AN INVESTIGATION OF BRECCIATION
ASSOCIATED WITH
THE SULLIVAN MINE OREBODY
AT KIMBERLEY B.C.

A Thesis
Presented In Partial Fulfillment
of the Requirements for the Degree
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by
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FRONTISPIECE

<u>Post-tourmaline Breccia</u>

Adjacent to the 4800 departure keel structure

Light colored fragments are tourmalinized argillite; locally referred to as "chert"

Dark Colored matrix is oxidized pyrrhotite

Central area of Sullivan Mine

BRECCIATION ASSOCIATED WITH THE SULLIVAN OREBODY - KIMBERLEY, B.C.

Abstract

Large volumes of breccia are associated with the Sullivan orebody. They are found in the foot-wall rocks, the hanging-wall rocks and to a lesser extent in the orebody itself.

Brecciation was an intermittent process. The following periods of activity are recognized.

1. Pre-conglomerate - pre-hydrothermal period
2. Post-conglomerate - co-hydrothermal period
   (a) pre-tourmalinization
   (b) post-tourmalinization

(pre-hydrothermal and co-hydrothermal are terms used by Bryner, (1961), in his classification of breccia columns. They are not used here to indicate oregenesis).

The pre-conglomerate pre-hydrothermal brecciation took place during Aldridge time. It is interpreted to have formed in a breccia column in advance of a magmatic intrusion. The column had progressed upward near to the surface existing at that time, when subsidence of the column resulted from withdrawal of magma at the base. A collapse of surface material followed, forming a steep walled basin some two hundred feet deep, floored with large blocks of rubble. The basin was subsequently filled to overflowing by conglomerate. The rubble blocks and conglomerate pebbles were derived from sedimentary rocks which had been lithified to mudstones and sandstones. The rubble found underlying the conglomerate is designated pre-conglomerate pre-hydrothermal breccia.

A pause in brecciation occurred during the deposition of the conglomerate and an unknown thickness of other sedimentary beds. When activity resumed, wide zones of chaotically mixed breccia were formed which cut through the previous breccia, the conglomerate, and overlying beds at least to the foot-wall of the ore zone. Twisted and torn fragments found in this breccia indicate that some relatively unconsolidated sedimentary rocks were involved.

Introduction of pyrrhotite as disseminated blebs and grains, chiefly in the breccia matrix followed, or was contemporaneous with this period of brecciation. Tourmalinization of both matrix and fragments also occurred.

A post-tourmaline brecciation of foot-wall rocks is recognized. Movement seems to have been concentrated along narrower zones than those of the chaotic pre-tourmaline phase. Passage of metasomatic agents through these breaks altered large volumes of tourmalinized rocks to chlorite, sericite, and albite. Vertical displacements of forty or fifty feet between adjacent large blocks of foot-wall rocks have formed linear breccia zones. Material from the ore zone flowed in, engulfing some of the tourmaline chert fragments, and forming foot-wall keel structures. Minor amounts of fine grained igneous material have been intruded into the keel breccias, and are also found as fragments in the sulphides.

Material of the sulphide zone is shown to have been quite mobile compared with the surrounding sedimentary rocks and alteration products. Much of the breccia found in the ore appears to be due to lateral movement of mobile material. The lateral movement of the plastic material

was initiated by vertical movement of the foot-wall rocks as the keel breccias formed.

There is evidence that hanging-wall rocks at least three hundred feet thick moved from the perimeter of the ore zone toward the centre. Hanging-wall structures are characteristically northerly trending folds with steep east limbs, low angle west limbs, and brecciated crests. The folds are associated with the keel structures but are opposed in the direction of displacement. The result is that there is very marked pinching and swelling of the ore zone. Sulphide material has penetrated the brecciated crests of some of the anticlinal structures.

The igneous intrusion responsible for the deformation may have been derived from the earth's mantle during a period of incipient island arc formation. A pause in the intrusive activity between the pre-hydrothermal and co-hydrothermal stages of brecciation, allowed time for differentiation to take place in the magma, and for volatile material to accumulate. Later resumption of intrusive activity resulted in the co-hydrothermal stage of brecciation, and the intrusion of diorite sills, culminating finally in the extrusion of Moyie andesite lava.

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CHAPTER I

INTRODUCTION

Brecciation affecting large volumes of rock has recently been recognized to be extensive in certain areas below, within, and above the Sullivan orebody. Studies of the brecciation show that it is intimately related to the metasomatic processes that have altered the rocks adjacent to the orebody. Certain igneous rocks have been found to be intrusive into the breccia, and to have subsequently been brecciated by later movement.

No previous description of this rock type has been published. The material presented here is based mainly on the observations of the author and his co-workers. Interpretations are the responsibility of the author alone, and are not necessarily those of the geological staff of the Consolidated Mining and Smelting Co.

This thesis consists of a report on investigations of the breccia which have been carried on at the Sullivan Mine, and at the University of Manitoba. Research has been concerned with

(1) Determining the location and extent of the breccia.

(2) Establishing the relationships of brecciated areas with the stratigraphy and structure of the surrounding rocks.

(3) Deducing a chronology of events related to the brecciation process.

(4) Forming an hypothesis of the cause of brecciation.

Thanks are due to the Consolidated Mining and Smelting Company for making information available for this study, to the Geological Survey of Canada, for a grant to aid in financing the University research program, and to the professors of the Geology Department at the University of Manitoba for their help and encouragement. To these persons and to many of my colleagues who have discussed the project and made valuable suggestions, I gratefully offer my thanks.

I. GENERAL DISCUSSION

Breccias are relatively unusual rock formations in the total volume of the earth's crust. Many are indicative of important processes in the tectonic history of the rocks in which they occur. Many and various origins have been deduced for occurrences which have been studied, with a resulting significant contribution to understanding the mobility of the earth's crust. Breccias are also rather commonly associated with orebodies and have often been found to have played a part in localizing the deposits. (McKinstry H.E., 1955) (Bateman A.M., 1950)

From the viewpoint of an economic geologist, the information to be derived regarding the regional "tectonic framework" and the local "ground preparation for the deposition of ore" may be of great practical importance. Where brecciation occurs in connection with an ore deposit, as at the Sullivan, it may contribute to understanding the provenance, mode of transportation, and method of fixation of the metals of the body. An attempt is made in the accompanying chart to relate the present study to the other investigations so as to show some of the ramifications involved. (Fig. #1)

The relationships indicated are not explored fully in this thesis, but are called upon at such times as they help to understand the brecciation process.

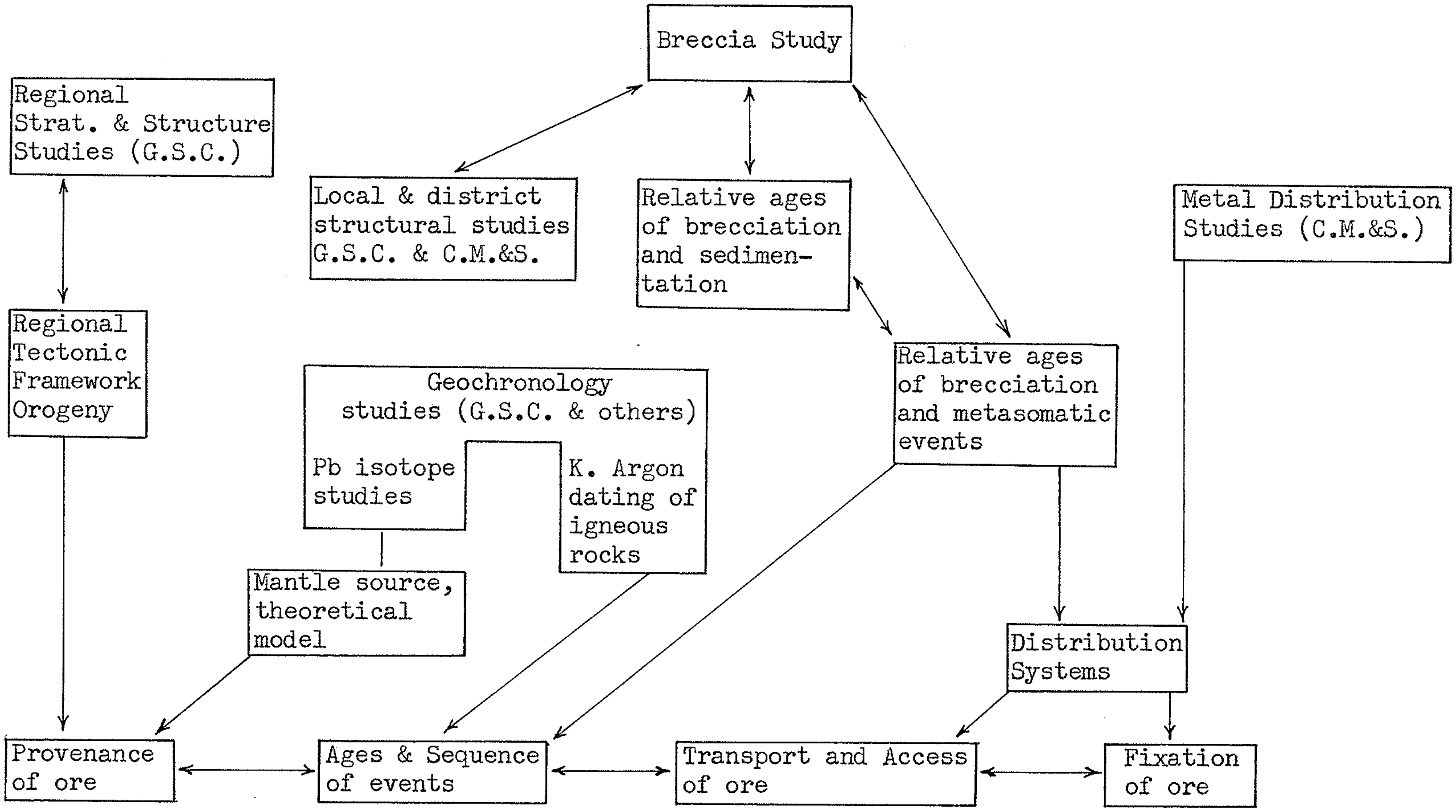
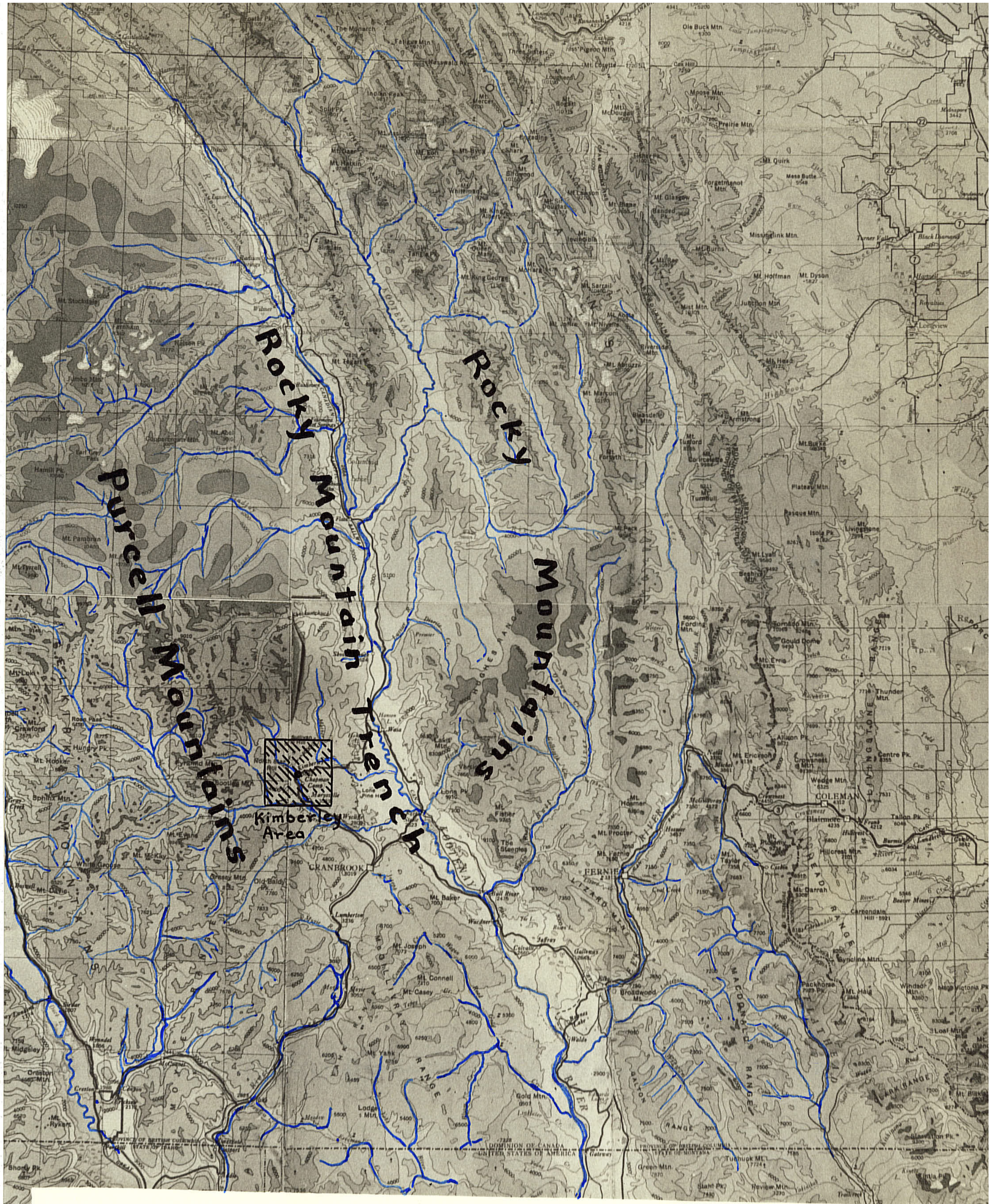


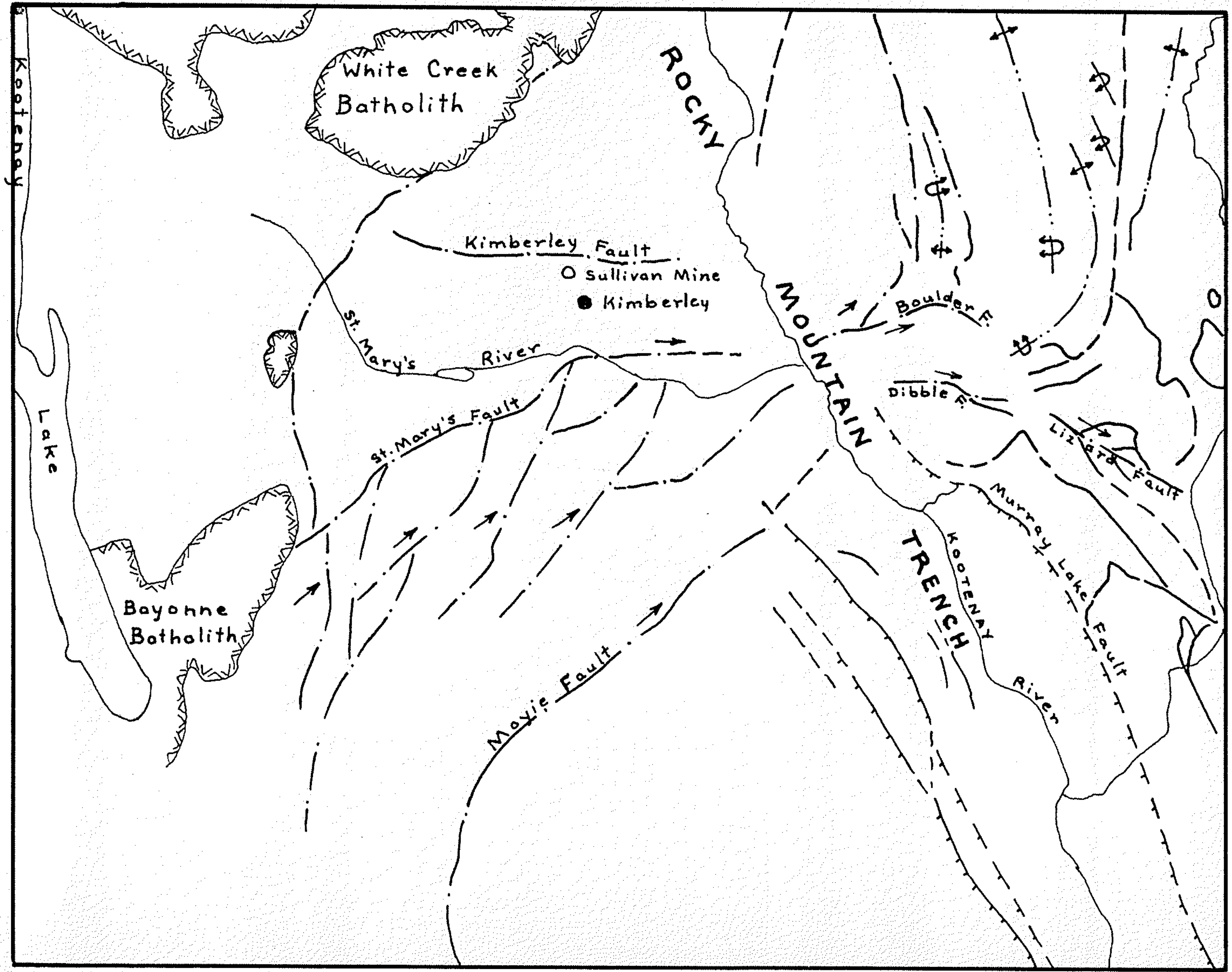
Fig. 1 Contribution of the Breccia Study to the Economic Geology of the Sullivan Orebody.



REGIONAL TOPOGRAPHIC MAP FIG. 2

Note: 1. Contrasting drainage pattern East and West of Rocky Mountain Trench

2. Curve in Rocky Mountains outlined by rivers



Tectonic Setting (after Leech) Fig.3

Fig. 3

CHAPTER II

REGIONAL SETTING

I. GEOGRAPHIC AND TOPOGRAPHIC SETTING

The Sullivan Mine is located adjacent to the city of Kimberley in South Eastern British Columbia. Kimberley is about 50 miles north of the international boundary and 50 miles west of the Alberta boundary.

The Crows Nest, Kettle Valley line of the Canadian Pacific Railway passes 20 miles south of Kimberley through the city of Cranbrook. The southern transprovincial highway follows the same route, and a branch of the highway passes through Kimberley leading North through Banff National Park to Calgary. (Fig. 2)

Kimberley is situated on the eastern flank of the Purcell range of mountains, overlooking the broad valley of the Rocky Mountain Trench, which is about twenty miles wide at this point. On the opposite, eastern side of the valley, the Rocky Mountains rise abruptly forming a precipitous wall contrasting with the more gradual slope of the Purcell Mountains. The Kootenay River flows southward through the Trench at an elevation between 2500 and 2600 feet. Kimberley is at an elevation of 3700 feet, and the highest mountains in the vicinity attain altitudes of between nine and ten thousand feet above sea level.

The discovery area of the Sullivan Mine lies north-westerly from Kimberley on Sullivan Hill at an elevation of about 4600 feet, and is presently the sight of an open pit operation. The main entrance to the mine is an adit driven at 3900 elevation from the valley of the Mark Creek, some 7000 feet south of the mine.

Regarding the topographic texture of the area around Kimberley (see Fig. 2), it is obvious that the Rocky Mountain Trench separates two contrasting areas. The trellis drainage pattern of the Rocky Mountains reflects the folding, over-thrusting and erosion of anisotropic rocks which vary from gypsum to limestone and quartzite.

The Purcell Mountain drainage on the other hand is very irregular due in part to the relative homogeneity of the Purcell system of rocks which form most of the range. Also, a notably greater proportion of igneous rocks intrude the sedimentary assemblage in this area than in the Rocky Mountains. The igneous intrusive rocks include Pre-Cambrian diorite sills and granite stocks, and Mesozoic granitic batholiths.

II. REGIONAL GEOLOGIC SETTING

Stratigraphic Position

The rocks in the area under consideration are mainly of middle Proterozoic age, 850 to 1600 million years old (Alta. Soc. Petrol. Geol. 1966 p. 15). This is the age range designated Helikian in the Pre-Cambrian classification proposed by Stockwell, (Stockwell, 1964).

These rocks are composed of a thick series of dominantly fine clastic sedimentary rocks with intrusive basic sills that has been named the Purcell Series. (Daly, 1904). Description and definition of the formations comprising the Purcell Series are given by Daly, (1904 & 1913), Schofield, (1915), Rice, (1937), Reesor, (1957), Leech, (1958), and Price, (1964).

The following table of formations, (Fig. 4) is from the work of Reesor (1957) and represents the section as it is found in the Purcell Mountain range.

Figure 5, after Price, (1964), indicates the correlation between formations in the Rocky Mountains, and those in the Purcell Mountains.

More detailed consideration is given in following paragraphs to certain pertinent features of the stratigraphy as related to the tectonic framework of deposition, and to orogeny during the period of accumulation of Proterozoic sediments.

III. TABLE OF FORMATIONS

(After Reesor 1958 p. 4-6)

Era	Period	Rock Unit (Thickness in feet)	Lithology
Cenozoic	Recent and Pleistocene		Stream and glacier deposits; felsenmeer and talus
		Fry Creek Batholith	Leuco-quartz monzonite, pegmatite, aplite
Mesozoic and/or Cenozoic	Jurassic or later		Relations not known
			Pegmatite and aplite
			Medium-grained quartz monzonite
		White Creek Batholith	Leuco-quartz monzonite
			Porphyritic (microcline) quartz monzonite
			Hornblende-biotite granodiorite (monzotonalite)
			Biotite grandodiorite (monzotonalite)
		Intrusive contact	
Palaeozoic (?) or Mesozoic (?)		Ultramafic stock	Serpentine; serpentinized clinopyroxenite
		Relations not known	
Late Proterozoic (?) or later		Moyie intrusions	Meta-diorite and meta-quartz diorite sills; rare dykes
		Intrusive contact	

TABLE OF FORMATIONS -- Concluded

Era	Period	Rock Unit (Thickness in Feet)	Lithology
Proterozoic	Upper Purcell	Dutch Creek formation (1,000 +)	Buff and reddish weathering silty dolomite, dolomitic quartzite, and much argillite; some grey weathering, very fine-grained, grey quartzite.
		Conformable, gradational contact	
	Lower Purcell	Siyeh formation (2,000)	Purple, green, and grey argillite; light and dark green laminated argillite; some very fine-grained, green weathering, green quartzite.
		Kitchener formation (4,200)	Buff weathering, dolomitic and calcareous quartzites, siltstones, and argillites; green argillite and black and grey bedded argillite; minor creamy to buff dolomite and black limestone.
		Creston formation (4,100-6,500)	Green and grey weathering, green-grey, and purple argillaceous quartzites, metasiltstones and argillites. Lower member (0-1,500 feet): dark weathering, black to dark grey argillites, arenaceous argillites, recrystallized equivalents of siltstones.
		Aldridge formation	Upper argillite member (1,000-1,500+): very rusty weathering, evenly laminated, black and grey argillites and arenaceous argillites. Remainder, of light grey weathering, light to dark grey quartzite with minor partings of black argillite and thin-bedded argillaceous quartzite, and rusty phyllitic equivalents.
		Aldridge	Very rusty weathering, thin-bedded, laminated, light coloured, very fine-grained quartzites and argillaceous quartzites; minor argillite; equivalent phyllitic, quartzites and schists.

Tectonic Environment of Sedimentation

J.T. Wilson, (1953), in his postulated system of island arc, mountain chain development, considers that the Rocky Mountain Trench marks the site of the boundary between the medianland (west of the Trench) and the secondary arc (east of the Trench). By this he implies a fundamental difference in the two areas during the time of sedimentary deposition. The secondary arcs (in this case the Rocky Mountains) are characterized by "normal" sedimentary rocks and little recent igneous activity. They represent an uplifted and folded inland sea bottom, formed on the continental shelf and analogous to the present Sea of Japan. The medianland is a complex of igneous and metamorphic rocks, which was involved from early times in the making of offshore island chains. Observations of workers in the region tend to confirm some of these generalizations and are presented in the following paragraphs as background to the thesis. Some emphasis is placed on evidence for Pre-Cambrian tectonic activity because it is directly related to the breccia problem.

The Sullivan orebody occurs in the Aldridge formation of the Proterozoic Purcell system. J.E. Reesor, (1958), describes this system of rocks as follows --

> The rocks comprise a series, not less than 30,000 feet thick of conformable, very fine-grained thin-bedded quartzites, argillaceous quartzites and argillites, with limey and dolomitic equivalents in the upper part of the section.

Elsewhere he notes that in the Purcell Mountains, primary structures such as ripple marks, cross bedding and mud cracks are common to plentiful at some localities in every formation, with the exception of the Upper Aldridge. The coarsest rocks in the entire Purcell system (with the exception of local intra-formational conglomerates in the Aldridge) were found in the upper part of the Creston formation. These comprise beds of medium to coarse quartzite and intraformational conglomerate located near the Rocky Mountain Trench on the East flank of the Purcell Mountains.

Correlation of strate is good from one hundred miles south of the forty-ninth parallel to Findlay Creek, a total of 200 miles in a south-north direction. However, many uncertainties in correlation occur from east to west across the Trench due to changes in sedimentary characteristics. There is a higher proportion of quartzites in the Aldridge of the Purcell Mountains than in the Rocky Mountains.

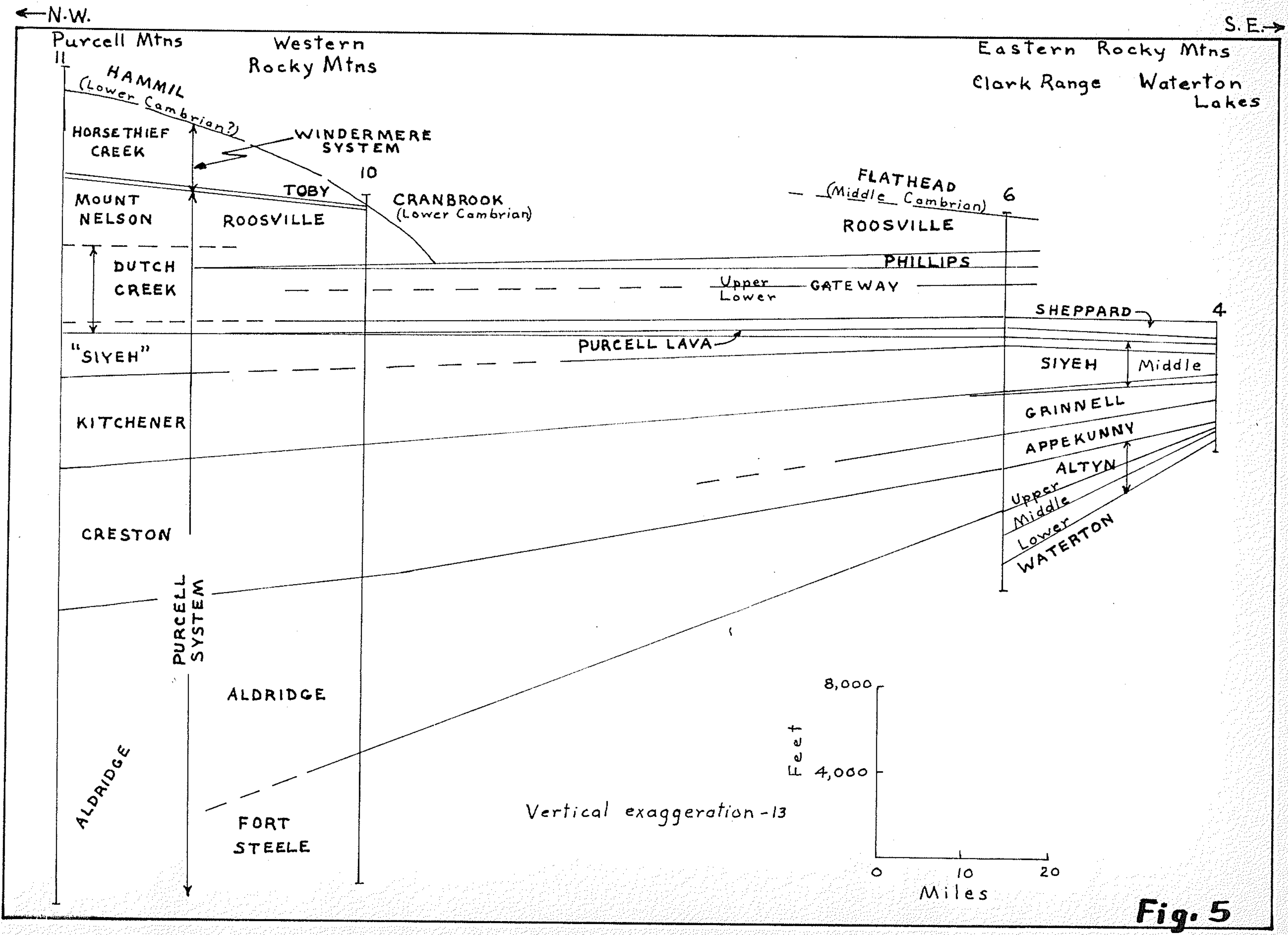
Reesor concludes that deposition was rapid, in a basin of relatively great tectonic stability, possibly the flood plane of a large subsiding delta.

> Only rarely, as shown by the Upper Aldridge sediments, has the rate of downwarp exceeded the rate of sedimentation so that shallow water features are not abundant. Yet even with this exception the series could only have been deposited in a region of relative tectonic stability over a long period. (Reesor J.E., 1956)

The early opinion of geologists, concerning the basin of sedimentation, seems to have been that there existed a geosynclinal trough, flanked both east and west by positive tectonic areas which contributed sedimentary material to the trough.

Wm. H. White, (1959, p. 62 to 64), was of the opinion that a great seaway extended from Montana to the Arctic, in which accumulated the Beltian system (of which the Purcell system is a part). He suggests the existence of older Pre-Cambrian lands to the west.

Fig. 5



Correlation Diagram between eastern Waterton Lakes National Park, southeastern Clark Range, (Rocky Mountains) Alberta, and the Dewar Creek, Rose Pass area, (Purcell Mountains) B.C. (After Price RA 1964)

More recently, opinion favours the concept of the Purcell System accumulating possibly as deltas on a continental shelf with provenance being entirely from an eastern craton.

Middle Proterozoic sedimentary rocks are described as follows:

> Very fine clastics derived from the shield to the east were deposited in the form of deltas along the old continental margin (...). (Nelson S.J. et al in Geological History of Western Canada, 1966, p. 7).

Also, in the same publication the statement is made that:

> Along the western edge of the Churchill craton, the Purcell series was deposited on a slowly sinking marginal shelf. (Burwash R.A. et al in Geol. Hist. W. Can., 1966, p. 16).

R.A. Price, (1964), in a study of the Purcell system in the Rocky Mountains of Southern Alberta and British Columbia, found it possible to correlate formations equivalent to those in the Purcell Mountains, across the Rocky Mountains to exposures in Waterton Park. He states (pp. 399):

> All current data concerning the character and regional relationships of the Purcell rocks are consistent with the hypothesis that the Purcell sediments were deposited on and adjacent to the western margin of the craton, under conditions analogous to those in the Gulf Coast geosyncline. This implies that the large volume of fine terrigenous clastic sediment that constitutes the bulk of the Purcell succession was derived from the older Pre-Cambrian rocks which occur in the interior of the continent, far from the site of deposition; and that none of it need have originated in some supposed western landmass.

Price observed unconformities at the base of the Sheppard and Gateway formations which he tentatively correlates with the Dutch Creek formation at the base of the Upper Purcell system. Schofield, (1915, p.36), reports finding pebbles from the underlying Purcell lavas, in the basal conglomeratic beds of the Gateway formation in the McGillivary Range south of Cranbrook.

Areas of uplift and erosion of the Purcell lavas existed prior to and during the deposition of the Gateway; therefore instability and uplift of areas of the Purcell sea bottom appear to have become important early in Upper Purcell time, probably not much later than the extrusion of the Purcell lavas.

In the section above the rocks in which the oldest unconformity is noted, there are numerous unconformable relationships shown where rocks of Windermere, Cambrian and Devonian ages lie upon Purcell rocks at a number of places in the area. Localized areas of erosion, and deposition are indicative of islands having been uplifted, perhaps the island arcs postulated by Wilson.

Structure

Folding

Leech, (1963, pp. 246), states:

> Although Pre-Cambrian and Paleozoic unconformities had long been known in the Purcell Mountains, the concensus was that the major structures date from a Mesozoic orogeny which culminated in the intrusion of the granitic rocks (...). Pre-Cambrian deformation (now known on stratigraphic evidence to be chiefly pre-Windermere and perhaps entirely so) had been considered to involve important uplift and probably tilting but to have produced only gentle open folds. (...)
>
> The recognition of the Pre-Cambrian age of granitic intrusions at Hellroaring Creek, and of Pre-Cambrian metamorphism and intrusion nearer Kimberley, sheds new light on the importance of Pre-Cambrian (possibly pre-Windermere) orogeny and, together with the Pre-Cambrian age of lamprophyres in the Sullivan Mine (p. 252), points to specific Pre-Cambrian structures. Pre-Cambrian folds were not all large gentle ones.

However it remains true that most of the major structural features were produced by the Mesozoic mountain building period. The Purcell geanticline lying between the Rocky Mountain Trench and the Kootenay Lake is related to the Cretaceous batholiths which cut it.

Leech believes that: -

> minor north trending folds with steep east limbs and westward-dipping axial planes (that) characterize the segment of the 'Purcell geanticline' in and north of the Kimberley area (...) are Pre-Cambrian and are older than the 'geanticline' on whose flank they occur. (Leech, 1963, pp. 246 and 247)

Faulting

Regional fault patterns, as interpreted by Leech, are shown in Fig. 3 (Leech, 1962, b. pp. 399). A notable feature is a tendency for the northly trending faults to turn eastward in the Cranbrook - Kimberley area. The reader's attention is directed to Fig. 2 where it can be seen that the trend of the Rocky Mountains (as outlined by the Kootenay, Lussier, Bull and Elk Rivers) turns westerly into the Trench in the same area. There is apparently a regional reversed S band in the strike of the major structures. This may be significant in relation to the occurrence of east striking Kimberley fault.

Leech, (1963), correlates the Moyie fault to the west of the Trench with the Dibble Creek fault in the Rocky Mountains, and gives evidence for believing that it is the site of an ancient structure which has had renewed activity at various times in the tectonic history of the area.

The Kimberley fault which cuts just north of the Sullivan Mine, brings Creston rocks into fault contact with Aldridge strata. This normal fault which strikes east and dips 45 - 55 degrees north, lies across the regional trends and it is parallel to the east trending portions of the other major faults. Thus it fits into the reverse S pattern of the area, but no southerly trending portion has been established, and no continuation has been recognized in the Rocky Mountains.

Very little can be said with assurance about the age of the Kimberley fault. Mine geologists at the Sullivan Mine indicate (Fig. 9 and Fig. 27) small displacements of the Kimberley fault by movements along northerly trending normal faults, but the evidence for this is not conclusive.

There is some evidence that the faults that displace the Kimberley fault, (called Sullivan type faults locally), had some pre-ore expression that influenced mineralization in the orebody. (Consolidated Mining and Smelting Co. of Canada Ltd. Staff, 1954, p. 153)

The Kimberley fault, therefore, may be older than the Sullivan type faults which in turn may be older than the ore.

Sullivan ore has been dated by Leech and Wanless by lead isotope methods and by the relationship of the ore to a cross cutting minette dike dated by the potassium-argon method. (Leech & Wanless, 1963, p. 252) Their determinations give a Pre-Cambrian age, at least 765 million years old. Therefore the Kimberley fault may be a Pre-Cambrian structure, possibly having genetic relationship to the Moyie fault which Leech considers to have been initiated at least as early as Cambrian time. (Leech, 1963, p. 247)

However, complicated renewals of movement on old structures is clearly a common occurrence. The Sullivan type faults, which appear to have had some pre-ore expression, have definitely had post-ore movement which has broken and displaced ore fragments. The inferred cutting of the Kimberley fault may well be due to a late stage of movement along the Sullivan type faults.

It is not possible as yet to give a minimum date to the Kimberley fault other than probable activity during the Mesozoic era. White, (1959, p. 84) considered the major faults of the East Kootenay district to be probably of Mesozoic age and related to the coast range orogeny. The earliest possible time of major movement would be Upper Purcell because Kitchener-Siyeh formations have been displaced along the fault.

CHAPTER III

LOCAL GEOLOGIC SETTING

The geology of the Sullivan Mine has been described by Swanson, & Gunning, (1945), Swanson, (1948), and the Consolidated Mining and Smelting Co. of Canada Ltd. Staff. (1954)

A summary of the geology of the mine as it relates to a study of lead isotope ratios carried out by the Geological Survey of Canada, is presented by Leech, & Wanless, (1963 pp. 248-256).

The following brief account is based chiefly upon the sources mentioned, and the writer's own acquaintance with the mine geology.

Structure

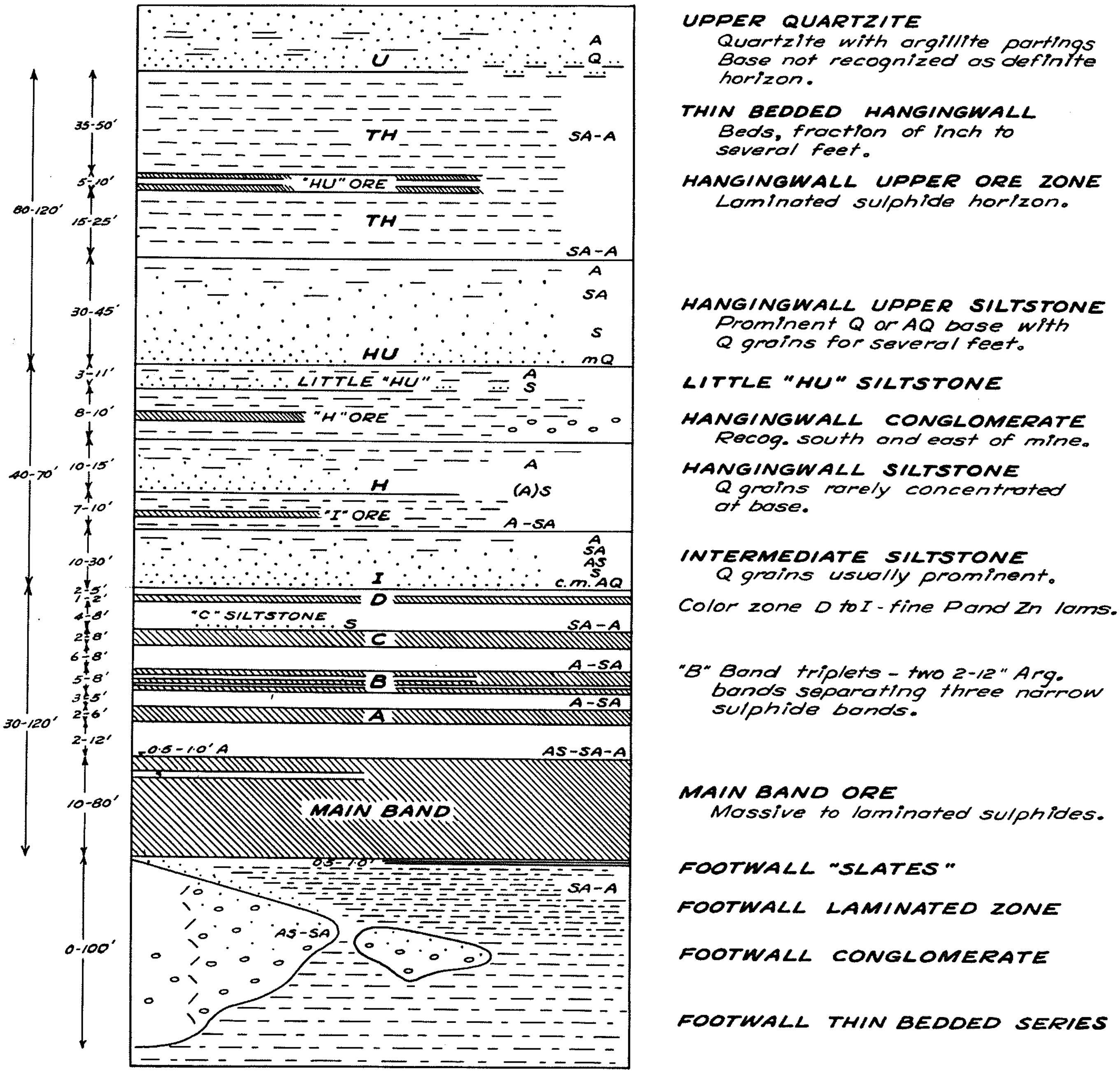
The Sullivan ore body occurs in a broad domical warp of low structural relief. This dome is on the east dipping eastern flank of the Mesozoic Purcell geanticline. Minor fold structures on the dome are northerly trending folds with steep east limbs, similar to the folds believed by Leech (1963) to be of Pre-Cambrian age. There are also a few easterly trending folds. The orebody is in the footwall block of the Kimberley fault and is cut by Sullivan type faults which trend north-easterly, dip steeply to the west and have normal displacements measurable in tens of feet. The Sullivan fault zones rarely exceed five feet in width, are composed of unconsolidated gouge and calcite, containing vugs and other openings.

THE CONSOLIDATED MINING AND SMELTING COMPANY OF CANADA LIMITED

SULLIVAN MINE

IDEAL GEOLOGICAL SECTION

A portion of the upper part of the Lower Aldridge Formation



LEGEND

Q	Quartzite.	⁘	Quartzite.
S	Siltstone.	∴	Siltstone.
A	Argillite.	▨	Sulphide Ore.
AQ	Argillaceous quartzite.	☰	Thin bedded.
AS	Argillaceous siltstone.	≡	Laminated.
SA	Silty argillite.	° ° °	Conglomerate.

Fig. 6

Stratigraphy

The ore zone is thought to occupy beds in the upper part of the Lower Aldridge formation which comprises some 4,500 feet of rusty weathering thin bedded, laminated, light coloured very fine grained quartzites, argillaceous quartzites and minor argillites. (Reesor, 1958, p. 6.) Included in this thickness are about 1,000 feet of Moyie metadiorite sills.

The upper division of the Aldridge, approximately 11,000 feet thick, cannot be directly related to the rocks exposed above the orebody because definite marker beds are lacking, and faults interrupt the continuity of exposure.

Conglomerate, which has intraformational characteristics occurs below part of the Sullivan orebody and has been observed locally elsewhere in the Aldridge. Reesor (1958, p. 63) notes the presence of conglomerate similar to that associated with the Sullivan orebody in the mountains near the headwaters of White Creek and the Middle Fork of Findlay Creek. Other Aldridge conglomerate bodies have been noted by Schofield (1915, p. 38) on Cameron Creek, a branch of the Goat River, and by Rice (1937, p. 7.) on the Kootenay King Mountain.

General Geologic Features of the Ore Body

(Fig. 7 & Fig. 8)

An outstanding feature of the orebody, established by the work of Swanson & Gunning, (1945), is its general conformability to stratigraphic boundaries. It occurs within a single stratigraphic zone 200 feet - 300 feet thick and has been mined for about 6,000 feet along strike and 4,500 feet down dip.

Certain aspects of the geology of the orebody change near the 3900 foot elevation and it is convenient to think of the mine as divided into a western section where the orebody is above 3900 elevation and an eastern section where it is below. The eastern section is characterized by strictly conformable ore bands dipping 30 to 40 degrees to the east with little metasomatic alteration of the metasedimentary rocks. In contrast to this, the western part of the orebody shows numerous departures from stratigraphic control; the dip of the ore is variable with flat areas alternating with steep dips, the thickness of the ore zone is highly variable over short distances, and in general this area shows a much greater degree of disturbance than the eastern part. The western area is characterized by massive alteration of footwall rocks to tourmaline chert, and chlorite, and of the hanging-wall rocks to albitite and chlorite.

Eastern Section

In a large portion of the eastern section, the ore is strictly confined to certain definite layers separated by argillaceous beds, (Fig. 6). The hanging-wall is formed by a graded argillaceous quartzite designated the "I" (intermediate) siltstone, which provides a marker throughout the area. Above "I" two other graded quartzites are recognized, which are designated "H" and "HU" respectively. Each of these beds has a moderately fine, massive quartzite base which grades upward through siltstone and silty argillite to a thin-bedded laminated argillite below the succeeding quartzite base. The laminated zones near the

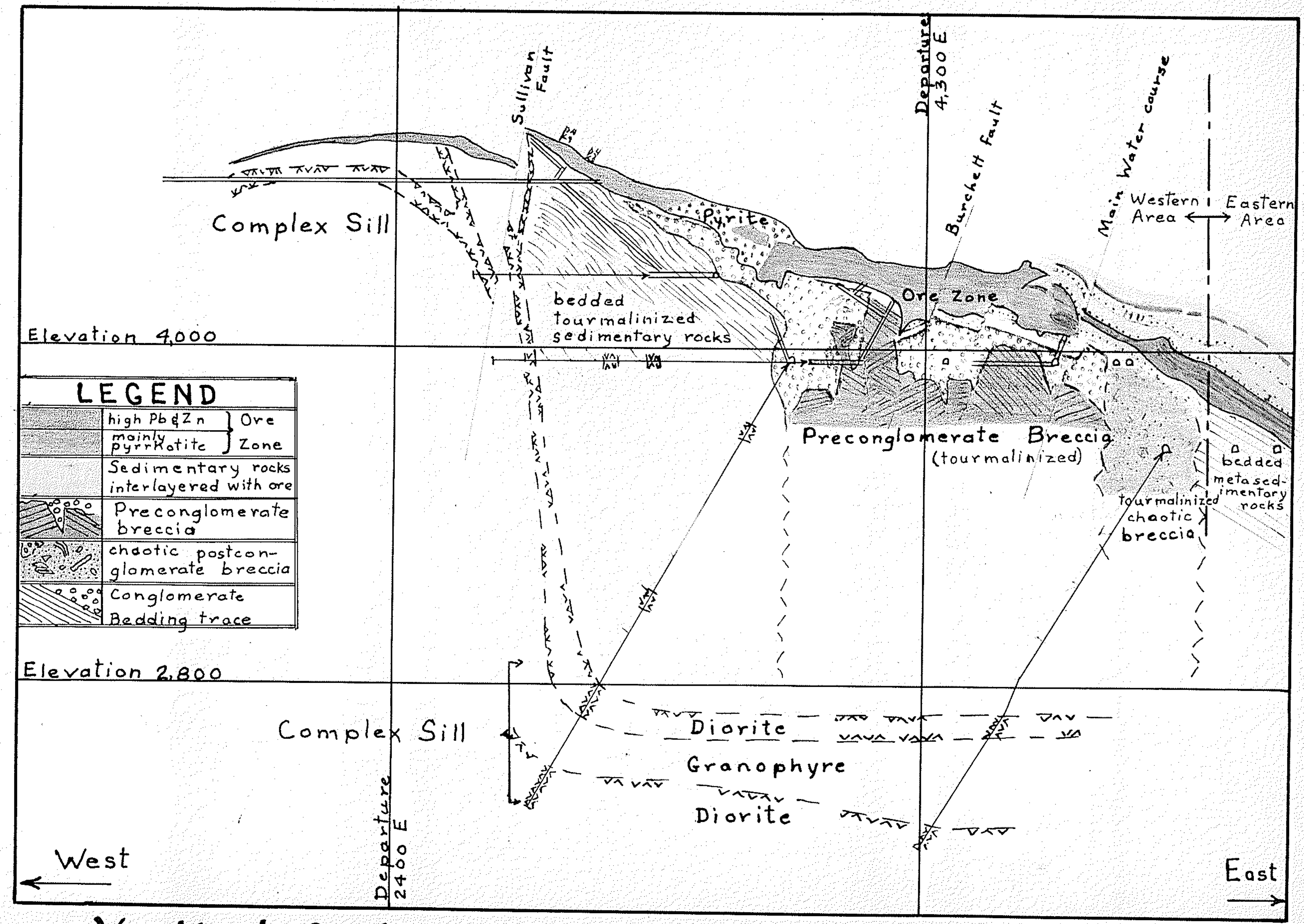


Fig. 7

Vertical Section through the Sullivan Orebody on Latitude 10750 N. looking North

Fig. 7

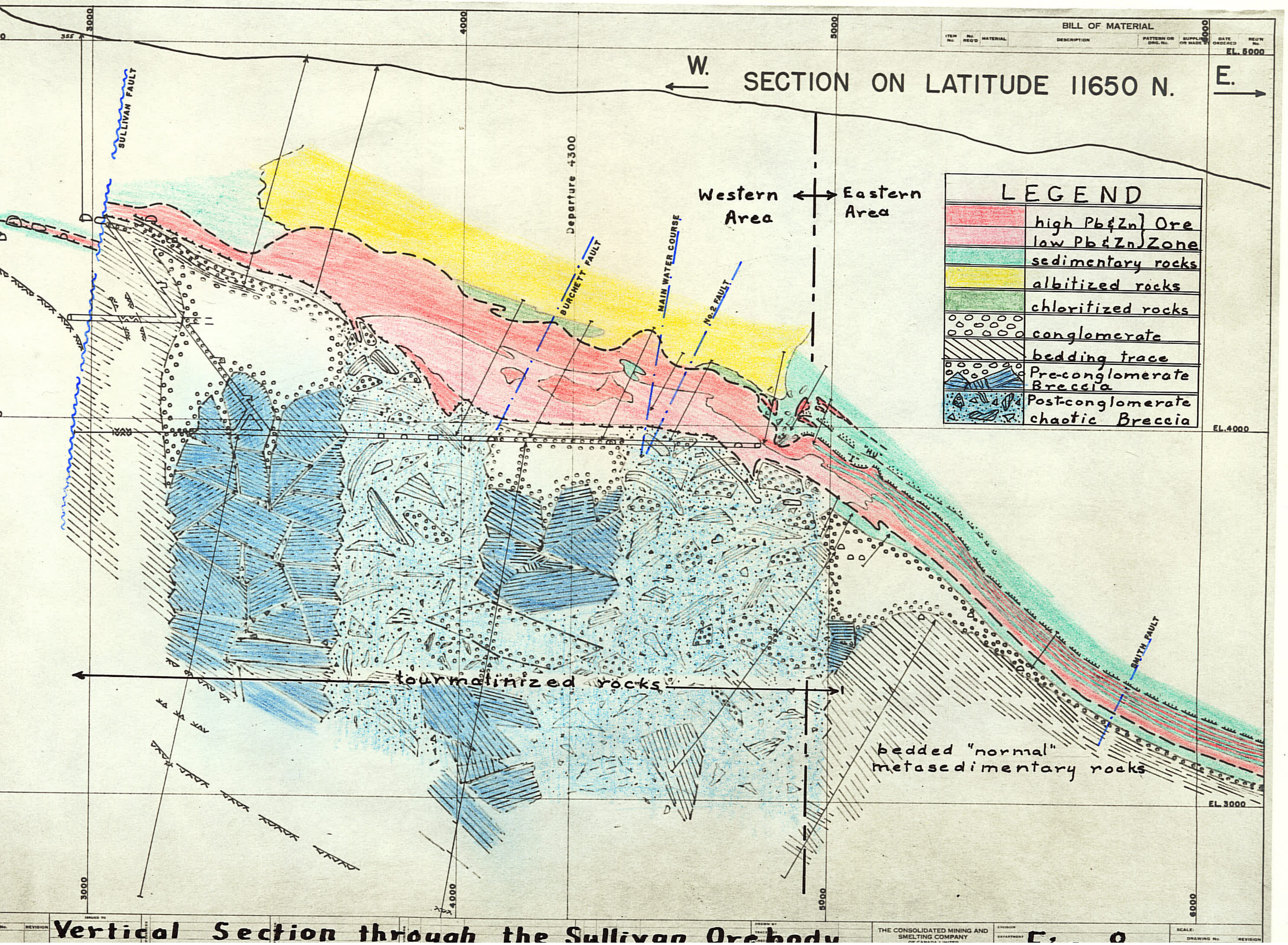


Fig.8

Vertical Section through the Sullivan Orebody top of the quartzite beds are locally mineralized sufficiently to become ore in the region where the orebody passes above the 3900 foot level.

Stratigraphic relationships of the sulphide foot-wall are not as clear as those of the hanging-wall because no well-defined marker horizon has been traced throughout the area. The upper contact of the foot-wall conglomerate makes the best reference plane, but is available only under the northern half to two-thirds of the orebody. The conglomerate will be discussed in detail later in the thesis.

The metamorphic grade of the sedimentary rocks is generally low in the greenschist facies. Original clay material has largely been converted to very fine sericite, and there has been some recrystallization of quartz grains. Biotite is not a prominent constituent.

Within the orebody, local development of higher temperature minerals has occurred. Biotite, garnet, scapolite, actinolite, talc and cordierite have been observed; the first two mentioned are in places quite abundant. Sedimentary textures are well preserved in all but the most severely metamorphosed rocks.

Western Section

The brecciation, which is the subject of this thesis, is mostly found in the Western section of the mine area. It is closely associated with the characteristic features that distinguish this area; i.e., disturbance, metasomatic alteration, discordant ore features, and high metal concentrations. The ore, in general, loses the excellent layered features that it exhibits in the eastern section, and becomes a contin uous sulphide deposit from foot-wall to hanging-wall. Layering within the ore is marked by laminae of sphalerite and galena in pyrrhotite. This layering is often discontinuous compared to that of the eastern section, but is believed to reflect bedding (Consolidated Mining & Smelting Co. Staff, 1954, p. 148). The mineralization of the laminated zones above the "I", "H", and "HU" beds has produced important ore bodies in this section. In some places ore is continuous through the hanging-wall marker beds. Towards the south of the western area, most of the ore is found in these upper beds and comparatively little below the "I" bed.

Tourmalinization has altered great volumes of rocks in the foot-wall of the ore zone into dense, dark coloured, very hard chert-like rock. Tourmaline occurs as extremely fine needles replacing the sericite of argillite and silty argillite. The quartz grains remain unaltered except around the edges where they are penetrated for short distances by the tourmaline needles and knit tightly into the matrix. Sedimentary structures and textures are preserved. Individual beds can readily be identified. A small amount of tourmalinization has also occurred in the hanging-wall rocks.

Chloritic alteration occurs prominently in the foot-wall and hanging-wall rocks adjacent to the orebody. The greatest alteration is related to the pyritic portion of the iron zone, a centrally located area which has a very low content of lead and zinc. Large volumes of chloritized rocks occur in the hanging-wall associated with albitite.

Albitite is found extensively in the hanging-wall, and to a much lesser extent in the foot-wall. Albite and chlorite often obliterate original bedding features, making it impossible to trace hanging-wall markers over appreciable areas in the western section.

Igneous Intrusive Rocks (Fig. 7 & Fig. 8)

A body of Moyie diorite underlies the strata beneath the orebody. In the central part of the mine area and to the east it is apparently sill-like and at a depth some 1500 feet below the sulphide foot-wall.

To the west it becomes dike-like and rises across the strata, approaching within a few tens of feet of the orebody, then turns down forming an elongated dome west of the orebody.

Dike apophyses from the diorite body have cut through the ore zone in places, but are not continuous in the ore. On the contrary, fragments of diorite are found scattered in the sulphides in the areas where the dikes cut the foot-wall and hanging-wall rocks. In general, the dikes are extremely variable in attitude and thickness so that it has only been possible to correlate three of them for any distance in the foot-wall, and none at all in the hanging-wall. One younger, 2-foot lamprophyre dike, known as the Lindsay dike, has been traced for several thousand feet in the northern part of the east section. It has been seen to cut across a dike of Moyie diorite. In the ore zone the Lindsay dike is disrupted and its continuation in the hanging-wall is offset.

Leech (Leech & Wanless, 1963, p. 251) describes in detail an occurrence of a lamprophyre dike intersecting the D ore layer (Fig. 22) on which the hanging-wall segment is displaced seven feet out of alignment with the foot-wall segment. Fragments of the dike appear in the $2\frac{1}{2}$ foot thick ore layer, crosscutting the banding in the ore which lies parallel to the ore contacts. This is very similar to the observation noted by Swanson & Gunning (1945, p. 63).

At one place in the mine, structure shows that a lamprophyre dike was intruded during the period of mineralization. This dike distinctly cuts heavily mineralized sediments in which pyrrhotite and sphalerite are the main sulphides, and is itself cut by a layer of galena a few inches wide that follows a minor fault.

The age assigned to the dike by Leech & Wanless, based on Potassium-Argon dating, is not less than 765 million years.

CHAPTER IV

THE FOOTWALL CONGLOMERATE

It is fundamental to the discussion of the conglomerate and breccia to show that they are distinct entities; therefore a description of the conglomerate fabric will be given.

The foot-wall conglomerate has been a familiar rock type to geologists at the Sullivan Mine for many years. Descriptions of it are included in the papers on Sullivan geology. Because new data has accumulated regarding its distribution and relationships, it will be reviewed in this section.

I. COMPONENTS

Pebbles: The conglomerate is composed of fragments of argillite, silty argillite, siltstone and quartzite. No foreign pebbles, differing from the Aldridge rock types, have been observed.

Matrix: The pebbles are set in a matrix that varies from argillaceous to locally quartzitic. A mixture of various sized quartz grains and small angular rock fragments very similar to that found in breccia has been observed. The ratio of pebbles to matrix varies from closely packed pebbles with as little as 15% matrix, to scattered pebbles with up to 60% matrix. It is likely that the amount of matrix is often overestimated because the pebbles do not show up well unless outlined by pyrrhotite or bleaching. Generally, in the writer's experience, a high pebble-to-matrix ratio prevails.

Shape of pebbles: There is a fair correlation between the composition and the shape of pebbles. Argillite and silty argillite pebbles are often laminated, tabular, and sub-angular, whereas the siltstones and quartzites are more massive, spherical and sub-rounded to rounded. In comparison with Pettijohn's (1956, p. 59) illustrations of roundness, they range from sub-angular to rounded.

Lithification: It is likely that the rocks from which the pebbles were derived were quite well indurated because they are rarely deformed. Also, it is improbable that the siltstone and quartzite pebbles could have been derived from unconsolidated sand beds.

Size: Most of the pebbles in the conglomerate are less than an inch and one-half in diameter, but occasional individuals up to three inches are common. Large boulders are unusual; the only accumulation exposed is at the base of the conglomerate, (Plate 2). These boulders have well rounded outlines although they have been fractured. Some large tabular pebbles nine inches or so in length and one to one and one-half inches in thickness have been observed, but their occurrence is rare.

Sorting: Most of the conglomerate is a massive body (as defined by Pettijohn, 1956, p. 159) without bedding. It presents a uniform appearance due to a fair degree of sorting. In one exposure there is a gradation from the boulder-sized components at the base, to normal sized conglomerate at higher stratigraphic levels. Sorting of pebbles into lenses of coarser and finer sizes is common near the top where there are

PLATE 1.

Typical Foot-wall Conglomerate

PLATE 2.

Boulder Conglomerate

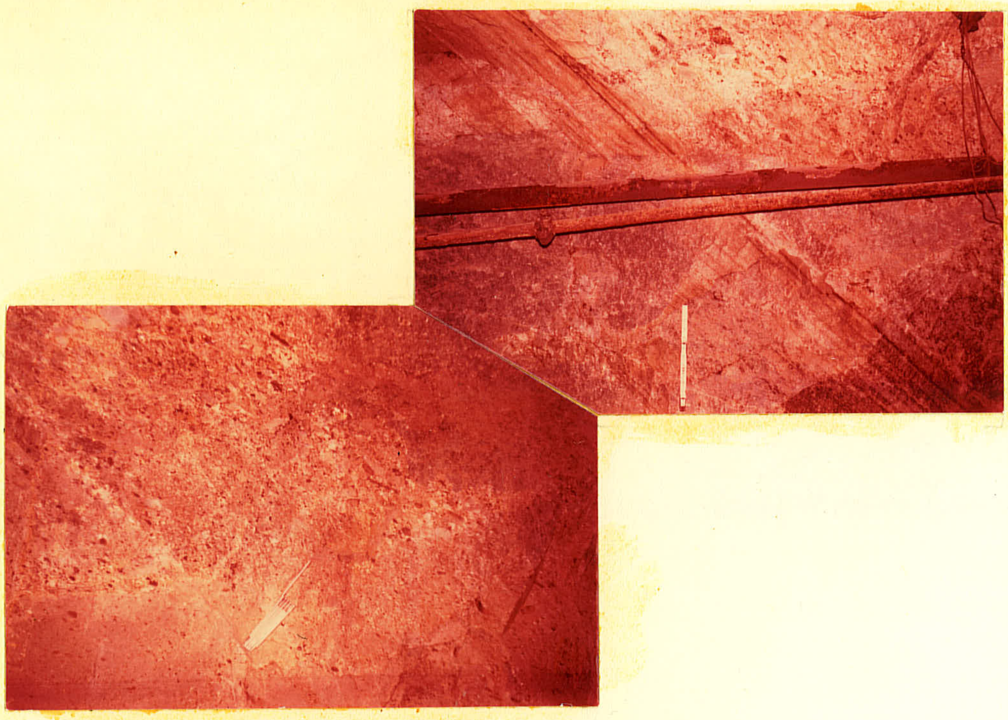


PLATE 2 a

Bedded Conglomerate

Conglomerate with
intercalated laminated
silty argillite bed,
and aligned pebbles
(3673 X.C.)

also intercalated lensey beds of grit and silty argillite.

Summarizing briefly, the conglomerate components are derived from rocks similar to the underlying sedimentary rocks which had probably reached the stage of lithification of sandstones and mudstones. The pebbles have not likely been transported far, but have received a certain degree of rounding and sorting. This relatively orderly fabric stands in contrast to the unsorted chaotic fabric of the breccia.

Sulphides: Pyrrhotite is the most abundant sulphide present in the conglomerate. Galena and sphalerite are present in certain localities in quantities sufficient to make ore. Arsenopyrite and chalcopyrite are present in small amounts.

The sulphides occur in a variety of ways. In places pyrrhotite appears mainly to be disseminated in the matrix, in others pebbles may be rimmed, or laminated, or composed entirely of pyrrhotite. Occasionally sphalerite and arsenopyrite pebbles are observed.

The distribution of sulphides throughout the conglomerate is variable. High concentrations occur usually with numerous pyrrhotite veins which are commonly associated with quartz and carbonate.

It has been suggested that some pyrrhotite laminated pebbles may have been derived directly from pyrrhotite laminated beds where the base of the conglomerate cuts unconformably across them. Similarly, certain isolated pyrrhotite pebbles with no visible connection to veinlets have been thought to be fragments of pre-existing pyrrhotite, although no source is known. In general, the evidence suggests that the sulphides have been introduced into the conglomerate replacing some matrix and some pebbles.

Location

The position of the conglomerate body has been outlined by isophachous lines based on intersections by diamond drilling and underground development headings, (Fig. 9). It underlies the northern two-thirds of the mine at varying distances below the sulphide foot-wall. At one time a continuous body, it has been disrupted in places by brecciation and later faulting.

Thickness

The fifty and one hundred foot isopach lines outline a thick portion of the conglomerate body. There are thicknesses greater than 200 feet within this area, but intersections to the base are few, so no detailed contouring has been attempted.

Contacts

> McEachern (1944) noted that the base of the conglomerate marks a disconformity (Swanson & Gunning 1945).

Studies and observations made since that time confirm and amplify this observation.

The body increases in thickness rapidly from zero to over 200 feet at its south and west boundaries. Several intersections in development headings indicate that the conglomerate is in contact with sharply truncated thin beds of argillite, siltstone and quartzite (Plate 3). Sections along latitude 11650 (Fig. 8) and departure 4300 (Fig. 10) show this contact cutting steeply down across some 200 feet of beds. The north and east contacts have not been seen, but the isopachs indicate thickening of the conglomerate which would require truncation of beds for its accommodation. The information available, indicates an

Fig. 9

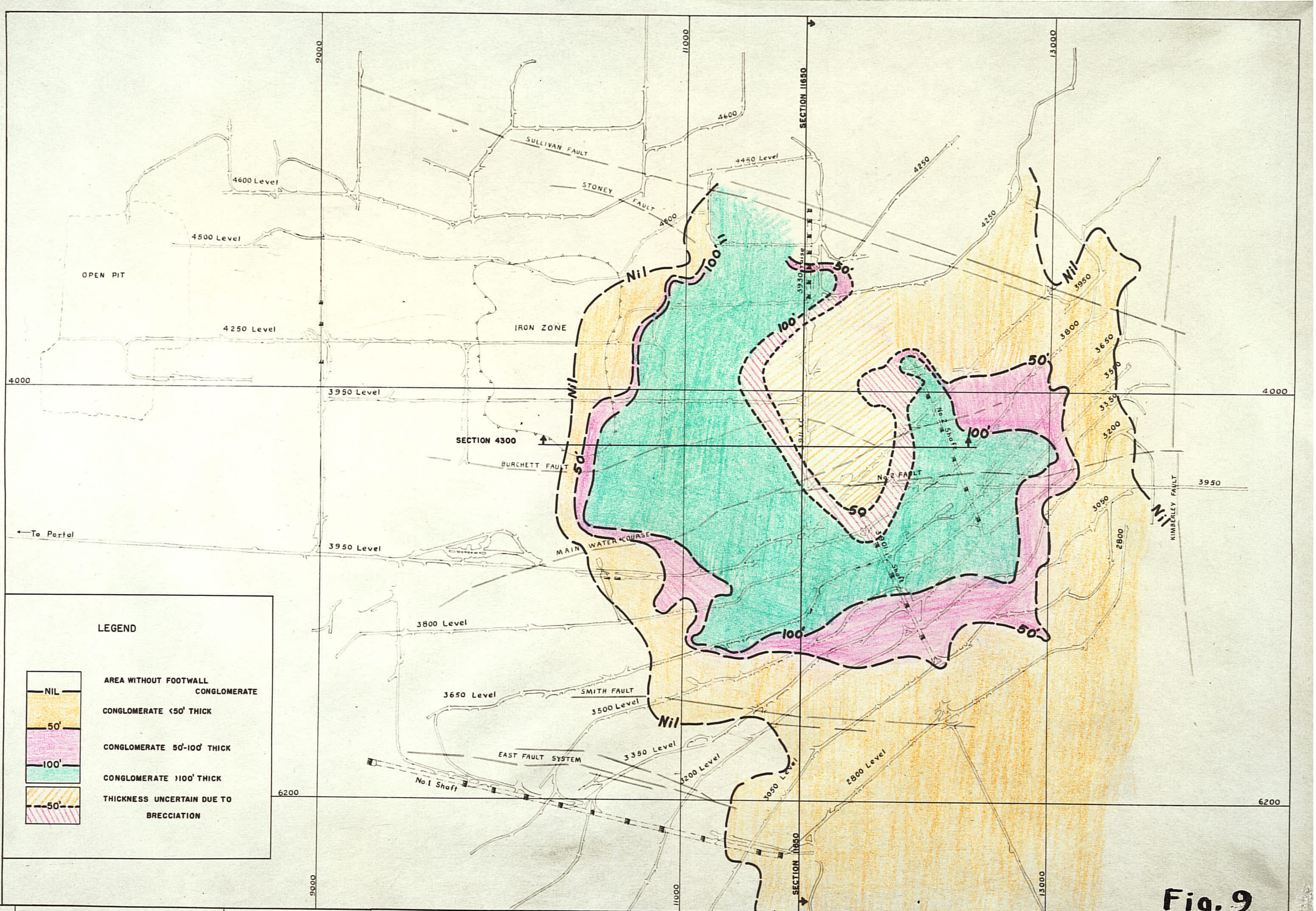


Fig. 9

SECTION:
DEPT.: GEOLOGY
MADE BY: D.E.J.

APPROVED BY

STRATIGRAPHIC THICKNESS OF THE FOOTWALL CONGLOMERATE

CONSOLIDATED MINING AND SMELTING CO.

TITLE SIMPLIFIED PLAN

PLATE 3

Discordant Contact at the Base of the Foot-wall Conglomerate.

← S. SECTION ON DEPARTURE 4300 E. N. →

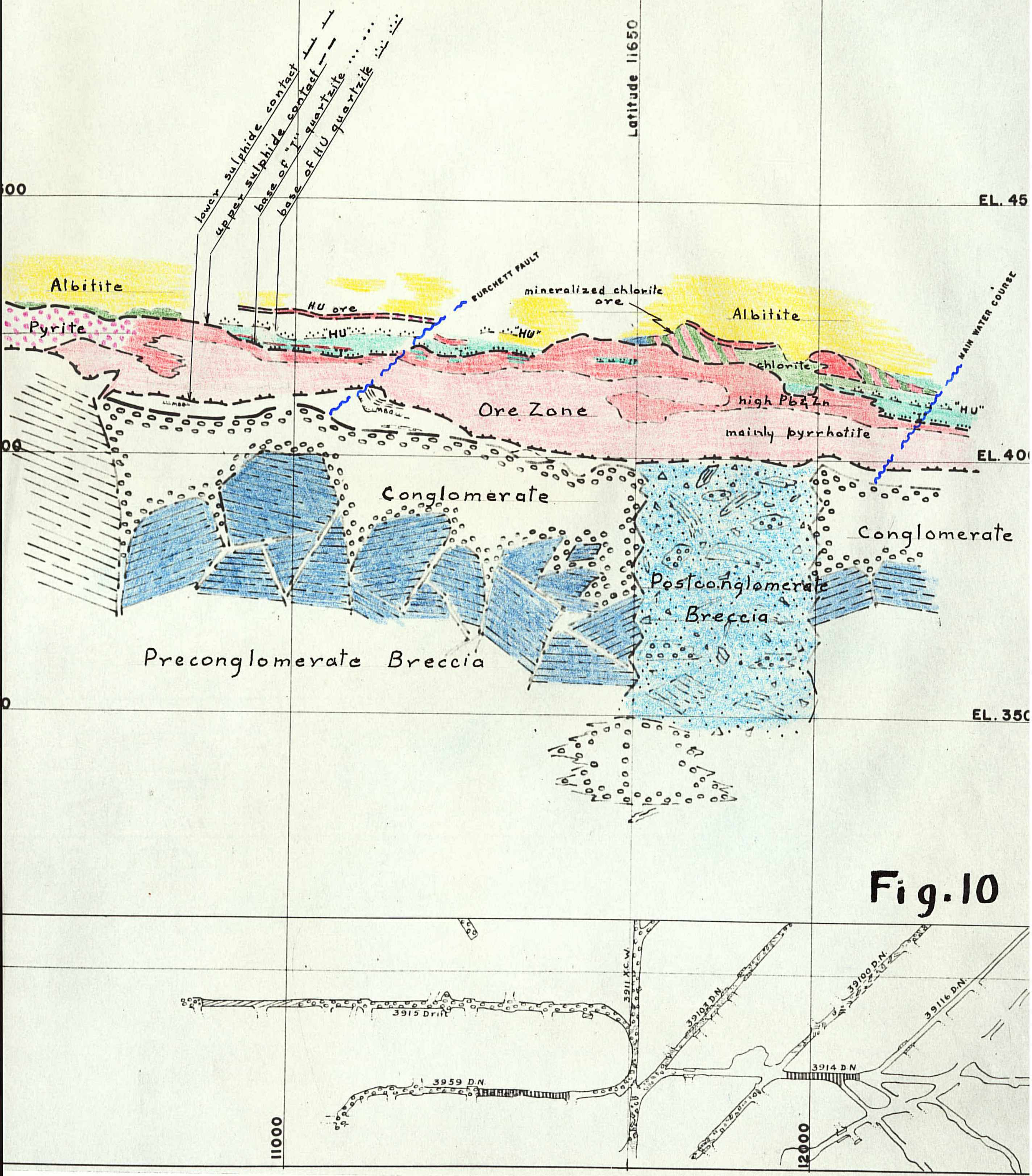


Fig.10

eastern contact cutting approximately ninety feet of beds at forty degrees to the bedding. It appears, therefore, that the thick part of the conglomerate is contained in a basin with steep south and west walls and a less steep east wall.

Base: The base on which the conglomerate rests is exposed in some of the 3950 level drifts and foot-wall headings, and is seen to be very irregular. Masses of thin-bedded sediments protrude upwards at least 100 feet into the conglomerate. The edges of some of the thin bedded blocks appear cracked and broken with fragments falling into the conglomerate, in other places the bedded rocks have sharp straight contacts. Bedding in the thin-bedded blocks is often inclined at different angles on either side of conglomerate-filled fissures. Many of these blocks of thin-bedded rocks measure in tens of feet and are not entirely exposed.

The impression given is that the bottom of the steep walled conglomerate basin was strewn with huge blocks of thin-bedded rocks and that a muddy gravel was more or less poured over them.

To the north and east of the thick part, the conglomerate body extends over the edge of the basin onto the surrounding terrain forming a pseudo-conformable bed. The base of this bed has been observed to have a disconformable contact. The bed has a lense-like cross section from north to south. The boundaries show an east-west elongation of the conglomerate body in this area.

Upper contact: Around the perimeter of the conglomerate body except for the southeast and northeast portion, the lower contact of the sulphide body is against the top of the conglomerate. Centrally however, there are thirty to forty feet of bedded sedimentary rocks separating the two. The reason for the convergence of the two contacts away from the centre area is not clear. It cannot all be accounted for by crosscutting of beds by a discordant sulphide footwall, although this is known to occur, because convergence takes place in the eastern section of the mine where the foot-wall conforms most strictly to stratigraphic control. Furthermore, there is a convergence between the conglomerate and the base of "I", particularly out towards the northwest fringe.

The upper surface of the conglomerate may have been somewhat centrally depressed making a basin which accumulated thicker deposits in the central area.

CHAPTER V

BRECCIA BELOW THE ORE ZONE

History

Breccia was not mapped as a distinct coherent unit of the Sullivan rocks until 1958. During the spring of that year, the heading 3920 Drift was driven through rocks which appeared to be composed of a chaotic jumble of different sized rock fragments. A proposal that breccia or "chaotic" breccia be recognized as a mappable rock unit was made at that time, and subsequently large areas of breccia have been recognized and mapped.

Pre-conglomerate Breccia

A large mass of the foot-wall conglomerate rests, apparently undisturbed, upon a very irregular base. The base is composed of large blocks of thin-bedded sedimentary rocks rotated with respect to one another as described in Chapter IV in the section on the "Base" of the conglomerate. This assemblage of rubble is designated the pre-conglomerate breccia in this thesis. It lies within the 50-foot conglomerate isopach (Fig. 9) which approximately outlines its occurrence.

Post-conglomerate Breccia

Two stages of brecciation later than the deposition of the conglomerate are recognized. The earlier stage brecciates the conglomerate, disrupting it and mixing blocks of bedded sedimentary rocks into it. This stage preceeded tourmalinization as is shown by the fact that both fragments and matrix have been tourmalinized. A later stage of brecciation broke the tourmalinized rocks allowing introduction of metasomatizing agents.

PLATE 4

Typical Post-Conglomerate Breccia in the foot-wall in the central area of the mine.

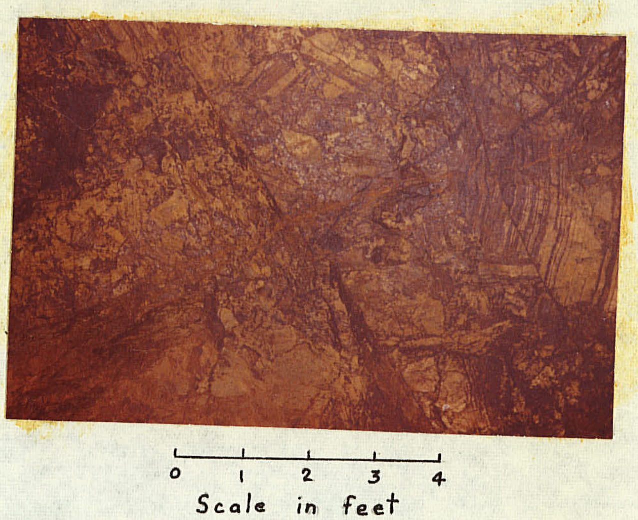


PLATE 5

Breccia in the foot-wall toward the western fringe of the mine.

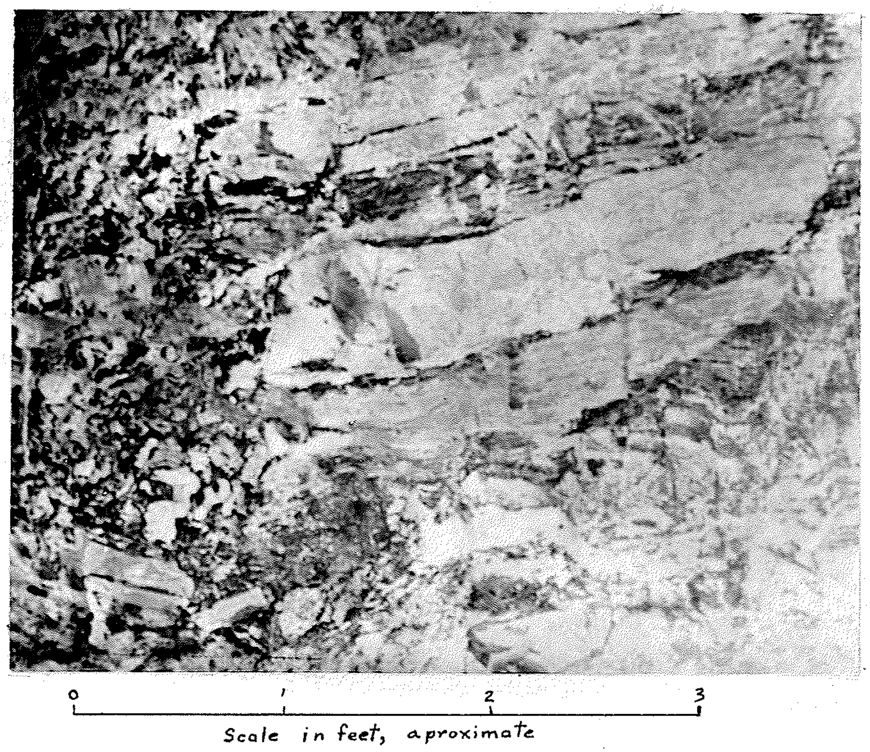


PLATE 6

Thin Bedded Block in Breccia

PLATE 7

Conglomerate Block in Breccia

PLATE 8

Breccia

Note torn and twisted end of a thin bedded block

PLATE 9

Breccia

Note bending of beds

The later stage has resulted in effects varying from chloritized or albitized fractures, to larger alteration zones containing chert remnants. Pyrrhotite matrix breccias associated with keel structures (Frontispiece) are also attributed to this stage.

The following description deals with the pre-tourmalinization phase of the post-conglomerate breccia as it is observed mainly in the rocks below the orebody.

Fragments: 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 been torn rather than broken. Blocks of conglomerate are mixed in with bedded and massive pieces, ahd the whole appearance is heterogeneous and chaotic. Apparently much of the broken rock was in a relatively soft state at the time of breaking.

Matrix: The blocks are now completely consolidated in a matrix of silty argillite with a plentiful sprinkling of fine-grained quartz. Pyrrhotite is disseminated through the matrix, and is also present in irregular veinlets that lace through the rock. Much of the breccia, both matrix and fragments, is now tourmalinized.

Distribution: Areas in which breccia occurs are indicated in Fig. 11. The boundaries are approximate for the following reasons:

1. the breccia commonly grades outward from highly disturbed and mixed zones through cracked rocks into relatively undisturbed rocks.

2. in some places the boundary zone occurs against pre-conglomerate breccia and is difficult to recognize.

3. in conglomerate areas the breccia may be distinguished only when mixing has brought thin-bedded blocks into the conglomerate, otherwise, existence of brecciation can only be vaguely discerned.

The method used to place the outlines was to plot all clearly brecciated areas first, and then to plot all clearly non-brecciated areas. The indefinite area between was taken as outlining the breccia zone. Benefit of any doubt was generally given to unbrecciated areas, so the outlines are considered to be minimal.

The outlines are quite irregular and do not show any sharply defined trends. There are two areas elongated in a north-south direction, and another with an irregular east-west elongation. More clearly defined are certain "keel" structures which are closely associated with brecciation. These structures are discordant downward projections of the lower contact of the sulphide zone (Fig. 7, Fig. 8, Fig. 12). Trending north or northwesterly, the keels are frequently parallel to hanging-wall folds with steep to over-turned east limbs (Fig. 11).

Strata affected: Brecciation has been traced up section from the rocks below the conglomerate to the lower contact of the sulphide zone. Brecciation of the conglomerate is certain where blocks of conglomerate are mixed with fragments of bedded rocks (Plate 7). Breccia is found below the mining headings in the foot-wall rocks at the 3900 level, in three diamond drill core holes shown on section Latitude 11650 N (Fig. 8). This breccia is discordant with respect

Fig. 11

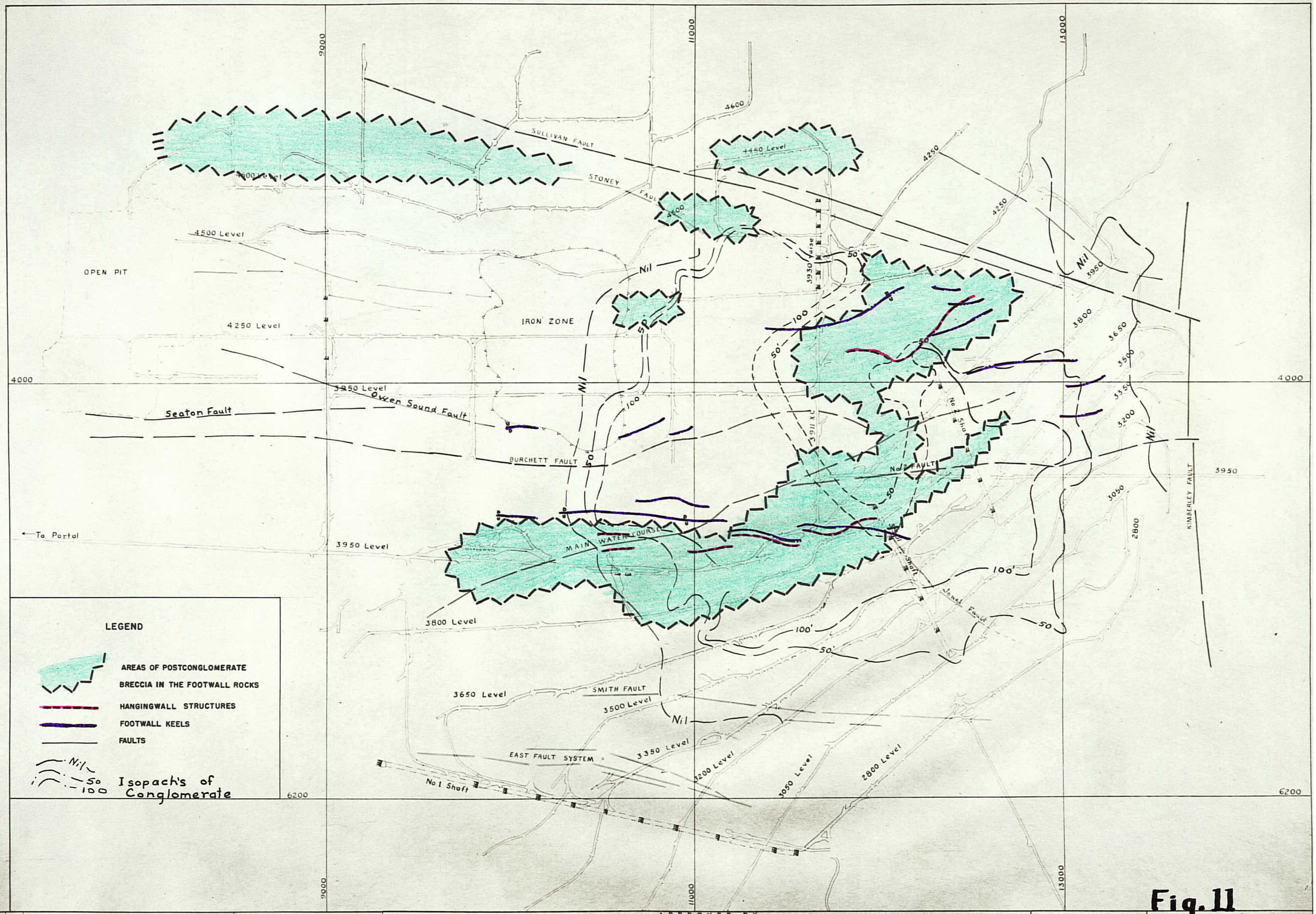


Fig. 11

SECTION:
DEPT.: GEOLOGY
MADE BY: D.F.J.

APPROVED BY

AREAS OF "CHAOTIC" BRECCIATION OF FOOTWALL ROCKS

CONSOLIDATED MINING AND SMELTING CO. OF CANADA, LTD.

TITLE SIMPLIFIED PLAN
SCALE 1" = 200'

to the stratified rocks, extending more or less vertically below the orebody, and cutting the pre-conglomerate breccia. Fig. 8 shows the contrast between the well-bedded lithology east of the post-conglomerate breccia and the variegated rock types encountered in the two diamond drill holes to the west, which have penetrated the chaotic breccia. Note also in Fig. 8 and Fig. 10 that normal foot-wall conglomerate, relatively undisturbed, is found on both sides of the chaotic breccia.

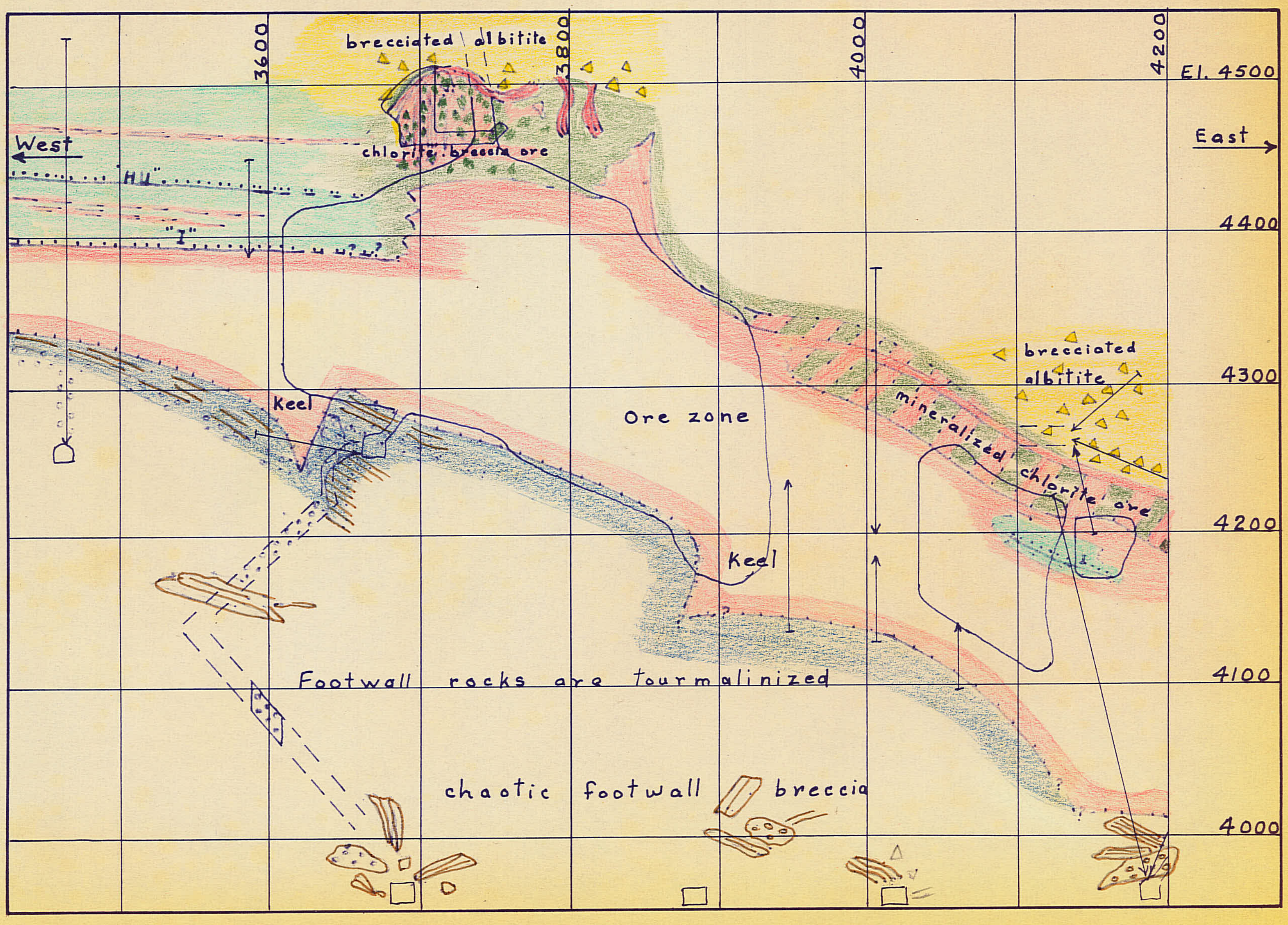
Further evidence of the sharply discordant nature of the breccia is well illustrated by a relatively narrow breccia zone, sharply discordant in its contacts with well-bedded foot-wall rocks, which is found in the southwest part of the mine.

The interpretation of breccia extending downward to considerable depth (Figs. 7 & 8) is based on a projection of information mapped in development headings, and the information available from diamond drill core from holes, four of which are indicated in Fig. 7. It should be realized that the outlines shown are interpretive, increasingly so with depth. Breccia, however, is found in the drill core down to the upper contact of the diorite sill.

Post-tourmaline Brecciation:

Keel structures: "Keel structure" is a term applied by geologists at the Sullivan Mine to downward projections of the sulphide-foot-wall rock contact below the average contact level. In some cases a keel has the aspect of a rather thin vertical fin of ore passing downward into a vein, in others the keel is a broader trough-like depression. One type may change to the other along strike. Cross sections through some of

Fig.12



Vertical Section on Latitude 11900N. to show keel, hanging wall structures, and brecciation Fig. 12

these structures are illustrated in Figs. 12 & 13 and in more detail in Fig. 14. They are shown in plan view on Fig. 11.

Some of the keels are continuous for hundreds of feet although they may be offset en echelon. Their strike is northerly but varies considerably.

A definite displacement of footwall strata accompanies the keel structures. On the two longest ones, the strata west of the keel are down some forty feet with respect to the east. On some of the smaller keels displacement is in the reverse direction. Severe brecciation of the rocks adjacent to the keel is commonly observed.

Figs. 14 & 15 show a keel which has been observed in some detail. The following facts seem pertinent.

1. All sulphide contacts tightly adhere to the footwall rocks, on the discordant east contact as well as on the more conformable west side.

2. Pyrrhotite veinlets anastomose through the breccia, and where they join the massive sulphides of the orebody no line of contact can be discerned. The vein pyrrhotite and the orebody pyrrhotite are continuous.

3. Galena laminations are found to be parallel to both the discordant and the conformable contacts. The laminations which are of the type usually thought to represent relics of sedimentary bedding, are very nearly continuous around the sharp corner at the base of the keel. Similar banding has been seen in the keel where it is quite narrow and vein-like.

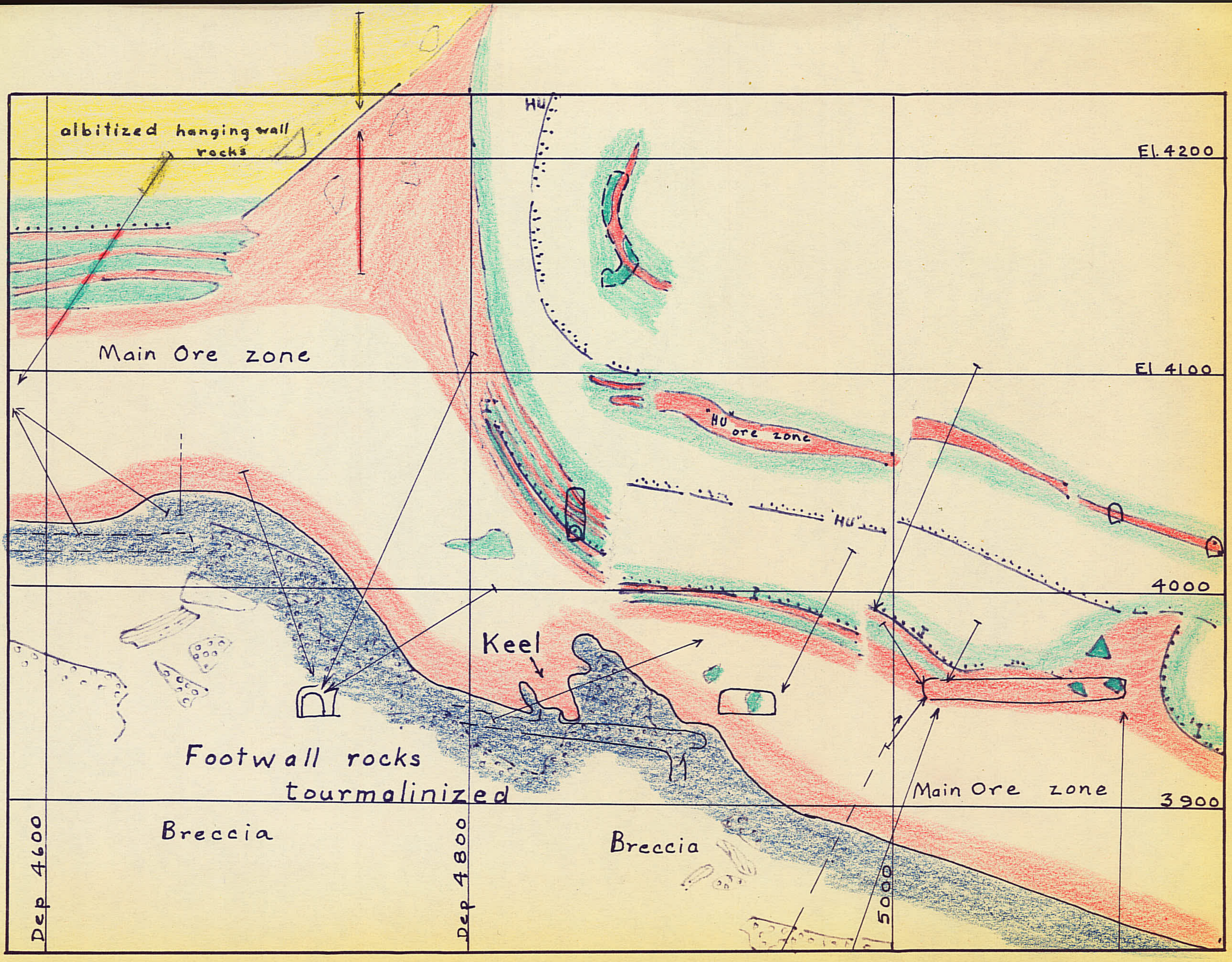
4. Tourmaline "chert" fragments are found in the main sulphide body.

5. A green, fine-grained, chloritized and epidotized feldspar dike occurs in the breccia adjacent to the keel. The dike surrounds tourmalinized fragments, and is found as fragments in the sulphides. (Fig. 12) (Plates 10 & 11) A relatively unaltered, white, fine-grained, feldspar dike of texture and feldspar composition similar to the green altered dike, is found intruding the breccia elsewhere in the vicinity. Plates 13 & 14 illustrate the textures of the two dikes. The chemical compositions shown on page 48 were determined by x-ray fluorescence analysis. Note that the fairly high titanium content (rutile & leucoxene) is common to both. It is possible that the two rock types represent different stages of alteration of the same dike.

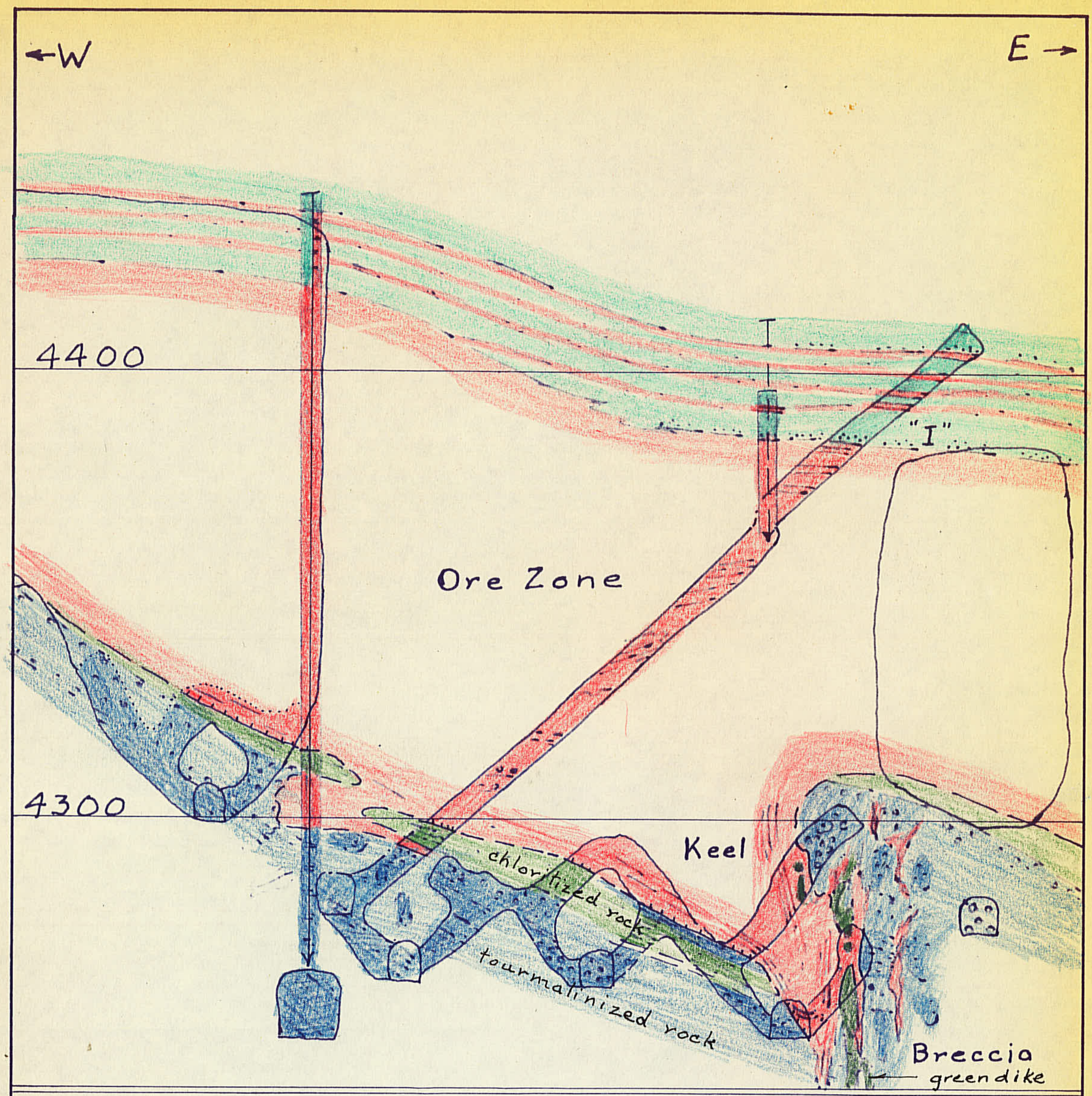
6. A displaced portion of the green dike found some 110 feet above the sulphide footwall is illustrated in Fig. 16 & Plate 12. Note that small fragments of the dike at the broken end are surrounded by ore much richer in galena than most of the adjacent pyrrhotite.

The points listed above indicate that the tourmalinized breccia was rebroken and intruded by the feldspar dike, which was in its turn broken. The breccia was laced with pyrrhotite veins at about the same time, or later. The main ore zone reacted in a contrasting plastic or fluid manner. This contrast in the rheologic properties of the sulphide zone compared with associated argillaceous, igneous, and altered rocks will be discussed in more detail prior to considering brecciation in the ore zone.

Fig. 13



Vertical Section on Latitude 11300 N. to show keel and hanging wall structures along 4800 Departure Fig. 13



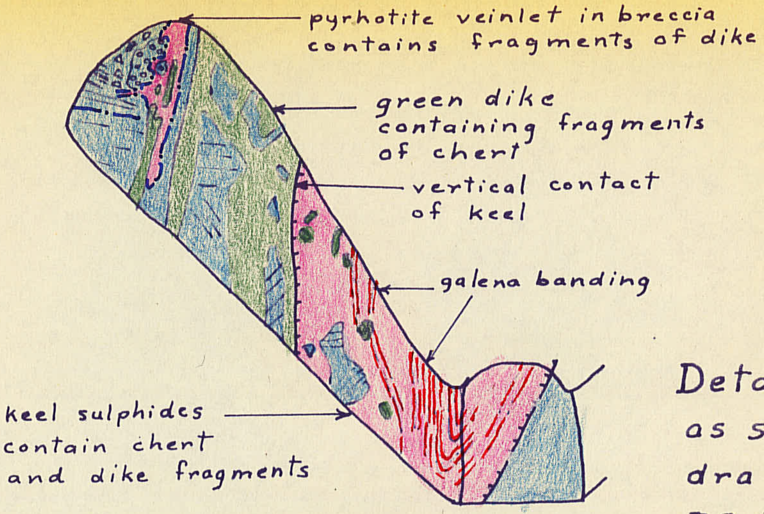
Scale 1" = 40'

Vertical Section looking North to show keel structure

Note — footwall structure has no counterpart in hangingwall

T-8-5 pillar

Fig. 14



Scale 1"≈10'

Detail of keel
as seen in a
drawhole
39-T-18^{S}E D.H $^{\#}$2

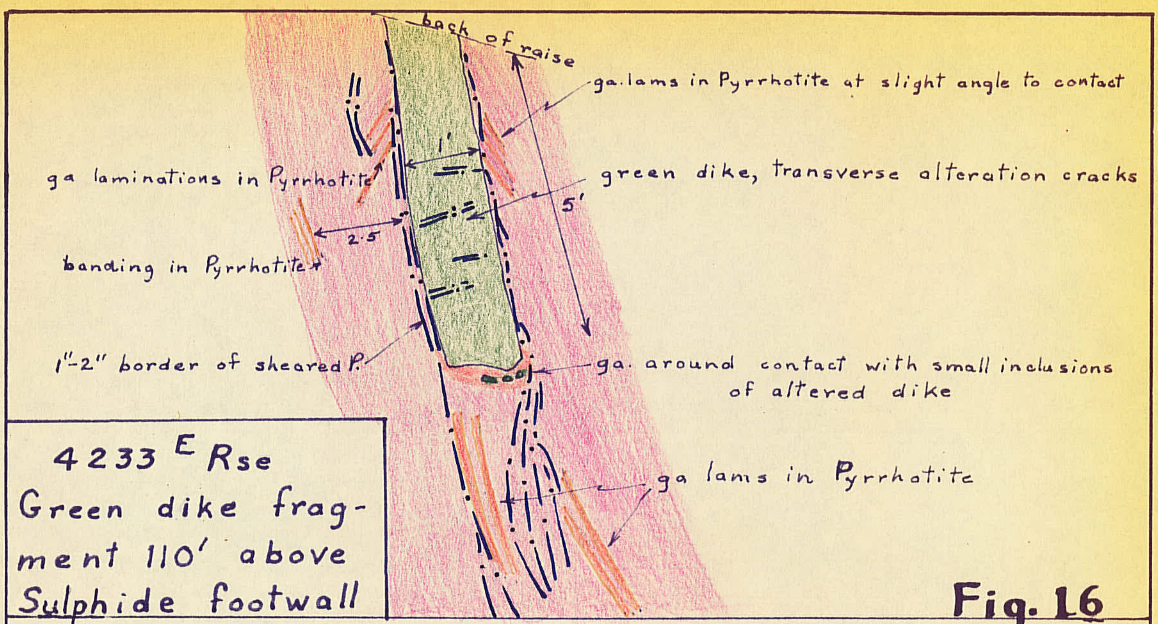
Fig. 15

←Plate 10

contact of green dike
with sulphide keel
Note chert inclusions
in dike

Plate 11 →

Fragment of green dike
in sulphide of keel



4233 ^{E}Rse
Green dike fragment 110' above
Sulphide footwall

Fig. 16

Plate 12

Dike in 4233 ^{E}R as in sketch above

I. MICROSCOPIC EXAMINATION

Breccia Matrix

When examined in thin sections, the breccia matrix is seen to be a poorly sorted aggregate of sand and silt grains ranging from 0.01 mm to 0.5 mm, each surrounded by a thin coating of tourmalinized argillite. The very fine tourmaline needles penetrate the edges of the quartz grains for a short distance, leaving the centres clear. The quartz grains are sub angular to sub rounded, and although occasionally fractured they do not exhibit signs of crushing, shearing or mylonitization. Scattered through the sand grains are tourmalinized chips of fine-grained argillite and coarser, laminated silty argillite. Quartz forms upward of 80% of the matrix in places. Views of typical matrix are shown in Plates 15 & 16.

Tourmaline: It is clear from the way that the matrix has been tourmalinized that tourmaline was introduced after brecciation. The breccia is not merely a cemented accumulation of previously tourmalinized fragments. Furthermore, fragments of all sizes (See Plates 8, 9 and 17) show deformation that indicates they were relatively soft (untourmalinized) when broken. It is concluded, therefore, that a great deal of the brecciation predates the tourmalinization process.

Sulphide minerals: Although pyrrhotite is by far the predominant sulphide mineral, it is not uncommon to find a few grains of chalcopyrite and arsenopyrite in pyrrhotite veins. Galena and sphalerite are relatively abundant locally within the breccia area, to the extent of

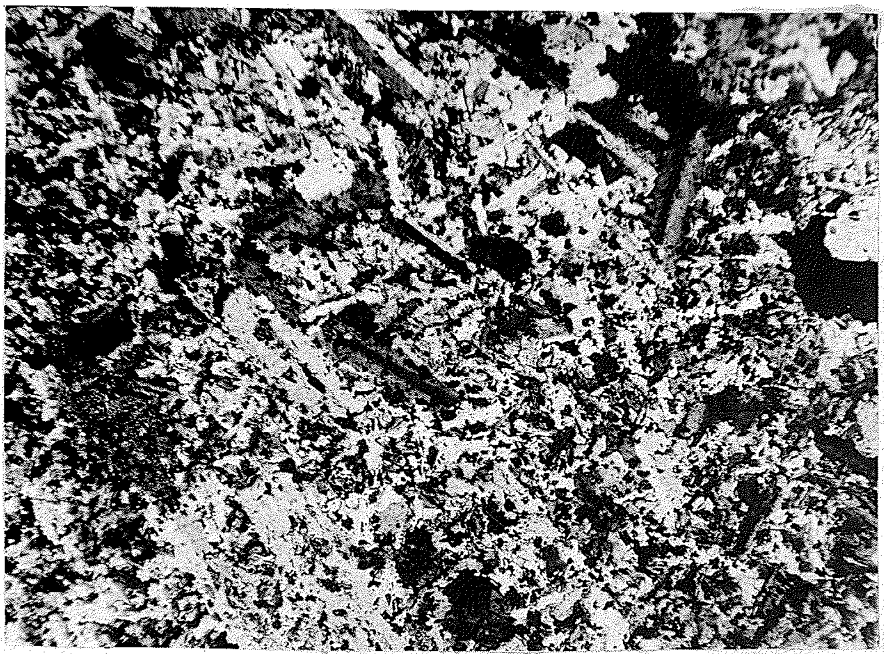


PLATE 13

Feldspar Dike
from Breccia

JU - 64 - 3

Analysis	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	TiO_2	MnO
	66.7	18.10	1.62	Tr.	3.05	--	7.60	2.72	0.03

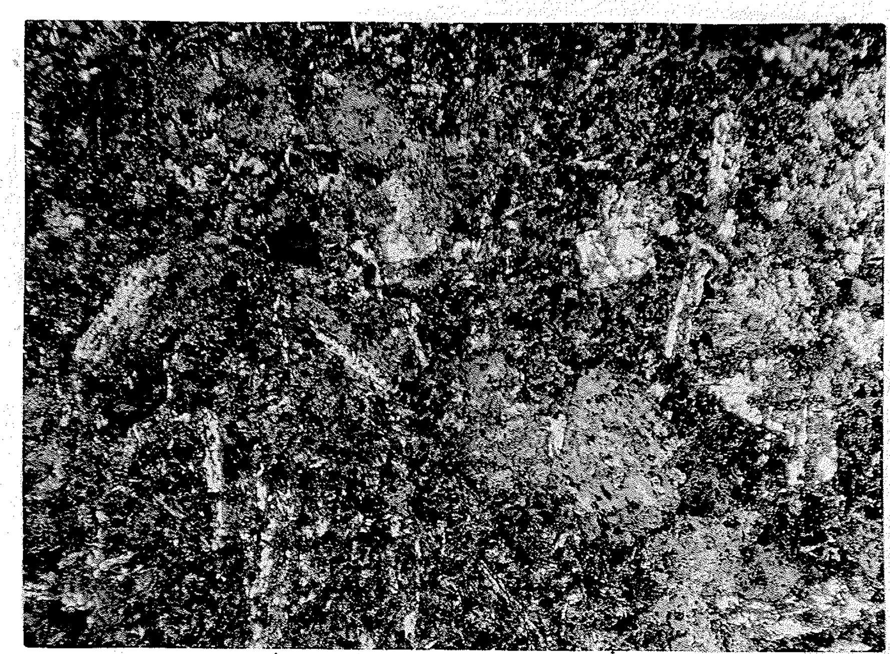


PLATE 14

Green Dike,
chloritized
epidotized
feldspar
dike

J - 937 - 64

Analysis	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	TiO_2	MnO
	51.0	13.10	15.60	3.90	8.50	--	2.65	2.40	1.03

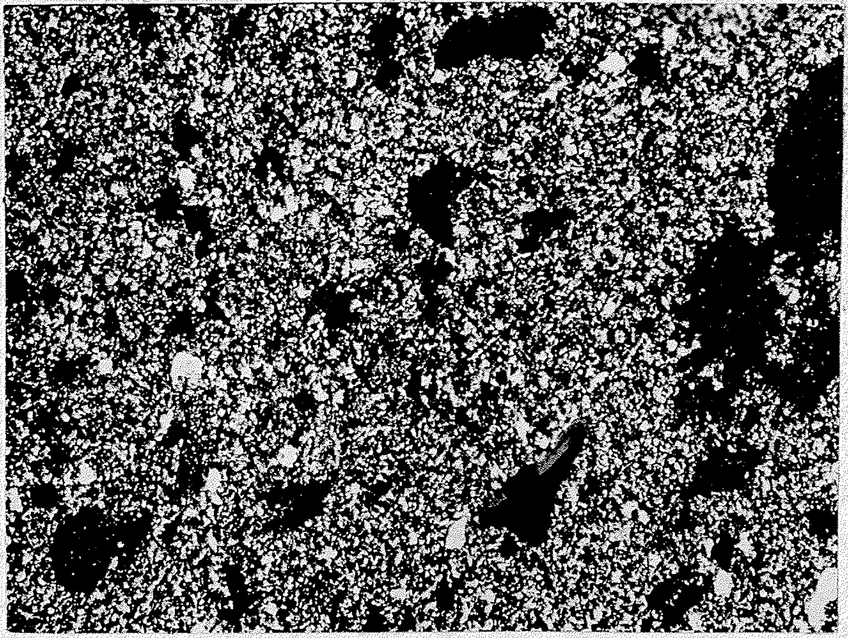


PLATE 15

Breccia Matrix
General view of matrix showing poorly sorted quartz and scattered rock fragments

JR - 65 - 15 15 X

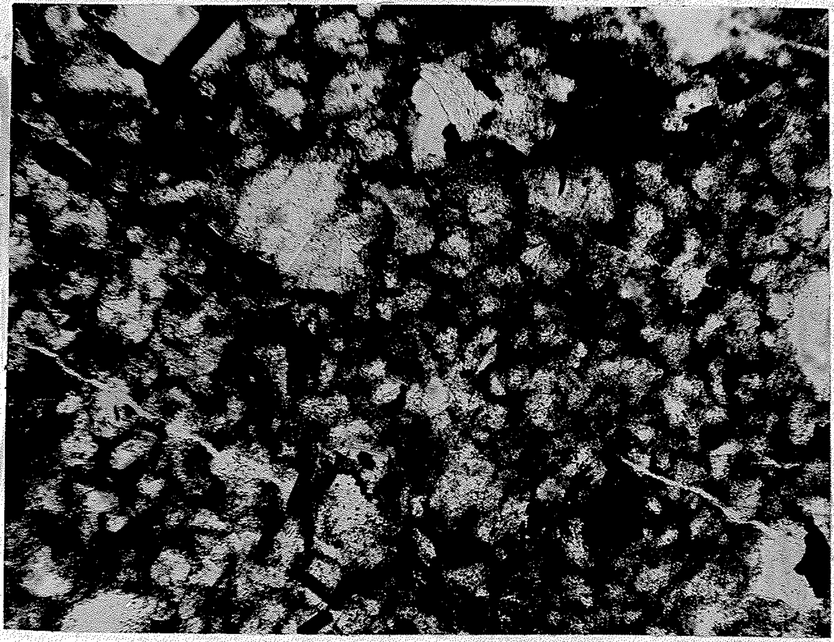


PLATE 16

Breccia Matrix

Note tourmaline needles penetrating quartz grains, and pyrrhotite in fractured grains.

JU - 65 - 14 76 X

making sub-ore to depths as much as 150 feet below the sulphide footwall.

Pyrrhotite is much more plentiful in the matrix than in the fragments, so that oxidized exposure surfaces show matrix areas dark coloured and fragments light coloured. Pyrrhotite is so abundant in many places that it forms the entire matrix. In general however, pyrrhotite is disseminated through the matrix as irregularly-shaped blebs or occurs in thin veinlets in the fine grained fragments. Plate 20 illustrates these relationships. Note in Plate 18, that pyrrhotite has filled a small quartz lined vug between breccia fragments, and in Plate 19 that thin veinlets of pyrrhotite cut straight through the various mineral grains of the matrix. Clearly the sulphide minerals have been introduced after brecciation of the rock. It is also apparent that the sulphide minerals are partly if not entirely later than the tourmaline. The evidence for this is;

1. Veins of sulphide minerals cut through tourmalinized rock.

2. Inclusions of tourmalinized rocks within the sulphide veinlets are common.

3. Sulphide grains cut across tourmalinized quartz grain contacts.

4. Sulphide minerals have textural relationships that indicate they formed later than the muscovite and chlorite alteration of tourmaline "chert".

5. Rarely, larger tourmaline grains are seen which have been broken and the cracks filled with sulphide minerals (Plates 26 & 27).

K Feldspar and muscovite: The presence of feldspar in tourmalinized breccia was first noted in very thin veinlets of microperthite. Elsewhere, grains similar in appearance to detrital quartz but partly altered to muscovite were suspected of being feldspar. Subsequently, staining techniques using hydrofluoric acid etch and sodium cobaltinitrite stain confirmed the presence of potassium feldspars in several specimens. Presence of plagioclase feldspar is indicated by positive reaction to the rhodizonate test, but this cannot be considered to be specific for the reasons outlined in Appendix A.

Distribution of K minerals: The specimens that reacted positively to the K feldspar stain indicated two types of orthoclase distribution. On one fine-grained specimen, very small grains of feldspar were abundantly sprinkled all over the etched surface. On others, the stain was concentrated along certain fractures, with decreasing numbers of disseminated grains away from the cracks. There is a definite close spatial association of feldspars with sulphide minerals. Where muscovite is in contact with sulphide minerals it always shows well-developed straight crystal outlines to which the sulphides conform. Sulphide minerals often penetrate along the cleavage planes of the muscovite books. Although K feldspar and muscovite are always closely associated with sulphide minerals, the reverse is not true; most of the breccia does not contain feldspar.

The distribution of the feldspars shows that they are not detrital although they resemble the quartz grains in size and shape. In addition

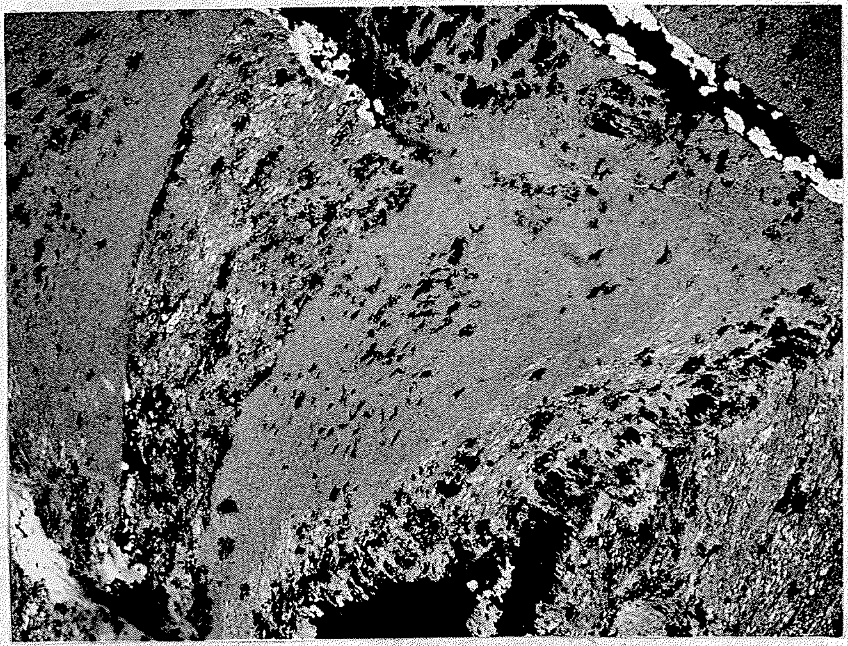


PLATE 17

Breccia

Twisted and
torn fragments
in breccia

JU - 64 - 6 (b) 11 X

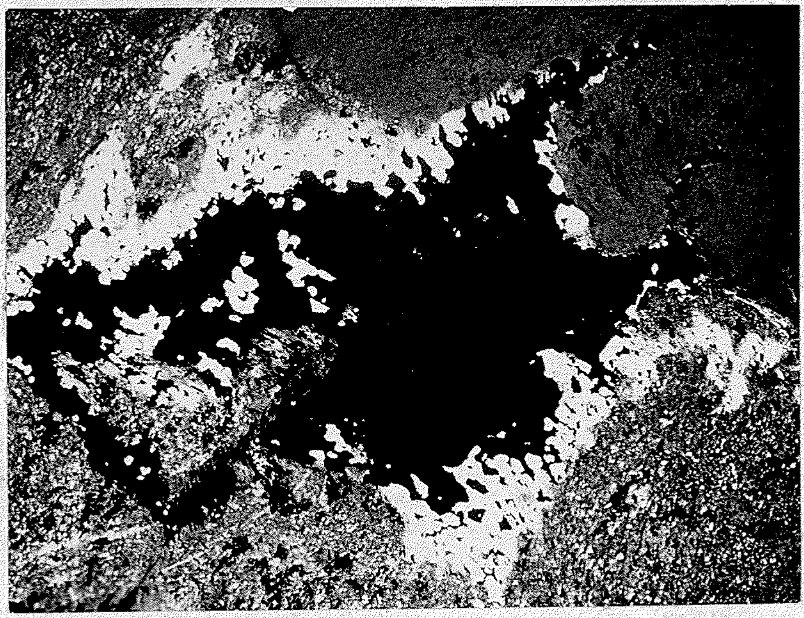
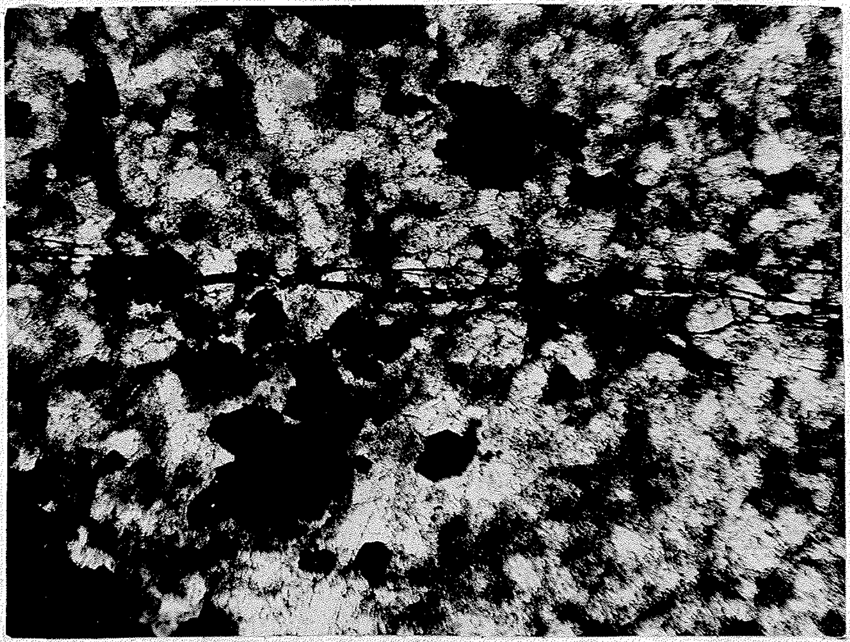


PLATE 18

Breccia

Pyrrhotite
filling a
quartz
lined vug

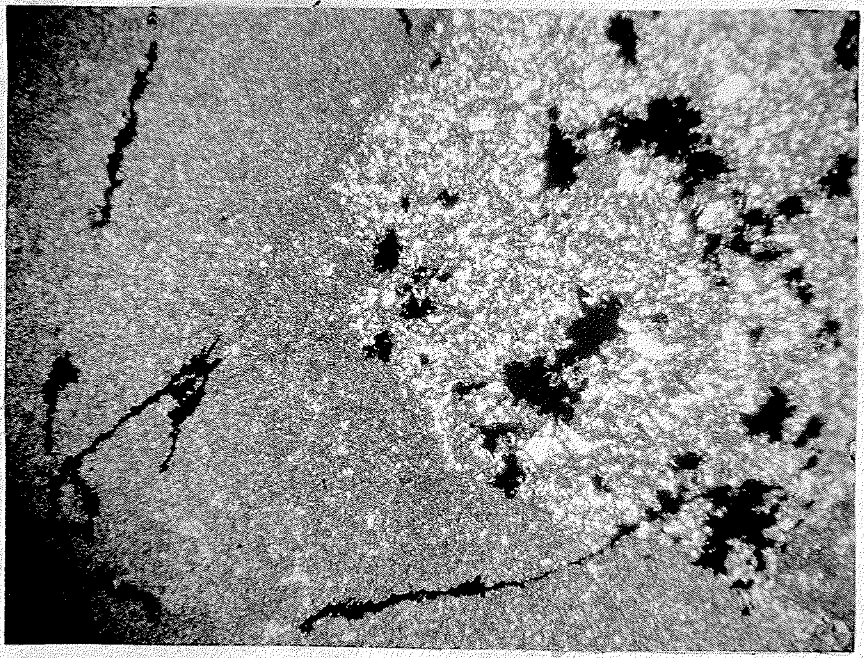
JU - 64 - 6 (a)



JU - 65 - 16 73 X

PLATE 19

Pyrrhotite
veinlet cutting
breccia matrix



JU - 65 - 1 A 20 X

PLATE 20

Breccia

Pyrrhotite
distribution
in matrix
(right) and
in fine grained
fragment (left)

PLATE 21

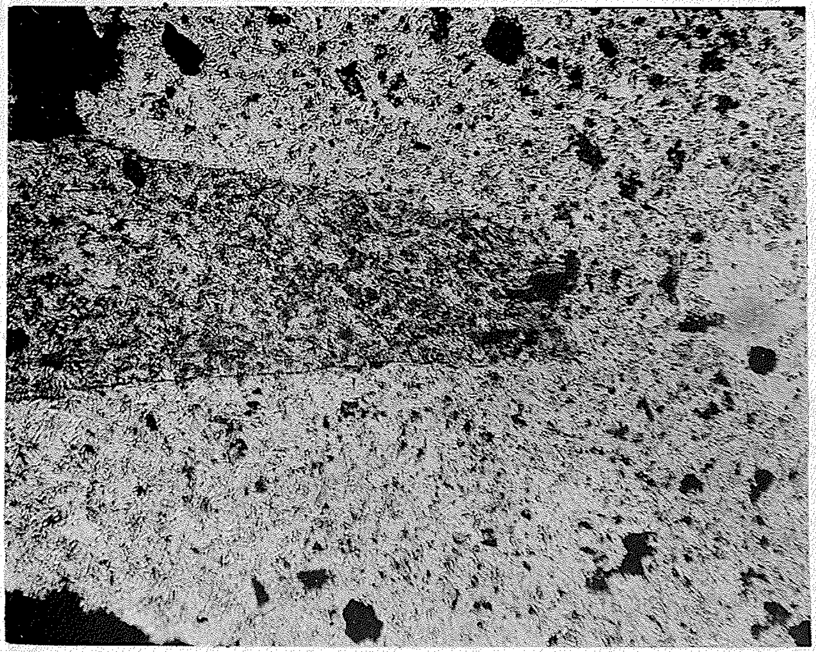
Breccia Matrix

Orthoclase
(centre)
altering to
muscovite

JU - 64 - 4 120 X

PLATE 22

Altered Tourmalinized
Argillite Inclusion
from Ore Zone
Orthoclase altering
to muscovite
(wedge shape)
note included
tourmaline needles



JU - 65 - 13 (a) 192 X
X nicols

they do not show the alteration due to weathering that might be expected in detrital grains. Their presence would seem to be due to a potassium metasomatism.

Post-tourmaline Alteration

Alteration zones cut through the tourmalinized foot-wall rocks in many places; the alteration effects varying in severity and in kind.

Detourmalinization: Mild alteration is often observed spreading out to short distances on either side of fracturesin the areas of massive tourmalinization, removing the cherty characteristics of the rock and leaving it very similar in appearance to normal argillites and silty argillites. More extensive alteration usually grades from a sericitized or chloritized central zone to mildly altered edges. Frequently in conglomerate, the matrix has altered more rapidly than the pebbles, leaving what appears to be "chert" pebbles in slightly chloritic silty argillite.

Very severe alteration has locally decomposed the tourmalinized rocks to a brownish soft muddy material which contains disseminated calcite crystals.

Chloritization: Chlorite is the most abundant alteration product. Large volumes of foot-wall rocks are chloritized at the west end of the iron zone (Fig. 9). Remnants of tourmaline chert are commonly found enclosed in the chlorite. Chloritic alteration is also often found for a few feet below the sulphide footwall. It is a characteristic of much of the chlorite that it is associated with pyrite rather than pyrrhotite.

Often the iron sulphide will be pyrrhotite in the tourmaline "chert" but will be pyrite in the chloritized portion of the same bed a few inches away. The chlorite is an iron-rich variety with anomalous brownish and berlin blue interference colors.

Sericitization: Sericitic alteration produced a light grey colored rock that has a bleached appearance in comparison to the darker grey of normal silty argillites, and the green of the chloritized rocks. Strong alteration produced in places muscovite crystals much larger in size than the tiny sericite flakes. Associated with the muscovite, in about equal amount, is a chlorite mineral characterized by a light greyish color with no pleochroism, and low birefringence with no anomalous coloring. An x-ray powder photograph of the mineral showed a pattern closest to chlorite (variety aphrosiderite).

$\mathrm{Mg}\ 1.0\quad \overset{\cdot\cdot}{\mathrm{Fe}}\ 3.2\quad \overset{\cdot\cdot\cdot}{\mathrm{Fe}}\ 0.4\quad (\mathrm{Al}\ 1.5\quad \mathrm{Si}\ 2.5)\quad 010\ (\mathrm{OH})\ 8$

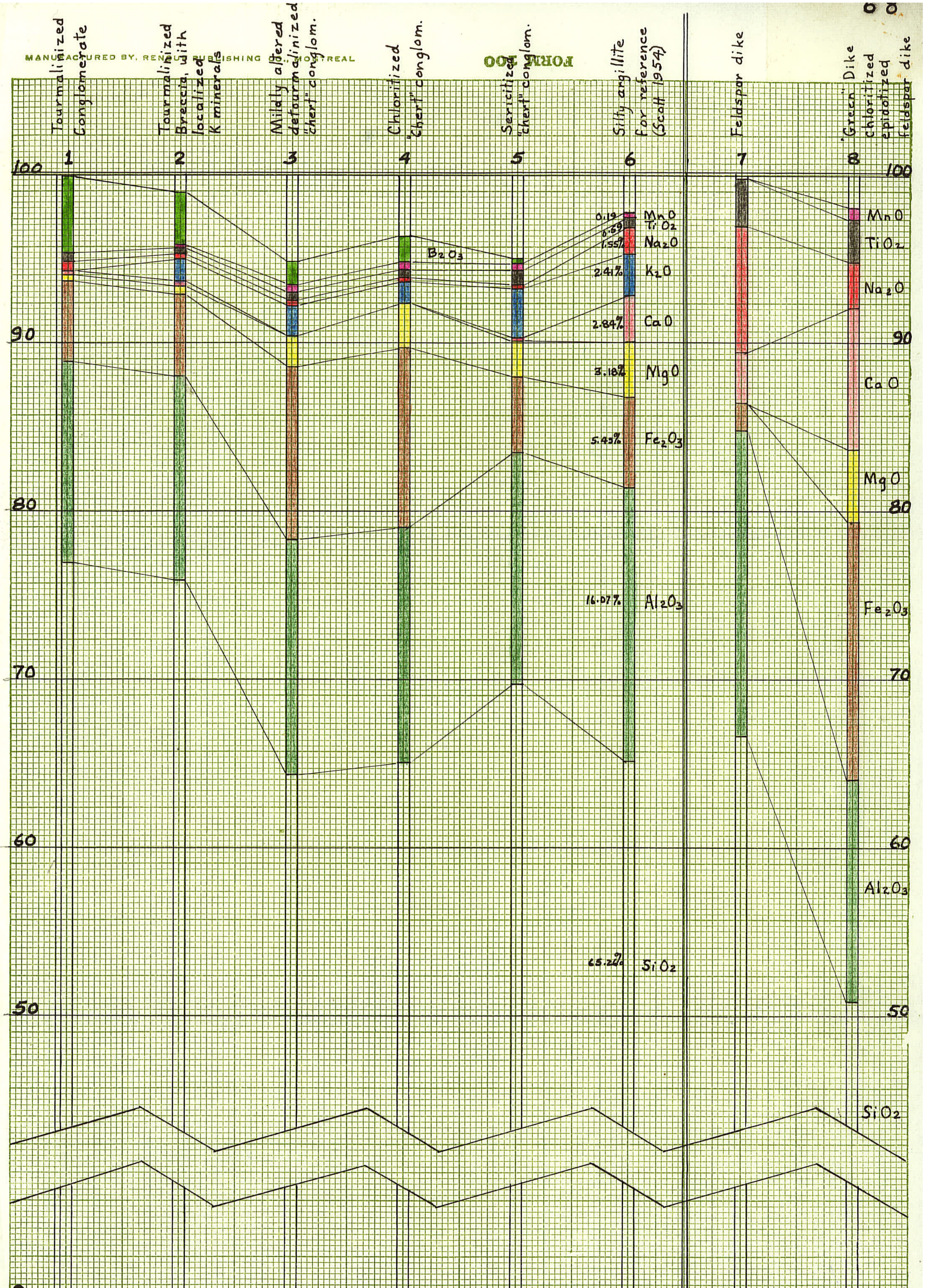
A.S.T.M. 12-243

Albitization: Albitized rocks in the tourmalinized foot-wall are fairly abundant locally in the central western area of the mine. They are associated rather closely with diorite dikes. Occurrences vary from narrow albitized zones along fractures through the tourmaline "chert", to broader, extensive masses of altered rock. In general the albitized masses are dense, fine-grained and white in color, but at contacts with "chert" there are narrow (two or three inch) brown and green colored bands suggestive of reaction rims. These rims were observed at the external contacts of albitized masses, and internally where there are remnants of "chert".

One broad alteration zone that cuts tourmalinized foot-wall conglomerate on the 4250 Level, has chlorite as the main alteration, but pebbles have been selectively albitized. Albitization of pebbles has been observed to occur into the tourmalinized rocks for a few inches beyond the contact of the main alteration zone.

Chemical analyses of "chert" and post-tourmaline alteration products: A series of 5 specimens were chosen to represent (1) tourmaline chert; (2) chert with minor development of orthoclase; (3) detourmalinization; (4) chloritic alteration; (5) strong sericitic alteration. The specimens were prepared for analysis by x-ray fluorescence and flame photometer method. The specimens were pulverized. Sulphide minerals were leached out by the chlorine-methanol method described in Appendix B. The results of the analysis are presented in Fig. 17 & 18.

The most notable changes accompanying increased alteration appears to be a decrease in silica accompanied by increased iron, magnesium potassium and manganese. Titanium is constant but sodium shows a slight decrease. There is a markedly higher potassium content in the sericitized rocks than in the chloritic rocks and about half as much iron. The lower iron to magnesium ratio is probably because of a less iron-rich variety of chlorite in the sericitic rock. Boron content decreases with increasing alteration. A specimen of chloritized breccia fragment taken from a keel structure shows micro-breccias of biotite-chlorite flakes into which sphalerite, pyrrhotite and quartz have been introduced. (See Plates 28 & 29). Tourmaline crystals are found in this chloritized rock which are much larger than usual (possibly recrystallized). Many of these have broken. Chlorite fills the cracks in some, sulphides in others, (See Plates 26 & 27).



Graph Relating Chemical Analyses Fig 17

18. Table of Chemical Analyses

Analysis No.

	1 ★	2 ★	3 ★	4 ★	5 ★	6 ★	7 ★	8 ★
B203	4.51	2.90	0.97	1.29	0.23	N.D.	0.03	0.03
MnO	Tr.	0.09	0.66	0.44	0.23	0.19	0.03	1.03
Ti 02	0.50	0.46	0.65	0.66	0.68	0.59	2.72	2.40
Na 20	0.70	0.30	0.20	0.23	0.19	1.55	7.60	2.65
K 20	Nil	1.33	1.72	1.25	2.92	2.41	Nil	Nil
CaO	0.10	0.36	Tr.	Tr.	0.10	2.84	3.05	8.50
MgO	0.25	0.40	1.90	2.60	2.40	3.18	Tr.	3.90
Fe2 03	5.00	4.86	10.34	10.60	4.36	5.45	1.62	15.60
Al2 03	11.90	12.20	13.85	14.05	13.80	16.07	18.10	13.10
Si 02	77.0	76.0	64.5	65.2	69.75	65.26	66.7	51.0
	99.96	98.90	94.79	96.32	94.66	97.54	99.85	98.21

★ Analyses by x-ray fluorescence and flame photometer. U. of Manitoba Geology Dept. K. Ramlal anlyst.

Description of samples

(A) Tourmalinized rocks and rocks altered subsequent to tourmalinization.

1. "Chert" conglomerate, dense, dark and hard. No visible alteration.

   Minor amounts of sulphide minerals.

   JU - 65 - 27 3930 A Rse. 8.8% sulphide

2. Tourmalinized breccia, dense dark hard "chert" K feldspar and

   some mica present, concentrated along fractures.

   JU - 64 - 4 39120 D.N. 19.9% sulphide

3. Detourmalinized "chert" conglomerate fairly soft with a few "chert" pebble remnants.
   Rock resembles slightly altered silty argillite.
   JU - 65 - 24 D-3 38331 SA 9.4 sulphide
4. Chloritized "chert" conglomerate. Soft greenish grey rocks.
   Occasional chert remnant.
   JU - 65 - 44 D-4 38331 SA 17.5% sulphide
5. Sericitized conglomerate, soft light grey rocks.
   Strongly mineralized with sphalerite and pyrrhotite.
   JU - 65 - 26 B-4 39-P-19 Rse. 37.7% sulphide

4. Chloritized "chert" conglomerate. Soft greenish grey rocks. Occasional chert remnant.

JU - 65 - 44 D-4 38331 ^{S}A 17.5% sulphide

5. Sericitized conglomerate, soft light grey rocks. Strongly mineralized with sphalerite and pyrrhotite.

JU - 65 - 26 B-4 39-P-19 Rse 37.7% sulphide

(B) Reference specimen, normal sediments.

6. Silty argillite collected by Scott.

(Scott 1954 Table II)

From below the sulphide foot-wall

D.D.H. 4728

(C) Feldspar and "green" dikes

7. The feldspar dike is a white fine-grained rock intruded into brecciated chert and found with included fragments. It contains considerable amounts of pyrite. Rutile and leucoxene are plentiful in the fine-grained matrix surrounding feldspar crystallites.

JU - 64 - 3 16.4% sulphides

8. The "green" dike is a fine-grained green colored rock intruded into brecciated chert and found as fragments broken in the ore zone. It has a texture similar to the feldspar dike but the feldspars have largely been altered to chlorite and epidote. Textures have been preserved by the rutile and leucoxene which mark the original fine-grained matrix. Feldspar crystallites remain as clear areas with occasional remnants of feldspar.

J - 937 - 64 7.6% sulphide

Summary

The evidence, both macroscopic and microscopic, shows that a number of metasomatic minerals have formed after tourmalinization of the foot-wall rocks. Orthoclase, and muscovite have formed where potassium has been introduced. Chlorite has formed where iron, magnesium and water have been available, and albitization attests to the local availability of sodium. Introduction of these materials into the tourmalinized rocks has involved re-breaking the breccias more or less severely. Minor amounts of igneous material in the form of the feldspar dikes, have been intruded into the breccia. Keel structures have formed where movement has been concentrated along linear zones, with resulting vertical displacements of forty or fifty feet. The relationships of sulphide minerals and quartz to chlorite and micas, indicate that the former pair were mobile after the latter had formed and had been bent and broken. The sulphide minerals were also mobile after the igneous dikes had been intruded. The nature of mobility in the sulphide zone will be discussed in the following chapter.

CHAPTER VI

RHEOLOGY OF SULPHIDE ZONES

Definition of Sulphide Zones

The term "sulphide zone", as used here, refers principally to the various ore bands of the Sullivan ore body but includes mineralized zones that would be excluded by the term ore. It should be clearly understood that the term sulphide zone refers to their present composition and does not imply that they were necessarily sulphide zones in the same sense at the time they were mobile. Descriptions are phrased in terms of the mobility of sulphide minerals but with the idea that the sulphides need not have existed at that time in their present mineral form.

Mobility of Sulphide Zones

Contrasting competence between ore bands and the surrounding silicate rocks is displayed in many relationships and on a variety of scales. Some of these have been mentioned previously in discussing brecciation of the footwall rocks.

Plates 23 and 24 show argillite beds near the hanging-wall of the main band of ore which have fractured whilst the sulphides and thinner argillite bands have deformed plastically. Plate 25 and Fig. 19 show how displacement of hanging-wall beds of the HU ore zone on small fractures has been accommodated by flow in the ore band. The faults do not cut through the ore zone. On a microscopic scale, (Plates 28 and 29) sulphides show continuity around broken ends of chlorite flakes. Plastic flow seems a less likely explanation for mobility of sulphides in the

PLATE 23

To Show Mobility in
Sulphide Bands

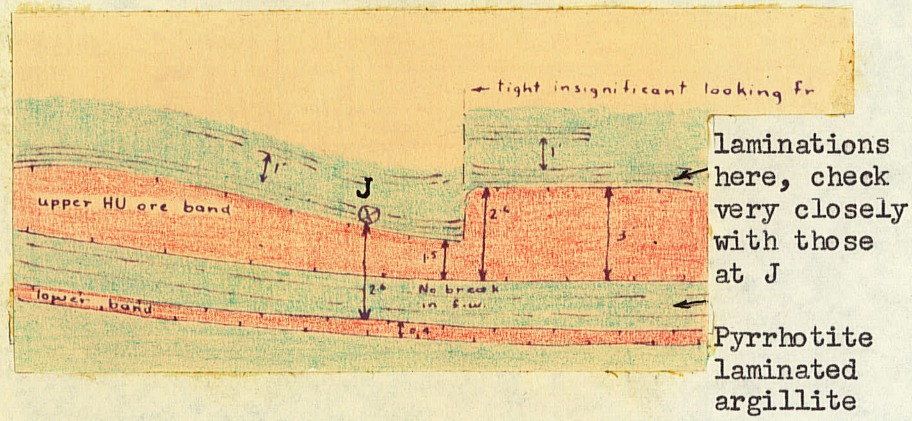
Note that movement which fractured thicker argillite bands is taken up by crumpling in sulphide bands

PLATE 24

To Show Mobility in Sulphide Bands

PLATE 25

Movement on small fault in hanging-wall has been adjusted to by plastic flow in ore band.



laminations here, check very closely with those at J

Pyrrhotite laminated argillite

FIGURE 19

A similar occurrence mapped at a different location

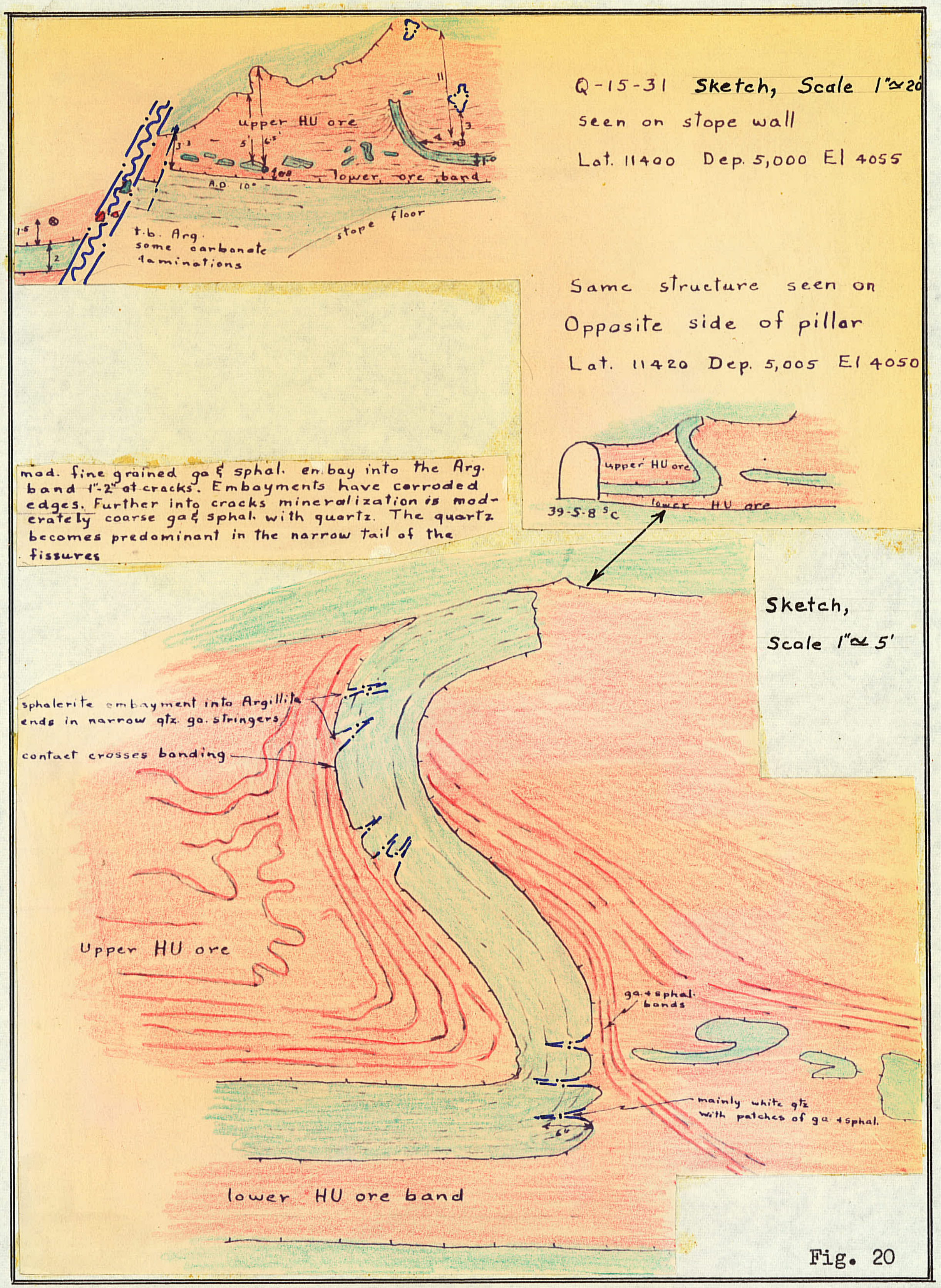


Fig. 20

Sketch of Broken Argillite Parting in HU Ore Zone. Note tension fractures.

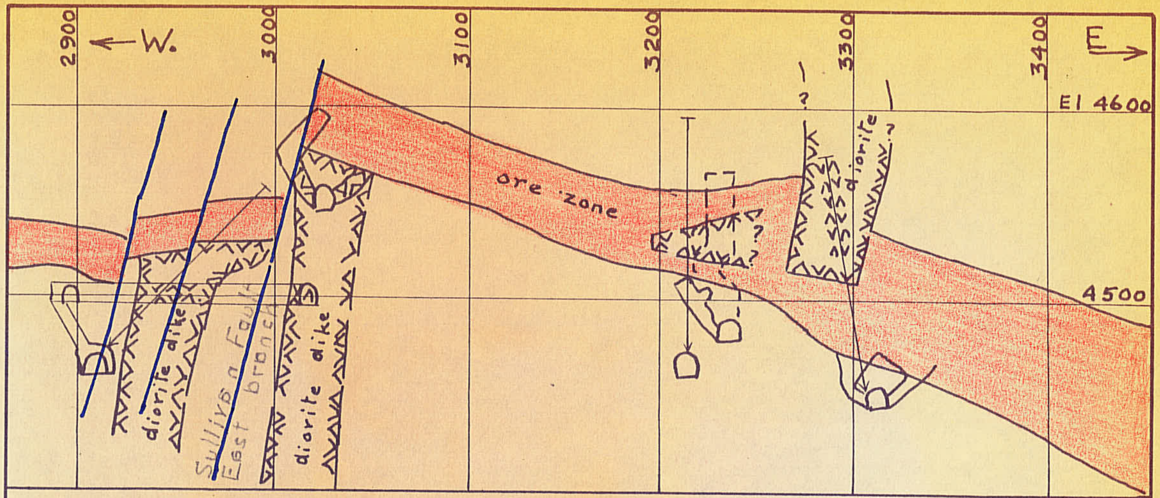
microbreccias than in the macroscopic cases. The unbrecciated quartz, closely associated with the sulphide minerals, which has penetrated the microbreccia to the same extent as the sulphides, was undoubtedly mobile in solution.

The following opinion has been expressed regarding the state of the ore zone and the sulphides during the mobile period (C.M. & S. staff, pp. 148):

> Folding on a large or small scale is quite common, and apparently continued during and after the period of mineralization because in places, the sulphides follow tiny tensional fractures developed on minor anticlines while elsewhere they show slickensides produced by slipping between beds during folding.

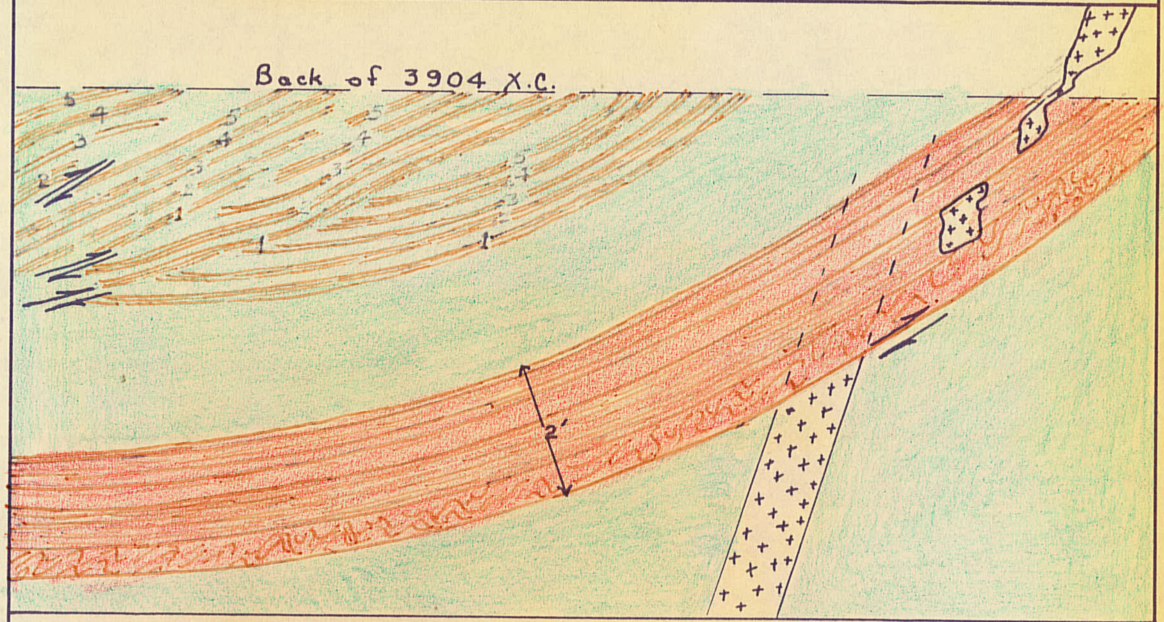
One example of sulphides penetrating tensional cracks is found in the HU ore zone (Fig. 20) where an argillite parting in the ore, broke and was thrust upward through the ore zone. Sulphides in the tension cracks were examined carefully and were found to change in character from the fine-grained pyrrhotite sphalerite mixture of the ore zone at the open end, to moderately coarse crystalline sphalerite and galena further in the crack. Beyond this, in the tail of the fracture, the filling gradually becomes quartz and carbonate with sparse sulphide minerals. Clearly the filling is not simply a plastic flow of ore into the fractures.

Further to this point it should be noted that the sulphides have not always behaved plastically under stress, as is shown by some of the younger faults of the Sullivan type which have sheared through the ore zone and in which broken ore fragments have been found below the sulphide foot-wall.



Sketch of a portion of geology from section on Latitude 11400 (X) North, showing diorite displaced in ore zone

Fig. 21



Sketch of Minette Dike Displaced Along the "D" ore band, and overthrusting of laminated bands showing the same direction of displacement. 3904 X.C.
after drawing by S. B. Hamilton

Fig. 22

Diorite and other igneous dikes that are found broken up in ore zones, provide examples of sulphide mobility. Other than the dislocated fragments, there is no record within the sulphides themselves of where movement took place. There is no shearing and no obvious flow lineation. Fig. 21 shows fragmentation of a diorite dike in the west central part of the main ore zone. Fig. 22 shows the fragmentation of the minette dike described by Leech (Leech and Wanless 1963 p. 251) and referred to previously on page 27. Note the minor thrust faulting, with movement in the same sense as that shown by the dike displacement, found in a laminated zone above the D sulphide band. The laminations carry disseminated sulphide minerals. The planes of thrusting would be imperceptible were it not for the presence of the displaced laminations. Similar tightly healed, practically imperceptible fractures are fairly common in the argillaceous rocks in other locations.

A feature often observed in connection with ore which surrounds displaced fragments, or penetrates cracks in them, is the segregation of minerals into bands paralleling the contacts. Thus the fragment of altered feldspar dike shown in Fig. 16 and Plate 12 has a concentration of galena around its broken end, and the sulphide veinlets penetrating the quartz vein shown in Fig. 24 and Plate 31 are banded with galena and sphalerite. Note also that mineralized conglomerate has flowed toward the crack in the quartz, and that mineralized sediments have flowed around the fragments of quartz vein Fig. 23 and Plate 30.

It seems clear that the property of "flowing" was not confined entirely to sulphide bands but was also present where the ore zone consists of disseminated mineralization in meta-sedimentary rocks.

Furthermore, whatever was the means of transportation of the sulphide minerals it was often capable of depositing them in layered concentrations.

In summary, the sulphide zones show many evidences of having been highly mobile compared to the argillaceous beds but it is doubtful that the mobility was due to properties of the sulphide minerals as they now exist.

Breccia in the Ore Zone

Breccia in the ore zone is most clearly apparent in certain fringe area stopes. A large portion of the ore in these locations is heavily disseminated rather than massive. In part it is made up of slightly mineralized fragments in a well-mineralized matrix. Cut-off grade may occur where fragments become very numerous.

Some of the ore zone breccias are simply non-mineralized bands pulled apart, in places as a result of folding. These can be readily reconstructed mentally. In other places complete dislocation and rotation of fragments occurs. Frequently the fringe breccias are stratigraphically confined between fairly continuous hanging-wall and foot-wall bands. One such occurrence is illustrated in W-7-30 stope (Fig. 23).

Here a continuous sulphide band below the "I" marker bed, overlies a mineralized breccia zone, which in turn overlies the foot-wall conglomerate. A sill-like quartz vein has been fragmented in the breccia zone and is now surrounded by mineralized breccia. Sulphides penetrate fractures in the quartz. In the same stope, brecciated sedimentary rocks are found in a quartz matrix (Plate 32). Clearly, repeated brecciation has occurred, before and after the inroduction of quartz.

Towards the central area of the mine, brecciation in the ore zone may be indicated by remnants of various types and sizes of silicate rocks. Some fragments of argillite or chloritized argillite layers near the hanging-wall are likely pieces of the regular succession, possibly still in place. Other fragments are obviously displaced. Fragments of tourmalinized foot-wall rocks, including foot-wall conglomerate, have been found well up in the ore.

Plate 33 shows fragments of argillite (light brown) in massive pyrrhotite of the main ore zone as seen on an oxidized wall of a 3900 level drift. Some of the fragments enclosed in massive sulphides remain as heavily mineralized ghostly remnants. Strong development of muscovite is noted in some. Garnets, (variety spessartite-pyrope) are fairly common, and actinolite and talc have been noted in places. A tendency for fragments to be rimmed by sphalerite and galena segregations has been mentioned before. The fragments in the ore zone have tended to react with the sulphides. Higher grades of metamorphism of inclusions within the ore zone indicate it was hotter than the surrounding rocks.

Fig. 23

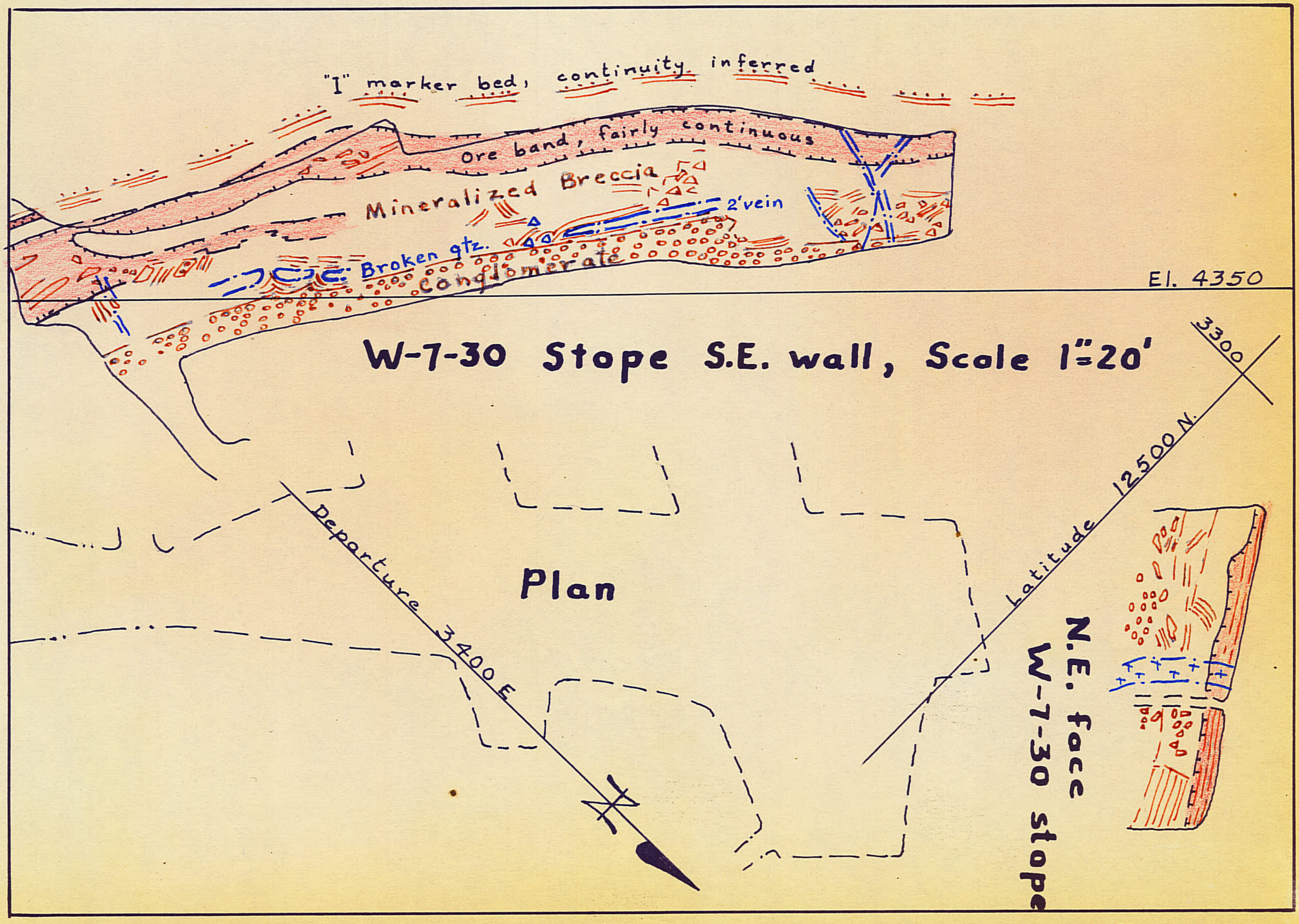
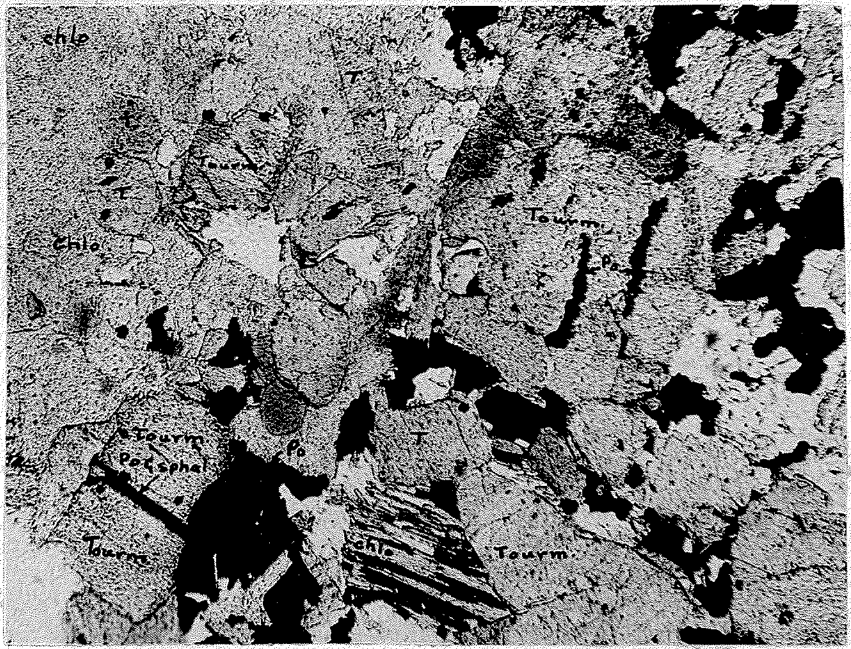


Fig. 23

Ore Zone Breccia, Fringe Area, Stratigraphically confined



JU - 939 - 64 76 X

PLATE 26

Chloritized Fragment from Keel Breccia.

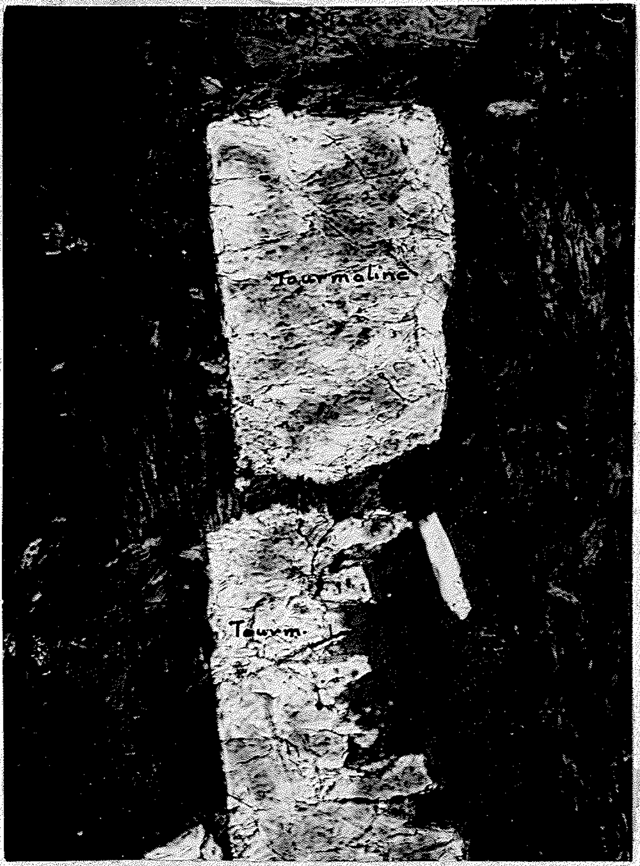
Tourmaline chlorite, quartz and sulphides.

Note sulphide minerals in fractured tourmaline.

PLATE 27

Fractured Tourmaline Crystal, chlorite fills fractures.

J - 939 - 64 320 X



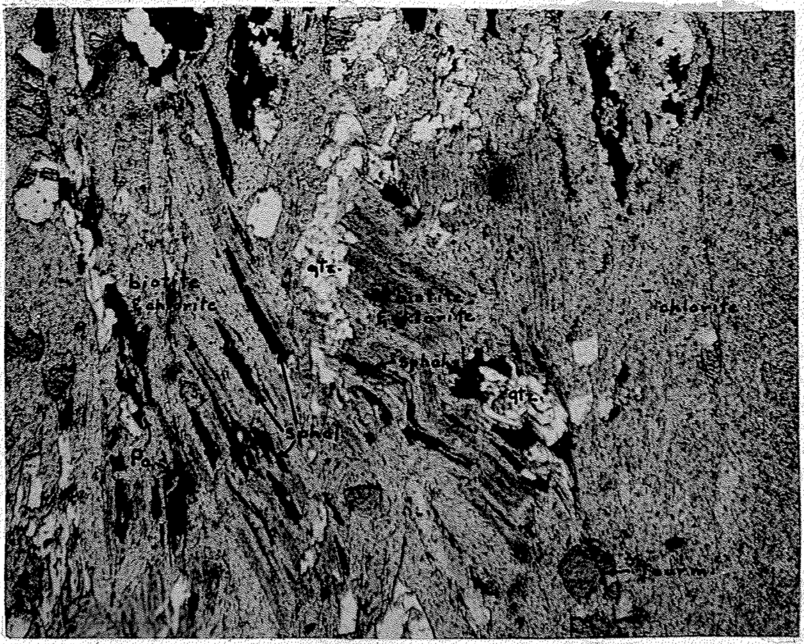


PLATE 28

Chloritized Argillite from Keel Breccia showing Sphalerite Pyrrhotite and Quartz

J - 940 - 64 38 X

plane light

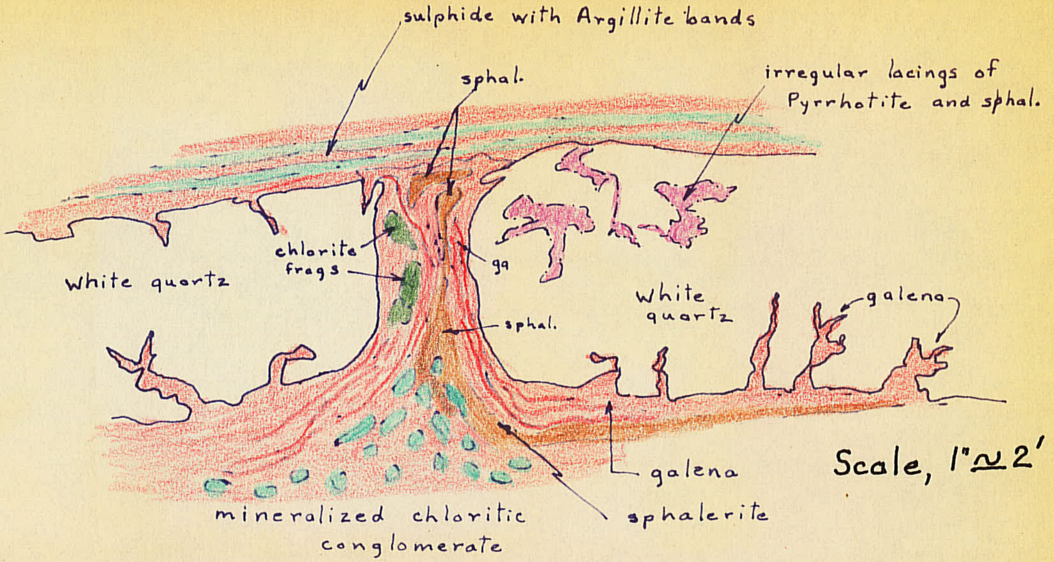
PLATE 29

Micro Breccia

Enlarged portion of photo above. Note brecciation of chlorite and filling of cracks with sulphide and quartz

J - 940 - 64 95 X

x nicols



Sketch of break in quartz vein, W-7-30 stope

Fig. 24

Plate 30

quartz vein in mineralized breccia

Plate 31

veinlets of sulphides cutting quartz
Note galena laminations (grey streaks) paralleling contact of right hand veinlet

PLATE 32

Mineralized Breccia, fringe ore W-7-30 Stope

Note - quartz forms matrix of part of the breccia

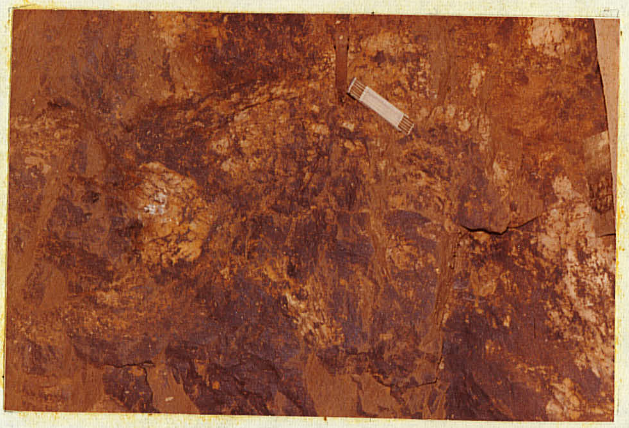


PLATE 33

Fragments of Argillite in Oxidized Massive Sulphides of the Main Ore Zone

CHAPTER VII

BRECCIA ABOVE THE ORE ZONE

The breccia above the ore zone differs in character and origin from the chaotic breccia in the foot-wall rocks.

Distribution - Limited Exposure

The hanging-wall breccia is most noticeable in the albitized rocks, particularly where white albitized fragments are found in green chloritized matrix. Most of the evidence of this breccia has been seen in diamond drill core, and is found to have a broad distribution in the albitized hanging-wall rocks.

Direct observation of the hanging-wall rocks is limited by relative scarcity of development headings above the ore. However, mining of the hanging-wall ore has exposed considerable areas particularly in the HU ore band. Normally this band is quite continuous and conformable, but it has been involved in brecciated hanging-wall structures.

Hanging-wall Structures

The hanging-wall structures have elements of both folding, and faulting with severe brecciation. Interpretation of the structure is often hampered by extensive alteration of the hanging-wall beds to chlorite and albitite, which obscures marker beds. Two of the structures are illustrated in Figs. 12 & 13.

Features of the structures are as follows:

1. Hanging-wall marker beds can be recognized to the east and the west of the structures.

2. Beds to the east turn steeply upward along the east flank of the structure.

3. Beds to the west are flat-lying and displaced downward from the same upturned beds on the east flank. There are no indications that the beds to the west have been folded to form a western flank to an anticline.

4. The hanging-wall of the ore is more or less concordant with the beds of the east flank but is sharply discordant with those to the west.

5. Breccia fragments are found in the ore and adjacent to it, especially along the discordant contact.

Although the origin of the structures is not fully understood a possible explanation is as follows:

The hanging-wall rocks were folded into a monocline which developed a steep east limb. As the fold developed, faulting with brecciation took place along the western axial plane. Mobile material from the ore zone was injected along the brecciated fault zone, pushing the east limb upward and eastward.

Thickening and Thinning of the Ore Zone

The ore zone has marked variations in thickness due to the hanging-wall structures and the foot-wall keel structures, which trend in the same direction and are closely associated in space, (Fig. 11). The raised portions of the hanging-wall often overlie the lowered foot-wall in a keel giving a very thick ore zone, (Fig. 13).

An extreme variation in thickness is illustrated in one area where the hanging-wall and foot-wall structures resulted in an attenuated ore zone only three feet thick some forty feet east of a portion 250 feet thick.

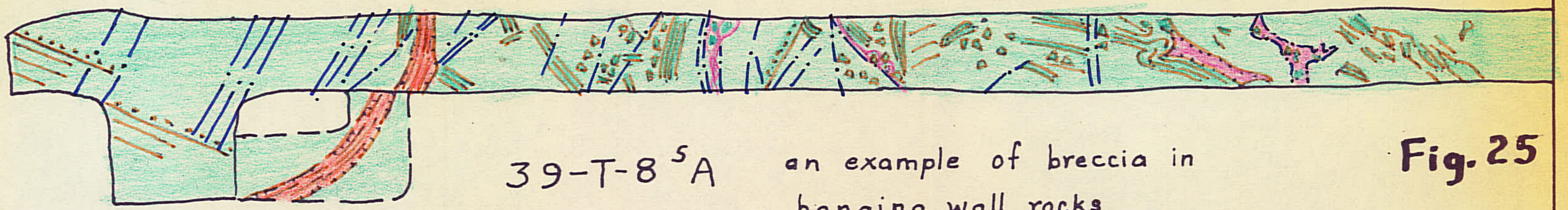
Mineralized Hanging-wall Breccia

Figure 25 shows a map of the wall of a sub-level drift which was driven into an area of hanging-wall breccia. The rocks here have not been albitized. A large portion of sulphide mineralization has occurred and shows as dark brown oxidized streaks and patches (Plates 34 and 35). The breccia is entirely consolidated, and the fragmental nature of the rocks is rather obscure where pieces are not outlined by sulphide minerals.

Mineralized chlorite breccia formed a portion of the ore mined in the hanging-wall stopes shown in Fig. 12. Large fragments of banded sulphides, apparently torn from a once continuous band, are surrounded by chlorite breccia. The matrix of the breccia contains disseminated pyrrhotite, sphalerite and galena sufficient to make ore. Above the ore is brecciated albitite with a chloritic matrix, similar to the specimens shown in Plate 36.

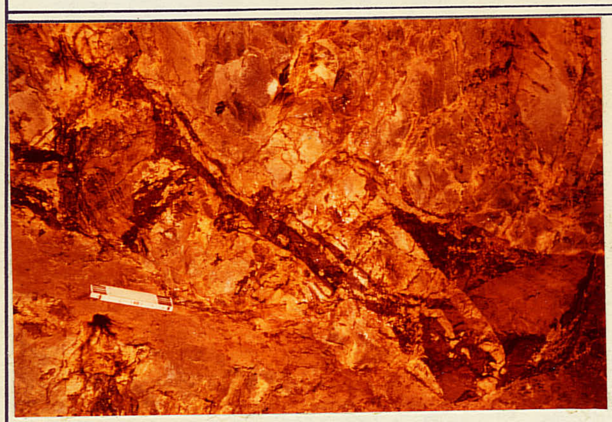
Translation of Hanging-wall Beds

Hanging-wall beds have been translated towards the centre of the mine from the north, west and south. The evidence for this is found in the displacement of the hanging-wall portions of igneous dikes. Fig. 26 shows the location of several of these dikes in the foot-wall of the orebody. The arrows show the direction of the component of displacement



39-T-8^{5}A an example of breccia in hanging wall rocks

Fig. 25



Plates 34 and 35

oxidized breccia in the hangingwall 39-T-18^{5}A

Plate 36

Albitite breccia, specimens from the hangingwall

Fig. 25

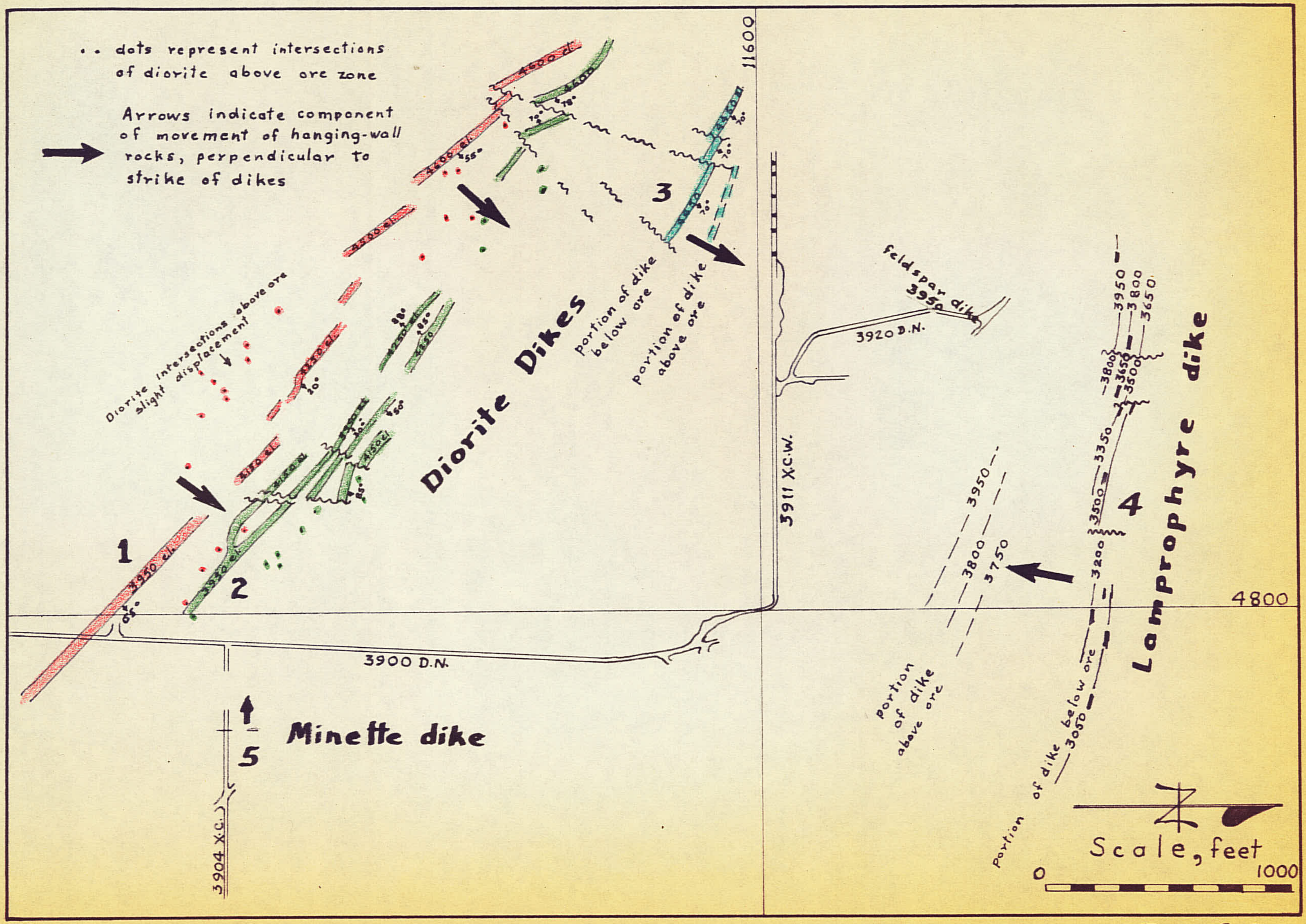


Fig. 26

Dikes; showing portions below and above the ore zone, with indicated movement of hanging-wall rocks

Fig.26

perpendicular to the strike of the dikes. The displacements are clear for dikes 3,4 and 5, but due to the irregular nature of diorite dikes 1 and 2, their displacements are not as certain.

Thickness of strata involved: Diorite dikes have been found in surface exposures some 300 feet above the hanging-wall which indicates that at least this thickness of rocks was involved in the translational movements. Furthermore, albitite extends about the same distance above the ore body and must also represent a minimum amount of rock present when brecciation took place.

Summary

It is not known whether the brecciation that affected the foot-wall ever penetrated directly through the ore horizon into the hanging-wall. At least part of the brecciation of the ore zone has been stratigraphically confined due to lateral movements. The sulphide zone shows evidence of having been mobile with an ability to flow when silicate rocks were breaking.

Brecciation above the ore is largely associated with the hanging-wall structures which have elements of both folding and faulting. These structures trend in the same direction as the foot-wall keels and are spatially related to them. However, they are not faults which displace the foot-wall rocks, the ore zone, and the hanging-wall rocks in the same direction.

The various effects noted may have resulted from vertical adjustments in foot-wall rocks which formed keels, and gave rise to lateral flowing movements in the ore zone. The movements in the ore zone may have been transmitted to the hanging-wall rocks causing buckling of strata, faulting and brecciation to produce the hanging-wall structures.

CHAPTER VIII

DISCUSSION OF THE ORIGIN OF THE BRECCIAS

PRE-CONGLOMERATE BRECCIA

The conglomerate basin was formed during the latter part of Lower Aldridge time. It seems to have been steep-walled, roughly circular and floored with large blocks of thin bedded rocks similar to those forming the walls.

The outline of the conglomerate basin is also the outline of a pipe-like breccia body that extends downward from the base of the conglomerate. The pre-conglomerate breccia can be observed directly in mining development headings to have thicknesses up to one hundred and fifty feet. It can be inferred from diamond drill core with less certainty, that the breccia extends downward one thousand feet to the top of a diorite body. The spatial relationship between the conglomerate basin and the underlying breccia requires that their origin be considered together.

The problem may be considered in terms of energy sources which operate (a) at the earth's surface or (b) from within the earth. The following processes have been considered:

(a) i. Erosional processes

(1) Current erosion, either subaerial or submarine is considered capable of producing steep-walled depressions. Skree-type breccia might then cover the floor.

(2) Slumping and gravity gliding can produce steep-walled separations of strata, and breccia.

ii. Meteor impact

Meteor impact is considered capable of producing craters and breccia columns.

(b) i. Faulting

Faulting is capable of forming breccia, but it is considered unlikely to produce basins and breccia pipes. Combinations of faults may influence the location of such structures.

ii. Cryptovolcanic explosion

Cryptovolcanic explosion is considered to be capable of producing craters and breccia columns without extrusion of volcanic material.

iii. Solution caverning

Caverns excavated by solution of soluble rocks may result in collapse of overlying rocks forming a steep-walled depression and a breccia column.

iv. Magmatic stoping

Magmatic stoping is considered to be capable of forming breccia columns which may reach near enough to surface to allow collapse of surface material in a period of relaxation of magmatic pressure.

Considering these possible origins in turn the following criteria seem applicable.

Subaerial or Submarine Erosion

(a) Fluted water-worn surfaces are not observed at the conglomerate contacts.

(b) Thin-bedded blocks at the base of the conglomerate are breccia fragments and not erosional remnants or stacks because they have been rotated.

(c) The breccia has considerable vertical extent and is not merely a veneer on a solid rock base.

These criteria indicate that the conglomerate basin was not an erosional feature.

Slumping and Gravity Gliding

Slumping and gliding are believed to be capable of producing steep-walled depressions in both unconsolidated and consolidated sediments. They are essentially lateral movements, and would not be expected to form a pipe-like breccia column. Breccias produced by gravity gliding are described by R.A. Baldry (1938) as thick zones along low angle slip planes at 7° to 10° to bedding, and extending for as much as several miles.

Kindle and Whittington (1958) describe intraformational breccia formed by penecontemporaneous slumping and sedimentation. Huge blocks and boulders of shallow water sediments slid out over deep water sediments, at several different times. The resulting breccias attained thicknesses up to 200 feet thick, but extended parallel to the strata.

Cryptovolcanic Explosion

Cryptovolcanic explosions or cryptoexplosions are described by Bucher (1935) as natural explosive structures related to maars and diatremes. They are the attempted but abortive beginnings of volcanism in a region. The structure is produced by explosions of gases under high pressure and without extrusion of any magmatic material. A cryptovolcanic explosion, if shallow and strong, is said to blow out an explosion basin filled with jumbled rocks and surrounded by a ring of debris. If deep-seated, weak and muffled, it produces a dome.

Dietz (1959) summarizes some of the features of "Cryptoexplosion Structures" as follows: -

(1) Circular outlines with radial or somewhat bilateral symmetry.

(2) A central dome-shaped uplift with intense structural derangement, surrounded by a ring syncline and in some cases by other ring-shaped uplifts and depressions of rapidly diminishing amplitude.

(3) Complex high angle and mostly normal faulting with minor folding.

(4) Sheared, brecciated, powdered rock and sometimes shatter cones in the central uplift.

(5) A variation in diameter from less than one to greater than six miles.

Dietz does not think that these structures are necessarily cryptovolcanic explosions, but favours meteoritic impact as an alternative.

The Sullivan structure resembles the cryptoexplosion structures in some points; the outline is more or less circular, and there is a domical structure, tilted on the flank of the Purcell geanticline. The dome is not clearly related to the breccia column, but is closely associated in space.

However, three aspects of the typical cryptoexplosion structure are missing.

(1) There is no known ring of debris. (This could have been eroded away during deposition of conglomerate).

(2) Severe crushing, shearing and powdering of rocks are not in evidence (see also Schrock & Malloth 1933).

(3) Complex high angle faulting is not a particularly notable feature.

Meteorite Impact

The diagnostic features of meteorite impact craters should be very similar to those of cryptoexplosions. The differences are still very much a matter of discussion. Bilateral symmetry might be expected in an astrobleme rather than roundness because meteors do not fall vertically to the earth but have tangential components of movement. Debris would tend to be pushed ahead of the meteor to make a thicker rim on the side of the crater farthest from the point of contact. Any fragments of the meteor would lodge in the area of the piled-up debris, but it has been estimated that a meteor would likely explode and vapourize on impact, leaving little or no identifiable material. A column of highly fractured, brecciated rocks would extend downward from the area of impact.

Buschbach T.C. and Ryan R. (1963) consider that lack of igneous rocks and a decrease of fracturing downward is indicative of meteorite impact rather than cryptovolcanic explosion.

The bedded rocks surrounding the conglomerate basin do not show the disturbance one would expect from a meteorite impact. Rim effects due to piled-up debris are missing, and the sheared, powdered rock, characteristic of impact and explosion, is not in evidence.

Furthermore, meteorite explosions are single catastrophic events which would not show evidence of recurrent brecciation.

Solution Caverning

Considering solution caverning, there is an immediate serious objection in that no soluble beds have been found in the Lower Aldridge. The nearest limey beds are found in the Upper Fort Steel formation under some 4,500 feet of Lower Aldridge. Creation of the conglomerate basin by collapse of the roof of a cavern does not seem probable.

Magmatic Stoping

Considerable attention has been paid in recent literature to the formation of breccia pipes and pebble columns by a process of magmatic stoping. This process is thought to act in the following manner. Magma under pressure in a magma chamber, begins to invade its cover rocks along lines of weakness, possibly the intersection of two faults. Pressures in the magma will vary, and at each point of advance there will be surges of pressure followed by relaxation. With each surge of pressure fracturing occurs, and with relaxation the fractured rock falls back. A column of breccia builds up in advance of the invading magma. Brecciation at the advance end of the column may consist merely of fractured rock, and gradually downward becomes more comminuted, rotated and mixed. Good reviews of breccia and pebble columns and mineralized breccia pipes are given by Leonid Bryner (1961) and Vincent D. Perry (1961).

Perry states that:

> repeated magma advances at various points, and resultant slumpage in the chimneys would eventually extend the breccias to or near the surface.

He further suggests that collapse to surface would likely occur during a period of withdrawal of magma.

Leech (G.S.C. Paper 64-1 p. 30) reports diatreme breccia columns occurring in the Rocky Mountains. He has this to say (Leech personal communication):

> At the highest levels the rock is fractured but not displaced. At a lower level the rock is brecciated with some rotation of fragments, then brecciated and containing "foreign" but local sedimentary fragments, with an increase in the proportions of matrix and a range of fragment shapes from angular to partially rounded by abrasion. An important point is that over a considerable vertical range the fragmental rock looks like a cross between a tectonic breccia and an unsorted or poorly-sorted conglomerate, whose fragments correlate with the local stratigraphic succession. At still lower levels the conglomeratic aspect increases because matrix (silt, sand and pebbles) increases, more fragments are subrounded or subangular and because rounded pebbles or cobbles of igneous or metamorphic rocks appear. The latter are rounded by abrasion in their passage through the pulsating column of brecciated rock.

and elsewhere

> going deeper the igneous components increase and also dykes may appear. The point is that a great depth of breccia has no igneous material.

This process of breccia column formation is favoured by the writer who visualizes the following origin of the conglomerate basin.

Reconstruction of the Development of the Conglomerate Basin

The magmatic stoping process appears to be one capable of producing the conglomerate basin during withdrawal of magma from beneath a breccia column which had approached sufficiently close to the surface to permit collapse. It is also a recurrent process which can be called on as a cause for later periods of brecciation. Following the classification proposed by Bryner (1961, p. 491) the pre-conglomerate breccia would be of the pre-hydrothermal type.

Nature of the rocks involved: Subsequent to the formation of the basin, it was filled with conglomerate. The pebbles originated from Aldridge-type sediments similar to those forming the walls of the basin, but clearly if the basin existed as a hole in the rocks, it could not at the same time provide the material to fill the hole. The pebbles then, were derived from fairly well-consolidated rocks outside of the depression but at no great distance. Other fragmental rocks were being formed at about the same time, and are now found in local accumulations at or near the Lower-Middle Aldridge contact at various places in the district.

Implications regarding sedimentary environment: The pre-conglomerate breccia blocks seem to have been fairly well-consolidated, judging from rectilinear outlines and lack of folding in most of those observed. If the deduction is correct that the surface layers were relatively hard, and were suffering erosion in places, then the Lower-Middle Aldridge contact may mark a surface of relative uplift, lack of deposition and local erosion.

Implications regarding magmatic activity: If the pre-conglomerate basin is assumed to have formed by magmatic action, there is an implication that the generation of magma had begun while the area was still receiving sediments. Perhaps this indicates that the igneous activity of the island arc system began long before the formation of prominent islands. Igneous intrusion beneath the deltaic wedge may have blocked subsidence of the area during the latter part of Lower Aldridge time causing a period of non deposition. Relief of pressure in the magma chamber indicated by subsidence in the breccia pipe, may have been of regional significance in promoting the subsidence necessary for the deposition of Upper Aldridge sedimentary rocks.

A period of magmatic quiescence is probably indicated during the time of deposition of the mine series sedimentary rocks, following the formation of the conglomerate basin. Slight downward adjustments in the breccia column may have made a concavity in the upper contact of the conglomerate. This could account for the forty feet or so of sedimentary material between the ore zone and the central part of the conglomerate, that is absent around the edges.

POST-CONGLOMERATE BRECCIA

Recapitulation

Post-conglomerate brecciation in the foot-wall is essentially a vertical disturbance. Conglomerate fragments have migrated downward in the chaotically mixed breccia. No great shearing stresses are indicated. Quartz grains in the matrix have not been crushed. Torn and twisted blocks and fragments suggest that some soft rocks were involved in this phase.

Rheomorphic Breccia Matrix

The breccia matrix may have been rheomorphic in the sense used by Goodspeed G.E. (1953). The matrix is certainly very pervasive through the breccia, and in places there are rather large volumes of matrix with only a scattering of small fragments.

One visualizes the brecciation process grinding up the rocks, especially friable sandstones, into a slurry which would have a mobility much greater than the whole mass, and yet would tend to float large blocks, and facilitate the mixing process. Some of the narrower sharp-walled breccia zones that are observed, (particularly towards the south end of the mine) may be true rheomorphic breccia dikes.

Distinguishing Pre-conglomerate and Post-conglomerate Breccias

Where post-conglomerate brecciation cuts pre-conglomerate breccia, it is practically impossible to distinguish one from the other. This poses the question "why postulate two stages of brecciation?" Perhaps one post-conglomerate period of brecciation could have produced the irregular base of the conglomerate. The most convincing evidence that some of the breccia precedes the conglomerate is that the top of the conglomerate is undisturbed over some of the largest irregularities at the conglomerate base, yet is disturbed and disrupted in areas of post-conglomerate brecciation.

Differing Outlines

Post-conglomerate breccia outlines tend to be elongated rather than circular, extending across the boundary of the pre-conglomerate basin. To a certain extent the elongation correlates with keel structures, especially the "4800 Departure" structure. However, the brecciated areas are much broader than the keels, and are largely a pre-tourmaline occurrence, whereas the keels occur in narrow belts of post-tourmaline brecciation.

Displacement of foot-wall rocks occurs across the keel structures, but no large displacement can be demonstrated across the broader breccia zones. Certainly, displacement of large blocks within the breccia is much more obvious than any misalignment of the conglomerate across the zones. In other words the post-conglomerate breccia appears to have punched through the conglomerate. The keels appear to have formed as a late stage of movement within the tourmalinized breccia mass.

It is not surprising that the post-conglomerate brecciation does not conform to the outlines of the pre-conglomerate basin. The latter was likely formed by collapse, whereas the former resulted from renewed magmatic activity with some unknown thickness of new sediments blanketing the area. Minor amounts of igneous material penetrated the breccia at the ore zone level. At a deeper level a core hole shows sedimentary rock fragments included in the fine grained diorite near the upper contact of the diorite sill. Both of these occurrences lend weight to the theory that renewed magmatic stoping caused the post-conglomerate brecciation.

Upward Extent of Post-conglomerate Brecciation

The upward extent of this brecciation cannot be determined. The footwall breccias are now separated from those in the hanging-wall, by the ore zone. If a continuous zone existed it is now effectively disguised, which is what one would expect due to dispersal of fragments by ore zone mobility, and their destruction by replacement. However, it seems equally possible that the ore zone was not penetrated, but absorbed brecciation movements in the same manner that the smaller ore bands absorbed fracturing and displacement of their wall rocks, i.e. by flowing rather than by breaking.

Relationship of Igneous Rocks to Breccia

Igneous rocks are not found as definite fragments in the breccia except where the various dikes are found broken in the ore. Some of the minor dikes were intruded into brecciated tourmaline chert and are therefore later than tourmalinization. Scott (1954) presented evidence that the hornfels alteration adjacent to the diorite sills preceded tourmalinization. One lamprophyre dike (#4 in Fig. 16) is known to have cut the diorite sill. It is younger than the diorite but older than some of the movements in the sulphide zone.

Igneous activity associated with a renewed period of brecciation is indicated. Just as there were periodic repetitions of brecciation, so there were successive intervals of intrusion.

Thickness of hanging-wall rocks prior to tourmalinization: Diorite dikes which are apophyses from the sill, are found in outcrop some 300 feet above the ore zone. If Scott's conclusions are correct, it may be assumed that the ore zone plus an unknown thickness of sedimentary cover (exceeding 300 ft.) was in place before tourmalinization and the succeeding brecciations, and metasomatic events.

Feldspar dike: A peculiarity of the feldspar dike is that it exhibits very irregular contacts in the foot-wall breccia, but in the ore zone it is narrow and straight-sided. This is taken to indicate interrupted development of vertical brecciation in the ore zone. There are, however, too few observations of dikes in the ore zone to allow any general conclusions regarding the nature of the wall rocks.

Brecciation in the Sulphide Zone

Brecciation in the sulphide zone appears to have had a different character from that in the foot-wall. Whereas the foot-wall brecciation involved mostly vertical movement, the ore zone breccias indicate lateral movement. It is postulated here that the ore zone had plastic characteristics compared to the relatively brittle foot-wall and hanging-wall rocks. The reasons for the plasticity are not known, but they seem clearly to be related to the presence of the sulphides. Without entering into the current controversy on syngenetic versus hydrothermal origin, there seem to be possible explanations from either viewpoint.

(1) The syngenetic protore was in a plastic colloidal state prior to crystallization, able to sustain its stratiform nature due to its high density, or

(2) The sulphide zone consisted largely of clays that became thixatropic due to the introduction of hydrothermal solutions during the process of mineralization.

R.D. McNeill (1966) appeals to mobilization of thixatropic clays, fluid mud layers, and plastic sediments, in the partially consolidated pile of sedimentary rocks undergoing diagenesis, to explain conformable breccias connected with the Orlando Mine, Tennant Creek, Australia. He suggests that this semi-consolidated pile was set in motion by gravity gliding. In the case of the Sullivan ore zone, thixatropic liquifaction of susceptible beds may have been triggered by brecciation movements below.

The presence of some foot-wall breccia blocks in the sulphide zone might possibly be attributed to floating of the blocks into a plastic sulphide zone of high specific gravity. The development of higher grade metamorphic minerals in the sulphide zone and evidence of reaction between fragments and ore, suggest that the zone was hot and chemically active.

Slumping of ore zone, translation of hanging-wall beds: Regardless of the composition of the sulphide zone, it is thought to have slumped towards the keel structures, initiating sliding of the hanging-wall beds, and resulting in the formation of the hanging-wall structures with their attendant brecciation. Sulphides then permeated certain portions of the brecciated hanging-wall.

The ore zone breccia and the hanging-wall breccias are not attributed to one catastrophic event. On the contrary there is evidence that quartz was introduced after one period of brecciation and prior to another. In the hanging-wall, albitite is occasionally found surrounding argillaceous fragments and as well, albitized fragments are found in a chloritized matrix.

The post-conglomerate brecciations with their associated alterations fit rather nicely into the co-hydrothermal type of Bryner's classification. Hydrothermal activity at this stage indicates a change in the nature of the magma during the quiescent period following the development of the conglomerate basin. Conceivably during this time, hydrothermal solutions had separated from the magma, and had accumulated in a cupola at the base of the breccia column.

Other Breccias

The literature concerning breccia pipes shows that they commonly occur in groups related to a common structure or set of structures. There is evidence that this holds true for the Sullivan breccia.

A short distance to the southwest of the orebody, drill holes encountered a thick conglomerate breccia body below the arch in the complex diorite sill. This body is apparently sharply discordant with the enclosing bedded sediments. It does not have associated tourmalinization, chloritization and albitization and is therefore of the pre-hydrothermal type.

Approximately one mile south of the mine, in the Mark Creek gorge, is the Stemwinder sulphide body. This steeply dipping lens is discordant, stratigraphically lower than the Sullivan ore zone, and in a synclinal structure. The mineralogy of the sulphides is very similar to that of the Sullivan ore. Conglomerate and breccia have been mapped in the wall rocks which have largely been converted to tourmaline "chert". At least one inclusion of conglomerate in the sulphide body is shown in the mapping. This occurrence overlies the diorite sill, but the lowest point so far explored is close to the sill. (Consolidated Mining and Smelting staff report, private file). Surface mapping about the Stemwinder and to the

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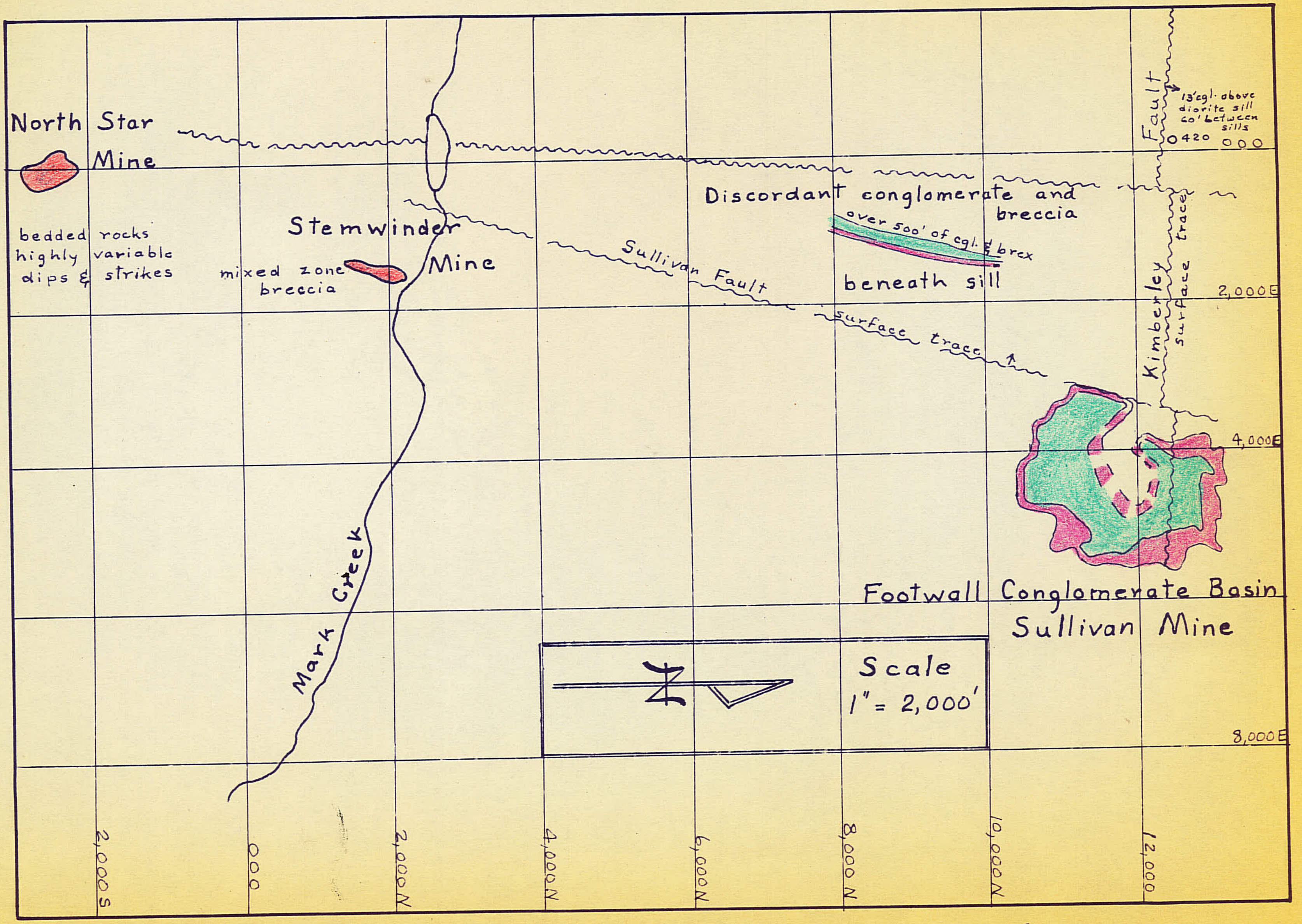

Conglomerate and breccia zones and ore bodies
in the vicinity of the Sullivan Mine

Fig. 27

Fig. 27

south, towards the North Star Mine, records a mixed zone consisting of thin-bedded rocks, conglomerate, and massive sandy rocks in a disorderly mixture. "Chert" is found in this rock as irregular stringers. The descriptions of the rock strongly suggest that this is another co-hydrothermal breccia, extending into close association with the conformable North Star orebody. Fig. 27 shows the relationship between the three orebodies. Their north-south alignment strongly suggests a common structural control, and by inference a structure controlling the location of breccia formation.

IN SUMMARY

Brecciation of large volumes of rock has occurred, below, within and above the Sullivan ore body. Two main stages of brecciation are recognized.

(1) Pre-conglomerate - pre-hydrothermal
(2) Post-conglomerate- co-hydrothermal

Collapse to surface above a breccia column formed by magmatic action is considered to be the most satisfactory of several explanations considered for the pre-conglomerate breccia and conglomerate basin.

Post-conglomerate brecciation was not a single catastrophic event, but occurred at intervals punctuated by:

(1) diorite intrusion
(2) boron metasomatism
(3) introduction of quartz
(4) potassium and sodium metasomatism
(5) chloritization

(6) introduction of sulphide minerals

(7) intrusion of minor igneous dikes

The order of events is in general as shown above, but overlapping, repetition, and interaction of processes is believed to have occurred.

Conglomerate pebbles, and fragments in the pre-conglomerate breccia were derived from fairly well-consolidated Lower Aldridge sediments which were probably indurated to the extent of being sandstones and mudstones.

Other fragmental rocks are found at approximately the same stratigraphic horizon. A thick discordant conglomerate - breccia body has been drilled below the diorite complex a short distance west and south of the foot-wall conglomerate body (Fig. 27). The discordant Stemwinder orebody which is mineralogically similar to the Sullivan, occupies a brecciated zone about one mile south. It is stratigraphically lower than the Sullivan, but still above the diorite complex.

Rocks described as the mixed zone are mapped between the Stemwinder and the conformable North Star orebody. The mineralogy of the North Star deposit is very similar to that of the Sullivan.

Lead isotope ratios in the three deposits are very similar. So are those of other deposits in the Aldridge. Age of the lead in the Sullivan orebody, deduced from the lead isotope ratios is 1,250 million years. (Leech and Wanless, 1963, pp. 266).

Brecciation below the ore zone was mainly produced by **vertical** movements, that in the ore zone was at least partly due to lateral movements. The plastic nature of the sulphide zone may have inhibited the vertical development of brecciation and is thought to have allowed slumping of the sulphide zone and sliding of hanging-wall beds.

Collapse to surface, forming the conglomerate basin, may have taken place when magmatic support was withdrawn from beneath a breccia column that had approached surface. A period of subsidence and renewed sedimentation in relatively deep water followed during Middle and Upper Aldridge time. The second, or post-conglomerate stage of brecciation began apparently while the new sediments were still quite soft, as indicated by twisted and torn fragments.

The pre-conglomerate breccia preceded metasomatism and therefore fits Bryner's class of pre-hydrothermal breccia. The post-conglomerate breccia is closely associated with metasomatic events and igneous intrusion, fitting Bryner's class of co-hydrothermal breccia. It seems reasonable to assume that brecciation, hydrothermal activity, diorite dikes and minor igneous dikes originated from a common parent magma. Concentration of hydrothermal fluids, took place in the cupola at the base of the breccia column, during the quiescent period.

CHAPTER IX

SPECULATION ON RELATION OF BRECCIA TO TECTONIC SETTING

Seeking a plausible correlation of the breccia phenomena with their tectonic setting would seem to be in keeping with current emphases in economic geology. The following thoughts are in many cases nearer to being queries than statements.

During Purcell time the area under consideration was part of the continental shelf receiving sediments from the distant eastern craton. Evidence of orogenic uplift and formation of islands is found following the extrusion of basaltic Moyie lavas at the end of Lower Purcell time.

It has been suggested previously in this paper that in late Lower Aldridge time there was a pause in sedimentation during which the surface layers became fairly well-consolidated. Igneous intrusion into the wedge of clastic material is believed to have approached surface at this time, producing breccia columns. Uplift was sufficient to allow local erosion of pebbles for the scattered deposits of conglomerate.

Withdrawal of magma from the magma chamber allowed the breccia column associated with the Sullivan orebody to cave to surface producing a localized depression in which conglomerate subsequently accumulated. There followed a period of subsidence and renewed sedimentation that formed the Upper Aldridge series.

Igneous activity was resumed with the intrusion of diorite, and brecciation of the still relatively soft rocks. Hydrothermal solutions that had been collecting in the cupolas of the magma chamber during the period of igneous quiescence, were introduced into the brecciated rocks during the co-hydrothermal breccia phase.

Subsidence of the area slowed so that by Creston time shallow water features were again being formed in the sediments.

Intrusion of diorite from the parent magma chamber is conceived of as an intermittent welling up of magma into the downwarping Purcell sediments along an incipient island arc, finally culminating in a break-through to surface with the extrusion of Moyie lavas. (See also Leech and Lowdon 1963, p. 254).

Hills (1963, p. 372) suggests that:

> sills require magmatic pressure sufficient to lift the overburden, and hence that they are more appropriate to shallow crustal depths.

This would suggest that in any given period of intrusion there would be one general depth above which the magma could form sills. A repetition of sills at various stratigraphic levels such as is found in the Purcell, may well have been due to successive intrusions. If so, the younger sills should be stratigraphically higher if sedimentary cover has accumulated in the interval between intrusions. They might also show progressive shift in remanent magnetism.

Hunt (1962) presents potassium argon dates that indicate Purcell plutonism extended over a period from approximately 1,580 million to 1,000 million years ago, an interval equal to the whole of Phanerozoic time. Acid igneous intrusive rocks in the St. Mary Lake - Kimberley area give ages between 700 - 800 million years. The minette dike, broken by movement in the ore zone is dated at not less than 765 million years.

The area in which Purcell diorites are found is co-extensive with the exposure of Purcell sedimentary rocks indicating the extensive proportions of the parent magma. This body could well be co-extensive with the silver-lead-zinc metallogenetic province in the Aldridge age rocks, that extends from Couer d'Alene to Kimberley. If this magma was indeed an early feature of the formation of an island arc system, it might well be an invasion of the crust by mantle material (see Wilson J.T. in Jacobs, Russell and Wilson, 1959, pp. 298 and 299). This would be in accord with the theory that the leads acquired their isotopic composition in an environment with lower U^{238}/Pb^{204} ratios than are found in the crust.

The foregoing discussion of tectonic relationships is speculative, and much more data is needed to solve the tectonic history. The following are areas of study that could yield desirable knowledge.

(1) Closer dating of individual diorite sills, and information regarding their roots and method of emplacement.

(2) Dating of the potassium metasomatism to determine the age of co-hydrothermal brecciation.

(3) Thorough study of the occurrences of conglomerate and fragmental rocks of the Aldridge to assess their origin.

(4) Determining criteria for distinguishing Pre-Cambrian structures. Of particular interest would be structural control of brecciation.

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APPENDICES

APPENDIX A. SELECTIVE STAINING OF K FELDSPARS AND PLAGIOCLASE, ON ROCK SLABS & THIN SECTIONS

The procedure used was that outlined by Bailey and Stevens (1960). A note of caution is suggested here.

The rhodizonate test gives a positive reaction with calcium bearing minerals other than plagioclase feldspars, for example calcite. It was found that other criteria besides a rhodizonate stain was necessary to determine the presence of plagioclase feldspar.

The cobaltinitrite test for K feldspar appeared to be quite specific in the rocks tested.

APPENDIX B. DIGESTION OF SULPHIDE MINERALS FROM SILICATE ROCKS USING METHYL ALCOHOL AND CHLORINE GAS

1. Pulverize the rock material.
2. Place the weighed pulverized material (about 2 gm) in a tall form 250 m.l. beaker.
3. Methyl alcohol is added uhtil a pulp density of about 5% is obtained.
4. The tall form beaker and its contents are placed in a 400 m.l. beaker containing water at approximately 100° F. sufficient to nearly float the tall form beaker.
5. A Teflon coated stirring magnet is added to the tall form beaker, and the beaker assembly is placed on a magnetic stirrer in a fume chamber.
6. A chlorine cylinder, suitably supported, is connected through rubber or teflon tubing to a glass tube which is inserted into the alcohol-silicate-sulphide slurry until the tip is approximately ½" from the bottom.
7. A glass tube connected to the laboratory air line is placed so as to direct a cooling stream of air at the surface of the alcohol immediately above the chlorine tube.
8. The air, chlorine and magnetic stirrer are turned on in that order. The chlorine flow is adjusted to give a steady stream of bubbles, but not so as to splash the slurry up the walls of the beaker.
9. The chlorine is allowed to bubble through the agitated pulp for about 25 minutes (or long enough to digest all sulphur present).
10. The contents of the beaker are filtered through #40 Whatman filter paper. Beaker and contents of filter are washed with methyl alcohol. Five thorough washings of the filtrate are recommended.

11. Dry the filtrate and transfer the bulk from the filter to a container and weigh. Ignite the filter and weigh the residue. Determine the amount of sulphide material removed.
12. The silicate residue is subsequently prepared for analysis by the x-ray fluorescence method.

The purpose of the air flow over the alcohol surface is to prevent auto-ignition of the air-chlorine-alcohol mixture during the reaction of the chlorine and the sulphur. Generally, however, this would not be necessary with the small quantities of sulphur being used. In fact, it was found that the warm water bath was desirable to speed the reaction of the chlorine with the sulphur.

It has been found that the above treatment would reduce .2 gm. of sulphide material in the slurry to a concentration less that 1 p.p.m. in the silicate as determined by nephelometric analysis.