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Environment of Deposition of the Sullivan Orebody

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The genesis of the Sullivan orebody is reviewed in terms of current concepts of stratiform ore formation. The source of metals and sulfur, the environment and time of ore formation, and the imprint of subsequent metamorphic events are explained in terms of a model which views the ore as one component of a chemical and clastic sequence formed within a rift basin above a thermal anomaly. Classic primary sedimentary structures are displayed in both the chemical (sulfide) and the clastic (silicate) rocks. Fractures and breccia zones beneath the western section of the mine provided passage-ways for boron and metal-rich sulfur-poor brines. Sulfides formed when the metals combined with reduced marine sulfur. The pattern of metal zoning is a reflection of the location of brine vents. The boron-rich solutions produced the tourmaline alteration zone. The sodium-rich brine produced albite within the ore sequence and in the hanging wall perhaps by the modification of analcite. The manganese variation of sulfide minerals between ore bands and laminations reflect changes in the chemistry of solutions during sedimentation and some degree of partitioning during metamorphism. The metamorphism has modified both the sulfide and silicate assemblages.

INTRODUCTION

Concepts regarding the origin of stratiform base metal deposits have evolved considerably in the past decade. The geologic setting of this large and significant orebody, within the framework of plate tectonics, is of particular interest. Before the language of the new tectonics had evolved, Freeze (1966) supported the view of earlier workers that hydrothermal replacement was important particularly in the western part of the orebody and recognized the strong syngenetic case that could be made for the laminated eastern ores. Jardine (1966) made a major contribution by detailing the relationship of the footwall breccia, conglomerate, mineralization and post-ore adjustments. The Sullivan mine staff first graphically illustrated the footwall breccia zone and provided an overview of the complex epigenetic and syngenetic features displayed in the mine in a paper by Morris (1972). Hutchinson (1973) suggested that deposits of the Sullivan type were formed in zones of rifting of archean crust, and were associated with tholeiitic magmatism, fumarolic activity, and turbidites. Ethier et al. (1976) reviewed the geochronological evidence and concluded that the tourmalinization and ores are syngenetic with both a contact metamorphic and regional metamorphic overprint. In discussing ore deposits from the viewpoint of plate tectonics, Sawkins (1976) suggested that the Sullivan type deposits were formed along continental margins or tension-related intracratonic troughs. In an update of the view of the mine geological staff, Ransom (1977) concluded that the ores are definitely syngenetic, formed by brines entering the basin along footwall fractures, first developing the boron alteration, then depositing the sulfide ores. Carne (1979) in a tabulation of characteristics of sedimentary-exhalative deposits indicates the tectonic control at Sullivan to be the intersection of fracture zones and normal fault along a possible rift margin.

This paper reviews evidence for the origin of the Sullivan deposit in the light of current concepts and data resulting from our research on the deposit, Campbell and Ethier (1977). Questions posed about the source of the ore metals, the source of sulfur, the environment and time of deposition, and the imprint of subsequent metamorphic events (Freeze, 1966) may be addressed in terms of a model which views the ore as part of a chemical and clastic sedimentary process in a region with a

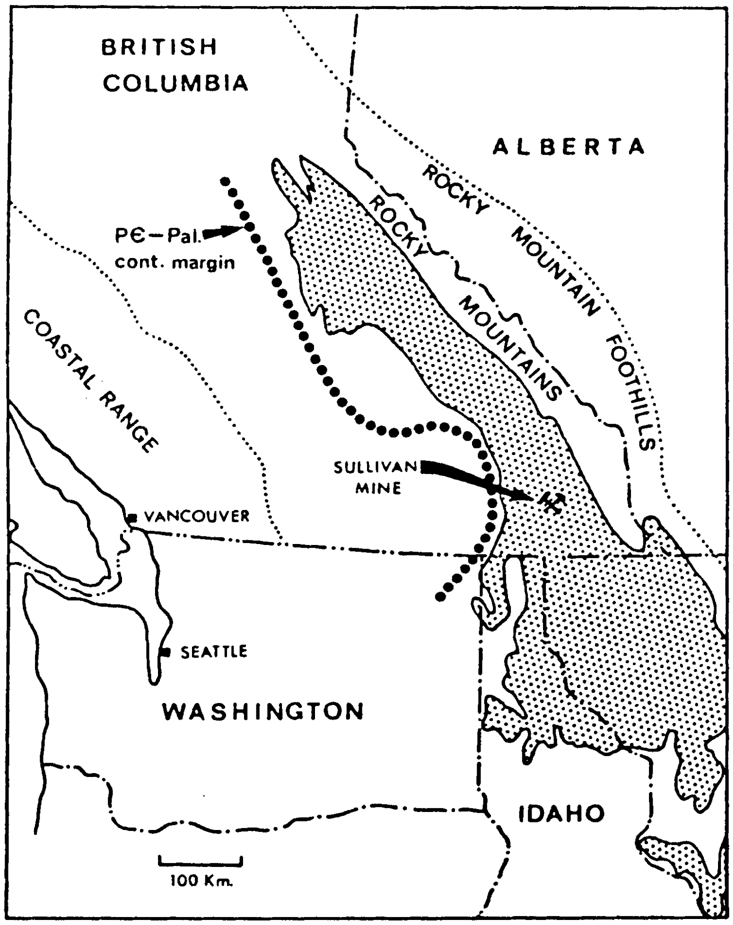

Fig.1. Location of the Sullivan mine, the stippled area indicates the distribution of Purcell (Helikian) and overlying Windermere (Hadrynian) rocks.

Table 1. Precambrian and Lower Paleozoic Stratigraphy Kimberley-Cranbrook Area, B.C. [After Price (1964), Gabrielse (1972), Reesor (1957) and Høy (1978)]

		Formation Name	Thickness (metres)	Description
	Lower Cambrian	Cranbrook	180 metres	conglomerate, quartzite, some magnesite-bearing
	-------------------- disconformity			
Helikian	Upper Purcell	Gateway	?	meta-argillite, Purcell lava pebbles, quartzite pebbles
	Lower Purcell	Purcell lava	100	chloritized andesite flows (1100 M.Y.B.P.)
		Siyeh	600	meta-quartzite & meta-siltstone, some limey; meta-argillites; stromatolites
		Kitchener	1200	
		Hellroaring Creek Stock		albitic granodiorite (1300 M.Y.B.P.)
		Purcell Sills		continental tholeiitic gabbro, quartz diorite, granophyre (1430 M.Y.B.P.)
		Creston	1900	meta-quartzite & meta-argillite
		Aldridge	3700	meta-quartzite, meta-argillite, some silty; graphitic and carbonaceous in part; some laminated, some rusty weathering. Includes Sullivan ore body and several smaller stratiform lead-zinc deposits at transition from Lower to Middle. Purcell sills intrude lower and middle parts of the formation
		Upper	700	
		Middle	500	
		Lower	2500	
		Fort Steele	2100+	meta-quartzite & argillaceous metaquartzite; crossbedded or laminated; also dolomitic meta-argillite. Contains at least three upward-fining sequences; fluvial deposits. Base not exposed
	Pre-Purcell Basement Complex			(1750 M.Y.B.P.)

long and relatively complex geologic history.

The Sullivan is a stratiform lead-zinc deposit in southeastern British Columbia (Fig. 1) located at the boundary between the Lower and Middle Aldridge Formation (Helikian) and adjacent to the Precambrian-Paleozoic continental margin (Monger, 1979). The relevant stratigraphic sequence is shown in Table 1. The block diagram shown in Figure 2 compiled from data presented by Freeze (1966), Jardine (1966) and the Sullivan Mine Geological Staff (1972), shows the main features of the geology of the deposit. These are: the tourmaline-rich footwall in the west, the footwall breccia zone, the footwall conglomerate, massive ore in the west overlying a pyrrhotite-rich footwall zone, laminated ores in the east showing distinct ore and waste bands, the albite hanging wall zone in the west, the central chlorite and pyrite zone, and the Sullivan sill complex below and in the west part of the mine.

To facilitate the discussion, the history of the deposit within the framework of the basin can be viewed as

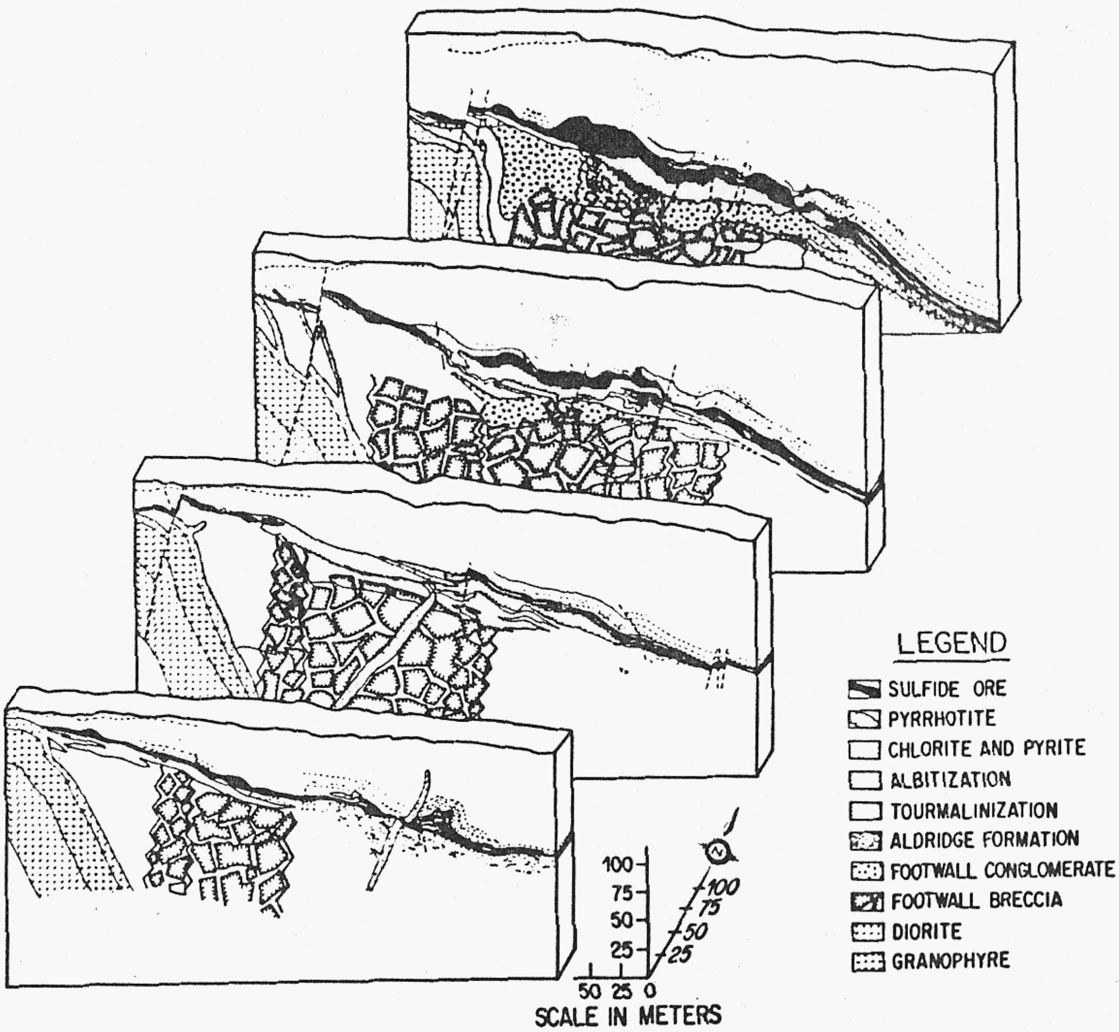

Fig. 2. Block diagram of the Sullivan mine compiled and modified from data presented by Freeze (1966), Jardine (1966) and the Sullivan mine geological staff (1972)

six critical sequential stages. In order, these stages consist of (a) Lower Aldridge basin sedimentation, (b) footwall collapse, (c) footwall conglomerate deposition, (d) sulfide deposition, (e) hanging wall development, and (f) metamorphism.

THE LOWER ALDRIDGE BASIN SEDIMENTATION

The Lower Aldridge Formation was deposited in a north-south trough on a Precambrian basement as the lowermost part of a miogeoclinal wedge. Figure 3 (a) depicts, in a diagrammatic east-west cross-section, the relationship of the Lower Aldridge to the Fort Steele Formation and the basement, based on work by Edmunds (1973, 1977), Harrison (1972), Reesor (1957), and Price (1964).

The Lower Aldridge consists of very fine-grained clastic sediments from a source area of low relief to the south and east. This sequence formed in deep water beyond the front of a prograding delta which is now the Fort Steele Formation (Price, 1964). The rocks show graded beds and current features, and many have a turbidity current origin (Bishop et al. (1970), Morris (1972), Edmunds (1973), Høy (1978)). Carbon-rich laminations and accessory pyrrhotite as laminations and disseminations are both characteristic of the sequence. The sedimentation rates for Lower Aldridge sediments must have been very low, on the order of 1 to 2 cm per 1000 years. This estimate is based on the 3800 m of sediments deposited in the 250 M.Y. from the time of the pre-Purcell basement (1750

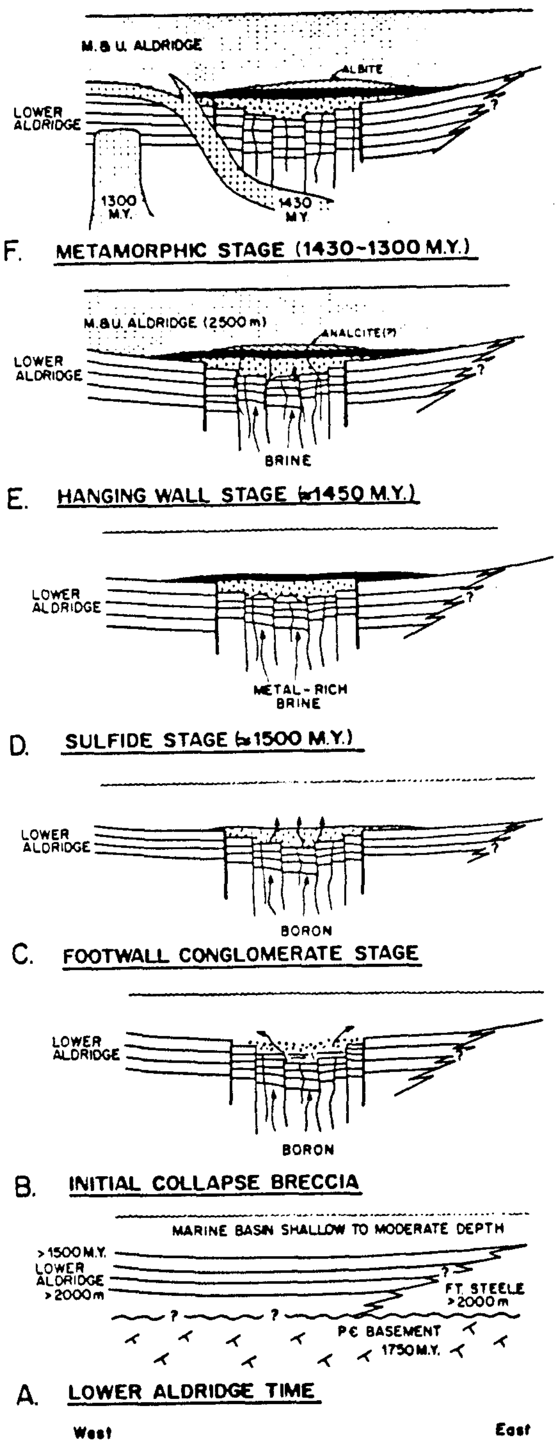

Fig. 3. Diagrammatic sequence of events. (a) Lower Aldridge time (b) initial collapse breccia, boron-rich sediment stippled, (c) footwall conglomerate stage (d) sulfide deposition, sulfides dark upper layer (e) hanging wall stage, (f) metamorphic stage showing intrusion of the Sullivan sill (1430 m.y.) and the Hellroaring Creek granitic stock (1300 m.y.)

M.Y.B.P.) to the deposition of the ore at 1500 M.Y.

Several features of the Lower Aldridge basin are germane to an understanding of ore formation. Among these is the north-south orientation of the depositional trough; although the original basin may or may not have been fault bounded, north-south trending faulting during deposition probably influenced the location of upwelling metal-rich brines. Secondly, widespread evidence of carbonaceous material [both disseminated and as laminates) indicates recurring euxinic conditions (Huebschman (1973), Edmunds (1977)], a state vital to the biogenic reduction of sulfur (Rickard, 1973). Thirdly, the presence of pyrrhotite throughout the Lower Aldridge basin demonstrates the ability of the basin to produce reduced sulfur. The pyrrhotite is syngenetic [Huebschman (1973), Campbell et al. (1980)], and there is no evidence that it was originally deposited as pyrite and subsequently altered. A similar conclusion has been reached regarding pyrrhotite at Mount Isa (Finlow-Bates et al., 1977).

FOOTWALL COLLAPSE

The breccia zones in the footwall of the Sullivan deposit were studied by Jardine (1966) and illustrated by the Sullivan mine geological staff (1973). Ransom (1977) concludes that the breccia and conglomerate were formed in a localized zone of extension. Although in detail the breccia zones are complex, they appear to have been the result of local fracturing along northerly trending zones and associated collapse features, as illustrated in Figure 3b. It is visualized that boron-rich fluids moved up along the fractures and produced boron-rich sediments in and adjacent to the zone of collapse. These boron-rich sediments take the form of tourmaline-rich laminates which are invariable bedded and show no evidence that tourmaline is epigenetic (Fig. 4). The tourmaline occurs as felted masses of microcrystalline needles alternating with graded pyrrhotite-rich laminations (Fig. 4d). Further textural and chemical details are provided by Ethier and Campbell (1977).

The nature of the breccia and the associated introduction of boron is taken as evidence of a rift associated with a thermal anomaly. The evidence indicates that the boron was introduced by a thermal brine circulation system either as a product of a granitic magma degassing at great depth or was gleaned from the sedimentary pile and concentrated in the same way as the metals.

Ozol (1977) reviewed the volcanogenic-sedimentary occurrences of boron concentrations and concluded that the regions above subduction zones are enriched in boron while volcanic gases and hydrothermal solutions associated with mid oceanic ridges and continental rifts are low in boron. He cites western North America as an anomalous boron-rich area above the subduction zone. Basaltic lavas in the area were controlled by rifting and bimodal series of volcanic rocks are also present.

FOOTWALL CONGLOMERATE DEPOSITION

The footwall conglomerate was deposited within the collapse area and overlaps the unbrecciated footwall to the east (Fig. 3c). The conglomerate is locally derived from ripped-up semi-lithified clasts of Aldridge material. Exotic clasts are completely absent. The fragments are poorly sorted and angular, rendering the unambiguous distinction between breccia and conglomerate difficult.

The conglomerate in places contains tourmaline and at other locations is free of tourmaline. In a typical tourmaline-rich smaple the pebbles may show internal laminations indicating the source to be a boron-rich laminate (Fig. 5). The matrix of such a sample may have a high content of pyrrhotite; textural evidence indicates the clasts were only semi-lithified when the con-

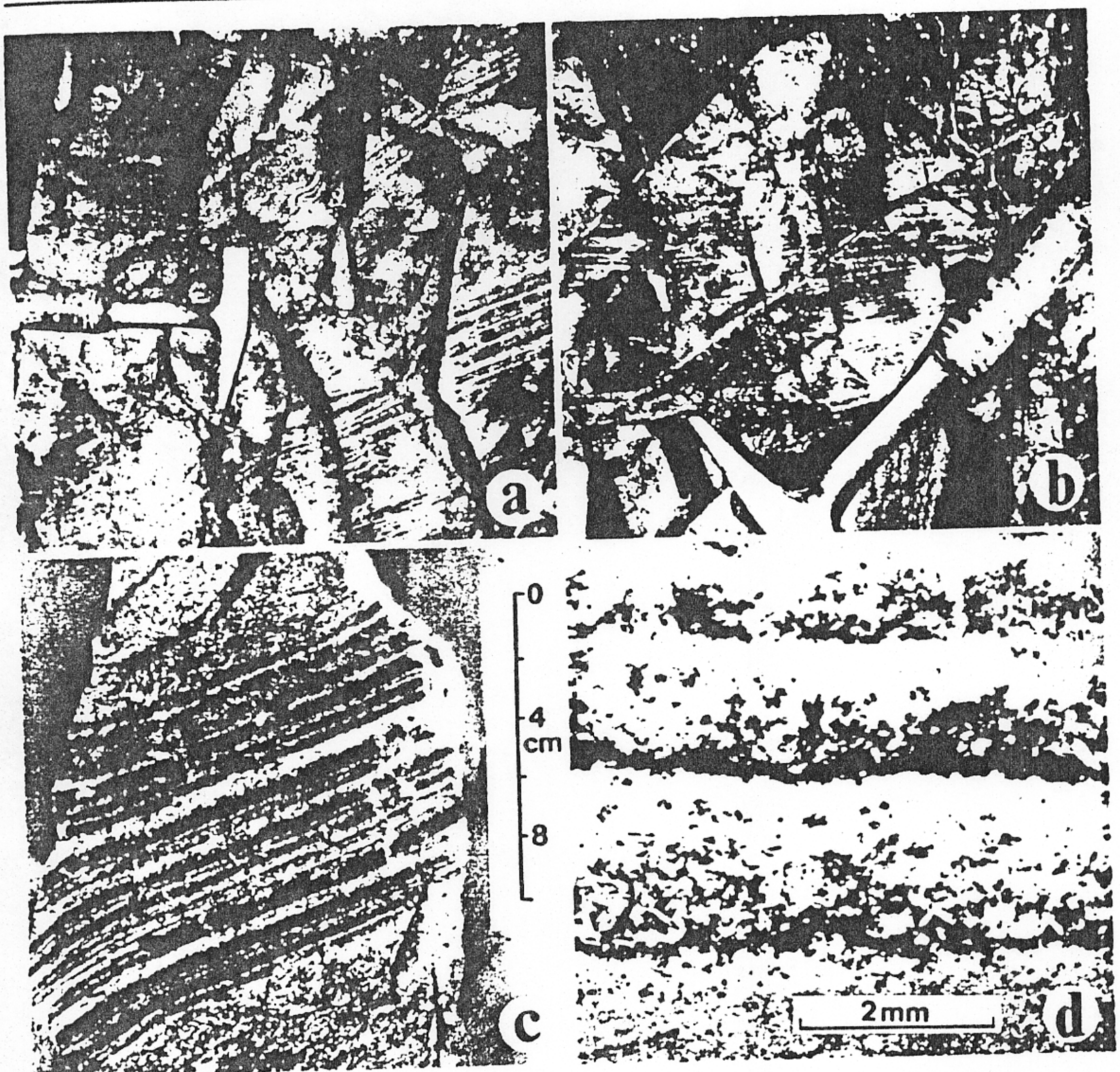

Fig. 4. Illustrations of tourmaline-rich footwall laminates; (a) laminates showing soft sediment crenulations and non-parallel elements (b) laminates of regular and persistant type (e) polished surface demonstrating graded appearance of laminate (d) photomicrograph of graded pyrrhotite units separated by tourmaline-rich silicate units

glomerate was deposited. In the tourmaline-poor phases of the conglomerate the clasts are predominantly quartz-sericite, and the difference between the clasts and matrix is mostly one of grain size. In places oriented pyrrhotite crystals rim clasts and outline them in the otherwise homogenous rock. These rims are interpreted as evidence of pyrrhotite forming between the clast and the matrix prior to lithification.

The footwall fracture and breccia zones, as outlined by Jardine (1966), show similar distribution patterns. This, plus the evidence that tourmalinization and brecciation preceded and continued during the formation of

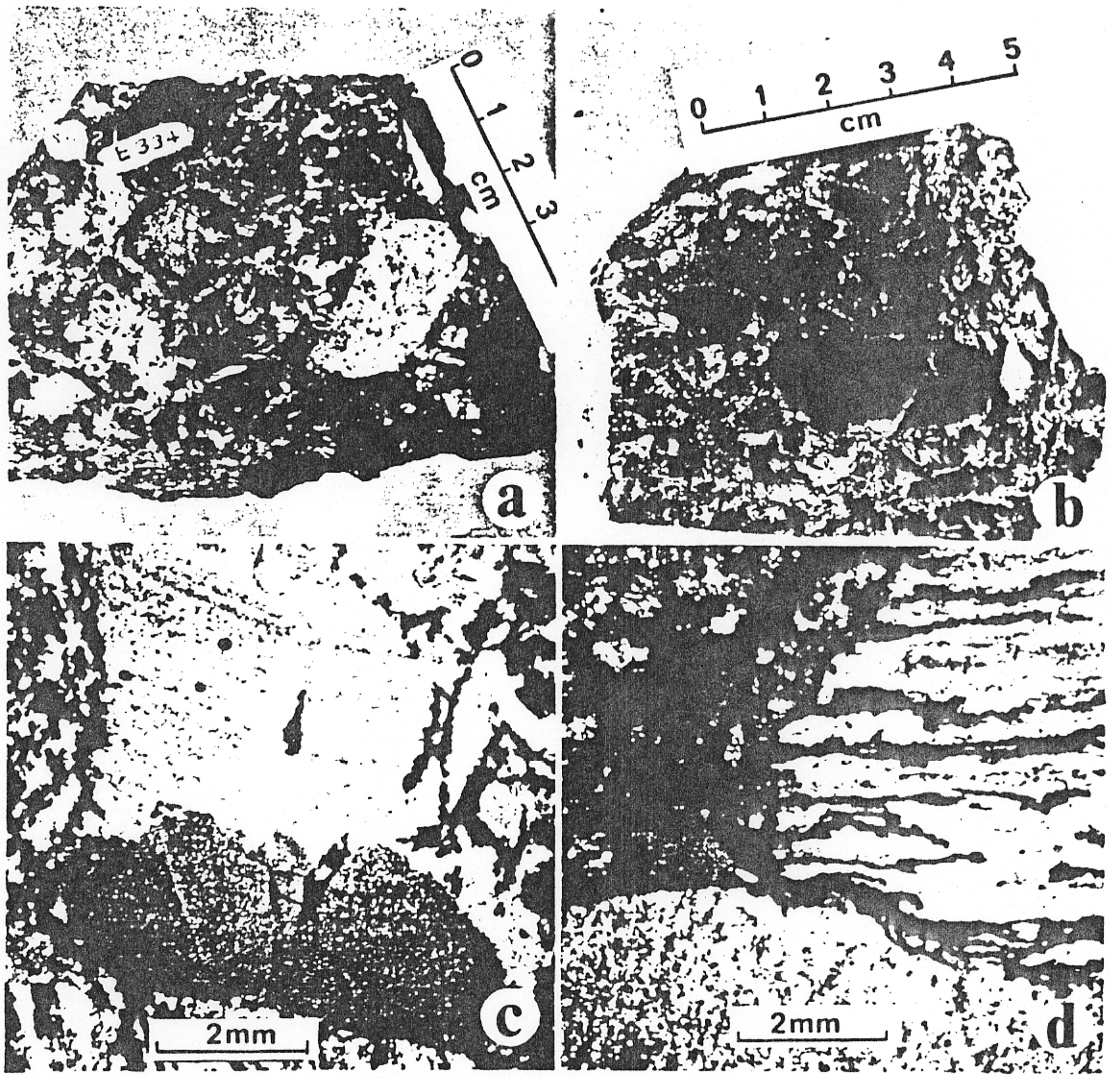

Fig. 5. Illustrations of the footwall conglomerate; (a) Mixture of tourmaline-rich (black) clasts and tourmaline-free clasts (light coloured) (b) matrix and clasts tourmaline-rich (c) varying degrees of tourmalinization, dark fractured clast at bottom is tourmaline-rich compared to the laminate above. The black is pyrrhotite (d) fragment of a pyrrhotite-rich laminate in section showing heterogeneous distribution of tourmaline (medium grey)

a locally-derived conglomerate, restricts the mechanism of genesis for this unit. Extensive transport is ruled out. Instead, a mechanism of milling during collapse readjustment and possibly movement and fracture during the introduction of the boron-bearing fluids is favoured.

SULFIDE DEPOSITION

Figure 3d depicts the ore forming above the breccia and conglomerate zones and extending east and west of these. During this phase a dense metal-rich brine, possibly similar to the

Sato type I (Sato, 1972), rose through the fractures in the collapse structure and reached the sea floor. Edmunds (1977) in a statistical study of the Aldridge Formation provides data indicating the lead and zinc content of the greywacke and argillite is anomalously high. Furthermore he concludes that the lead and zinc are precipitated from connate waters that passed through the greywacke. This evidence supports the rather broad dispersal of metals by a brine that saturated the argillaceous and arenaceous units adjacent to the fractures. Based on an interpretation of the Pb isotope data presented by Le Couteur (1973, 1979), the age of the ore deposit is about 1500 M.Y. This interpretation accepts the fact that the ore is older than the sill (1430 M.Y.) that cuts the ore, and the average $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ values for seven samples is 16.52 and 15.48, respectively (Le Couteur, 1973). These latter ratios, when interpreted in terms of the models suggested by Doe and Zartman (1979) are consistent with a 1500 M.Y. age and an orogenic environment. Other deposits that contain lead isotope values that fall into this category are Captain's Flat, Cobar, Bathurst and Kuroko according to the authors. Furthermore, Le Couteur indicates that the lead (and by analogy the other metals) had a crustal source and was concentrated and transported by brines.

A study of sulfur isotopes from minerals throughout the deposit produced data that are consistent with a marine sulfate origin for the sulfur and the formation of syngenetic sulfides (Campbell et al., 1978). The model visualized is one where a metal-rich, sulfur-poor brine is introduced into a euxinic environment in which sulfate is being reduced to sulfide. The degree of openness of this basin determines the rate of replenishment of the sulfate and the rate of reduction depends on nutrient for the bacteria, sulfate concentration, temperature, and catalysis of chemical reduction. The interplay between the rate of replenishment of the sulfate and the rate of sulfate reduction produces the isotopic patterns observed in the deposit. The isotopic values are more negative in terms of $\delta^{34}S$ when the rate of replenishment increases relative to the reduction rate and the values are more positive when the rate of replenishment decreases relative to the rate of reduction. The stratigraphic dependence of sulfur isotopes is a subtle indicator of the changes in the environment of deposition, and supports the concept of basin geometry and temperature controlling the sulfite production and thereby the chemical precipitation of the sulfides.

Sulfur isotope data from portions of the western massive sulfides (above the breccia zone) show anomalously high positive $\delta^{34}S$ values. These are interpreted as indicating sulfate reduction at higher temperatures and under more reducing conditions than in the eastern zone away from the breccia and fracture system (Campbell et al., 1980).

Megascopic and microscopic features assist in detailing the nature of the ore-forming process, which is basically one of ongoing very slow clastic deposition with the chemical precipitation of sulfides superimposed. In the western section, sulfide precipitation overwhelmed clastic deposition resulting in the formation of massive ore. In the eastern sector, the ore is finely laminated and takes the form of five discrete ore bands which may be traced throughout this part of the mine (Ransom, 1977). These bands are designated, in ascending order, Main A, B, C, and D bands (Fig. 10). B band may be further subdivided into a triplet of smaller bands. Ore bands are separated from each other by waste bands which are also traceable throughout the entire eastern sector.

Sedimentary features such as soft sediment slump, graded beds, transections and sedimentary boudins can be observed in the eastern laminated ores (Fig. 6). In thin and polished section the ores show compositional banding which reflects variations in both the chemical (sulfide) constituents and clastic constituents. It is therefore possible, for example, to map in thin section bands of sphalerite plus muscovite, followed in sequence by pyrrhotite, quartz plus biotite, garnet,

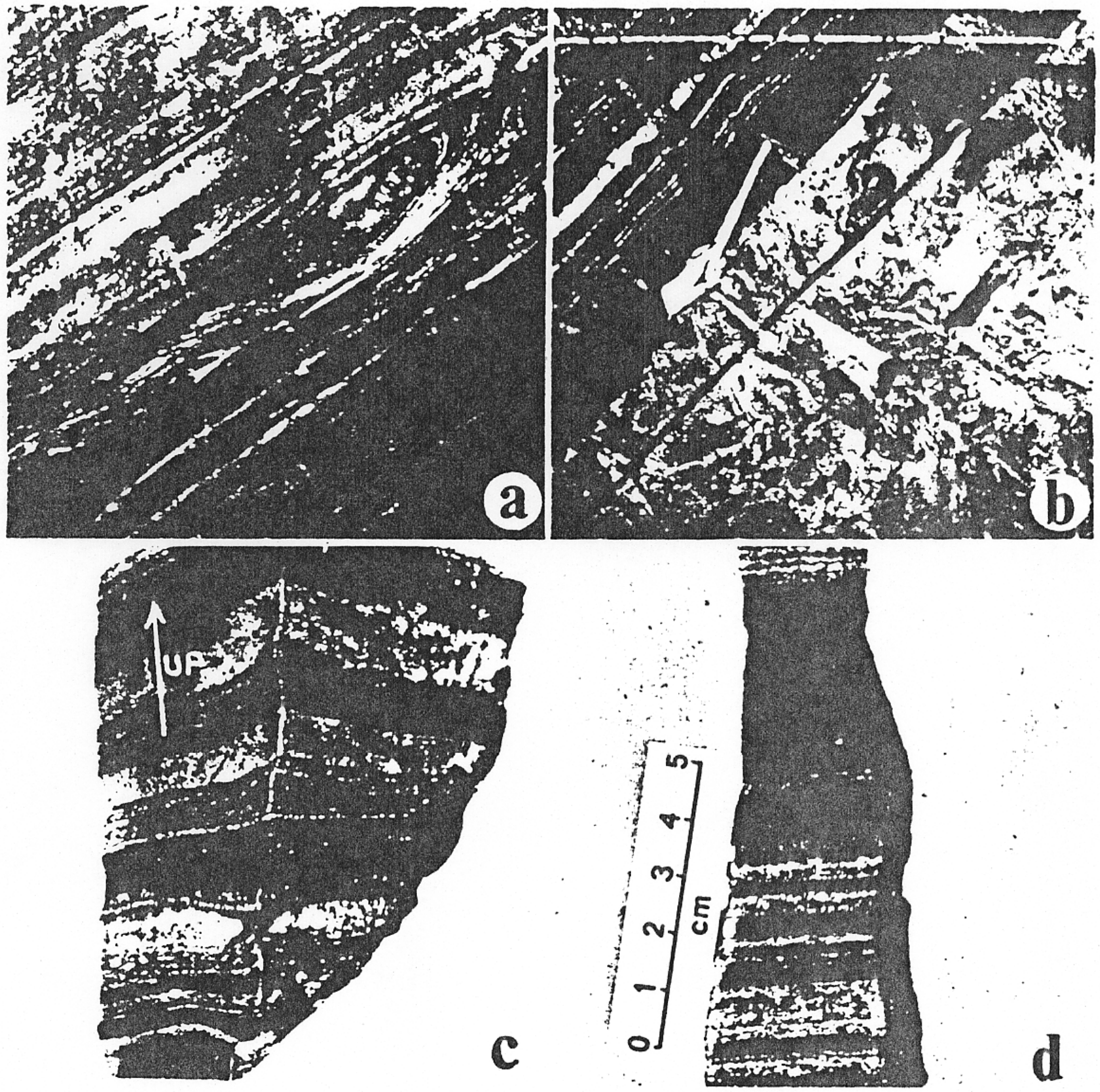

Fig. 6. Sedimentary features in the eastern section of the mine. (a) Truncation of beds and soft sediment flame textures (b) waste band with pyrrhotite-rich blebs and schlieren in silicate units (c) detail of sulfide (light) and silicate units showing pyrite boudin of sedimentary origin toward base (d) random alternation of sulfide (light) and silicate (grey) units

and pyrrhotite. In some rather rare places a lamina of nearly pure albite is present in the sequence and is interpreted as representing an original analcite horizon formed by the sodium-rich brine at a time when perhaps the system lacked enough sulfite to produce sulfides (Fig. 7c,d).

In polished section the compositional banding is demonstrated by the variations in minerals phases. The contacts between the various bands although now characterized by annealed textures are considered to represent original variations in the amount of sphalerite, galena and iron sulfides precipitated (Fig. 7a).

Metal zoning in the Sullivan deposits has been used as an argument for epigenetic replacement (Freeze, 1966).

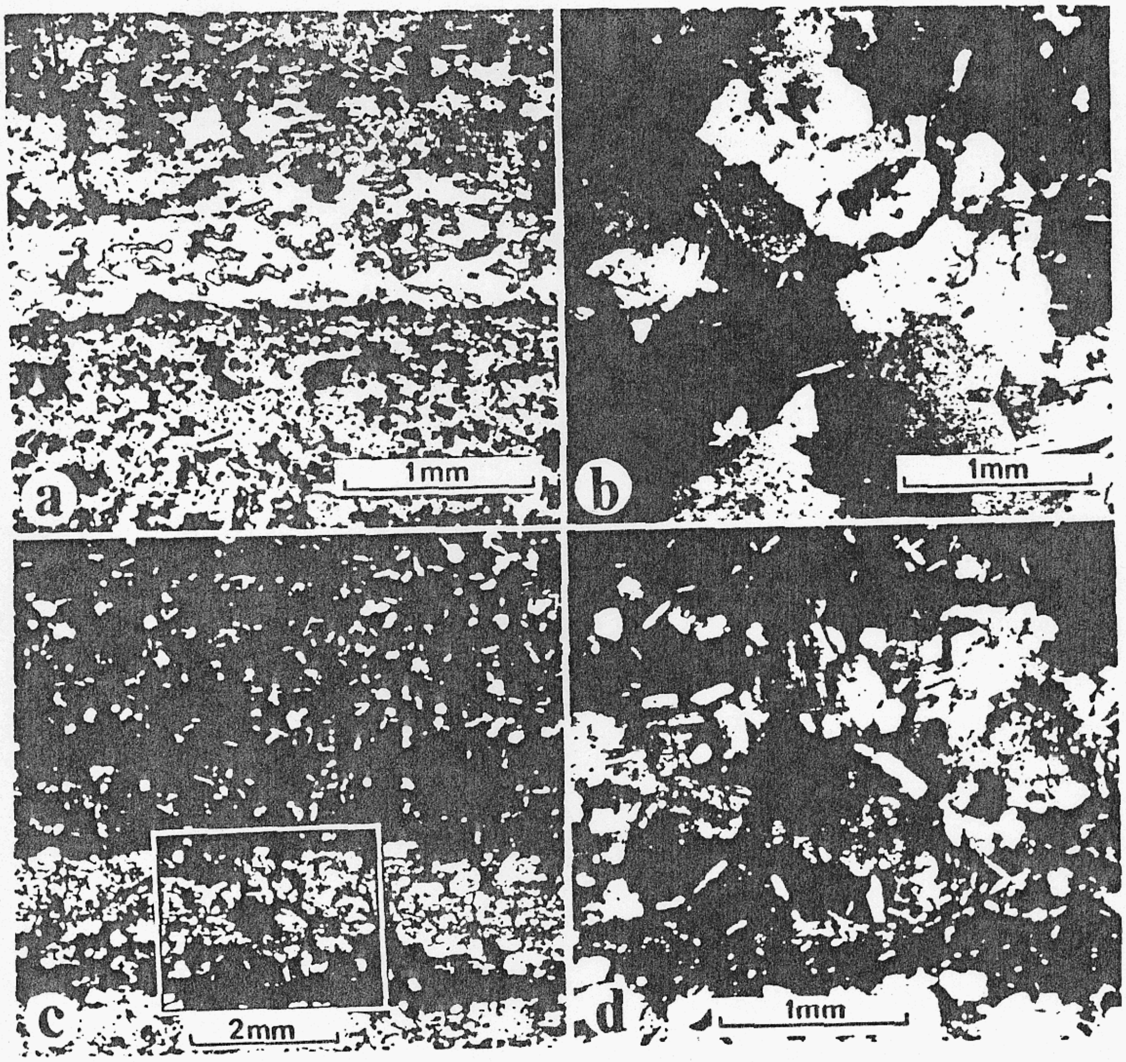

Fig. 7. (a) Typical sulfide banding, lower portion sphalerite pyrrhotite; Middle band galena, pyrrhotite; band of pyrrhotite; upper portion disseminated sulfides (b) Mosaic of albite from hanging wall alteration zone (c) sequence from base of photograph of quartz-sericite, sphalerite, band of albite, pyrrhotite and sphalerite, upper portion sulfides with quartz and sericite. Section from C ore band (d) enlargement of central protion of albite band in 7 (c) to show detail

However, zoning indicates nothing about the time of deposition but rather is a record of metal ion stabilities in response to a combination of physical and chemical factors including temperature gradient, sulfur concentration, and pH variation. Figure 8 is a lead-zinc ratio map taken from Freeze (1966), and the north-south chaotic breccia and fault zones shown by Jardine (1966). There is some correspondence between the breccia zones, faults and the metal zoning, and this fact has been elaborated upon by Ransom (1977). In particular, Pb is concentrated near the breccia zones (i.e. centrally) and decreases relative to Zn toward the perimeter of the ore zone. This pattern

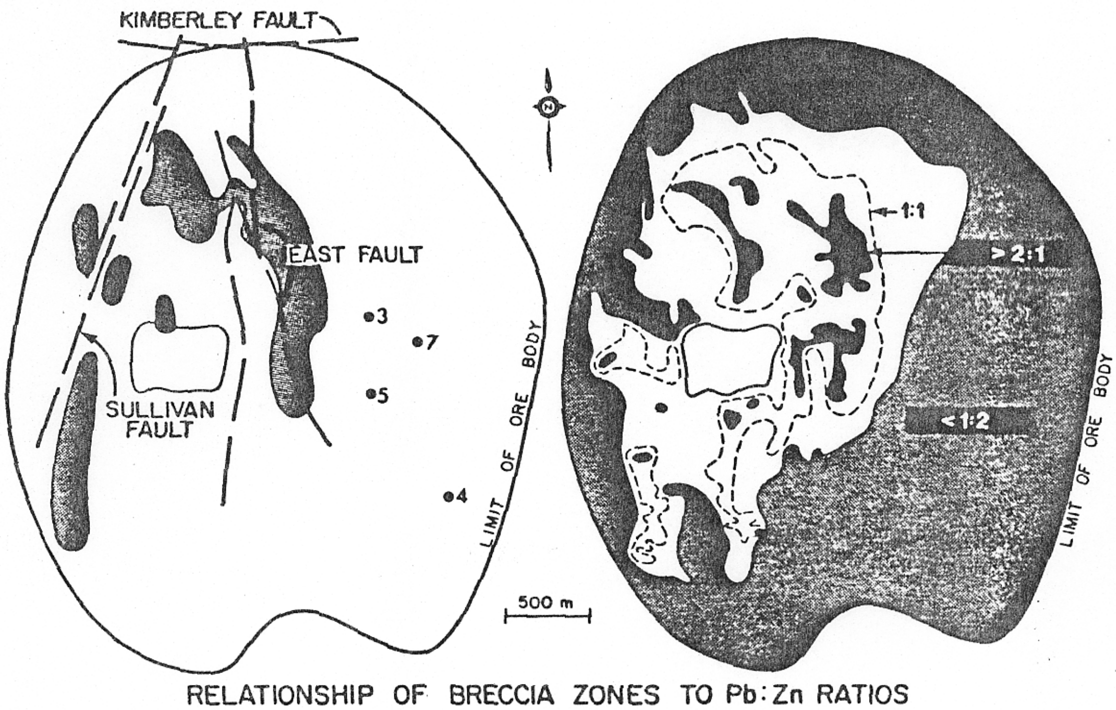

Fig. 8. The diagram on the left shows the breccia zones (shaded) and some of the major fault zones after Jardine (1966). The diagram on the right shows the Pb/Zn ratio map modified from data presented by Freeze (1966). The loop in the left centre of each is the pyrite chlorite zone. Sample locations and numbers related to data in Figure 10

is consistent with a syngenetic sedimentary process, assuming chloride metal complexing and a temperature gradient decreasing away from the fractures that channelled the hot upwelling brine. In such a system it has been calculated (Helgeson, 1969) that the lead chloride complexes, would break down at higher temperatures than the zinc chloride complexes, leading to a zonation of galena-rich (relative to sphalerite) ore near the brine vents and galena-poor ore toward the edge of the deposit.

The source of the brines is difficult to determine unambiguously. As previously mentioned, the lead isotopes can be interpreted as indicating the metals were gleaned from the Aldridge sedimentary pile which in turn came from the Churchill and possibly Superior terrain of the Canadian Shield (Le Couteur, 1973). In the footwall breccia zone two significant geochemical indicators in the form of cassiterite-bearing fractures (Freeze, 1966), and minor scheelite mineralization (Ransom, 1977), tend to suggest that a granitic magma contributed at least some elements to the brine. It appears then that the heat source that drove the brine system was initially associated with the basic tholeiitic or quartz diorite magmas and then a granite that initially moved boron through the ore-forming system and later metal-rich brines.

The stratigraphic dependence of trace element variation also documents a sedimentary process. The microprobe was used to study manganese in pyrite, sphalerite, and pyrrhotite between laminae. The results for one sample taken from the A band in the southeast part of the mine are shown in Fig. 9. The most obvious feature is a

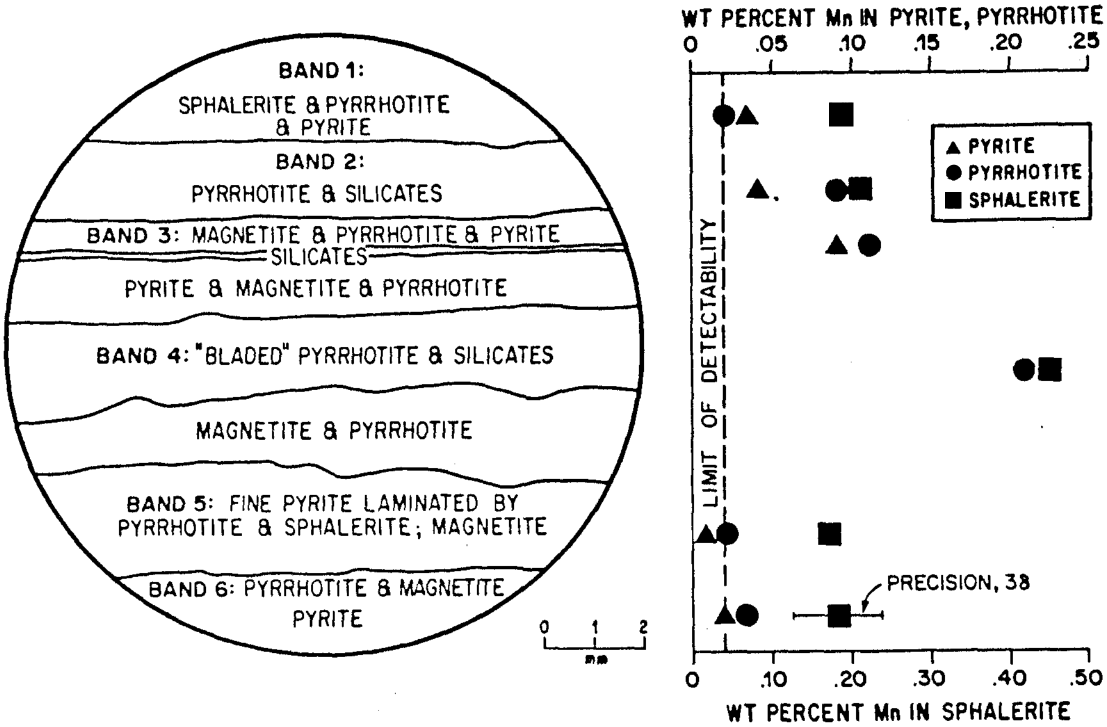

Fig. 9. Diagram of a microprobe section showing the manganese contents of the various minerals adjacent to the bands in which they occur

high manganese content in both sphalerite and pyrrhotite in the lamina marked "band 4". In addition in bands 1, 2, 5 and 6 where the three sulfide phases were analyzed, the Mn content of sphalerite > pyrrhotite > pyrite in all but band 1. These two observations indicate a varying manganese content in the brine during the time these sulfides precipitated (producing the high content in band 4), and a tendency toward partitioning of Mn in the phases initially and/or subsequently.

In addition to the interlaminar variation on the microscopic scale, variations in manganese content can be shown on a larger scale. Manganese in sphalerite was analyzed with the microprobe in 40 samples taken from the five ore horizons at four sampling locations in the eastern sector of the ore body (Fig. 8). The results are shown in Figure 10 and statistical tests indicate the manganese content in sphalerite from C and D band is significantly different from that in the A, B and Main band. Thus, on both, a microscopic and megasopic scale, laminated ores indicate variations in manganese supply with time.

HANGING WALL DEVELOPMENT

The geologic cross-section after the deposition of the Middle and Upper Aldridge is shown in Figure 3e. The Middle Aldridge is about 2300 m thick and consists of AE turbidites (Bouma, 1962), ungraded coarse-grained arenites formed by axial currents. At the beginning of Middle Aldridge time the basin changed from restricted and euxinic to an open environment. Pyrrhotite was no longer as common a syngenetic accessory, throughout the sequence, which accounts for the distinction between the rusty-weathering Lower Aldridge

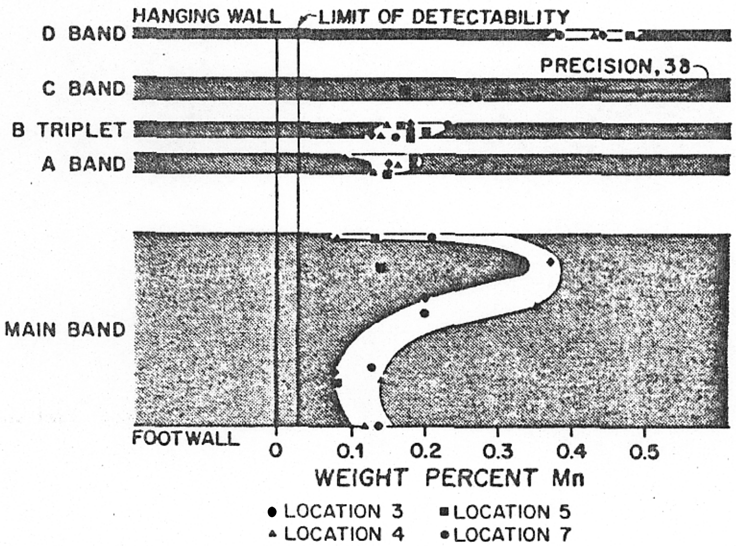

Fig. 10. Stratigraphic variation of manganese in sphalerite. Location of sections shown on Figure 8

and the grey Middle Aldridge. It is believed the decrease in sulfite production accounted for the cessation of sulfide ore deposition. At the onset of Middle Aldridge sedimentation, sodium-rich brines continued to emanate from the western breccia zone and formed what possibly was an analcite-rich zone above the orebody in the west. Subsequent burial and metamorphism altered the analcite to albite. As was noted earlier, some albite within the ore in the eastern sector is also interpreted as having been originally analcite. It seems logical to consider this sodium-rich zeolite as the precursor of albite in view of the development of zeolites in exhalative brine environments and adjacent to certain sulfide deposits (Plimer, 1977, Iijima, 1972).

The Upper Aldridge, 300 m thick, is thin bedded carbonaceous argillite and shows ripple marks. It is interpreted as being of shallow water origin.

METAMORPHISM

Figure 3f shows the geologic relations after the Sullivan sill had been emplaced beneath the orebody (1430 M.Y.) and the Hellroaring Creek stock (1300 M.Y.) had been intruded some 20 km from the mine. The Sullivan sill is not an isolated intrusive body but one of a group of intrusives that may account for up to half the section in the lower and middle Aldridge Formation (Edmunds, 1977a). This massive injection of gabbroic and quartz diorite magma implies crustal instability in extension zones along or adjacent to continental margins (Sawkins, 1976). Hutchinson (1973) also categorized this environment as one of extension similar to that found in the Red Sea. The Hellroaring Creek stock on the other hand is unique. It is a tourmaline-bearing albitic granodiorite with pegmatitic phases. It conforms to the geometry of the mafic sills and may be genetically related to them as a late differentiate.

Regional metamorphism during the East Kootenay orogeny (750 M.Y.) resulted in raising the regional metamorphic grade to greenschist. Sillimanite grade is developed locally, possibly as a result of contact affects adjacent to a satellite of the Hellroaring Creek stock on Matthew Creek.

Metamorphism caused some re-distribution of, and phase changes in the sulfides, and modified the silicate assemblages. It is apparent from the cross-cutting relationships of galena, at scales ranging from tens of feet to microscopic, that dislocations following deposition have caused or facilitated sulfide movement. Adjustments in the western sector over the breccia zone have given rise to footwall and hanging wall dislocations that demonstrate post-ore readjustments (Jardine, 1966).

Phase changes in the sulfides due to metamorphism include the appearance, in the southeast sector of the orebody, of pyrite and magnetite (Ethier et al., 1976). Thus, in general terms one can visualize a metamorphic fluid moving up and out from the western zone, driven possibly by heat from the Sullivan sill, and altering some of the pyrrhotite to the south and east to produce the magnetite plus pyrite. This produced a southern and eastern fringe of metamorphic magnetite.

The silicate metamorphic assemblage also shows a change toward the eastern fringe. In this case, well developed manganese garnets plus chlorite are altered to biotite by a potassium-rich fluid that initially moved out from the western sector then partially overlapped the earlier formed garnet zone during the cooling-down stage. The metamorphic overprint suggests that, although regional metamorphism has modified the entire sequence, the silicates reflect a pattern consistent with local heating from below the western region. It is possible that the pyrite chlorite zone (Fig. 2) has a metamorphic origin but further study will be necessary to detail its genesis and history.

CONCLUSION

The area that produced the Sullivan orebody evolved over a period of several hundred million years. It started with the definition of a north-south basin which had an extremely slow rate of clastic deposition. North-south tensional fractures and an associated thermal anomaly directed brine convection and locally reduced oxygenation in the collapsed bottom structure. The brine appears to have evolved from a boron-rich system to one rich in metals, leading to the formation of sulfide ores when these combined with reduced sulfur in the basin. The ore deposition finally ceased (although it waxed and waned several times to produce the ore bands) when the basin stopped being euxinic at the start of the Middle Aldridge time.

The presence of boron, tin and tungsten strongly suggests the involvement of granitic magma in this process, perhaps as a late differentiate of the mafic magmas that formed the sills. If this is accepted, then the magma chamber that ultimately gave birth to the Hellroaring Creek and Matthew Creek stocks is the most likely source. The great stability of the area and continuity of such a process is emphasized with the realization that the brine pump started before 1500 M.Y. and the granite was not emplaced until 1300 M.Y. It may be that longevity in terms of process is essential in the formation of ore zones of the magnitude of Sullivan.

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