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GEOLOGY OF THE SULLIVAN OREBODY KIMBERLEY, B.C., CANADA

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ABSTRACT

The Sullivan orebody is a 160 million tonne conformable iron-lead-zinc sulphide lens enclosed by clastic sedimentary rocks of the Middle Proterozoic Aldridge Formation, the basal formation of the 10,000 m thick Purcell Supergroup. Regional metamorphism is upper greenschist facies.

The roughly circular orebody is about 2000 m in diameter and is up to 100 m thick in its western part. Here, massive pyrrhotite containing occasional wispy layers of galena is overlain by sulphide rock in which conformable layering consists of pyrrhotite, sphalerite, galena and pyrite intercalated with beds of clastic sedimentary rock. Eastward across a transition zone, the orebody is composed of five distinct conformable units of well bedded sulphide rock interbedded with clastic sedimentary rock. Each bed of sulphide rock thins eastward from the transition zone. Three bedded sulphide sequences occur above the main orebody, particularly in the area of the transition zone. Locally, these are ore.

Much of the orebody is underlain by locally derived intraformational conglomerate which is more than 80 m thick in the west and thins to the east. Footwall rocks are cut by tabular bodies of chaotic breccia containing blocks of conglomerate and bedded sedimentary rock; these

extend downward unknown distances from the sulphide footwall in the west. Footwall mineralization consisting of thin conformable laminae, veins and locally intense fracture filling is common in the west and very rare in the east.

The footwall and hangingwall rocks and locally the orebody in the west have been extensively altered by hydrothermal solutions. A crosscutting zone of tourmalinite underlying the sulphide lens in the west is 1000 m by 1500 m across at the sulphide footwall and extends at least 500 m beneath the orebody. Albite-chlorite-pyrite alteration occurs in crosscutting zones in the footwall tourmalinite and extends more than 100 m into the hangingwall over the western part of the orebody. A zone of pyrite-chlorite alteration 300 m in diameter crosscuts massive sulphide rock immediately overlying footwall albite-chlorite-pyrite alteration zones.

The Sullivan orebody is interpreted as a hydrothermal synsedimentary deposit which formed in a sub-basin on the Aldridge marine floor. It is located directly over conduits through which mineralizing fluids passed. Boron, iron and magnesium were added to footwall sediments. Changes of fluid and/or basin chemistry then led to rapid deposition of massive sulphides over the western vent area and deposition of delicately-bedded sulphides in the eastern part of the sub-basin. Post-ore sodium-rich hydrothermal fluids altered tourmalinite, sulphide rocks and hangingwall rocks over the vent area.

RÉSUMÉ

Le gisement de Sullivan est une lentille de sulfures de fer, plomb et zinc de 160 millions de tonnes, concordante avec les roches sédimentaires clastiques de la formation d'Aldridge d'âge protérozoique moyen. Celle-ci est à la base du supergroupe de Purcell qui atteint 10.000m d'épaisseur. Le métamorphisme régional est de faciès schiste vert supérieur.

Le gisement est approximativement circulaire, d'un diamètre d'à peu près 2000m et atteignant 100m d'épaisseur dans sa partie ouest. Ici, de la pyrrhotite massive contenant à l'occasion des couches effilochées de galène, est recouverte par une roche sulfurée litée consistant en pyrrhotite, sphalérite, galène et pyrite avec intercalations de roche sédimentaire clastique. Vers l'est, au-delà d'une zone de transition, le gisement se compose de 5 unités distinctes, concordantes, de roches sulfurées bien litées avec intercalations de roche sédimentaire clastique. Chaque lit sulfuré s'amincit vers l'est à partir de la zone de transition. Trois séquences sulfurées litées se trouvent aussi aux dessus du gisement principal, particulièrement dans la région de la zone de transition. Elles sont localement exploitables.

La pluspart du gisement recouvre un conglomérat intraformationnel de dérivation locale qui a plus de 80m d'épaisseur à l'ouest et qui s'amincit vers l'est. Les roches du mur sont recoupées par des corps tabulaires de brèche chaotique contenant des blocs de conglomérat et de roche sédimentaire litée; ces corps s'étendent en profondeur, à partir du mur des sulfures à l'ouest, sur des distances inconnues. Les roches au mur du gisement sont communément minéralisées à l'ouest mais très rarement à l'est; cette minéralisation consiste en laminations minces, concordantes, en veines et en remplissage de fractures localement très nombreuses.

A l'ouest, les roches du mur et du toit et localement le gisement lui-même ont été extensivement altérés par des solutions hydrothermales. Une zone de tourmalinite discordante, mesurant en section 1.000m par 1.500m, s'enfonce d'au moins 500m sous le gisement. Une altération en albite-chlorite-pyrite forme des zones discordantes dans cette tourmalinite, au mur, et s'étend sur plus de 100m dans le toit, de la partie ouest du gisement. Enfin, une zone d'altération à pyrite-chlorite, de 300m de diamètre, recoupe les sulfures massifs là où ils recouvrent des zones d'altération à albite-chlorite-pyrite.

Le gisement de Sullivan est interprété comme un dépôt hydrothermal synsédimentaire qui s'est accumulé dans un bassin secondaire du fond marin en même temps que la formation d'Aldridge. Il est situé à l'aplomb des conduits des fluides minéralisants. Bore, fer et magnesium ont été ajoutés aux sédiments du mur. Des changements dans la chimie des fluides ou/et du bassin ont alors conduit au dépôt rapide des sulfures massifs au-dessus de l'orifice, à l'ouest, et au dépôt des sulfures délicatement lités dans la partie est du bassin secondaire. Des fluides hydrothermaux riches en sodium ont ensuite altéré la tourmalinite, les roches sulfurées et les roches du mur autour de l'orifice hydrothermal.

INTRODUCTION

The Sullivan orebody at Kimberley, British Columbia (Fig. 1) is a large, gently dipping iron-lead-zinc sulphide deposit lying conformably in Proterozoic clastic sedimentary rock of the Aldridge Formation. The orebody is located at the western edge of the Rocky Mountain Trench, on the eastern flank of the Purcell Mountains about 80 km north of the United States boundary. The original mineral claims were staked on surface showings of sulphide mineralization in 1892, but little work was done on the claims prior to completion of a Canadian Pacific Railway branch line to Kimberley in 1899. Systematic development of the property was commenced in 1900 by a Spokane, Washington mining group and a smelter was completed in nearby Marysville in 1903. This venture failed owing to metallurgical difficulties, and the property was acquired in 1909 by the Federal Mining and Smelting Company. The Consolidated Mining and Smelting Company of Canada Ltd. (now Cominco) took a lease and option on the property in late 1909 and completed purchase by 1913.

During the next five years, selective mining and sorting produced high-grade lead and silver ore causing little metallurgical difficulty. In fact, during World War I, this was the largest single source of lead in the British Commonwealth. In the meantime, deep drilling revealed an immense lens of complex sulphide ore. A main adit at the 3900 foot level, some 200 m below the outcrop, was started in 1915 and a major effort was directed toward solving the milling and metallurgical problems. In 1920, a differential flotation process was developed that proved successful for obtaining lead and zinc concentrates suitable for smelting. From the date of acquisition by Cominco to the end of 1979, the Sullivan Mine produced approximately 123,200,000 short tons (111,600,000 tonnes) containing 6.8% lead, 5.9% zinc and 2.4 oz. (82 g/t) silver. Remaining diluted reserves at that time were 54,000,000 short tons (49,000,000 tonnes) containing 4.5% lead, 5.9% zinc and 1.1 oz. (37 g/t) silver.

This paper describes the geology of the Sullivan orebody and its clastic host rocks. The regional and local geological setting of the orebody and sedimentological characteristics of the Aldridge Formation, a flysch sequence at the base of the Purcell Supergroup, are summarized to facilitate understanding of the setting of the orebearing sequence. The iron-lead-zinc sulphide ore occurs as broad, continuous and complex lenses interbedded and deposited contemporaneously with a distinctive sequence of clastic rocks of restricted distribution. The western, thickest, part of the orebody is massive to poorly layered and contains minor interbedded clastic sedimentary rock. Outward from dominantly massive ore, interbedded clastic sedimentary rock becomes more abundant and the orebody, particularly to the east, is a sequence of delicately bedded sulphide rock intercalated with beds of sulphide-poor quartz wacke and mudstone.

The western part of the orebody is underlain by breccia zones and an extensive zone of tourmalinite in which stringer sulphides are locally common. Intense post-ore alteration formed rocks composed of various proportions of albite, chlorite and py-

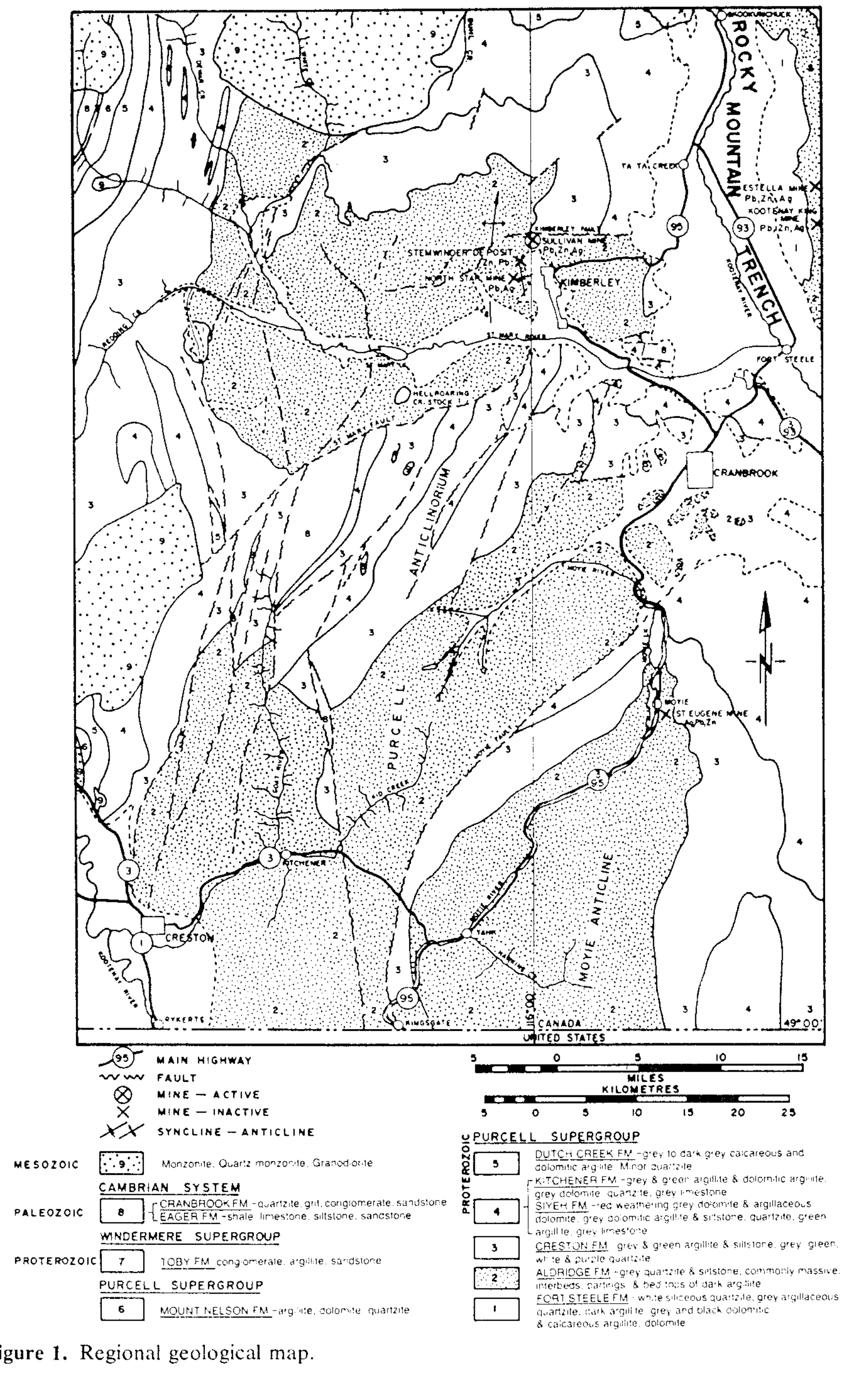

Figure 1. Regional geological map.

rite. This alteration forms restricted crosscutting zones in footwall tourmalinite, occurs through the ore zone immediately over these crosscutting zones and in hangingwall rocks over the western part of the orebody.

REGIONAL GEOLOGICAL SETTING

Purcell Supergroup

The Purcell Supergroup in southeastern British Columbia and the laterally equivalent Belt Supergroup in the United States according to Harrison (1972) constitute a thick prism of dominantly clastic sediments deposited in a large epicratonic re-entrant of the Middle Proterozoic sea at the western margin of the North American Craton. However, recent identification of Precambrian rocks in the Shuswap terrain (Wanless and Reesor, 1975) to the west of principal exposures of Purcell rocks suggests that Purcell sediments were deposited in an intracratonic basin. Aspects of the depositional environment of the Belt-Purcell have been compared to present day sedimentation in the Gulf Coast geosyncline (Price, 1964; Winston, 1973). The sedimentary rocks form a monotonous succession of drab-coloured siltstone and mudstone with units of quartz arenite, dolomite and limestone.

Although details of stratigraphy and sedimentology of Belt-Purcell sedimentary rocks have periodically received intensive local study over the past seventy years, vast gaps in modern geological mapping hinder synthesis of much of the depositional history. Away from the margins of the basin, lateral facies changes are difficult to recognize and are commonly reflected only as subtle changes in grain size.

Nomenclature of the clastic Belt-Purcell metasedimentary rocks has been inconsistent and descriptions found in the literature may seem remarkably alike even though field examination clearly reveals dissimilarities. Early workers (Willis, 1902; Daly, 1912; Schofield, 1915) recognized the difficulties inherent in regional correlation of the lithostratigraphic units they defined and the general inadequacy of the terms quartzite and argillite as applied to the clastic sequence. More recent authors (Harrison and Jobin, 1963; Price, 1964) have demonstrated successful lithologic subdivision based on grain size of previously defined formations and have thus established better regional correlations of the lithostratigraphic units (Harrison and Campbell, 1963; Harrison, 1972).

Maximum thickness of sedimentary rocks of the Purcell Supergroup exceeds 10,000 m, with the base unexposed (Fig. 2). Earliest known sedimentation was initiated with deposition of the upward-fining fluvial/deltaic sequences of quartz arenite, quartz wacke and mudstone of the Fort Steele Formation exposed 25 km due east of Kimberley (Fig. 1) on the east side of the Rocky Mountain Trench. Each of the sequences starts with cross-bedded quartz arenite at the base and grades upward to finely laminated mudstone at the top (Höy, 1978). The Fort Steele Formation is at least 200 m thick.

Fine-grained clastic beds at the top of the Fort Steele grade into very rusty-weathering, fine-grained quartz wacke and mudstone of the Aldridge Formation. A considerable thickness of the Fort Steele sequence appears to be the time equivalent of the Aldridge Formation exposed in the Purcell Mountains west of the Rocky Mountain Trench (Höy, this volume). The Aldridge Formation is at least 5000 m thick in the Purcell Mountains and is less than 4000 m thick in the Rocky Mountains.

The Aldridge Formation grades upward over 300 m through a sequence of carbonaceous mudstone interbedded with minor beds of grey and green mudstone and fine-grained quartz wacke to the 1800 m thick Creston Formation, composed of grey, green and maroon quartz wacke and mudstone with minor white arenite. East of the Rocky Mountain Trench, the Creston sedimentary rocks are interpreted as fan delta and mudflat deposits (Höy, 1978) and in the Purcell Mountains (Fig. 1) they are thought to have been deposited in a deltaic environment prograding from the south (Winston, 1973).

Conformably overlying the Creston Formation are 1200 m of green and grey dolomitic mudstone, buff-weathering dolomite containing abundant "molar tooth" structures and minor quartz arenite of the Kitchener Formation. The Kitchener is in turn overlain by 200 to 400 m of green, slightly dolomitic and calcareous mudstone of

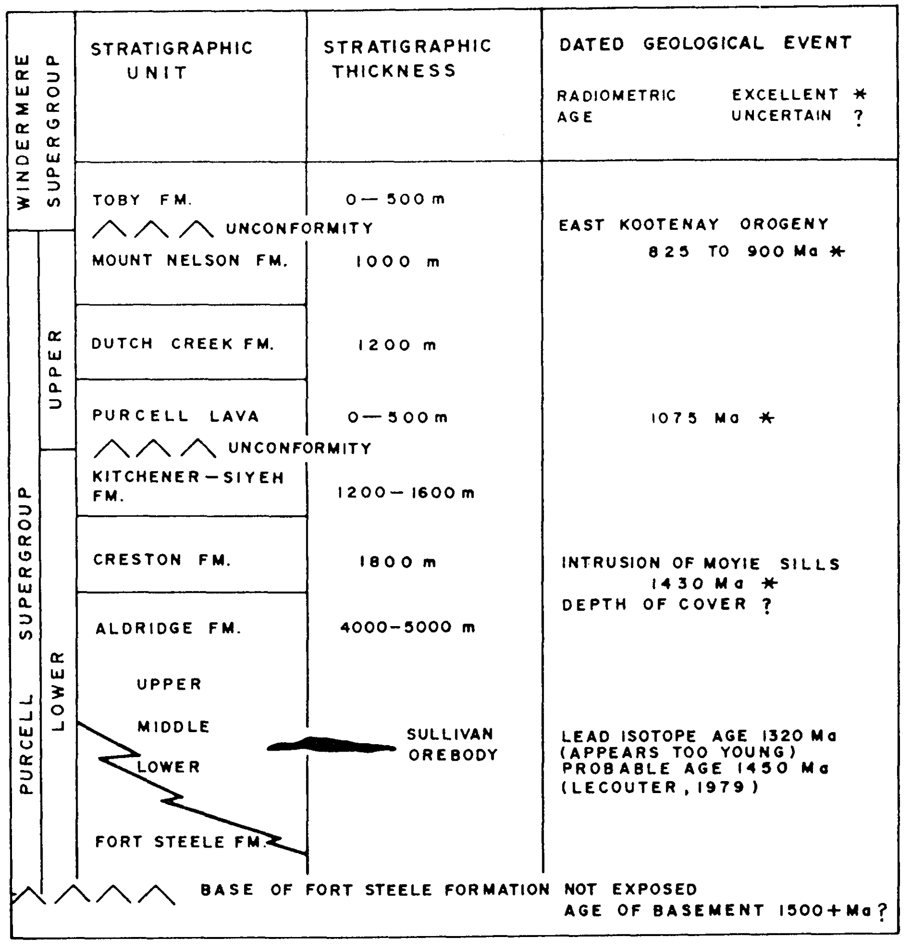

Figure 2. Stratigraphic chart of the Purcell Supergroup in the Purcell Mountains of Southeastern British Columbia.

the Siyeh Formation. Although poorly defined in the Purcell Mountains west of the Rocky Mountain Trench, the Siyeh is readily recognized in the Rocky Mountains and is conformably and locally unconformably overlain by 0 to 500 m of basaltic to andesitic flows of the Purcell Lava which are taken to mark the close of lower Purcell sedimentation. To the northwest and west in the Purcell Mountains, the Purcell Lava is only sparsely represented by weathered tuffaceous beds.

Resting with apparent conformity on the lower Purcell rocks are about 1200 m of grey to dark grey, calcareous and dolomitic mudstone and minor quartz wacke of the Dutch Creek Formation. The Dutch Creek is particularly well developed in the western Purcell Mountains and is there overlain by about 1000 m of grey, green and maroon mudstone and calcareous mudstone of the Mount Nelson Formation. The close of Purcell sedimentation is marked by folding during the East Kootenay Orogeny (White, 1959) and disruption of the basin by large-scale vertical faults (Lis and Price, 1976) concurrent with deposition of basal sedimentary rocks of the Windermere Supergroup.

Middle Proterozoic igneous activity in the Purcell sedimentary basin in southeastern British Columbia is dominated by intrusion of gabbroic sills of two ages. The oldest are the Moyie Sills (Daly, 1912) which are most common in the Aldridge Formation. Sills and slightly discordant sheets predominate; locally, however, dykes and step-like discordant sheets such as those found near Kimberley are abundant. Gabbroic sills can aggregate 2000 m of thickness in a typical Aldridge section and are most abundant in the lower part of the section. The sills are more abundant in the Purcell Mountains than in the Rocky Mountains. The youngest event of gabbro intrusion is thought to be comagmatic with the Purcell Lavas, and is represented by abundant sills in the upper part of the Creston Formation and in the Kitchener and Siyeh Formations (Bishop, 1974). The pegmatitic Hellroaring Creek Stock and related satellites intrude metamorphosed and deformed Aldridge sedimentary rocks and Moyie Sills in an area about 15 km southwest of the Sullivan Mine. The stock is of Middle Proterozoic age (Ryan and Blenkinsop, 1971).

Lower Purcell sedimentary rocks have everywhere undergone metamorphism, to at least greenschist facies. There is a general increase in metamorphic grade with depth in the stratigraphic pile (Edmunds, 1977; Bishop, 1974) except in the contact aureoles of major Cretaceous intrusions. Muscovite and chlorite are characteristic metamorphic minerals of pelitic rocks of the Kitchener Formation and deeper in the section biotite first appears as a metamorphic mineral in the upper part of the Aldridge Formation. Minor areas of amphibolite facies are restricted to the cores of fold structures displaying large-magnitude structural relief.

Purcell rocks are folded about north-trending axes to form the Purcell anticlinorium (White, 1959). Folds comprising the large structure are open and gentle with north-plunging axes. Some folds are overturned to the east and some display axial plane schistosity. Large areas within the anticlinorium have nearly flat-lying strata. Major faults with a history of complex movement disrupt the Purcell terrain and separate large regions further disrupted by block faulting (Fig. 1). Two of these major faults, the Moyie and St. Mary faults, pass south of Kimberley and throughout much of their extent have a northerly trend, but then abruptly arc to the east into the Rocky Mountain Trench. Both of these faults repeat lower Purcell strata on their north and west, upthrown sides. There is evidence for repeated movement along the major faults beginning as early as the time of Purcell sedimentation (Höy, this volume; Lis and Price, 1976).

Geochronology of Purcell rocks has been reviewed by many authors including Obradovich and Peterman (1968); Gabrielse (1972); and Harrison (1972). Harrison reviewed available information concerning age of basement, Purcell sedimentation, igneous activity and metamorphism and attempted to reconcile conflicting aspects of the data. The general framework from Harrison's conclusions, modified with recent data, is presented in Figure 2. The East Kootenay Orogeny marking the close of Belt-Purcell sedimentation has been reasonably well documented at 825 to 900 Ma (Miller, 1973). A minimum age for deposition of sedimentary strata of the Siyeh Formation is provided by a 1075 Ma date for the Purcell Lava (Hunt, 1962; Obradovich and Peterman, 1968).

A metamorphic event affecting Aldridge sedimentary rocks and the Moyie Sills has been dated at about 1300 Ma (Obradovich and Peterman, 1968; Bishop, 1974). This agrees well with the 1300 Ma age of the Hellroaring Creek Stock (Ryan and Blenkinsop, 1971; Harrison, 1972) yet there is little recognized evidence recording the event in the sedimentary record of the lower Purcell. Minimum age of 1430±20 Ma for the Aldridge Formation is provided by U-Pb zircon data obtained from differentiates of the Moyie Sills (Zartman *et al.*, in press); however, age of basement rock upon which the Purcell rocks were deposited and therefore the maximum age for sedimentation is known only by inference. Basement rock is nowhere exposed within the area of outcrop of Purcell rocks in southeastern British Columbia, thus ages of approximately 1800 Ma (Burwash *et al.*, 1962), 1960 Ma for rocks in the core of the Thor-Odin Dome (Wanless and Reesor, 1975) and 1700±100 Ma (Giletti, 1968) for basement far removed from the area of Purcell sedimentation can be considered maximum ages. Recent data (Reid *et al.*, 1973) suggest that Aldridge equivalent rocks in northernmost Idaho are underlain by and perhaps derived from a felsic orthogneiss terrain about 1500 Ma old.

In summary, deposition of lower Purcell sediments covered a time span of at least 425 Ma from 1500 to 1075 Ma. Textural and compositional homogeneity suggest a provenance of gentle relief drained by low-gradient river systems. The few data concerning transport direction and source for initial Purcell sediments suggest, at least in part, an easterly source. By Middle Aldridge time, south to north transport by turbidity currents was firmly established and the deep Purcell sedimentary basin was gradually filled (Bishop *et al.*, 1970). Initial filling of the basin was followed by westerly and northerly deposition of deltaic sediments of the Creston Formation prograding from the east and south across the basin. Moyie Sills were injected in early Creston time at 1430 Ma (Zartman *et al.*, in press) followed by a major metamorphic event accompanied by intrusion of the 1300 Ma Hellroaring Creek Stock. The relative ages of the 1300 Ma event and deposition of the Kitchener and Siyeh Formations are equivocal as no evidence for a 1300 Ma event has been found in these youngest sedimentary rocks of the lower Purcell. Extrusion of the Purcell Lava at 1075 Ma marks the close of lower Purcell geological events.

Aldridge Formation

The Aldridge Formation in the Purcell Mountains (Schofield, 1915) has the sedimentological characteristics of a flysch sequence (Bishop *et al.*, 1970). It is composed of a monotonous and repetitious sequence of alternating beds of very fine-grained quartz wacke and mudstone and lesser amounts of very fine- to coarse-grained quartz arenite. Beds have considerable lateral continuity and show sharply defined bottom surfaces which may be covered by abundant sole markings. Internal structures near bed tops are usually indistinct and bed-surface features such as ripple marks are rare. Graded bedding occurs throughout most of the stratigraphic sequence but rapid lateral and vertical compositional changes other than grading are exceedingly rare.

Cominco geologists have divided the Aldridge Formation into three map units; the Lower, Middle and Upper Aldridge. A similar division was applied by Leech (1952) and Reesor (1956) to Aldridge rocks exposed in the Purcell Mountains. Lower Aldridge sedimentary rocks are composed of a rhythmic succession of thin- to medium-bedded, typically graded beds of very fine-grained quartz wacke. Deep in the known Lower Aldridge section, cross laminations within beds are frequent and detrital quartz grains range from a more common silt-size to rare sand-size. Toward the top of the Lower Aldridge section, matrix material separating detrital grains becomes more abundant, grain size decreases and internal structures other than grading become rare.

Interbedded with the rhythmic sequence of graded beds are laminated sequences of mudstone ranging from a few millimetres to several metres thick. Laminae and discontinuous blebs of pyrrhotite emphasize layering in the laminated mudstone and weathering of the pyrrhotite imparts a conspicuous rusty colour to outcrops.

Massive to poorly bedded, elongate lenses of intraformational conglomerate occur locally near the top of the Lower Aldridge. Clasts range in size from a few millimetres to as much as 30 cm and are composed of Aldridge rock types in a mudstone matrix. Frequently there is a clast-size grading with coarser fragments concentrated near the base of the deposits. Clasts may be closely packed and well-sorted but frequently the framework is open and the average matrix to clast ratio is five to one.

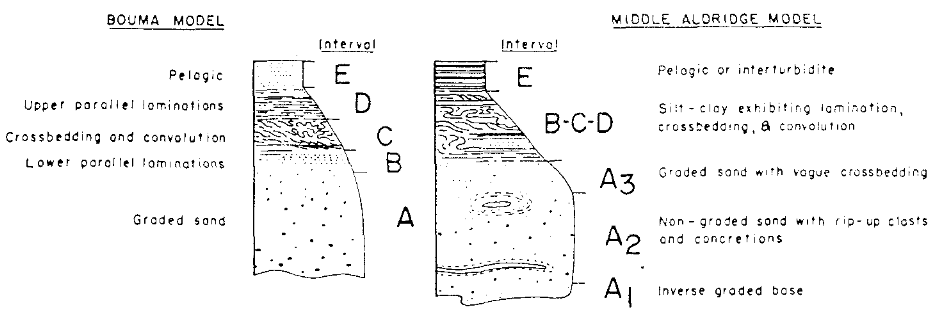

Figure 3. A comparison of the turbidite model of Bouma (1962) with that of the Aldridge Formation.

The Middle Aldridge is marked by the appearance of distinctive graded arenaceous beds whose lighter weathering colours contrast sharply with the rusty weathering Lower Aldridge. Thinly bedded, rusty weathering rocks similar to those in Lower Aldridge sequences are interbedded with thicker, graded arenites but are definitely subordinate. Regularity of internal texture and structure, and bed form have led to the conclusion that the graded arenaceous sedimentary rocks of the Middle Aldridge are mostly turbidites (Bishop *et al.*, 1970). Many of the bed forms correspond to the A-E turbidite structure described by Bouma (1962); however, the more common structure is illustrated in Figure 3. Typically the basal unit can be divided into three subunits of which the lower, A_1, is inversely graded and often exhibits sculpturing and load casting. A_2 is ungraded and may contain rip-up clasts near the base and concretions near the centre. A_3 is normally graded and may show vague current lamination. The middle unit, equivalent to the Bouma B/C/D sequence, is indistinct. Laminated or cross-laminated sequences may characterize a locality or may be missing, such that the upper inter-turbidite material rests directly on A_2 or A_3. The upper unit includes finely laminated interturbidites of dark grey mudstone.

Erosional sole-features measured in the Middle Aldridge indicate general south to north sediment transport. Depositional current features, mainly ripple cross-laminations measured at the tops of the arenaceous units, indicate west to east current direction in the western Purcell Mountains and east to west current direction in the eastern Purcell Mountains. The north-trending trough defined by the sole markings probably represents only a small part of a much larger complex basin holding the initial deposits of the Belt and Purcell Supergroups.

Thin-bedded to laminated carbonaceous mudstone becomes the dominant lithology of the 300 m thick Upper Aldridge. The contact between the Middle and Upper Aldridge is gradational over stratigraphic thicknesses ranging from a few to tens of metres. Disseminated grains and blebs of pyrrhotite aligned along bedding occur in places in carbonaceous mudstone of the Upper Aldridge and here the rock is rusty weathering.

LOCAL GEOLOGICAL SETTING

The Sullivan orebody occurs near the top of the Lower Aldridge Formation and has the shape of an inverted and tilted saucer. The maximum north-south dimension is about 2000 m and the east-west dimension is about 1600 m (Fig. 4). It has flat to gentle easterly dips in the west, moderate easterly to northeasterly dips in the centre, and gentle easterly to northeasterly dips in the east (Figs. 5 and 6). The footwall rocks are composed of intraformational conglomerate and massive lithic wacke overlain by quartz wacke and pyrrhotite-laminated mudstone. The ore zone is overlain by several upward-fining sequences of quartz wacke and mudstone.

The orebody attains maximum thickness of 100 m approximately 100 m northwest of its geographic centre, and thins outward in all directions. To the east, the orebody thins gradually to a sequence of pyrrhotite-laminated mudstone 3 to 5 m thick that persists laterally for some distance. To the north, the orebody thins less gradually, and the ore zone is truncated by the Kimberley fault (Fig. 6). To the west, the orebody thins abruptly and is cut by dyke-like apophyses of the footwall gabbro. To the south, within the limit of economic mineralization, thickness changes are generally irregular and abrupt.

Restricted distribution of immediate host rocks and ore zone, and contrasting abrupt thinning to the west and gradual thinning to the east suggest that the immediate host rocks and orebody were deposited in a sub-basin receiving locally derived material, sulphides and some component of normal Lower Aldridge sediment. Although the major structures forming the sub-basin have yet to be defined, several northerly striking normal faults (Sullivan-type faults) may now occupy fault loci which were active during sedimentation.

Additional evidence suggesting structural control of the sub-basin is the geometry of a gabbro body beneath the orebody. This gabbro is typically concordant about 500 m below the eastern edge of the orebody. Following this gabbro westward, it rapidly transgresses upward to meet the footwall of the orebody near its western margin but, in continuing westward, it transgresses downward to again resume its sill-like form at approximately its original stratigraphic position.

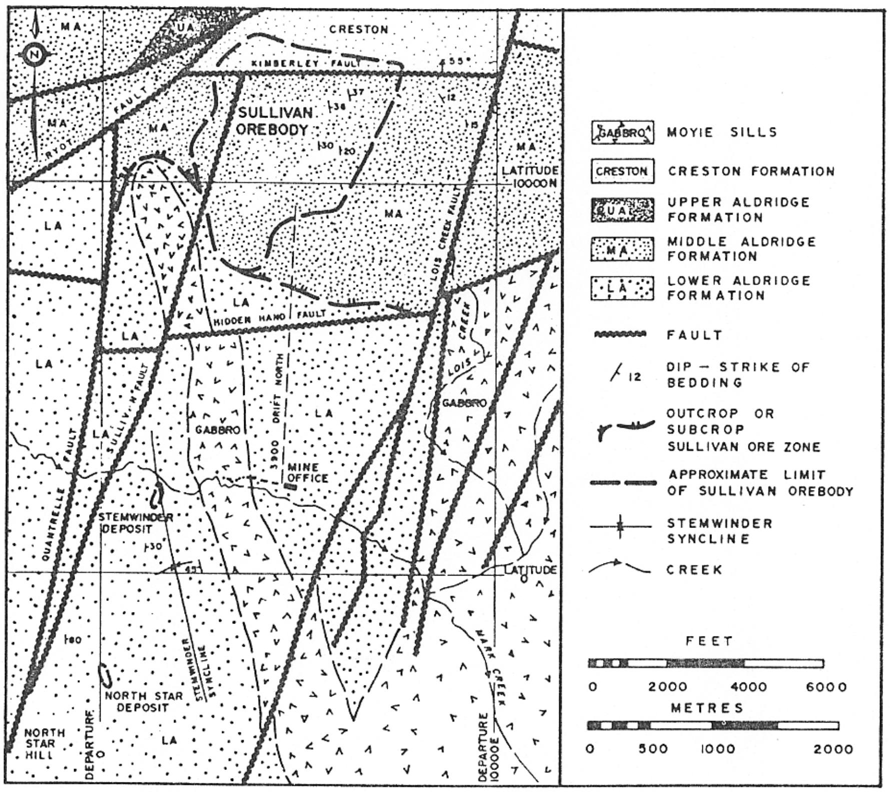

Figure 4. Generalized geological map of the Kimberley area.

The resultant configuration is a north-northwest-trending arch which is sub-parallel to the north-northeast trend formed by the Sullivan, Stemwinder and North Star orebodies (Fig. 4). The trend of mineralized zones crosses the trend of this arch. Contact relationships of the intrusion in apparent crosscutting areas have only been observed in several drill cores obtained beneath the orebody. These show core-to-bedding angles immediately east of the intrusion which are most consistent with very limited discordancy. An hypothesis explaining this ambiguous transgressive habit is that the intruded sedimentary rocks are draped over a horst, implying that faults on the east side of the horst at least were active during sedimentation, and affected geometry of the sub-basin.

The orebody lies on the folded and faulted eastern limb of a broad north-trending anticline (Fig. 1). The structure plunges gently to the north and is locally asymmetric and overturned to the east. The Kimberley, Ryot and Hidden Hand fault systems, the 010° trending Sullivan-type faults and other minor faults form an intricate mosaic disrupting the fold limb. South of the Hidden Hand fault (Fig. 4), rocks on the eastern limb of the broad anticline are folded about north-trending axes to form an anticline and syncline having the shape of an open S as viewed from the north. The North Star orebodies, mined at the turn of the century, were located in a gentle fold structure on the east limb of the syncline and the crosscutting Stemwinder deposit is situated in the hinge of the syncline which opens northward. Open to isoclinal minor folds on the

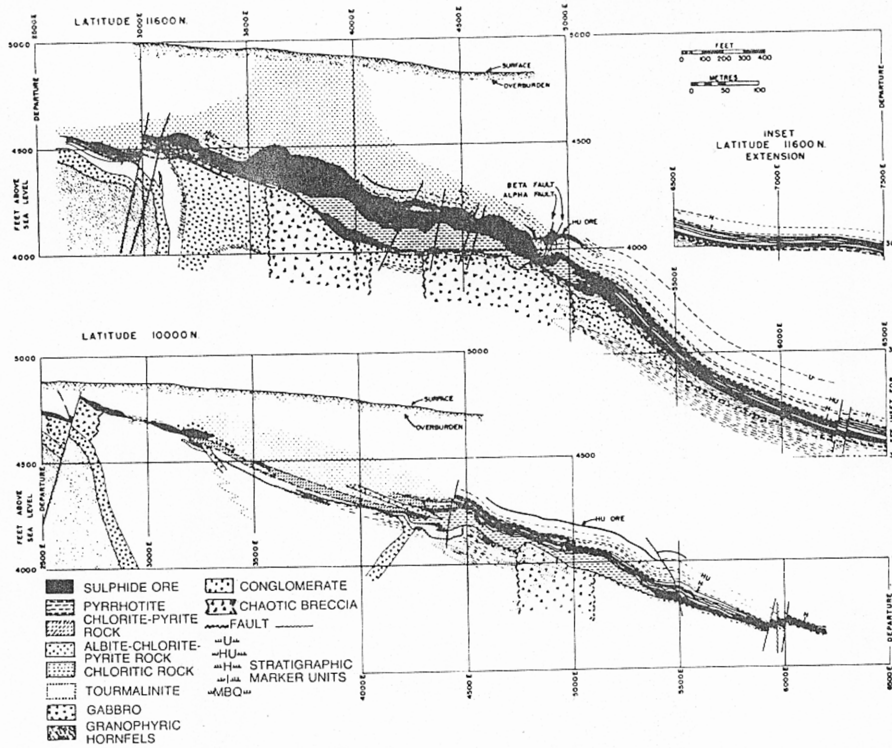

Figure 5. East-West geological cross-sections through the Sullivan orebody.

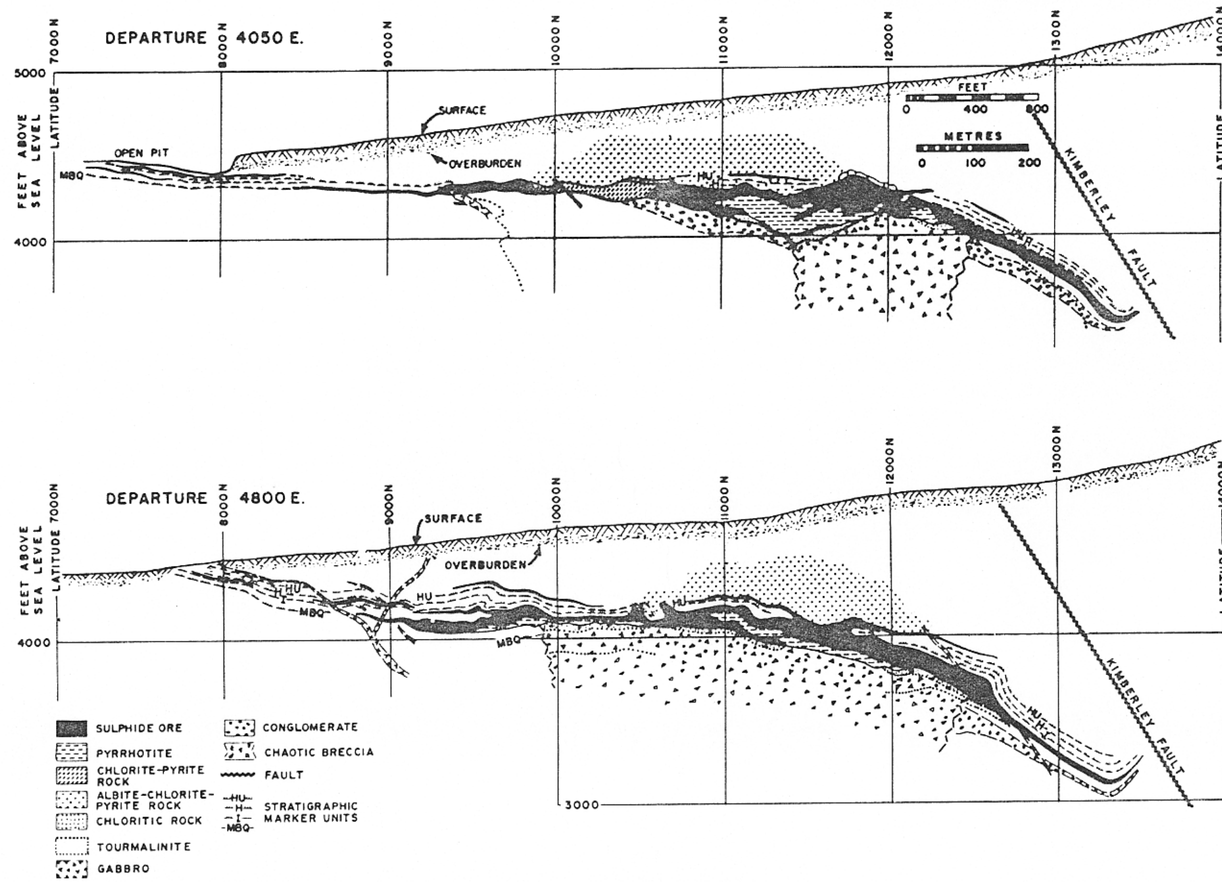

Figure 6. North-South geological cross-sections through the Sullivan orebody.

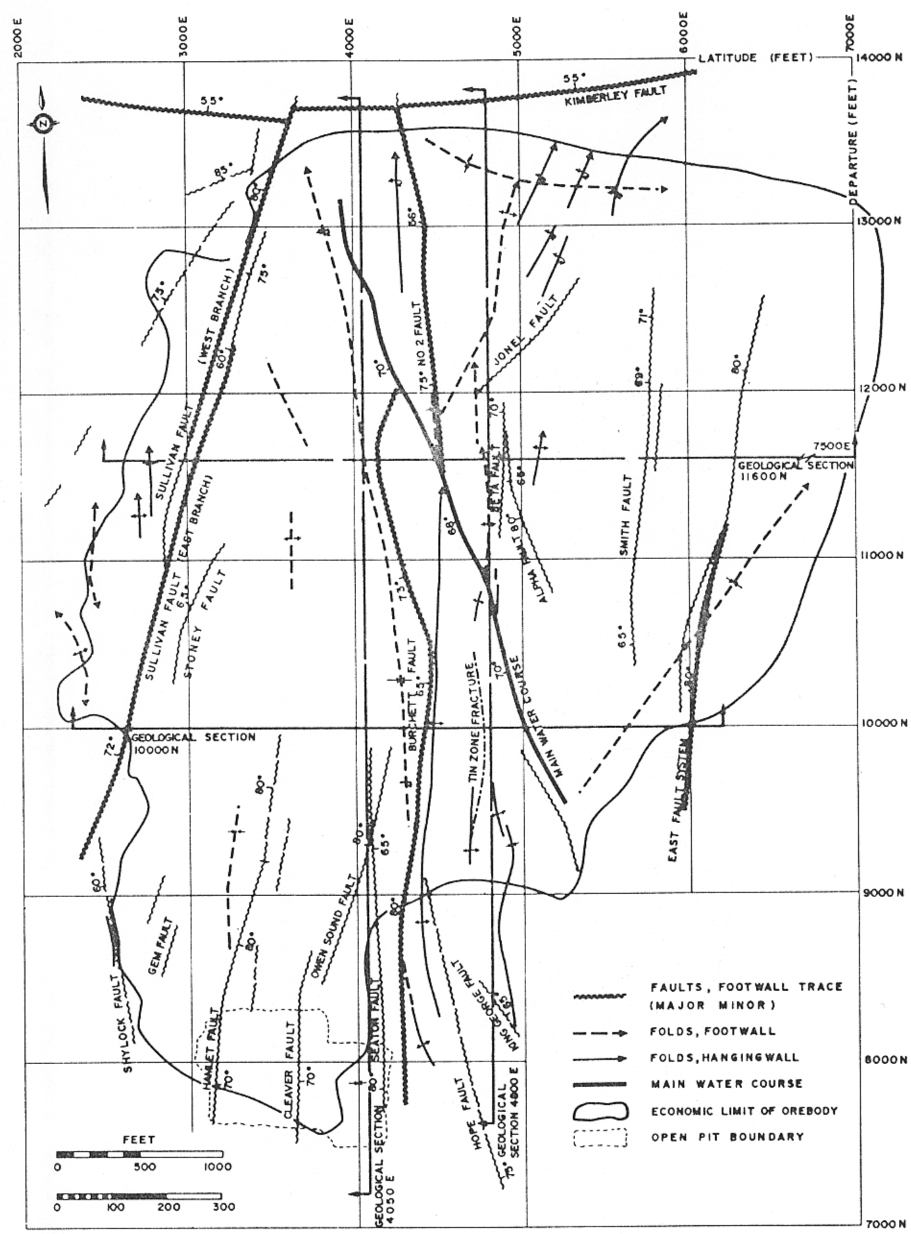

Figure 7. Structural features in and adjacent to the Sullivan orebody.

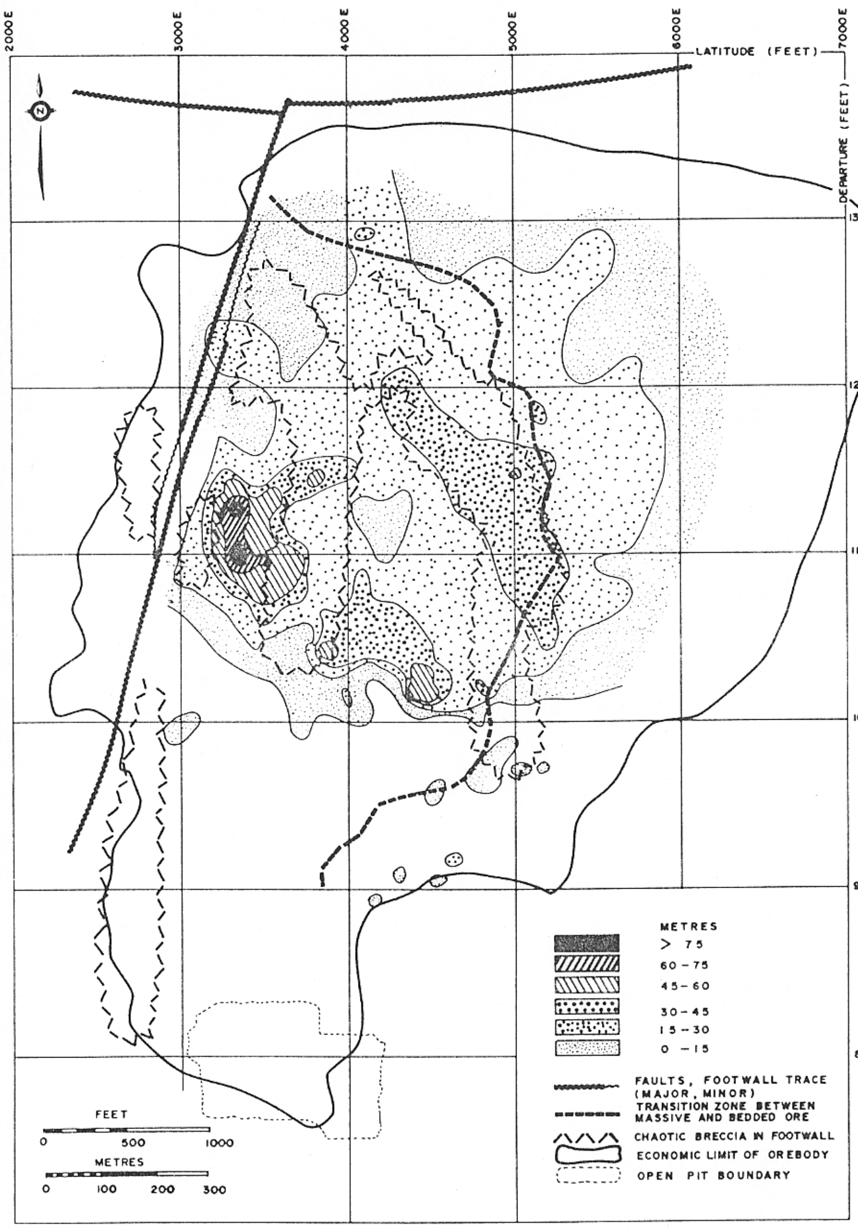

Figure 8. Isopach map of the footwall conglomerate.

limbs of the syncline are doubly-plunging and are not cylindroidal. Between the Hidden Hand fault and Kimberley fault, minor folds encountered in footwall development headings at the Sullivan tend to be open and asymmetric to the east. Some degree of intrafolial deformation within the sulphide orebody may account for the change in fold geometry north of the Hidden Hand fault. North of the Kimberley fault, rocks on the east limb of the broad anticline are locally overturned.

The Kimberley and Hidden Hand faults lie across the regional structure and are generally parallel to east-trending segments of the Moyie and St. Mary faults. The Kimberley fault dips 45° to 55° north and truncates the ore zone to the north. With over 3000 m of stratigraphic displacement, the fault juxtaposes rocks of the Creston and Kitchener Formations against rocks of the Lower Aldridge. Displacement on the north-dipping Hidden Hand fault is of the order of a few hundred metres of apparent normal dip-slip movement.

The Sullivan-type faults cut the orebody with a consistent west side down normal displacement ranging from a few metres to 30 m. The largest member of the group, the Sullivan fault, occurs near the western margin of the orebody (Figs. 4, 5 and 7). At the northwest margin of the orebody, a northeast-trending fault apparently truncates the westward extension of the Kimberley fault. Several Sullivan-type faults offset the trace of the Kimberley fault although earlier phases of movement along the Sullivan-type faults may have occurred.

GEOLOGY OF THE SULLIVAN OREBODY

Introduction

The Sullivan orebody consists of sulphide rock composed of more than 70% sulphides in thick, gently dipping conformable units enclosed by unaltered or altered quartz wacke and mudstone. Ore is massive to wispy-layered in the western part and passes outward on the north, east and south to delicately-bedded sulphide rock interbedded with fine-grained clastic sedimentary rocks. In this paper, the term massive, when applied to sulphide rock, connotes material that is internally homogeneous to vaguely bedded. The term massive is not applied to well-bedded sulphide rock nor used to imply a relative amount of sulphides. Major differences exist in footwall rocks, ore zone and hangingwall rocks in different areas of the mine. Hence, in this discussion, for simplicity, the ore zone and enclosing rocks will be divided into a western part and an eastern part joined by the transition zone shown on Figures 5 and 8. This transition zone is commonly only a few metres or tens of metres wide.

Generally to the west of the transition, in the massive part of the orebody, the bulk of sulphide ore occurs in a single conformable lens in which layering is poorly developed. The footwall, ore zone and hangingwall sedimentary rocks are generally altered. The footwall rocks are unusually rich in tourmaline and the hangingwall rocks rich in albite and chlorite. Footwall sulphide veins and disseminated sulphides are locally abundant and broad linear zones of brecciation disrupt a complex sequence of massive and bedded footwall sedimentary rocks.

On the other side of the transition zone, generally to the east, footwall and hangingwall sedimentary rocks enclosing well-bedded ore are relatively unmodified. Other than metamorphic recrystallization they retain many of their primary chemical and physical characteristics, and bedding in footwall rocks is largely undisturbed except for local folding attributed to soft-sediment deformation. Footwall sulphide veins are rare.

Description of the geology of host rocks and ore zone will follow that of the stratigraphic sequence as shown on the ideal stratigraphic section (Fig. 9). Intraformational conglomerate unconformably overlies normal Lower Aldridge sedimentary rock beneath much of the orebody. Conglomerate is thick and stratigraphically complex beneath the western part of the orebody and thins outward to a simple stratigraphic unit. Stratigraphic relations between the conglomerate and the sulphide

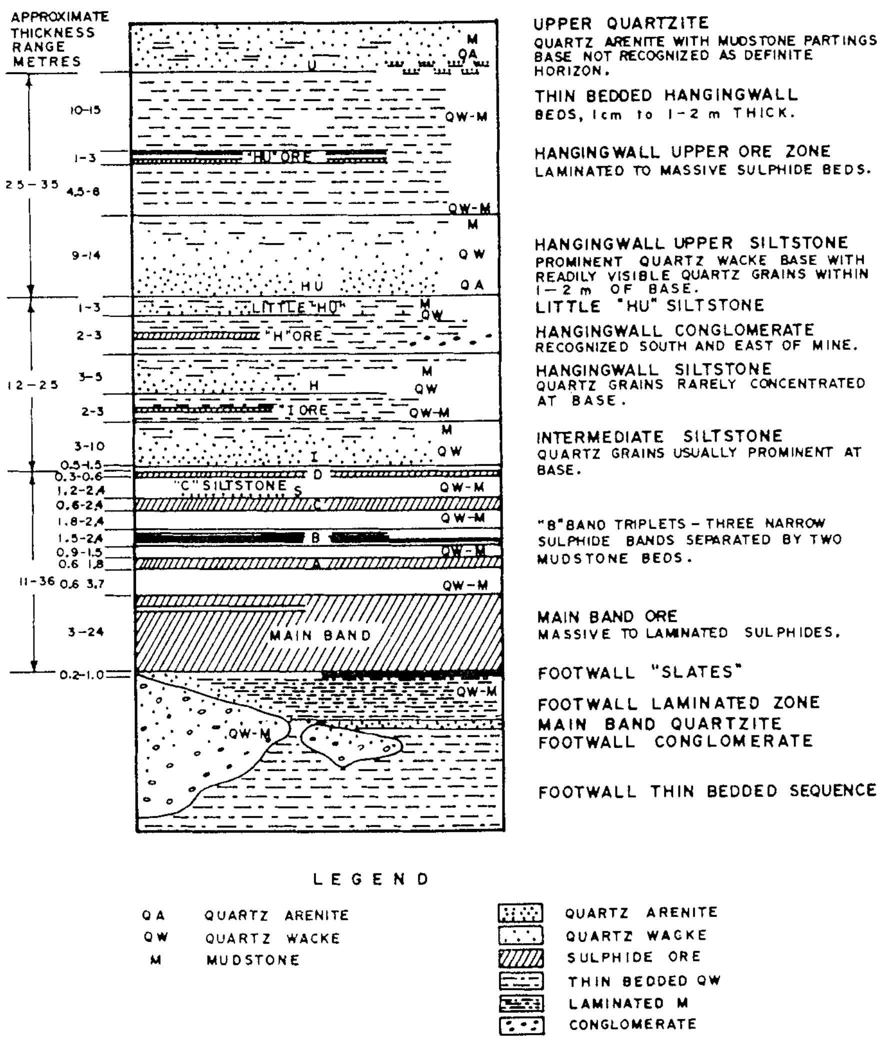

Figure 9. Idealized geological column of the bedded part of the Sullivan orebody.

footwall are also complex beneath the western part of the orebody but become extremely uniform beneath the well-bedded part of the orebody. Footwall stringer mineralization although volumetrically not very large is locally abundant west of the transition zone. Conformable and disseminated sulphide mineralization, principally pyrrhotite, is common in the footwall on both sides of the transition.

Several readily identifiable sequences grading from quartz wacke to mudstone and each overlain by pyrrhotite-laminated mudstone form the immediate hangingwall of the orebody. These can be traced throughout much of the hangingwall except where obliterated by alteration. The pyrrhotite-laminated mudstone grades laterally to conformable hangingwall ore which is generally situated stratigraphically above the transition zone. To the south and southwest, hangingwall mineralization persists laterally at mineable grades beyond the point at which lower sulphide zones become sub-economic or were not deposited.

Geology of the Footwall Rocks

Beneath the ore zone the deep footwall succession is typical of the upper part of the Lower Aldridge. Thin- to medium-bedded mudstone is interbedded with subordinate fine-grained quartz wacke. With appropriate marker beds it is possible to make lithostratigraphic correlations over large areas in the footwall.

Conglomerate. Intraformational conglomerate underlies the northern two-thirds of the orebody. The base of the conglomerate is nearly everywhere disconformable. Beneath the western part of the orebody the conglomerate sequence is over 80 m thick (Fig. 8) with the base poorly defined in several areas. The conglomerate thins rapidly to the south and north and more gradually to the east. Contacts in areas of thickest conglomerate sharply truncate bedded sedimentary rocks through stratigraphic thicknesses of 60 m or more. The thick part of the conglomerate is confined on its south, west and north sides by steep, discordant contacts and by a less steep but unconformable contact to the east. In areas where conglomerate is thicker than 45 m, sulphides rest on it or are separated by only a few metres of thinly laminated sedimentary rock. Elsewhere beneath the western part of the orebody thinly laminated sedimentary rock up to 15 m thick lies between the top of the conglomerate and the base of sulphide rock.

Clasts and matrix of the conglomerate are of the same composition as the underlying sedimentary rocks and no foreign clasts have been identified. The conglomerate generally lacks bedding but may be weakly bedded in places. It is locally graded at its fringes. Clasts range in abundance from 10 to 95% and in size from 2 mm to greater than one metre in diameter, and average one to 3 cm (Fig. 10). Typically, clasts are well-sorted although bimodal distribution of clast size is common. Clast shape is related to lithological type. Homogeneous mudstone clasts are frequently tabular or disk-shaped and well-rounded. Laminated to thin-bedded and pyrrhotite-laminated clasts are nearly equant or rhombic and frequently have tapered corners. Arenaceous clasts are rounded to subrounded and very large clasts tend to exhibit high sphericity. In cases of bimodal or polymodal distribution of clast size, smaller clasts tend to be subangular and larger clasts subrounded. Occasional round disk-shaped clasts of tourmalinite and well-rounded arenaceous clasts containing disseminated sphalerite are found in the conglomerate beneath the eastern part of the orebody. In many places, footwall beds exhibit structures formed by soft-sediment deformation which are truncated by massive conglomerate.

Stratigraphy of the conglomerate is relatively simple beneath the eastern part of the orebody and more complex to the west. To the east the conglomerate is usually a single massive unit overlying thin-bedded quartz wacke or pyrrhotite-laminated mudstone. Locally a thick sequence of poorly sorted massive conglomerate is overlain by a well sorted unit containing tightly packed clasts and separated from the main conglomerate unit by a thin sequence of pyrrhotite-laminated mudstone. To the west, the conglomerate is a composite unit made up of frequent interbeds of massive, poorly to well sorted conglomerate, thinly bedded, well bedded sedimentary rocks and thick units of rock in which bedding has been intensely disrupted.

Footwall Bedded Sequence. Thin- to medium-bedded, commonly graded quartz wacke interbedded with pyrrhotite-laminated mudstone conformably overlies the conglomerate beneath the eastern part of the orebody. With the exception of two well-defined marker units, the Main Band Quartzite (MBQ) and the Footwall "Slates" (Fig. 9), rock-types making up the sequence overlying the conglomerate are not laterally persistent. Gradual lateral changes preclude unit by unit correlations over distances greater than a few hundred metres. Lamination for lamination correlation over a few hundred metres can be made for the pyrrhotite-laminated mudstone (Freeze, 1966).

The Main Band Quartzite, a 1.5 m thick graded quartz wacke bed, forms the base of an upward-fining sequence immediately beneath the orebody. This bed is recognized over large areas beneath the north, east and south parts of the orebody. The base of the bed is commonly deformed by load casting and contains well-sorted quartz grains and clasts up to 4 mm in diameter which often appear to float in a carbonate matrix. One or more graded quartz wacke beds overlain by the Footwall "Slates" form the remainder of the upward-fining sequence beneath the sulphide footwall. The Footwall "Slates" is a 0.2 to 1.0 m thick sequence of chloritic, laminated mudstone which can be traced over large distances. Pyrrhotite laminations occurring at 2 to 40 mm intervals, along with minor layers of disseminated sphalerite and opaque (graphite?) material impart a distinctive layering to the rock.

Sedimentary rocks overlying the conglomerate beneath the western part of the orebody display even more rapid lateral change than do those overlying the conglomerate to the east. No marker beds have been recognized in the sequence.

Below the periphery of the western part of the orebody, the sequence may contain as much as 10 m of interbedded tourmalinite and chlorite-rich or sericite-rich quartz wacke and mudstone overlain by pyrrhotite-laminated, variably chloritic rock containing from 10 to 50% pyrrhotite, sphalerite and galena. Extremely rapid lateral changes occur in strata exposed in footwall development. Chlorite-rich or sericite-rich rock laminated with pyrrhotite may grade rapidly over a few centimetres to pyrrhotite-laminated tourmalinite or may contain large, irregular, frequently strata-bound masses of tourmalinite through which the layering passes undisturbed (Shaw, in preparation). Alternatively, well-bedded rock may pass laterally into rock devoid of bedding. Only the pyrrhotite-laminated rock immediately beneath the sulphide footwall can be traced over any distance with confidence. Locally beneath the centre of the conglomerate. The best documented phase, the post-conglomerate chaotic rock occurs beneath the sulphide footwall (Figs. 5 and 6).

Chaotic Breccia. Extensive zones of breccia (Figs. 11, 12, 41) have been recognized in the western part of the ore zone and Jardine (1966) identified several phases. The earliest phase, the pre-conglomerate breccia, is poorly documented and very difficult to differentiate from breccias formed after deposition of the conglomerate. The best documented phase, the post-conglomerate chaotic breccia, disrupts both conglomerate and well-bedded sedimentary rocks in the footwall.

According to Jardine (p. 45):

"The rock is composed of fragments of Aldridge-type sedimentary rocks varying from sand-size to pieces measured in tens of feet. Bedded fragments are often wispy, twisted and rotated, with ends that appear to have torn rather than broken. Blocks of conglomerate are mixed in with bedded and massive pieces, and the whole appearance is heterogeneous and chaotic. Apparently much of the broken rock was in a relatively soft state at the time of breaking.

"The blocks are now completely consolidated in a matrix of silty argillite . .

Figure 10. Footwall conglomerate containing closely packed pebbles of typical Aldridge rock types. Pebbles contain disseminated and laminated pyrrhotite and several are rimmed with pyrrhotite. Core diameter is 3.2 cm.

Pyrrhotite is disseminated through the matrix and is also present in irregular veinlets that lace through the rock."

The irregular areas of post-conglomerate chaotic breccia outlined by Jardine show three elongate trends in a north-south direction and another with an irregular east-west direction. Vertical extent of brecciation in the footwall has not been clearly defined. The limits of brecciation at depth shown in Figures 5 and 6 are interpretive.

Geology of the Ore Zone, Eastern Part

The ore zone in the eastern part of the orebody is as much as 36 m thick (Fig. 13) and consists of bedded sulphide rock with interbedded barren clastic sedimentary rock in its upper part. It is characterized by sharp contacts and extremely regular stratigraphy. Primary sedimentary structures such as bedding and local soft-sediment deformation are preserved in detail. Figure 9 illustrates the ore zone sequence from the base of the Main Band to the base of the "Upper Quartzites". The principal sulphide beds are labelled Main Band and "A" through "D" Bands from base to top

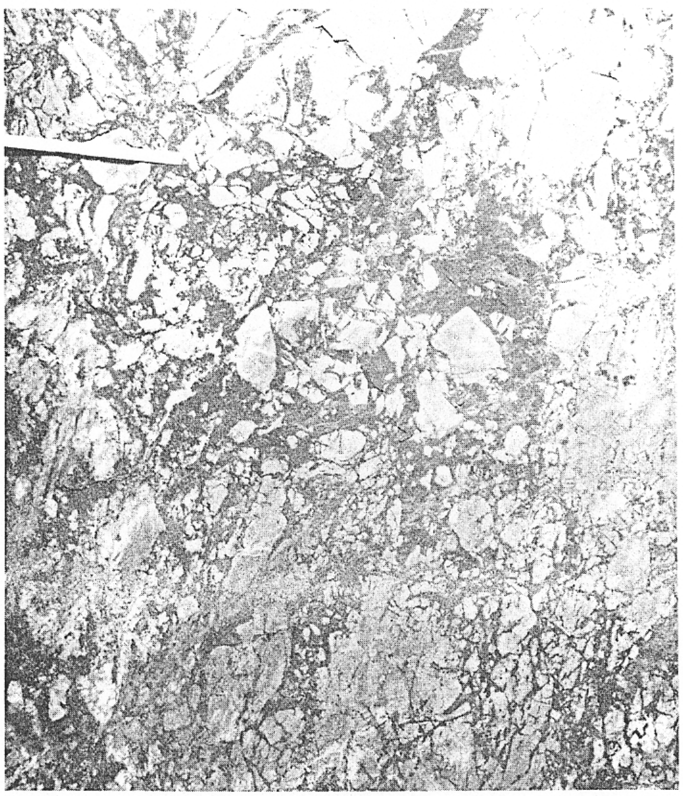

Figure 11. Chaotic breccia fragments enclosed in a pyrrhotitic matrix. Angular fragments ranging from centimetres to metres across are in many places intermixed. Pyrrhotitic matrix may contain 1 to 5% sphalerite and trace amounts to abundant stringers of arsenopyrite. Rule is 1.5 cm wide.

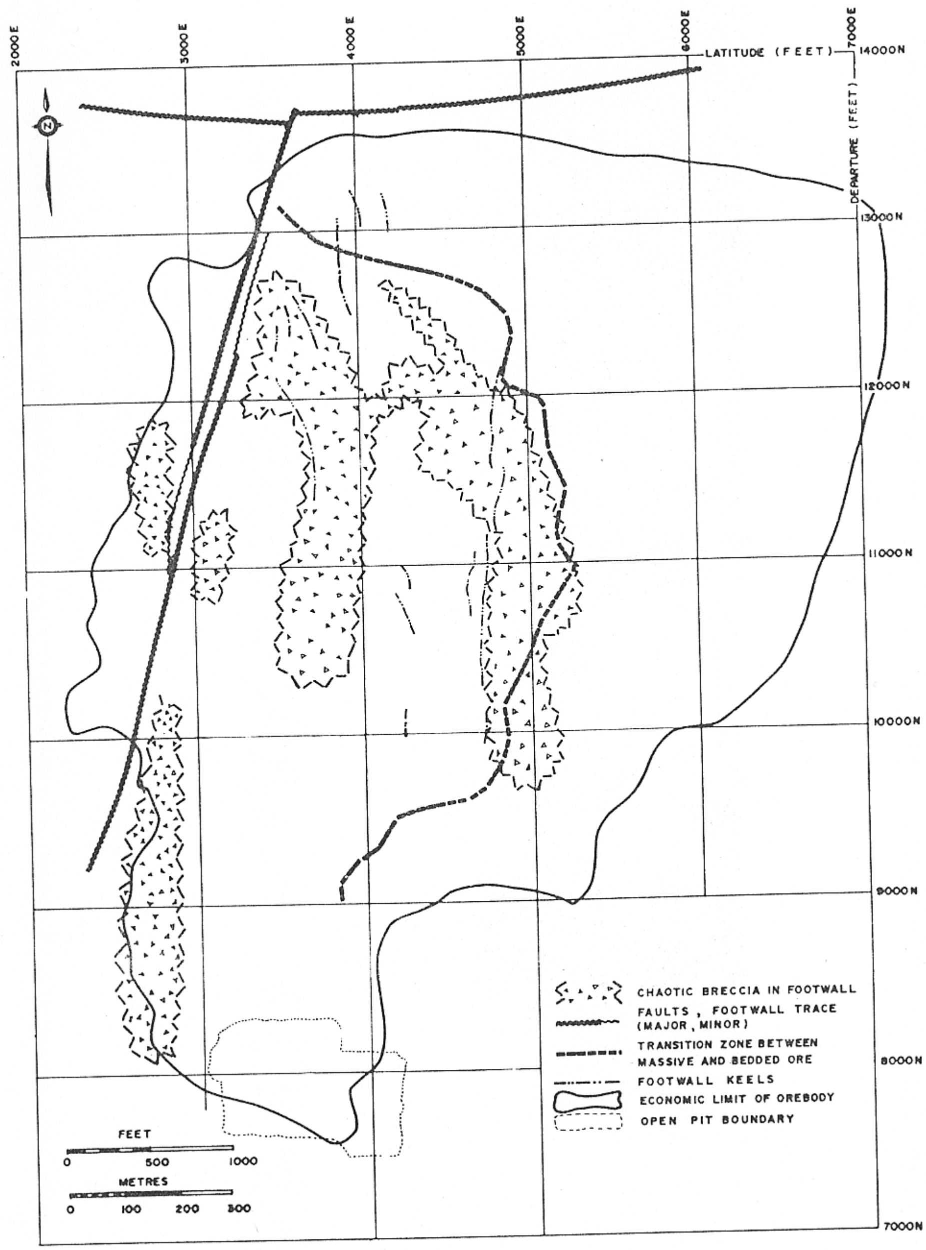

Figure 12. Distribution of chaotic breccia in the footwall of the Sullivan orebody.

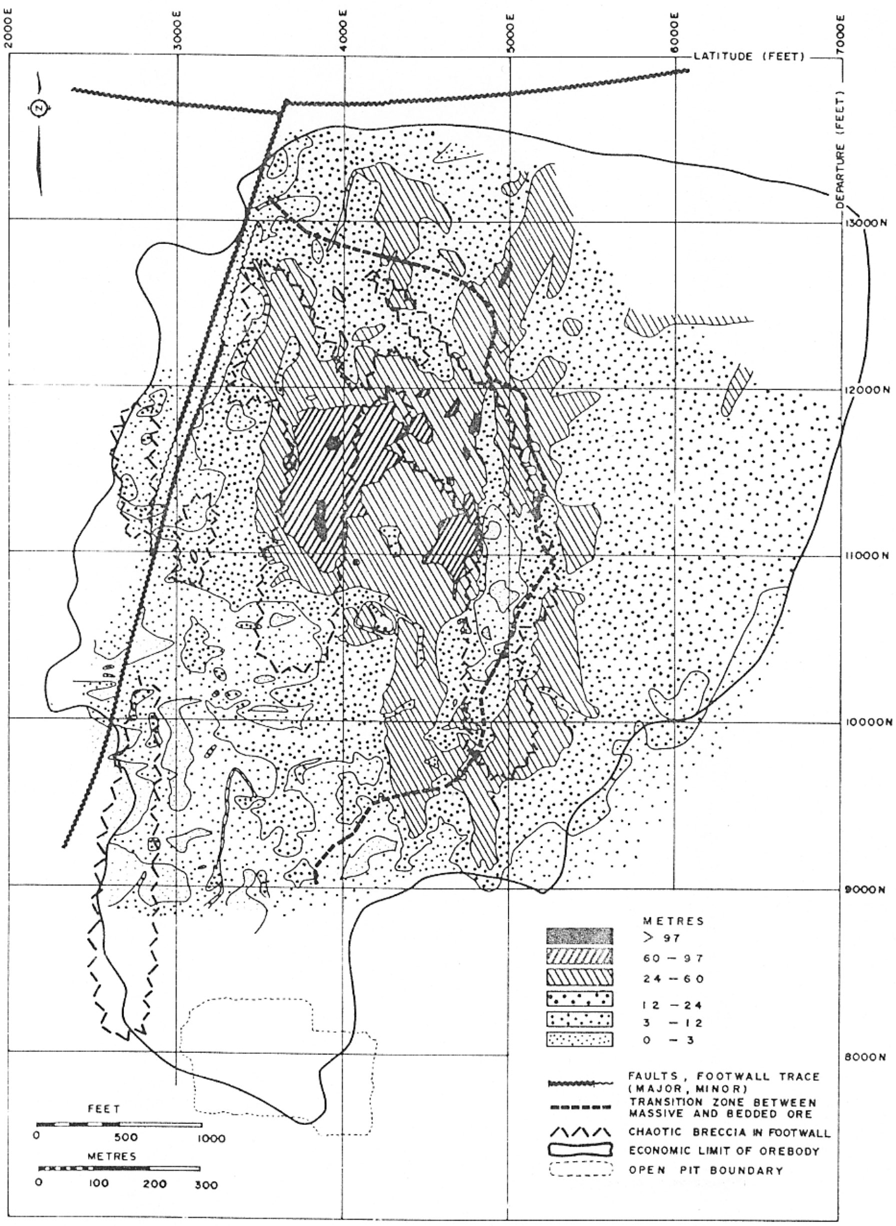

Figure 13. Isopach map of the Sullivan orebody exclusive of hangingwall ore.

in the section. In the transition zone joining the eastern and western parts, individual sulphide Bands lose their identity as the sulphide rock becomes more massive and the intercalated clastic sedimentary rocks disappear.

Main Band. The Main Band is the lowest sulphide band of economic significance and is the major sulphide accumulation in the eastern part of the orebody. Up to 24 m thick, the Main Band overlies the "Footwall Slates" with a sharp conformable contact where the rock changes from mudstone to sulphide rock composed of more than 70% sulphide across a single bedding plane (Figs. 14, 32). The lower two-thirds to three-quarters of the Main Band in the eastern part of the orebody has definite characteristics which set it apart from the overlying sulphide bands. It is particularly rich in sulphides, lacks mudstone interbeds but exhibits internal bedding (Fig. 15) and often contains fragments of various rock types.

Figure 14. Photomicrograph of the base of the Main Band, at the transition zone. Darker layers in Footwall "Slates" at bottom are biotite. The sulphide assemblage is: basal layer sphalerite, middle layer galena and pyrrhotite, upper half of sulphide section sphalerite. Gangue minerals are calcite, muscovite, pale brown biotite and minor quartz. Four centimetres of section shown. Plane light.

The lower two-thirds to three-quarters of Main Band sulphide rock consists of a series of dense, thin beds of fine-grained sulphides without significant amounts of argillaceous clastic material, either as interbeds or disseminated grains. The sulphides are mainly pyrrhotite, sphalerite and galena occurring in distinct beds containing varying proportions of these minerals (Figs. 15, 16, 32). Usually, either pyrrhotite or sphalerite is the dominant sulphide in a bed with smaller quantities of the subordinate sulphide and galena. Beds composed almost entirely of sphalerite or galena are also present. The beds are usually less than 3 cm thick, but may be up to 30 cm thick. Most beds have what appear to be sharp boundaries, but microscopic examination reveals that the boundaries are gradational. For example, if pyrrhotite constitutes the major fraction of a sulphide bed and the adjacent bed is largely sphalerite their boundary consists of a one millimetre zone containing a mixture of the two, and each bed will contain small amounts of the sulphide forming the

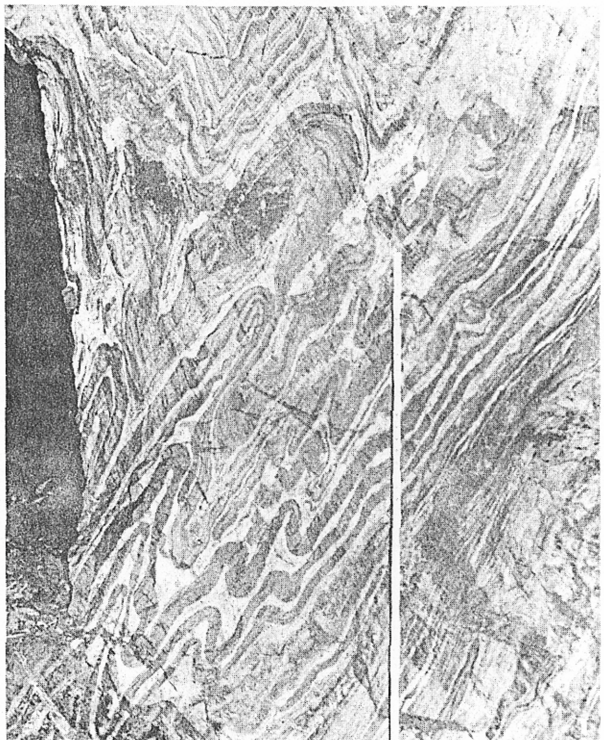

Figure 15. Highly deformed sulphide bedding with no mudstone interbeds near the centre of the Main Band. Light grey beds are composed of galena, medium gray beds pyrrhotite with minor sphalerite, and dark grey beds sphalerite with minor pyrrhotite. Rule in inches. Top to upper left.

major component of the adjacent bed. The sulphide grains range from 0.005 to 0.5 mm in diameter but almost all are less than 0.1 mm in maximum dimension. Sphalerite occurs as equidimensional, brown grains from 0.02 to 0.3 mm in diameter. Pyrrhotite occurs as indistinct grains up to 0.5 mm in diameter. Galena occurs as irregular grains from 0.02 to 0.4 mm in diameter.

Sulphides compose 75% of the sulphide rock with calcite, quartz and various silicate minerals making up the remainder. The non-sulphide minerals occur as randomly oriented or aligned grains ranging in size from 0.05 to 1.0 mm in diameter and also as part of larger masses (Fig. 14). Calcite is more plentiful than quartz and comprises 15% of the rock. Silicate minerals include chlorite, muscovite and occasionally scapolite or garnet. The size and shape of the grains of quartz and silicates is

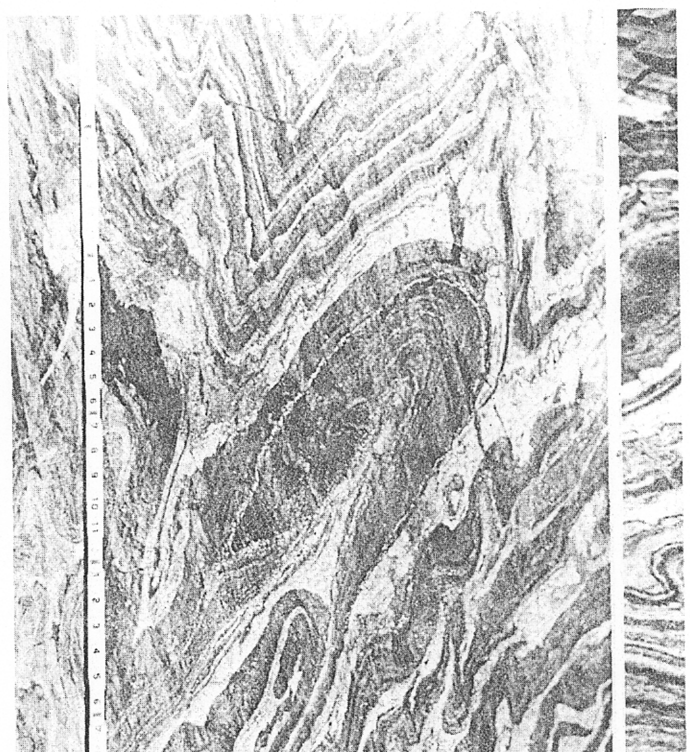

Figure 16. Details of bedding and folding in a part of the area illustrated in Figure 15. Beds composed predominantly of galena (light grey) and pyrrhotite (medium grey) have been strongly attenuated along fold limbs. The parallel fabric extending from the lower right to upper left of the photograph is tectonic. Rule in inches.

usually coarser and more irregular than grains of the same minerals in adjacent argillaceous clastic rock.

Megascopic fragments are locally common. They are occasionally up to one metre across but are commonly less than one centimetre in diameter. Fragments include altered and unaltered clastic sedimentary rock, carbonate rock and granular quartz-rich rock. Inclusions composed essentially of a single mineral include pyrite (buckshot pyrite), calcite, quartz, sphalerite, scapolite and garnet. The monomineralic inclusions may be up to 0.5 cm across. On rare occasions megascopic fragments and inclusions may make up as much as 20% of particular beds in localized areas and it is common to find beds with 2 to 5% fragments and inclusions.

The upper one-third to one-quarter of the Main Band in the eastern part of the orebody is different from the lower part as it contains thin, closely spaced interbeds of mudstone and quartz wacke in the sulphide beds. The mudstone and quartz wacke beds are usually similar to those outside the ore zone, though in some cases they may be chloritic, or contain some sulphides. The non-sulphide material within the sulphide beds of the upper part of the Main Band consists of equidimensional grains of quartz, calcite, chlorite, biotite, garnet, tremolite, clinozoisite and, rarely, hornblende. These grains are similar in shape but larger than grains of the same minerals occurring in the lower part of the Main Band.

The sequences containing thin interbedded sulphide rock and clastic sedimentary rock contain up to 60% sulphide minerals as laminae or as beds up to 30 cm thick. Average grain size of sulphides in this rock is coarser than that in sulphide rock in the basal part of the Main Band and there is a greater range in sulphide grain size from bed to bed within a single section. Certain laminae contain grains up to 1 mm in diameter whereas adjacent laminae contain grains less than 0.1 mm in maximum dimension. The various sulphide laminae show less intermixing of sulphides than does sulphide rock in the basal part of the Main Band. Individual beds may be largely pyrrhotite or galena, and sphalerite with galena, or pyrrhotite with sphalerite are common combinations. Composition of strata at the top of the Main Band varies gradually through the mine area. Nodules composed largely of sulphides, usually pyrite, are common. These are up to 20 cm in maximum dimension (which is always conformable to the stratigraphy, in contrast to sulphide fragments in sulphide rock near the base) and up to 3 cm thick. Adjacent laminae always bend over or under the nodules.

In several localities in the southeastern part of the orebody, the lower one-half to two-thirds of the Main Band has a conspicuous fragmental texture (Fig. 34). The rock is massive sulphide and contains a variety of fragmental material including clastic sedimentary rock and tourmalinite as well as inclusions consisting of pyrite, calcite, quartz, and sphalerite, all of which are set in a matrix of about 30% quartz grains, calcite, chlorite and phlogopitic mica and about 70% pyrrhotite, sphalerite and galena. Fragments of tourmalinite and mudstone are generally subangular to subrounded and range up to 6 cm in length. Largest fragments occur near the base and the massive fragmental rock grades upward through a transition zone to sulphide rock with well-developed bedding. The massive rock contains abundant megacrysts of pyrite (buckshot pyrite). Mudstone fragments are similar to adjacent footwall rocks, or are altered to chloritic rock. Chloritic fragments may have quartz and calcite veins.

Ore Bands "A" through "D". The "A", "B", "C" and "D" ore Bands consist of thin-bedded sulphides with mudstone interbeds similar to those described in the upper part of the Main Band. The regularity of the sulphide beds is very marked (Figs. 17, 18, 30, 35). The Bands are readily recognized throughout the eastern part of the mine over an area more than 2000 m by 1200 m and usually the different Bands can be distinguished owing to their individual character. The "B" Band contains three beds of sulphides, called the triplets, separated by two beds of mudstone ranging from 5 to 15 cm thick. Normally, the triplets can be recognized throughout the eastern part of the mine and serve as a stratigraphic marker. Individual beds have

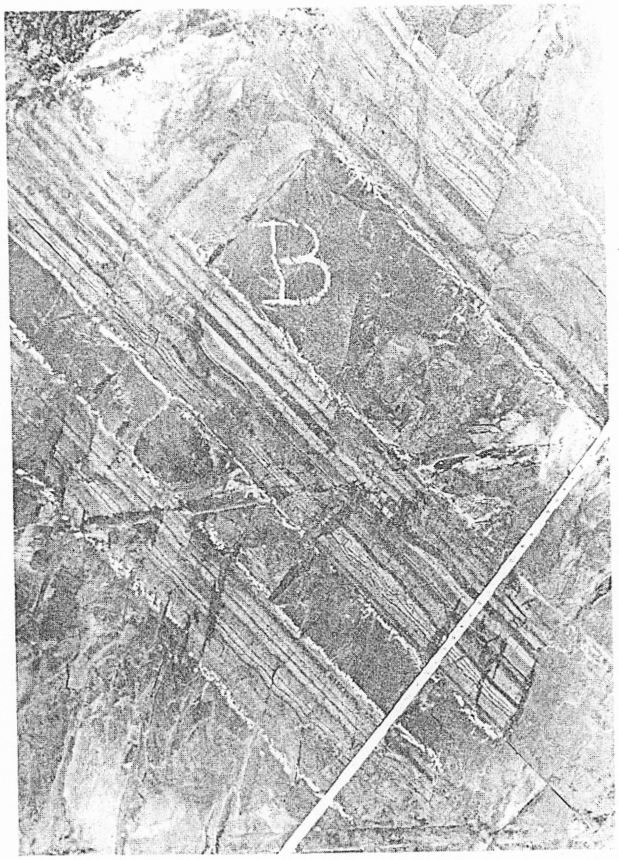

Figure 17. Sulphide beds of the "B" Band triplet, characteristic of upper sulphide bands in the eastern part of the orebody. Three sulphide beds composed of planar sulphide layers interbedded with mudstone are separated by graded beds of quartz wacke. Slight crenulation of sulphide beds is thought to be tectonic. Axes of folds trend northeast. Rule divided in inches. Top of section to upper right.

sharp contacts, are continuous and of nearly uniform composition throughout large areas. Iron sulphides are more widespread and continue laterally beyond the limits of ore-grade lead and zinc.

Waste Bands Between Ore Bands. The sequence of thin-bedded sulphides with mudstone interbeds, which has its base within the Main Band and upper limit in and above the "D" sulphides, contains four 0.6 to 4 m thick beds of graded quartz wacke. Each of these beds of waste, separating essentially similar sulphides, consists of one or more graded units without laminated interbeds. The graded beds have the same texture and composition as those in the footwall bedded sequence. However, they are thicker, with noticeable coarse-grained lower portions, and are not found beyond the limits of the ore zone.

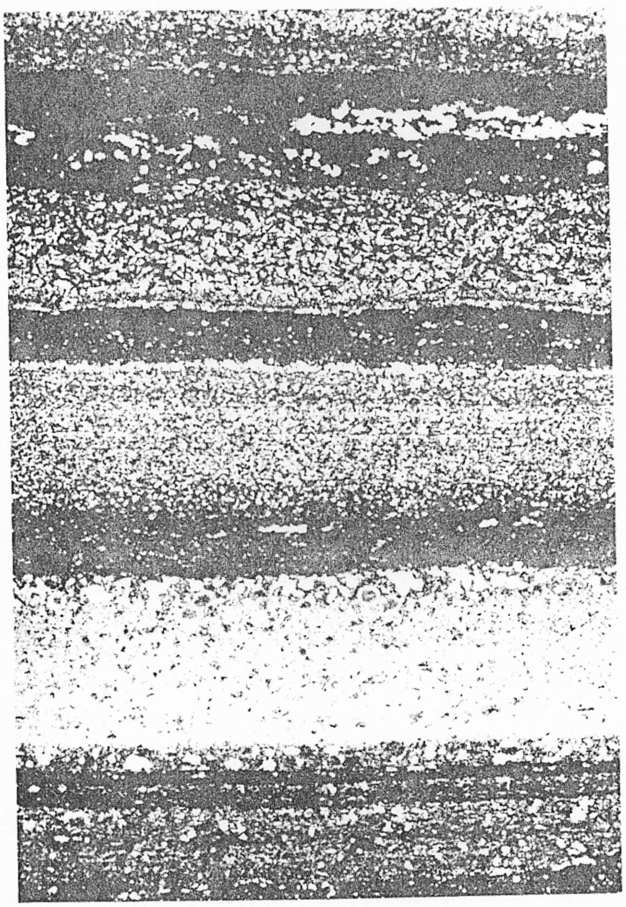

Figure 18. Photomicrograph of bedded ore from the "C" Band. Black and dark grey layers are sulphides. Light-coloured layers are composed of muscovite, quartz, biotite and chlorite. Bladed opaque mineral is pyrrhotite. Rounded mineral in light-coloured layer is zoned garnet. Plane light. Four cm of section shown. Top up.

Geology of the Ore Zone, Western Part

The western part of the orebody has important differences from the eastern. It consists of massive- to poorly-bedded sulphide with subordinate interbedded sediment. Contacts are conformable and bedding attitudes within the ore are generally parallel to those in the enclosing sedimentary rocks. However, discordant contacts between different sulphide assemblages within the orebody are recognized. Rapid thickness changes, or abrupt terminations of lithologic units and locally severe deformation preclude detailed correlation within the western part of the orebody and across the transition to the eastern part.

The western part of the orebody is commonly greater than 50 m thick. The abrupt thickness changes in the west contrast sharply with gradual thickness changes in the east. Isopachs of the orebody (Fig. 13) define a particularly abrupt zone of thinning along a trend at approximately 4800 departure in the area of the Alpha and Beta fault zones (Figs. 5 and 7). The orebody thins eastward across this northerly trend, from more than 60 m to as little as 2 m, and adjacent to this thin part, hangingwall bedding is generally conformable with layering in the ore. Host rocks and ore zone may be deformed, highly altered and brecciated in and near the zone of thinning. Disrupted and discordant footwall contacts occur along keel-like structures at the base of the sulphides and extend down for several metres (Figs. 5 and 12). Along discordant contacts of keels the rocks are frequently brecciated and altered. Layering in sulphides within some keels is generally conformable to contacts of the keels and wraps around the sharp downward projection of the structures. Some keels have one conformable limb and one fault-bounded limb, while others pass downward into sulphide veins.

The sulphide rock footwall in the western part of the orebody, although almost everywhere strictly conformable, is commonly not as planar as the footwall to the east. Over large areas sulphide rock, principally pyrrhotite, overlies sulphide-laminated sedimentary rock with a sharp contact. In a few places rapid lateral changes in lithology and rapid changes in vertical distribution of pyrrhotite result in a gradational contact. Rarely, sulphide rock may overlie conglomerate or breccia with a matrix largely composed of sulphide and apparently gradational with the sulphide rock. Minor folding of the sulphide footwall suggests soft-sediment deformation.

Structures and textures within the western part of the orebody are quite different from those in the eastern part (Fig. 5). The most conspicuous difference is between regular bedding in the eastern part (Figs. 15, 16, 17 30, 31, 35) and less regular layering in the west (Figs. 32, 33). Large-scale layering in the west is defined by generally conformable lenses of nearly barren pyrrhotite. The largest such lens occurs at or near the sulphide footwall (Fig. 5) in the thickest part of the orebody and extends for about 350 m along strike and 250 m down dip. It has a maximum thickness of about 35 m. Broadly conformable at its footwall, the perimeter of the lens has an abrupt or gradational change to commercial ore (Fig. 5). Locally within the pyrrhotite lens, sphalerite and galena occur as disseminated grains, wispy fine- to coarse-grained concentrations, fracture fillings and veins without alteration envelopes.

Close examination of the pyrrhotite lens reveals internal layering which is generally parallel to the sedimentary layering in the enclosing rocks. Fragments of vein quartz, granular quartz, carbonate rock, mudstone and altered mudstone are present, particularly near the base. The rock consists of 60 to 80% pyrrhotite, 10 to 30% calcite, about 5% of each of quartz, chlorite and sphalerite, with smaller amounts of muscovite, pyrite and galena. Figures 19 and 20 show textures similar to those in lenses of nearly barren pyrrhotite. Weakly disseminated chalcopyrite (up to 2%) occurs locally. Pyrrhotite grains are less than 0.05 mm in diameter. The grain size of the quartz, calcite and chlorite varies between wide limits but is usually 0.1 to 1 mm in diameter. Non-sulphide minerals occur as single isolated grains and as several contiguous grains forming a mass which often has regular smooth outlines. The latter vary in size up to a few centimetres across. The pyrrhotite lens grades rapidly upward to sulphide rock in which layering is defined by wispy concentrations of galena and sphalerite in a pyrrhotite matrix. This fine-scale layering is laterally discontinuous with frequent pinch-outs and disruptions; however, the layering is parallel to general sedimentary attitudes. Toward the upper part of the orebody, bedding is clearly defined. Sulphide rock is interbedded with fine-grained clastic sedimentary rock, and bedding within sulphide rock is defined by discrete and often delicate laminae of galena and sphalerite.

Toward the centre of the orebody, precise stratigraphic control is lost in the transition (Fig. 5) from well-bedded ore to poorly layered ore. However the lower sequence of barren pyrrhotite and overlying poorly layered ore west of the transition correlates stratigraphically with the Main Band to the east whereas the more distinctly bedded material toward the top of the central part of the orebody correlates with the upper Bands to the east.

Footwall Mineralization

Minor stratiform and stratabound mineralization is abundant below both the eastern and western parts of the orebody. Discordant mineralization, in contrast, is common beneath the western part of the orebody but is rare beneath the eastern part.

Beneath the eastern part of the orebody, concordant footwall mineralization is most common in the stratigraphic sequence between the conglomerate and the sulphide footwall. Within the conglomerate, sulphide mineralization, predominantly pyrrhotite, occurs as laminae in clasts, as rims surrounding clasts and as disseminations. Pyrrhotite and sphalerite are the principal sulphides in rocks overlying the conglomerate and form discrete laminae in mudstone. Less common are disseminated sulphides concentrated in laminae up to a few millimetres thick. Sphalerite becomes more abundant with approach to the sulphide footwall but generally remains subordinate to pyrrhotite.

Beneath the western part of the orebody, concordant footwall mineralization is more abundant than beneath the eastern part and occurs through at least 40 m of strata. Pyrrhotite and sphalerite are the most abundant sulphides and occur as thin, sulphide-rich laminae and disseminations in mudstone and tourmalinite. Across 1 to 2 cm sections pyrrhotite laminae may make up as much as 25% of the rock although more typically they account for 2 to 5%. Usually quite continuous, the laminae may grade laterally into sulphide disseminated along bedding planes and then into unmineralized rock. In conglomerate underlying the western part of the orebody, clasts may be laminated and rimmed with pyrrhotite (Fig. 40). Clasts composed of 60 to 80% pyrrhotite are common; however, clasts composed entirely of pyrrhotite are rare.

Discordant mineralization, in the form of veins, is locally intense beneath the western part of the orebody and relatively rare beneath the eastern part. Geometry of the veins ranges from planar and regular with sharp matching contacts to irregular with indistinct non-matching contacts (McAdam, 1978).

Planar regular veins appear to cut the irregular veins. The principal sulphide is pyrrhotite; pyrite, sphalerite, and galena may be abundant, and chalcopyrite and arsenopyrite are subordinate. The dominant non-sulphide minerals are quartz and calcite. Individual veins may be dominated by either sulphide or non-sulphide. Planar veins are best developed in relatively hard quartz wacke, quartz arenite or tourmalinite; vein walls become more irregular in softer argillaceous or chloritic rock. Many of the planar veins are zoned with pyrrhotite in the core and sphalerite, arsenopyrite

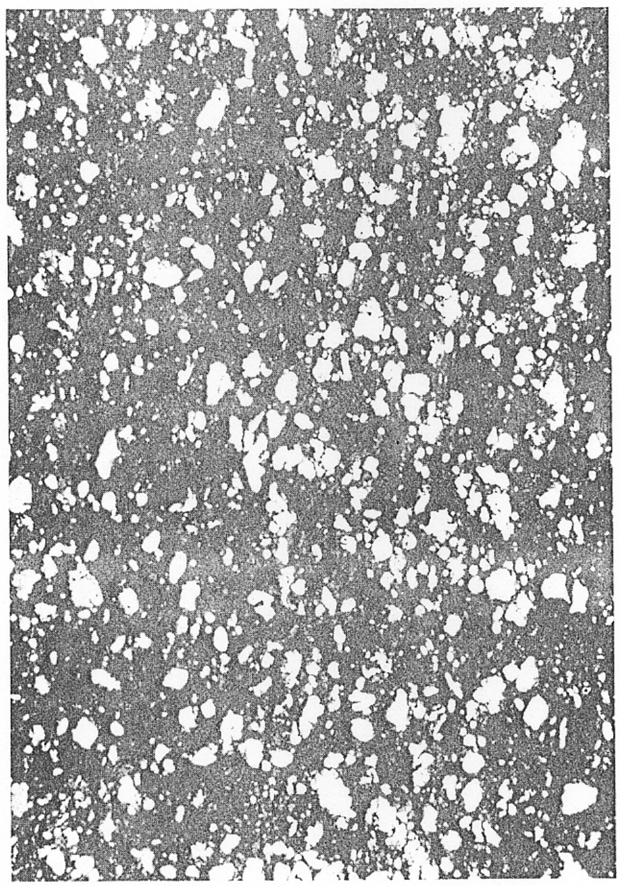

Figure 19. Photomicrograph of unbedded ore containing about 10 per cent galena-sphalerite from the western part of the orebody. Light coloured minerals include calcite, quartz and chlorite (grey, platey mineral). Black area is principally pyrrhotite. A sample with unusually high abundance of non-sulphide material was selected to show the texture. Plane light. Long axis of figure represents 3.4 cm and is parallel to primary and tectonic layering.

or, more rarely, galena at the margins. Locally, the proportions of non-sulphide minerals correlate with the abundance of quartz in adjacent host rock. For example, in quartz arenite, veins often contain abundant quartz, whereas calcite may predominate in chloritic or sericitic rock.

Irregular veins frequently form networks composed dominantly of pyrrhotite, galena and sphalerite with minor amounts of quartz, pyrite, arsenopyrite, chalcopyrite, cassiterite, and tourmaline. Galena and pyrrhotite occupy a central position in the irregular veins with sphalerite and locally arsenopyrite concentrated along vein margins. Sulphides occupying vein margins may be disseminated in wall rock or extend as laminae into it.

Alteration related to individual sulphide veins, although generally inconspicuous, may extend several centimetres into chloritic or biotitic host rock. Alteration

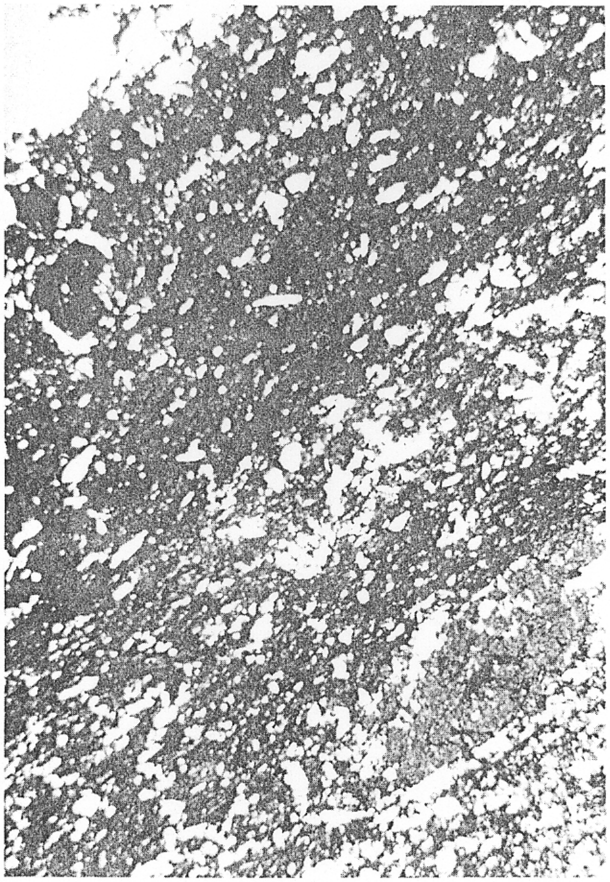

Figure 20. Photomicrograph of ore containing about 30% sphalerite-galena from the western part of the orebody. Dark grey and black areas are sulphides. The pronounced fabric is tectonic. Non-sulphide material is carbonate, quartz and chlorite (medium grey). Long axis of photograph represents 3.4 cm. Top unknown. Plane light. Unusually high non-sulphide content.

includes complete destruction of mafic minerals, or migration in which components are concentrated away from or toward the vein (McAdam, 1978). Sulphides in places form up to 30% of the rock within zones of chaotic footwall breccia. Pyrrhotite is the predominant sulphide in the breccia, but sphalerite, galena, chalcopyrite and arsenopyrite are locally abundant. Disseminated to massive sulphides occur in the matrix of the breccia in many places. Elsewhere, the breccia more closely resembles a zone of abnormally intense irregular vein mineralization.

Hangingwall Bedded Sequence

Four graded sequences called the "I", "H" "Little HU" and "HU" markers occur above the "D" Band (Fig. 9). Each starts with a graded quartz wacke bed at the base and grades upward to a thick mudstone top. The top pyrrhotite-laminated parts of three of these sequences correlate laterally with the "I", "H" and "HU" ore zones in the hangingwall.

"Intermediate Siltstone". The main sulphide zone, which includes the stratigraphic sequence from the base of the Main Band to the top of "D", is overlain by the Intermediate siltstone ("I") an argillaceous graded bed, up to 3.5 m thick, recognized throughout the eastern and northern part of the mine. It thins laterally beyond the limits of the orebody. "I" appears to be present above the central and western part of the orebody but here is not commonly recognized, because of hangingwall alteration. "I" consists of quartz wacke containing 1 to 2 mm glassy quartz grains in the lower few centimetres and grades upward through quartz wacke to very fine-grained, soft, mudstone at the top. The bed is underlain by fine-grained soft mudstone and the marked change at the base of the graded bed serves as an excellent stratigraphic horizon marker. The base of the bed is often deformed into load waves, some of which are cut off and mixed into the upper few centimetres of the underlying mudstone. The bed consists mainly of quartz, sericite and biotite with scattered grains of pyrrhotite. In areas where the hangingwall sequence is altered to chlorite and albite, the Intermediate siltstone is similarly altered. There does not seem to be any selective alteration or mineralization of the coarser-grained base of the bed.

"I" Ore. The "I" ore zone consists of a section of mudstone with sulphide laminations, overlying the thick "I" graded bed and underlying the "H" graded bed. In some places the sulphide laminae are thick and numerous enough to make ore. The "I" laminated ore zone can be identified in most of the mine area that is free of alteration. Sometimes it is identified on the basis of the laminated section lying between "I" and "H", but usually it can be recognized owing to distinctive spacing of iron-sulphide laminae ("I Laminations") near the centre of the sequence (Freeze, 1966). The "I" laminated zone is 2 to 3 m thick.

"H" Sequence. The "H" stratigraphic interval is similar to the "I" sequence. It consists of a basal bed, up to 3 m thick, of graded quartz wacke and an upper section of laminated mudstone with thin sulphide laminations. In places the laminated section contains enough lead and zinc to be ore.

"HU" Sequence. The "HU" sequence consists of two thick-graded beds with overlying laminated mudstone. The lower bed is called "Little HU" and is 1 to 3.5 m thick. The upper bed, "HU", is commonly about 6 m thick and grades from quartz wacke at the base to very fine, non-laminated mudstone at the top. Most of the bed is

fine-grained quartz wacke. It is light grey in colour and consists of quartz and sericite. The graded section of the series is overlain by laminated argillite which contains the "HU" Ore. The base of "HU" is the most reliable marker in the mine.

The hangingwall ore zones, "I", "H" and "HU", are distributed in a broad crescent-shaped pattern about the thickest part of the orebody. These ore zones are delicately bedded and thickest in the vicinity of the Burchett fault, Number 2 fault and the Main Water Course (Fig. 7) and at the southern margin of the orebody. A hangingwall conglomerate averaging 4 m thick and containing some ore-grade sulphide clasts occurs beneath the "H" ore. It has been traced for more than 1000 m along the southern margin of the orebody. The "HU" ore (Fig. 21) consists of both sulphide rock and rock composed of interbedded sulphide and mudstone with the former more prevalent in thicker sections of ore. Crosscutting breccias have been observed up to the level of "HU" Ore.

Figure 21. Delicate sulphide bedding of "HU" ore. Compare with Figure 17. Rule divided in inches.

"U" Quartzites. The "HU" sequence is overlain by 10 to 15 m of graded quartz wacke beds and then by the "U" Quartzites which are generally regarded as the base of the Middle Aldridge Formation. They consist of alternating beds of quartz wacke and laminated mudstone. No economic concentrations of lead or zinc sulphides are known above the base of the "U" Quartzites.

Post-Ore Breccia

Two types of post-ore breccia have been recognized in the western part of the orebody. In the southwest (Fig. 8), a breccia crosscuts the orebody and hangingwall rocks up to the stratigraphic position of the hangingwall conglomerate. Breccia also occurs in albite-chlorite-pyrite-carbonate altered rock in the hangingwall. The southwest breccia is a discordant breccia body in footwall and ore zone rocks and expands to form a concordant lens at the base of the "H" marker in the hangingwall. The discordant part is 12 m wide and at least 250 m long with a northerly trend; the breccia extends downward for at least 45 m from the "H" marker with the base unexposed. The overlying concordant lens is about 5 m thick with dimensions of 120 by 250 m.

The breccia consists of angular to rounded fragments of mudstone, chloritic mudstone and tourmalinite in an altered matrix composed of chlorite, biotite, carbonate, quartz and pyrrhotite comprising as much as 60% of the rock. Locally, galena and sphalerite become significant components of the breccia matrix. In the overlying lens, mudstone clasts predominate but tourmalinite clasts and occasional clasts with some pyrrhotite, sphalerite or galena also occur. Breccia associated with albite-chlorite-pyrite-carbonate altered rocks in the hangingwall occurs over the west-central part of the orebody and is clearly associated with alteration and post-alteration deformation.

Ore Mineralogy and Petrography

Mineralogy of the orebody is relatively simple. Pyrrhotite and pyrite with a ratio of about 7 to 3 are the most abundant sulphides and galena and sphalerite are the principal ore minerals. Minor but economically important minerals include tetrahedrite, pyrargyrite, boulangerite and arsenopyrite (deleterious). Cassiterite is an important minor constituent in the western part of the orebody. Minerals constituting less than one per cent include chalcopyrite, jamesonite, magnetite, and less abundant scheelite and stannite. Principal non-sulphide minerals are quartz and calcite with abundant tourmaline, chlorite, muscovite, albite, pale brown to reddish-brown mica, garnet, tremolite, epidote and hornblende. Either quartz or calcite may make up 50 to 70% of the non-sulphide suite, chlorite 30% and the other minerals up to about 20%.

The ore has a metamorphic texture. Massive pyrrhotite in the western part of the orebody is composed of a polygonal mosaic of pyrrhotite grains with sphalerite and chalcopyrite concentrated at triple point junctions. In layered ore, pyrrhotite grains are euhedral to irregular-shaped and surrounded by a network of galena and sphalerite. Boulangerite, tetrahedrite and pyrargyrite occur at interstices between sphalerite and galena grains and rare stannite occurs as euhedra at grain boundaries. Pyrite is euhedral and granular and usually forms fine- to coarsely crystalline layers that are roughly conformable to the sulphide footwall.

Textures of the distinctly bedded ore in the eastern part of the orebody are dominated by the shape of the metamorphic non-sulphide minerals. In silicate-rich layers pyrrhotite has a tabular habit and the grains are commonly oriented in a reticulate pattern with plates of mica. Occasionally, fine granular intergrowths of elongated grains impart a crude foliation parallel to the bedding. Galena and sphalerite occur interstitial to pyrrhotite or as nearly mono-mineralic granular layers. Individual layers within a laminated sequence are sharply defined and differ strikingly in composition and mineralogy from one to another (Figs. 18, 30, 31). This strong mineralogical differentiation sharply defines laterally persistent bedding; changes along the plane of bedding are gradational. The most striking lateral change is the gradual increase of granular pyrite laminae and buckshot pyrite toward the southeastern perimeter of the orebody. Outward from the centre of the orebody pyrite laminae appear first in the upper ore layers delicately interlayered with pyrrhotite and ore minerals. The amount of pyrite gradually increases to the southeast, and at the economic margin of the orebody, Bands "A" through "D" are predominantly pyrite, the layered part of the Main Band is composed of nearly equal amounts of delicately laminated pyrrhotite, pyrite and magnetite and the basal part of the Main Band is predominantly pyrrhotite. Pyrite also occurs locally as coarse megacrysts and as spongy aggregates of euhedra adjacent to the Kimberley and Sullivan faults. Spongy pyrite occurs in layers normally occupied by pyrrhotite and along closely spaced fractures at various angles to bedding.

Overall grain size of sulphide and gangue ranges from about 0.005 mm to rarely as much as one centimetre. Average grain size is about 0.05 to 0.1 mm.

Distribution of Metals in the Orebody

Distribution of valuable metals in the orebody has been described by several authors starting with Pentland (1943) who described a zonal distribution of lead, zinc and tin. Swanson and Gunning (1945) suggested that the lead and zinc distribution might be controlled by merging linear patterns. Freeze (1966) presented generalized plans showing the distribution of lead, zinc, tin, antimony and arsenic. Freeze also described a general tendency for the metals, particularly lead, zinc and silver, to be zoned across the bedding as well as in the plane of bedding. Ransom (1977) presented detailed distribution maps for lead, zinc, silver and tin.

The term "central iron zone" used by previous authors in discussions of metal distribution can be misleading. It has been applied to the rectangular area lying south of the centre of the western part of the orebody (Fig. 22). Iron sulphide content in this zone is no greater than that in adjacent areas of the orebody; rather, lead and zinc sulphide contents are much less. The "central iron zone" is principally composed of pyrite, chlorite and carbonate and is a zone of alteration superimposed on the original patterns of metal distribution.

Of the important metals in the orebody only iron has a simple and uniform plan distribution. The iron distribution map (Fig. 22) was constructed using assay data from numerous closely spaced core holes. Data at each point is the product of the true thickness of the orebody at that point multiplied by the average content of iron in per cent across the intersection. The result is reported in feet-per cent as shown on the figure. The distribution pattern for iron generally reflects the thickness of the

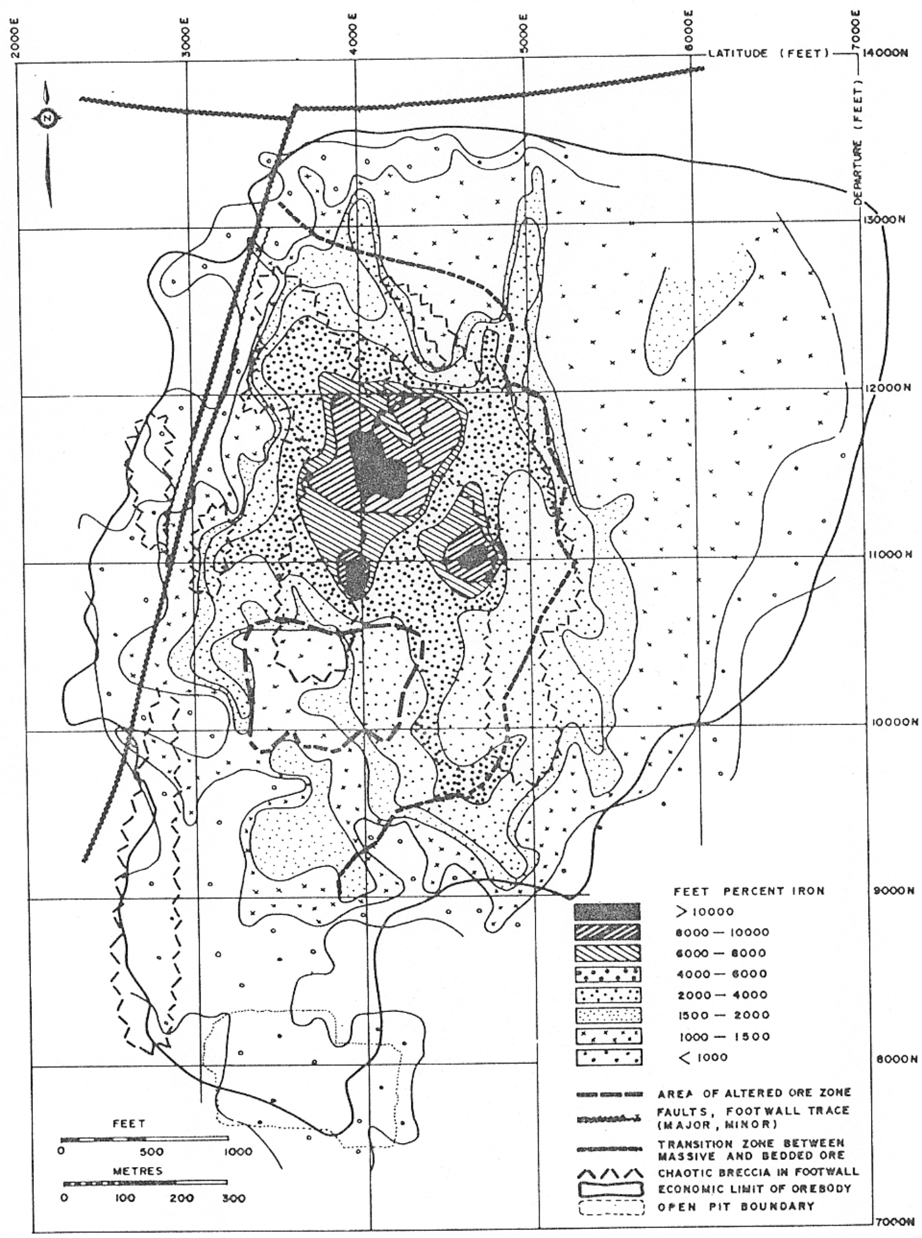

Figure 22. Distribution of iron in the Sullivan orebody.

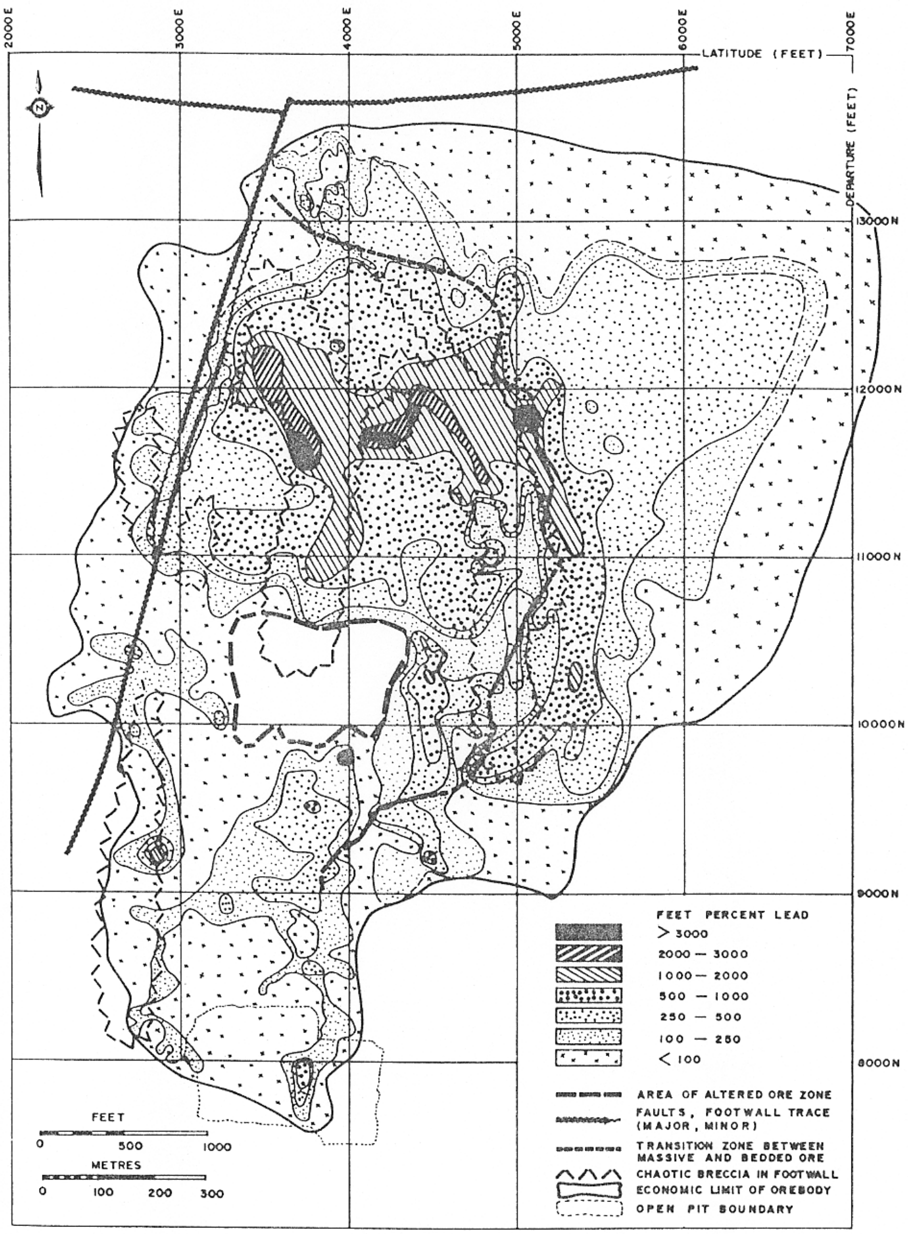

Figure 23. Distribution of lead in the Sullivan orebody.

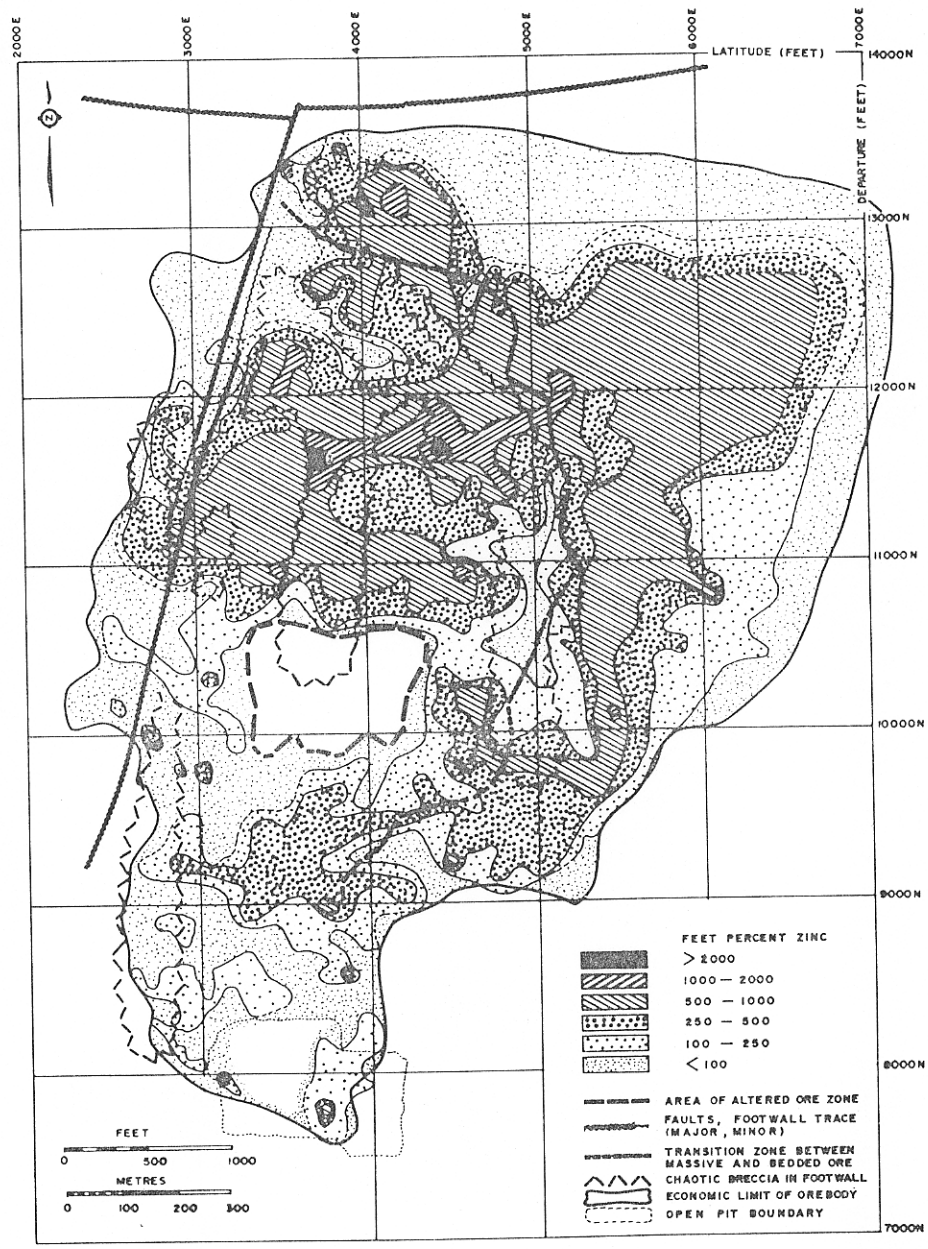

Figure 24. Distribution of zinc in the Sullivan orebody.

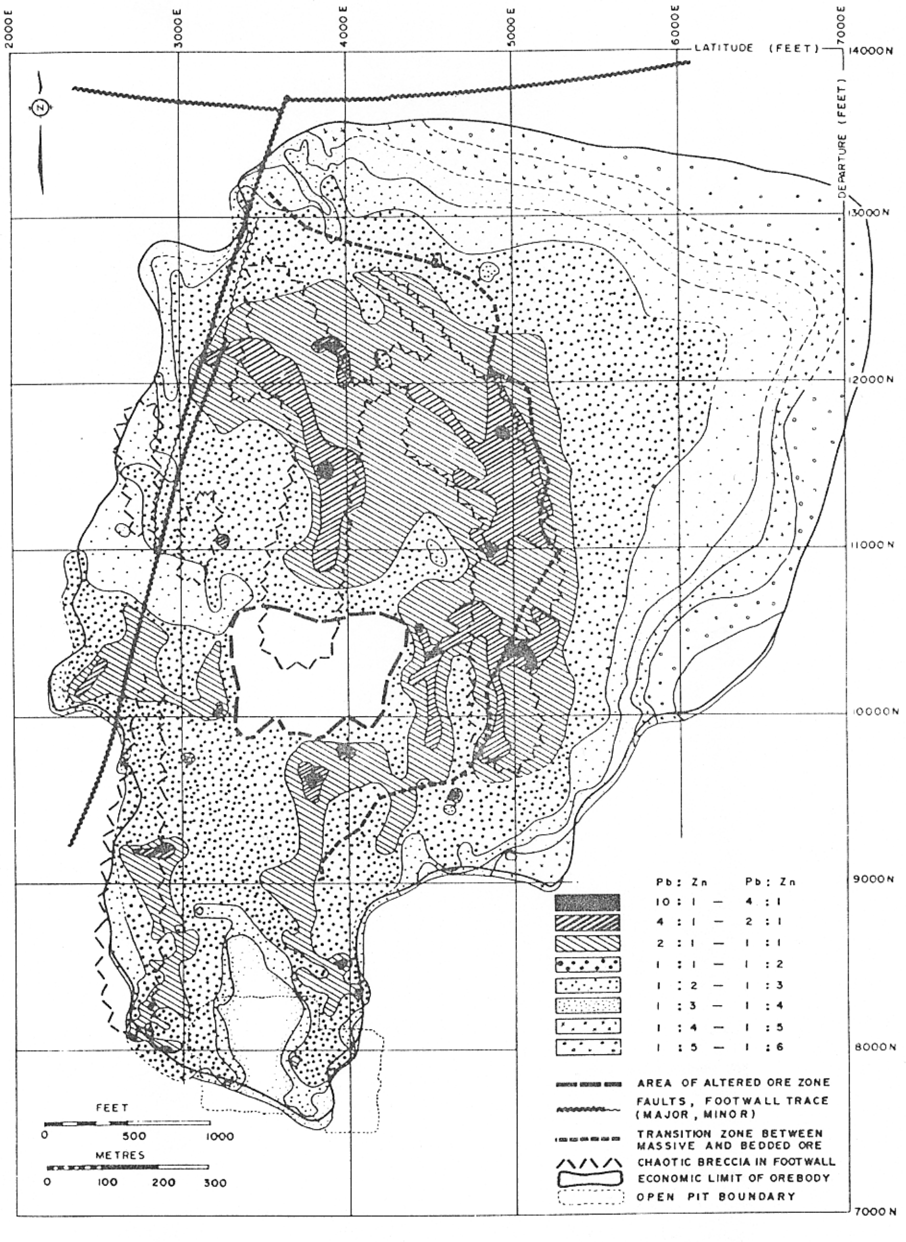

Figure 25. Lead to zinc ratio in the Sullivan orebody.

orebody as shown on the isopach map (Fig. 13). This suggests that the principal controls of iron sulphide distribution are the gross geometry of the sub-basin and a nearly constant supply of iron.

Metal distribution maps for lead and zinc (Figs. 23 and 24) are prepared in a manner similar to that for iron. At the periphery of the orebody both lead and zinc have patterns similar to that of iron. The patterns for lead and zinc are notably different from the iron pattern in areas of the orebody underlain by the chaotic breccia. Areas enclosed by the 1000 feet-per cent lead isopleth are generally coincident with distribution of chaotic breccia. The lead to zinc ratio map (Fig. 25) shows the coincidence, particularly the lead to zinc ratio greater than 2:1, of lead and zinc distribution with the underlying chaotic breccia. Zoning in the eastern part of the orebody is concentric with a gradually decreasing lead to zinc ratio toward the periphery, although the isopleth lines intersect the line denoting the economic limit of the orebody.

Silver distribution in the orebody has a pattern similar to the pattern of lead distribution. High values (Fig. 26) are approximately coincident with the plan distribution of chaotic breccia in the footwall. Silver occurs with galena, probably in solid solution with bismuth and lead. Other principal silver-bearing minerals are tetrahedrite and pyrargyrite.

Tin is concentrated in the western part of the orebody and highest values occur in areas underlain by the chaotic breccia (Fig. 27). The average tin grade in mill feed is 0.031%; tin grades as high as 2.5% occur in the tin zone fracture (Fig. 7) described by Freeze (1966). The principal tin mineral is cassiterite; stannite is rare.

Vertical distribution of metals has been well documented in the eastern part of the orebody where stratigraphic control is well established. Owing to poor stratigraphic control in the western part, details of vertical metal distribution are outlined in a block by block manner as mining progresses. For the west and central part of the orebody Freeze (1966, p. 275) stated:

> ". . . there is a distinct tendency for these metals (lead, zinc and silver), to be zoned in a vertical sense, particularly in the centre of the mine. This relation arises because galena and sphalerite tend to form extensive layers of rich beautifully banded ore against the hangingwall of the main ore bands. This well banded ore passes downward into a rich, massive mixture of pyrrhotite, galena and sphalerite that in turn passes into a thick irregular zone of pyrrhotite that carries only a trace of galena and sphalerite. Generally, this barren, pyrrhotite zone extends to the sulphide footwall."

Carswell (1961), using assay data from widely distributed core holes in the eastern part of the orebody, documented a decrease of Pb/Pb+Zn ratio from the Main Band through "D" Band and a fairly uniform distribution of iron in the same sequence. Carswell did not consider possible effects of lateral zoning in the plane of the layering in his study of vertical distribution.

To minimize effects of lateral zoning, vertical zoning has been studied within a very narrow zone about the coincident 0.9 lead to zinc ratio isopleth for each Band in the eastern part of the orebody. Geometric means for each of lead, zinc, silver and iron in the five Bands are plotted in Figure 28. Raw data for the documentation are unweighted assay values for lead, zinc, silver, and iron. Metal distribution in the

Main Band is characterized by a uniform increase of lead from base to top, moderate enrichment of silver in central Main Band and enrichment, then depletion of zinc in central Main Band to top Main Band. Iron maintains a remarkably uniform abundance through the Main Band and the overlying "A" through "D" Bands except for effects of dilution by waste beds in the "B" Band triplet. Silver and lead abundance decrease at a uniform rate from "A" Band through "D" Band. Zinc abundance also decreases in a uniform way from "A" Band through "D" Band; however, the rate of change is less than that for lead and silver. The increase in rate of change for lead and zinc abundance from "C" Band to "D" Band may be partly influenced by the lateral metal zoning differences for the "D" Band.

Wall-Rock Alteration

Extensive volumes of altered rock occur below, within and above the ore zone in the western part of the mine. Tourmalinite is included with wall-rock alteration because most of the tourmalinite, except for that near the sulphide footwall, has crosscutting relations. Altered rocks unusually rich in chlorite, albite, pyrite, biotite, garnet and calcite occur in restricted crosscutting footwall structures, in a zone which crosscuts the orebody, and also occupy an extensive volume of rock in the hangingwall. Although minerals in altered rock have a metamorphic texture, their occurrence is interpreted as reflecting pre-metamorphic chemical modifications.

Tourmalinite. The western part of the orebody is underlain by an extensive zone of tourmalinite: a very dark grey to black or brown, extremely hard rock composed almost entirely of tourmaline and quartz. Its distribution in the footwall is outlined in plan (Fig. 29) and in section (Figs. 5 and 6). The western limit of tourmalinite is the contact zone of the gabbro intrusion, and elsewhere the limit is approximately coincident with the transition between massive and bedded parts of the orebody (Fig. 29). Tourmalinite and tourmalinite interbedded with tourmaline-free metasedimentary rock occur throughout the 450 m sequence between the sulphide footwall and footwall gabbro. In the hangingwall, tourmalinite, although subordinate, is best developed above the eastern limit of footwall tourmalinite and is particularly common in hangingwall rocks above the 4800 departure (Alpha and Beta fault trend) zone of thinning (Figs. 5 and 7). Disseminated tourmaline and rare patches of tourmalinite are erratically distributed elsewhere in the hangingwall overlying the western part of the orebody.

Tourmalinite is rare in the ore zone and interbedded waste rock. It occurs in the ore zone usually as tectonically rafted, irregular blocks. More common in the ore zone, are disseminated (trace to 2%), pale, euhedral tourmaline grains. Euhedral poikilitic grains occur in clastic rocks interbedded with the ore.

On a large scale (footwall gabbro to sulphide footwall), tourmalinite has crosscutting relations. However, with proximity to the sulphide footwall a remarkable variety of geometric relations occur. Near the sulphide footwall, and over distances of a metre to hundreds of metres in the plane of bedding, contacts between tourmalinite and other rock types range from perfectly conformable to steeply transgressive relative to bedding. Transgressive and conformable contacts are generally sharp, occurring over distances of a few millimetres to a few centimetres. Disconformable contacts range from regular to highly irregular. Locally, bedding may be

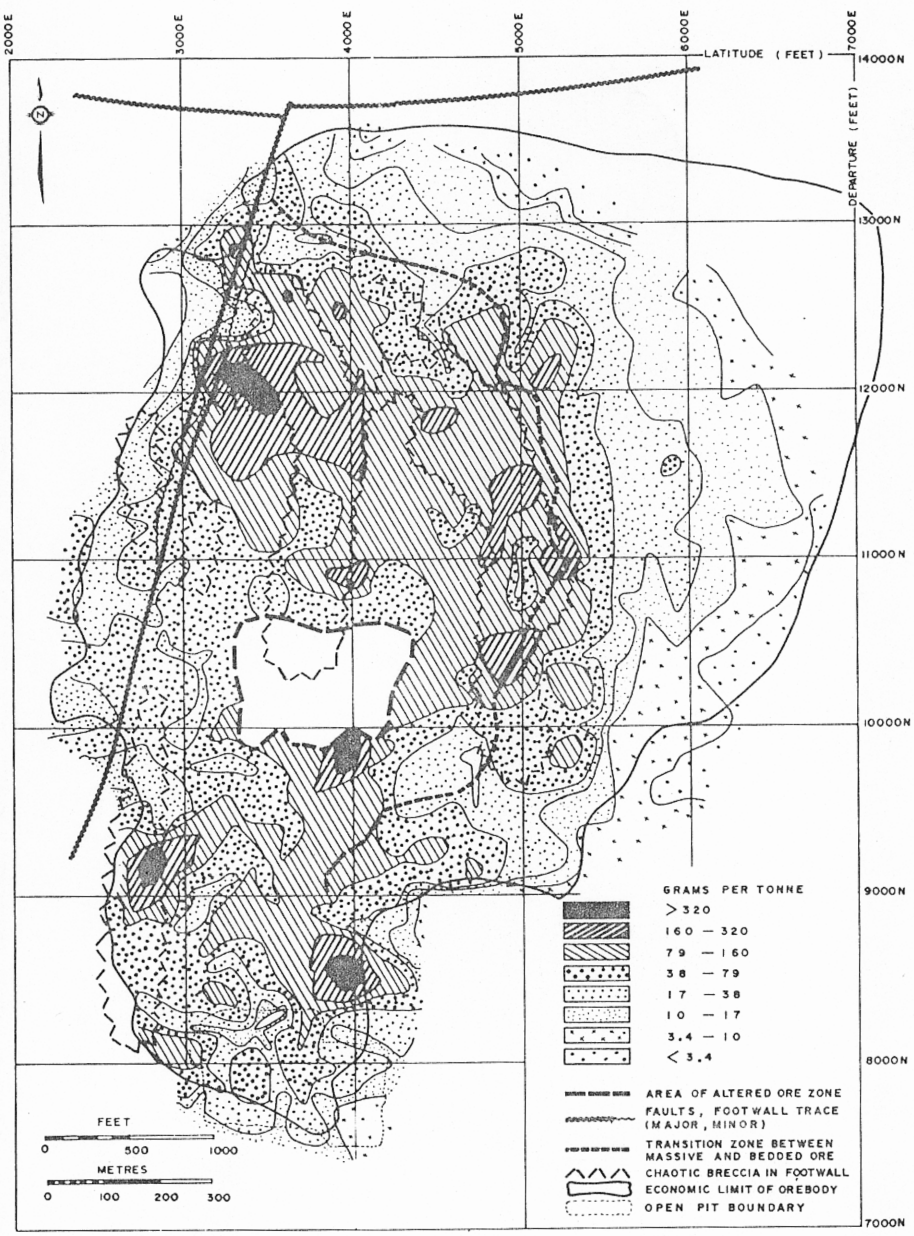

Figure 26. Distribution of silver in the Sullivan orebody.

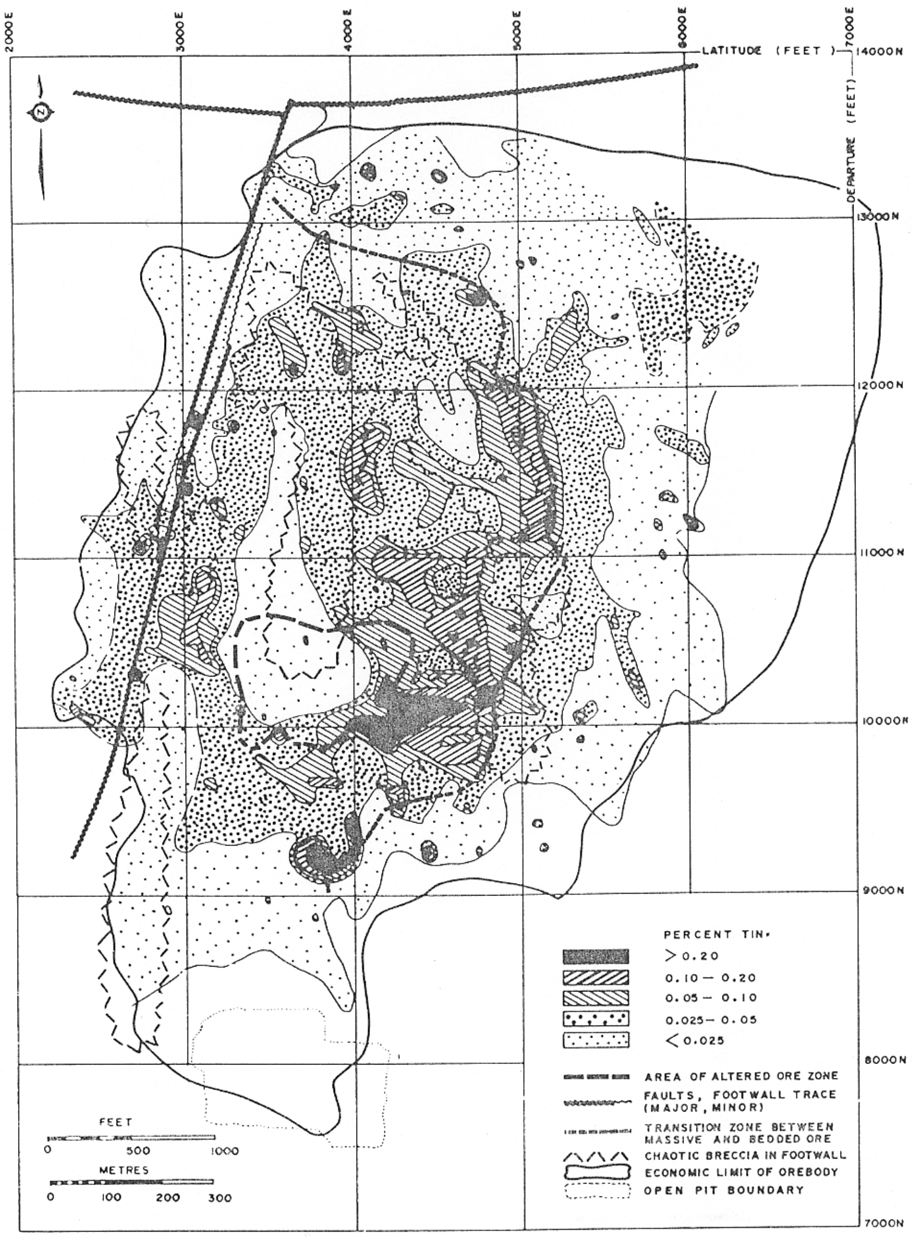

Figure 27. Distribution of tin in the Sullivan orebody.

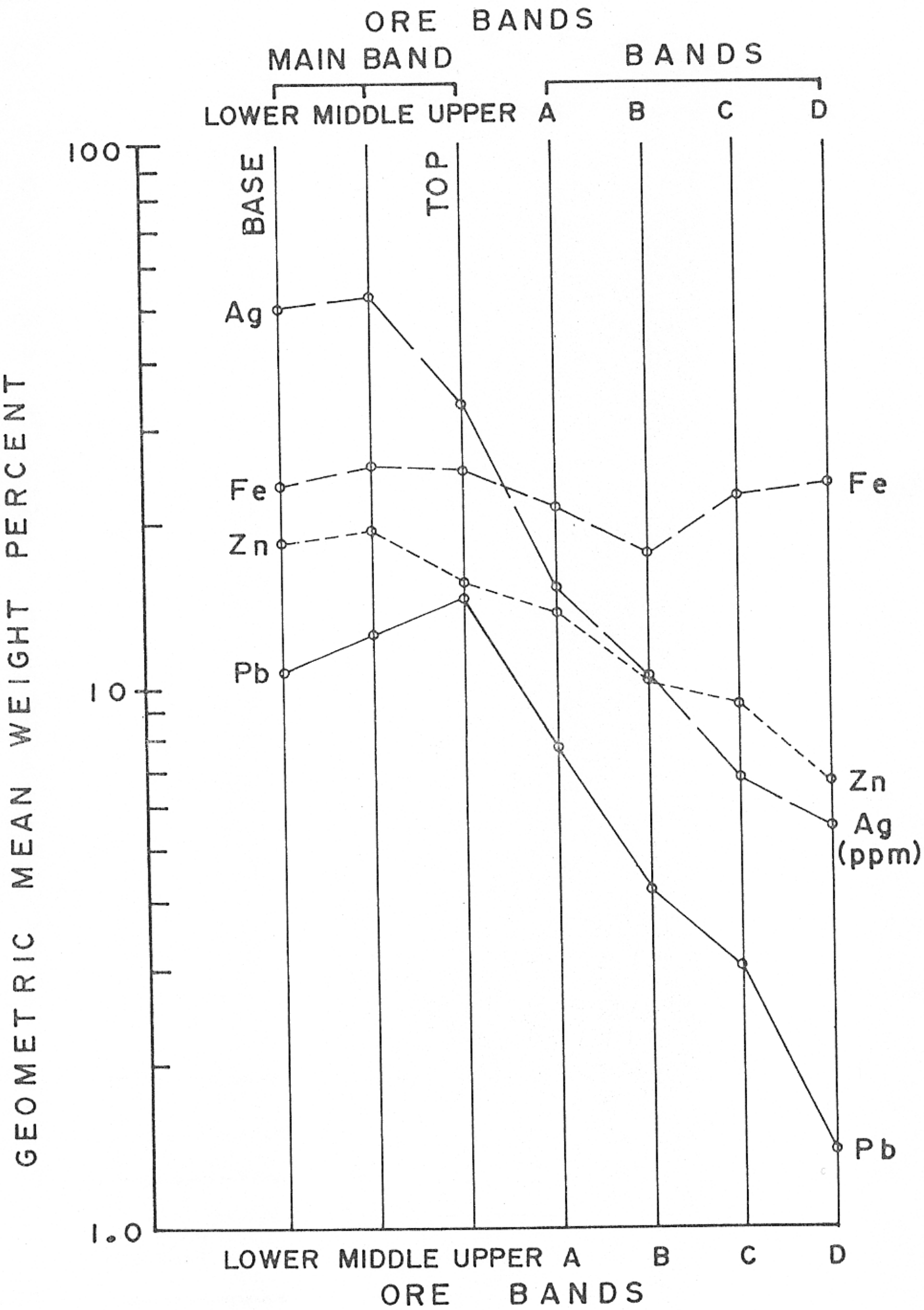

Figure 28. Vertical distribution of metals in the bedded eastern part of the Sullivan orebody.

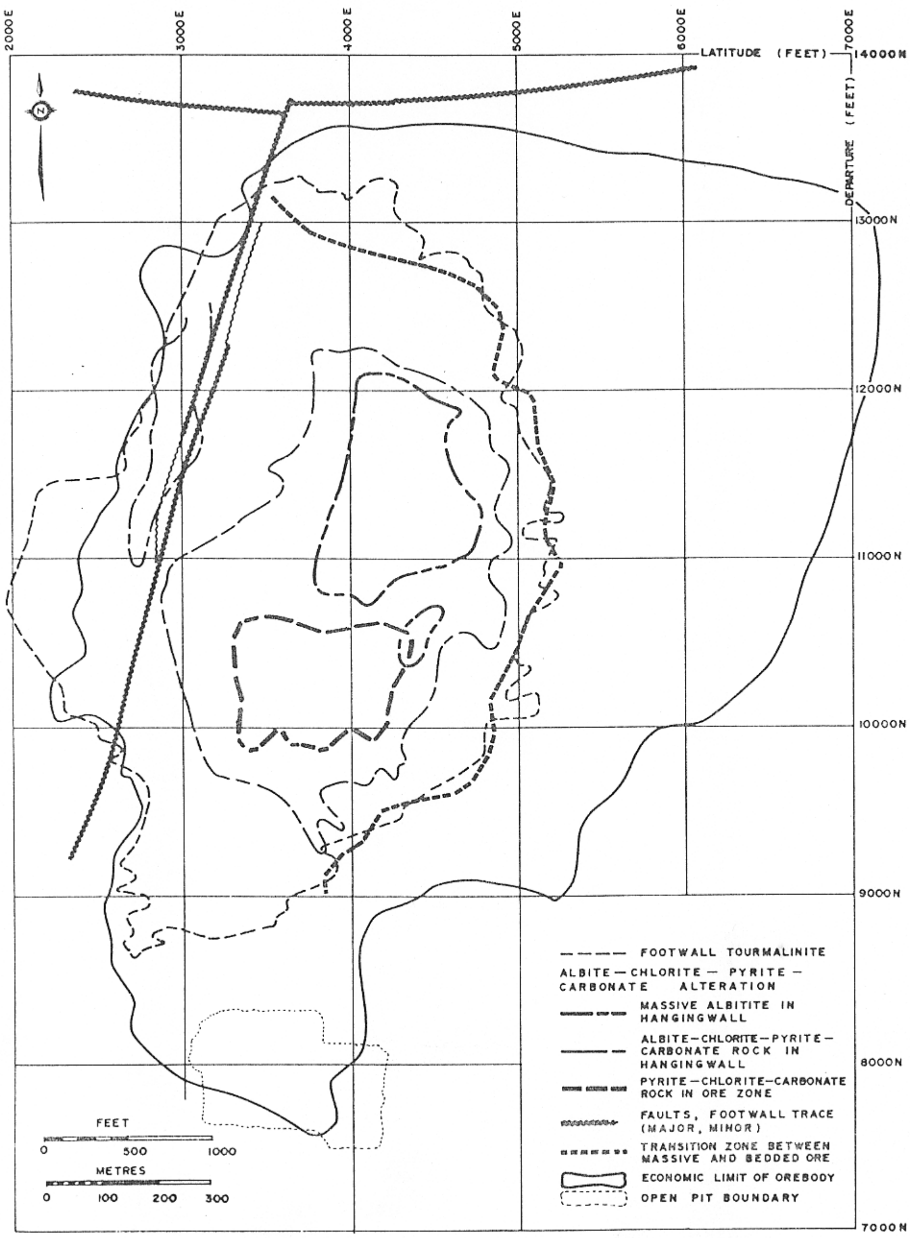

Figure 29. Distribution of altered rocks in and adjacent to the Sullivan orebody.

traced across disconformable contacts between tourmaline-rich and tourmaline-poor rocks. Small-scale, crosscutting tourmaline-bearing structures such as tourmalinite veins or tourmalinite alteration envelopes are unknown in the footwall sedimentary rocks (Shaw, in prep.).

Tourmalinite beds 3 to 15 m thick occur in which bedding is defined by faint pyrrhotite laminations. Thicker sequences of tourmalinite with very well developed bedding and remarkable preservation of primary sedimentary structures are also common. Delicate laminations and soft-sediment deformation structures are frequently more distinct in tourmalinite than in tourmaline-poor rock. Less common are centimetre-scale interbeds of tourmalinite and tourmaline-poor rock recognized at the southern limit of the tourmalinite zone. Close to the sulphide footwall, tourmaline is pervasive throughout entire beds whereas in the deep footwall, tourmaline is most abundant at the coarse base of graded beds and in thin-bedded zones.

In tourmalinite, tourmaline occupies interstices between quartz grains. Figures 42 and 43 illustrate some of the textural variations observed. Typically, quartz grains with indistinct boundaries are set in a very fine-grained felted matrix of acicular to stubby tourmaline grains forming 50% to more than 75% of the rock. The tourmaline grains are micro-crystalline, ranging in length from about 1 to 10 microns. Irregular and disseminated blebs and delicate laminae of pyrrhotite are common. Minor minerals include muscovite, chlorite, potassium feldspar, plagioclase and garnet in descending order of abundance. Pyrrhotite and sphalerite constitute up to 10 to 15% and occur as disseminated grains or blebs, or concentrated in delicate laminae.

Of particular interest is the tourmalinite phase of footwall conglomerate. Tourmalinite clasts in a tourmalinite matrix is by far the most common mode of occurrence. However, tourmaline-poor clasts are also found associated with clasts of tourmalinite in tourmalinite matrix. In thin section, tourmaline-poor clasts contain a very small percentage of micaceous material and are composed of quartz and subordinate feldspar grains and sparse intergranular tourmaline needles. In conglomerate beneath the eastern part of the orebody, occasional, rounded to flat ovoid clasts of tourmalinite are found in association with the tourmaline-free clasts in a tourmaline-free matrix. Here tourmalinite clasts are frequently indented or partly wrap or drape around adjacent tourmaline-free clasts. This relation suggests that tourmalinite clasts were at least semiplastic at the time of deposition. In contact zones of the gabbro intrusions, boron has been removed from tourmalinite and the rock recrystallized to hornfels with only scattered crystals of tourmaline. The tourmaline is coarsely-crystalline and forms blue-green needles, tiny rosettes and veins.

Albite-Chlorite-Pyrite-Carbonate Alteration. Altered rocks rich in albite, chlorite, pyrite or carbonate are restricted to the western part of the mine and in plan lie generally within limits defined by the zone of tourmalinite in the footwall (Fig. 29). Albite-chlorite-pyrite-carbonate alteration occurs in crosscutting zones within the footwall tourmalinite. These zones range from one centimetre to as much as 30 m wide. Overlying the crosscutting alteration in the footwall, the ore zone has been altered to a pyrite-chlorite-carbonate assemblage. Pervasive alteration in the hangingwall has resulted in a zone of albite, chlorite and pyrite as much as 100 m thick.

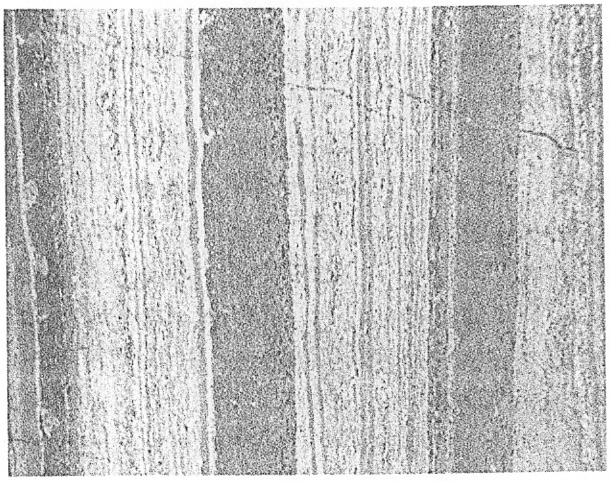

Figure 30. Delicate layering of fine-grained, laminated sulphide rock of the "A" Band. Medium brown colour metallic mineral is pyrrhotite; metallic grey mineral is galena; dark brown layers are composed of clastic sedimentary rock with disseminated sphalerite. Sample is 3.5 cm from base to top with top at left.

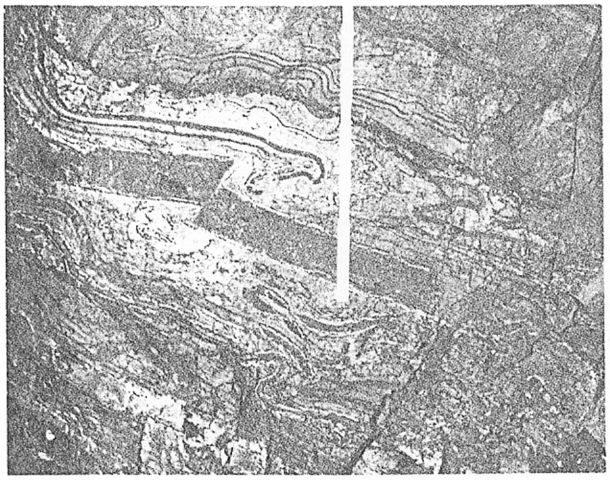

Figure 31. Tectonic deformation near the top of the Main Band. Mudstone interbeds fracture in a brittle fashion but sulphide beds are ductile. The white ruler is 46 cm long, 1.5 cm wide. Top of section is up.

Figure 32. Galena layers in pyrrhotite, typical of ore in the western part of the orebody. This is the base of the main band of the orebody, at the transition zone, and the location of the specimen shown in Fig. 14. The head of the hammer is at the footwall contact.

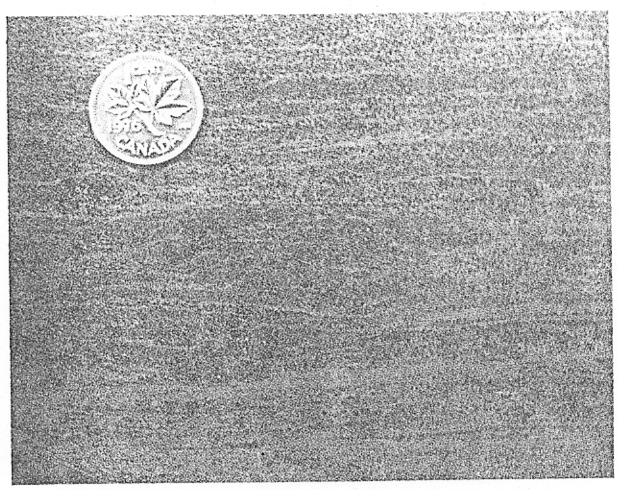

Figure 33. Irregular layering of pyrrhotite and sphalerite typical of the western part of the orebody. Dark brown lenticular bodies are composed of altered sedimentary rock. Top of sequence is up. Coin is 1.9 cm in diameter.

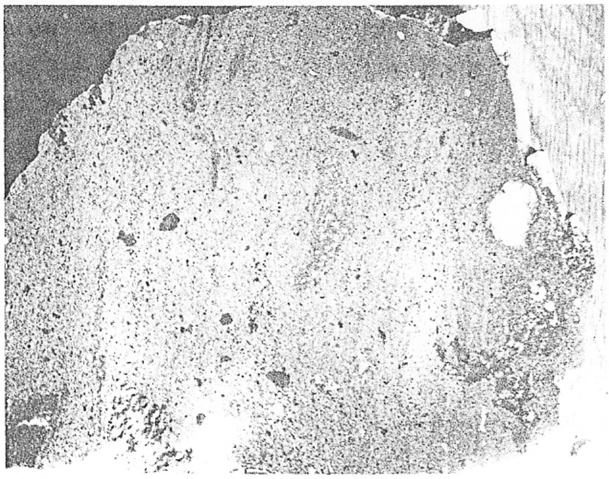

Figure 34. Sulphide rock, south end of the orebody from the basal one-third of the Main Band. The largest fragment (centre) is medium-grained sphalerite and about 5 cm long. Dark fragment at the lower left is altered argillite. White fragments on the right are quartz and light-coloured equant grains are pyrite. Stratigraphic top not known.

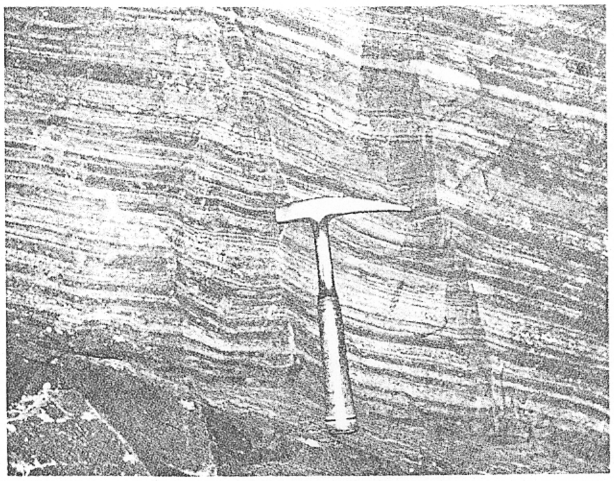

Figure 35. Slightly deformed parallel and planar layering of the "A" Band in the southeastern part of the orebody. Grey layers are pyrrhotite and brassy layers are pyrite-rich. The handle of the hammer is at the base of the "A" Band.

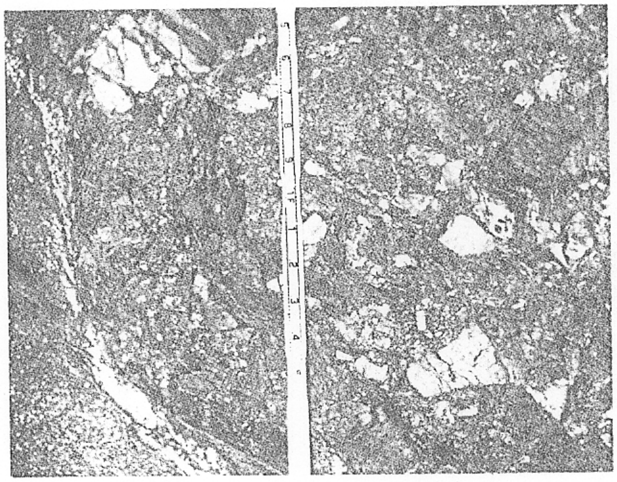

Figure 36. Chlorite-albite breccia overlying coarsely crystalline pyrite in the hangingwall of pyrite-chlorite-carbonate altered ore in the western part of the orebody. Rule divided in tenths of a foot.

Figure 37. Albite-chlorite breccia from hangingwall in western part of the orebody. Original orientation unknown.

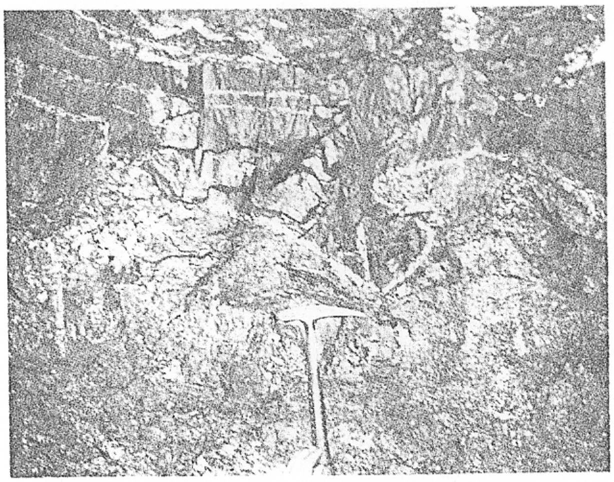

Figure 38. Alteration contact: faintly-layered pyrrhotite (above) altered to coarsely crystalline pyrite adjacent to the pyrite-chlorite-carbonate altered zone in the western part of the orebody. Layering in pyrrhotite is defined by galena concentrations (chalked) and layering is truncated by pyrite. Top of section is up.

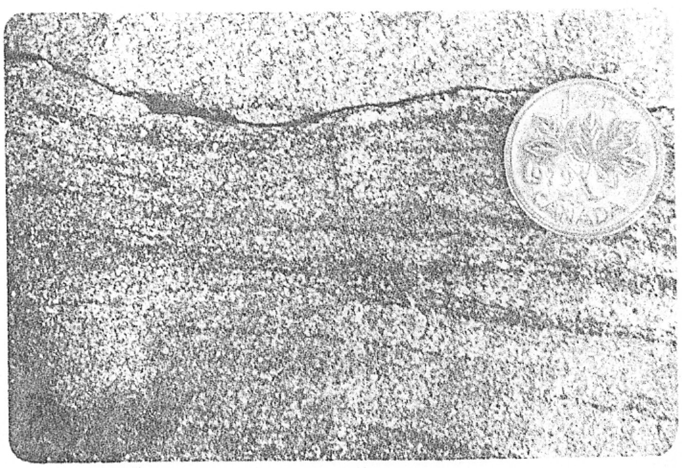

Figure 39. Layering, defined by sphalerite concentration, in coarsely crystalline pyrite-carbonate rock from discordant contact zone between faintly layered pyrrhotite and pyrite as shown in Figure 38. Layering often continues across the contact for short distances. Top unknown.

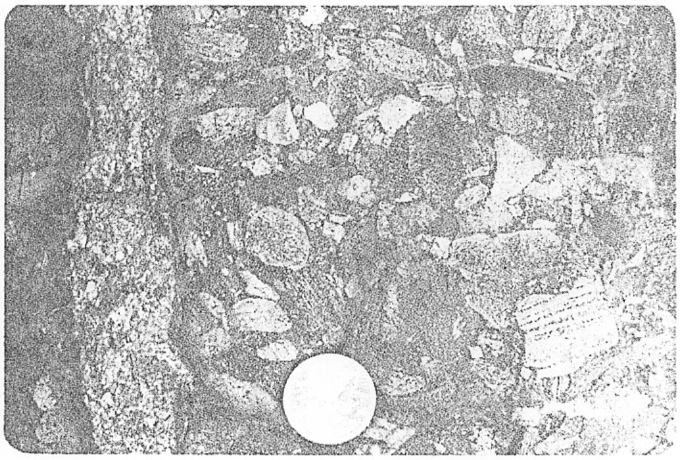

Figure 40. Pyrrhotite-rich clasts in tourmalinite matrix from footwall of the western part of the orebody. Planar quartz-pyrrhotite vein at left of photograph. Top unknown.

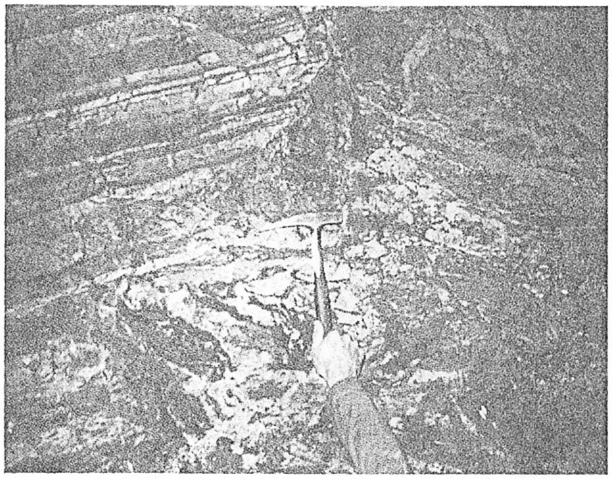

Figure 41. Disrupted bedding at the margin of a chaotic breccia zone beneath the western part of the orebody. Light rusty zones are tourmalinite and dark rusty zones are pyrrhotite-rich.

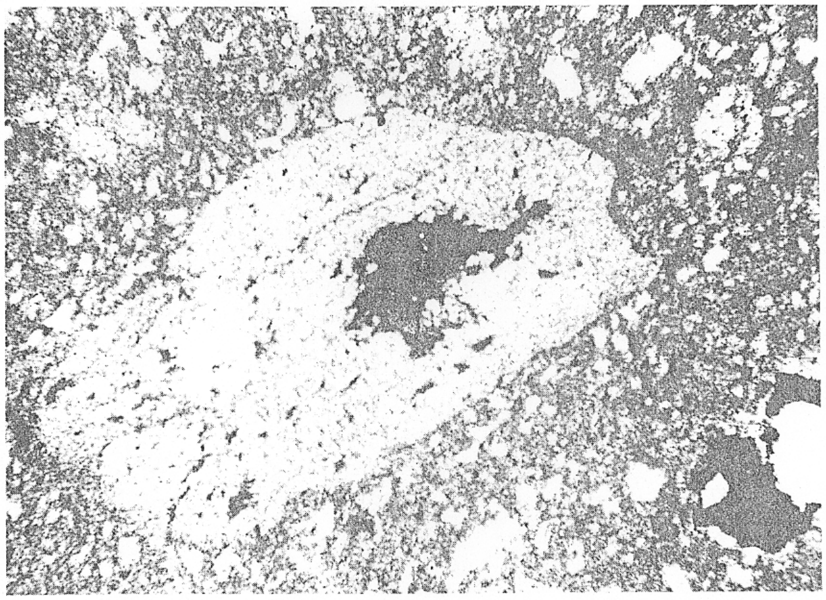

Figure 42. Felted tourmaline (dark grey) matrix of tourmalinite conglomerate. White grains are quartz and black grains, pyrrhotite. The large grey clast with the pyrrhotite centre contains less tourmaline than the ground mass. Plane polarized light. Field is 1.1 mm long.

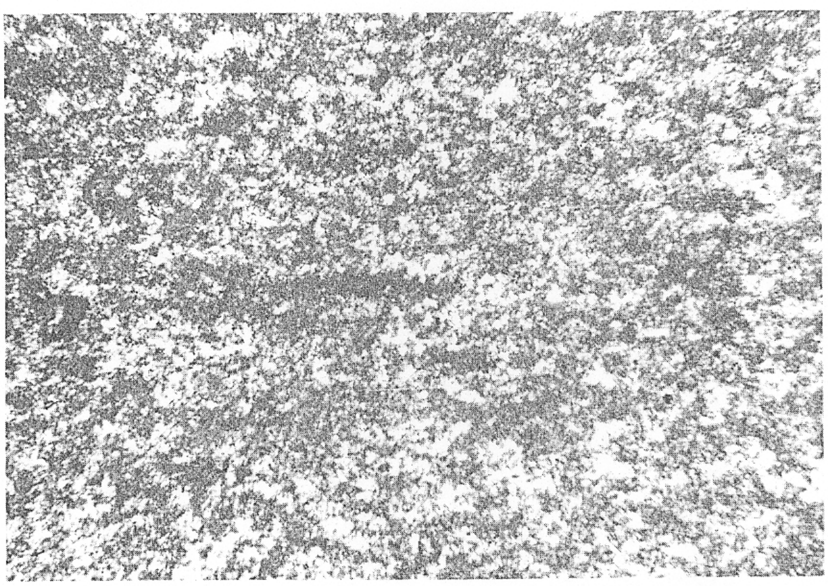

Figure 43. Faintly-layered tourmalinite from zone of interbedded tourmalinite and mudstone. Light coloured grains are quartz and feldspar. Plane polarized light. Field is 0.15 mm long.

Figure 44. Granoblastic texture of fine-grained albitite from core of albite-chlorite-pyrite alteration zone in hangingwall above western part of orebody. Crossed nicols. Field is 0.6 mm long.

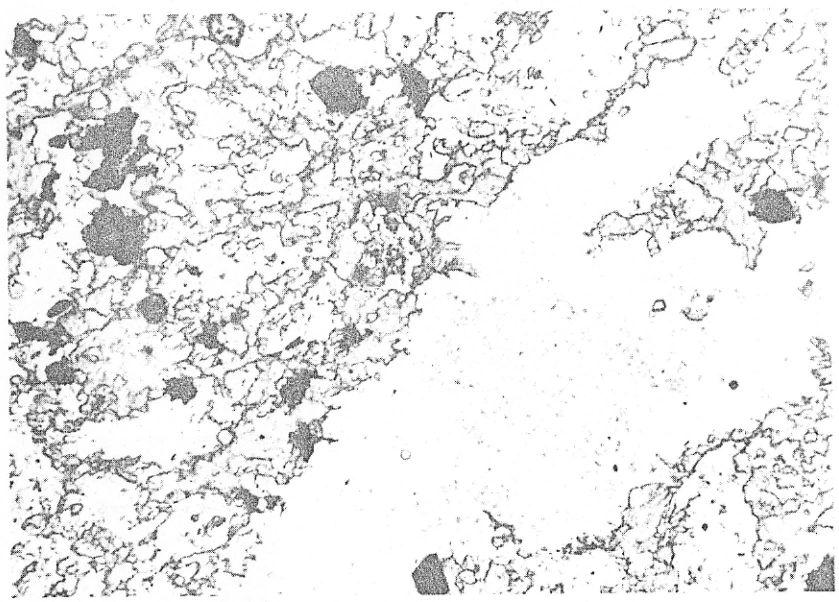

Figure 45. Albite-chlorite-pyrite altered rock from immediate hangingwall of western part of orebody. Vein is composed of coarsely crystalline albite dusted with minute tourmaline grains. Black grains are pyrite. Plane polarized light. Field is 0.6 mm long.

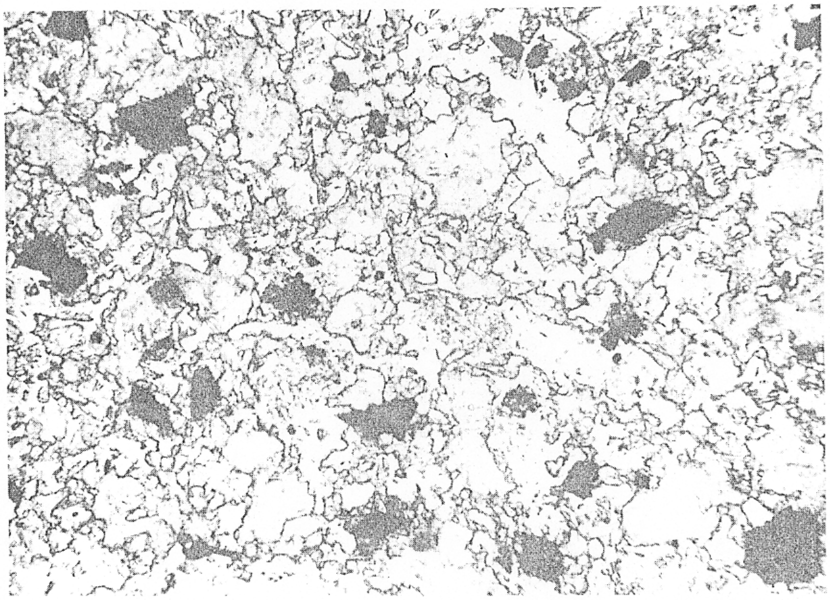

Figure 46. Chlorite-albite-pyrite rock from margin of albite core in hangingwall of western part of orebody. Chlorite, albite and pyrite are medium, light and dark grey, respectively. Plane polarized light. Field is 0.6 mm long.

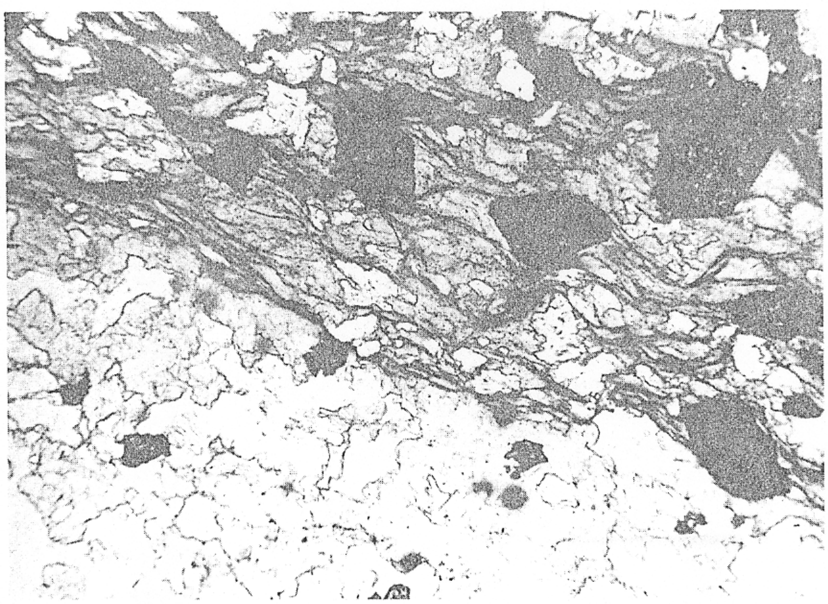

Figure 47. Phyllonitic chlorite from deformed zone in albite-chlorite rock. High relief mineral is sphene. Plane polarized light. Field is 0.6 mm long.

Isolated, crosscutting albite-chlorite-pyrite-carbonate alteration zones in the footwall expand upward to a stratabound zone at the sulphide footwall (Fig. 5). Within this interval, albitite occurs as veins and large masses in chlorite-pyrite rock and in zones of breccia composed of intimately mixed albitite and chloritic rock. Mineral zoning on all scales is conspicuous in non-brecciated parts of the alteration zones. Within a typical alteration zone cutting tourmalinite, a central core of albitite-pyrite grades outward to a peripheral zone of chlorite-pyrite. Adjacent to the alteration zone pyrrhotite in otherwise unaltered tourmalinite has been altered to pyrite. Fresh tourmalinite adjacent to an alteration zone is a dark grey to black lustrous rock. Within the alteration zone, the rock is dull, soft and chloritic.

Distribution of alteration in the orebody overlying the zone of crosscutting albite-chlorite-pyrite-carbonate in the footwall is outlined by the boundary of the pyrite-chlorite-carbonate zone (Fig. 29). This boundary is defined by the limit of ore, not by the limit of alteration pyrite. Idealized cross-sections through the pyrite-chlorite-carbonate alteration zone in the ore are shown in Figures 5 and 6.

Pyrite-chlorite-carbonate alteration of normal pyrrhotite-rich lead and zinc ore commonly crosscuts and obliterates primary textures and structures in the orebody, such that only large-scale layering of interbedded coarsely crystalline pyrite and massive chloritic rock remains. Choritic alteration of sedimentary rock appears to extend beyond the limit of pyrite and the contact between chloritic and unaltered rock is gradational over several metres. In massive sulphide ore, contact between the pyrite alteration assemblage and unaltered pyrrhotite-rich ore is sharp and highly irregular (Fig. 38). Contacts vary from conformable to sharply transgressive to bedding. Bedding defined by concentrations of galena and sphalerite in pyrrhotite is abruptly truncated at the contact. Locally, the bedding persists a short distance into the pyrite (Fig. 39).

Immediately overlying the pyrite-chlorite-carbonate zone in the orebody and extending outward from it in the hangingwall, brecciated albite-chlorite rock and bedded, massive or brecciated chloritic rock (Figs. 36, 37) ranging from a few centimetres to as much as 30 m thick overlie the sulphide hangingwall. Overlying these rocks is massive albitite with subordinate chloritic rock in which original sedimentary structures and textures have been obliterated. Massive albitite forms a core that grades outward to an envelope of albitic and chloritic rock in which the original gross sedimentary layering is preserved. Quartz, albite and carbonate veins are common in the albitic and chloritic rock and extend a short distance into overlying sedimentary rocks. Preliminary petrographic study indicates that a potassium mica envelope surrounds lateral margins of the albitic and chloritic rock.

Texture of chloritic rock within the ore zone and of massive chloritic rock immediately above the sulphide hangingwall (lower part of the chloritic envelope) is phyllonitic with porphyroblastic bundles of coarse plates of chlorite and euhedral pyrite and sphene, all set in a very fine-grained matrix of oriented fibrous chlorite. Figures 44 to 47 illustrate some of the textural variations observed in thin section.

Texture of massive albitite overlying chloritic rock above the sulphide hangingwall is granoblastic. Albite grains are anhedral to subhedral and grain boundaries are regular or sutured. Chlorite occurs as intergranular bundles of radiating plates and as large patches of decussate plates. Distribution of chlorite and annealed stringers with a mortar texture define recrystallized crushed zones in albitite. Euhedral and crushed pyrite is locally abundant in the crushed zones. At the outer fringe of the chloritic envelope arenite beds are altered to granoblastic albite, and argillaceous beds are altered to very fine-grained schistose chlorite.

Accessory minerals in altered hangingwall rocks include tourmaline (2 to 5%), sphene (2 to 7%), subordinate white mica, zircon, scapolite, calcite and quartz. Tourmaline occurs near the base of massive albitite as clusters of tiny, pale brown to amber, stubby crystals in cores of early, large, albite crystals. There is no tourmaline in surrounding annealed crushed zones. Sphene occurs as euhedral grains or as broken and altered fragments of euhedral crystals and is most abundant adjacent to or within chlorite-rich patches. Zircon grains are commonly well rounded and appear to retain a detrital morphology.

ROCK CHEMISTRY

The alteration processes that affected the Sullivan host rock and ore have resulted in profound chemical modifications of the original rock compositions. No attempt is made to reconstruct possible chemical reactions because mineralogy of ore, the parent rocks and altered products prior to the first regional metamorphic

TABLE I
COMPOSITION OF SULLIVAN ORE AND WASTE

	1		2		3	
	$\bar{X}$	$\hat{\sigma}$	$\bar{X}$	$\hat{\sigma}$	$\bar{X}$	$\hat{\sigma}$
SiO_2	67.9	8.4	47.34	7.29	18.13	6.29
Al_2O_3	14.3	3.9	11.02	2.60	4.58	2.08
TiO_2	0.5	0.4	0.41	0.33	0.13	0.07
FeO	5.0	1.8	18.54	6.05	25.30	6.97 as Fe
MgO	2.1	0.8	2.58	1.06	1.21	0.43
CaO	2.1	1.0	7.81	5.34	2.76	1.74
Na_2O	1.8	0.8	0.79	0.57	0.65	0.41
K_2O	3.0	1.7	1.41	0.61	0.43	0.19
CO_2	1.3	0.1	5.79	4.71	0.63	0.52
H_2O	0.6	0.1	–	–	–	–
S	0.5	0.2	–	–	22.40	3.77
Pb	0.03	0.01	–	–	7.72	8.91
Zn	0.06	0.01	–	–	11.71	6.91
MnO	0.07	0.07	2.58	1.35	0.77	0.34
TOTAL	99.26 %		98.27 %		96.42 %	
	N = 96		N = 17		N = 17	

1) Sullivan waste beds
2) Non-sulphide component of ore, calculated on a sulphide-free basis (several types of ore are included)
3) Sulphide ore, selected samples from the eastern and western parts of the orebody

TABLE II
AVERAGE* CONCENTRATIONS OF SELECTED TRACE METALS IN SULLIVAN ORE

Antimony	0.026%	Manganese	0.244%
Arsenic	0.083%	Thallium	0.00097%
Copper	0.033%	Indium	0.00146%
Bismuth	0.0036%	Cadmium	0.0142%
		Tin	0.031%

* Average values from composite samples of Sullivan mill-feed during 1958-1977 period.

TABLE III
COMPOSITION OF ALDRIDGE ROCK AND ALTERATION PRODUCTS ADJACENT TO THE SULLIVAN OREBODY

	1	2	3	4
SiO_2	71.53	69.65	30.33	59.34
Al_2O_3	12.74	12.45	15.34	18.90
TiO_2	0.55	0.50	0.67	0.91
Fe_2O_3 (total Fe)	3.52	9.22	29.29	5.42
MgO	1.62	2.49	13.95	3.18
CaO	1.66	0.40	0.60	1.06
Na_2O	2.08	0.68	0.67	7.78
K_2O	2.81	0.02	0.03	0.10
B_2O_3	0.0015	5.00	0.005	0.31
LOI*	–	–	7.75	3.32
TOTAL	96.52%	100.41%	98.64%	100.20%
	N = 94	N = 27	N = 4	N = 5

1) Average Aldridge composition
2) Average tourmalinite composition
3) Average chloritic rock composition
4) Average albite-chlorite-pyrite composition
* Loss on ignition

event are unknown. Study of petrography and chemistry of rocks and minerals in the orebody indicates that the assumption of isochemical metamorphism is valid. Therefore, broad chemical changes indicated by comparison of whole rock analyses are generally valid.

Chemistry of the Ore

Sullivan ore contains about 200 times as much lead and zinc as does interbedded waste material (Table I) and is strongly enriched in sulphur-bound iron. By calculating the composition of the non-sulphide component of the ore on a sulphide-free basis (Table I) it is possible to compare its chemistry with the average composition of interbedded waste. In comparison to waste the non-sulphide component of the ore is carbonate- and iron-rich and relatively poor in SiO_2, Al_2O_3 and K_2O. Iron and manganese are markedly more abundant in the non-sulphide component compared to waste. Iron content of the non-sulphide component may be attributed to the abundance of iron-rich chlorite which contains an average of 28.4% iron as FeO. Manganese occurs in spessartine-rich garnets and as a component in carbonate minerals.

Nine metals that occur in trace amounts are routinely assayed for in Sullivan mill feed and Table II presents average values for these. Antimony is most abundant in ore from the southwestern part of the orebody in the vicinity of the open pit (Freeze, 1966) where it attains concentrations as high as 0.3%. Manganese is also most abundant in ore in the vicinity of the open pit where it is recorded in amounts up to one per cent. Arsenic is most abundant immediately south of the "central iron zone" (Freeze, 1966) where it attains maximum concentrations of about 0.6%. Thallium is principally distributed along the eastern fringe of the orebody where it attains maximum values of about 0.02%. There are no data concerning the distribution in ore of copper, indium, bismuth or cadmium.

Average Sullivan waste (Table I) is quite similar to the average regional composition of rock of the Aldridge Formation (Table III). The average composition of Sullivan waste is in accord with the abundance of white mica and carbonate in the matrix surrounding quartz grains. Values for lead and zinc in the waste are an order of magnitude greater than average values of lead and zinc in the Aldridge rock.

Chemistry of Tourmalinite

Mean values for the major chemical components of tourmalinite from the footwall are presented in Table III. No attempt has been made to analyze the rocks for H_2O, F or Li_2O. The boron reported is an approximate mean value obtained from analysis by semiquantitative emission spectroscopy.

It is appropriate to compare tourmalinite composition to that of average Aldridge sedimentary rock (Table III). The principal differences, aside from abundant boron in tourmalinite, are markedly lower K_2O, Na_2O and CaO and higher Fe_2O_3 and MgO in tourmalinite compared to average Aldridge. With increase of tourmaline in the matrix at the expense of quartz and minor minerals, composition of the tourmalinite approaches that of pure tourmaline. Although this trend is distinct, the pure end-member rock has not been observed.

Although the chemical composition of tourmaline from typical tourmalinite has not been determined, chemistry of individual tourmaline porphyroblasts from several localities in the Sullivan orebody has been studied by Ethier and Campbell (1977). Their data suggest that composition of isolated tourmaline porphyroblasts is highly variable and that the distribution of Fe-rich and Mg-rich tourmaline is erratic. This is in accord with an interpretation that composition of tourmaline is a function of the bulk chemistry of sedimentary rocks prior to metamorphism and partitioning of iron between silicate and sulphide phases during metamorphism.

Chemistry of Albite-Chlorite-Pyrite Altered Rock

Composition of albite in the altered rock is remarkably uniform in both the foot- and hangingwalls. The average composition is $An_{0.65}$, $Ab_{98.96}$, $Or_{0.39}$ with a range of An_0 to $An_{2.5}$.

Composition of chlorite is dependent on character of associated rock type.

Magnesium- and iron-rich chlorite is restricted to altered rocks; iron-rich but magnesium-poor chlorite occurs in unaltered sulphide rock and low-magnesium and low-iron chlorite is found in Aldridge metasedimentary rocks outside the mine area.

Average compositions of chlorite-pyrite footwall rock and albite-chlorite-pyrite-carbonate hangingwall rock are presented in Table III. During alteration of footwall tourmalinite to chlorite-pyrite rock, boron content is reduced to near regional background values of 15 to 30 ppm and silica is markedly reduced. Added components include Fe_2O_3, MgO and Al_2O_3. Albite-rich rocks in the footwall are chemically similar to albite-rich rocks in the hangingwall. During alteration of Middle Aldridge rock of the hangingwall to albite-chlorite-pyrite-carbonate rock, silica is markedly reduced and K_2O is almost completely removed. On release, potassium may have migrated laterally to produce the potassium-rich envelope in the hangingwall.

Isotope Chemistry

Early investigations, particularly those of Leech and Wanless (1962) and Sinclair (1966), documented two principal groups of lead isotopes in Purcell rocks. The most important is a 1200 to 1500 Ma old group of uniform isotopic composition and the second a more radiogenic group of Mesozoic-Cenozoic age. Many of the lead occurrences, some stratiform, in Purcell rocks contain lead of the old uniform group. The small vein and massive sulphide deposits in the Moyie Sills also contain lead of the old, uniform group. More recently Zartman and Stacey (1971) and LeCouteur (1973) provided new and more refined data allowing interpretation of small-scale variation.

The uniform 1200 to 1500 Ma lead forms a short elongate array resembling a multistage anomalous line (LeCouteur, 1973). LeCouteur speculated that the elongate array is the result of frequent mixing of lead derived from the older craton in the sedimentary environment and by mixing brines circulating in the sediment. The small scatter in isotopic composition could be the result of small initial differences in source lead laterally or vertically in the sedimentary column, or the result of lead of different composition leached from the same rock depending on extraction efficiency of the brine.

Using a model that derived lead and the other metals from Aldridge sediments by circulating brines, LeCouteur further speculated about age of the sedimentary source using a "frequent mixing model". LeCouteur postulated the following history.

t = 4550 Ma	Lead homogenized throughout the earth.
t = 3000 Ma	Substantial sialic crust formed, now part of North American Craton. Considerable variability in U/Pb from place to place from 3000 Ma on.
t = 2700 Ma	Kenoran Orogeny. Lead developed in one U/Pb environment since 3000 Ma mixed into other U/Pb environments.
t = 1800 Ma	Hudsonian Orogeny. Lead developed in one U/Pb environment since 2700 Ma mixed into other U/Pb environments.

t = 1500 Ma	Deposition of sediment eroded from rocks of Kenoran and Hudsonian age begins in Purcell basin to form Aldridge strata. Lead is homogenized during erosion and sedimentation but different U/Pb environments may still exist in the stratigraphic pile.
t = 1250–1450 Ma	Lead leached from Aldridge sediments by circulating brine and deposited as galena.

Although interpretation of lead isotope data is speculative, this model accounts for uniform lead isotopic composition in large deposits, such as the Sullivan orebody, by deriving lead from a large volume of sediments by circulating brine very early in the history of the sediment.

The apparent conflict between the model age of lead in the orebody and the U-Pb age of zircon in the gabbroic intrusions cutting the orebody is the result of many factors. A principal source of the discrepancy is the assumption of geochemical mixing of radiogenic and ordinary lead during a brief period of geological time to result in a final ore lead of radiogenic character. Sullivan lead is apparently not the result of simple single stage development.

Isotopic composition of sulphur in the Sullivan orebody was studied by Campbell *et al.* (1978). Isotopic composition of sulphur in the orebody ranges from −10.4 to +4.7 per mil with a mean $\delta^{34}S$ value of −2.2 per mil. Variations in sulphur isotopic composition appear to be stratigraphically controlled. At the footwall of the Main Band sulphides, ^{34}S is enriched but decreases toward the middle. Toward the top of the Main Band, ^{34}S increases again and then decreases at the top. A similar although more complex pattern is found for massive ore in the western part of the orebody. Campbell *et al.* (1978) ascribed the stratigraphic variation to changing conditions affecting supply of H_2S, and temperature gradients in the basin and concluded that Proterozoic seawater was the sulphur source.

GEOLOGICAL HISTORY

The Sullivan orebody is a conformable deposit of bedded iron, lead and zinc sulphides enclosed by fine-grained clastic sedimentary rocks of the Aldridge Formation. The orebody was deposited on the sea floor directly over conduits consisting of brecciated zones of footwall sediments, sulphide stringer zones and boron-rich sediments. The orebody has extensive alteration within the ore and in the hangingwall over the conduits.

Understanding of the genesis of the Sullivan orebody has evolved over an extended period as mining has advanced. During the 30s and 40s, when most mining was in the western part of the orebody where alteration is present, the prevailing view favoured an epigenetic hydrothermal process (Swanson and Gunning, 1945; Freeze, 1966). In the late 50s, Owens (1960) collected data suggesting rapid deposition of sulphide contemporaneously with deposition of the enclosing sediments. This view, continuously modified by ongoing collection of geological data, has prevailed among Cominco geologists since the mid-60s. Although there is now general agreement among most geologists concerning formation of the orebody from hydrothermal emanations on the sea floor (Sangster, 1972; Cominco Staff, 1972; LeCouteur, 1973), there is more than one approach to interpretation of some of the available data by those familiar with the deposit, and two of these are discussed below.

Both models postulate that at the Sullivan, footwall conglomerate, chaotic breccia and soft-sediment deformation of pre-ore sediments are manifestations of preconsolidation, pre-ore deformation which produced a sub-basin or depression on the sea floor toward the close of Lower Aldridge time. Cross-strata footwall permeability was produced along synsedimentary faults, fractures and chaotic breccia zones. These conduits allowed hydrothermal solutions access to the sea floor. Evidence for hydrothermal activity along these channels consists of: tourmalinite, stringer sulphide zones and crosscutting albite-chlorite-pyrite-carbonate alteration. Preconsolidation deformation of footwall sediments and ore is common adjacent to these structures.

The first model postulates that hydrothermal solutions welled up through conduits into the sub-basin to form a pool of metal-rich saline fluid in an environment lacking in high-velocity ocean currents and wave action. Detrital influx was relatively slow and intermittent. The source and transporting media of boron, ore metals and sulphur and the role of heat are speculative. Lead isotope data (LeCouteur, 1973) are consistent with circulation and concentration of seawater trapped within Lower Aldridge sediments to form brines and derivation of ore metals by leaching of sediments by the brine. Sulphur isotope data (Campbell *et al.*, 1978) are consistent with seawater sulphate reduction in the sedimentary pile. Heat source providing energy for circulation and permitting efficient metal extraction from the sediments can be viewed as a simple increase in regional heat flow.

The sequential distribution of tourmalinite, sulphide rock, sulphides with interlayered mudstone and finally albite-chlorite-pyrite-calcite rock suggests that components were deposited from solutions which changed composition and rate of discharge through time or that conditions in the basin changed significantly through time. Initial deposits included boron, minor iron and sulphur and very minor lead and zinc. The bulk of the boron was added epigenetically to deep footwall sediments. At the top of the tourmalinite zone, near the sulphide footwall, the stratiform nature of tourmalinite and lack of crosscutting relations indicate that boron was deposited here during clastic sediment deposition. Conditions favourable for deposition of abundant boron ceased prior to major sulphide deposition, and laminated mudstone with several per cent pyrrhotite was deposited over conglomerate and tourmalinite in the central western part of the orebody. Chaotic breccia on the other hand, probably reached its full development immediately prior to and during early deposition of ore sulphides.

Major sulphide deposition began as changes in solution composition introduced more iron, lead and zinc or as conditions in the brine pool matured causing iron, lead and zinc sulphide precipitation. Abundant fragmental material and disturbed layering near the base of the sulphide rock in the western part of the orebody suggest disruption of accumulating sulphides. Scarcity of argillaceous clastic grains either intermixed or interbedded in the lower part of the sulphide succession indicates rapid sulphide deposition. This suggests that metals and reduced sulphur were present in solution at the time of upwelling into the basin. Evidence is permissive, although not conclusive, for early deposition of iron sulphide in the western part of the orebody before major deposition of lead and zinc.

The accumulation of sulphides ultimately consisted of a pyrrhotite lens, several tens of metres thick in the centre, overlain by a similar thickness of pyrrhotite containing layers, up to 3 m thick, of galena and sphalerite. The sulphide accumulation was probably somewhat domical in shape forming a slight topographic high in the basin. Sulphides may have slumped, both inward toward the deepening active basin and outward away from the accumulating pile.

Deposition of the Main Band in the eastern part of the orebody commenced during deposition of the lead- and zinc-rich upper part of the sulphide accumulation in the western part. Two depositional processes are envisioned. Rapid deposition of sulphide in a quiet brine pool receiving little or no argillaceous clastic material is envisioned for the lower one-half to three-quarters of the Main Band. Uniform bedding, great lateral continuity of layers and mineralogically simple, commonly monomineralic layering suggest direct precipitation in a tectonically stable environment. Delicate bedding of sulphides and increased abundance of interbedded clastic material in the upper part of the Main Band and overlying sulphide Bands suggest direct precipitation of sulphides from a brine and intermittent influx of clastic material mixed with a proportion of locally derived hydrothermal clay. Frequent surges of solution from the west may have regularly replenished metal in brine to the east. Occurrence of fragments and grading in sulphide rock of the Main Band near the fringe of the orebody suggest deposition in limited areas by mass flow from collapsed parts of the domed sulphides in the west.

Precipitation of lead and zinc from the brine may have been controlled by oxygen fugacity, temperature and pH. Lead was mainly deposited close to areas of chaotic breccia, probably exhalation centres, whereas zinc precipitated at greater distances from these centres.

The second model invokes metal derivation from a magmatic source. Ore metals are visualized as having been released from the magma at a time of crustal disturbance (reflected in disruption of footwall sediments) and then carried into the marine basin in hydrothermal solutions. The source of solutions may have been an early phase of the parent magma for the footwall gabbroic sill. Boron-bearing solutions first permeated the footwall sequence in the area of the conduits. Deposition of ore sulphides resulted from later, more active discharge of hydrothermal solutions through the conduit system.

Sulphides formed as discrete particles in response to marked changes of temperature and pressure both during movement up the conduits and immediately on entering the marine basin. The lower two-thirds to three-quarters of the sulphide accumulation is thought to have resulted from rapid deposition, including deposition of sulphide particles and fragments formed in the conduit system. The rate of sulphide deposition was so rapid that detrital argillaceous beds, or even grains, are insignificant in the sulphide rock. Bedding formed in the sulphides as a result of variations in the rate of discharge of hydrothermal solutions.

Chloritized and non-chloritized argillaceous fragments, small to large and often rounded pyrite grains, quartz grains and carbonate particles in the lower Main Band represent ejected vein and wall-rock material. The second model holds that the coarse-grained and altered character of these fragments could only have been formed in the conduit. Their character is so different from hosting assemblages that it appears unlikely that it was developed by in situ metamorphism. These fragments were torn from the conduit walls by rapidly ascending hydrothermal fluids and deposited with the accumulating sulphides. No material of this character is found in well-bedded sulphides of the upper Main Band and overlying sulphide beds. Metagabbro blocks in ore may be of similar origin. The preponderance of metagabbro dykes below the ore and the tendency for metagabbro to trail off in the ore sequence suggests that these intrusions may be penecontemporaneous with the ore. Ore deposition slowed after accumulation of most of the thick ore in the west and lower Main Band in the east, because there is a greater proportion of argillaceous clastic material intermixed with the sulphides in the upper part of the full sulphide succession.

Both genetic hypotheses postulate that deposition of these upper beds was controlled primarily by changes in physical and chemical conditions within the marine sub-basin. Both also invoke quiet periods when clastic sedimentation predominated to produce sections consisting of interbedded mudstone and the "A" to "D" sulphide Bands. Immediately following deposition of the "D" Band, clastic material transported by turbidity currents swept across the sub-basin and was deposited as thick, graded sequences starting with the "I" siltstone. Hydrothermal activity continued during sedimentation and at the close of deposition of each of the "I", "H" and "HU" massive graded sequences, favourable conditions recurred for formation of tourmalinite, accumulation of metal-rich saline fluids and deposition of sulphide. Prior to deposition of "HU" ore the underlying massive sulphides in the west apparently slumped to provide the ore-grade sulphide clasts in the "HU" conglomerate.

The close of synsedimentary sulphide deposition coincided with onset of Middle Aldridge turbidite sedimentation. Although continuing influx of turbidites to the basin may have prevented preservation of the brine pool, the hydrothermal activity continued. The fluids produced crosscutting albitic and chloritic rock in footwall tourmalinite and extensive alteration both in the orebody and in up to 100 m of accumulating hangingwall sediment. Activity gradually waned as fluids cooled and as the conduit system sealed itself by deposition of quartz and carbonate veins.

Emplacement of the footwall intrusion, which resembles the Moyie sills and dykes, caused metamorphism of the ore in its contact zone. The contact metamorphism and later regional metamorphism produced silicate mineral assemblages of upper greenschist facies. From arsenopyrite data, Ethier *et al.* (1976) estimated temperature of metamorphism to be 400 to 490°C. Fractionation of sulphur isotopes indicated metamorphic temperatures of 300°C; oxygen isotope fractionation between quartz and magnetite indicated a 400 to 560°C range. Folding and faulting later in Proterozoic time and during the Laramide Orogeny deformed the orebody.

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