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DEPARTMENT OF ENERGY, MINES AND RESOURCES

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PRECAMBRIAN VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN CANADA: A REVIEW

D.F. Sangster

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Report and 11 figures

D.F. Sangster

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ABSTRACT

The paper brings together much of the current Canadian and foreign concepts relating to these deposits and its purpose is to summarize the main geological and chemical features of Canadian Precambrian deposits of this type, to compare and contrast these with similar ores in Japan, and to provide a selected bibliography. The Precambrian deposits occur in a wide variety of rock associations and types, they differ in several important aspects from Phanerozoic ores of the same type, and, as a group, provide many examples of post-ore metamorphic effects.

The Sullivan mine, a large lead-zinc deposit occurring in Proterozoic sediments, is shown to have many geological features in common with volcanogenic ores and is considered to be an example of an exhalative deposit in a sedimentary, rather than volcanic, environment.

RÉSUMÉ

Cette étude réunit plusieurs théories formulées au Canada et à l'étranger au sujet des dépôts de ce genre. L'auteur présente un résumé des principales caractéristiques géologiques et chimiques des gisements précambriens canadiens de cette catégorie, les compare à diverses minéralisations similaires du Japon et offre un choix de références bibliographiques. Les gisements précambriens dont il est question se présentent dans un grande variété de roches, tant du point de vue des types que des groupements; ils diffèrent, sous divers aspects importants, des minéralisations phanérozoïques du même type et enfin, en tant que groupe, offrent plusieurs exemples des effets d'une métamorphisation s'étant produite après la minéralisation.

Selon l'auteur, le minerai de la mine Sullivan, grand gisement plombo-zincifere situé dans des sédiments protérozoïques, partagerait plusieurs caractéristiques géologiques avec les minerais d'origine volcanique et doit être considéré comme un exemple de dépôts d'exsudation en milieu sédimentaire plutôt que volcanique.

PRECAMBRIAN VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN CANADA: A REVIEW

INTRODUCTION

This paper arises from the author's own observations together with the available literature and is presented as a geological review of the subject. In spite of the ever-increasing amount of literature on volcanogenic massive* sulphide ores, an overview of the Canadian situation, particularly in the Precambrian, has not appeared.

Little of what is contained in this review will be news to major mining and exploration companies. Rather, it is directed toward the junior mining concerns, oil companies launching into metals exploration, consultants, students, and government agencies who may require a summary of these important deposits. The paper attempts to bring together much of the current Canadian and foreign concepts relating to these deposits and its purpose is to summarize their main geological and chemical features, to compare and contrast these with well-documented ores of similar type in Japan, and to provide a selected bibliography on several aspects of these ores. By this means, the paper is intended to provide background reference, as well as to guide exploration for and research into, massive sulphide deposits in Canada.

Stratabound volcanogenic* massive sulphide deposits are an extremely important part of Canada's mineral heritage. Of total Canadian metal production in 1969, for example, 71 per cent of the zinc, 50 per cent of the copper, 32 per cent of the lead, and 59 per cent of the silver came from this type of mineralization. In terms of metal value, Cu, Pb, Zn, and Ag from volcanogenic deposits accounted for approximately one-third (31 per cent) of Canada's total metal production value in that year.

Economic deposits of this type have been recognized in rocks ranging in age from Archean to Triassic. However, of the approximately 100 deposits of this type in Canada known to the writer, more than two-thirds occur in the Precambrian. Moreover, the Precambrian ores occur in a wide variety of rock associations and types, they differ in several important aspects from Phanerozoic ores of the same type, and, as a group, provide many excellent examples of post-ore metamorphic effects.

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*The term "volcanogenic" stresses the genetic connection between these deposits and volcanism and/or volcanic processes. The term "massive" refers to mineralization composed almost entirely of sulphides and does not carry any textural connotation.

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Acknowledgments

It would be futile to name the many geologists who have contributed, by personally sharing with the author their experiences and observations of Canadian volcanogenic deposits, to the many facets of this extremely interesting and geologically significant class of ores. Instead, by acknowledging with pleasure the scientific guidance, moral encouragement, and even material assistance of Canadian mining and exploration companies, consultants, provincial and federal geological institutions, and universities, the author hopes that his colleagues will thereby realize that their contributions have been recognized and sincerely appreciated.

Special thanks are extended to Charles Bruce, who drafted the diagrams, and to W. R. A. Baragar, Geological Survey of Canada, for reviewing the manuscript.

GENERAL GEOLOGICAL FEATURES

Nature and Depositional Environment of Host Rocks

A majority of the Precambrian massive sulphide ores occur within a volcanic complex several tens of thousands of feet thick comprised of three main volcanic lithologies (Goodwin, 1968). Typically, the first and lowermost portion of the complex is a thick series of pillowed and vesiculated flows characteristically basaltic. This is followed upward by flows, flow breccias, and tuffs of mainly andesitic composition. The third and uppermost portion of the complex contains abundant, and is possibly predominantly composed of, volcanics of dacitic to rhyolitic composition which may be either massive, textureless flows and/or abundant pyroclastics of various size ranges. The acidic phase usually marks the end of a single volcanic cycle after which another cycle may begin, in which case the succeeding rocks are the typical basal basalts, or the volcanism may cease, in which case the complex becomes surrounded or mantled in a thick sequence of greywacke-type sediments derived partly or entirely from the volcanics themselves. In some cases, the waning phases of volcanism appear to be contemporaneous with sedimentation and, in such cases the rocks may grade imperceptibly, both laterally and vertically, from "true" tuffs and fine pyroclastics, through reworked tuffs and volcanic sediments, into greywackes containing various amounts of volcanic component, and finally into "true" sediments in which the volcanic component is lacking or minimal.

It is also characteristic of the ore-containing volcanic piles that they be intruded by rocks of diverse composition such that, as a whole, they exhibit as much differentiation as the extrusives themselves. Hence, within many regions of massive sulphide deposits it is not uncommon to find major intrusions of ultramafics, gabbro, diorite, granodorite, and even granite. Acidic intrusions are usually much more abundant than the mafic or ultramafic variety and frequently are found as large stocks at or near the centre of the volcanic pile. As such, they may represent part of the magmatic hearth which originally spawned the volcanism and later moved upward to intrude its own daughter products. The Matagami area is somewhat anomalous in that, instead of an acidic pluton in the volcanic core, it is centred around an elongate intrusion of layered gabbroic rocks (Sharpe, 1968).

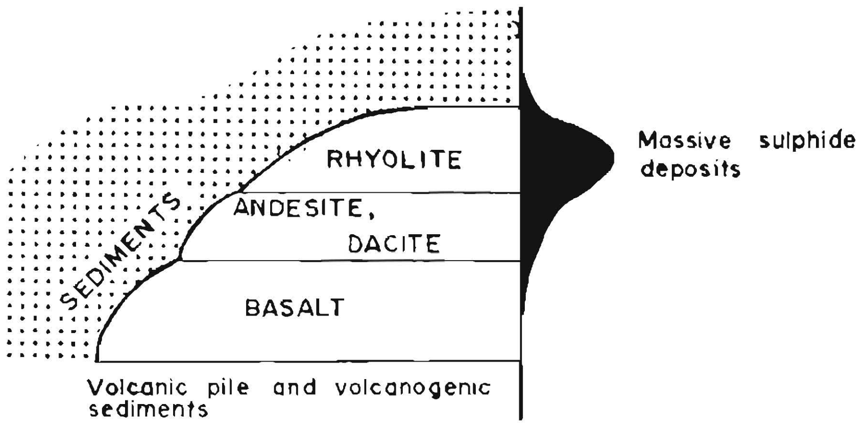


Figure 1. Relative abundance of massive sulphide deposits in the volcanic and sedimentary components of a schematic Archean volcanic pile (modified after Goodwin, 1968).

The most common host rocks in the immediate vicinity of most orebodies are the acidic, usually clastic, phases of volcanism. Agglomerates, coarse tuffs, or occasionally, massive dacitic to rhyo-dacitic flows constitute the ore horizon of many massive sulphide bodies. Ore may occur entirely within the acidic portion, or at the contact between dacite (rhyolite) and andesite, or, less commonly, entirely within the andesitic portion of the pile. The volcanic pile (and volcanogenic sediments) is diagramatically illustrated by Figure 1. In multicyclic volcanic accumulations, ore formation often occurs in association with only one of the acidic phases; similar rocks in other phases of the same pile will be barren. Even within one volcanic cycle, the acidic portion sometimes consists of several rhyolite-andesite phases, only one of which contains ore. For example, Spence (1967) has recognized up to five acidic phases of volcanism in the Noranda area but sulphide ores are associated with only one of these.

The close spatial association between acid agglomerates (or coarse pyroclastics) and massive sulphide ores is a characteristic feature of so many established mining camps in the Precambrian that, in attempting to emphasize this close association, the author once remarked to his colleagues that whenever he stood on the outcrop containing the largest fragments of acid pyroclastic in any given mining camp, he could invariably hear the mine mill nearby. His colleagues immediately dubbed this distinctive lithology "mill-rock" and since then, "mill-rock" has been observed close by most massive sulphide deposits in Precambrian volcanic rocks. In most cases, more than one-third of the pyroclastic fragments in "mill-rock" are of block-size or larger (greater than 64 mm). The rock would therefore be termed a tuff-breccia or pyroclastic breccia according to the classification of volcanoclastics proposed by Fisher (1966). "Mill-rock" is generally found in, or close to (commonly stratigraphically above), the volcanic unit in which the massive sulphides occur. With diminution of fragment size, "mill-rock" grades laterally into lapilli-tuff or tuff. Although the method of fragmentation to produce "mill-rock" and its equivalents is reasonably clear (i.e. explosive volcanism), the method of deposition is not. The extremely coarse fragments may have been deposited directly after the explosion but the finer particles could have been air-borne, water-borne or borne by pyroclastic flows. The latter, generally referred to as ignimbrites when they occur sub-aerially (Marshall, 1935) have recently been suggested as occurring under water as well (Fiske, 1963). In the author's experience, "mill-rock" (the coarsest fragments), whatever its method of deposition, can be found within one half-mile of most Precambrian massive sulphide deposits. In addition to volcanic rock fragments, it is not uncommon to find fragments of sulphides also occurring in "mill-rock" (Rokachev, 1965). The sulphide clasts are either angular or subround (or both) and are generally composed predominantly of pyrite although lesser amounts of other sulphides have also been observed (e.g. Sinclair, 1971). In some of the larger fragments sulphide banding can be discerned. The maximum size of the sulphide fragments in any exposure of "mill-rock" is generally slightly less than the largest fragments of volcanic rock. The pyroclastic origin of the larger sulphide fragments is reasonably clear but with diminishing fragment size in the pyroclastic unit, sulphide <u>fragments</u> become increasingly difficult to distinguish from sulphide <u>grains</u> which may or may not be of pyroclastic origin. In spite of the obvious importance of "mill-rock" in the exploration for massive sulphide deposits, the writer is aware of only one mineral exploration company which is <u>systematically</u> measuring and mapping the size and composition of volcanoclastic fragments in its exploration program. Neither provincial nor federal government geological maps, even on one mile scale, point out or locate the occurrences of coarse acid pyroclastics; volcanic fragmental units are routinely identified but occurrences of unusually coarse fragments (in any one pyroclastic unit) should also be identified because of their common close association with massive sulphide ores.

In addition to "mill-rock", quartz porphyry is a common host to, or close associate of, these ores and in many areas the geologist has difficulty in deciding whether the porphyry is extrusive or intrusive. In the Flin Flon area, for example, massive lenses of quartz porphyry originally considered by Stockwell (1960) as extrusive, can now, with new exposures available, be traced along strike into pyroclastic units of the same lithology. It is likely that, near the top of a volcanic pile, shallow intrusives could conceivably "break through" and form local extrusive accumulations and result in both intrusive and extrusive equivalents of the same lithology.

Rocks which are transitional between the "pure" volcanics and "pure" sediments, and variously referred to as volcanic sediments, sedimented volcanics, slightly reworked tuffs, "tuffwackes", etc., constitute the next most common host rock of massive sulphide ores after the acid volcanics. These rocks, as a rule, exhibit better, and laterally more persistent, layering than do the true volcanic rocks. They contain deposits which generally show more pronounced layering (bedding?) than do those in the massive volcanic rocks and have a tendency to be more blanket-like in form rather than ovoid. In all other respects, however, (size, grade, mineralogy, composition, etc.) the deposits are identical with those occurring in "pure" volcanic rocks. The layered host rocks, exhibiting more sedimentary features than volcanic, are best developed in the waning stages of volcanism and hence are usually found on top of, and peripheral to, the main volcanic pile. In spite of difficulties in correlating Precambrian volcanics and sediments, there is some evidence to show that sediments correlative with an ore-bearing volcanic cycle (or pile) will themselves contain massive sulphide ores adjacent to the volcanic centre. A correlation of this type has been suggested by Bailes (1971) for the Flin-Flon-Sherridon area of Manitoba.

The abundance of pillows in the basalts and andesites of the complex, the graded bedding in greywackes, and the frequent association with cherty iron-formation implies a submarine depositional environment for the Precambrian volcanics and sediments. Phanerozoic rocks, containing similar massive sulphide ores, commonly contain marine fossils in addition to the above features. The Precambrian host rocks are considered to have been deposited under submarine conditions, although a more complete appreciation of the depositional environment of Canadian Precambrian host rocks awaits comprehensive interpretation of their volcanic and sedimentary textures.

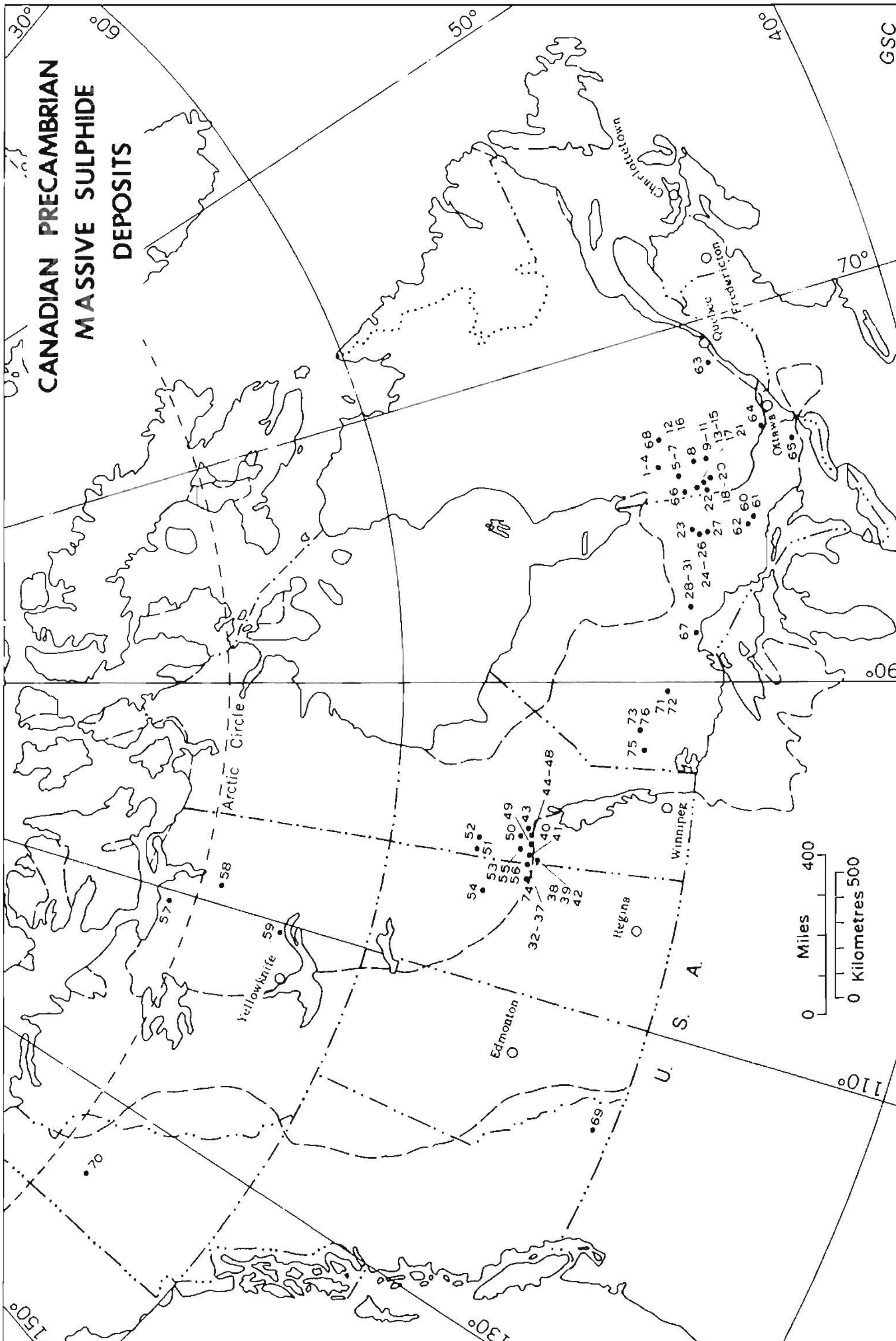
Compositionally, the volcanic host rocks appear to have been derived by differentiation of a tholeiitic-type parent magma and chemically resemble standard tholeiitic and calc-alkalic rocks of the basalt-andesite-rhyolite association (Goodwin, 1968, p. 75; Baragar and Goodwin, 1969; Irvine and Baragar, 1971). Rocks of this suite are typically identified with the island arc or eugeocynclinal environment where similar rocks occur in the Phanerozoic. In such an environment, extrusion of calc-alkaline volcanics is frequently followed almost immediately by orogenesis, thereby accounting for the almost universally metamorphosed nature of most volcanogenic massive sulphide ores.

Sulphide Deposits

Distribution

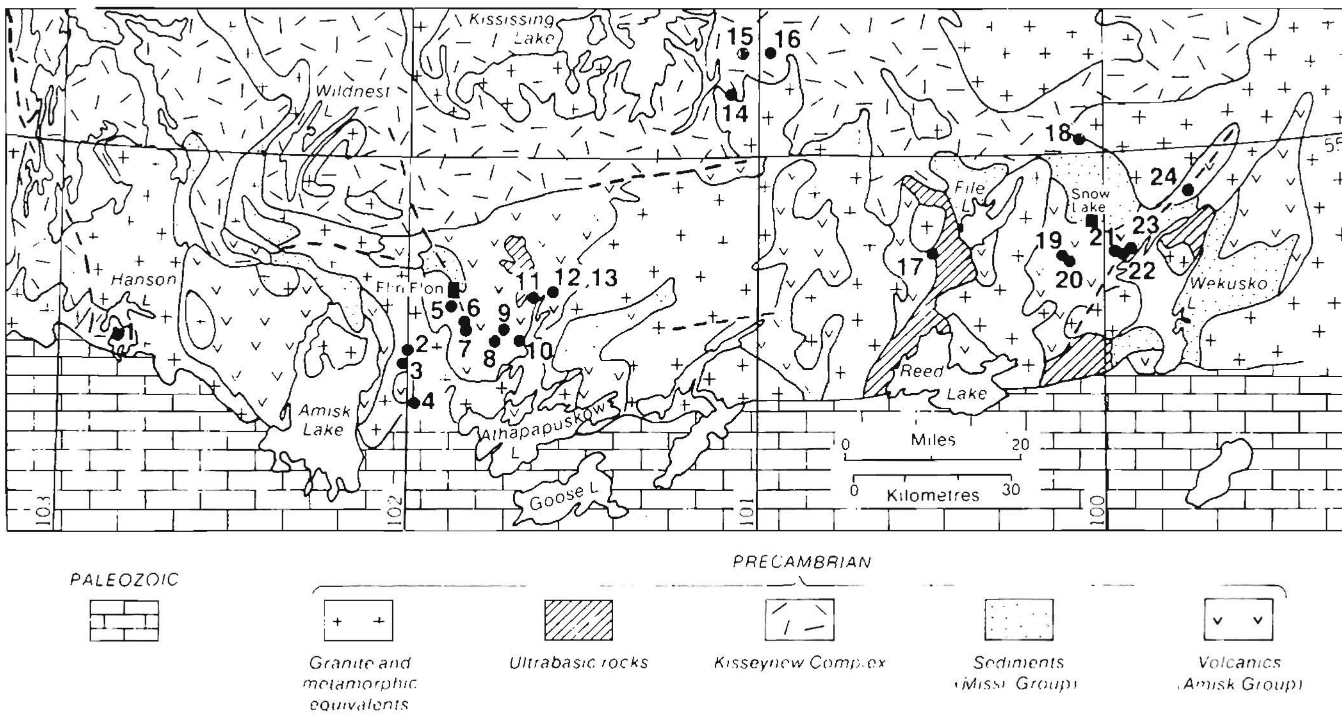
Examination of Figure 2 shows that most of the deposits occur in clusters, particularly in the Superior Province, and that over half of the more than 70 deposits shown occur in 6 or 7 main centres. The ores, occurring as deposits of various sizes, are found clustered within roughly circular areas usually 10-20 miles in diameter. The oval or circular nature of these areas may be in part tectonic but, since the distribution of ores frequently coincides with that of acidic volcanic rocks, it may also be in part an original depositional feature. These circular areas, characterized by massive sulphide orebodies within or peripheral to a central area of acidic volcanism, are considered to be only a small part of larger volcanic complexes. For example, Goodwin and Ridler (1970) have proposed nine volcanic complexes, each with its felsic volcanic component, within the Abitibi orogen of eastern Superior Province. Similarly, the Flin Flon and Snow Lake mineral areas of Manitoba (Fig. 3) are marked by local areas of acidic volcanic rocks with closely associated sulphide orebodies although it is not yet clear whether these are separate complexes or two parts of the same complex. The tendency to occur in swarms or clusters is so characteristic of this type of sulphide deposit that it is sometimes a major factor leading to re-exploration of volcanic belts containing only one or two known massive sulphide orebodies.

The near-universal post-ore metamorphism mentioned previously all but precludes preservation of primary features of the sulphide masses. However, in a few areas such as Noranda and Matagami, metamorphism is minimal and a few observations on the original nature and distribution of the ores are possible. For example, it is often possible to demonstrate that deposits in any one area tend to occur within a fairly narrow stratigraphic


CANADIAN PRECAMBRIAN
MASSIVE SULPHIDE
DEPOSITS
GSC
Arctic Circle
Yellowknife
Edmonton
Regina
Winnipeg
Ottawa
Quebec
Fredericton
Charlottetown
U. S. A.
Miles
0
400
Kilometres
0
500
30°
40°
50°
60°
70°
90°
110°
130°
150°

1. Matt. Lake
2. New Hosco
3. Radiore
4. Orchan
5. Joutel
6. Mines de Poirier
7. North. Exp.
8. Barrute
9. Man. -Barvue
10. Louvem
11. East Sullivan
12. Vauze
13. W. MacDonald
14. Waite
15. Amulet
16. Lake Dufault
17. Millenbach
18. Quemont
19. Horne
20. Delbridge
21. Mobrun
22. Aldermac
23. Texas Gulf Sulphur (Kidd Creek)
24. Jameland
25. Kam-Kotia
26. Cndn. Jamieson
27. Genex
28. Geco
29. Willecho
30. Willroy
31. Nama Creek
32. Flexar
33. Coronation
34. Flin Flon
35. Schist Lake
36. Mandy
37. Birch Lake
38. White Lake
39. Cuprus
40. North Star
41. Don Juan
42. Centennial
43. Osborne Lake
44. Stall Lake
45. Rod
46. Anderson Lake
47. Ghost Lake
48. Chisel Lake
49. Dickstone
50. Wim
51. Fox Lake
52. Ruttan Lake
53. Sherridon
54. Brabant
55. Bob Lake
56. Jungle
57. High Lake
58. Hackett River
59. Big Indian Mtn.
60. Errington
61. Vermillion
62. Geneva Lake
63. Tetrault
64. New Calumet
65. Syngenore
66. Normetal
67. Zenmac
68. Coniagas
69. Sullivan
70. Hart River
71. Mattabi
72. Sturgeon Lake-Mattabi
73. South Bay (Uchi Lake)
74. Western Nuclear
75. Trout Bay (Red Lake)
76. Copper-Man

Figure 2. Location of some Canadian Precambrian massive sulphide deposits.



Base metal sulphide deposits numbered as follows:

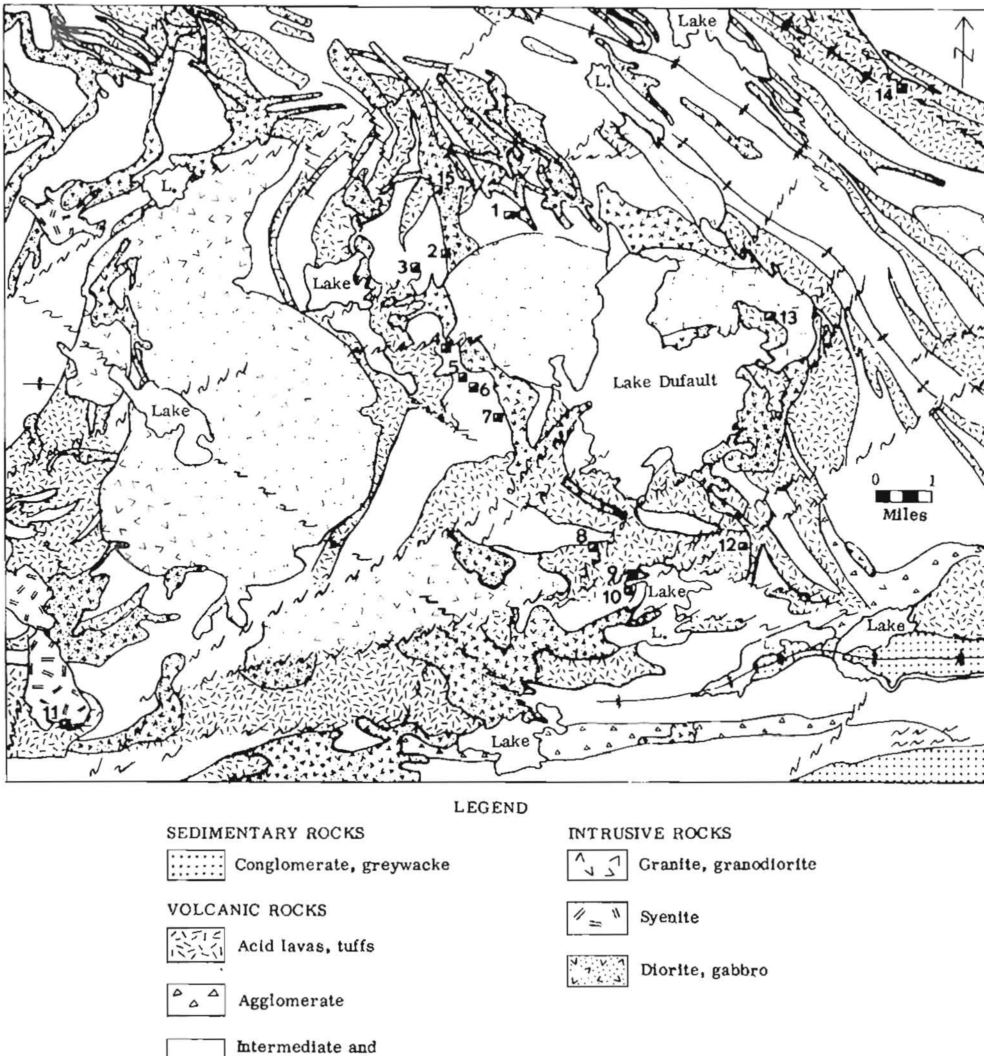
1. Western Nuclear	7. Schist Lake	13. North Star	19. Chisel Lake
2. Flexar	8. White Lake	14. Sherridon	20. Ghost Lake
3. Birch Lake	9. Cuprus	15. Bob Lake	21. Anderson Lake
4. Coronation	10. Centennial	16. Jungle	22. Stall Lake
5. Flin Flon	11. Pine Bay	17. Dickstone	23. Little Stall Lake (Rod)
6. Mandy	12. Don Juan	18. Wim Lake	24. Osborne Lake

Figure 3. General geology of Hanson Lake - Flin Flon - Snow Lake mineral belt and locations of massive sulphide deposits. Geology slightly simplified from Geol. Surv. Canada Map 1164A (Carrott River).

interval or even along a single horizon. In the Noranda area, for example, ore occurs close to or at both the upper and lower contacts of only one of five rhyolite formations in the area (Spence, 1967). These acidic phases are separated by andesitic units and the major ore-producing contact between rhyolite and andesite is referred to as the "favourable horizon" (Sharpe, 1968). Considering the rapidity in which a lava pile is accumulated, it is apparent that the Noranda area massive sulphide ores formed virtually simultaneously within a near-circular area approximately 10 miles in diameter. Similarly, in the Matagami area, most of 13 sulphide orebodies are distributed along a distinctive and extensive stratigraphic zone which is "marked by concomitant accumulations of pyroclastic deposits, siliceous chemical sediments, and probably iron formation" (Sharpe, 1968, p. 106-107). The "favourable horizon" in this area is traceable for 24 miles along strike around the periphery of a mafic complex which has intruded the volcanic pile. In the Kamiskotia area near Timmins, Pyke and Middleton (1971, p. 161) state "....... the known sulphide deposits occur mainly in felsic pyroclastic rocks of brecciated zones confined to a particular stratigraphic unit ......". In this case the favourable unit is traceable over a strike length of about ten miles.

Allied to the concept of a "favourable horizon" of ore deposition, is the relationship between massive sulphide deposits and the various forms of exhalite (chemical sediments of predominantly volcanic origin; Ridler, 1971b). The most common forms of exhalite are chert and the four facies of iron-formation, namely oxide, carbonate, sulphide, and silicate. In the Noranda and Matagami areas mentioned above, exhalite, in the form of chert and weak sulphide iron-formation, is the regionally stratigraphic equivalent of the economic base metal sulphide bodies and as such constitutes a valuable marker in the search for favourable horizons. The three major forms of exhalite iron-formation i.e. oxide, carbonate, sulphide, are considered to represent a change of facies corresponding to an increase in water depth. Although the exact relationship between massive sulphide deposits and volcano-sedimentary iron-formation (exhalite) is as yet unclear, there does appear to be a tendency for economic sulphide accumulations to occur toward the centre (deeper water) portions of the basin as defined by the various iron-formation facies (Goodwin and Ridler, 1970; Ridler, 1971a; Hutchinson et al., 1971). This is largely an empirical observation and independent of whether or not the various iron-formation facies are precise stratigraphic equivalents of the massive sulphides or not.

In addition to this demonstrable stratigraphic control, studies in relatively undeformed areas have suggested a possible tectonic control as well. Just as thermal springs and even volcanoes are frequently aligned along, or parallel to, a major fault, rift, or other major linear feature, so it can be demonstrated, in some areas, that massive sulphide orebodies, considered to be exhalative or hot spring deposits (see Section on genesis), can be aligned parallel to prominent local linears. The linear concept of ore control was proposed as early as 1904 by Hobbs and has lately been developed by Kutina (Kutina et al., 1967; Kutina, 1968, 1969). The relationship between linears and orebodies is best developed in the Noranda area, probably the least deformed of the major Precambrian massive sulphide camps (Fig. 4). The major lineaments of this mineral area are northeast-trending faults. Examination of the sulphide ore distribution reveals that three orebodies (Old Waite, East Waite, and Lake Dufault) also lie along a northeast-trending line parallel to nearby faults. If lines are then drawn through the other orebodies of the



1.	L. Dufault	6.	Amulet "A"	11.	Aldermac
2.	East Waite	7.	Millenbach	12.	D'Elbridge
3.	Old Waite	8.	Joliet	13.	W. MacDonald
4.	Amulet "F"	9.	Quemont	14.	Mobrun
5.	Amulet "C"	10.	Horne	15.	Vauze

Figure 4. General geology and location of massive sulphide deposits, Noranda area, Quebec (after Spence, 1967).

area, parallel to the Waite–Dufault trend, then two features become apparent: 1) one such line passes through two widely-separated sulphide bodies, the Amulet F and Mobrun, and 2) there is a marked regularity in the spacing of the lines expressed as multiples of X, arbitrarily taken as the distance between the Amulet C and Amulet A orebodies, the two closest in the area. The equi-directional and equidistal nature of these lines passing through the sulphide ores, parallel as they are to recognized geological features such as faults, may, as suggested by Kutina (ibid.), be indicative of fundamental tectonic processes which have expressed themselves over long periods of time. Since the rocks of the Noranda area, particularly those in the northwestern part, are only slightly deformed, the possibility exists that the faults are merely the more obvious manifestations of a pervasive structural grain which began very early in the geological history of the area and continued to affect the rocks long after they were deposited. The structural stress may have been active during actual deposition of the volcanics as subtle zones of weakness along which the ore-bearing solutions rose to precipitate sulphides at or near the existing ocean floor. Thus, only when these postulated lines of weakness intersected the ocean floor interface during a particular phase of volcanic activity (i.e. the favourable horizon) did sulphide accumulations take place. In other words, ore formation occurred at the intersection of a structural plane with a sedimentary horizon. Further investigations of the distribution of massive sulphide deposits adjacent to volcanic centres may reveal that the ore clusters are not as random as they might appear at first sight.

Internal features

Ore types

Most, but by no means all, massive sulphide bodies comprise two main ore-types, massive ore and stringer ore, distinguished largely by the relative proportions of sulphide and silicates. Of the more than 70 deposits shown in Figure 2, 34 are known to contain both massive and stringer ore-types. The remainder, with one exception, are comprised of massive ore only. The one exception, Louvem (no. 10), is considered by the author to be a rare example of stringer-type ore without the accompanying massive sulphides.

i. Massive ore: Although "massive" is a relative term and rather wide variations in total sulphide content exist between one deposit and the next, in the writer's experience the term would normally apply to ore consisting of at least 50 per cent sulphides by volume (corresponding to approximately 60 per cent by weight). Schermerhorn (1970) has coined the term "pyritite" to refer to massive pyritic ore.

The two longest dimensions of massive sulphide bodies and layering within the mass are, in relatively undeformed ores, parallel to bedding planes or flow contacts in the host rocks. Sharp contacts of the sulphide body hanging-wall with country rock are the rule while footwall contacts are generally much more diffuse. Several orebodies are known where unaltered country rock on the hanging-wall passes directly into high-grade ore (20-25 per cent, or higher, combined metals) whereas the footwall contact can only be determined by assay.

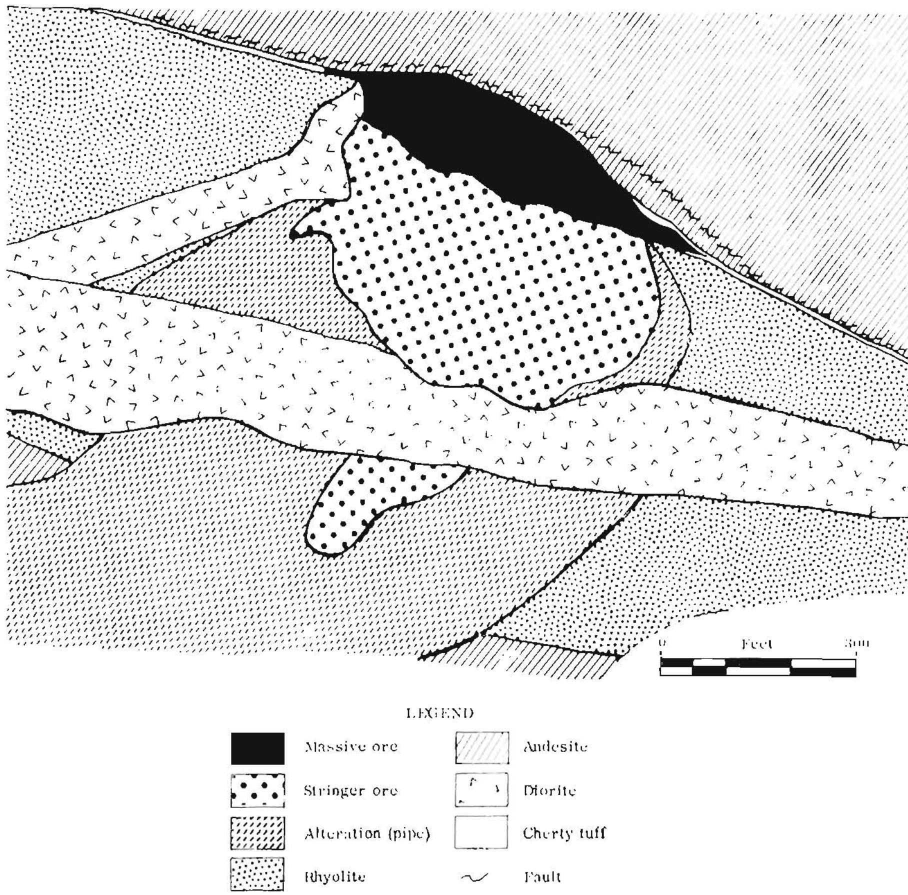


Figure 5. Generalized east-west section, Lake Dufault deposit, Noranda area (after Purdie, 1967). Stratigraphy is right side up as shown.

Stratigraphic thicknesses range up to 70 feet; deposits of greater dimension are known but in these there is usually evidence of structural thickening of ore such as in the hinge zone of folds. The other two dimensions of the massive ores are several times greater than their thickness and unmetamorphosed deposits, with some exceptions, are roughly circular in plan, particularly those occurring in massive volcanic rocks.

Mention has been made previously of the relation, in the case of undeformed deposits, between shape of the massive ores and the nature of the country rock. Briefly, sulphide bodies in layered rocks (volcanic sediments, tuffs, etc.) are blanket-shaped with the two dimensions parallel to the layering greatly exceeding the thickness. Orebodies in massive volcanic rocks, on the other hand, tend to be much more ovoid or lenticular in cross-section.

ii. Stringer ore: Also referred to as "disseminated" or "vein" ore, stringer ore is always found on the stratigraphic footwall of the massive sulphide ore lens (Figs. 5, 6, 7). The total sulphide content of stringer ore is considerably less, and much more variable, than massive ore and would seldom exceed

25 per cent. In undeformed deposits, it consists of anastomosing sulphide veinlets, veins, and irregular replacements extending downward, for a few inches, a few feet, or a few hundreds of feet, roughly perpendicular to the main sulphide orebody. In doing so, the stringer ore zone cross-cuts stratigraphy, in contrast to the massive sulphide lens which roughly parallels stratigraphy.

Stringer ore is not found with all massive sulphide deposits but, where it is, it constitutes a distinct, mappable unit which, when followed upward, frequently grades into massive ore by a coalescence of the veins and small replacement bodies which comprise stringer ore. In other deposits, stringer ore changes into massive ore rather abruptly within 3-5 feet. The writer has noted, however, that ore-grade material in the stringer zone is almost invariably in direct contact with massive ore and only in the very large orebodies does it constitute ore more than 200 feet stratigraphically below the massive sulphide lens. Barren sulphides, however, are known to continue downward for thousands of feet but in diminishing abundance until background sulphide content of the host rock is reached.

The shape of the stringer ore zone, again in undeformed ores, is generally cylindrical or funnel-shaped with the massive ore lying in the widest part of the "funnel" at the top. The upward dilation of the stringer ore zone ends at the massive sulphide orebody and in only one or two instances is the

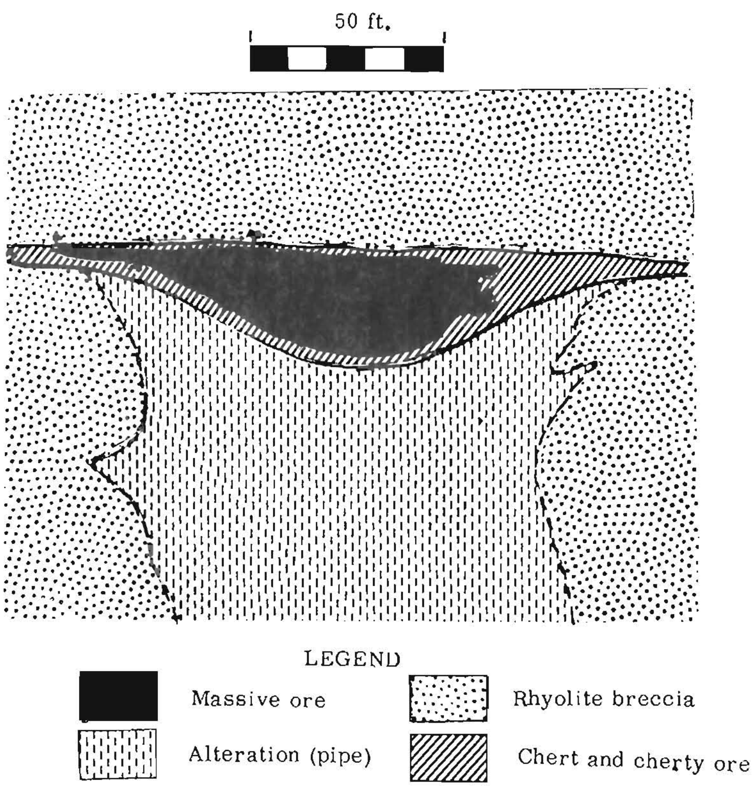


Figure 6. Delbridge deposit, Noranda area. Plan of 850 level, Lens B (after Boldy, 1968). Stratigraphic top is to the top of the diagram.

author aware of it extending beyond the massive ore, either laterally or upward. The Amulet "A" orebodies in the Noranda area are an example of several massive sulphide deposits "stacked" one on top of the other within stringer ore in the intervening area (Dresser and Denis, 1949, p. 378).

Mineralogy and composition of ore

The mineralogy of volcanogenic massive sulphide bodies (including stringer-type ore) is remarkably simple considering their abundance and diversity in size, geological setting, and post-ore metamorphism. The iron sulphides, particularly pyrite and pyrrhotite, characteristically comprise at least half the total sulphide content. Sphalerite, chalcopyrite, and galena, in widely varying proportions, constitute most of the remaining sulphides.

The contents of major sulphide species in several selected deposits are shown in Table I. These values represent averages for the entire orebody; in detail, the proportions of various sulphides vary considerably within the deposit.

Detailed mineralogical studies of volcanogenic sulphide ores have revealed a wide diversity of minerals to be present in very minor amounts. Table II has been prepared to present some examples of this varied assemblage.

When the bulk composition of Precambrian volcanogenic massive sulphide ores is expressed in terms of the three main ore elements (Cu-Pb-Zn), two features immediately become apparent (Fig. 8): the ores are remarkably deficient in lead relative to copper and zinc and are considerably lower in lead than similar deposits in Phanerozoic rocks; and secondly, more than 70 per cent of the deposits contain more zinc than copper.

Major byproducts won from massive sulphide ores are cadmium, silver and gold with lesser amounts of selenium, tellurium, bismuth, and tin. Recoverable silver contents generally fall in the range 1-3 oz./T., seldom exceeding 4 oz./T. Gold shows considerably more variation and recoverable gold values range from 0.01 to 2.0 oz./T.

Zoning

An extremely important and characteristic feature of volcanogenic massive sulphide deposits is that the vast majority of them are zoned, in one form or another, and that the zonal arrangement shows a consistent pattern relative to host rock stratigraphy.

The zoning in the deposits is expressed in four ways: morphology, mineralogy, texture, and composition. Morphological zoning has already been alluded to in the discussion of ore-types. Where both massive and stringer ore coexist in a deposit, the stringer ore always occurs on the stratigraphic footwall of the massive orebody (Figs. 5, 6, 7). Mineralogical zoning is, in part, a function of morphological zoning and manifests itself in the varying proportions of the five main sulphide species: pyrite, pyrrhotite, sphalerite, chalcopyrite, galena. Hence, in an ideal deposit, sphalerite would be considerably more abundant in the massive ore than in the stringer ore. Similarly, the ratio pyrite: pyrrhotite is commonly higher in the massive than in the stringer ore. Galena, where it occurs, is found only in the massive ore. Consequently, an ideal orebody would consist of a pyrite-sphalerite (chalcopyrite-galena) massive orebody underlain by pyrrhotite-chalcopyrite stringer ore (Fig. 5). Furthermore, within the massive sulphide ore, galena-sphalerite are more abundant in the upper half of the mass (with galena increasing toward the hanging-wall) whereas chalcopyrite increases toward the footwall and grades downward into chalcopyrite stringer ore. Mineralogical zonation is, of course, best developed in ores having the full complement of ore minerals. As the number of mineral phases decreases, so the zonation tends to become obscure and may not be in evidence at all in some orebodies. For example, at the Flexar mine in Saskatchewan, a massive lens consisting mainly of chalcopyrite and pyrrhotite without a stringer zone, shows no evidence of zonation whatsoever. Textural zoning is concomitant with mineralogical zonation in that the more sphalerite-rich portions of the ore are generally banded, expressed as monomineralic layers of pyrite and sphalerite, whereas the chalcopyrite-rich portions seldom show banding even though the total sulphide content of the two portions may be similar. Compositional zoning, of course, parallels the distribution of the three major ore sulphides - sphalerite, chalcopyrite, galena - but has the advantage of being more quantitative and can usually be detected in routine assay plots. Sphalerite, because of its wide variation in colour, is sometimes difficult to recognize and a weak or poorly-developed zonation could easily be missed on the basis of mineralogical examination alone. Compositional zoning, whereby zinc and lead are most abundant toward the hanging-wall side of the massive ore with copper increasing toward the footwall and passing into copper-rich stringer ore, results in some of the exceptionally rich "copper keels" of some orebodies. In most ores, however, the compositional zoning is due more to a downward decrease in zinc rather than an increase in copper. For example, a typical deposit may contain 12% Zn and 1% Cu in the upper part of the massive ore decreasing to 2% Zn and 3% Cu toward the footwall i.e. the zinc has decreased six-fold whereas the copper has increased only three-fold. In the United Verde orebody, a Precambrian massive sulphide deposit in Arizona (Anderson and Creasey, 1958), the Cu/Cu+Zn ratio increases from 0.14 in the upper part of massive ore to 0.87 in the stringer ore.

Ore texture and structures

Most of the textures now present in massive sulphide ores are the result of post-depositional processes such as diagenesis and metamorphism. Metamorphic textures are by far the most common and will be dealt with later in a discussion of metamorphism of ores.

In studies of modern sea-floor sediments, great care is generally taken to distinguish between depositional processes (and textures) and diagenetic processes (and textures). In these extremely young sediments the distinction is important and is made possible because of the very short total history of the material being studied. In Precambrian ores and sediments, however, so much of earth history has passed and so many other processes have been operative since the original deposits were formed, that to distinguish between primary depositional and diagenetic textures is, in most instances, decidedly futile.

Recent experiments have indicated that, of the common sulphides, pyrite alone remains brittle over a wide range of temperature, confining pressure, and strain (Graf and Skinner, 1970) whereas pyrrhotite, galena, and sphalerite deform plastically and/or anneal readily under much less severe conditions (Graf and Skinner, 1970; Stanton and Willey, 1970). These studies would therefore suggest that primary textures of sulphides would be best preserved in pyrite, and indeed, most of the textures described in younger pyrite deposits have also been found in Precambrian ores. Such features as colloform and framboidal pyrite are common, even in Archean orebodies, particularly those with a high carbon (graphite) content. Some of the best botryoidal pyrite observed by the writer has come from deposits in the Timmins area where graphitic bands in even the massive ore are a common occurrence. Similarly, the Cuprus deposit in Manitoba has both a high carbon content and well-developed botryoidal or colloform pyrite.

Extreme thin layering of fine-grained pyrite can also, by analogy with modern sulphide sediments, be attributed to primary deposition. Thin layering can also result from comminution of pyrite during deformation but this can generally be recognized by the abundance of fractured pyrite grains whereas primary layering will contain, albeit on a microscopic scale, undisturbed colloform rosettes of pyrite.

Besides textures, several primary structures are also recognizable in certain well-preserved deposits. Mention has been made previously of the common occurrence of sulphide clasts in silicic volcanic agglomerates (i.e. "mill-rock") coeval with the orebodies. By a similar token, angular blocks and fragments of volcanic host rocks are frequently found in the massive sulphide portion of several deposits. The low metamorphic grade and lack of schistosity in the clasts bespeaks of a primary origin and distinguishes it from the "Durchbewegung" fabric described by Vokes (1969, p. 129) for the flowage of a sulphide mass around detached silicate fragments during metamorphism.

In a very few deposits, the author has observed such soft sediment structures as slump-folds, and flame-structures, or load-casts. The former are recognized by their confinement to a single sulphide layer or a small number of adjacent layers; beds above and below the structure are undisturbed. The best-developed load casts observed were in a thin-bedded alternating series of pyrite and graphitic shale, part of a more massive pyrite deposit. The load-casts were developed by slumpage of the pyrite into the underlying sediment resulting in "flames" of shale which disrupted the pyritic layers. Soft-sediment deformation has also been recognized in layered sulphides of the Mattagami mine (Roberts, 1966).

Excellent examples of graded bedding in monomineralic sulphide layers, again mainly of pyrite, have been observed in the Kidd Creek deposit in the Timmins area. The layers are generally only a few inches thick and are composed of angular pyrite grains in a carbonaceous matrix. The structure is entirely similar to that commonly found in greywackes and results from differential settling of sulphide fragments. A related structure, consisting of a relatively large fragment of sulphide (or sulphides), surrounded by finer grained sulphide layers abutting the fragments on both sides but passing above and below it, is frequently observed in some deposits. In appearance, the structure is analogous to the "drop-stones" of glacial origin and has on occasion been referred to as "volcanic drop-stones" in reference to the assumed pyroclastic origin of the sulphide fragments.

Alteration

Wall-rock alteration adjacent to sulphide ores has been a topic of investigation of economic geologists and geochemists for decades. One type

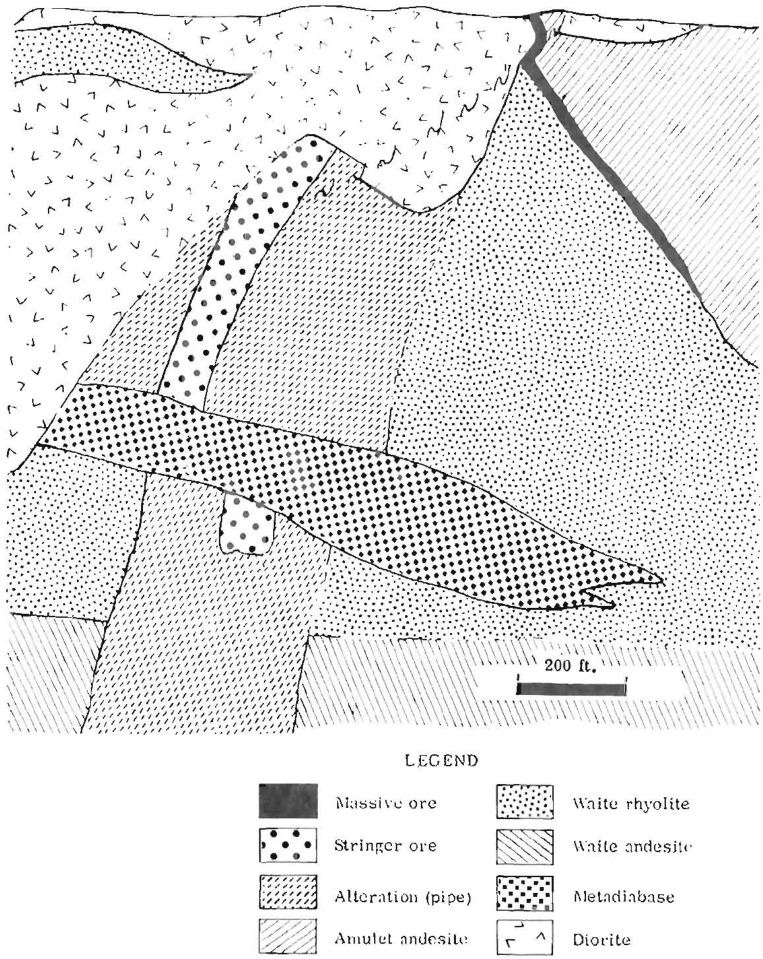


Figure 7. Vauze mine, Noranda area. North-south section (north to the left). Slightly simplified from Spence (1967) and Sullivan (1968).

of alteration adjacent to volcanogenic massive sulphides has been recognized as characteristic of these ores (e.g. Dugas, 1966, p. 49-50; Gilmour, 1965; Sharpe, 1968, p. 107-109).

Although, even in areas of lowest grade metamorphism, host rocks to sulphide ores have undergone at least some change in their mineralogical and chemical composition, the alteration associated with volcanogenic massive sulphide deposits is easily recognized and invariably occurs on the footwall side of the massive ore. In some cases it has been traced for 3,000 feet stratigraphically below the main ore mass. In undeformed deposits, the alteration zone is pipe-like in shape and contains within it, usually as a shoot toward the centre, the pyrrhotite-chalcopyrite stringer-type ore (Figs. 5, 6, 7). The diameter of the alteration pipe increases upward until it is coincident with that of the massive ore. Only rarely does the alteration pipe extend into

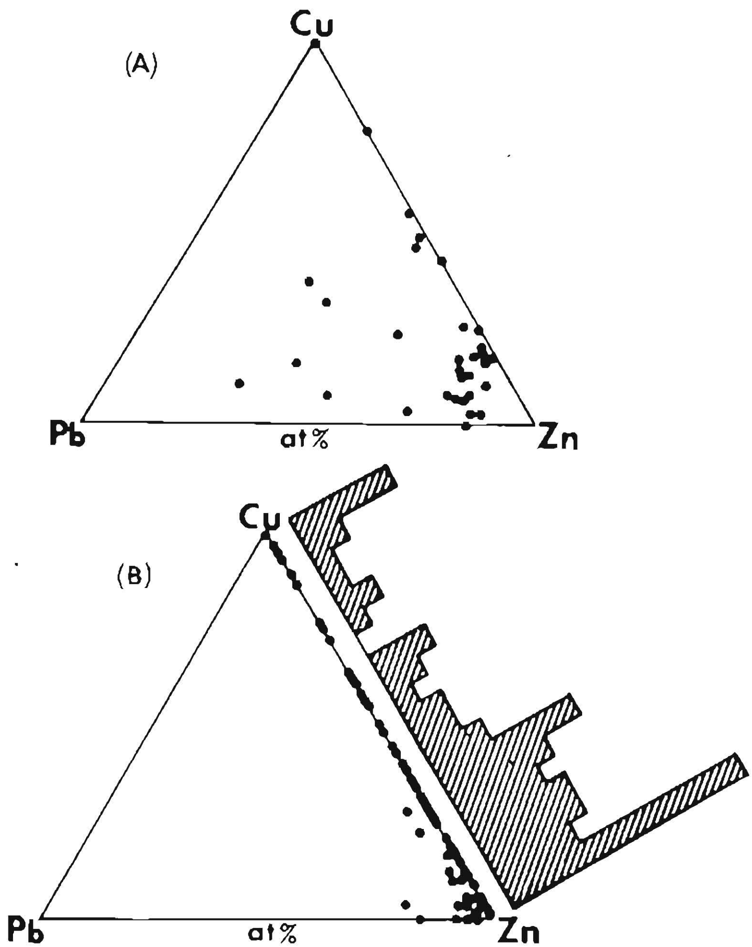


Figure 8. (A) Atomic ratios of Cu-Pb-Zn abundances in Canadian Phanerozoic volcanogenic massive sulphide deposits.
(B) Same ratios for Precambrian deposits. Histogram illustrates bimodal nature of Cu/Cu+Zn ratios. Compositions of ores in both diagrams have been calculated from production or reserve figures.

the hanging-wall, or laterally beyond, the massive sulphide lens (e.g. Amulet "A"). Gilmour (1965, p. 71-72) has presented an excellent description of the alteration pipe below the Vauze deposit, a small orebody in the Noranda area which possesses many of the features typical of volcanogenic sulphide ores (Fig. 7). The following is paraphrased from Gilmour (op. cit.):

'The core of the alteration pipe is composed of massive chlorite containing disseminated sulphides and magnetite. The chlorite content of the rock decreases outward and the margin of the massive chlorite is gradational and poorly defined. There is an incomplete zone of massive sericite about the chloritic pipe. The chloritized and sericitized rhyolite grades into massive, siliceous rhyolite.

Within the tabular body of alteration, the disseminated sulphides occur as a shoot .... The margin of the core of intense alteration .... tends to be roughly defined as a zone which is made up of large blocks of bleached rhyolite enclosed by a matrix of chlorite and biotite.'

The pipe-like shape of the alteration zone is perhaps the most spectacular form of this diagnostic feature of these ores. In many deposits, however, the altered zone is expressed merely as a chloritization of the footwall rocks and is lacking in the hanging-wall. The abundance of disseminated sulphides in the alteration zone (and the contained stringer ore) leads to the common occurrence of a diffuse footwall contact of the orebody in contrast with the hanging-wall which is normally very abrupt.

Development of chlorite is the main mineralogical expression of the footwall alteration followed, in decreasing order of frequency, by sericitization, silicification, and carbonation. Chloritization and sericitization, the two most common types of alteration, result in a desilication of the host rocks, particularly where they are developed in rhyolite. In deposits where chemical studies have been made, the most obvious chemical changes in the alteration pipe are a relative increase of Fe, Mg, and S and a decrease of Si, K, and Na (Riddell, 1953; Roberts, 1966; Lickus, 1965; Sakrison, 1966). Magnesium metasomatism, in particular, appears to have been the dominant process in the formation of the footwall alteration pipes and zones.

METAMORPHIC EFFECTS

The changes brought about in massive sulphide ores and their host rocks as a result of metamorphic processes is not merely of academic interest. Sulphides, because of their wide stability range, are capable of surviving even the highest metamorphic grades. A massive sulphide deposit, after undergoing even mild metamorphism, is often radically different in many ways than it was before deformation; metamorphic changes can directly influence the exploration for, and development of, these ores.

For example, during metamorphism the textures and structures of the host rocks are often destroyed and their mineralogy radically altered making it difficult for the exploration geologist to recognize, and to trace, favourable host rocks. Similarly, changes are also wrought in the sulphide ores resulting in a different mineralogy, grain size, and form of the ore deposit which can affect its geophysical, and even geochemical, response. Mineral textures affect the beneficiation of ores and the shape of the deposit influences the techniques and efficiency of the mining process.

Consequently, knowledge of the effects of metamorphism can be useful in the exploration for and exploitation of massive sulphide ores.

On host rocks

Metamorphism of volcanic and volcaniclastic rocks is a subject treated at length in many standard petrology texts and will not be discussed in detail here. The ability to "see through" metamorphism and to deduce the original nature of the rock is a valuable asset to any geologist, particularly when working in the Precambrian. As an aid in the interpretation of "what it was" from "what it is", Table III has been compiled from the literature.

Since most volcanogenic sulphide ores are closely associated with the acid phases of volcanism, the distinction between metamorphosed silicic volcanic rocks and metaquartzites becomes of paramount importance. Similarly, the recognition of a cherty tuff layer can be of assistance as a marker horizon and aid in the structural interpretation of volcanic terraines which are characteristically complex because of rapid lithologic and facies changes.

On sulphide deposits

Form

Judging from examples in undeformed areas, the original form of most massive sulphide bodies was probably roughly circular or oval in plan with dimensions parallel to bedding being several times greater than thickness. Beginning with this assumption, certain preliminary deductions may be drawn concerning the changes of form or morphology which can occur in sulphide masses during metamorphism.

One of the most common of these is the development of linear or blade-like orebodies aligned parallel to lineations, such as fold axes, hornblende crystals, or corrigations in the foliation planes, in the enclosing rocks. Examples of bodies of this shape (and origin) would be those of Balmat, N. Y. (Lea and Dill, 1968), Chisel Lake, Man. (Martin, 1966) and Stall Lake Mines Ltd., Man. (Coats et al., 1970). Rod-shaped orebodies such as these develop in areas of medium to high metamorphic grade which show penetrative lineation. In rocks of lower metamorphic grade, where deformation is expressed mainly by shearing and folding, without well-developed lineation, the deposits tend to be flattened parallel to schistosity, perhaps as a result of transposition along shear planes. Frequently, orebodies deformed predominantly by shearing, give the appearance of having been sliced into several ore lenses separated by narrow widths of highly schistose and altered wall-rock. The effects of these two types of deformation i.e. shear and penetrative lineation, on the shapes of massive sulphide orebodies has been described by Howkins and Martin (1970) for deposits in the Flin Flon - Snow Lake areas. In the former area, where shearing is the predominant structural element, ore lenses have plunge-to-strike length ratios of about 3:1. In the Snow Lake area, where lineation in the high metamorphic grade rocks is well developed, orebodies have plunge-to-strike length ratios up to 10:1. Howkins and Martin also note that "pencil-like structures of the Snow Lake deposits have a continuity along plunge which results in more accurate predictions of the ore locations at depth."

Areas of intense, polyphase regional deformation, or local areas adjacent to large intrusions, commonly contain orebodies which have been so distorted that their form is best described as amoeba-like. Such deposits are extremely difficult to develop because of their irregular and unpredictable shapes. Successful exploitation of these ores generally depends on studies of detailed structures in the host rocks. In cases where this has been done, the irregular nature of the ore zones has generally been found to be controlled by the interference pattern produced by intersecting deformation trends such as two periods of folding with widely divergent axial planes. The highly distorted zones adjacent to large intrusions are particularly difficult to interpret because of the irregular nature of the strain on country rocks resulting from the forceful emplacement of the intrusive body. Examples of deposits with amoeba-like shapes would be Joutel, Mines de Poirier, and South Bay mines.

Mineralogy

As Vokes (1969) has quite rightly pointed out, the abundant mineralogical changes brought about in silicate rocks during metamorphism do not find their counterparts in sulphide assemblages; massive sulphide ores are no exception. The wide stability range of sulphides, the relatively few phases (and components) present in most ores, and the ease with which high-temperature sulphide phases revert to low-temperature phases on cooling, all contribute to ensure that the metamorphism of sulphide masses is generally not reflected in their mineralogical assemblages.

Nevertheless, in spite of these restrictions, certain mineralogical changes do occur in sulphide masses which have undergone metamorphism. Most of these changes are caused by thermal events and most occur in the iron sulphide species. The formation of pyrrhotite from primary pyrite is perhaps the most common change and perhaps most of the pyrrhotite presently found in Precambrian ores has formed in this manner, particularly pyrrhotite occurring with sphalerite in the massive sulphide portion of the ores; stringer-type ore can, and commonly does, contain what appears to be primary pyrrhotite as the iron sulphide phase. The breakdown of pyrite to magnetite can also occur as well as the generation of "new" pyrite from pyrrhotite or ferromagnesian silicates.

Exsolution of chalcopyrite in sphalerite is also a common phenomenon in metamorphosed ores and could result in a high copper content in the zinc concentrates if not ground finely enough. The sphalerite itself commonly emerges from the metamorphism considerably enriched in iron relative to its original composition. This can be deleterious in that it depresses the zinc content of sphalerite concentrate since sphalerite commonly contains 10-20 mol % FeS in solid solution.

Small amounts of gahnite ($ZnAl_2O_4$) found in some metamorphosed zinc ores probably formed by reaction between sphalerite and aluminous silicates.

McDonald (1967) has suggested that increased metamorphism of sulphide assemblages results in ores of increasingly complex mineralogy but admits that these mineralogical variations may be due to original metal contents. The present writer has also noted this trend among Precambrian sulphide ores but would suggest that the increased complexity is more apparent than real due to the increased grain size of the more highly metamorphosed ores, thereby making the accessory minerals more readily seen.

Texture

Increase in grain size is probably the most common textural change wrought in sulphide masses during metamorphism. Although there is a general correlation between grain size and metamorphic grade, a recent attempt to quantify this relationship yielded only fair correlation (Tempelman-Kluit, 1970).

In ores of high metamorphic grade, recrystallization and grain growth produce a sulphide assemblage which is best described as a "sulphide pegmatite"; large porphyroblasts of pyrite and sphalerite are surrounded by crystalline matrix of pyrrhotite and chalcopyrite. Original banding in the sphalerite portion of the ore is almost totally destroyed. The Geco orebody is a good example of a massive sulphide which has undergone high-grade regional metamorphism (Suffel et al., 1971).

Although most Precambrian massive sulphide ores have undoubtedly undergone at least some post-ore deformation, evidence of strain texture is not as common as one would expect. The reason for this is not clear but the relative timing of maximum stress with respect to maximum thermal effects may be an important factor. Sulphides lacking strain texture may indicate that thermal annealing took place after the release of strain. When the reverse is the case i.e. strain in the absence of appreciable heat, such as deformation in rocks of low metamorphic grade, or the continuation of deformation after the thermal "peak", ores may exhibit such textures as comminution of pyrite and sphalerite, deformation twinning in sphalerite, "steely" galena, and streaky chalcopyrite. Preferred morphological orientation of sulphide grains, particularly galena and sphalerite, is a commonly observed phenomenon but preferred crystallographic orientation is much more difficult to document. Through the use of an X-ray technique, Roberts (1966) was able to demonstrate that the (0001) plane in pyrrhotite of the Mattagami Lake orebody lay in the axial plane foliation. Similarly, Kanehira (1969) through a study of the optical extinction positions of pyrrhotite in the Coronation mine, showed that there existed a preferred orientation of the c-axes perpendicular to foliation.

Annealing of sulphide grains, if allowed to proceed to completion, will result in textural equilibrium among the sulphide phases. Equilibrium of this type is best recognized by a study of the interfacial angles between adjacent sulphide grains; thermodynamic stability is indicated when the interfacial angles approach 120° (Stanton, 1964). Certain lead-zinc ores in the Grenville Province contain sulphides approaching textural equilibrium. The increase in sulphide grain size brought about by regional metamorphism is of more than academic interest because the coarser-grained ores, during beneficiation, generally yield cleaner concentrates with less grinding than do the fine-grained ones. Texturally-equilibrated ores, in particular, are more economical to mill and concentrate because of minimal interfacial contacts between the grains as described by Stanton (1964).

Massive sulphides which have undergone intense deformation frequently have the appearance of having flowed plastically. The aspect of flowage is enhanced by the common occurrence of fragments of schistose wall-rock within the sulphide mass and the "flow-lines" in the sulphides curve around these silicate fragments. Spurr (1923), noting this phenomenon in the Mandy deposit of Manitoba, concluded that the sulphides had been introduced as a magma and that the "flow-lines" he observed were akin to flow-banding in rhyolite and other viscous magmas. The silicate inclusions were regarded by Spurr as having been detached from wall-rock during the forceful intrusion of the sulphide magma. More recently, the occurrence of schistose fragments in flow-banded sulphides has been termed "Durchbewegung" fabric by Vokes (1969) who attributes the banding to post-ore deformation and the silicate inclusions as fragments of wall-rock which have been detached as a consequence of plastic flow of the sulphides during metamorphism.

Selective melting of sulphide assemblages, at geologically reasonable temperatures, to produce myrmekitic textures has been experimentally demonstrated by Brett and Kullerud (1967) in the Fe-Pb-S system and by Craig and Kullerud (1968, 1969) in the Cu-Pb-S and Cu-Zn-S systems, respectively. There is some evidence that certain sulphide ores may even have melted, at least to some degree. For example, Mookherjee and Dutta (1970) describe vermicular intergrowths of pyrrhotite-chalcopyrite-sphalerite in small veins projecting into a post-ore diabase dyke from the main sulphide mass at Geco mine, Ontario. This, and other textures in the veins, was interpreted as evidence of incipient melting of the sulphides adjacent to the diabase-ore contact.

Composition of ore

Except for minor changes in Fe, Zn and S content due to interaction between sulphides and silicates there is little evidence that the bulk composition of massive ores is significantly altered during metamorphism. Internally, however, there is much evidence of a redistribution of elements which, in some instances, tends to disrupt, modify, or otherwise obscure the compositional zoning previously described as a characteristic feature of volcanogenic ores.

The rearrangement of elements in metamorphosed ores is due almost entirely to the relative mobilities of the ore-forming sulphides. Chalcopyrite and galena are much more mobile than sphalerite and pyrite and respond plastically to deformative and thermal processes. For example, metamorphism of Archean sulphide deposits, which contain only minor galena, will mobilize the small amounts of galena out of its original position in the uppermost portion of the massive ore and redeposit it in small gash veins in the stratigraphic hanging-wall of the deposit. Sulphosalts, such as tetrahedrite-tennantite, frequently accompany galena in these veins which, if large enough, can constitute important silver-rich concentrations. In the massive ore, gash veins of all sizes, consisting predominantly of chalcopyrite and quartz, respectively the most mobile of the sulphides and gangue silicates, are a common occurrence. Characteristically these copper-rich gash veins are aligned roughly perpendicular to banding or the long dimension of the orebody and are usually contained within the main sulphide mass. In some deposits, however, chalcopyrite veins, with or without sphalerite, penetrate into the host rock for short distances. These veins can be distinguished from stringer-type ore because they are less abundant and not accompanied by heavy chloritic alteration. Also, remobilized chalcopyrite veins usually cross-cut schistosity whereas metamorphosed stringer ore is essentially parallel to metamorphic foliation.

On a large scale, intense deformation is capable of moving the entire sulphide mass by transposition along the metamorphic foliation planes. This may result in a detachment of the massive ore from the stringer ore, such as may have occurred at the Manitou-Barvue deposit (Ramsay and Swail, 1967). Where the deposit has been folded, particularly by isoclinal folding, mobilization of the sulphide mass can be brought about by plastic flowage of the more ductile sulphides (chalcopyrite, galena, and to a lesser extent, sphalerite) and comminution of the brittle ones (pyrite). In well-developed instances, this differential mobility during isoclinal folding will result in a noticeable

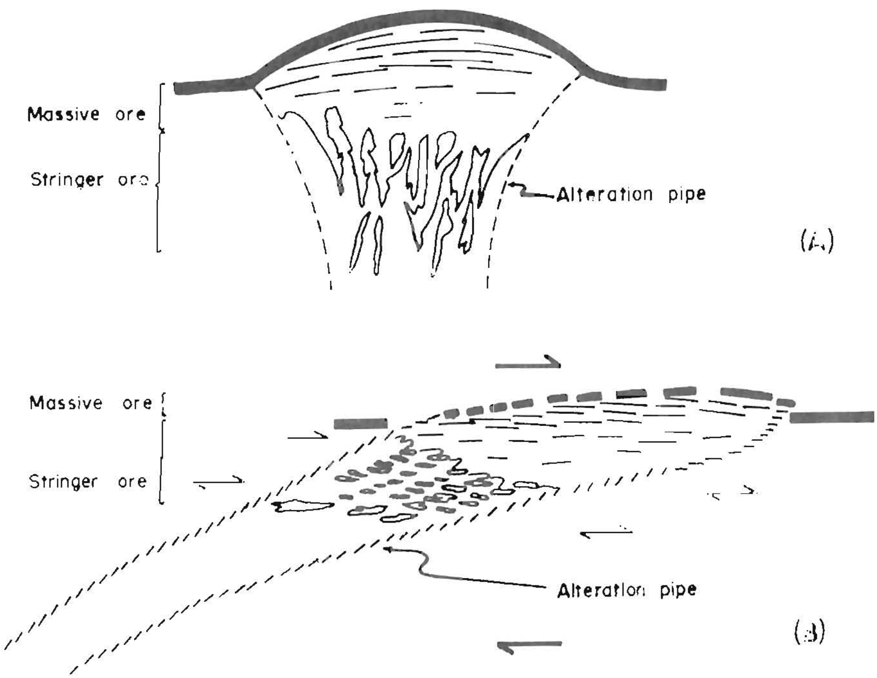


Figure 9. (A) Schematic diagram illustrating main geological features of an undeformed volcanogenic massive sulphide deposit.
(B) Same deposit as (A) but modified by shearing in the sense shown by heavy arrows above and below the orebody. Compare with Fig. 10 of the Flin Flon mine.

increase in grade (particularly copper) and thickness toward the nose of the fold whereas the limbs will tend to be thinner and more pyritic.

In highly metamorphosed ores, there may be a slight lowering of over-all grade due to the inclusion of numerous contorted siliceous fragments which have been forcefully detached from the wall-rock by plastic flowage of the sulphides and incorporated into the ore mass.

On the footwall alteration zone

Mention has been made earlier of the flattening effect produced on massive sulphide ores by transposition along shear or schistosity planes. Since the first schistosity developed in a rock undergoing metamorphism is commonly parallel to stratigraphy, transposition along these planes will effectively stretch the massive sulphide lens in a plane parallel to its original stratigraphic dimensions. The same effect may be achieved by sliding a pack of cards to form a cross-sectional parallelogram from the original rectangle. If the process is continued it will produce a body several times longer than the original, but which retains its original position relative to stratigraphy i.e. parallel to stratigraphic layering. If an alteration pipe occurs vertically beneath the massive sulphide lens, its original position will be

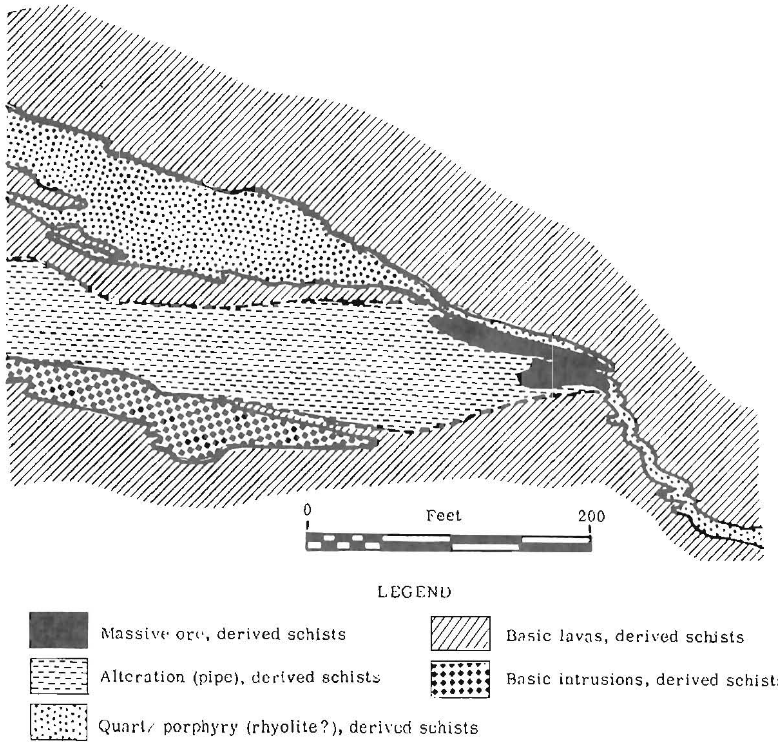


Figure 10. Flin Flon mine, Manitoba. Plan of 3,000-foot level (from Byers, et al., 1965). Stratigraphic top is to the top of the diagram.

nearly perpendicular to regional stratigraphy and incipient schistosity. Movement along the schistosity planes will rotate or transpose the pipe into a position nearly parallel to both schistosity and the massive sulphide lens (Fig. 9). The final position of the pipe will be en echelon to the main sulphide body rather than perpendicular to it as it was originally. Transposition also has the effect of decreasing the apparent thickness of the pipe due to the stretching action during transposition. The stringer zone ore, under these circumstances assumes a final position near one end, but still in the footwall, of the massive ore. The appearance of the metamorphosed complex has been described in the older literature as a chloritic shear zone within which the massive sulphide ore has been emplaced. Excellent examples of this type of deformation are found in the Flin Flon (Fig. 10), Stall Lake, Normetal, and perhaps Geco orebodies.

Metamorphism can also have a profound effect on the mineralogical constitution of the alteration zones. The original chloritic alteration is commonly altered to an assemblage consisting of various proportions of hornblende, biotite, cordierite and anthophyllite (Froese, 1969). If sufficient calcite was present in the original alteration zone, tremolite-actinolite, garnet, and Ca-pyroxenes may also form. Chlorites of low-to-medium

$\frac{Mg}{Mg+Fe}$ ratios are unstable under higher metamorphic conditions and will re-equilibrate into the mineral assemblages noted above. High-magnesium chlorites, on the other hand, have stability fields which extend into the higher metamorphic conditions and may account for the preservation of chlorite alteration pipes in staurolite facies regional metamorphism at Stall Lake mines in Manitoba.

Cordierite-anthophyllite assemblages in the alteration zone are usually the result of regional metamorphism. Under the proper conditions, however, simple thermal metamorphism may also produce cordierite-anthophyllite by isochemical metamorphism of alteration pipes. In the Noranda area, "dalmatianite" i.e. cordierite-bearing pipes (Walker, 1930; Dugas, 1966, p. 49) is only found in deposits occurring within the thermal aureole of the Dufault granodiorite stock (de Rosen-Spence, 1969). Deposits such as Vauze, Quemont, Mobrun, Horne, etc., occurring at some distance from the intrusive margin, do not contain cordierite in their alteration pipes (Fig. 4).

GENESIS

Conclusions regarding ore genesis of virtually all types of mineral deposits have had a long history of pendulum-like swings and the massive sulphide ores of the Canadian Precambrian are no exception. For example, Spurr (1923) in commenting on the Mandy mine in Manitoba, concluded "that the ore could have been introduced in no other way than in plastic form, as an intrusive mass ...... the viscosity was like that of tar and is analogous to that of those rhyolites and obsidians which show a fine flow-banded structure."

By 1933, however, Lindgren's text "Mineral Deposits" was in its fourth printing and the hydrothermal theory of ore genesis predominated in Canada, as elsewhere, for several decades. This was evident in opinions expressed in two separate volumes (1948 and 1957) on the Structural Geology of Canadian Ore Deposits, published by the Canadian Institute of Mining and Metallurgy. In these volumes, the authors were unanimous in ascribing a hydrothermal origin to massive sulphide ores of the type described in the present paper.

In 1957, however, Knight proposed the Source Bed Concept and suggested that a great number of sulphide orebodies had formed contemporaneously with their host rocks. This was followed, in 1958, by Oftedahl's theory of exhalative sedimentary ores in which base metal accumulations were thought to have been produced by sea-floor fumaroles of volcanic origin. Thus, when the Canadian Institute of Mining and Metallurgy held its 1959 symposium on "The occurrence of massive sulphide deposits in Canada" in 1959 (C.I.M. Bull., Feb. 1960), although most authors tenaciously clung to the hydrothermal replacement theory, several advocated a close genetic relationship between massive sulphide ores and volcanism. Stanton (1959), in particular, strongly supported a volcanic-exhalative and biologic origin for ores in the Bathurst area of New Brunswick. He later (1960) expanded this concept for all orebodies of the "conformable pyritic" type.

By 1960, Gilmour had applied Oftedahl's and Stanton's concepts to the Noranda area but did not publish his conclusions until 1965 at which time he remarked (Gilmour, 1965): "It is suggested that the massive sulphide deposits were formed on or near the surface through the agency of fumarolic emanations." Similar views were expressed by Goodwin (1965) with reference to base metal deposits in the entire volcanic belt from Noranda to Timmins. The volcanic exhalative concept gained ready acceptance among economic geologists and its general tenets were subsequently applied to sulphide ores of Matagami Lake and Val D'Or districts of Quebec (Latulippe, 1966).

In general terms, the volcanic exhalative theory advocates that massive sulphide ore formation is an integral part of, and coeval with, the volcanic complex in which the deposits occur. The common occurrence of several orebodies at or near the same stratigraphic horizon over large areas, the consistent relation between stratigraphy and zoning of the ores, and the widespread association with silicic volcanism, combine to make a deep-seated site of ore formation untenable.

The exhalative concept does not differ markedly from the classical hydrothermal replacement theory in terms of process; in both instances, ore deposition was from hydrothermal solutions originating within the crust of the earth and rising along fractures or other zones of weakness. The main point of departure between the two theories is the site or the timing of ore deposition relative to the host rocks. In the exhalative theory, ore deposition takes place at or near the volcanic rock-seawater interface between successive volcanic episodes whereas the hydrothermalists normally regard ore deposition as a secondary feature imposed on the host rocks a considerable time after their formation and lithification. Metal sulphide precipitation in both theories, however, was probably influenced by the long held concepts of temperature and pressure gradients, dilution of ore fluids, etc.

For example, metal-bearing fumarolic exhalations, issuing forth on the ocean floor during a period of quiescence in the volcanism, are thought to have deposited sulphides at, or close to, the source orifice. In most cases, deposition took place almost immediately upon emanating from the fumarolic vent. Rapid cooling and/or dilution of the metalliferous solutions probably aided the precipitation of sulphides. The passageway through which the fluids rose is now preserved as the alteration pipe stratigraphically beneath many orebodies. Extensive leaching, metasomation, and replacement by ore sulphides undoubtedly took place within the pipe which clearly transects the host rocks. Upon issuance, however, ore deposition was probably largely as a chemical precipitate and is pictured as being a heavy, somewhat gelatinous mud at the time of formation. Honnorez (1969) has described a present day sulphide deposit forming, on the island of Vulcano, from fumaroles related to an 1890 volcanic eruption.

The sulphide clasts which are found either in "mill-rock" and/or in the massive sulphide body itself, may have formed by any of several processes. Some may be the result of post-depositional slumpage and brecciation of an original bedded sulphide layer such as described by Kajiwara (1970) to explain the brecciated nature of ore in the Shakanai mine in Japan. A variation of this method would be brecciation of a sulphide layer by a later volcanic explosion erupting underneath it. Clark (1971, p. 213) has suggested a third method involving original precipitation of sulphides in open fissure veins and breccia pipes. Continued deposition of ore minerals in these vertical channels would result in blockage of the passageways, leading to an increase in pressure, and climaxing in one or more minor explosions which free the sulphide accumulations from the channel walls and distribute the sulphide breccia fragments around the volcanic orifice(s) as a volcaniclastic.

Massive sulphide ores occurring in the volcanically derived sedimentary apron surrounding and/or mantling the volcanic complexes seldom include the stringer ore portion or alteration pipe so common in the ores within the volcanic pile. If the alteration pipe is regarded as the source orifice for these ores, then deposits in the mantling sediments probably represent solutions emanating from similar orifices remote from the site of sulphide deposition. The metal-rich solutions are pictured as moving away from the source, possibly downslope on the ocean floor, to then collect, and later precipitate sulphides, in a slight hollow or other depression (Gilmour, 1971). Alternatively, the lack of an alteration pipe beneath some massive sulphide ores could be explained by early, submarine transport such as sliding down the volcanic slope, as suggested by Jenks (1971) and Schermerhorn (1970), or stripping by turbidity currents (Suffel, 1965, p. 306). Late faulting could also account for the lack of appreciable alteration beneath the Horne mine (Hodge, 1967).

Mention has been made earlier in this paper, in a discussion of a favourable horizon for sulphide bodies, that the exact relationship between exhalite (generally chert and/or iron-formation of the oxide, carbonate, or sulphide facies) and economic massive sulphide bodies is not clear. Although many orebodies are overlain by, or grade laterally into, chert with or without variable amounts of iron oxide or sulphide, it has yet to be demonstrated that these occurrences are the stratigraphic correlatives of any of the widespread oxide, carbonate, or sulphide facies of iron-formation which are so characteristic of Precambrian volcano-sedimentary basins. In spite of the great number of massive sulphide deposits and iron-formations in the Precambrian (the Superior Province is a good example), examples of where it is possible to "walk-out" oxide iron-formation through to a massive sulphide body, containing economic amounts of base metals, are extremely rare. Oxide facies can, however, be traced into sulphide facies barren of base metals and, as Goodwin and Ridler (1970) and Ridler (1971a) have pointed out, this zonation may be indicative of a shelf-to-basin transition. As such, the barren sulphides facies may, by its presence, be a valuable indication of a depositional environment favourable for sulphide accumulation irrespective of whether or not the barren sulphides constitute lateral equivalents of the economic sulphide bodies. The empirical observation relating the spatial correlation between the two differing forms of sulphide deposits (metal-rich and metal-poor) has led Ridler (1971a) to summarize as follows: "Wherever a volcanic complex is within the sulphide or sulphidic carbonate facies and exhaling base or precious metals, significant mineralization may occur." If, in fact, the barren sulphides are the stratigraphic, as well as the genetic, equivalents of the metal-rich sulphide deposits, then, as Ridler (1970a) quite rightly points out, geochemical investigation of the regional exhalite may prove a rewarding exploration exercise. Since any single volcanic pile may be comprised of one, two, or even three volcanic cycles, each containing one or more exhalite horizons, demonstration that the "favourable horizon" exhalite equivalent is geochemically distinctive from the other (barren) exhalites would constitute an exciting breakthrough in the exhalative concept of metallogenesis. Lickus (1965) and Sakrison (1966) have shown that the chemistry of a cherty tuffaceous layer, stratigraphically equivalent to the Vauze and Lake Dufault orebodies in the Noranda area significantly changes its character as the ore zones are approached. This is a valuable observation because it at once renders the exhalite ("favourable horizon") amenable to exploration for "blind" orebodies.

COMPARISON WITH JAPANESE KUROKO DEPOSITS

With the recent publication of the book "Volcanism and ore genesis" (Tatsumi (ed.), 1970), Japanese geologists have revealed the extent of their excellent studies and descriptions of volcanically-related ore deposits in Japan. Although several types of mineralization are included in the book, of interest to the present study are the comments relating to "Kuroko-type" deposits.

Briefly, a Kuroko deposit is "a stratabound polymetallic mineral deposit genetically related to submarine acid volcanic activity of Neogene Tertiary in Japan" (Matsukuma and Horikoshi, 1970, p. 153). The unmetamorphosed nature of these ores, together with their excellent documentation by Japanese geologists, has naturally led to the unofficial acceptance of these as the "type-deposits" for volcanogenic sulphide ores. It is therefore of interest to compare (and contrast) similar ores in the Precambrian with those of the type locality.

In 1970, the International Association on the Genesis of Ore Deposits (I.A.G.O.D.), at the invitation of the Science Council of Japan, held its meeting in Japan. The author was fortunate enough to attend this meeting as well as partake in field trips to several Kuroko deposits. This provided an unexcelled opportunity to compare and contrast geological features of these ores with Canadian Precambrian massive sulphide deposits, based on the author's own experience with the latter.

All the Kuroko deposits of Japan occur in association with Miocene volcanic rocks and fossiliferous sediments deposited on the eastern margin of a major geosynclinal basin. The depositional environment of the host rocks, on the basis of paleontological studies, is considered to be a warm inland sea. Paleontology has also shown that Kuroko mineralization occurred within a relatively short period of time (Middle Miocene) over a strike-length of approximately 500 miles, the length of the so-called Green Tuff region of Japan. Within this "greenstone belt" (to apply Precambrian terminology) more than 100 Kuroko-type occurrences are known but most are clustered into 8 or 9 districts (Aoki, et al., 1970).

Host rocks to the Kuroko deposits are acidic pyroclastic flows considered to have been deposited from turbidity currents accompanying submarine eruption (Horikoshi, 1969). Much of the Kuroko mineralization shows close spatial association with lava domes or masses, particularly those showing evidence of explosive activity.

Within the deposit, Kuroko ores show a consistent stratigraphic succession of ore and rock types and an idealized, fully-represented Kuroko deposit would contain the following types in descending stratigraphic succession (Matasukuma and Horikoshi, 1970, p. 163):

Hanging-wall: Upper volcanic and sedimentary formation.

Ferruginous quartz zone: Composed chiefly of hematite, quartz and minor pyrite.

Barite ore zone: Massive barite ore.

Kuroko zone: Sphalerite-galena-barite.

Oko zone: Cupriferous pyrite ores.

Sekkoko zone: Anhydrite-gypsum pyrite ore.

Keiko zone: Copper-bearing, siliceous, disseminated and/or stockwork ore.

Footwall: Silicified rhyolite and pyroclastic rocks, disseminated and veined by sulphides.

Fine laminations and compositional layering parallel to associated tuff beds, graded bedding of sulphide fragments, colloform textures, and penecontemporaneous brecciation of sulphide layers are characteristic features of the Kuroko and Oko ores.

Compositionally, the ore deposits are zoned roughly in the following sequence (from top to bottom): barium, lead, zinc and copper. In the upper part of Kuroko ore, the predominant copper-bearing mineral is tetrahedrite-tennantite while in the Oko and Keiko ores chalcopyrite predominates.

Alteration directly related to mineralization generally consists of silicification and argillization (montmorillonite-zeolite and sericite-chlorite). Argillization is usually more extensive in the rocks overlying the deposits and is considered by Japanese geologists to represent post-ore "leakage" of mineralizing solutions. Silicification of host rock is most common in the footwall to the orebodies and is an integral part of Keiko (siliceous copper) ore. Silica in the ferrugineous chert horizon overlying the sulphide ore may be the exhalative equivalent of the footwall silicification.

To best explain all the geological features of Kuroko mineralization, Tatsumi and Watanabe (1970) proposed three main ore-forming processes:

1. Fissure-filling, dissemination or replacement by ascending ore-forming fluids in pre-existent rocks or sediments (Keiko orebodies).
2. Chemical precipitation from ore-forming fluids emanating onto a sea floor of pre-existing sediments or volcanic rocks (Kuroko and Oko orebodies).
3. Mechanical sedimentation of ore fragments formed by crushing of early orebodies during precipitation or by later explosion.

In some deposits, all three processes appear to have contributed to ore deposition, in others only one or two appear to have been operative.

Even this extremely brief outline of some of the main characteristics of Kuroko deposits reveals several features in common with Precambrian volcanogenic ores, namely:

1. Both occur with calc-alkaline, submarine, volcanic rocks.
2. Both show a tendency to occur in clusters or districts related to centres of volcanic activity.
3. Both show a strong spatial correlation with the acidic, explosive phase of volcanism.
4. Both consist of two main ore types, massive ore (Kuroko and Oko) and stringer ore (Keiko). The massive ore in both cases is essentially conformable with surrounding rocks whereas stringer ore clearly cross-cuts stratigraphy. The massive ore in both instances is banded.
5. Both are frequently capped by a layer of ferruginous chert (hematite for the Japanese ores, magnetite for the Precambrian) which may extend beyond the limits of the orebody and serves as a marker horizon.
6. Both show a compositional zoning relative to stratigraphy with lead-zinc decreasing and copper increasing downward.
7. Both are underlain by a zone of alteration enclosing the stringer-type ore.

In view of these many points of similarity between Kuroko and Precambrian massive sulphide deposits, there seems ample justification for comparing the two and, by inference, ascribing to them a similar mode of origin. There are, however, several consistent, and therefore perhaps important, differences between the two which may impose certain restrictions on a straight "one-to-one" correlation between Kuroko and Precambrian ores.

1. Footwall alteration in Kuroko deposits is predominantly silicification (>90% SiO_2) of pre-existing felsic rocks whereas most Precambrian (mainly Archean) footwall alteration is characterized by magnesian metasomatism (Riddell, 1952; Lickus, 1965; Sakrison, 1966; Roberts, 1966) accompanied by a marked decrease in silica relative to the unaltered host rock. No explanation for this difference in alteration chemistry is offered but, because rocks and ores in the two instances are separated by about 3.0 b.y. of earth history, it may be related to fundamental and long-term changes in earth chemistry whereby volcanic-related hydrothermal solutions may have changed with time in terms of major-element chemistry.
2. Post-ore alteration, which can be directly related to mineralization, of hanging-wall rocks is rare (or largely unrecognized) in the Precambrian but common in the Kuroko. The difference, however, may be more apparent than real because mineralogical alteration of hanging-wall rocks may conceivably be more obvious in the younger rocks where direct comparison with fresh, unaltered rocks is possible. The pervasive mineralogical breakdown in Precambrian volcanic rocks may have effectively masked any subtle alteration of rocks immediately overlying the orebodies. At the present state of knowledge, however, hanging-wall alteration related to mineralization is not a recognized feature of Precambrian massive sulphide ores. Although hanging-wall chemical alteration of both the Vauze and Lake Dufault orebodies has been documented by Lickus (1965) and Sakrison (1966), the alteration is very sporadic and confined to only a few feet above the ore contact.
3. Assuming, for the present, that chalcopyrite-pyrite-quartz (Keiko) stringer ore is the equivalent of the Precambrian chalcopyrite-pyrrhotite-chlorite stringer ore, than all the major ore types in Kuroko deposits (Kuroko, Oko, Keiko) can be matched with their counterparts in the Precambrian. However, the Japanese Sekkoko (or Sekko) ore-type, consisting of bedded anhydrite and gypsum, does not have an equivalent in the older sulphide masses. In fact, bedded sulphates of any kind are unknown in the Archean which contains the bulk of the known Canadian Precambrian massive sulphide ores. Since sulphur isotope studies of Sekkoko ore (Sakai, et al., 1970; Tatsumi, 1965) suggest the sulphate is derived from seawater, the lack of sulphates in the Archean may indicate a corresponding lack of sulphate in Archean oceans possibly resulting from a low oxygen content in the atmosphere at that time. Hence, the absence of Sekkoko-type bodies associated with Precambrian volcanogenic ores may be attributed more to the chemical evolution of the earth's atmospheric and oceanic compositions than to major differences in ore-forming processes in Tertiary and Precambrian deposits.
4. Although the major ore-types (with the exception of Sekkoko) are common to both, the relative abundances of certain minerals differ between the Canadian and Japanese ores. For example, bornite and tetrahedrite-tennantite are commonly major constituents of Kuroko deposits but are rarely more than accessory minerals in the Precambrian ores. Similarly galena and barite, the former a minor, and the latter seldom, a constituent of Precambrian massive sulphide ores, comprise the major portion of the massive Kuroko ore. The reason for the

paucity of bornite and tetrahedrite-tennantite in Precambrian ores is not clear but absence of barite may, as with anhydrite and gypsum, reflect a lack of sulphate in early Precambrian seas. Similarly, the lack of lead in the ancient ores may be a function of long-term geochemical evolution because the crust (and/or mantle) would not have had time to generate and accumulate lead produced by radioactive decay of uranium and thorium. Since the earth's over-all "lead budget" is continually increasing by this process, the paucity of lead in the early Precambrian, like the paucity of sulphate, can probably be attributed to over-all changes in earth chemistry. If this premise is accepted then, in spite of these major differences in mineralogy, comparison of the Tertiary and Precambrian ores would still be justified.

In contrast to the above trend of a more varied assemblage in the Tertiary ores, pyrrhotite, a very abundant mineral in most Precambrian ores, is a rare constituent in the Japanese ones. Primary pyrrhotite does not occur in Kuroko ores; minor occurrences of secondary pyrrhotite have been reported as the products of thermal alteration of pyrite by nearby post-ore dykes. This absence of primary pyrrhotite in Kuroko ores may suggest that pyrrhotite in Precambrian deposits is largely or entirely the result of regional metamorphism, even in deposits in areas of low-grade metamorphism such as Vauze and Mattagami Lake. Conversely, the Precambrian pyrrhotite could in large part, be primary and indicative of a slightly different depositional environment relative to the Kuroko.

In summary, although the Kuroko deposits compare favourably with Precambrian massive sulphide counterparts in most of their major features, the Precambrian ores, particularly those in the Archean, possess unique properties which must be taken into consideration before rigorously equating the two. The relative lack of lead and sulphates and the predominantly Mg- instead of Si- metasomation in the footwall rocks are characteristic of the older Precambrian ores. In the author's opinion, these chemical characteristics are "restraints" imposed on the bulk compositions of Archean ores by the primitive geochemical evolution of the Earth and its atmosphere at that time.

If, as proposed earlier, volcanogenic massive sulphide ores have, in fact, formed from submarine exhalations, perhaps the chemical differences between Precambrian and Kuroko ores are manifestations of the geochemical evolution of the earth's lithosphere, hydrosphere, and even atmosphere.

THE SULLIVAN MINE - AN EXHALATIVE DEPOSIT IN NON-VOLCANOGENIC ROCKS

Occurring in argillites and siltstones of Proterozoic (Helikian) age, the Sullivan mine has produced more than 100 million tons of lead, zinc, and silver ore, making it one of the largest lead-zinc mines in Canada today. The mine is situated on the east side of the Purcell anticlinorium in southeastern British Columbia (Fig. 2, no. 69). The lowermost Purcell, the Aldridge Formation, is at least 15,000 feet thick and the lowermost portion consists principally of grey-green, rusty weathering, thinly interbedded impure fine-grained quartzite, siltstone, silty argillite, and argillite (Freeze, 1966). The Sullivan mine occurs near the top of the rusty weathering Lower Aldridge.

The deposit has been described by several authors (Swanson and Gunning, 1945; Carswell, 1961; Freeze, 1966) and the following brief description of the deposit is paraphrased from Leach and Wanless (1962, p. 250).

'The orebody occurs within a single stratigraphic zone 200-300 feet thick and has been mined for about 6,000 feet along strike and 4,500 feet down dip. It is thus in general conformity with the strata, although the stratigraphic position of greatest sulphide concentration varies slightly from place to place..... Within individual ore bands the conformability of sulphides and strata is impressive. Only a relatively small part of the ore is in veins cutting the metasedimentary rocks.

'The principal sulphides are galena, sphalerite, pyrrhotite, and pyrite.... Magnetite is common but not quantitatively important, and cassiterite occurs in small but commercially recoverable amounts...

'Most of the ore is distinctly layered. The layers, whose thickness ranges from a fraction of an inch to more than a foot, consist of sulphides in contrasting proportions and of sulphides alternating with metasedimentary rock. The layering in the sulphides reflects those of the host rock...

'The original shape of the ore deposit... was apparently discoidal and there is a zonal distribution of many elements within it. A relatively central zone consists almost entirely of pyrite and pyrrhotite and various metal ratios have a roughly symmetrical distribution around the centre; for example the ration Pb/Zn is greatest near the "iron zone" and decreases toward the periphery of the deposit.'

Beneath the central part of the orebody, and extending for more than 1,500 feet below the footwall of the ore zone, is a roughly funnel-shaped zone of tourmalinized wall-rock. Alteration in the hanging-wall has affected considerably less rock and has resulted in chloritization and albitization of the metasediments more-or-less directly above the "iron zone" in the ore and the central part of the tourmaline alteration "pipe". Consideration of the geological relationships described above and shown in Figure 11 suggests that formation of Sullivan orebody may be similar to that of the volcanic exhalative type of Stanton (1960) and that ore deposition was essentially contemporaneous with sedimentation of the host rock argillite. In this genetic model, the tourmaline-rich pipe would represent the feeder zone through which the ore-bearing solutions penetrated the footwall sediments to reach the sea floor, at which point deposition of sulphides took place. The annular, zonal arrangement of elements in the orebody supports the idea of a central feeder zone. The thicker part of the orebody, the abundance of pyrrhotite, and the higher tin content are all coincident immediately above the central part of the tourmaline pipe i.e. the feeder zone source vent of the hot mineralizing solutions. Chlorite and albite in the hanging-wall sediments above the central zone represent small amounts of post-ore "leakage" of the (by then) barren solutions. These solutions, which produced tourmaline ($(Na, Ca)(Al, FeMg)_3B_3Al_6Si_6O_{27}(OH)_4$) in the hotter environment of the feeder zone, would, when passing into the sedimentary-diagenetic environment above the ore horizon, be reconstituted into chlorite ($(Mg, Fe)_5(Al, Fe)_2Si_3O_{10}(OH)_8$) and albite ($(Na, Ca)AlSi_3O_8$), minerals which are stable under these less intense conditions of diagenesis and sedimentation. Boron, a natural constituent of seawater, would escape into the Proterozoic seas.

Besides the Sullivan, at least three other small orebodies also occur in the Aldridge and bear many similarities to the main Sullivan ore. These ores, as well as the ubiquitous iron sulphide disseminated throughout the Lower Aldridge and which gives it its characteristic rusty weathering appearance, are considered to have reached their present position in the Aldridge in a manner analogous to that of the Sullivan i.e. through deep

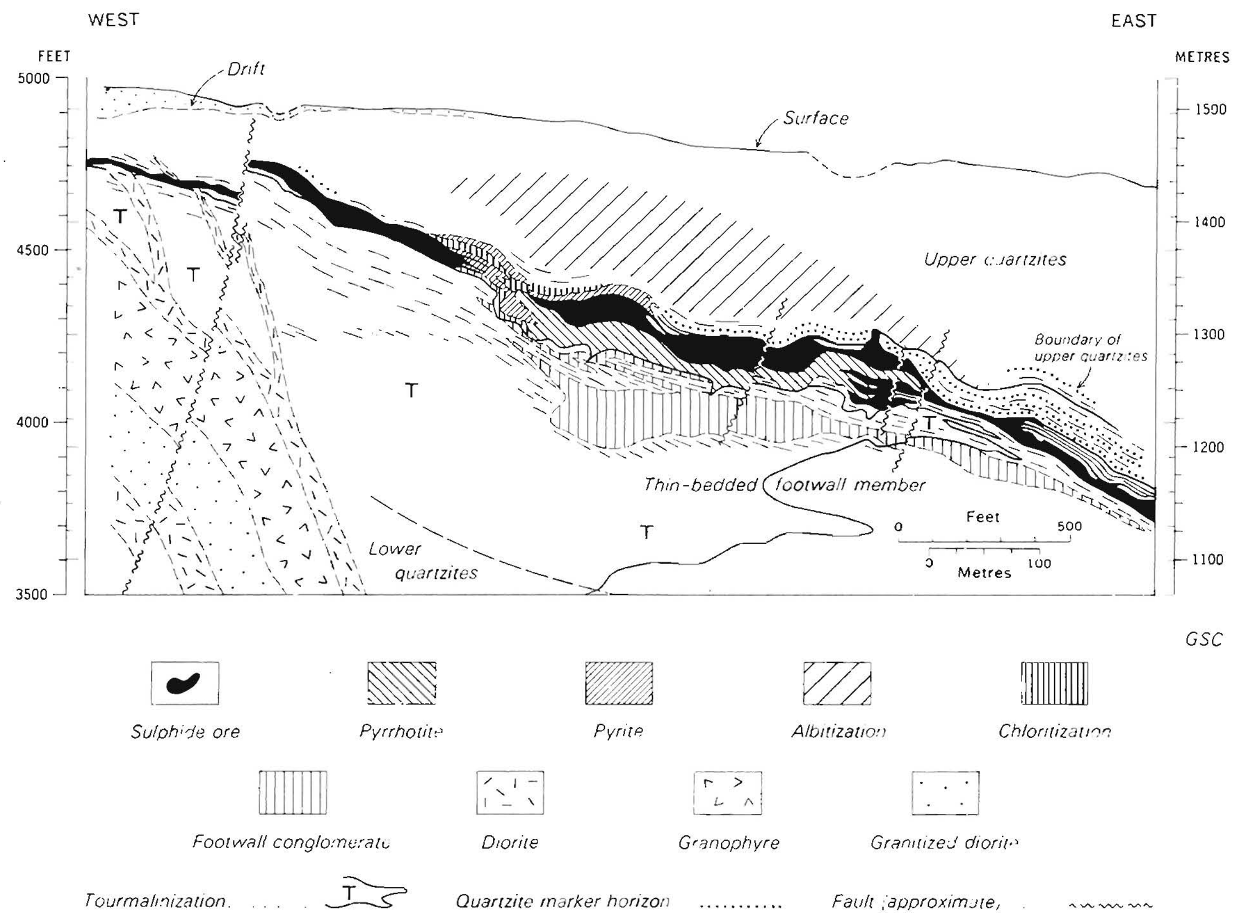


Figure 11. Sullivan mine, British Columbia. Geological cross-section (After Freeze, 1966; diagram from Little, 1970).

fractures to the sea floor whereupon the metals were deposited contemporaneously with sedimentation. A similar origin for the Sullivan deposit has recently been proposed by Gilmour (1971).

The tourmaline zone beneath the orebody (analogous to the chlorite alteration pipe beneath massive sulphide ores in volcanic rocks), the metal zoning, the relative lack of alteration on the hanging-wall, and the massive, disrupted nature of the ore in the central part of the body (over the postulated feeder pipe) giving way laterally to increased banding and continuity of layers on the fringe of the ore (quieter depositional environment ?) all combine to make an exhalative theory of origin reasonably plausible.

The major difference between the Sullivan orebody and the "normal" volcanogenic massive sulphide bodies described in the previous chapters is, in the author's opinion, the depositional environment. A few volcanic layers occur in the Purcell sequence but are insufficient to classify either the host rocks or the environment as volcanogenic. In fact Price (1964) has suggested that the Aldridge rocks were deposited mainly in a deltaic depositional environment. Recently, Kanasewich (1968) postulated, on the basis of deep seismic reflections, that a Precambrian rift valley may exist beneath southern Alberta and British Columbia. The position of the rift is such that the Sullivan orebody is situated just within the north edge, leading Kanasewich to speculate that the deposit was formed in an ancient rift in a manner similar to that occurring at present for the Red Sea hot metalliferous brines (Degens and Ross, 1969) i.e. that metalliferous solutions rose along deep-seated fractures in a rift, or ocean floor spreading, tectonic environment and deposited metals directly on the ocean floor. The process is entirely analogous to that postulated for the volcanogenic massive sulphides, the only difference being that, for the latter, the process was operative in an active, eugeosynclinal, volcanic, possibly island arc environment. The similarity in ore-forming processes, however, has resulted in deposits with many parallel internal features as discussed above. For these reasons, then, Sullivan is regarded as being of exhalative origin but in a sedimentary, rather than volcanic environment.

Table I

Major sulphide mineral content of selected Precambrian massive sulphide ores (as per cent of total sulphides)

	Pyrite	Pyrrhotite	Sphalerite	Chalcopyrite	Reference
Geco	50	17	20	10	Milne, 1969
Lake Dufault	39	14	26	20	Purdie, 1967
Rod	30	12	15	40	Coats et al., 1970
Coronation	25	13	-	62	Whitmore, 1969

Table II

Minor metallic minerals in selected massive sulphide ores

Chisel Lake	Lake Dufault	Texas Gulf Sulphur (Kidd Creek)	Coronation	Zenmac
Arsenopyrite	Argentite	Cassiterite	Arsenopyrite	Cassiterite
Bournonite	Chalcocite	Rutile	Cubanite	Spinel
Native gold	Cubanite	Covellite	Marcasite	Violarite
Altaite	Dyscrasite	Digenite	Native gold	Magnetite
Hessite	Galena	Marcasite	Magnetite	Ilmenite
Tennantite	Mackinawite	Acanthite	Ilmenite	
Geocronite	Silver antimonial	Arsenopyrite	Hematite	
Arsenic	Stannite	Stromeyerite		
Tetrahedrite	Magnetite	Native silver		
Boulangerite		Bornite		
Pyrargyrite-proustite		Galena		

Table III

Possible metamorphic equivalents of primary rock types commonly associated with Precambrian massive sulphide deposits (modified slightly from Hutchinson, 1970)

Primary or Low-Grade Metamorphic Rock	Medium-Grade Metamorphism	High-Grade Metamorphism
Chert	Siliceous schist	Quartzite
Pyritic, cherty iron-formation	Pyrite-pyrrhotite-magnetite mica schist	Pyrrhotite-magnetite mica quartzite
Rhyolite Rhyolite tuff Rhyolite breccia Rhyolite agglomerate	Quartz-feldspar-sericite gneiss	Quartz-feldspar gneiss
Andesitic tuff (chlorite-schist)	Biotite-chlorite-quartz schist	Biotite-quartz gneiss
Andesite (chlorite-schist)	Epidote-plagioclase-amphibolite	Hornblende-plagioclase-amphibolite gneiss
Basalt (chlorite-schist)	Epidote amphibolite	Amphibolite (gneiss)

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