrian to Devonian. Although this indicates that the structure is at least post-Devonian, there is considerable evidence to suggest that it had a long history of development that extended well back into the closing stages of the Proterozoic era. The secondary folds that have developed on this major anticline are mostly open but a few are overturned. These secondary folds are broken up by several northeasterly-trending reverse or thrust faults, a few of which extend for remarkable distances and the stratigraphic displacement across some of them is very large. Generally, the northwest block appears to have been thrust to the southeast. Not much is known about the manner in which these faults developed, but one is known to be interrupted by a large Cretaceous or Early Tertiary batholith and the initial development of some of these faults may go back to Late Precambrian time.

Closer in, the orebody lies between the north-dipping Hidden Hand and Kimberley faults (Fig. 17-1). Essentially, both of these structures appear to be normal faults and the stratigraphic displacement on the latter could be in the order of 10,000 feet. Numerous northeasterly-to northwesterly-trending normal faults and fractures that dip steeply West or vertically, occur in the mine and its general vicinity. The Sullivan fault belongs to this group and these structures are generally referred to as Sullivan type faults, etc. The stratigraphic displacement across this system of faults is not usually large, commonly in the order of a few tens of feet. The latest movements on some of them in the mine have displaced the ore. However, marked changes in the character of the ore on either side of them indicate that they probably have a pre-ore history.

## STRATIGRAPHY AND SEDIMENTATION

The oldest sediments in the region belong to the Purcell system. They were laid down in the Beltian trough or geosyncline during the Proterozoic Era and, in the Purcell range, they may be as much as 45,000 feet thick. The geosyncline appears to have been a relatively simple basin of deposition that was abundantly supplied with clastic sediment from a lowlying borderland. Generally, the uplift of the borderland in the region of the mine seems to have kept pace with the subsidence of the basin of deposition because most of the sediments in the latter were deposited in shallow water.

The oldest formation, the Fort Steele, has been mapped on the west flank of the Rockies in the Cranbrook area (Rice 1937). Although it has not been identified positively in the Purcell range, there is some evidence to suggest that its metamorphic equivalent may be present near the mouth of Matthew Creek about 10 miles southwest of the mine. This formation is of interest here only because the lower two-thirds of the exposed section consists principally of orthoquartzites that have textures clearly indicative of deposition in shallow water in which strong wave and current action prevailed. The top third of this formation consists mainly of thin bedded silty argillite, argillite and calcareous argillite, suggesting that these beds were deposited in deeper or at least in quieter waters.

Aldridge formation conformably overlies the Fort Steele formation and is at least 15,000 feet thick. It is of special interest to us because it contains the Sullivan orebody near the transition between its lower and middle members (Reesor, 1954).

The Lower Aldridge is about 4,000 feet thick in the Purcell range. It consists principally of grey-green, rusty weathering, thinly interbedded impure fine-grained quartzite, siltstone, silty argillite and argillite.

The rusty appearance of these rocks and those of the Upper Aldridge is so distinctive that it has been used as a major criterion in mapping in this region. These rocks generally contain pyrrhotite as fine disseminations, as laminations or as small variously shaped masses. Less commonly, pyrite, iron bearing silicates and/or carbonates are present instead of pyrrhotite. This raises the question of whether these sediments are more nearly related to normal pelitic sediments or to ironstones. The few chemical analyses on these rocks that are available indicate a total iron oxide content around 5%. This seems to be too low and the writer would estimate that locally, appreciable thicknesses of these rocks would approach 10% total iron oxides. Pettijohn (1956), in discussing shales, argillites and siltstones, gives a range of 6% to 8% for the iron oxide content of normal pelitic sediments. He would consider 15% to be unusual and those with over 20% to belong to the true ironstones. It would appear then that most of the sediments of the Lower and Upper Aldridge do not depart too far from normal pelitic sediment in this regard and the rusty appearance probably is largely due to the readiness with which the iron-bearing minerals weather.

The widespread distribution of the iron-bearing minerals and their tendency to be associated with primary sedimentary features strongly supports the suggestion that probably most of this iron was deposited contemporaneously with the common detrital constituents. However, since the total amount of iron is, with minor exceptions, well below the amount found in true ironstones, there is little to support the suggestion that the depositional environment may have been conducive to the formation of extensive bodies of iron-rich sediments.

Cross-bedding and scour channels are common structures in the Lower Aldridge sediments and ripple marks are found occasionally. Graded bedding is rare in the lower part of the unit but may be more frequent near the top. This is particularly true at the mine where the ore zone series contains several thick, graded beds. Lenses of intraformational conglomerate are fairly common near the top of the lower member, particularly in the Purcell range. Some of these deposits have been traced for up to three miles before pinching out and are known to attain a thickness of approximately one thousand feet. These deposits have been observed to overlie the scoured and at times deeply channeled surface of the underlying beds and their boulders as far as we can tell have been derived exclusively from materials in the basin of deposition itself. The chaotic conglomeration of boulders of all types, sizes and degree of sphericity embedded in an unsorted paste of mud that is so characteristic of much of these deposits can best be ascribed to violent submarine slides. The Middle Aldridge in the Purcell range is about 9000 feet thick. It consists principally of successions of thin to medium thick, graded beds of fine grained impure quartzite and siltstone that are separated by thin partings of argillite. The arenaceous successions alternate with zones of thin bedded argillite and silty argillite of about the same thickness. Although graded bedding is very common in the siliceous beds, clean sorting of the various size fractions is rare. Instead, the sized clastic particles are embedded in a paste of argillaceous material that ultimately becomes the principal constituent of the upper part of each bed. Loadcast structures are not uncommon at the contacts between the sandy bottoms of overlying beds and the argillaceous tops of underlying beds.

Ripple marks, scour channels, cross-bedding and other structures indicative of deposition in shallow water, where the forces of currents and waves are active, are the exception.

Iron sulphide and/or iron-bearing silicates or carbonates are much less abundant. Therefore, the weathered rocks of the Middle Aldridge are not nearly as rusty as the rocks of the Lower and Upper members.

In general, it would appear that much of the Middle Aldridge section in the Purcell range accumulated rapidly in a relatively deep water environment. O. E. Owens (1959) has studied the Aldridge formation intensively, both in the Rockies and in the Purcell mountains while he was a member of the Sullivan geological staff. He concluded that the graded beds of the middle Aldridge were deposited from turbidity currents, a suggestion that appears to be very well in accord with the criteria set forth by authorities on this phenomenon.

The textures and structures in the dominantly black and white, color-laminated argillites of the Upper Aldridge indicate that these rocks were deposited in relatively quiet, probably deep water. However, the textures and structures found in the younger rocks of the Purcell system indicate that shallow water conditions roturned and generally prevailed throughout most of the remainder of Purcell time.

From the foregoing description of the regional characteristics of the rocks in the Aldridge formation and in view of the general scarceness of graphitic or other organically derived carbonaceous material in these sediments, it is reasonable to conclude that the depositional environment that prevailed in this part of the geosynclinal basin was not one that would favor the precipitation and accumulation of base-metal sulphides in important concentrations either by chemical or biochemical agencies. Evidence will be given later on to show that this conclusion holds for the area about the mine as well.

## IGNEOUS ROCKS

No volcanic flows or deposits of pyroclastic material have been identified positively in the Aldridge formation. In fact, the only flows that have been recognized in the whole of the Purcell system are a few thin basaltic ones with closely associated tuffaceous deposits. They are found in the Siyeh formation or its equivalent, about 21,000 stratigraphic feet above the Sullivan ore zone. Although volcanic flows and pyroclastic deposits have been diligently sought after in the Aldridge formation and not found, it is possible that some may have been missed or not recognized. However, the amount, if any, must be small and utterly inadequate in themselves as a source of metals for a deposit as large and as rich as the Sullivan.

The Lower Aldridge sediments, however, are extensively intruded by many sills and some dikes of the Moyie intrusives which are essentially quartz diabases. This class of rocks is generally considered to be related to volcanic processes in contrast to those that are normally considered to be related to ıtonic igneous activity. It is only proper therefore that some consideration should be given to the possibility that the mechanism and timing of the intrusive activity could have been favoreble for metalliferous substances to gain access to the basin of deposition at the time that the Sullivan ore zone beds were being deposited either by exhalative processes or by submarine thermal springs.

As yet, there have been no direct measurements reported for the absolute ages of the various formations in the Purcell system. On the other hand, dates using the K-Ar method, have been assigned recently to several of the Moyie type sills that intrude the Aldridge formation in this region. Hunt (1961) in reporting on his investigations employing this technique interpreted his data to mean that the intrusions studied by him were injected during two main periods, one about 1500 million years ago and the other about 1100 million years ago. He suggests that the latter period corresponds approximately with the extrusion of the Purcell volcanics which are found in the Siyeh formation or its stratigraphic equivalent. It was noted previously in this paper that the Purcell volcanics lie about 21,000 stratigraphic feet above the Lower-Middle Aldridge contact which is the approximate position of the Sullivan ore zone. Hunt (1961) reports that a sill outcropping in Irishman Creek near Yahk, B. C. belongs to the earlier period and that the sill near the 3700 portal of the Sullivan mine was intruded during the later period. From Hunt's indicated position of the sill on Irishman Creek, it would appear to have intruded beds appreciably above the inferred position of the Lower-Middle Aldridge contact. This probably means that the timing for most of the Moyie intrusions was too late to have been effective in providing metalliferous compounds to the basin at the time the beds of the Sullivan ore zone were being deposited. This reduces considerably the possibility that these intrusives in themselves could have been effective suppliers of metal through a mechanism such as suggested by Kraume (1955) or Stanton (1960). Also, the reader who is familiar with the papers already published on the Sullivan will recall that dikes of similar composition and closely associated with one of these dated sills have been extensively replaced by sulphides where they cross the Sullivan ore body. This is considered to be very compelling evidence that the ore is younger than the intrusions.

Granodioritic stocks and batholiths outcrop in the region, the nearest exposures being about 10 miles southeast of the mine. Recent potassium-argon dating determinations on these granitic intrusions haa reveeled that not all of them are related to the Coast orogeny as they at one time were thought to be.

A small granitic stock, and its pegmatitic off-shoot, located on Hellroaring Creek about 12 miles southwest of the mine, has been found to be Precambrian (800 million years) in age (Leech, 1961).

This intrusion invades Aldridge sediments and Moyie type sills, and it is quite possible that it was injected during the Post Purcell-Pre Windermere diastrophic period. This period of diastrophism has been referred to by White (1959) as the East Kootenay orogeny.

Although the outcrop area of the Hellroaring granitic pluton is small, a large area of metamorphosed Fort Steele or Aldridge sediments that locally contains sillimanite and garnet-bearing quartz-muscovite schist outcrops about 5 miles southwest of the mine. This suggests that a much larger body of granite may be present at shallow depth (Rice, 1937, Leech, 1961). The discovery of a Precambrian granite in the area is of great interest in view of the suggestion by Swanson and Gunning (1945) that the Sullivan orebody and the Moyie intrusives might be products of a differentiating mass of deep seated Precambrian magma.

Several small lamprophyre dikes, some breccia-bearing, have been found in faults in and near the mine. Actually they may be fairly common throughout the region but they are rarely seen because they decompose very readily and so become concealed. These dikes tend to intrude Sullivan type faults and fractures and in the mine, one of these dikes intruded the ore zone after the main phase of pyrrhotite deposition, but before the local introduction of the galena (Swanson and Gunning, 1945). Potassium-argon age determinations on biotite crystals from this dike indicate that it is at least 800 million years old and it therefore has a Precambrian age (Leech, 1961). These relationships seem to substantiate fairly conclusively that the Sullivan orebody was formed in Precambrian time.

## SOME ASPECTS OF THE LOCAL GEOLOGY

The Sullivan orebody occupies a large segment of a somewhat warped domical structure which lies on the east limb of a north-trending anticline with axis a few miles west of the mine.

In general, the degree of conformability in attitude between many of the sulphide bands and the sulphide bands and the sedimentary beds is, indeed, most remarkable. Although this feature is not as strikingly apparent in the central part of the orebody, because much of the sulphide tends to be massive, the broad outlines of the sulphide mass are conformable with the enclosing sediments. Most of the ore in the outer zone of the deposit is distinctly banded and much of it is intimately interbanded with layers of sediment, some of which may be cleanly and sharply separated from the sulphide bands. Even in areas of strong folding, the individual layers and/or laminae of sulphides or sediment may be preserved to a remarkable degree. However, this is not always true, because it is not uncommon to find folds within which the relatively brittle sedimentary beds have been fractured and the segments dispersed throughout the apparently more plastic sulphides and argillites.

It is perhaps desirable to note at this point that in areas of strong folding, there is a distinct tendency for the beds to be overturned toward the east. This is not the attitude to be expected for dragfolds that have developed on the east limb of an anticline whose axis lies to the west. Swanson and Gunning (1945) suggested that these puzzling folds may have formed during another period of folding than the one which produced the anticline. The recently emerging evidence for an important orogeny during the Post Purcell-Pre Windermere interval lends strong support for this suggestion.

The beds that comprise the ore zone may be up to 300 feet thick and as mentioned previously, they appear to have been deposited during a transition from a long period of sedimentation in a shallow water environment to an even longer period of sedimentation in a relatively deep water environment in which submarine landslips and turbidity currents were prevalent and were instrumental in spreading the abundant supply of sediment over wide areas of the geosynclinal basin.

The composition of the ore zone beds as deduced from nearby unmineralized or weakly mineralized sections is somewhat similar to the rocks in the footwall and hangingwall zones. That is, they are greyish to greenish argillites, siltstones, quartzites, etc. On the whole, the ore zone contains appreciably more argillite than either the footwall or hangingwall sections and the proportion of thick massive graded beds separating the thinbedded argillites, etc., is greater and better developed. The characteristics of these beds are maintained over a surprisingly wide area in contrast to the variability found in the footwall and hangingwall beds. The best marker bed in the mine is up to 40 feet thick and contains almost 16 feet of clean fine-grained quartzite and siltstone at its base. Although cross-bedding and channel scour have been observed, these structures are not nearly as common as they are in the footwall strata.

The ore zone sequence and the hangingwall sequence resemble each other in that both contain graded beds. However, the former differs from the latter in that the clastic minerals are better sorted.

Not all of the beds of the ore zone have been replaced, in fact most of the ore and/or sulphide minerals are found beneath the 'I' marker bed in the lower part of the section. The ore also tends to occupy progressively higher stratigraphic position as the deposit is traced up dip. This is clearly the case toward the southwest and northwest margins of the deposit. These fortunately happen to be areas where the diagnostic characteristics of the marker beds have not been obliterated by metamorphism or metasomatic alteration and the evidence is clearly discernable. Profitable lenses of hangingwall ore are found only in the thin bedded zones beneath the 'H', 'Hu' and 'U' markers in special structural situations. Hangingwall ore that follows the bedding is generally strikingly banded (Figs. 17-2, 17-3). This is particularly true for the outer limits of these lenses. However, the inner zone of most of these lenses is generally associated with a zone of strong fracturing or folding and the textures and structures are considerably more complicated.

Swanson and Gunning (1945, p. 652) noted that minor structures in the folded ore suggest that movement and mineralization may have been partly contemporaneous. There is considerable evidence that this may have occurred on a larger scale in a slightly different manner. In folded areas, particularly in the upper part of the mine, there is a fairly marked tendency for thicker and better grade ore to occur in anticlinal or dilatent structures in contrast to adjoining synclinal or compressed structures. Bancroft (1927) noted this and referred to these structures as zones of decompression and compression respectively. A good example of this can be seen in Figure 17-4 between departure 4500 and the dike. The sulphide zone beneath the hangingwall sag is much thinner than it is in the anticlines on either side. In addition, the zone in the synclinal part is composed essentially of pyrrhotite with so little lead and zinc that this section is not ore. In the anticlinal zone, on the other hand, the sulphides are thicker, and of better grade. A somewhat similar example is shown in Figure 17-5 near departure 5,000. Essentially the same situation maintains along the whole length of these structures. Bancroft suggested that the anticlinal or dilatant zones were more permeable, thereby enabling the mineralizing solution to penetrate the structure more readily than it could in the synclinal or compressed zones. Variation in the intensity of deformation during an extended period of mineralization might account for the variations in the amount of sulphide mineral present, particularly if there was a tendency for the proportion of the various metal ions in the incoming solutions to vary with time. The latter is in accord with the general paragenetic relations of the various sulphides in the deposit. Actually, the examples shown on the figures are extreme cases, but parallels exist in the vicinity of nearly all of the folds.

In addition to the very large tonnages of bedded and massive sulphides that constitute the main ore zone, there are several rich but thinner bodies of banded sulphides that have been found in the thin bedded zones beneath the 'H' and 'Hu' marker beds and the base of the Upper or 'U' quartzite. Most of the hangingwall bodies mined so far have been found in or near zones of folding and fracturing, and considerable wallrock alteration is commonly associated with the ore and these structures. Figure 17-3 shows some relations of one of the largest and richest of these hangingwall orebodies. It lies in the thin bedded zone beneath the 'U' quartzites. The section shows that the orebody has a mushroom-like form. There is a narrow pipe of cross-cutting sulphides and associated disseminated mineralization that breaks through the hangingwall of the main ore zone and cuts across 40 feet of hangingwall beds until it reaches the thin bedded zone between the 'Hu' bed and the 'U' quartzites. It then spreads outward over a relatively large area but the thickest and richest ore was found in the highly disturbed zone near the pipe-like structure. From here it gradually fades away both up and down dip as it passes into less disturbed ground.

Although most of the sulphide in the mine is conformable with the enclosing sediments, sulphides that truncate the bedding on a minor to moderate scale are not at all uncommon. Locally, fractures extending as much as 100 feet into the hangingwall of the main orebody carried enough galena and sphalerite to permit them to be mined and weakly mineralized sediment in some cases is known to extend upward along some of the fractures well beyond the high grade lenses. Figure 17-2 reveals that the footwall beds have been extensively and irregularly replaced by sulphides. Also tongue-like processes of ore associated with strong fractures and intense alteration of the walls are shown to extend well into the tourmalinized footwall rocks, indicating that the ore is not only cross-cutting but was deposited after the rocks were tourmalinized.

The map and sections show many of the folds, faults and fracture zones that are associated with the orebody. Unfortunately, owing to the limitation of detail that can be represented, they do not reveal the extent and intensity of widespread brecciation found in the hangingwall and footwall rocks. Most of the brecciation is associated with the area of strong folding and faulting. In the hangingwall, it is most clearly displayed in the albite rocks and these appear to have been strongly brecciated during two periods, one before or during albitization in which the fractures were healed by albite and the other that is post-albitization, having fractures that are weakly sealed by chlorite. Galena, sphalerite and pyrite have been observed locally in the chlorite seams. Much of tha brecciation in the footwall rocks is post-tourmalinization and locally these breccias are heavily mineralized with pyrrhotite and/or minor galena and sphalerite. However, the history of brecciation in the footwall rocks appears to be quite complex and is tha subject of a special study by one of the members of the geological staff, and apart from mentioning the presence of these important structures, it is felt that further comment should await the completion of this study.

## TIN ZONE FRACTURE

The 'tin-zone' fracture is one of the large cross-cutting mineralized fractures in the mine (Fig. 17-6), and it could have served as one of the main feeders to the ore zone. It is of interest here because of the suggestion made by some of those who favor a syngenetic origin for the Sullivan, that the numerous cross-cutting veins found in the mine may not represent primary mineralization but rather that they probably consist of sulphides that have been remobilized in the main ore zone and then redistributed in the fractures by some heat generating process such as a nearby intrusion or by regional metamorphism associated with dnep burial or downwarping.

The tin-zone fracture strikes northerly and dips about 80° easterly. It has been explored for at least 300 feet beneath the footwall of the main ore zone, where it still contains significant amonats of tin, lead and zinc. Where the structure has been explored intensively, it was found to pass upward through the main ore zone, with diminishing intensity, becoming a relatively insignificant structure as it approaches the hangingwall. The fracture zone is widest and most highly mineralized where it passes from normal footwall sedimente into tourmalinized footwall sediments, probably because the latter is a more brittle rock than its unaltered counterpart. In 'normal' footwall sediments, the vein system is narrow and tends to be confined essentially to two clearly defined walls. The space between the walls is filled with a mash of crushed and pulverized sediment that is considerably chloritized. Narrow seams of cassiterite-bearing sulphides consisting of pyrrhotite, sphalerite and galena penetrate the crush zone, and fine veinlets and mineral clusters may spread for a few feet along minor fractures into the walls. The galena and sphalerite are coarse textured and locally, have been crushed and sheared, indicating that some minor post-ore movement has occurred.

The character of the fracture zone changes strikingly upon passing from 'normal' sediments into tourmalinized sediments. The zone of fracturing is considerably wider; open cavities, some large, are common, having formed by the shifting of large blocks with smooth conchoidal surfaces. Minor fracturing and crushing that produced many sharp angular fragments may extend for 10 to 15 feet into the walls on either side of thn main fracture and the development of gouge is minimal. Within the main fracture, mineralizing solutions deposited a large irregular lens of pyrrhotite that is quite rich in tin. Generally, the cassiterite is distributed through the pyrrhotite as small crystals and grains. Locally the pyrrhotite may contain very rich pockets of this mineral. Some pyrite and minor galena and sphalerite are locally associated with the pyrrhotite, and the last two minerals appear to have formed after the pyrrhotite and cassiterite.

The highly fractured tourmalinized sediments on either side of the main fracture are mineralized by a network of veinlets composed of the above mentioned sulphides with pyrrhotite predominating. Again, cassiterite is characteristically associated with pyrrhotite and where pods or lenses of this mineral are veined by galena and sphalerite, fractured grains and crystals of the enclosed cassiterite may be veined by these minerals. Arsenopyrite has been observed as crystal aggregates up to fist size, but cassiterite has not been observed to be in intimate association with this mineral. This observation is supported by assay data. Small scattered grains of scheelite occur in the tin-bearing pyrrhotite lenses and veinlets. Surprisingly, tourmaline and garnet are rare or absent as a vein mineral in this structure.

The walls of the fractures and veinlets associated with this structure are moderately chloritized in the 'normal' sediments and only slightly so where it cuts tourmalinized sediments. Some quartz and calcite are present in the vein, the latter being localized in post-sulphide fractures.

Inasmuch as the main ore zone near the 'tin-zone' fracture consists principally of pyrrhotite, the

The ore zone sequence and the hangingwall sequence resemble each other in that both contain graded beds. However, the former differs from the latter in that the clastic minerals are better sorted.

Not all of the beds of the ore zone have been replaced, in fact most of the ore and/or sulphide minerals are found beneath the 'I' marker bed in the lower part of the section. The ore also tends to occupy progressively higher stratigraphic position as the deposit is traced up dip. This is clearly the case toward the southwest and northwest margins of the deposit. These fortunately happen to be areas where the diagnostic characteristics of the marker beds have not been obliterated by metamorphism or metasomatic alteration and the evidence is clearly discernable. Profitable lenses of hangingwall ore are found only in the thin bedded zones beneath the 'H', 'Hu' and 'U' markers in special structural situations. Hangingwall ore that follows the bedding is generally strikingly banded (Figs. 17-2, 17-3). This is particularly true for the outer limits of these lenses. However, the inner zone of most of these lenses is generally associated with a zone of strong fracturing or folding and the textures and structures are considerably more complicated.

Swanson and Gunning (1945, p. 652) noted that minor structures in the folded one suggest that movement and mineralization may have been partly contemporaneous. There is considerable evidence that this may have occurred on a larger scale in a slightly different manner. In folded areas, particularly in the upper part of the mine, there is a fairly marked tendency for thicker and better grade ore to occur in anticlinal or dilatant structures in contrast to adjoining synclinal or compressed structures. Bancroft (1927) noted this and referred to these structures as zones of decompression and compression respectively. A good example of this can be seen in Figure 17-4 between departure 4500 and the dike. The sulphide zone beneath the hangingwall sag is much thinner than it is in the anticlines on either side. In addition, the zone in the synclinal part is composed essentially of pyrrhotite with so little lead and zinc that this section is not ore. In the anticlinal zone, on the other hand, the sulphides are thicker, and of better grade. A somewhat similar example is shown in Figure 17-5 near departure 5,000. Essentially the same situation maintains along the whole length of these structures. Bancroft suggested that the anticlinal or dilatant zones were more permeable, thereby enabling the mineralizing solution to penetrate the structure more readily than it could in the synclinal or compressed zones. Variation in the intensity of deformation during an extended period of mineralization might account for the variations in the amount of sulphide mineral present, particularly if there was a tendency for the proportion of the various metal ions in the incoming solutions to vary with time. The latter is in accord with the general paragenetic relations of the various sulphides in the deposit. Actually, the examples shown on the figures are extreme cases, but parallels exist in the vicinity of nearly all of the folds.

In addition to the very large tonnages of bedded and massive sulphides that constitute the main ore zone, there are several rich but thinner bodies of banded sulphides that have been found in the thin bedded zones beneath the 'H' and 'Hu' marker beds and the base of the Upper or 'U' quartzite. Most of the hangingwall bodies mined so far have been found in or near zones of folding and fracturing, and considerable wallrock alteration is commonly associated with the ore and these structures. Figure 17-3 shows some relations of one of the largest and richest of these hangingwall orebodies. It lies in the thin bedded zone beneath the 'U' quartzites. The section shows that the orebody has a mushroom-like form. There is a narrow pipe of cross-cutting sulphides and associated disseminated mineralization that breaks through the hangingwall of the main ore zone and cuts across 40 feet of hangingwall beds until it reaches the thin bedded zone between the 'Hu' bed and the 'U' quartzites. It then spreads outward over a relatively large area but the thickest and richest ore was found in the highly disturbed zone near the pipe-like structure. From here it gradually fades away both up and down dip as it passes into less disturbed ground.

Although most of the sulphide in the mine is conformable with the enclosing sediments, sulphides that truncate the bedding on a minor to moderate scale are not at all uncommon. Locally, fractures extending as much as 100 feet into the hangingwall of the main orebody carried enough galena and sphalerite to permit them to be mined and weakly mineralized sediment in some cases is known to extend upward along some of the fractures well beyond the high grade lenses. Figure 17-2 reveals that the footwall beds have been extensively and irregularly replaced by sulphides. Also tongue-like processes of ore associated with strong fractures and intense alteration of the walls are shown to extend well into the tourmalinized footwall rocks, indicating that the ore is not only cross-cutting but was deposited after the rocks were tourmalinized.

The map and sections show many of the folds, faults and fracture zones that are associated with the orebody. Unfortunately, owing to the limitation of detail that can be represented, they do not reveal the extent and intensity of widespread brecciation found in the hangingwall and footwall rocks. Most of the brecciation is associated with the area of strong folding and faulting. In the hangingwall, it is most clearly displayed in the albite rocks and these appear to have been strongly brecciated during two periods, one before or during albitization in which the fractures were healed by albite and the other that is post-albitization, having fractures that are weakly nealed by chlorite. Galena, sphalerite and pyrite have been observed locally in the chlorite seams. Much of the brecciation in the footwall rocks is post-tourmalinization and locally these breccias are heavily mineralized with pyrrhotite and/or minor galena and sphalerite. However, the history of brecciation in the footwall rocks appears to be quite complex and is the subject of a special study by one of the members of the geological staff, and apart from mentioning the presence of these important structures, it is felt that further comment should await the completion of this study.

## TIN ZONE FRACTURE

The 'tin-zone' fracture is one of the large cross-cutting mineralized fractures in the mine (Fig. 17-6), and it could have served as one of the main feeders to the ore zone. It is of interest here because of the suggestion made by some of those who favor a syngenetic origin for the Sullivan, that the numerous cross-cutting veins found in the mine may not represent primary mineralization but rather that they probably consist of sulphides that have been remobilized in the main ore zone and then redistributed in the fractures by some heat generating process such as a nearby intrusion or by regional metamorphism associated with deep burial or downwarping.

The tin-zone fracture strikes northerly and dips about 80° easterly. It has been explored for at least 300 feet beneath the footwall of the main ore zone, where it still contains significant amounts of tin, lead and zinc. Where the structure has been explored intensively, it was found to pass upward through the main ore zone, with diminishing intensity, becoming a relatively insignificant structure as it approaches the hangingwall. The fracture zone is widest and most highly mineralized where it passes from normal footwall sediments into tourmalinized footwall sediments, probably because the latter is a more brittle rock than its unaltered counterpart. In 'normal' footwall sediments, the vein system is narrow and tends to be confined essentially to two clearly defined walls. The space between the walls is filled with a mash of crushed and pulverized sediment that is considerably chloritized. Narrow seams of cassiterite-bearing sulphides consisting of pyrrhotite, sphalerite and galena penetrate the crush zone, and fine veinlets and mineral clusters may spread for a few feet along minor fractures into the walls. The galena and sphalerite are coarse textured and locally, have been crushed and sheared, indicating that some minor post-ore movement has occurred.

The character of the fracture zone changes strikingly upon passing from 'normal' sediments into tourmalinized sediments. The zone of fracturing is considerably wider; open cavities, some large, are common, having formed by the shifting of large blocks with smooth conchoidal surfaces. Minor fracturing and crushing that produced many sharp angular fragments may extend for 10 to 15 feet into the walls on either side of the main fracture and the development of gouge is minimal. Within the main fracture, mineralizing solutions deposited a large irregular lens of pyrrhotite that is quite rich in tin. Generally, the cassiterite is distributed through the pyrrhotite as small crystals and grains. Locally the pyrrhotite may contain very rich pockets of this mineral. Some pyrite and minor galena and sphalerite are locally associated with the pyrrhotite, and the last two minerals appear to have formed after the pyrrhotite and cassiterite.

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The walls of the fractures and veinlets associated with this structure are moderately chloritized in the 'normal' sediments and only slightly so where it cuts tourmalinized sediments. Some quartz and calcite are present in the vein, the latter being localized in post-sulphide fractures.

Inasmuch as the main ore zone near the 'tin-zone' fracture consists principally of pyrrhotite, the

The tin bearing mineral in the Stemwinder probably is cassiterite. In any event, tin appears to be more abundant in the ore lens just referred to than in the essentially barren pyrrhotite body. However, assay data on tin are not well distributed throughout the deposit and the above relation may not be truly representative. Arsenic and antimony are present as minor metals, but the minerals in which they occur have not been identified. Garnet has not been reported to be closely associated with the sulphides as s in many places in the Sullivan. However, small crystals of amphibole, probably tremolite, were observed to be scattered through some of the massive pyrrhotite.

The sediments enclosing the deposit are extensively but irregularly tourmalinized along both walls and some sedimentary relics within the sulphide mass are tourmalinized.

A definite structural control has not been established. However, the body is located along the axial plane of a doubly-plunging syncline that trends northerly, approximately parallel to the Sullivan-type faults and fractures. In the Sullivan, it was found that some of these fractures appear to have served as channel ways or locally to have influenced the distribution of the ore minerals. The Stemwinder orebody therefore may have formed by the deposition of sulphides from solutions rising along a set of release joints that developed along the axial plane of the Stemwinder syncline following a relaxation of forces that produced the fold (Billings, 1954, p. 118). This structural picture has been established largely through surface mapping and diamond drilling. However, attitudes observed in the sediments underground, though limited and infrequent are in accord with the surface data.

The deposit is enclosed by sediments that are thought to lie well beneath the footwall of the Sullivan ore zone. The section contains numerous lenses of intraformational conglomerate that interfinger with lenses of thin bedded or laminated argillite, silty argillite, etc. Many of the rounded fragments of tourmaline rock found in the pyrrhotite along the margins of the deposit may therefore be altered pebbles unreplaced by sulphides.

The marked similarity in the mineralogy of the Stemwinder and the Sullivan ore bodies, in addition to similarities in wall rock alterations and in some structural associations, suggest that there is a close genetic relation between the two deposits. However, the Stemwinder definitely cross-cuts the enclosing beds and it is almost impossible to conceive that it could be anything but an epigenetic sulphide deposit that formed at moderately high temperatures.

## WALL ROCK ALTERATIONS

Much of the rock in the vicinity of the Sullivan mine has been intensely altered, by processes that involved the transfer of large tonnages of chemical substances into and out of the rocks affected. Quantitatively, tourmalinization and albitization are the most important processes that were active in the wallrocks about the mine. Tourmalinization is most widespread and abundant in the footwall rocks, particularly beneath the central portion of the orebody. It also has been active to a lesser degree along certain strongly deformed and fractured zones and so some tourmaline rock is present locally in both the ore zone and hangingwall beds. Locally, the contacts between the normal and the tourmalinized sediments are decidedly conformable. However, the general boundaries of the tourmalinized zone are distinctly transgressive as can be seen in Figure 17-9

Albitized rock is confined largely to the sediments in the hangingwall zone but some has been found in the footwall zone, particularly near the walls of some diorite dikes or associated with chlorite in certain large fractures that cut the tourmalinized footwall rocks. The effect of bedding on the distribution of albite is locally evident but fractures and other cross-cutting structures acted as the dominant controls in its distribution even more than in the case of tourmalinization.

Chloritized rocks seem to have formed under two sets of conditions. In one, chlorite is weakly but pervasively developed on a regional scale and is probably related to regional metamorphism and/or thermal effects of the Moyie intrusions. In this case, the chlorite would not be a true form of wall rock alteration. Chlorite that is believed to have formed as a true metasomatic alteration is closely associated with the orebody and is characterized by the development of zones of massive chlorite. These are found in some large footwall and hangingwall fractures and especially near the contact between the orebody and the albitized rocks, and in the hangingwall in the area about the central iron zone. This e undoubtedly formed by the passage of magnesium-bearing thermal waters and is therefore a true eration product. Coarse biotite and actinolite are found locally, with massive chlorite and their formation is probably related to the same process.

relationship between the pyrrhotite in the fracture and in the main zone is vague. This also applies to the cassiterite. It was mentioned previously that the 'tin-zone' fracture weakens and narrows rapidly toward the hangingwall of the main ore zone and the amount of cassiterite associated with the fracture falls off to almost zero.

It must be clearly evident from the foregoing, that the 'tin-zone' fracture formed largely, if not completely, as a post-tourmalinization structure. If, therefore, as some have suggested, the sulphides and the cassiterite that are in it, are the products of a remobilization and migration from a pre-existing tin-bearing sedimentary sulphide deposit, such as the main ore zone, then the sulphides and the cassiterite especially, have migrated an amazing distance from their source and strangely only downward. The writer feels that in this case deposition from ascending metalliferous solutions is a much better explanation for the origin of the minerals in this vein even though many aspects of the process are not as yet clearly understood.

A very interesting minor feature shown on Figure 17-6 will be described now because this bit of evidence also supports a post-tourmalinization timing for the development of another tin-bearing sulphide lens. In addition, it illustrates that in some places strong, localized thermal effects have been closely associated with the introduction of cassiterite and sulphides into the footwall rocks.

The rocks for a few hundred feet north of the 'tin-zone' fracture, on the 3900 level, consist of 'normal' footwall sediments. They then change abruptly, at a small watercourse, to strongly fractured tourmalinized sediments. The fractures in this tourmalinized zone are filled by narrow veinlets of pyrrhotite and the immediate borders of the veinlets are more or less chloritized. Again, the pyrrhotite in most of the veinlets contains scattered grains of cassiterite. Continuing northward, small skeletal crystals of garnet and chlorite begin to appear in the tourmaline rock and they continue to become more abundant and better formed to the north. Eventually, many of the garnets are found to have a sieve-like texture and they contain inclusions of other minerals such as chlorite and biotite. The rock now changes rapidly to a narrow zone composed of a mixture of massive garnet and ill-defined clusters of coarse garnet, actinolite and biotite as well as minor quartz, muscovite and epidote. A few relics of relatively unaltered tourmaline rock were found in the above. Locally, the garnet-amphibole-biotite rock is mineralized with pyrrhotite and some galena and sphalerite. An examination of thin sections of this rock revealed fractured garnets veined by cassiterite-bearing pyrrhotite. Finally, a small irregularly shaped lens of cassiterite-bearing pyrrhotite was found within the thin shell of garnet-amphibole rock. The galena and sphalerite present appear to have been introduced after the pyrrhotite and cassiterite. Continuing northward the sequence of rock types is repeated in reverse order.

## STEMWINDER DEPOSIT

In order to emphasize the point that discordant sulphide bodies are not uncommon or insignificant features at or near the Sullivan, although they may tend to be small by comparison to the huge Sullivan orebody, the writer has chosen the Stemwinder orebody as a final example of local deposits of this kind.

The Stemwinder deposit is a large one and it lies nearly half-way between the Sullivan and the North Star mines (McEachern, 1946). It is of interest because mineralogically, it is very similar to the Sullivan. It consists principally of pyrrhotite with considerably less sphalerite and galena. Traces of tin (probably cassiterite), arsenopyrite and chalcopyrite have been observed or inferred from assay data. Texturally, the deposit is probably more consistently fine grained than the ores of the Sullivan. However, the most striking difference is the absence of banding in the sulphides of the Stemwinder.

The deposit is essentially tabular in shape (Figs. 17-7, 17-8), is several hundred feet long and has been explored for an even greater distance in depth where it is still open. In places, it is well over 100 feet thick. Although the walls of the sulphide body are not sharply defined, they strike northeasterly and dip steeply to the southwest.

The sulphide body is not an intimate mixture of the various sulphide minerals. Rather, it consists principally of a large mass of pyrrhotite that contains an abundance of unreplaced rock fragments, particularly near its northern and southern limits. Sphalerite is more abundant than galena and these minerals are localized mostly in a small tablet-shaped lens that lies with gradational contact along the footwall of the main mass of pyrrhotite. Within this small lens of ore, pyrrhotite and sphalerite are very fine grained and intimately intermixed. Galena, on the other hand, tends to be concentrated in a small core within the sphalerite-pyrrhotite mass and its texture is coarser.

Swanson and Gunning (1945) described the principal characteristics and relationships amongst the various types of altered rocks and these will not be repeated here. However, there is one aspect of the formation of tourmaline rocks that has come to light after their paper was published. It will be presented now because the writer believes that it may indicate that the Kimberley sill had intruded the sediments prior to the period of tourmalinization. Figure 17-9 shows that as the sill approaches and passes beneath the orebody it becomes dike-like and, near the western margin of the deposit, it is in contact with or even partially invades the ore zone beds.

The thermal effects of this intrusion can be observed best where the sediments have not been tourmalinized. For example, as the intrusion is approached in the southern part of the mine, the normally fine grained sediments become recrystallized to a sugary textured chlorite-biotite hornfels that extends to the intrusive contact. Within the local arch-like structure of the intrusion itself, the large mass of sediment that was enveloped by the magma was converted to an even coarser grained granitoid rock called biotite granophyre.

In the zone of intense tourmalinization, on the other hand, the tourmaline in the rocks well removed from the intrusion crystallized as a felt-like mass of pale brown cryptocrystalline needles surrounding the detrital grains of quartz, feldspar, etc. This tourmaline undoubtedly formed by the reconstitution of the original argillic constituents of the matrix or their diagenetically transformed counterparts, through the action of thermal fluids carrying boron ions. As the intrusion is approached, texture of the rock again coarsens to that of a hornfels. However, brown tourmaline is now a common mineral in addition to the minerals found in the hornfels mentioned earlier. These tourmalines are medium grained rather than cryptocrystalline. Finally, sedimentary zenoliths found within the intrusion, in the zone of tourmalinization, consist of coarse partly brown, partly blue tourmaline and quartz instead of the normal minerals that make up biotite granophyre.

The textural changes described in the foregoing suggest that the variation in the size of the tourmaline crystals was controlled by the textures of the hornfelsic and granophyric rocks which had formed in response to heat generated by the intrusion. That is, tourmalinization occurred some time after the intrusion of the sill. It will also be remembered that the cassiterite and associated sulphide minerals in the 'tin-zone' fracture had formed after the wall rocks were tourmalinized. If then, these conclusions are correct, they seriously weaken the argument for the Sullivan being a partly remobilized syngenetic deposit because the heat from the Sullivan sill could not have been available to effect this postulated remobilization.

The writer realizes that the explanation he has suggested for the relationships just described is not at this time too strongly supported by the evidence at hand. For instance, it might be suggested that the variation in the textures of the tourmalines could conceivably be the result of the Kimberley sill intruding the sediments after they had been tourmalinized rather than before and the writer is not able to present any evidence that would clearly refute this suggestion. However, he feels that in this case one should expect to find more tourmaline in the granophyric sediments that are enclosed in the intrusive where the latter is associated with the large mass of tourmalinized rocks rather than being largely confined to small scattered zenoliths near the border of the intrusive.

This leaves only one other probable way of raising the level of thermal energy in the deposit, namely: by a general rise of the geothermal gradient through deep burial or downfolding of the sediments on a regional scale. This suggestion is not supported by evidence. For example, although the sulphides in the Sullivan orebody locally contain moderately high temperature minerals such as spessartite garnet, actinolite, tremolite, scapolite and cordierite (H. T. Carswell, 1961), beds that are only a few inches away often do not contain any minerals indicative of correspondingly high temperatures. In fact, the mineral assemblages in much of the sediment in question generally indicate that the temperature of these rocks has been about that normally encountered during diagenesis or for the temperature range assumed for the lower limits of the chlorite-albite metamorphic facies. This point is supported also by investigations on the temperature of formation of the pyrrhotite, sphalerite and pyrite that are associated with the cordierite, etc. Carswell (1961) found that the minimum temperature of formation for sphalerites in the Sullivan ranged from 460° - 490° C. and for pyrrhotite from 325° - 400° C. Thus the contrast in temperature of formation between the minerals in the sediments and in the adjoining mixed sediment - sulphide layers appears to be incompatible with what one should expect if the temperature of the whole sedimentary pile had been raised appreciably by regional downwarping, etc. Nevertheless, the marked tendency for high temperature mineral assemblages to be more or less associated with many conformable sulphide-rich layers favors the suggestion that thermal energy travelled through or along some beds better than others. This is a mechanism for heat transfer that one would expect to be associated with the passage of metal-bearing thermal waters through beds of differing permeabilities.

## DISTRIBUTION OF METALS

In the preceding pages, highlights of the local and regional geology were given in order to show that some of the recent hypotheses suggested for the origin of conformable base-metal sulphide deposits do not fit too well with the situation at the Sullivan. As a concluding step, let us now examine the patterns of distribution displayed by several of the more important metallic constituents of the deposit to determine whether this phase of Sullivan geology will shed some light on the question of origin.

The abundance of assay information required to outline reserves and to maintain grade control in a large integrated base metal complex such as Cominco, provides excellent opportunities to study the variation in the distribution of the more important metals in the deposit. The geological staff has been interested in this subject and has prepared distribution and ratio maps for several of the metals as a matter of scientific interest as well as for their proven practical value. The maps clearly reveal that there are patterns to the distribution of many of the metals in the mine and that comparisons can be made and relationships drawn with respect to geological features such as structures, zones of alteration, etc. The maps also provide excellent bases for speculation into the question of the origin of the deposit and some of them are being presented now because they do appear to offer some, if not conclusive, support for an epigenetic origin. This of course, becomes more significant when coupled with other supporting geological evidence.

Pentland (1943) gave the first published statement concerning the distribution of metals in the deposit when he described the zoning of lead, zinc and tin in his paper on the occurrence of tin in the mine. In general, he noted that there is a marked, if not precisely defined, tendency for these metals to have a concentric but not similar distribution aboet the central iron zone.

Swanson and Gunning (1945) cautioned against a hasty acceptance of a concentric zonal concept because the subject was complicated and in their opinion required more study. They suggested that a more intensive investigation might reveal a pattern arising from the merging of two or more linear patterns.

*Distribution of Iron*

The so-called central iron zone, as presently outlined, has a roughly rectangular shape and it lies somewhat south of the centre of the structural dome on which the deposit lies. It is a compound unit, the western half consisting principally of massive pyrite and/or a mixture of pyrite and chlorite. The eastern half on the other hand, consists of vaguely banded pyrrhotite and/or a mixture of pyrrhotite and chlorite (Figs. 17-10 to 17-15). Iron sulphide, principally pyrrhotite extends outward from this zone, more or less in all directions beneath the commercial ore. Incidentally, the latter generally contains abundant pyrrhotite in addition to galena and sphalerite and the pyrrhotite would appear to be largely unreplaced host material with respect to much of the sphalerite and galena. Iron continues to be an important constituent right to the margins of the deposit. However, toward the southeast margin, pyrrhotite gradually gives way to fine grained crystalline pyrite and magnetite in variable amounts commonly accompanies the pyrite. Viewed from the centre of the deposit, this change generally appears in the upper bands before it does in the main band. Another important pyrite zone has been found near the northeast margin of the deposit associated with sediments that are distinctly schistose. The pyrite here is coarsely crystalline and contains considerable carbonate and somewhat less chlorite.

Considerable pyrrhotite is present in the tourmalinized rocks beneath the central part of the deposit either as laminations or blebs in the unfractured areas or as veins and stockworks of veins in fractured and brecciated zones. Numerous veins of glassy quartz and pyrrhotite also cut these rocks.

*Distribution of Lead and Zinc*

Figure 17-10 shows the broader variations in the lead-zinc ratio for a large part of the main orebody. In general, it can be seen that there is a marked tendency for lead to be proportionally more abundant than zinc in an irregular belt about the central part of the domical structure. Lead gradually gives way to zinc as the dominant metal toward the margins of the deposit. Superimposed on this rudely concentric pattern is a clear but secondary tendency for the trend of ratio values to be lineally oriented in a northerly direction. In most cases these lineal patterns correspond in direction and position to Sullivan type folds and fractures.

Figures 17-11 and 17-12 show, in undefined units, the variation in lead and zinc content respectively for the main orebody. Both reveal a similar tendency for the two metals to be concentrated about the central part of the domical structure. Again, there are secondary north-trending patterns of highs and lows that are associated with some of the Sullivan type structures.

In addition to the zonal distribution in plan, there is a distinct tendency for these metals to be zoned in a vertical sense, particularly in the central part of the mine. This relation arises because galena and sphalerite tend to form extensive layers of rich, beautifully banded ore against the hangingwall of the main ore band. This well banded ore passes downward into a rich massive mixture of pyrrhotite, galena and sphalerite that in turn passes into a thick irregular zone of pyrrhotite that carries only a trace of galena and sphalerite. Generally this barren, pyrrhotite zone extends to the sulphide footwall. However, in several places, mineable ore shoots occur along the footwall contact owing to the introduction of galena and to a lesser extent, sphalerite, into the massive pyrrhotite as laminations, streaks or narrow, vaguely defined bands. These ore shoots probably represent relatively more permeable zones caused by a differential movement between the pyrrhotite mass and the footwall sediments during folding and their development apparently coincided more or less with a period in which lead was the main metal being introduced into the ore zone.

The distribution of lead and zinc in the hangingwall ore bodies has the same general pattern as in the main zone. That is, the highly disturbed central zone of these orebodies is generally richer in lead than zinc and zinc becomes the more abundant metal toward the margins.

*Distribution of Silver*

Most of the silver in the mine is associated with galena, probably as a solid solution in the latter. Small grains of tetrahedrite have been observed under the microscope, but the mineral probably is rare. Small bits of a white mineral that was thought to be native silver have been noted on occasion in microscopic studies of certain mill products.

Silver is not distributed uniformly throughout the mine and furthermore the silver content of galena varies considerably. In the main orebody, the high silver zone parallels fairly closely the high lead belt and both the silver content of the ore and the ratio of silver to lead gradually diminishes toward the margins of the deposit.

The ratio of silver to lead is in general somewhat higher for the hangingwall ore than it is for the ore in the main vein. There is also a definite tendency for the hangingwall orebodies that border the central iron zone to have higher silver to lead ratios than hangingwall orebodies that are more remote. In a very general way, the silver to lead ratio varies inversely with distance from the central iron zone.

According to Guild (1917) the maximum amount of silver that is soluble in galena is 0.1 percent (0.30 ounces per unit of lead). Inasmuch as the ratio for many samples in some of the hangingwall ore shoots is appreciably higher than this, it is quite probable that some of the silver occurs as ex-solved native silver or as other argentiferous minerals whose textures are so fine that they have escaped detection.

The reason for the tendency for the hangingwall orebodies to have a higher silver to lead ratio than the main orebody is not clearly understood. The relationship suggests that they may have formed at somewhat higher temperatures. Possibly they represent material that was deposited early in the depositional period whereas the silver in the main orebody may have been diluted by a later phase of low-silver lead that did not have access to the hangingwall orebodies.

*Distribution of Tin*

Cassiterite is definitely the dominant tin mineral in the Sullivan Mine. Other tin minerals may be present in small amounts but they have not been isolated and identified as yet. Tin occurs in strong traces in the mineral boulangerite but the amount in this mineral is not enough to influence significantly the distribution pattern for tin in the main orebody.

Our studies on the variation of tin (Fig. 17-13) in the main orebody reveal that most of it is concentrated in an irregular belt around the central iron zone, especially on its eastern side, and falls off to bare traces at the margins. In addition, most of the tin in the belt of highs is associated with the pyrrhotite-rich zone that lies just above the footwall of the orebody and the values tend to fall off toward the hangingwall. In detail, the distribution of values can be decidedly variable, small very rich pockets being associated with certain Sullivan-type folds, faults or fractures.

It was mentioned previously that tin is also found in some mineralized fracture zones in the footwall rocks, such as the 'tin-zone' fracture. As might be expected, the tin-bearing footwall veins near the central iron zone carry more tin than the footwall veins nearer the margins.

Local concentrations of tin have also been found in the hangingwall zone but these occurrences are relatively rare. They are more abundant in the central part of the mine and are generally associated with structurally disturbed zones in which the hangingwall rocks have been tourmalinized and fractured prior to the introduction of pyrrhotite, cassiterite, etc.

Although pyrrhotite is the most common mineral associate of cassiterite, the relationship is not a direct one, because there are very large tonnages of pyrrhotite that contain practically no tin. Structures and temperature zoning may have been the principal factors governing the distribution of this mineral, the stability field of the tin ions in the mineralizing fluid being considerably narrower than that for iron.

The tin content of the hangingwall ore bodies is not well documented. From the data at hand it would appear to be low even where these ore shoots lie above areas of high tin in the main orebody.

*Distribution of Arsenic*

Arsenopyrite is the only arsenical mineral that has been identified in the mine. Assays indicate that most of this element in the main orebody is concentrated in a belt around the central iron zone. Its distribution pattern is therefore somewhat similar to that of tin and silver (Fig. 17-14).

Although both tin and arsenic appear to have been deposited early in the ore forming period, our information indicates that they were not deposited simultaneously to any important extent.

Information on the distribution of arsenic in the hangingwall orebodies is limited to only one of them. The scanty data indicate a central high with values diminishing toward the margins.

Small scattered crystals of arsenopyrite are frequently observed in beds near the footwall of the main orebody, particularly where these beds have been tourmalinized and then fractured and mineralized. Locally rather rich patches have been observed in fractured footwall sediments well removed from the tourmalinized zone. However, most of those occurrences were observed visually and we do not have any quantitative data on the distribution of arsenic in this environment.

*Distribution of Antimony*

Boulangerite is the predominant antimonial mineral in the Sullivan. Jamesonite, tetrahedrite, gudmundite (Ramdohr 1955), chalcostibite (Carswell 1961) are other antimonial minerals that have been recognized but they occur only in small or trace amounts.

Our studies on the distribution of antimony in the main orebody reveal that there is a decided tendency for this element to be concentrated in an irregular belt near but somewhat in from the margins of the deposit and to be low in the central zone (Fig. 17-15). This is a reversal of the relationship found for tin and arsenic. Again the details of the distribution pattern have been influenced decidedly by certain Sullivan-type fractures and associated folds.

Boulangerite occurs most abundantly in or near open fractures particularly where they cut the ore. It crystallized as spectacular felt-like masses of fine flexible needles on the walls or in openings associated with the fractures. The fact that most of the fragile needle-like crystals were not crushed and broken suggests that they crystallized late in the period of sulphide deposition and after the last period of movement along many of boulangerite-bearing fractures. However, smeared and crushed aggregates of galena and boulangerite on the walls of some of the fractures indicate that part of the boulangerite had crystallized before the last movement.

*Summary*

In summary, it is evident that the dominant pattern for the distribution of most of the metals in the Sullivan is a clear tendency for the variation in values to be roughly concentric to the central iron zone which is located near the centre of the domical structure on which the deposit is situated. Superimposed on this broad concentric pattern are numerous smaller but important northerly trending lineal patterns that in most cases are clearly associated with certain Sullivan-type faults, fractures and/or folds. In addition, it is clearly evident that tin, arsenic, probably tungsten and to a lesser extent silver, are concentrated near the central iron zone where the effects of wall rock alteration are most intensively developed. Antimony, on the other hand, tends to be concentrated away from the central iron zone, nearer the margin of the deposit, where the effects of wall rock alterations range from weak to minimal. It should be noted that the lead and zinc content maps do not show the concentric pattern nearly as clearly as do the maps for the other metals, because so much of these metals is concentrated in the anticlinal warp at the north-central part of the mine. Here, the total thickness of the ore-zone is very much greater than elsewhere. However, the lead-zinc ratio map has a very distinctly concentric pattern and it shows that the central part of the orebody is relatively richer in lead than zinc. On the other hand, as the margins are approached, the zinc content of the body gradually increases until it becomes several times that of lead.

The zonal relations of the metals just described are manifestly not features that one would expect to find in a sulphide body that was formed in a marine sedimentary basin. On the other hand, the relations of these distribution patterns with respect to the central iron zone and the areas of intense wall-rock alteration are what would be expected for an epigenetic hydrothermal deposit in which the metal-bearing fluids emanated from a central source, with the spread of these fluids into the ore zone beds being facilitated by the Sullivan-type fractures, etc.

The position of the lead-rich zone with respect to the zinc-rich zone in the orebody is not what would be expected for a simple case of temperature zoning where the metallizing solutions spread out from a central source. Under these circumstances, the higher temperature minerals should crystallize near the point of dispersal and the lower temperature minerals farther away. Applying this to the Sullivan, one would then expect tho zinc-rich belt to be near the central iron zone and the lead-rich belt to be near the margins which is not the case. The history of ore deposition at the Sullivan is therefore probably more complex and may have proceeded somewhat as follows: At the onset of metallization, the ore-bearing fluids were rich in iron, contained some zinc and were poor in lead. They spread widely and deposited iron sulphide abundantly. As time passed the fluids became zinc-rich but still carried considerable iron and possibly somewhat more lead. Because of the warming action of the advancing fluids on the country rocks, the fluids following were able to move well out from the central iron zone before the metals were precipitated. Shortly after this the intensity of mineralization appears to have fallen off substantially and by the time the fluids had become lead-rich the ore zone rocks may have cooled to the point that most of the galena was deposited just beyond the central iron zone instead of near the margins of the deposit.

## CONCLUSION

In view of the abundance and the remarkable perfection of the interbanding of sediments and sulphides in the Sullivan orebody, (Fig. 17-16 to 17-18), it is quite natural and understandable that some geologists would suggest in print or in formal discussions on the subject of strata-bound or conformable massive sulphide deposits that the Sullivan orebody is some form of a syngenetic sedimentary deposit rather than a hydrothermal replacement deposit as stated in the latest papers by Cominco geologists on the subject (Swanson and Gunning, 1945; Staff, 1954). Apparently one of the main difficulties with the hydrothermal theory in the eyes of many who favor a syngenetic origin is that they find it very difficult to believe that the extent and perfection of the banding at the Sullivan could be effected by a replacement process.

Because of this conflict of opinion, the writer has attempted to review the sedimentological, structural, igneous and metallogenetic evidence, both locally and regionally, that pertains to the Sullivan in order to determine how well the evidence at hand supports or is in conflict with the various theories proposed.

The study of the composition and the textures of the Aldridge beds, and the ore zone beds in particular, indicates that they must have formed in a shallow to moderately deep marine environment that was essentially uniform over considerable distances. At this time, this part of the Beltian basin appears to have been supplied with such an abundance of fine grained clastic sediment that any chemically precipitated carbonate or sulphide or organic debris must have been well diluted by the incoming muds, and furthermore, turbidity currents appear to have been very effective in homogenizing and respreading the sediment widely across the floor of the basin. Assuming, for the moment, that most of the sulphides of iron, zinc and lead in the orebody are sedimentary, their remarkable thickness and richness within such a highly restricted area would seem to call for such uniqueness in the depositional environment of even a barred basin that it is almost impossible to rationalize it with the record for the clastic sediments so closely associated with the sulphides.

Also if submarine thermal springs of volcanic affiliations had been largely responsible for the introduction of the sulphides in the basin, surely other minerals that are commonly deposited in abundance around these springs would be present with the sulphides. And surely the rocks through which these mineral-charged fluids had passed would bear their imprint as do the wall rocks in the vicinity of modern thermal springs.

Our study of the evidence of igneous activity in the region reveals that the only known lavas and their associated pyroclastics were extruded only after many thousands of feet of sediment had accumulated above the ore zone beds. Even the oldest of the dated Moyie intrusions intrudes beds of Aldridge sediments that are younger than the ore zone beds. The reeent discovery of a late Precambrian granito pluton and its pegmatitic offshoots in the area establishes the fact that magmas capable of differentiation were active in the area about the time the orebody was formed as postulated by Swanson and Gunning (1945).

At the mine, the large masses of intensely metasomatized wallrock and the numerous cross-cutting sulphide veins and massive replacements of similar mineralogy are clear indications that mineralizing solutions had been very active after the sediments had become consolidated and altered. The remarkable zoning can also be explained better by an epigenetic hydrothermal than by a sedimentary process. Finally in view of the fact that orebodies are relatively rare because they are the result of unusual geological circumstances, the probability that an unusually large and rich sedimentary base metal sulphide deposit would be so intimately associated with epigenetic orebodies and their unique structural and environment must be very low indeed.

In conclusion, it must be apparent that the geologic evidence at hand offers very little support for a marine sedimentary origin for the Sullivan and that it abundantly if not conclusively supports an epigenetic hydrothermal origin. Even if this is accepted as the best working hypothesis, it must be realized that only the broad framework of the formative processes has been delineated and a tremendous amount of research is still needed to complete the picture satisfactorily.

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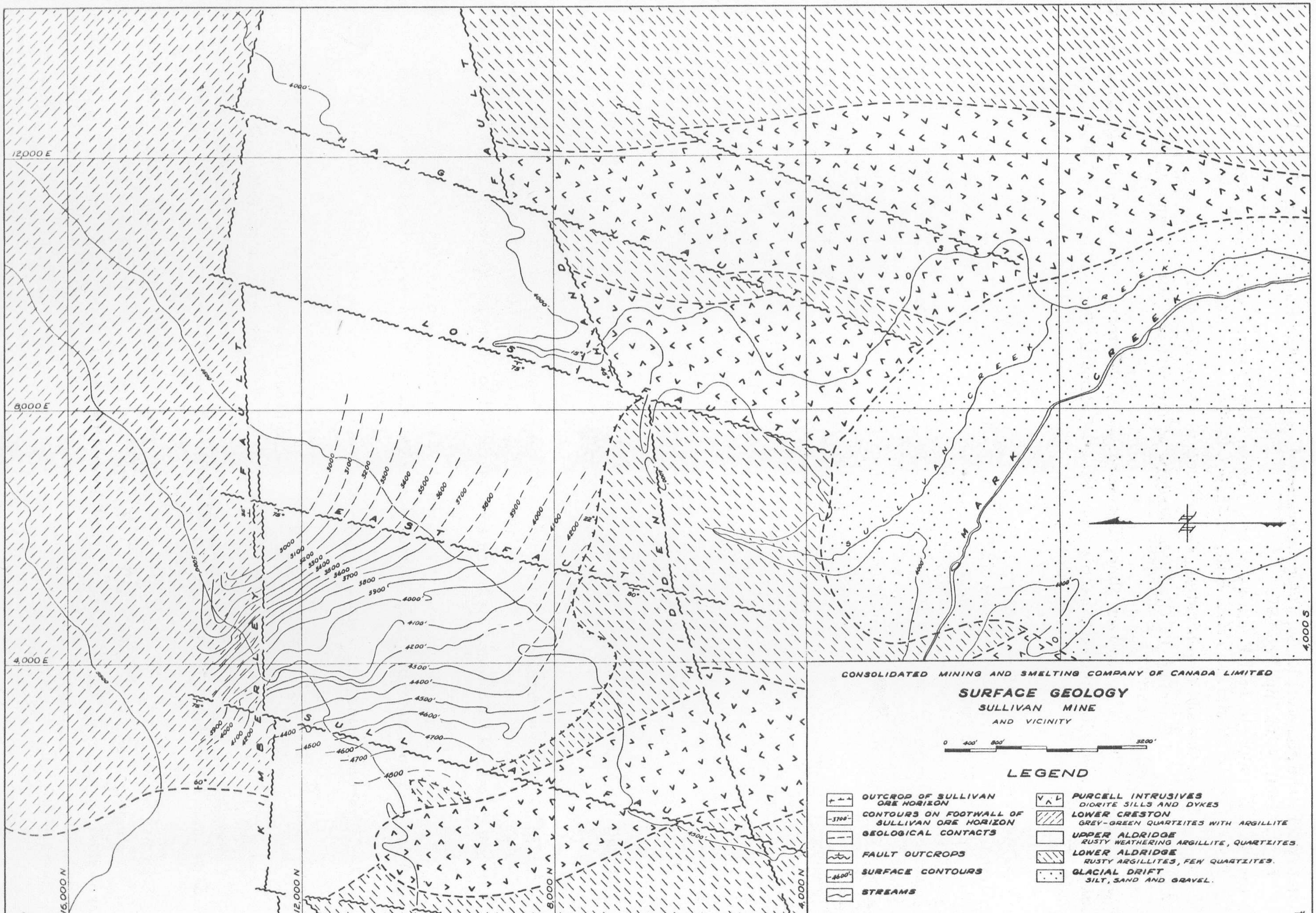
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SULLIVAN MINE
AND VICINITY
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CONTOURS ON FOOTWALL OF SULLIVAN ORE HORIZON
GEOLOGICAL CONTACTS
FAULT OUTCROPS
SURFACE CONTOURS
STREAMS
PURCELL INTRUSIVES
DIORITE SILLS AND DYKES
LOWER CRESTON
GREY-GREEN QUARTZITES WITH ARGILLITE
UPPER ALDRIDGE
RUSTY WEATHERING ARGILLITE, QUARTZITES.
LOWER ALDRIDGE
RUSTY ARGILLITES, FEW QUARTZITES.
GLACIAL DRIFT
SILT, SAND AND GRAVEL.
HAIG FAULT
LOIS FAULT
EAST FAULT
SULLIVAN FAULT
KIMBERLEY FAULT
DENNY FAULT
SULLIVAN CREEK
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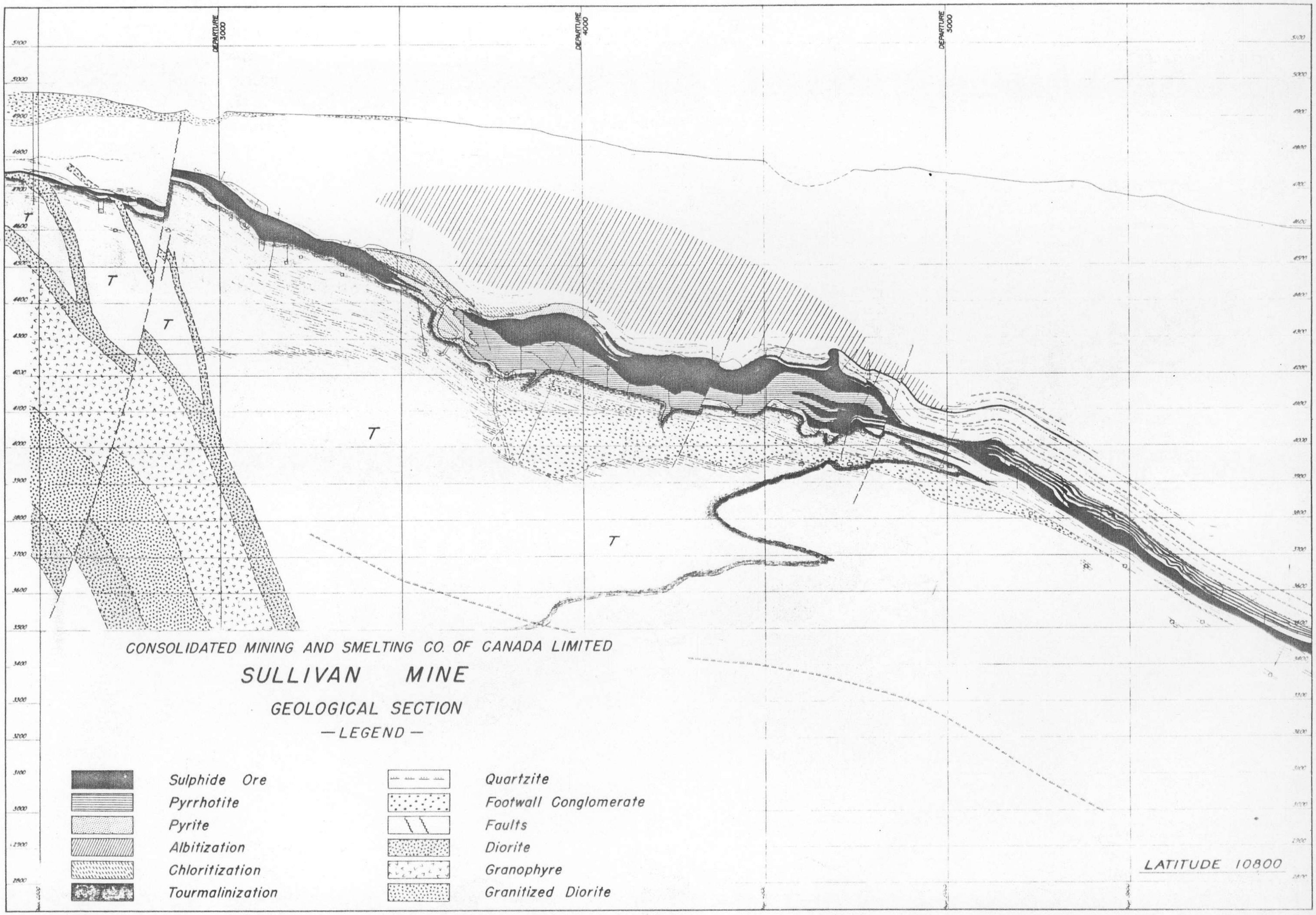
Figure 17-1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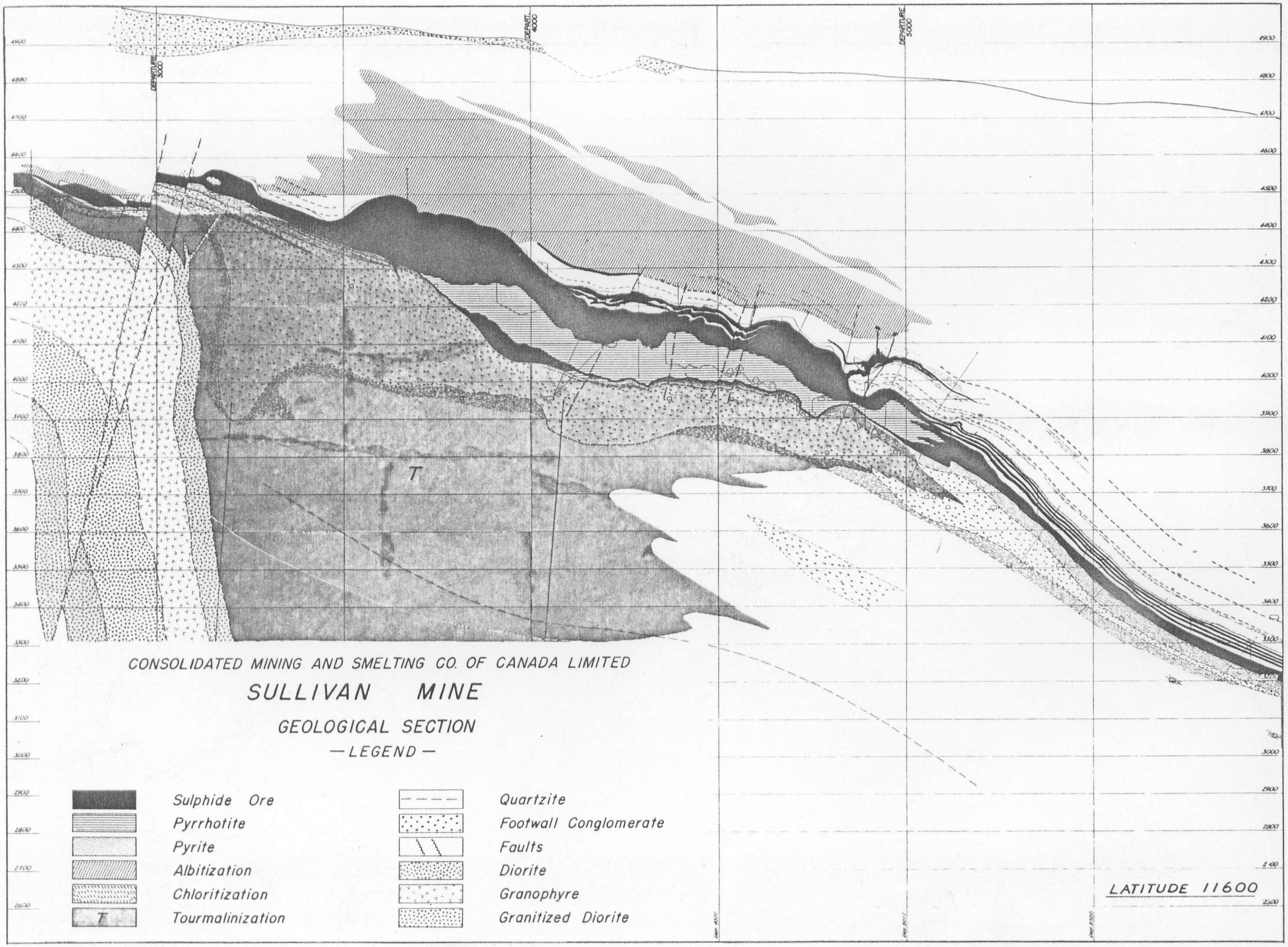
Sulphide Ore
Pyrrhotite
Pyrite
Albitization
Chloritization
Tourmalinization
Quartzite
Footwall Conglomerate
Faults
Diorite
Granophyre
Granitized Diorite
LATITUDE 10800

Figure 17-2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Pyrrhotite
Pyrite
Albitization
Chloritization
Tourmalinization
Quartzite
Footwall Conglomerate
Faults
Diorite
Granophyre
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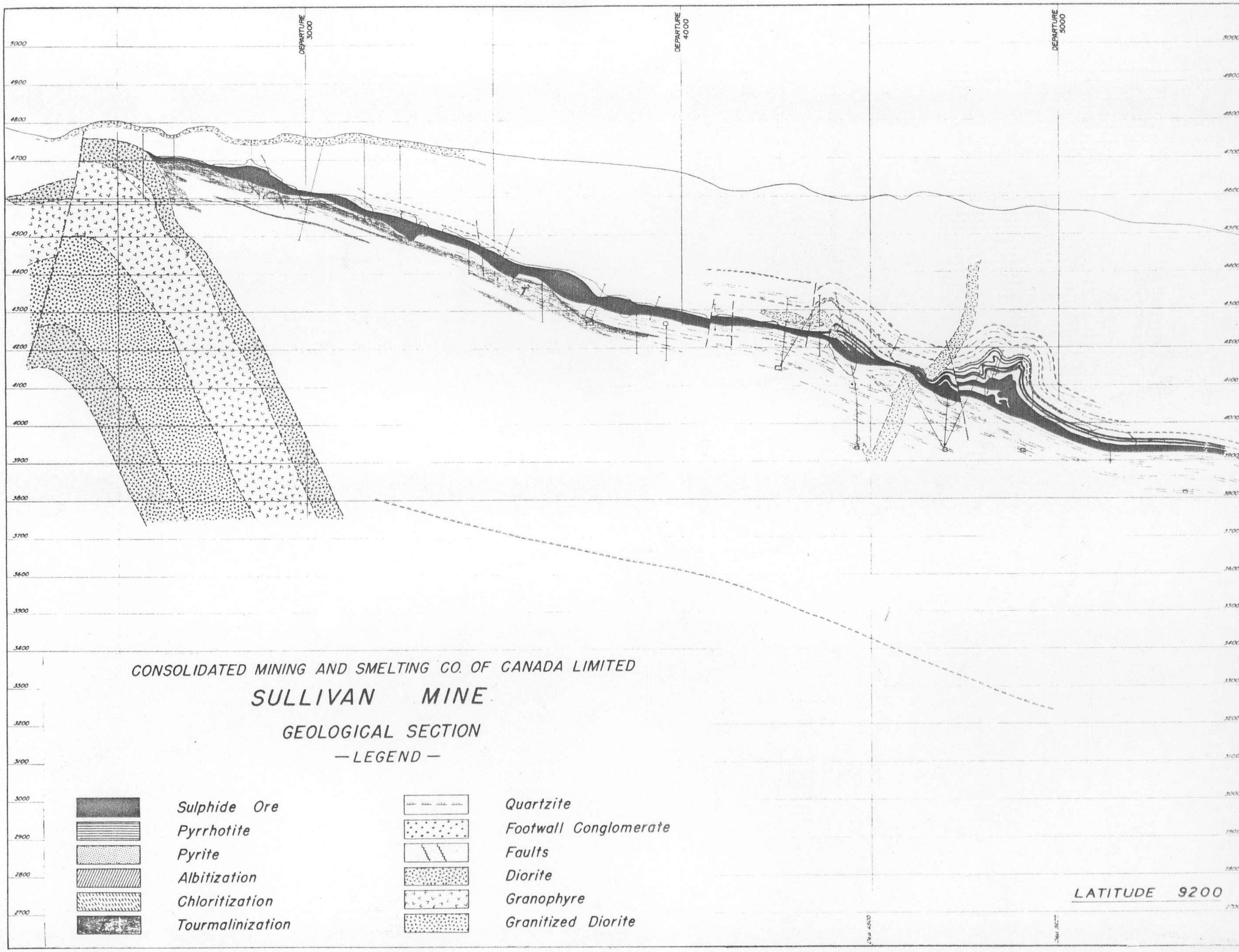
Figure 17-3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Pyrite
Albitization
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Tourmalinization
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Granophyre
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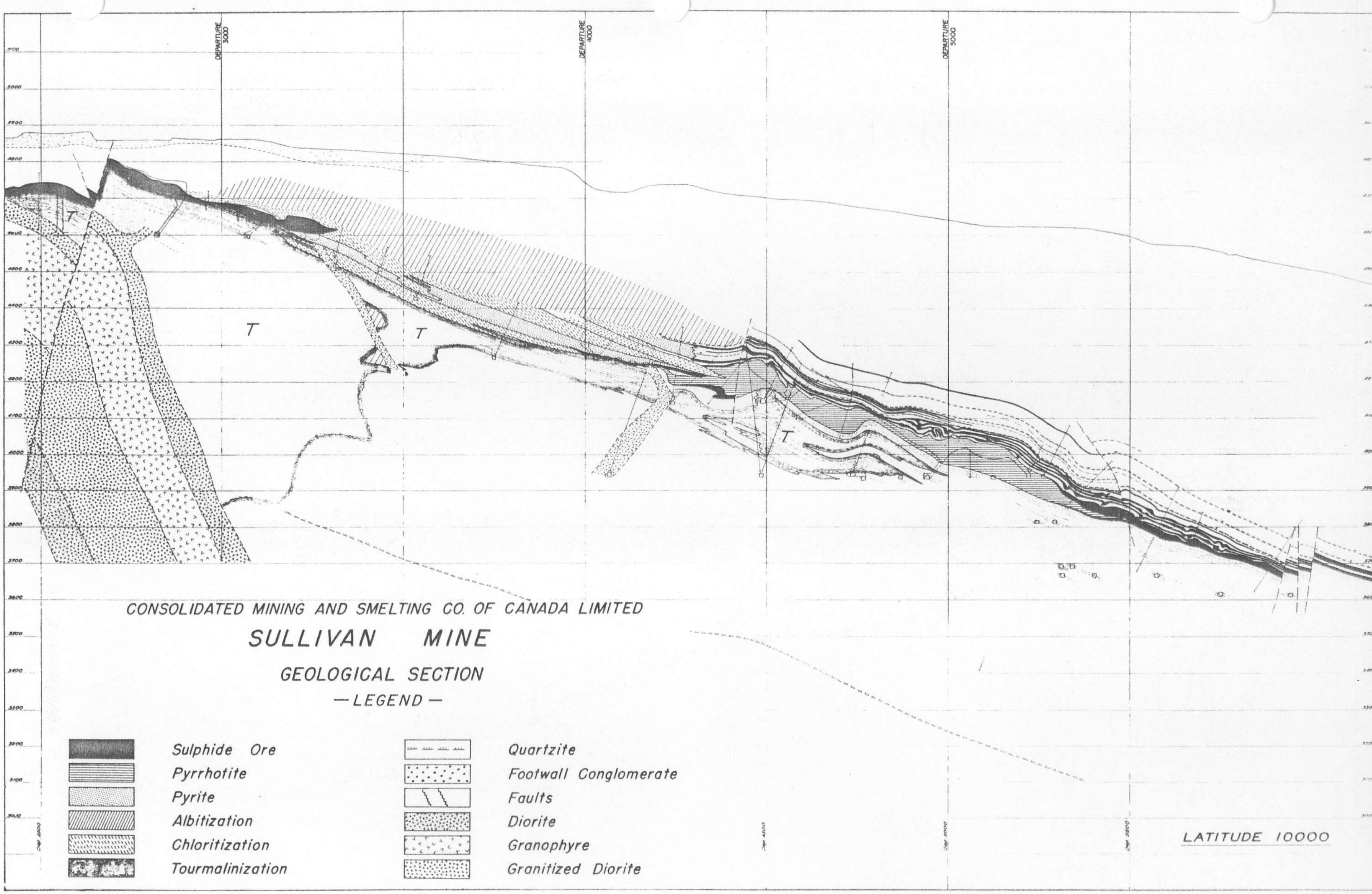
Figure 17-4



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SULLIVAN MINE
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Pyrrhotite
Pyrite
Albitization
Chloritization
Tourmalinization
Quartzite
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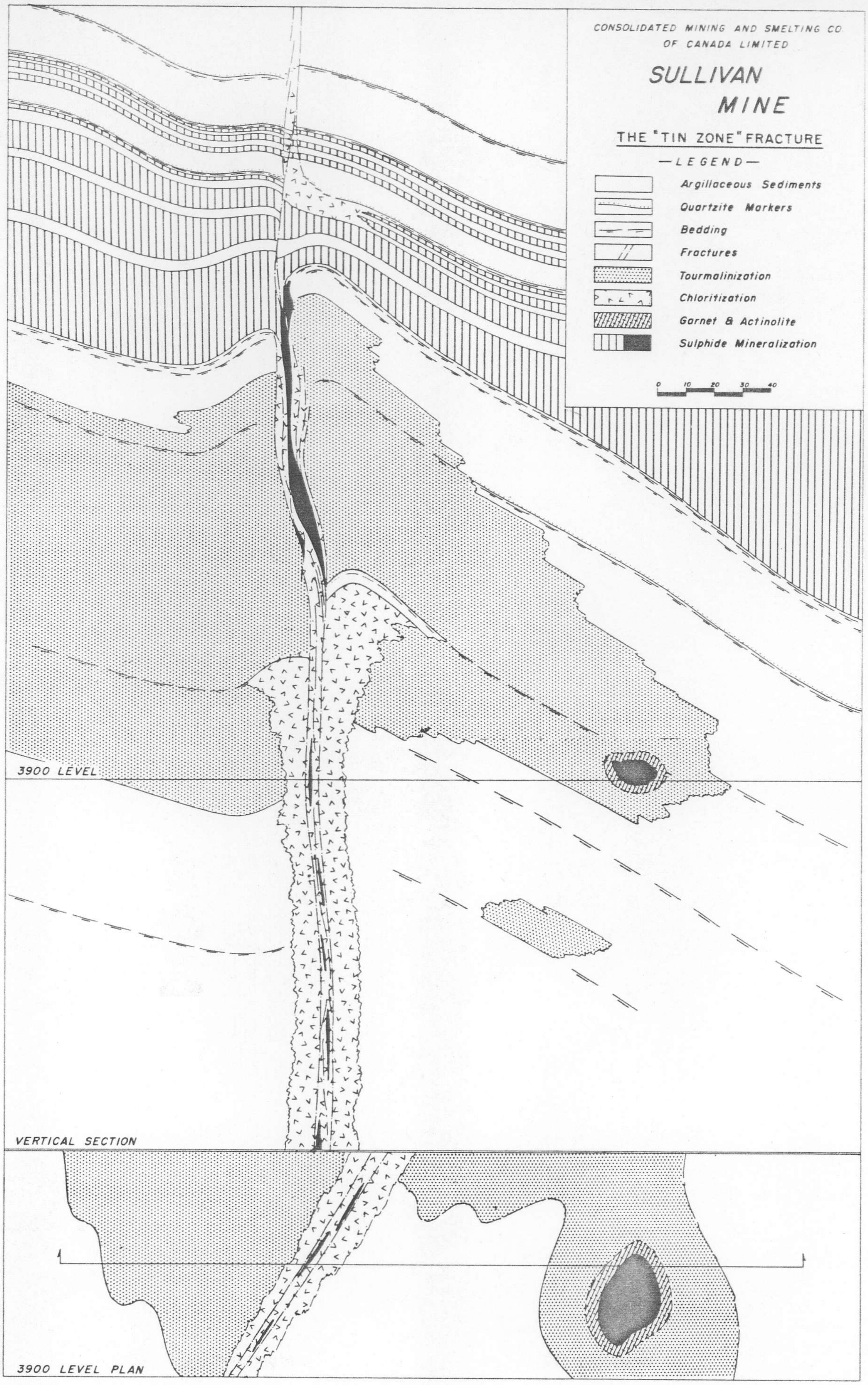
Faults
Diorite
Granophyre
Granitized Diorite
LATITUDE 10000


Figure 17-5



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SULLIVAN
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THE "TIN ZONE" FRACTURE
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Argillaceous Sediments
Quartzite Markers
Bedding
Fractures
Tourmalinization
Chloritization
Garnet & Actinolite
Sulphide Mineralization
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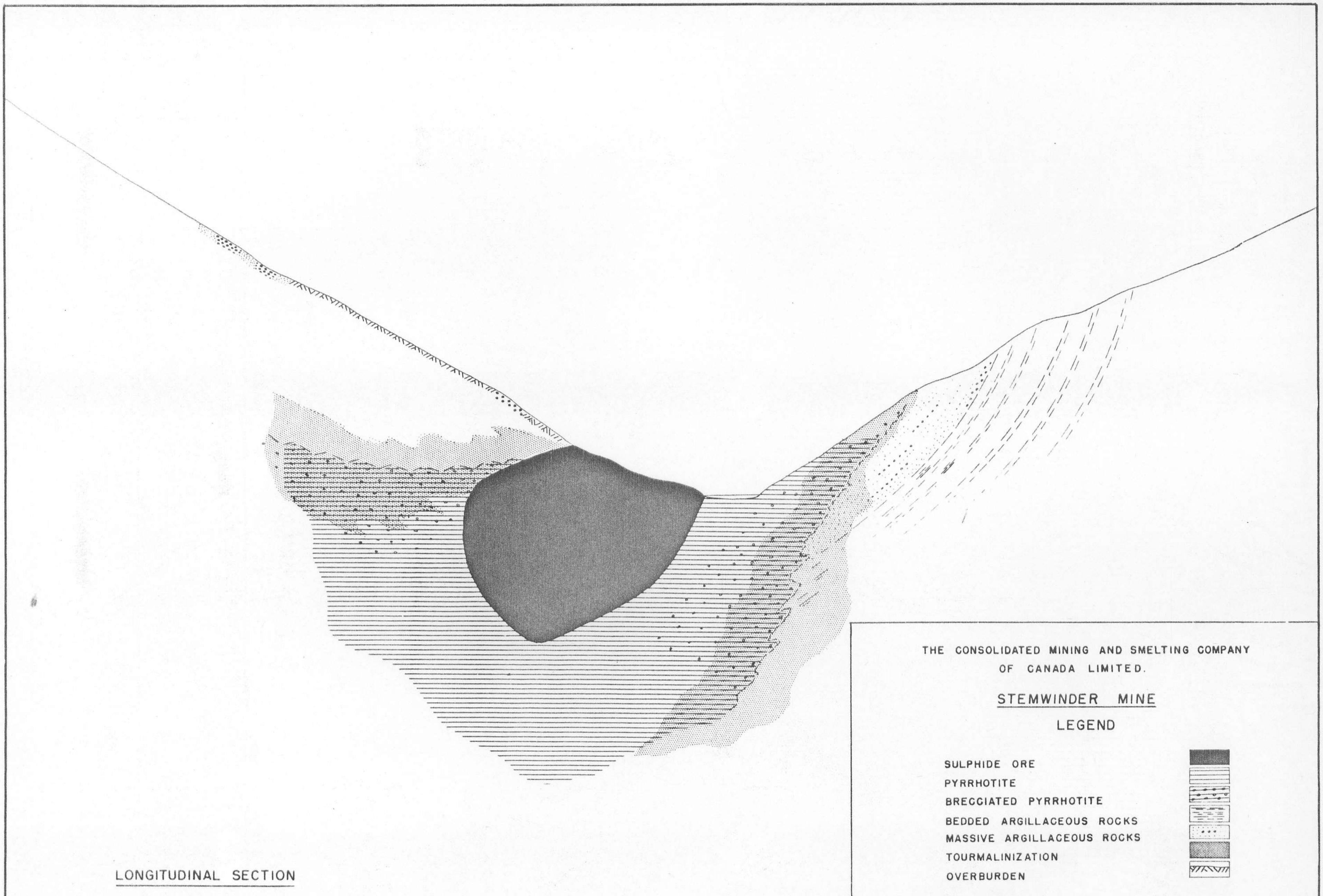
3900 LEVEL PLAN


Figure 17-6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SULPHIDE ORE
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BRECCIATED PYRRHOTITE
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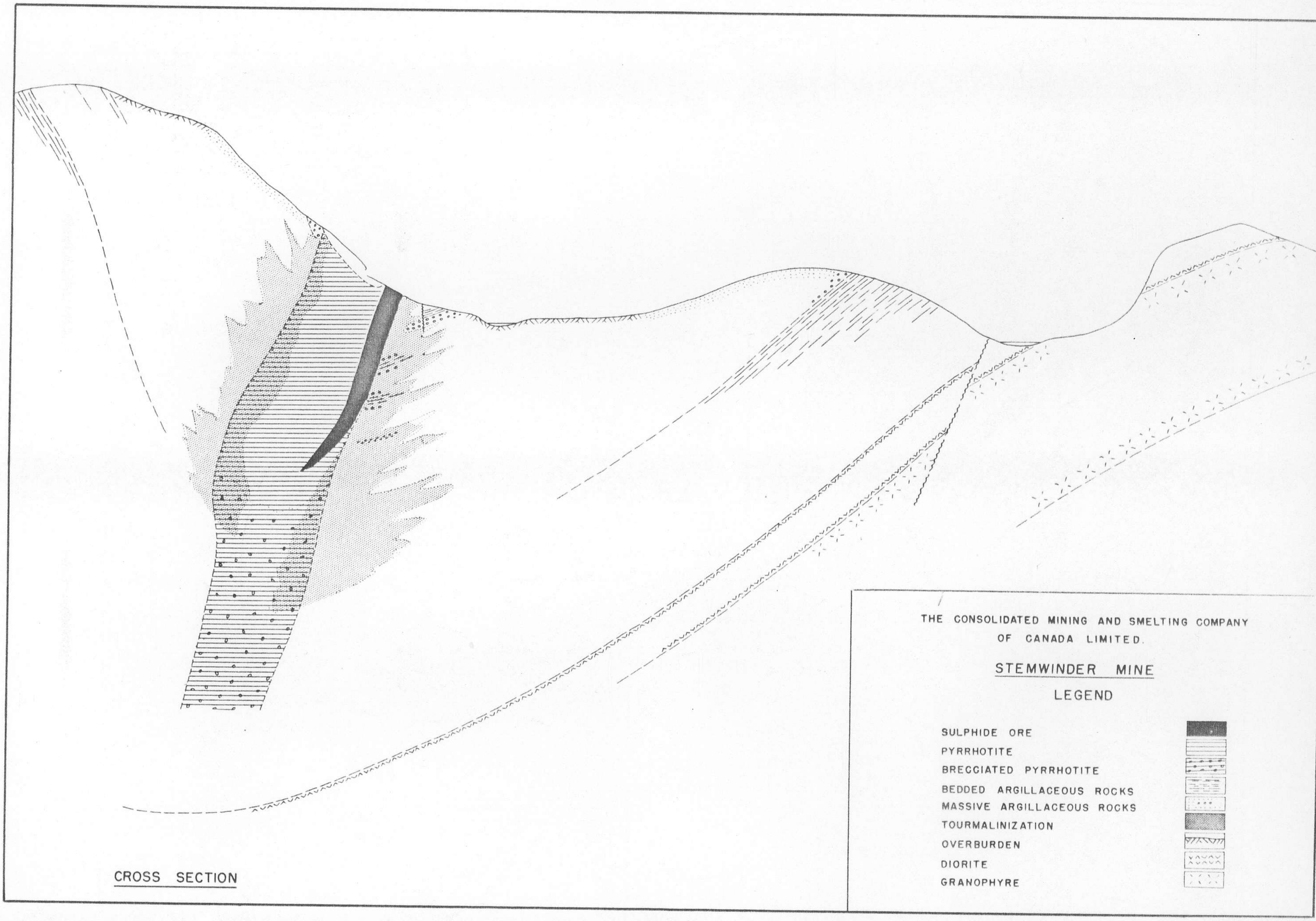
MASSIVE ARGILLACEOUS ROCKS
TOURMALINIZATION
OVERBURDEN
LONGITUDINAL SECTION

Figure 17-7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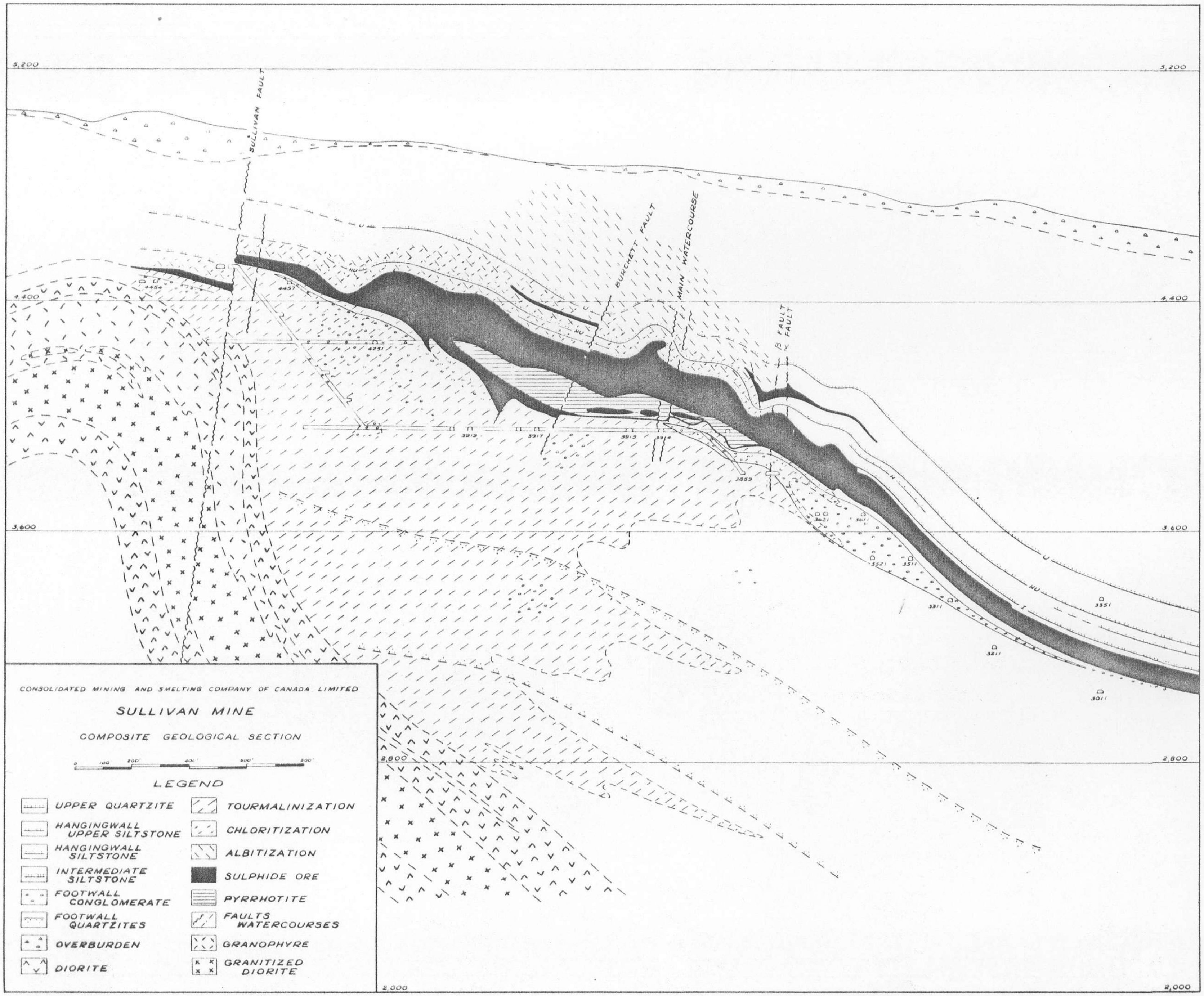
DIORITE
GRANOPHYRE
CROSS SECTION

Figure 17-8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HANGINGWALL UPPER SILTSTONE
HANGINGWALL SILTSTONE
INTERMEDIATE SILTSTONE
FOOTWALL CONGLOMERATE
FOOTWALL QUARTZITES
OVERBURDEN
DIORITE
TOURMALINIZATION
CHLORITIZATION
ALBITIZATION
SULPHIDE ORE
PYRRHOTITE
FAULTS WATERCOURSES
GRANOPHYRE
GRANITIZED DIORITE
SULLIVAN FAULT
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MAIN WATERCOURSE
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Figure 17-9

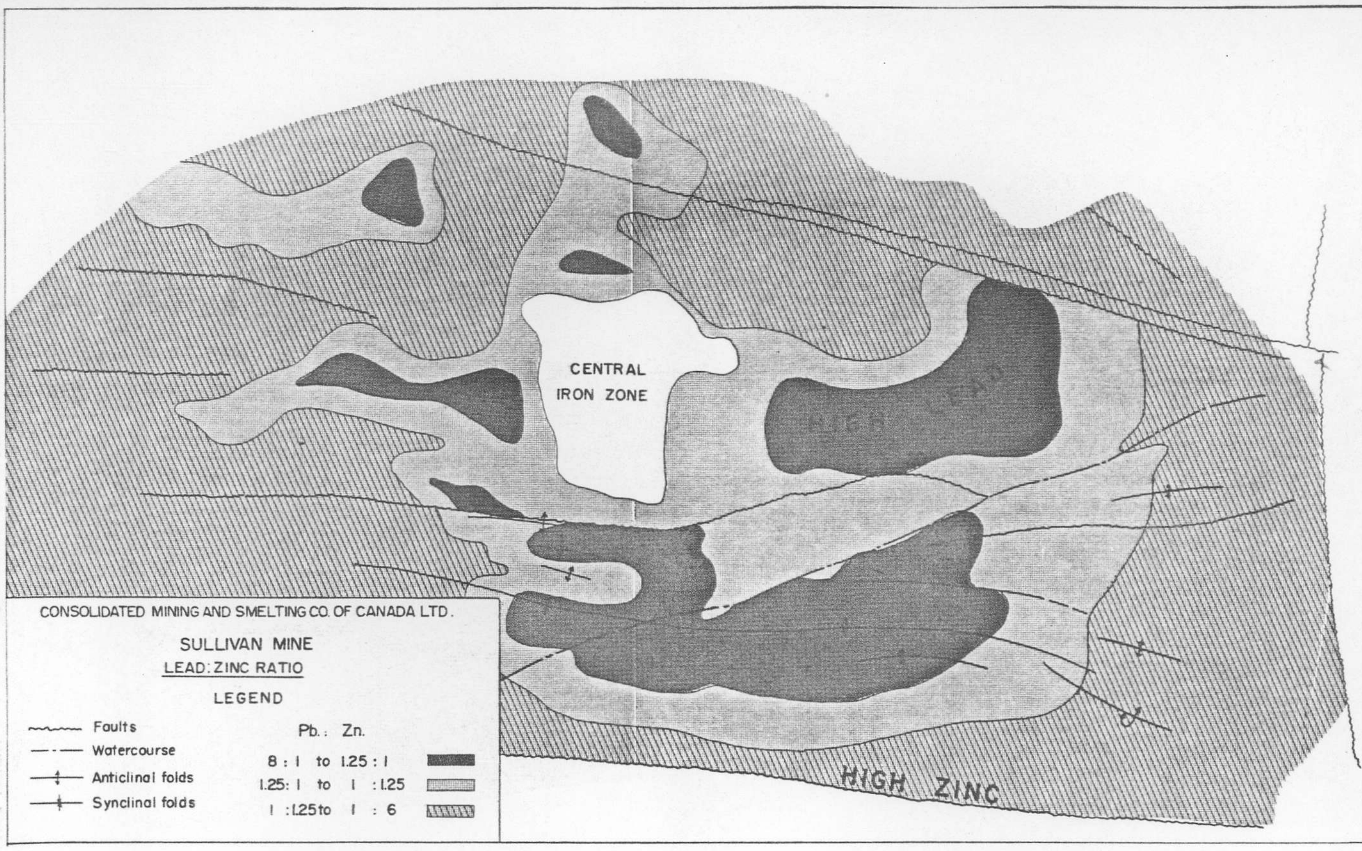
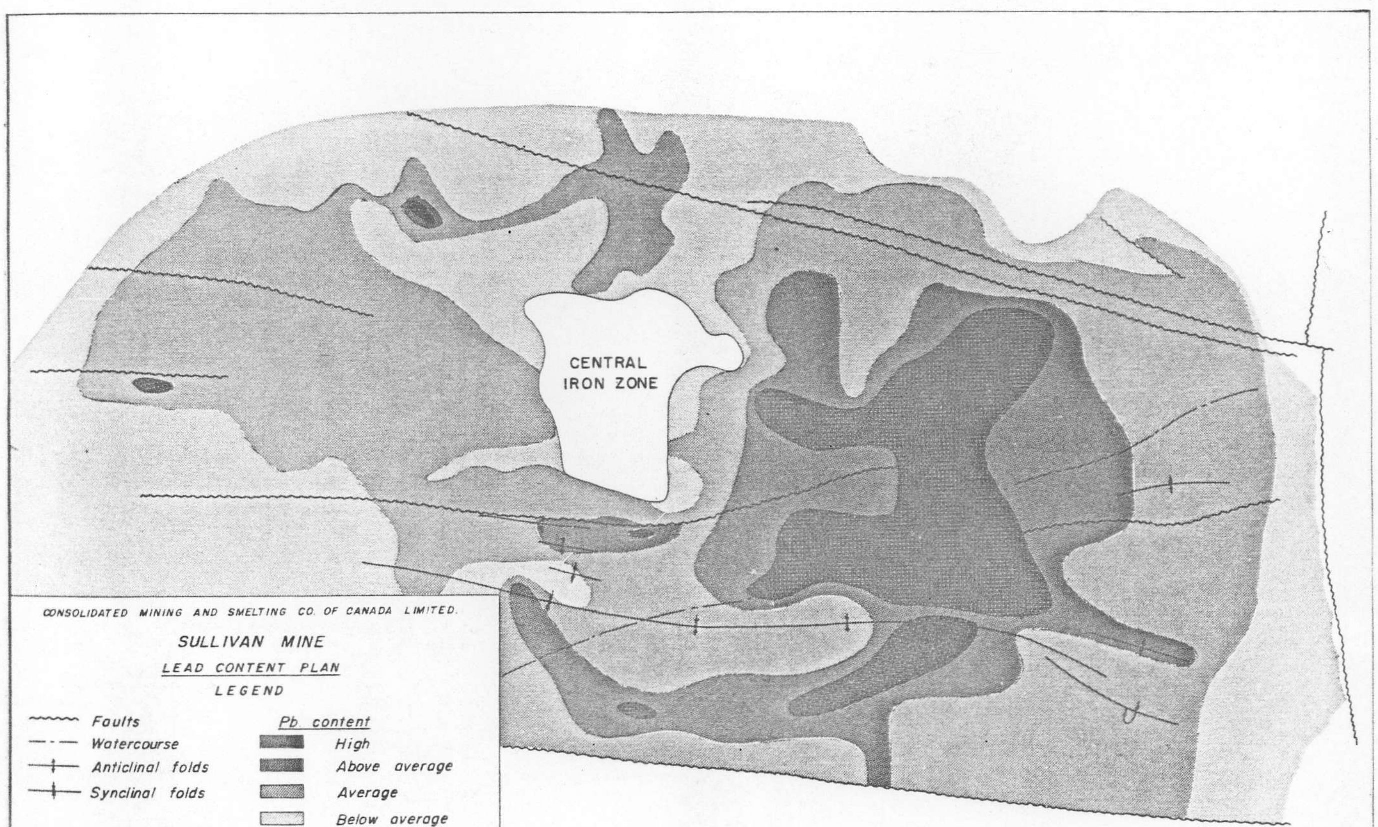



Figure 17-10

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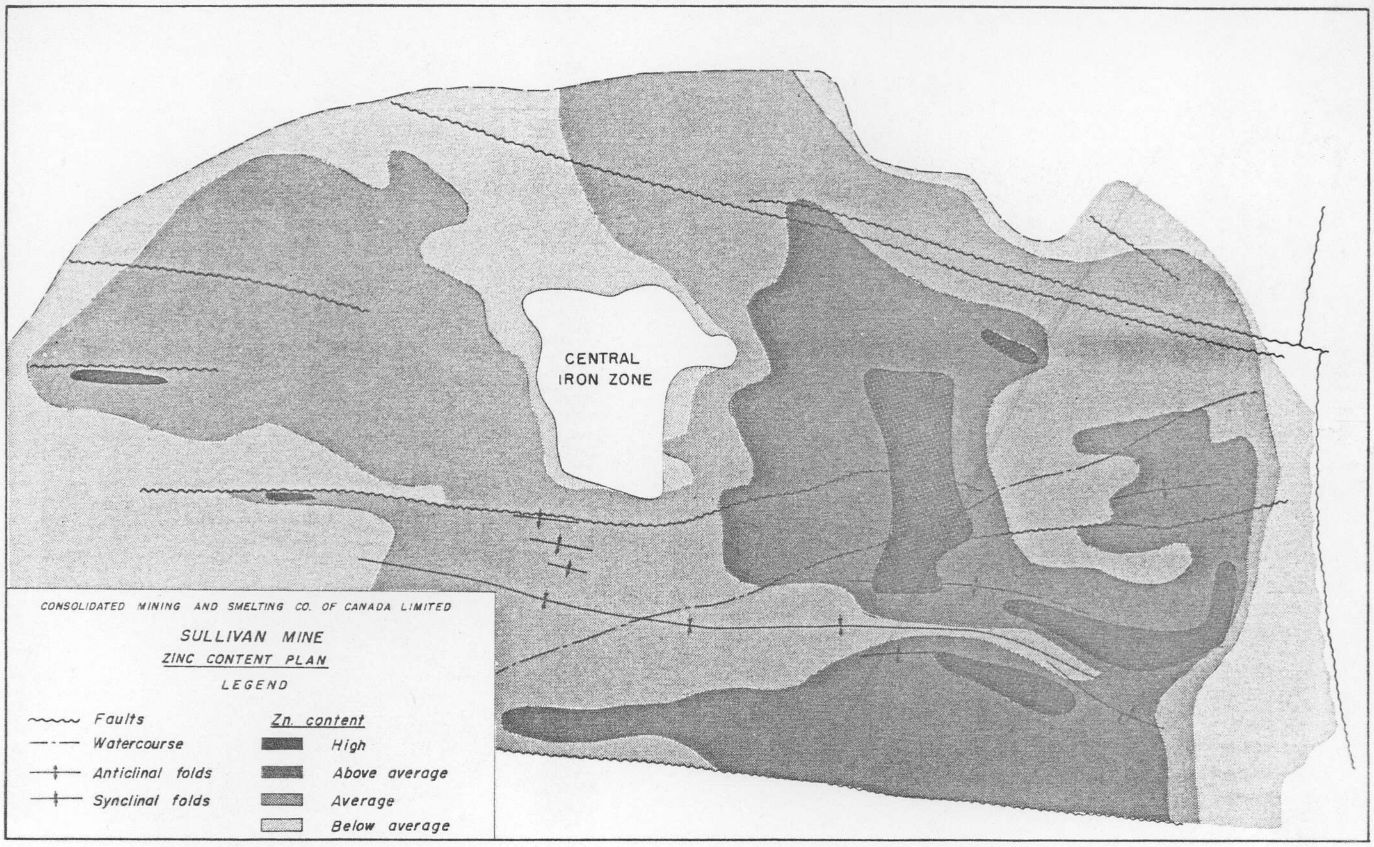


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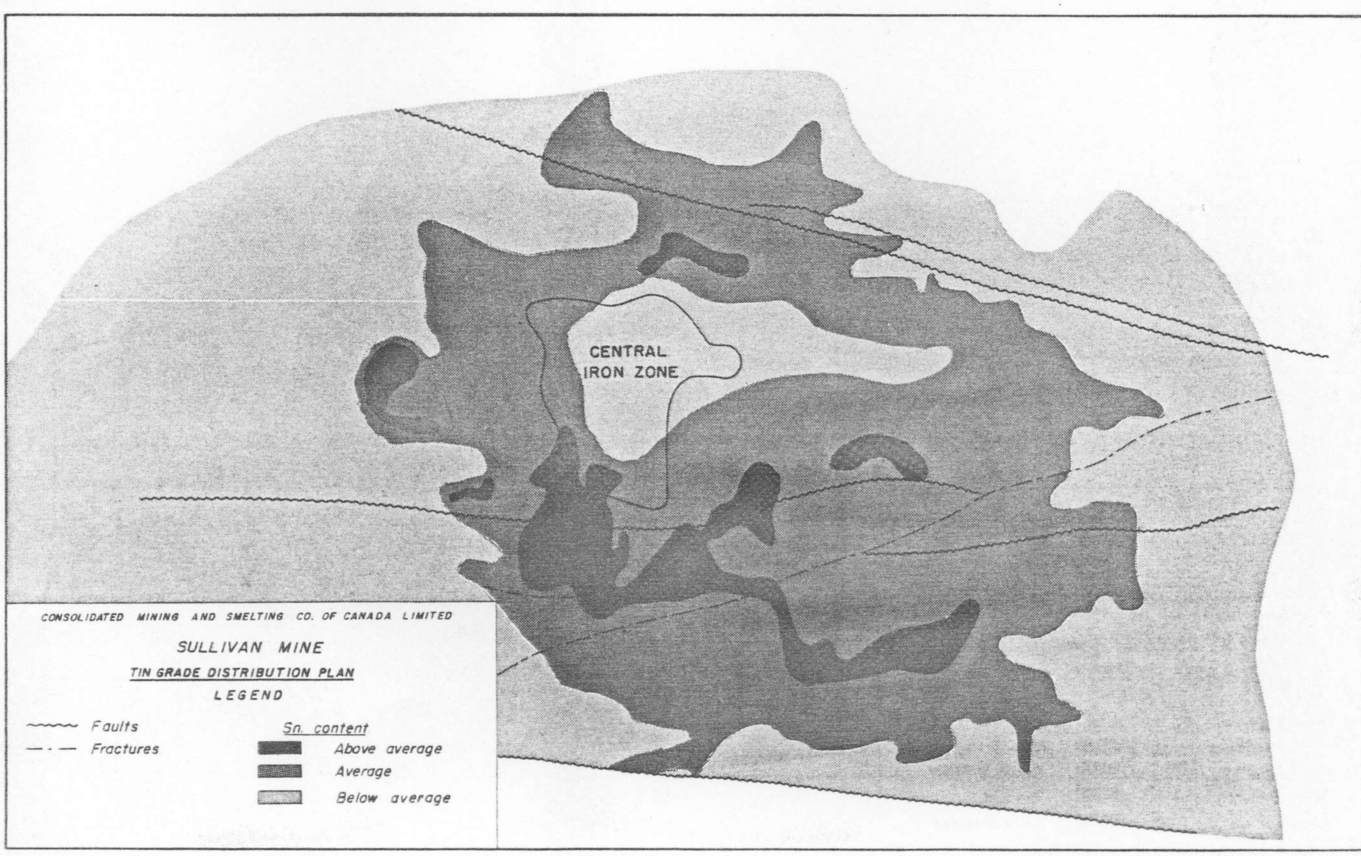


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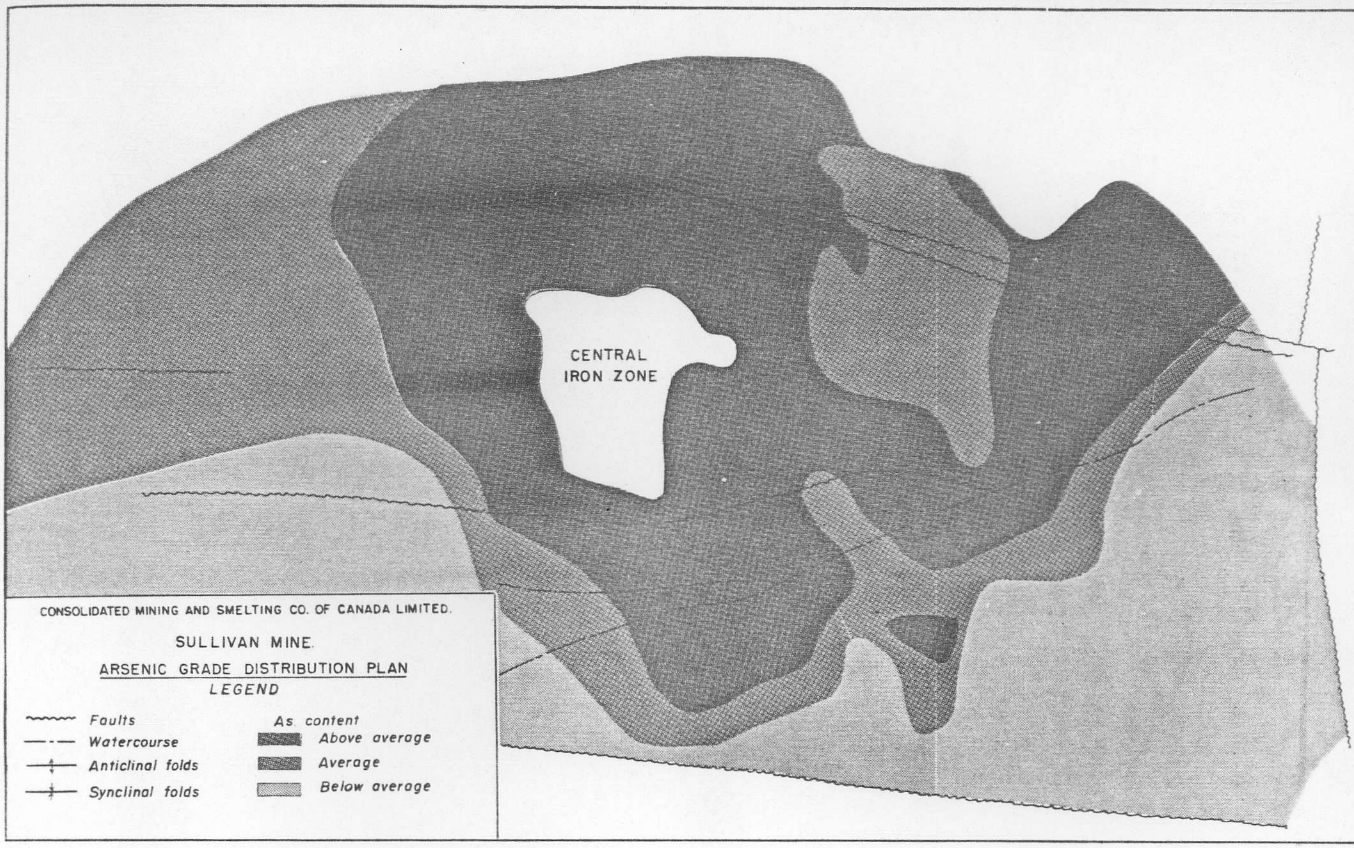


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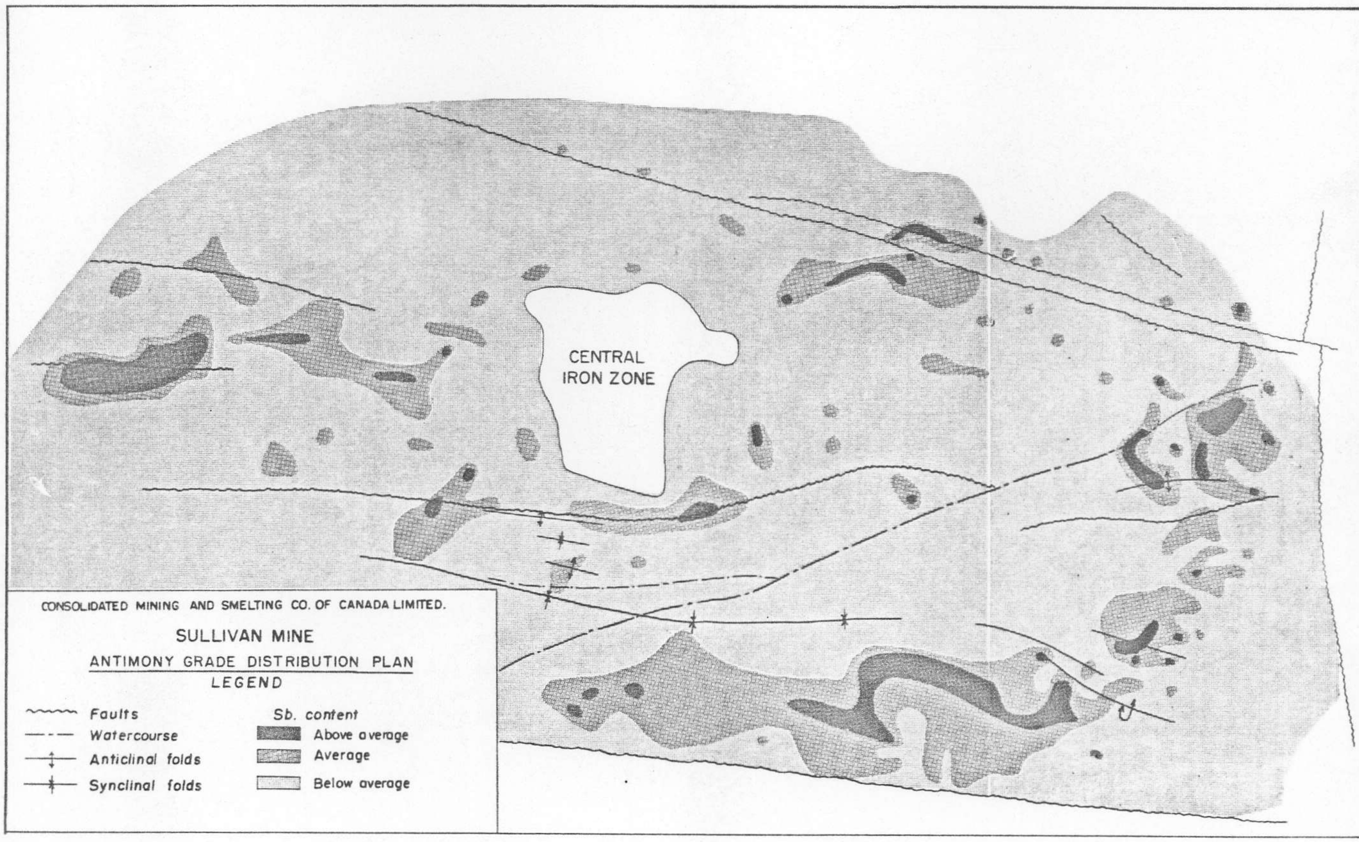


Figure 17-15

Figure 17-16

Drag folds in interbedded sulphides and argillite. The light coloured material is pyrite. Sphalerite is present in some of the darker beds. Massive argillite occurs above and below the banded sequence.

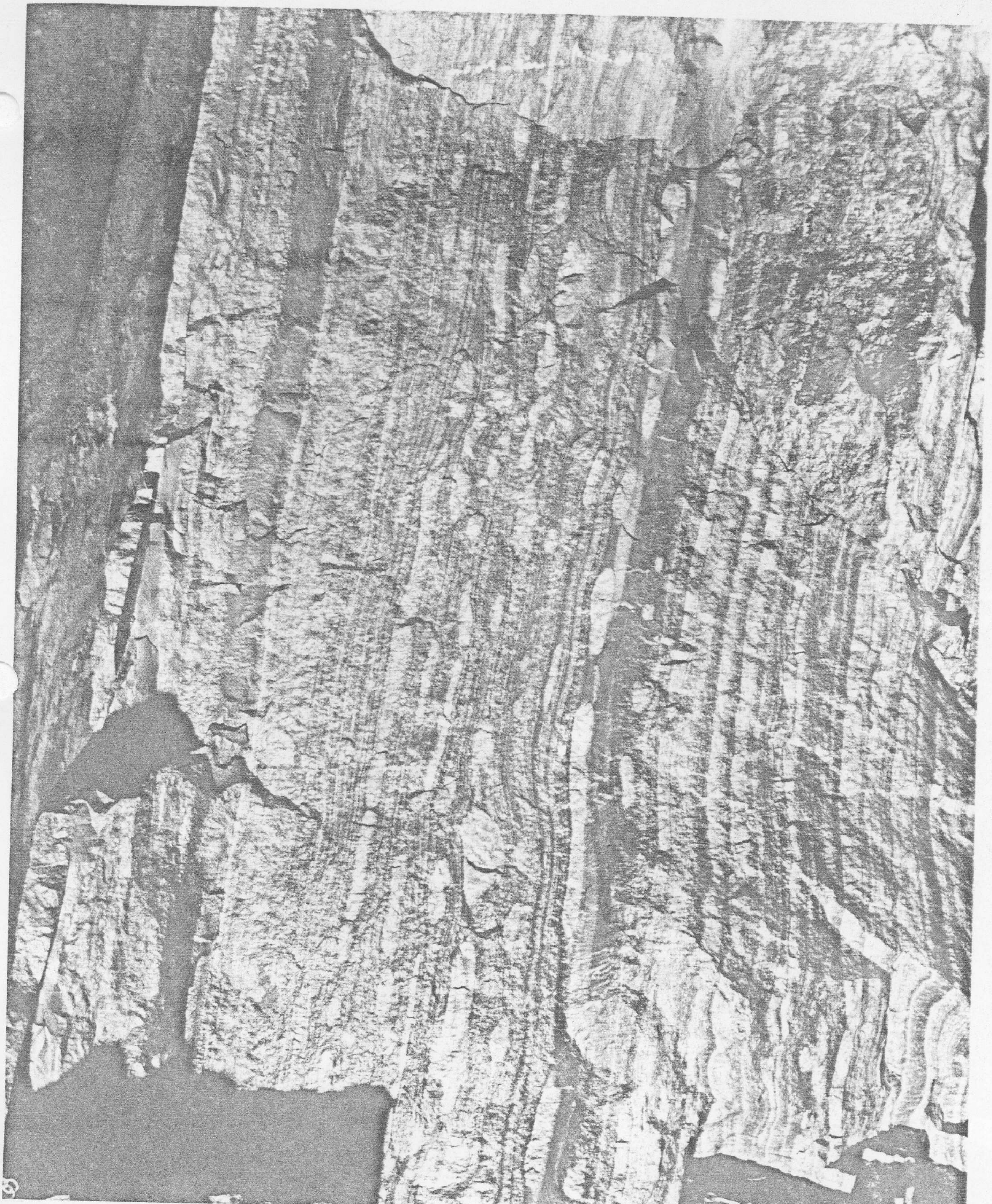

Figure 17-17

Nodular and lenticular pyrite units in interbedded pyrite and argillite. The dark, uniform appearing beds are argillite.

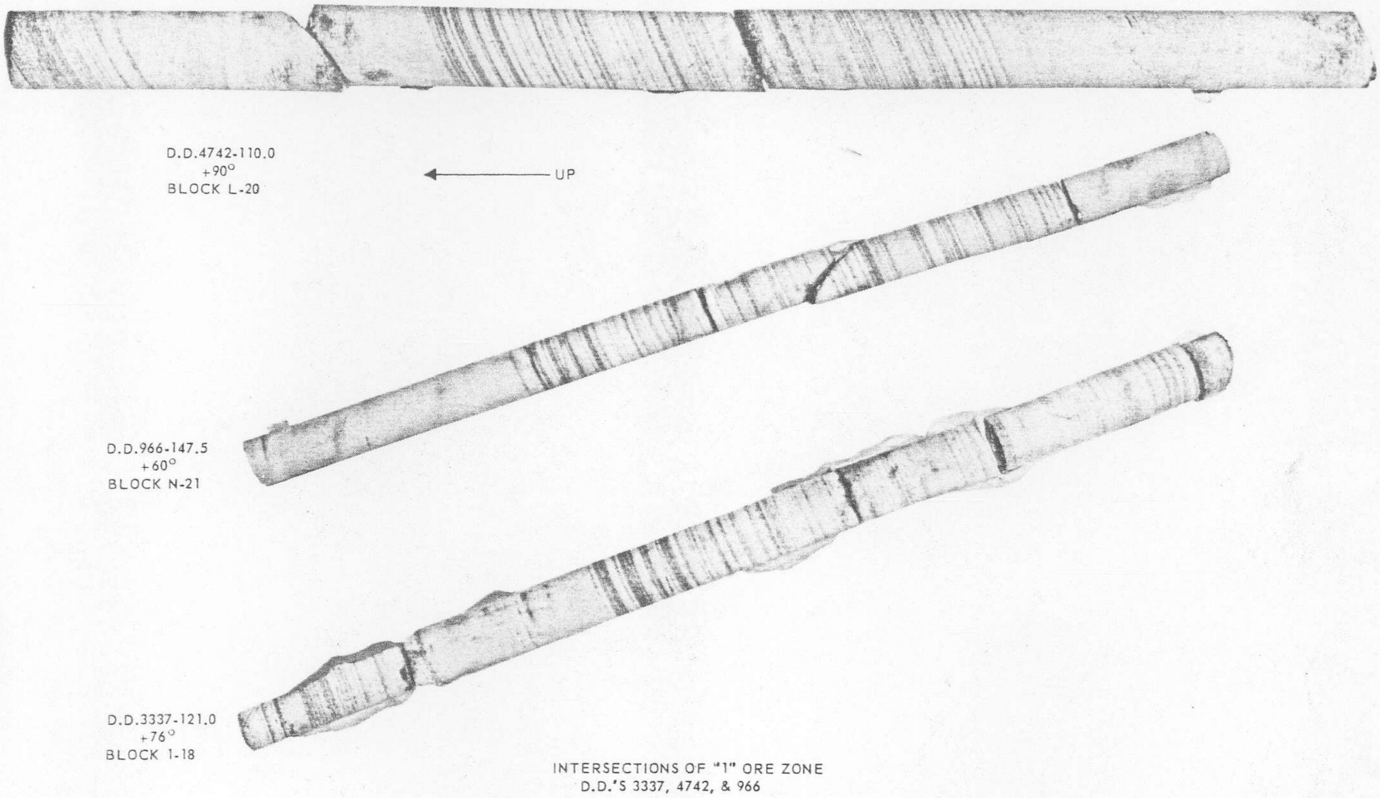


Figure 17-18

Pyrrhotite laminated argillite comprising the "I" laminated unit. The lateral interval represented by the three core specimens exceeds 1200 feet.