GEOLOGY OF THE FOX OREBODY, NORTHERN MANITOBA

A Thesis
Presented to
The Faculty of Graduate Studies
University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

Gary Norman Lustig

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ABSTRACT

The Fox Mine is an Aphebian Cu-Zn massive sulphide deposit. This study documents the relationship between the ore body, its host metavolcanic rocks, its alteration zone and the metamorphic history of the area.

The Fox Mine area can be divided into four blocks, separated by faults, which are essentially conformable with the stratigraphy and foliation. The rocks within the area are primarily metavolcanic, ranging from mafic to felsic. Minor amounts of metasedimentary rocks are also present. The metavolcanic and metasedimentary rocks of the area have been intruded by mafic and felsic intrusions of several ages, and have undergone medium-grade (amphibolite) metamorphism.

The ore body is massive, essentially stratiform and stratabound, and exhibits a strong copper-zinc zonation. Zinc is concentrated along the margins, with copper in the center. The ore body shows signs of metamorphism to a level equal to the surrounding silicate rocks.

The alteration zone completely surrounds the ore body and consists of several distinct assemblages of the minerals cordierite± anthophyllite±biotite±sillimanite±staurolite±quartz±muscovite. These assemblages are thought to be derived from the metamorphism of a primary chlorite±sericite alteration.

The Fox ore body is compared with other massive sulphide deposits considered to be of volcanogenic origin, and is compatible with this model assuming the deposit has been isoclinally folded. Evidence for this folding is found in the copper-zinc zonal patterns.

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CHAPTER 1

INTRODUCTION

Statement of the Problem

The objective of this study is to document the geological setting, and deformational and metamorphic history of the Fox ore-body, presently being mined by Sherritt Gordon Mines Limited. This documentation provides a basis for a discussion of the origin of the ore body in terms of existing genetic models of massive sulphide deposition.

Location and Access

The Fox Mine is located 45 kilometers southwest of Lynn Lake, Manitoba, and approximately 790 kilometers northwest of Winnipeg, (Figure 1). Access to the mine site is by Highway 396 from Lynn Lake.

Previous Work

The earliest reconnaissance mapping of the area was carried out by Norman (1933, 1934, 1936). Stanton (1949) mapped the Dunphy Lakes area, and Milligan (1960) remapped the area as part of a compilation of the geology of the Lynn Lake District. The area has recently (1976-1978) been remapped by H. V. Zwanzig of the Manitoba Geological Survey, as part of a programme of structural and stratigraphic mapping in the Lynn Lake area.

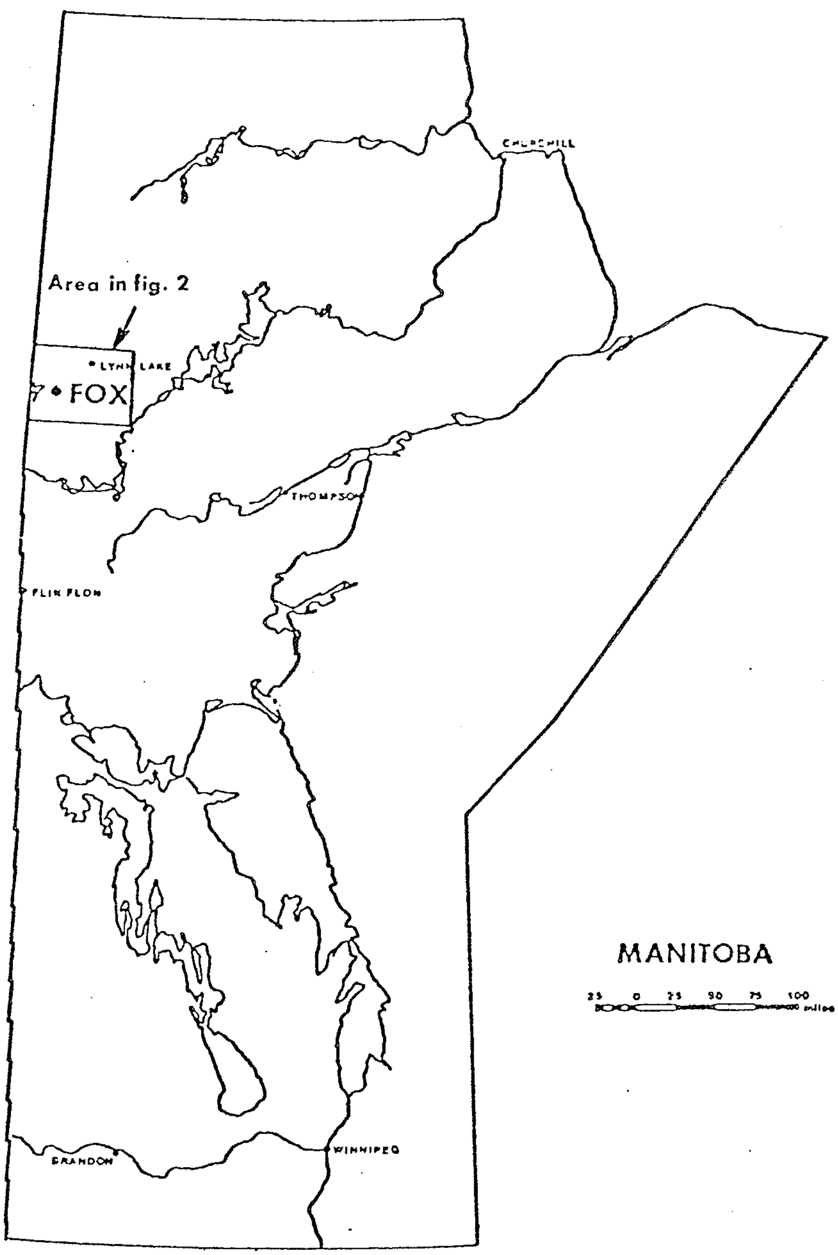


Figure 1: Location Map

Glass (1972) first reported on the geology of the Fox Mine. More detailed studies have been carried out by Obinna (1974), and Turek et al (1976).

Discovery and Production History of the Fox Mine

The Fox ore body was discovered in 1961, when a diamond drill hole intersected massive sulphides during follow up to a horizontal loop electromagnetic and magnetometer survey. Production commenced in May 1970, with ore reserves on December 31, 1970 of 11,884,110 tonnes grading 1.84% copper and 2.70% zinc. After 6 years of production, ore reserves are 7,108,694 tonnes (December 31, 1976) averaging 1.95% copper and 2.10% zinc (Worobec, 1977).

Ore is concentrated at a mill on the mine site with a capacity of 2,772 tonnes per day. Copper concentrate is shipped to Hudson Bay Mining and Smelting in Flin Flon, and to Mitsubishi Metal in Japan. Zinc concentrates are sold to Hudson Bay Mining and Smelting (Worobec, 1977).

Present Work and Acknowledgements

Field work was carried out during June, July and August 1976, while the author was employed by the Mineral Evaluation Branch of the Manitoba Department of Mines, Resources and Environmental Management. The surface geology was mapped along cut lines spaced two hundred feet apart and plotted on a base map at a scale of 1" to 200' (1:2,400). The geology of the 2100 level was mapped with reference to underground survey stations, and plotted on base maps provided by the Fox Mine

Engineering Department at a scale of 1" to 50' (1:600). In addition to the geological mapping, five underground drill holes were logged and sampled.

In the course of surface and underground mapping, 358 samples were collected. From these, 68 thin sections, 13 polished thin sections, and 6 polished sections were prepared. Chemical analyses were performed on five specimens by K. Ramlal of the University of Manitoba.

The author wishes to acknowledge the financial and logistical support provided by the Manitoba Department of Mines, Natural Resources and Environment during the course of the field work. The assistance and access to the Fox Mine area and drill data provided by Sherritt Gordon Mines Limited was invaluable for this study, and is gratefully acknowledged. The author also wishes to thank Dr. W. C. Brisbin of the University of Manitoba for his excellent advice and assistance, and Drs. F. J. Elbers and J. Koo of the Manitoba Mineral Resources Division who suggested the study. The author benefited greatly from discussions with Dr. H. V. Zwanzig, Dr. G. H. Gale, and D. Baldwin of the Manitoba Mineral Resources Division, R. Fernandez and P. Olsen of Sherritt Gordon Mines Limited, and Dr. A. C. Turnock of the University of Manitoba.

CHAPTER 11

GEOLOGY OF THE FOX MINE AREA

Regional Geology

The Fox Mine is situated near the western end of an east-west trending greenstone belt that extends approximately 170 kilometers from Laurie Lake in the west through Lynn Lake to Southern Indian Lake in the east (Figure 2). The belt consists of mafic to felsic metavolcanic rocks and derived metasediments of the Wasekwan Group (Milligan, 1960). The Wasekwan Group forms the oldest rocks of the Lynn Lake area (Milligan, 1960). Although once considered to be Archean in age (Stockwell, 1964), the Wasekwan Group is now generally accepted to be of Aphebian age (Moore, 1977; Sangster, 1978).

The metavolcanic rocks thin towards the west (Figure 2), and have been tentatively correlated by Zwanzig (1977), with the Wasekwan Group, Division A, mapped by Gilbert (1976), in the Lynn Lake area. Gilbert considers this subdivision to be near the base of the Wasekwan Group, and possibly the oldest rocks in the area. Stratigraphic correlations between the Lynn Lake area and the Fox Mine area are difficult because a continuous stratigraphic unit does not extend across the area. A stratigraphic succession within the Wasekwan Group has not been established for the Fox Mine Area (Zwanzig, 1977).

Overlying the Wasekwan Group metavolcanic rocks and derived metasediments is a thick unit of arkosic metasediments known as the Sickle Group (McRitchie, 1974). They occur mainly to the south of the Wasekwan Group rocks near the Fox Mine, although one thin unit of

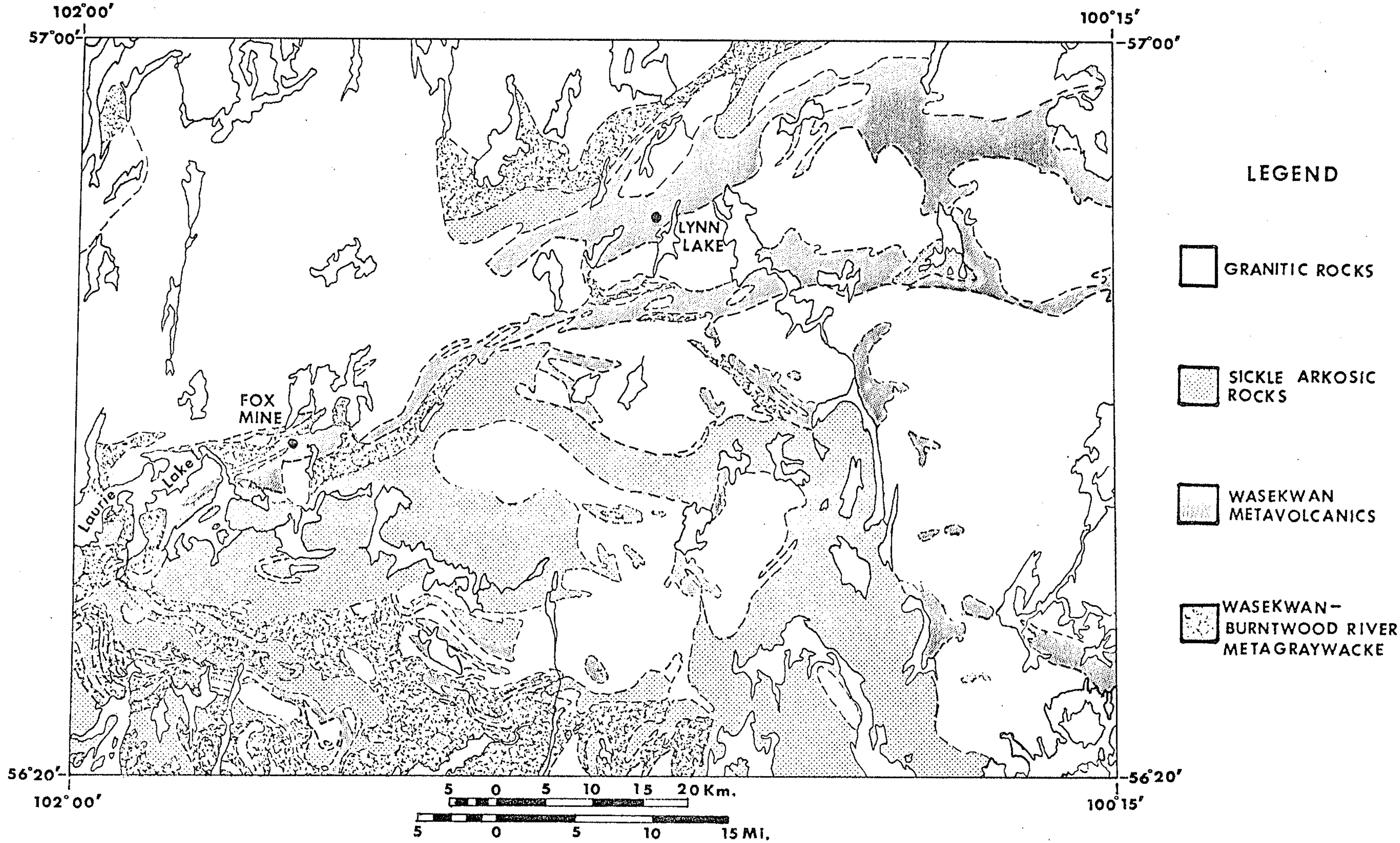


Figure 2: General Geology of the Lynn Lake Area (modified after Zwanzig, 1976)

arkose is present just north of the mine.

Rocks of the Sickle Group and Wasekwan Group have been correlated with the Missi and Amisk Groups, respectively, in the Flin Flon area (Bailes, 1971). Zwanzig (1977) has described the Fox Mine area as a "patchwork of fault-blocks", with tight folds within the blocks that cannot be traced across major faults. A paucity of top indicators and outcrop have hampered detailed structural interpretation of the area.

All the rocks of the area have been metamorphosed to amphibolite facies with an increase in grade from northeast to southwest (Zwanzig, 1977).

Local Geology of the Fox Mine Area

General Geology

Bedrock in the Fox Mine area consists mainly of intermediate to mafic metavolcanic rocks (Map 1, Section 1, Table 1) and volcanically derived metasedimentary rocks of the Wasekwan Group (Stanton, 1949, Milligan, 1960). These rocks have been intruded by mafic and felsic dykes and stocks of several ages, and have undergone medium grade (amphibolite facies) metamorphism.

The area is divided into four blocks, separated by faults. These faults have been recognized and mapped by the presence of mylonitic rocks in some locations, as well as stratigraphic relationships and lineaments observed in the field. These faults are generally conformable with the northeast-southwest trend of the regional foliation and stratigraphy. The relative age and stratigraphic relations of the rocks across the faults are unknown.

TABLE 1

TABLE OF FORMATIONS*

Recent and Pleistocene		Sand, Clay and Muskeg
UNCONFORMITY		
PRECAMBRIAN PROTEROZOIC APHEBIAN	Unit 12	Late Felsic Intrusives
	Unit 11	Early Felsic Intrusives
	Unit 10	Mafic Feldspar Porphyry
	Unit 9	Mafic Intrusive Rocks
		INTRUSIVE CONTACT
		Sickle Group
	Unit 8	Meta-arkose
		Wasekwan Group
	Unit 7	Metasedimentary Rocks
	Unit 6	Felsic Metavolcanic Rocks
	Unit 5	Intermediate Metavolcanic Rocks
	Unit 4	Mafic Metavolcanic Rocks
	Unit 3	Amphibolite
	Unit 2	Alteration Zone
	Unit 1	Massive Sulfides

(table based on authors mapping)

* The Sickle Group stratigraphically overlies the Wasekwan Group, but the relative ages of the units within the Wasekwan Group are unknown. Some of the intrusive rocks may be pre-Sickle in age.

The northernmost block consists of a large granodiorite intrusion which intrudes a sequence of metagreywacke and felsic metavolcanic rocks.

The second block, south of the northern most block, has been interpreted to contain the Sickle-Wasekwan contact. A sequence of mafic metavolcanic rocks (Wasekwan) lies in contact, to the south, with a meta-arkose unit (Sickle). A few poorly preserved primary structures within the meta-arkose, as well as top indicators west of the mine (Zwanzig, 1976), indicate that the units in this block have tops to the south. They are now overturned and dip steeply to the north. This facing direction is consistent with the interpreted Sickle-Wasekwan stratigraphy in this block. The fault marking the southern contact of this block cuts the meta-arkose and accounts for the absence of the remainder of the Sickle Group. South of this fault is the block that contains the ore zone and its enveloping alteration zone. The sequence consists of intermediate metavolcanic tuffs, breccias, and massive flows, with some interbedded meta-sedimentary rocks. The alteration zone consists of a quartz-muscovite schist, and a cordierite-anthophyllite-cummingtonite-phlogopite-sillimanite rock. This block has been extensively intruded by mafic dykes which generally strike parallel to the foliation. No top indicators have been found within this block, consequently the structure within this block is not understood. The sequence may have a single facing direction or, alternately, it may be completely folded into one or more isoclines.

The southern-most block consists of intermediate massive and pillowed flows, volcanic breccias and derived metasediments which have been intensely deformed. Although both layering and foliation are essentially parallel, and of the same orientation as the units to the north, the presence of lithologic boundaries oblique to the foliation indicate the possibility of an earlier pre-metamorphic episode of folding. This block has been extensively intruded by granitic rocks which have a well-developed foliation and are possibly subvolcanic in origin. There are also numerous later granitic and gabbroic intrusions.

Description of Lithologic Units

Relative ages of the units of the Wasekwan Group are not known within the study area. Zwanzig (pers. comm., 1977) considers that the thick mafic metavolcanic unit may be the oldest unit in the area, and possibly very near the base of the Wasekwan Group.

Units 1 and 2 are described in detail in Chapter 111.

Wasekwan Group

Amphibolite (unit 3)

The amphibolites are composed primarily of hornblende and plagioclase; they cannot be classified on the basis of original rock type. They are most common within the southern block, usually in isolated exposures, and could be derived from mafic intrusive or mafic volcanic rocks.

Mafic Metavolcanic Rocks (unit 4)

Mafic metavolcanic rocks outcrop in a 250 meter wide belt in the north-central block and in several locations within the southern block. They appear as dark green medium grained rocks with frequent felsic bands and folded quartz veinlets (Figures 3 and 4). Pillows are rare and highly deformed and tops cannot be determined (Figure 5).

The mafic metavolcanic rocks have a generally well-developed foliation and consist of 36 to 85% hornblende, 15 to 53% plagioclase, 0 to 10% biotite, and 1.5% opaque minerals, usually magnetite and pyrrhotite. The felsic bands commonly contain quartz, plagioclase, diopside, and hornblende, and are possibly due to premetamorphic alteration. Chemical analysis (Table 2) of a representative sample indicates that the rock was originally an alkali basalt, based on the classification of Irvine and Baragar (1971).

Figure 3: Isoclinally folded quartz veinlets and felsic streaks in mafic metavolcanic rock - scale is in inches
Location: 71200E, 10546N

Figure 4: Quartz veinlets in mafic metavolcanic rock dislocated by shearing parallel to the foliation.
Location: 7150E, 10620N

Figure 5: Highly deformed pillows within the mafic metavolcanic rocks south of the mine.
Location: 72400E, 8550N

TABLE 2

CHEMICAL ANALYSIS OF SELECTED SAMPLES

	1	2	3	4
SiO_2	45.10	55.60	57.55	63.50
Al_2O_3	16.40	14.98	14.70	18.64
Fe_2O_3	3.40	1.96	1.76	5.43
FeO	11.24	10.22	9.94	1.94
MgO	5.70	4.57	4.37	1.50
CaO	10.07	5.07	3.70	0.23
Na_2O	3.30	3.92	4.54	0.36
K_2O	0.23	0.88	0.20	4.33
H_2O	1.67	1.59	1.16	1.97
CO_2	0.15	0.16	0.18	0.14
TiO_2	1.06	0.84	0.74	0.36
P_2O_5	0.13	0.07	0.26	0.07
MnO	0.32	0.20	0.47	0.02
S	0.009	0.01	0.12	3.46
Ni	0.001	0.0015	0.0011	0.0016
Cu	0.0073	0.0019	0.0104	0.0108
Co	0.0044	0.0041	0.0031	0.0023
Zn	0.0126	0.0125	0.0540	0.0026
Total	98.80	100.09	99.75	100.36

1. Sample 632, 72400E, 8250N, Mafic Metavolcanic (Alkali Basalt, Sodic Series)[1]
2. Sample 608, 72170E, 8970N, Intermediate Flow (Tholeiitic Basalt, K-Poor Series)[1]
3. Sample 578, 72000E, 8620N, Intermediate Tuff (Andesite, K-Poor Series)[1]
4. Sample 603, 70965E, 10216N, Quartz-Sericite Schist (Rhyolite)[1]

[1] Based on the classification of Irvine and Baragar (1971)

Intermediate Metavolcanic Rocks (unit 5)

Intermediate metavolcanic rocks are the most abundant of the lithologic units in the southern half of the area. Although generally massive to gneissic in appearance, primary structures are preserved in some locations.

The intermediate metavolcanic rocks are medium-grained and generally have a granoblastic to foliated texture. They have been completely recrystallized and show no primary igneous textures. The average mode determined from three thin sections is 45% plagioclase, 20% hornblende, 24% cummingtonite, 4% quartz, 3% opaques (usually magnetite), 4% chlorite, and rare actinolite and garnet. The plagioclase is untwinned and moderately to strongly altered to sericite. The hornblende is generally coarse-grained and poikiloblastic, with inclusions of plagioclase. The cummingtonite generally exhibit an idioblastic cross section and is characteristically polysynthetically twinned. Where present, chlorite exhibits an anomalous "Berlin blue" birefringence. Chemical analysis of two representative samples are shown in Table 2 (2 and 3). Based on the classification of Irvine and Baragar (1971), they range from theoleiitic basalt to andesite.

The intermediate metavolcanic rocks can be divided into three subunits, based on relict primary structures, vis:

(a) Pillowed Flows

Pillowed flows are rare, observed in isolated outcrops in the southern block, which generally cannot be traced more than several tens of meters along or across strike. They consist of more mafic selvages and numerous epidote-rich, irregular patches in the centers of the pillows (Figure 6).

(b) Volcanic Breccias

The volcanic breccias are more common than the pillowed flows, and are found in underground exposures in the south-central and southern blocks, and in surface exposures in the southern block. The breccias generally consist of felsic fragments, ranging in size from 30 mm. to 200 mm., in a mafic hornblende-rich matrix (Figures 7, 8 and 9). The fragments are greatly elongated parallel to the plunge of the regional lineation. The origin of the breccias has not been determined, but they are probably pyroclastic.

(c) Tuffaceous-Volcaniclastic Rocks

Tuffaceous-volcaniclastic rocks occur in the southern block, and are distinguished from the intermediate flows and breccias by the presence of relict bedding in some locations. They possibly represent intermediate tuffs and derived volcaniclastic sediments. They consist of a granoblastic matrix of quartz and altered plagioclase, with poikiloblastic cummingtonite and biotite. The average mode determined from seven thin sections is 54% plagioclase, 25% amphibole, 10% quartz, 6% biotite, 3% magnetite and 2% garnet.

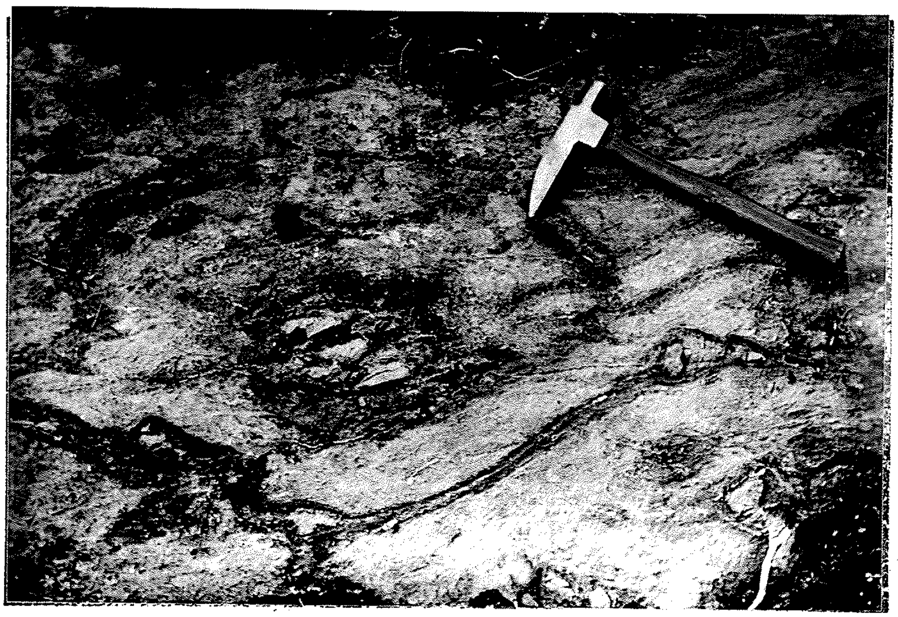


Figure 6: Deformed pillows within the intermediate metavolcanic rocks.
Location: 72180E, 8960N

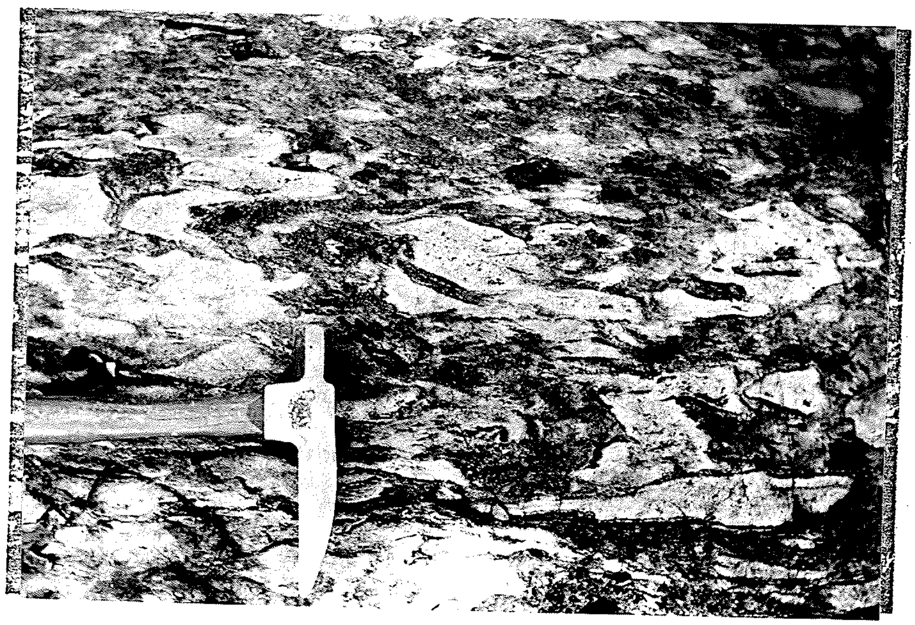


Figure 7: Intermediate volcanic breccia, possibly autoclastic in origin.
Location: 72600E, 9000N

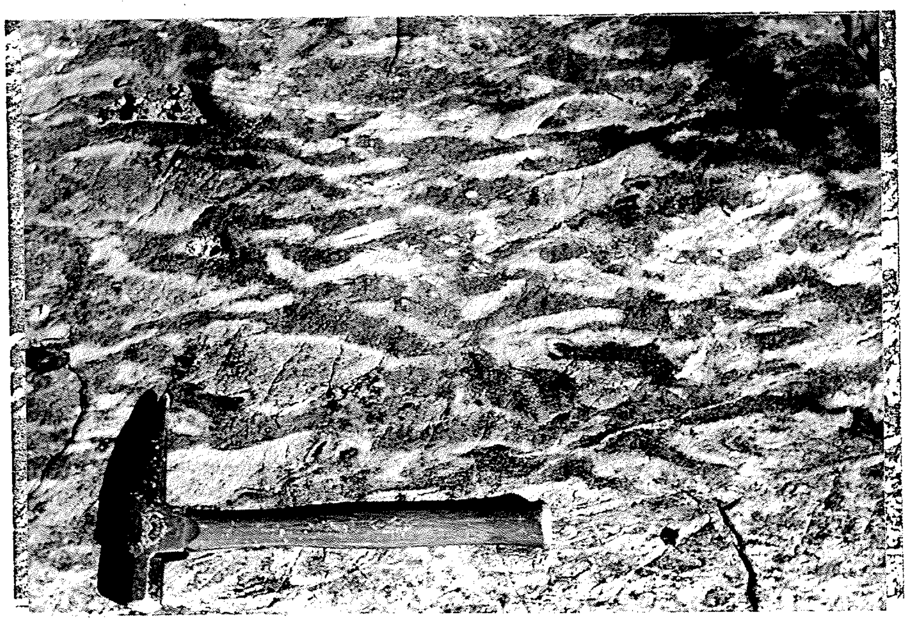


Figure 8: Deformed intermediate volcanic breccia.
Location: 70160E, 0500N

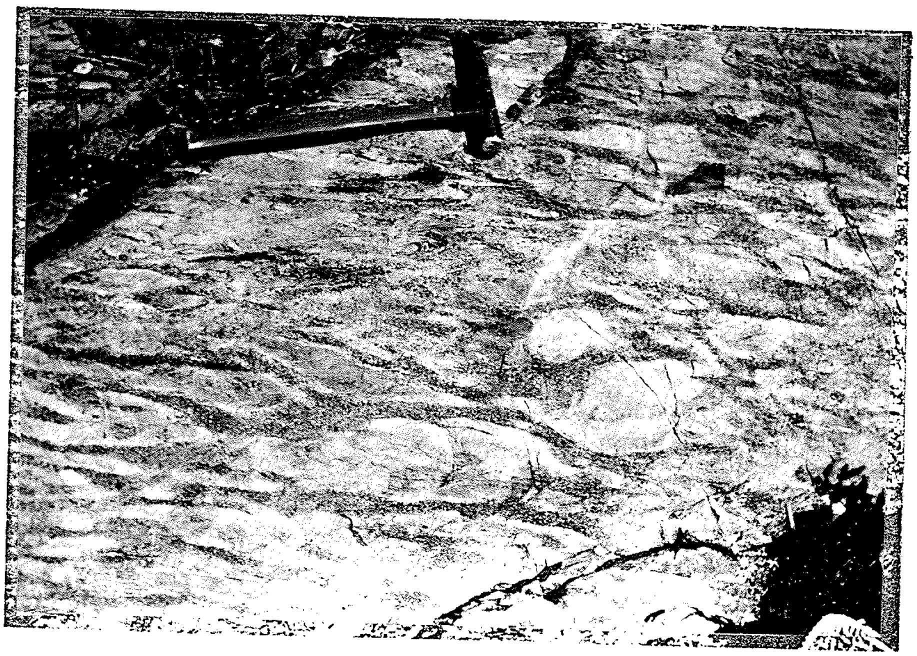


Figure 9: Deformed intermediate volcanic breccia, possibly a pillow breccia.
Location: 70800E, 8500N

A 1-meter wide band of anthophyllite-plagioclase rock, that can be traced for over 250 meters, occurs within this unit. It consists of large porphyroblastic anthophyllite needles in a granoblastic plagioclase matrix. The origin of this band could be similar to that proposed by Robertson (1953) for anthophyllite-rich bands in the Batty Lake area near Sherridon, Manitoba. He described anthophyllite bands traceable over several miles at a constant stratigraphic position, and considered them to be a product of Mg and Fe metasomatism of a tuffaceous horizon.

Felsic Metavolcanic Rocks (unit 6)

Felsic metavolcanic rocks are rare in the Fox Mine area. They are found as thin lenses within the metasedimentary rocks of the northern block, as well as a few isolated occurrences adjacent to the alteration zone. A thin section of one sample, taken on the surface at approximately 72050E and 9320N, consists of a very fine matrix of quartz and plagioclase with larger porphyroblasts of biotite, garnet and quartz. The approximate mode is 51% plagioclase, 31% quartz, 10% biotite, 3% chlorite, 2% garnet and 3% opaques. This sample has a banded appearance and could possibly be a recrystallized blastomylonite as defined by Spry (1969). It has a relict cataclastic texture with approximately 85% fine-grained, recrystallized matrix, and 15% larger porphyroclasts of strained quartz. The biotite and chlorite have a cross cutting habit and appear to be post-tectonic in origin.

Metasedimentary Rocks (unit 7)

The metasedimentary rocks are found in the south-central and northernmost blocks. In the south-central block this rock type occurs as a thin stratigraphic unit, probably originally a greywacke. It is moderately to heavily mineralized mainly by pyrrhotite. The approximate mode determined from a thin section from an unmineralized section of this unit, sampled underground at the 2100 foot level, is 49% quartz, 30% biotite, 20% plagioclase and 1% opaques. The feldspars are highly altered, and the alteration is more intense adjacent to quartz veinlets. Texturally, this thin section consists of a polygonal matrix of quartz and feldspar with oriented biotite grains.

In the northernmost block, metasediments occur in a large unit intruded to the north by a large granitic body. In this block the metasediments are commonly interlayered with felsic metavolcanic rocks (unit 6).

Sickle Group

Meta-arkose (unit 8)

There is only one unit of the Sickle Group within the study area. This unit is a thin, arkosic metasedimentary rock, bounded to the south by an inferred fault and unconformably overlying Wasekwan mafic metavolcanic rocks to the north. This thin unit represents the base of the Sickle Group. It can be correlated with the basal arkose of the Sickle Group exposed at Hatchet Lake, 4 kilometers southwest of the mine site (Zwanzig, 1976).

Within the mapped area, this unit varies in thickness from 35 to 90 metres. Some relict graded bedding, as well as top indicators from adjacent pillowed flows in the Hatchet Lake area (Zwanzig, 1976), indicate that the tops of the unit are facing towards the south, and the unit is now overturned, steeply dipping to the north.

The arkose unit is usually light buff in color and has a crossbedded appearance. There are frequent undeformed quartz pebbles, and rarely, highly deformed felsic and mafic volcanic clasts. Rare argillaceous lenses, 2 cm to 5 cm thick, are interbedded with the arkose.

In thin section, the meta-arkose exhibits relict cataclastic textures, ranging from a recrystallized mylonite at the southern contact to a recrystallized protomylonite near the northern contact. The recrystallized mylonite consists of 80% fine-grained matrix and 20% clasts (Figure 10), while the protomylonite consists of 75% clasts and 25% recrystallized fine-grained matrix (Figure 11). The clasts consists of polycrystalline, strained quartz, up to 1.55 mm. in length in a fine-grained matrix of quartz, plagioclase, rare potash feldspar, muscovite, and biotite.

The average mode calculated from three thin sections is 75% quartz, 14% plagioclase, 8% muscovite, 5% biotite, and 1% amphibole. The coarse grain size of the clasts, as well as the composition, indicate that this unit was possibly derived from a granitic source, although no granite clasts were observed within the study area.

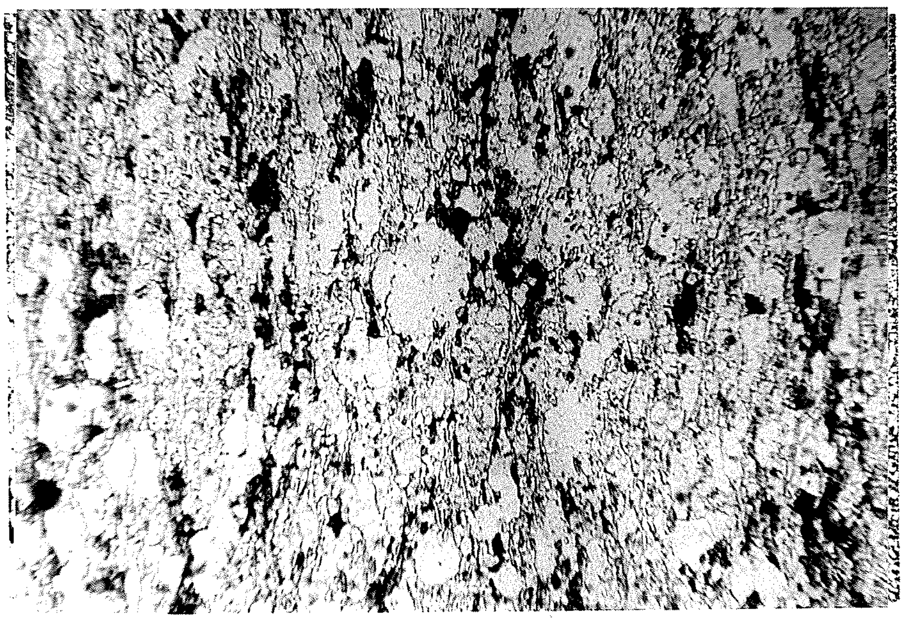


Figure 10: Photomicrograph of Sickle meta-arkose at southern fault contact. Large polycrystalline quartz porphyroclasts in a recrystallized matrix of quartz, feldspar and muscovite, plane light, width of field 4.64 mm (25 x). Location: 71200E, 10180N.

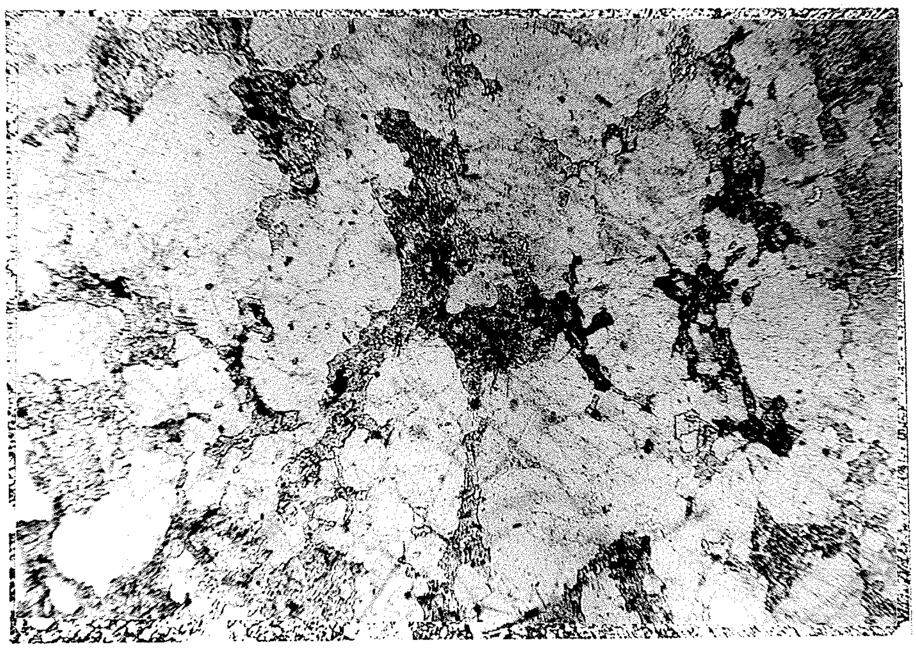


Figure 11: Meta-arkose near the northern contact. Large quartz porphyroclasts with a lesser amount of quartz, feldspar and muscovite matrix, plane light, width of field 4.68 mm (25x).
Location: 71400E, 10300N.

Intrusive Rocks

Mafic Intrusive Rocks (unit 9)

Milligan (1960), divided the mafic intrusive rocks in the Lynn Lake area into pre-Sickle and post-Sickle categories. These age distinctions cannot be determined definitely in the area mapped, but the intrusive rocks can be divided into early (pre-D_2 deformation) and late (post-D_2 deformation), based on their fabric.

The early intrusions generally consist of thin dykes and sills, usually less than one metre thick (Figure 12), with well developed foliation. The early mafic intrusions within the mafic metavolcanic units are difficult to identify due to an equal development of schistosity in both units, and a coarsening of grain size within the metavolcanic rocks due to metamorphism.

Late mafic intrusions are common throughout the area and are frequently irregular in shape and discordant to the stratigraphy and foliation. They are massive, exhibiting a weak, or no foliation or lineation, and medium- to coarse-grained. These intrusive rocks are common in the southernmost block, where they occur as isolated small stocks, and a larger dyke, 30 m to 60 m thick, extending across the southernmost part of the study area.

In thin section, the late mafic intrusive rocks are generally coarse-grained with a granoblastic texture. The average mode, estimated from four thin sections, is 48% hornblende, 44% plagioclase, 3% chlorite, 2% biotite, 2% magnetite, 1% garnet, and trace to several percent actinolite, quartz and sphene.

Figure 12: Narrow mafic dyke intruding the contact between intermediate metavolcanic (top) and early felsic intrusive (bottom).
Location: 72200E, 8430N.

Mafic Feldspar Porphyry (unit 10)

The mafic feldspar porphyry occurs as thin dykes or sills at several locations north of the ore body. This unit exhibits a blasto-porphyritic texture with recrystallized plagioclase phenocrysts up to 1 cm long.

The matrix consists of a polygonal aggregate of medium- to fine-grained plagioclase and hornblende. Minor amounts of biotite are also present. A weak foliation is defined by the crude alignment of hornblende and biotite.

Early Felsic Intrusive Rocks (unit 11)

The early intrusions are generally lenticular in shape and are foliated to an extent equal to that of the metavolcanic rocks. Several of these intrusions are found in the southern block. They are distinguished by a very rough weathered surface caused by poly-crystalline quartz porphyroclasts weathering out differentially relative to a biotite-plagioclase matrix.

Late Felsic Intrusive Rocks (unit 12)

The late granitic intrusions occur as small (less than 100 m in diameter) stocks of granodiorite and quartz diorite, as well as a large granodiorite batholith that marks the northern boundary of the study area. It is part of a large, wedge-shaped batholith mapped by Stanton (1949), which extends approximately 10 km to the east. Slabs of this unit were etched in hydrofluoric acid and stained for potassium in a cobaltinitrate solution according to the method of Hutchinson

(1974). This revealed the presence of 3 to 10% potassium feldspar, 40 to 50% plagioclase, and the remainder was quartz, hornblende, and biotite.

Structural Geology

General Statement

The structural setting of the Fox Mine is distinguished by the presence of three faults which separate the area into four blocks, whose stratigraphic relationships are uncertain. These faults are essentially parallel to both the stratigraphy and regional foliation. The foliation is parallel to primary layering in most places except for a few locations in the southern block.

No major folds were observed within the area mapped, however it is possible that faulting has interfered with the recognition of such folds and that individual fault blocks could be parts of limbs of folds. Zwanzig (1976, 1977) and Zwanzig and Keay (1977), have indicated that the area around the Fox Mine consists of numerous isoclinal folds, often truncated by faults.

In the southern block, the lithologic contacts are oblique or perpendicular to the foliation. The stratigraphy strikes generally northeast-southwest while the foliation strikes east-west. The structural complications within this block could be due to an early folding or faulting episode which has been followed by further deformation and metamorphism.

Structural Elements

Primary Structures

Bedding is commonly observed in most of the metasedimentary units, although primary features which could be used to interpret the facing direction of the units are only found within the Sickle arkosic unit. Within this unit, graded bedding is observed which indicates that the unit is facing south. Cross beds within this unit have been modified by shearing and give unreliable facing directions.

Primary layering in the volcanic rocks is rare, usually restricted to the tuffaceous and volcanically derived metasediments, and may be partially due to metamorphic differentiation. Primary volcanic structures have been observed in numerous locations, including pillowed flows and flow breccias. The original shape of pillows and breccia fragments has been highly deformed.

Foliation

There is a single direction of foliation developed throughout the area striking east-west and dipping 60° to 80° towards the north. The foliation is produced by the parallel alignment of amphibole, biotite, and muscovite in the metasedimentary and metavolcanic units. It is roughly parallel to the stratigraphy in all blocks but the southern block, where it has a very consistent but slightly more southeasterly orientation.

Lineations

Mineral lineations, marked by elongated hornblende crystals, are formed throughout the area. They plunge 50^{o} to 70^{o}, trending on the average 315^{o}. Volcanic fragments are also elongated in this direction, with their down plunge dimension up to five times their intermediate length.

The metasediments of the northernmost block commonly have lineations shown by the plunge of the axes of minor folds. These minor folds, which are described below consist of folded foliation and layering.

Minor Folds

Minor folds are rare in the Fox Mine area. The earliest folds are small, isoclinal folds developed in volcanic fragments and small quartz veinlets. They are intrafolial, rootless folds that have been modified by later shearing (Figures 3 and 4). The axial plane of these folds strike east-west, parallel to the foliation, and the axes plunge northwest, parallel to the mineral lineation.

Folding of the foliation is rare within the mafic metavolcanic rocks, but is fairly common within the metasedimentary and felsic metavolcanic rocks of the northern block. The folds are generally of similar and chevron style, with an amplitude of usually less than one meter. The axial plane strikes east-west, parallel to the foliation, and the axes plunge steeply, usually to the northeast, but in some places to the northwest.

Faults

Northern Fault

The presence of a fault separating the thick mafic metavolcanic sequence (unit 4, map 1), and the metasedimentary rocks (unit 7) in the northern part of the area mapped is inferred from the presence of a distinct topographic lineament. Airborne and ground electromagnetic surveys indicate a conductive zone at this contact that is similar to that of other major faults of the area (H. Zwanzig, personal communication, 1977). The two units on either side of the inferred fault are considered to be essentially conformable where observed elsewhere (H. Zwanzig, personal communication), indicating that the fault involves relatively minor displacement and has not appreciably altered the stratigraphic sequence. The direction and exact amount of displacement are unknown.

Central Fault

There are several lines of evidence for the presence of this fault. With the Sickle arkose unit younging towards the south, a major fault would be necessary to explain the absence of the remainder of the Sickle Group, which is at least 1250 meters thick west of the mine (Zwanzig, 1976). Another interpretation which could explain this relationship would be that the Sickle meta-arkose is in a synclinal keel, but the absence of any stratigraphic symmetry on either side of the meta-arkose renders this interpretation unlikely.

The meta-arkose shows cataclastic textures which have been re-crystallized. A sample taken within three meters of the inferred fault exhibits a blastomylonitic texture, with 20% polycrystalline porphyroclasts of highly strained quartz in a fine-grained matrix of quartz, plagioclase, muscovite, and biotite. Thin sections prepared from samples near the northern contact have similar cataclastic textures, but with a much greater proportion of porphyroclasts relative to matrix (Figures 10 and 11). This progressive decrease in cataclasis northward from the fault is interpreted as evidence of a major dislocation at the southern contact of the meta-arkose. The direction and amount of displacement is unknown.

Ore Body Fault

The presence of a fault adjacent to the ore body is inferred due to the presence of blastomylonitic textures at several locations within the ore and alteration zones, as well as slickensides in underground exposures indicating some degree of movement. These slickensides are within the quartz-sericite schist along the southern margin of the alteration zone, and were observed in the footwall drift on the 2100 level. The presence of highly sheared rocks at several locations throughout the ore zone could indicate the presence of a wide fault zone. There has been some metamorphism post-dating this fault, indicated by some cross cutting micas within the mylonitic rocks, as well as the recrystallization of the quartz and feldspar. The extensive development of post-tectonic metamorphic textures within the alteration zone could have obscured the location of the fault. Because of this the exact location is speculative and the direction and amount of displacement is unknown.

Minor Late Faults

Numerous late faults of minor displacement can be observed in underground exposures. They are generally dipping less than 70^{o}, either to the north or south, and slickensides indicate a slip direction perpendicular to the regional strike. Displacement is usually less than 1 metre (Figure 13).

Deformational Events

The observed structures indicate that the Fox Mine area has undergone several deformational episodes. Although the structures have been attributed to separate events, the time between the events may be short, and some structures may be contemporaneous.

First Deformational Event - D1

The first deformational event was an episode of brittle deformation, possibly folding and faulting. Evidence for the earliest deformational event is most commonly found in the mafic metavolcanic rocks, which contain numerous quartz veinlets (Figure 4). These veinlets are interpreted to be filling D_1 tension fractures. The folding of these veinlets is attributed to a later event.

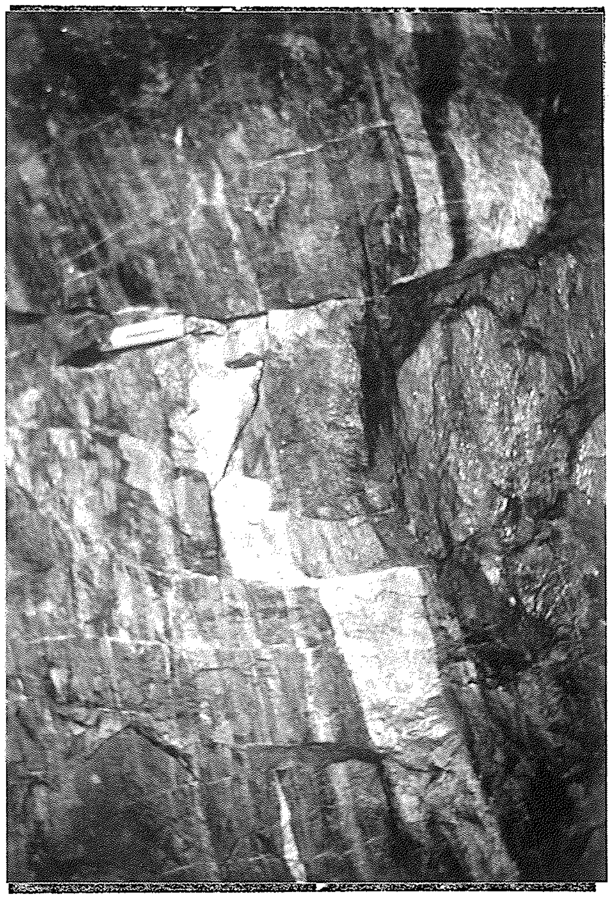


Figure 13: Late sub-horizontal minor faults on the 2100 level. Scale is 6 inches (15.2 cm) long.

Second Deformational Event - D2

The second deformational event is represented by the folding of the quartz veinlets into isoclinal folds (Figures 3 and 4). This event coincided with the development of the regional foliation and the medium-grade (amphibolite facies) metamorphism.

Third Deformational Event - D3

The third deformational event involves extensive slip, commonly parallel to the previously developed foliation, although the dislocations can be observed to be slightly oblique to the foliation in some locations. Amount of slip could vary from relatively small (Figure 4), to major dislocations, which may coincide with movement on the major faults. Slip surfaces associated with this event may be recognized by the dislocation of the limbs of quartz veinlets folded during D2.

Fourth Deformational Event - D4

The fourth deformational event is minor folding of the foliation. This could possibly coincide with D3 as no evidence of folding of the dislocations has been found.

Fifth Deformational Event - D5

The latest deformational event is the extensive low angle faulting observed in the underground exposures off-setting the layering and foliation (Figure 13).

Metamorphism

Progressive Metamorphism

Progressive metamorphism in the Fox Mine area reached medium grade/amphibolite facies of regional metamorphism. Petrographic evidence indicates that there was one major period of medium grade/amphibolite facies metamorphism, during which the foliation was developed. This was followed by a minor phase, recognized by the rare occurrence of micas cross-cutting the main foliation. The metamorphic conditions at the Fox Mine can be indicated by the following mineral assemblages:

1) Plagioclase - hornblende - biotite,
2) Plagioclase - anthophyllite - cummingtonite - biotite - garnet,
3) Plagioclase - hornblende - cummingtonite - chlorite,
4) Quartz - plagioclase muscovite - biotite,
5) Quartz - cordierite - sillimanite - muscovite - phlogopite,
6) Quartz - cordierite - anthophyllite - cummingtonite - staurolite,
7) Quartz - plagioclase - muscovite.

The first three assemblages are derived from mafic and intermediate volcanic rocks. Assemblage (4) is from the Sickle arkose. The remaining three assemblages are typical of the alteration zone.

Pressure Temperature Conditions

The equilibrium mineral assemblages indicate that the Fox Mine underwent metamorphism of the amphibolite facies as defined by Turner (1968). Using the more recent classification of Winkler (1974), the presence of cordierite and staurolite indicate that the rocks have undergone cordierite-almandine medium grade metamorphism (low to medium pressure). The pressure temperature condition at the peak of metamorphism can be indicated graphically as shown in Figure 14. The kyanite-andalusite-sillimanite stability field are those of Holdaway (1971). The chloritoid-staurolite curve is from Richardson (1968), the muscovite + quartz-orthoclase + Al_2SiO_5 curve is from Althaus (1970), and the granite melt curve is from Luth et al (1964).

Temperatures vary from 550° (at pressures from 3.4×10^5 kPa (3.4 kb) to 4.6×10^5 kPa (4.6 kb) to 650°C at 3.1×10^5 kPa (3.1 kb). Pressures range from 2.2×10^5 kPa at 620° to 6.4×10^5 kPa at 630°C.

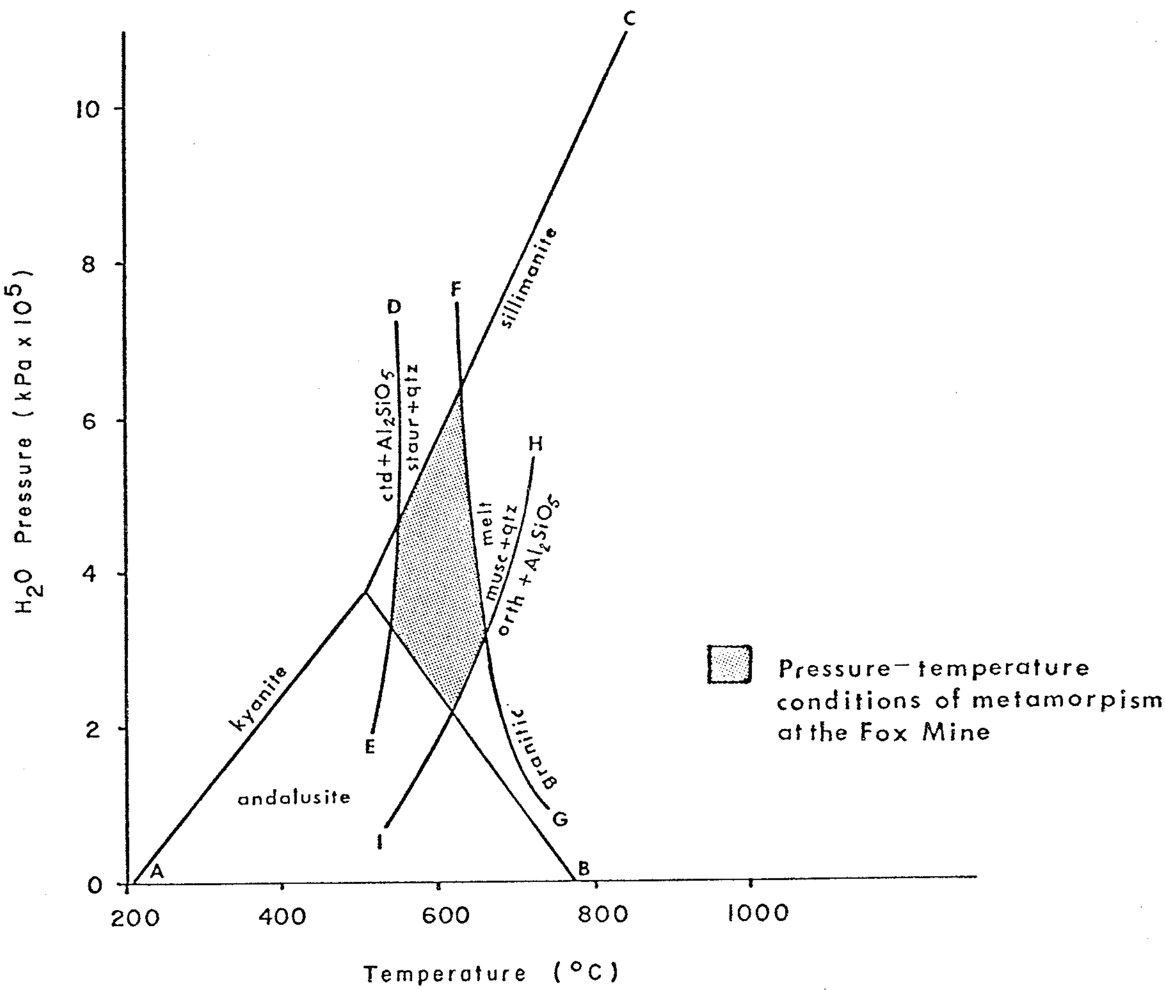
Retrogressive Metamorphism

The presence of minerals such as chlorite and actinolite in minor quantities within the intermediate and mafic metavolcanic rocks is due to retrograde metamorphism post-dating the medium grade/ amphibolite main phase(s) of metamorphism.

Metamorphic History

The main phase of medium grade/amphibolite facies metamorphism probably reached its peak during the D_2 deformation, coinciding with the development of the foliation. The presence of anthophyllite, cordierite and phlogopite with a weak foliation, or in places, a random orientation could indicate that the highest temperature during progressive metamorphism occurred somewhat later than the peak of stress during deformation. Growth of micaceous minerals cross-cutting the regional foliation probably occurred during the D3 or D4 events (or both).

Retrogressive metamorphism occurred during D4 or D5.



Source of curves:

A-B-C Holdaway, 1971
D-E Richardson, 1968
F-G Luth, Jahns, and Tuttle, 1964
H-I Althaus, 1970

Figure 14: Pressure-temperature conditions of metamorphism at the Fox Mine.

CHAPTER 111

GEOLOGY OF THE ORE ZONE

General Statement

Geological mapping was carried out on the 2100 level, supplemented by logging five horizontal diamond drill holes intersecting the ore body (map 2). The massive sulphides are in an elongated body, fault bounded along one side and associated with a metamorphosed alteration zone. The ore zone dips approximately 70° to the north and ranges in length from 410 meters at the surface, to 76 meters at the 2900 level. Average width is approximately 25 meters.

The ore body consists of a number of lenses on the upper levels and exhibits a pronounced pinch and swell form on the 2100 level (map 2), which is possibly a large scale boundinage structure.

The massive sulphides exhibit a strong copper-zinc zonation (maps 3 and 4), with zinc generally along the margins and copper towards the center. Disseminated sulphides are found in the center and towards the eastern end of the massive sulphides. The disseminated sulphides are generally copper-rich, hosted by a quartz-rich rock in the center of the massive sulphides, and by the alteration zone at the eastern end of the massive sulphides.

Massive Sulphides (Unit 1)

The massive sulphides can be divided into two distinct zones, copper-rich and zinc-rich. The copper-rich zone consists of chalcopyrite and pyrrhotite (Figure 15), with lesser amounts of sphalerite and pyrite. The zinc-rich zone consists of pyrite and sphalerite (Figure 16), with lesser amounts of pyrrhotite and chalcopyrite. Layering within the zinc-rich pyritic zones has been reported by Glass (1972), and was observed in one sample in the present study (Figure 17). Other minerals present in the massive sulphides include cubanite, arsenopyrite, tetrahedrite, and magnetite.

The principle gangue mineral of the massive sulphides is quartz, with rare occurrences of plagioclase and carbonate.

Sulphide Mineralogy

Chalcopyrite

Chalcopyrite occurs as large irregular blebs, usually associated with pyrrhotite (Figure 15). It also commonly occurs interstitially with idioblastic pyrite cubes, and often fills fractures within the pyrite (Figure 18). Exsolution lamellae of cubanite commonly occur within the coarser-grained chalcopyrite (Figure 19). This indicates that the chalcopyrite crystallized at temperatures above 250 - 300°C (Ramdohr, 1969), probably during metamorphism. Some stringers of pyrrhotite also occur within the chalcopyrite. Ramdohr (1969) suggests that this condition is usually not true exsolution, but is a result of the breakdown of cubanite exsolution lamellae to pyrrhotite and chalcopyrite.

Chalcopyrite commonly occurs also as exsolved, very small, ovoid grains in sphalerite (Figure 19). The grains occur either in a random pattern or are oriented in a straight line, possibly along cleavage planes.

Sphalerite

Sphalerite occurs as large grains associated with pyrite (Figure 16), and as irregular interstitial grains with pyrite, chalcopyrite and pyrrhotite (Figure 15 and 20). It is rarely observed filling fractures within pyrite grains. It is readily identified by its low reflectance in polished sections and almost invariably contains inclusions of chalcopyrite varying from very small (.01 mm) exsolution blebs to larger inclusions of uncertain origin. Rare deformation twins have been reported by Obinna (1974), but they were not observed during this study.

Pyrite

Pyrite occurs as idioblastic to subidioblastic crystals and is common throughout the ore and alteration zone (Figures 16 and 18). Its concentration is highest in the zinc-rich massive sulphide zones, but it is also the most abundant sulphide in disseminated barren zones surrounding the ore body. The pyrite is generally medium-grained, with grains averaging .5 mm in width. Some porphyroblasts are as large as 10 mm. Pyrite grains are generally highly fractured, and the fractures are commonly filled with chalcopyrite (Figure 18). The pyrite varies from large grains with interstitial chalcopyrite to small grains surrounded by large chalcopyrite and sphalerite grains.

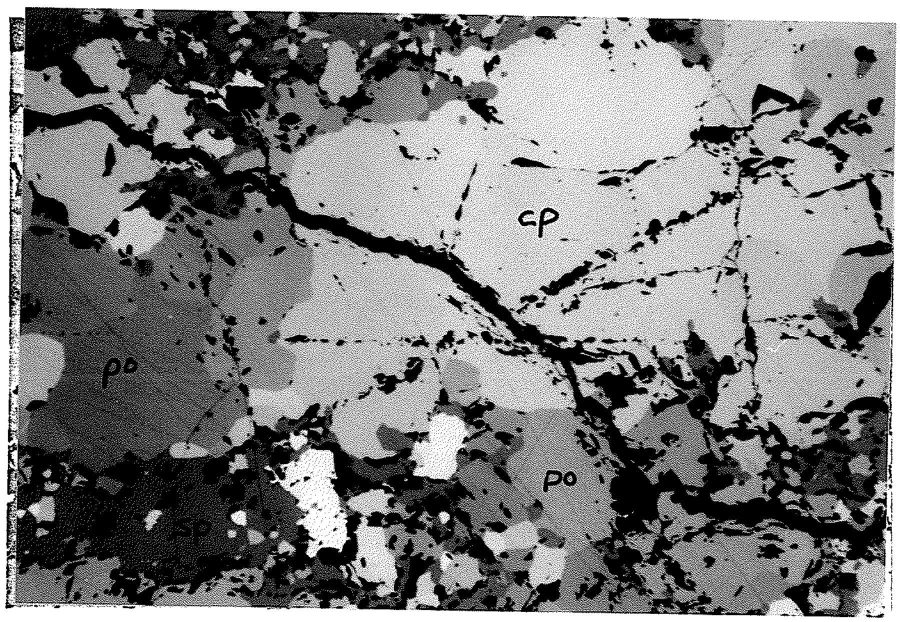


Figure 15: Copper-rich massive sulphides. Large chalcopyrite grains within pyrrhotite, with lesser amounts of sphalerite. Reflected light, crossed polarizers, width of field 1.83 mm (63x).
Location: 70995E, 10230N, 2100 level.

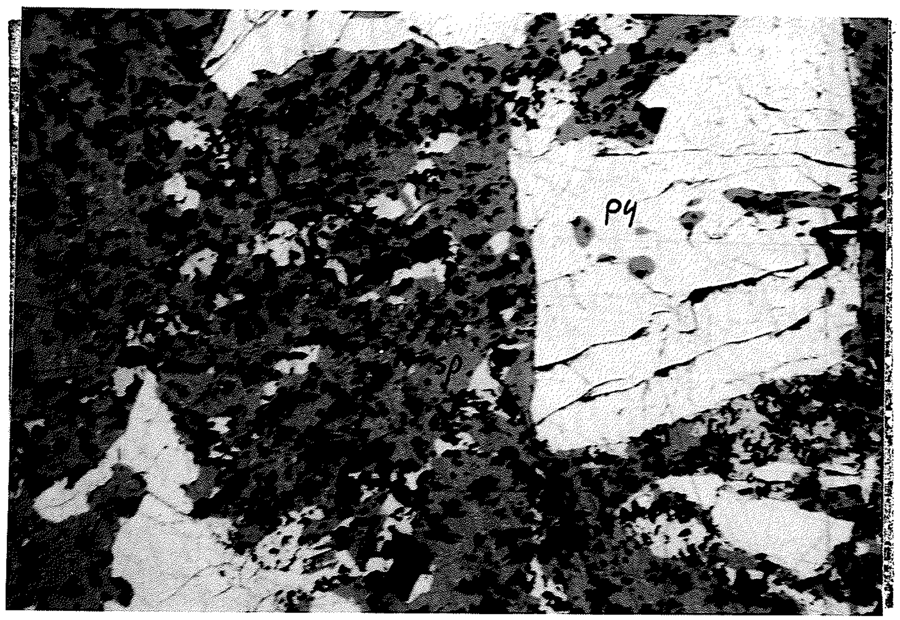


Figure 16: Sub-idioblastic pyrite cubes in sphalerite. Pyrite appears to be partly replaced by sphalerite. Reflected light, crossed polarizers, width of field 1.74 mm (66x). Location: 70955E, 10308N, 2100 level.

Figure 17: Possible primary layering in pyritic zinc ore, crosscut by coarse grained pyrrhotite and chalcopyrite vein.
Location: 70920E, 10365N, 2100 level.

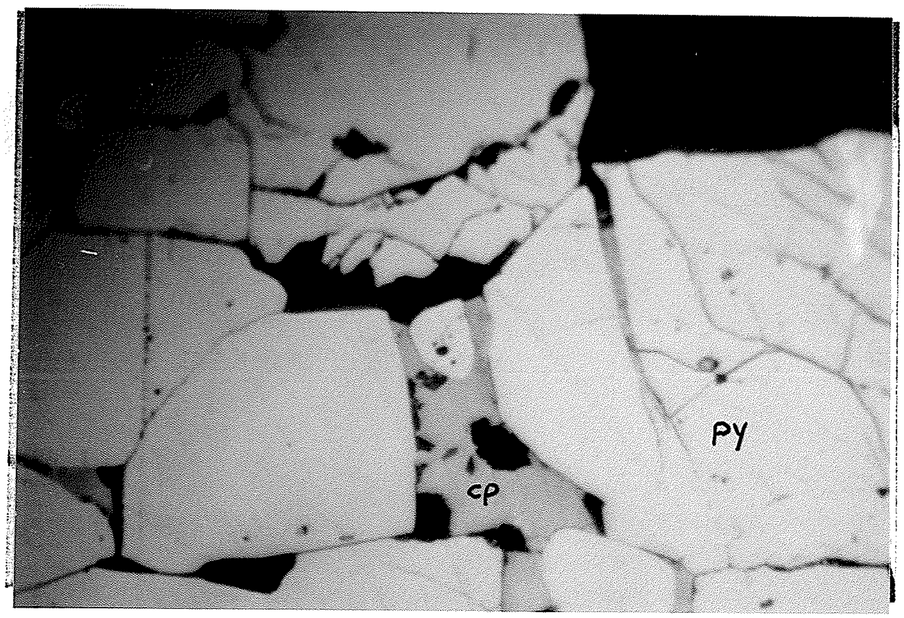


Figure 18: Chalcopyrite interstitial to pyrite. Fractures in pyrite have been healed by mobilized chalcopyrite. Reflected light, crossed polarizers, width of field 0.74 mm (157x).
Location: 71020E, 10273N, 2100 level.

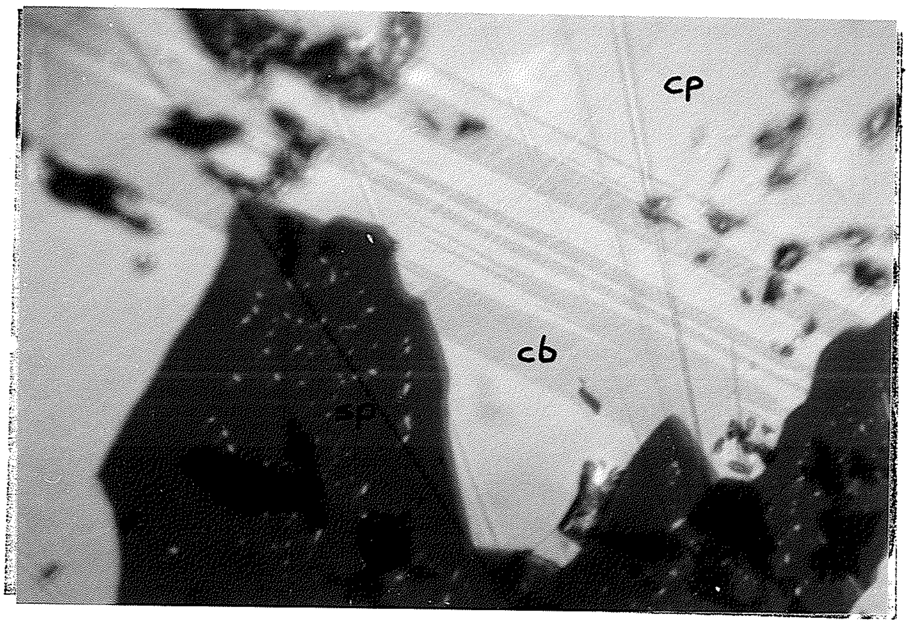


Figure 19: Cubanite exsolution lamellae in chalcopyrite. Exsolution blebs of chalcopyrite in sphalerite. Reflected light, oil immersion, crossed polarizers, width of field 0.21 mm (544x).
Location: 71020E, 10273N, 2100 level.

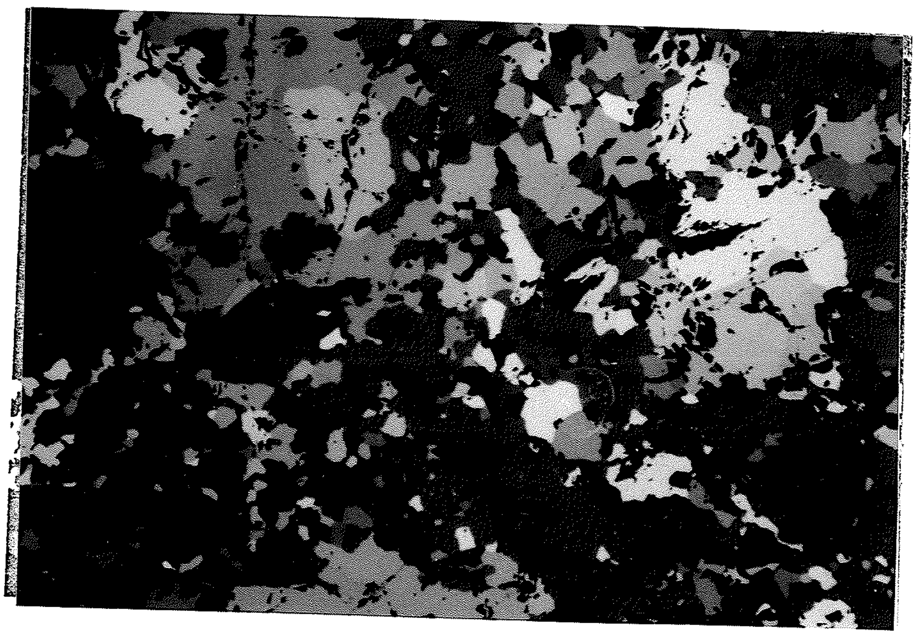


Figure 20: Sphalerite in pyrrhotite. Pyrrhotite light to medium gray, sphalerite, dark grey. Reflected light, crossed polarizers, width of field 1.82 mm (64x). Location: 70995E, 10230N, 2100 level.

Pyrrhotite

Pyrrhotite is common throughout the sulphide body, frequently occurring in stringers with chalcopyrite, possibly caused by metamorphic mobilization. Under crossed nicols, large pyrrhotite masses appear to have a polygonal texture (Figure 15), and rarely show twinning. Ramdohr (1969) mentions that twinning in pyrrhotite is rare, and that lamellae caused by the breakdown of pyrrhotite into two phases is more common. The two phases are usually either troilite and intermediate pyrrhotite or hexagonal pyrrhotite and monoclinic pyrrhotite, with the former being more common. There is usually a difference in both hardness and reflectivity between the phases, but this was not the case in the samples examined. Pyrrhotite occurs with all sulphide assemblages and is possibly the most common sulphide mineral within the ore zone.

Other Minerals

Other ore minerals include minor occurrences of arsenopyrite, galena, tetrahedrite, magnetite, ilmenite, and native gold.

Gangue Mineralogy

Quartz

Quartz is the dominant gangue mineral of the massive sulphides. It generally occurs as unstrained grains with straight to slightly-curved boundaries with other quartz grains. Where in contact with sulphides, the quartz conforms to the outline of the sulphides. There are several zones where the quartz content exceeds that of the sulphides

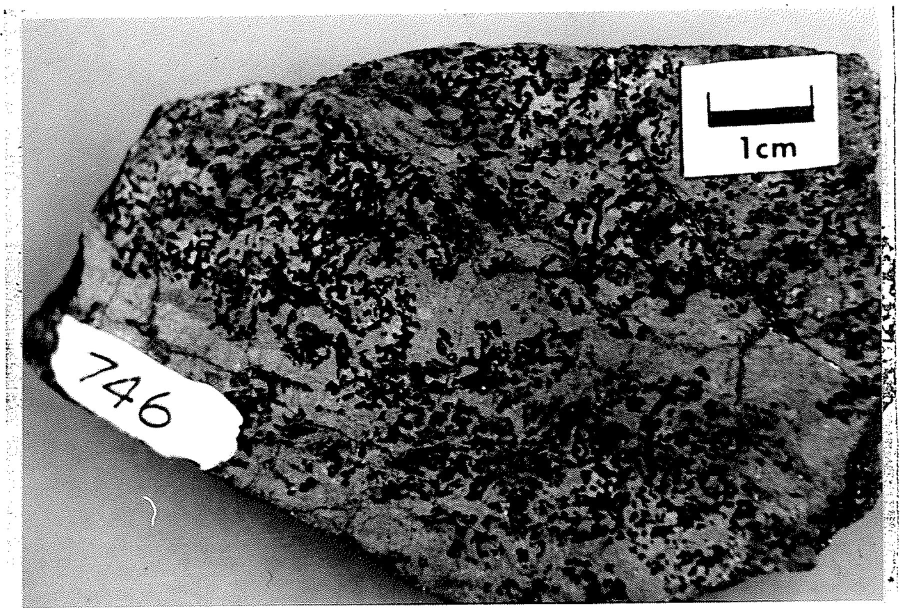


Figure 21: Irregular myrmekitic-like intergrowth of quartz (black) in pyrrhotite (medium gray), with streaks of sphalerite. Minor chalcopyrite (light gray) associated with quartz. Location: 71010E, 10248N, 2100 level.

and the rock has the appearance of a quartzite (Unit 1a). Quartz often shows myrmekitic-like intergrowths within the massive sulphides (Figure 21).

Carbonate

Carbonate occurs commonly with quartz as a gangue mineral and, in some sections, is the only gangue mineral present. It is characteristically twinned and irregular in shape, frequently forming large grains.

Plagioclase

Plagioclase only rarely occurs within the massive sulphides and is usually so highly altered to sericite that its identification is uncertain.

Other Minerals

Rare occurrences of mica and cordierite are found throughout the massive sulphides.

Disseminated Ore

The disseminated ore is generally copper-rich and can be divided into two units. One is within a quartz-rich rock towards the center of the ore body. It has only limited occurrence on the 2100 level but is more common on the upper levels (section 1, map 4, unit 1a). It has the appearance of a medium-grained quartzite, with disseminated pyrite throughout. Chalcopyrite and pyrrhotite occur as irregular stringers, possibly the result of metamorphic mobilization. This rock could be the metamorphic equivalent of a ferruginous chert, a cherty tuff unit associated with many massive sulphide deposits (Hutchinson, 1973; Lambert and Sato, 1974; Sangster, 1972; and Sato, 1974). Hopwood (1976), however, considered the origin of cherty rocks of this type to be due to silicification of the original wall rocks, and not as chemical precipitates.

The second type of disseminated ore is within the cordierite-anthophyllite and cordierite-muscovite-phlogopite alteration. Mineralization occurs primarily as pyrrhotite and chalcopyrite, with lesser amounts of pyrite (Figure 22). This portion of the ore body was studied mainly from drill core, where chalcopyrite and pyrrhotite appeared as coarse irregular grains. It is possible that they are in the form of stringers as in the quartz-rich disseminated sulphides. Ore-grade mineralization of this type is generally confined to the eastern end of the ore body.

Copper-Zinc Zonation

Vertical Copper-Zinc Zonation

Copper versus copper+zinc ratios were calculated from ore reserve blocks (Figure 23). This has shown a very pronounced variation from zinc-rich with a ratio of 0.27 above the 300 level to copper-rich below the 2600 level. This variation is typical of copper-zinc deposits in Canada. Similar vertical variations occur in the Flin Flon deposits, the Noranda deposits, and the Kidd Creek deposit (H. D. B. Wilson, personal communication).

Copper-Zinc Zonation on the 2100 Level

Copper versus copper+zinc values were calculated from assays on twelve drill holes (map 3). These were then contoured, with the 0.5 contour as the division between copper and zinc zones. All values below 0.5 are rich in zinc relative to copper, while values above 0.5 are rich in copper relative to zinc. A very strong zonation exists, usually with very sharp boundaries, between the copper and zinc-rich zones. Values in the copper zone are generally very high, in the .85 to .95 range, indicating that very little zinc is present. Values in the zinc zones are, on the average, in the 0.30 to 0.40 range, with some areas of very low values. It is possible that copper sulphides, being more mobile (Gill, 1960), have moved into the zinc zones, although these could have been primary values.

Zinc zones are generally towards the margins of the massive sulphide zone, with copper occupying the center. There is a thickening of the zinc zone at the west end of the northern limb. The disseminated zones surrounding the massive zone is usually copper-rich relative to zinc, although values of both may be very low, with pyrite being the most abundant sulphide. The large, ore-grade disseminated zone can be seen on the east end of the deposit, within the cordierite-anthophyllite-phlogopite alteration (map 2).

Figure 22: Large cordierite grain (cd) (left) altered to pinite. Muscovite (ms) and minor pyrite (py) in pyrrhotite (po). Combined illumination, crossed polarizers, width of field 1.87 mm (62x).
Location: 71090E, 10238N, 2100 level.

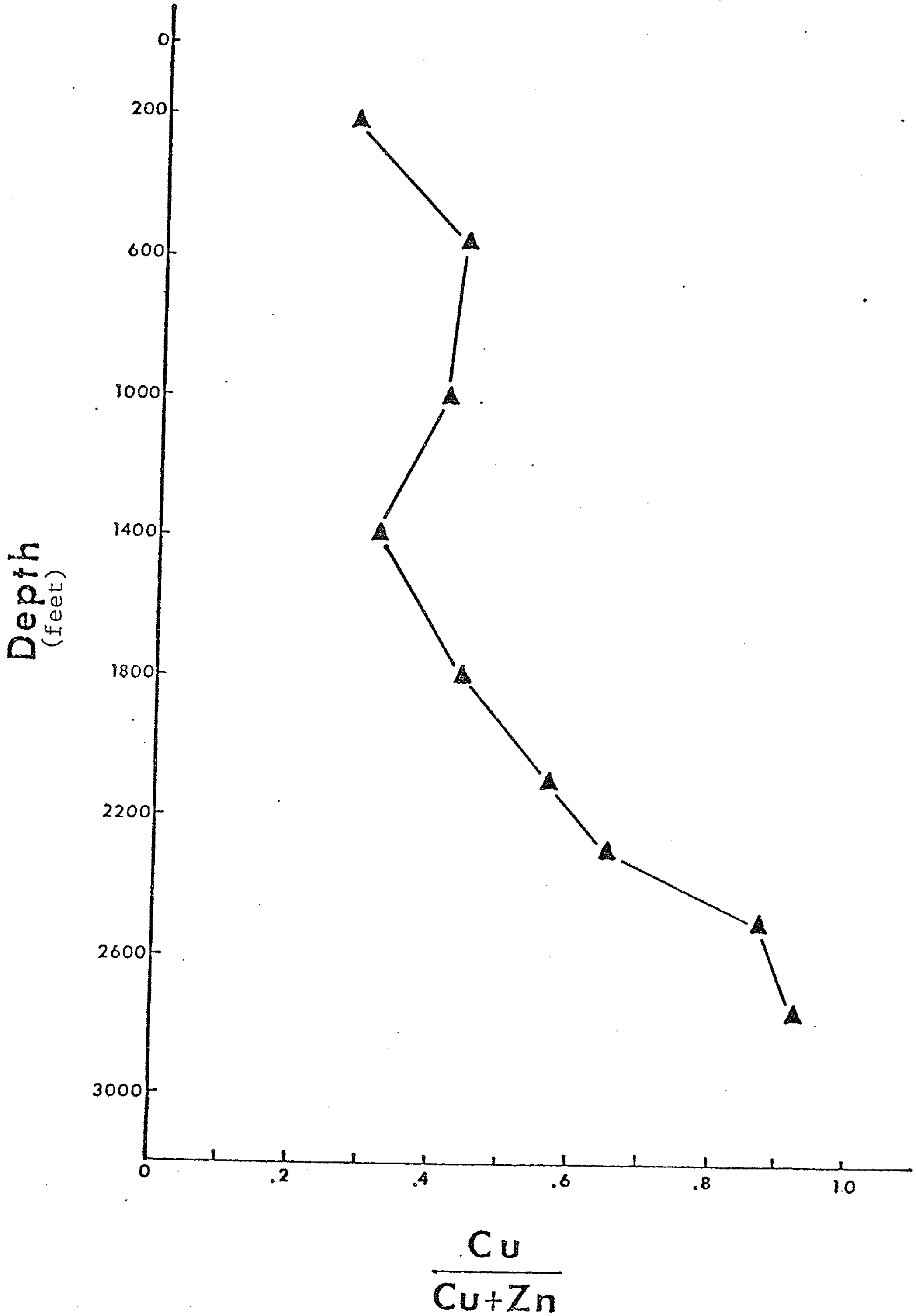


Figure 23: Copper versus Copper + Zinc variation with depth.

Copper-Zinc Zonation on the 1600 Level

Copper versus copper + zinc ratios have been calculated from assay values in nine drill holes on the 1600 level (map 4). This level has not been mapped for this study, but ore outlines and massive and disseminated sulphide outlines have been based on geological maps provided by the mine geologist. On this level, a similar pattern to that of the 2100 level, can be observed. A thickening of the zinc zone to the west of the north limb occurs here also. This level has a large quartz-rich disseminated zone with high copper ratios to the east becoming more zinc-rich towards the west. It is surrounded by massive copper and zinc-rich zones.

An ore-grade disseminated zone is also present at the eastern end of the ore body, hosted by the alteration zone. There is a small isolated massive sulphide lens to the east of the main body which also shows a strong zonation, but with copper occupying the north end and zinc on the south with another zinc zone in the center. As on the 2100 level, the non-economic disseminated sulphides surrounding or enveloping the ore body are all copper-rich relative to zinc.

Discussion

Massive sulphide deposits in volcanic rocks frequently exhibit a consistent zoning pattern. Sangster (1972), in his compilation of Canadian Precambrian volcanogenic massive sulphide deposits, described a typical zonation with a stringer ore consisting of chalcopyrite and pyrrhotite overlain by massive sphalerite-pyrite ore. Lusk (1969), described a similar zonation in the Ordovician Heath Steele ore body in New Brunswick, with chalcopyrite-pyrrhotite in the footwall grading into pyrite-sphalerite-galena in the hanging wall. He also states that sphalerite and galena are commonly absent in chalcopyrite-rich zones. The Kuroko deposits of Japan (Sato, 1974), while lacking in pyrrhotite, consist of a chalcopyrite-pyrite stringer ore overlain by massive pyrite-chalcopyrite ore and galena-sphalerite-barite ore. Large (1977) considered the chalcopyrite-pyrrhotite assemblage to have been precipitated as stringers and massive replacements below a sea-water-rock interface, due to mixing of metal-rich hydrothermal fluids with sea water at the top of a volcanic pile. He considers the sphalerite-pyrite assemblages to have been deposited directly on the sea floor in the vicinity of the hydrothermal vent.

Metal zonation in deposits considered to be of an epigenetic origin is thought to be due to varying solubilities, volatilities and diffusion rates of different metallic ions (Park and MacDairmid, 1970).

The zonation present in the Fox ore body bears some resemblance to the zoning described in previous paragraphs. The Fox ore body consists of massive sphalerite-pyrite ore and massive and disseminated chalcopyrite-pyrrhotite ore which may be interpreted as the equivalent to the hanging wall, footwall and stringer ore respectively. To fit the Fox ore body into Large's model (1977) would require that the Fox ore body has been folded isoclinally with the nose of the fold to the west. Although no other evidence of folding is available, the thicker zinc zone towards the northwestern ends of the ore body observed on both the 1600 and 2100 levels, could be interpreted as a relict fold nose separated from the southern limb during further deformation.

The observed vertical zonation may have resulted from folding of the ore body, which may be more complex than just a simple isocline, or may have an epigenetic or metamorphic origin. This has not been resolved during the present study.

The presence of higher copper values, relative to zinc in the non-economic disseminated sulphide envelope around the ore body, could be explained by a later solid diffusion of copper sulphides in the presence of a temperature gradient. Gill (1960), has shown that copper sulphides will move very rapidly at temperatures about $400^{o}C$. In the presence of a temperature gradient, the copper sulphides will move towards the cooler end. Iron and zinc sulphides show only slight tendencies towards solid diffusion. Turek, et al (1976) suggested that such a thermal gradient did exist during the cooling stages of regional metamorphism, due to the sulphide mass retaining heat longer than the surrounding host rocks.

Metamorphism and Mobilization of the Ore Body

Numerous authors have studied the effects of metamorphism on massive sulphides. Gill (1969) has shown that at confining pressures of 5.5×10^4 kPa (.55kb), chalcopyrite and pyrrhotite will flow plastically into fractures formed in pyrite. Chalcopyrite recrystallizes at $565^{o}C$ and pyrrhotite at $525^{o}C$ to $666^{o}C$ (Gill, 1969). With extreme deformation, pyrite and sphalerite would be granulated and the grains spread out by the plastic flow of the chalcopyrite and pyrrhotite. Graf and Skinner (1970) concluded that pyrite deforms in a brittle fashion and pyrrhotite plastically, under most, if not all, geological conditions.

More recent experiments (Gill, 1970), have shown that plastic flow in chalcopyrite and pyrrhotite will take place at room temperature under high confining pressure with low strain rates. Gill (1970) indicated that at temperatures above 560^{o}C, sphalerite will begin to flow plastically, possibly even more readily than chalcopyrite.

Gill (1969) states that if temperatures are held above 565^{o}C, chalcopyrite and pyrrhotite would recrystallize completely leaving no evidence of deformation. Stanton and Gorman (1968) and Stanton (1972) demonstrated that annealing of sulphides takes place rapidly even at low temperatures, resulting in a polycrystalline unstrained state. Metamorphism of sulphides generally results in an increase in grain size and the development of porphyroblasts (Kalliokoski, 1965, McDonald, 1972, Sangster, 1972).

Lawrence (1967) has proposed that partial melting has occurred at the Broken Hill ore body at temperatures around 700^{o}C. Studies by Craig and Kullerud (1968) have shown that partial melting in the system Cu-Fe-Pb-S can begin as low as 508^{o}C.

Metamorphism of sulphides can also cause mineralogical changes. One of the most common changes observed in metamorphosed pyritic ores is the transformation of pyrite to pyrrhotite (McDonald, 1967; Sangster, 1972; Bachinski, 1976). Sangster (1972) considered pyrrhotite in the sphalerite-rich zones of massive sulphide deposits to be partially or completely derived from the metamorphism of pyrite, and the pyrrhotite in the stringer and massive chalcopyrite-rich zones was of primary origin.

Mobilization of sulphide deposits due to metamorphism can result in separation of the sulphides from gangue constituents, differential migration of trace and major constituents, and movement of the sulphides relative to the enclosing rocks (McDonald, 1967). Movement can take place by plastic flow (Vokes, 1971; McDonald, 1967), solid diffusion (Gill, 1960), migration of partial melts (Vokes, 1971; Lawrence, 1967), and fluid state mobilization of dissolved metals in metamorphogenic hydrothermal solutions (Vokes, 1971; Guha and Koo, 1975).

Although Vokes (1971) considers movement of sulphides by metamorphic mobilization to involve relatively short distances (centimeters to one meter), some authors consider plastic flow to be the mechanism for concentrating sulphides in the noses of folds, and emplacing sulphide deposits into zones of weakness (McDonald, 1967).

Primary depositional textures are generally absent from the Fox Mine sulphides. Layering occurs only rarely within the sulphides. One isolated sample shows interlayering of pyrite and quartz-rich layers (Figure 17). Metamorphic textures have been observed both microscopically and macroscopically. Chalcopyrite (Figure 18), and pyrrhotite can be seen to penetrate fractured pyrite grains. Pyrrhotite generally exhibits a polygonal-polycrystalline texture with no deformational twinning (Figure 15). Pyrite grains are commonly large and form porphyroblasts up to 1 cm in diameter. Pyrrhotite and chalcopyrite generally form coarse irregular grains, often forming veins within both the massive and disseminated sulphides and the wall rocks. Internally the chalcopyrite and pyrrhotite grains show no sign of deformation.

Mobilization of chalcopyrite and pyrrhotite, and to a lesser extent sphalerite, has apparently occurred within the Fox ore body, at least on a microscopic scale as shown by the penetration of these minerals into fractures within pyrite grains. The veins of chalcopyrite and pyrrhotite mentioned previously, may be an example of plastic flow on a macroscopic scale.

The presence of pyrrhotite in the dominantly pyritic zinc zones of the Fox ore body, could be due to a metamorphic mineral transformation, although complete transformation of pyrite to pyrrhotite has not occurred.

The textures observed, such as chalcopyrite and pyrrhotite penetrating fractured pyrite grains, coarse grain size and porphyroblastic grain growth indicate that the sulphides have undergone metamorphism, probably to the same extent as the silicate wall rocks.

Under these metamorphic conditions partial melting of the sulphides may have occurred which, combined with deformation, may have altered both the shape and metal distribution of the ore body.

Alteration of the Host Rocks

Alteration of the host rocks associated with the Fox Mine is divided into pre-metamorphic alteration and post-metamorphic alteration. Pre-metamorphic alteration is considered to be primary alteration caused by mineralizing fluids associated with the main Cu-Zn mineralization, regardless of whether the deposit is of epigenetic or synvolcanic origin. This pre-metamorphic alteration has been metamorphosed and is subdivided into three units characterized by particular metamorphic mineral assemblages: cordierite-anthophyllite-cummingtonite ± biotite ± phlogopite, cordierite-quartz-muscovite ± phlogopite ± biotite ± sillimanite, and a quartz-sericite schist. All three units are interlayered and are found within the ore body and along the margins.

On the 2100 level, the alteration zone has a width of 60 meters and extends for at least 500 meters east and west along strike, and apparently continues below the ore body for some distance as shown by deep drilling. No symmetry of the alteration units is apparent that could suggest folding, but faulting and irregular primary distribution of pre-metamorphic alteration units could account for this. The first two units generally have a very coarse grain size, with anthophyllite porphyroblasts up to 7 cm long. A weak foliation can be observed in some locations, but crystal growth commonly appears to be random. The quartz-sericite schist has a well-developed foliation and a smaller grain size.

The post-metamorphic alteration is irregular in occurrence and is recognized by the alteration of plagioclase and cordierite.

Pre-Metamorphic Alteration

Cordierite-Anthophyllite ± Cummingtonite ± Biotite ± Phlogopite (unit 2a)

This unit is found in large lenses at both ends of the ore body, and as scattered small lenses south of the massive sulphides. It consists of very large cordierite grains, interstitial to, and including large anthophyllite and cummingtonite laths (figure 24). Two types of cordierites have been recognized. One is massive and untwinned with very fine dusty opaque inclusions. It is commonly fractured with sericitic alteration along the fractures. The other type is highly poikiloblastic with inclusions, usually of quartz, occupying up to 50% of the grain. Micas, anthophyllite and cummingtonite are often found as inclusions as well. Quartz sometimes forms myrmekitic intergrowths within the cordierite, although generally it forms round to slightly oval grains. Anthophyllite occurs as elongated bladed masses usually aligned parallel to the foliation, with generally a random orientation within the plane of the foliation. Cummingtonite commonly occurs with anthophyllite and is similar in shape and orientation. Biotite and phlogopite occur as large grains oriented in a crude foliation or randomly oriented. Phlogopite can be distinguished from biotite in thin section by its lighter color and paler pleochroism (light brown to colorless). Biotite is rare in this unit, and never occurs with phlogopite. Sulphide mineralization present in this unit includes pyrite, pyrrhotite, chalcopyrite, arsenopyrite and minor sphalerite. These minerals are in the form of disseminations and irregular stringers throughout this unit.

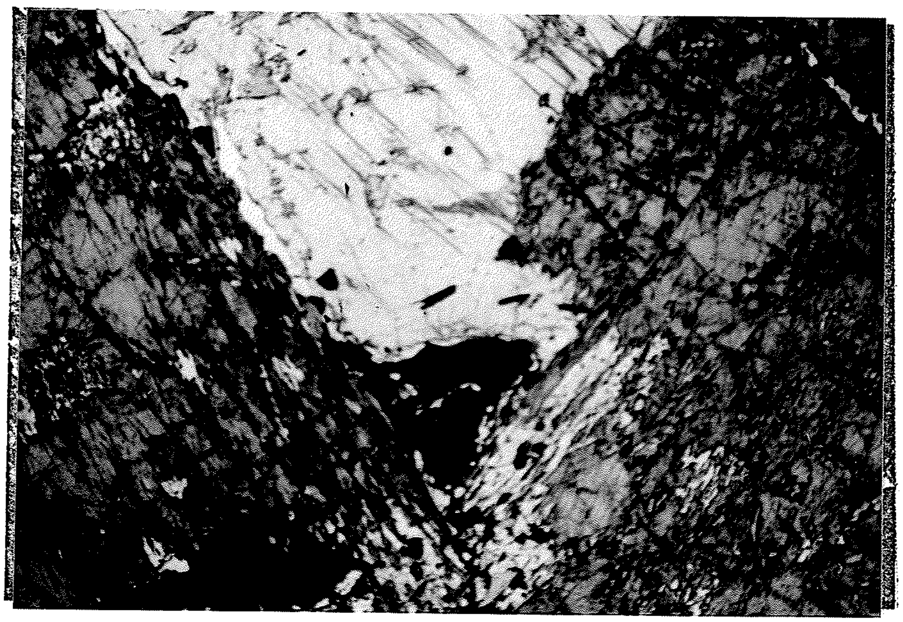


Figure 24: Cordierite-anthophyllite rock. Very large cordierite (light) and anthophyllite (dark) porphyroblasts, with minor pyrrhotite. Plane light, width of field 9.70 mm (12x) Location: 70516E, 10560N, 2100 level.

Cordierite-Quartz-Muscovite$\pm$Phlogopite$\pm$Biotite $\pm$Sillimanite (unit 2b)

This unit is distinguished from the previous unit mainly by the absence of anthophyllite and cummingtonite. Texturally, it is very similar to the cordierite-anthophyllite rock, with a weak foliation and frequently random orientation of micas. Quartz is present as interstitial grains, occasionally containing knots of fibrous sillimanite (figure 25). Muscovite and phlogopite occur as long, oriented to unoriented grains, and commonly penetrate cordierite grains. Plagioclase is rare within this unit and, if present, is usually highly altered. Cordierite is commonly weakly altered to pinite and chlorite (figure 22).

Quartz-Sericite Schist (unit 2c)

The quartz-sericite schist occurs as a medium grained, well foliated rock along the southern margin of the ore body, and as lenses within the other units of the alteration zone. It consists primarily of quartz, which is frequently unstrained, with interstitial grains of sericite. Plagioclase commonly occurs as untwinned grains and is weakly to completely altered. Phlogopite, as well as cordierite and sillimanite, rarely occur within the quartz-sericite schist. Contacts between the quartz-sericite schist and the other units of the alteration zone and the massive sulphides are generally very sharp (figure 26). Sulphide, mainly pyrite, occurs along the foliation planes. Some larger grains of quartz exist and could be porphyroblasts or relict phenocrysts. A chemical analysis of a sample of this unit (table 11) indicates that it is rhyolitic to dacitic in composition.

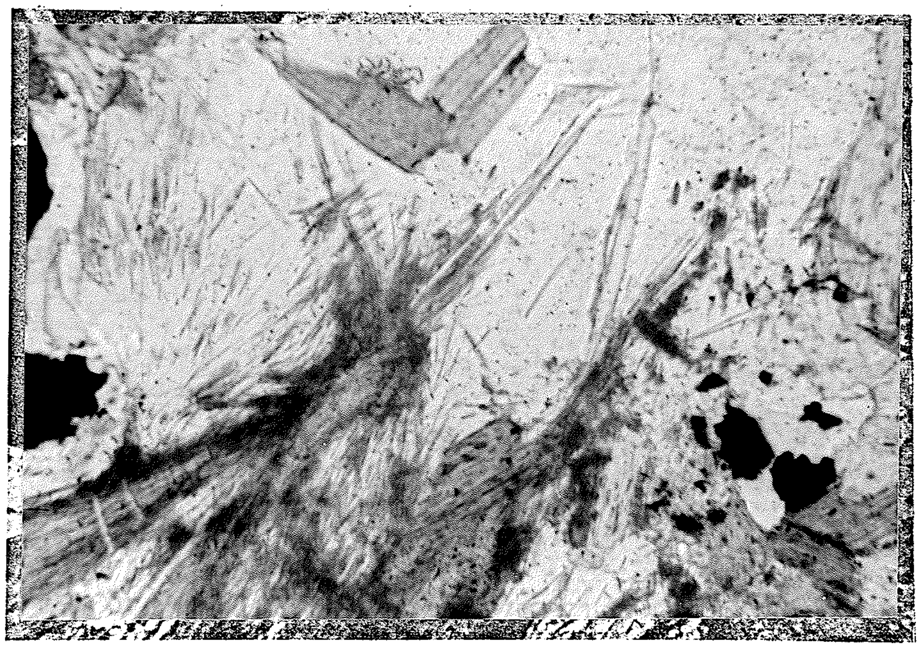


Figure 25: Knot of needle-like sillimanite in quartz, with phlogopite.
Plane light, width of field 0.75 mm (158x).
Location: 70975E, 10223N, 2100 level.

Figure 26: Sharp contact between cordierite-anthophyllite rock (top) and quartz-sericite schist (bottom). Plane light, width of field 9.50 mm (12x). Location: 70516E, 10291N, 2100 level.

Origin of the Pre-Metamorphic Alteration

Early interpretations of the origin of cordierite-anthophyllite rocks have considered them to result from metasomatic introduction of magnesium and iron (Deer *et al*, 1963).

Valance (1967) states that unaltered volcanic rocks of similar composition to cordierite-anthophyllite rocks do not occur in nature, but mafic lavas altered by essentially diagenetic processes approach this composition.

Later work has indicated that cordierite-anthophyllite assemblages can be derived from the metamorphism of chlorite-quartz schists through the following reaction (Deer *et al*, 1976):

$$\underset{\text{clinochlore}}{5Mg_3Si_2O_5(OH)_4 + 6Mg_2Al_2SiO_5(OH)_4} + \underset{\text{quartz}}{23SiO_2}$$

$$\underset{\text{anthophyllite}}{3Mg_7Si_8O_{22}(OH)_2} + \underset{\text{cordierite}}{3Mg_2Al_4Si_5O_{18}} + 19H_2O$$

Although cordierite-anthophyllite rocks can form from a variety of source rocks by a number of processes, the close association between rocks of this mineralogy and massive sulphides (Sangster, 1972) leads to the assumption that the ore-forming process is, in some way, involved in its formation.

Froese (1969) has described a cordierite-anthophyllite assemblage at the Coronation Mine in Saskatchewan. He considered it to have formed by the isochemical metamorphism of a pre-existing chloritized zone associated with the mineralization. Rosen-Spence (1969) considered cordierite-anthophyllite rocks associated with massive sulphides in the Rouyn-Noranda area to be the products of primary chlorite alteration thermally metamorphosed by the Dufault granodiorite. The Millenbach deposit in Quebec has a foot wall alteration zone containing spotty occurrences of anthophyllite along with chlorite and sericite (Simmons, 1973).

Cordierite-anthophyllite rocks have also been studied in the Ordovician massive sulphides at Notre Dame Bay, Newfoundland (Bachinski, 1976; Upadhyay and Smitheringdale, 1972). The majority of the deposits have undergone greenschist facies metamorphism and the ore bodies are associated with chlorite alteration zones. The Gullbridge deposit has undergone contact metamorphism to the hornblende-hornfels facies (Bachinski, 1976) that has resulted in two alteration assemblages: cordierite + anthophyllite, and cordierite + biotite + andalusite. Bachinski (1976) considered the following reactions to have resulted in the assemblages observed at the Gullbridge deposit:

1) chlorite + quartz + pyrite = cordierite + anthophyllite + pyrrhotite + magnetite + water

2) quartz + chlorite + muscovite = cordierite + biotite + andalusite + water

The cordierite-rich alteration zones at the Fox Mine may have had a similar origin, with the cordierite-anthophyllite-cummingtonite assemblage resulting from the isochemical metamorphism of a quartz-chlorite primary alteration, and the cordierite-quartz-phlogopite-muscovite-sillimanite assemblage resulting from a sericite+ chlorite alteration.

The quartz-sericite schist differs from the other alteration assemblages in both mineralogy and texture. It is included in the alteration zone because of its spatial relationship with the other alteration assemblages, and its inclusion in the alteration zone by the mine geologists. Its distribution is irregular, in the form of narrow lenses and stratiform units. One possible origin of this unit is the silicification of volcanic or sedimentary rocks. The quartz-sericite schist may also represent an original stratigraphic unit, possibly equivalent to the quartz porphyry or quartz crystal tuff, associated with many massive sulphide deposits (Walker et al, 1975; Hopwood, 1976; Koo and Mossman, 1975; Gilmore, 1971). These quartz porphyry units could be extrusive, intrusive, or pyroclastic in origin.

The configuration of the alteration surrounding the Fox ore body differs from that of many massive sulphide deposits. General works on the geology of massive sulphide deposits generally show that chloritic and sericitic alteration zones stratigraphically underlie massive sulphide bodies, often in the form of a pipe (Sangster, 1972; Lambert and Sato, 1974; Hutchinson, 1973).

These pipes are considered to represent alteration of the foot wall rocks by mineralizing hydrothermal solutions that precipitated the massive sulphides at the rock-sea water interface. The alteration at the Fox Mine is found along both sides of the ore body, and continues for a considerable distance along strike. If the configuration of the ore body is interpreted as an anticlinal fold, a footwall alteration pipe would have been folded also and would now be expected to be located only in the core of the fold. The explanation must be more complex.

Alteration pipes that extend stratigraphically above massive sulphides have been documented by several authors. Spence and Rosen-Spence (1975) and Simmons (1973), have shown that alteration pipes continue stratigraphically above the Amulet and Millenbach deposits in Quebec, in some cases resulting in deposition of another deposit at a higher stratigraphic level. Iijima (1974) indicated that the sericite-chlorite alteration in some Kuroko deposits of Japan extends into hanging wall rocks, as hydrothermal activity may continue for 1 or 2 million years, and thus affect rocks that postdate the deposition of sulphides.

Alteration patterns such as these, if folded isoclinally with the ore body, could result in a pattern similar to that at the Fox Mine, although the long stratiform shape of the alteration would suggest considerable attenuation during deformation. This would be consistent with the attenuated fold form interpreted from the zoning in the ore body. Alternately, the alteration may be stratigraphically controlled.

Koo and Mossman (1975) have commented on the difficulty in distinguishing between chloritized shear zones, and chlorite alteration associated with mineralization. It is possible that the cordierite-anthophyllite alteration zone as the Fox Mine could have resulted from the metamorphism of a chloritized shear zone alone or one combined with primary alteration associated with mineralization. Taking all of the evidence into account, the best interpretation appears to be that a chloritic alteration zone has been metamorphosed and that the alteration zone was probably related to the deposition of the sulphides and extended both stratigraphically above and below them.

Post-Metamorphic Alteration

Post-metamorphic alteration, especially of plagioclase, is found throughout the area, but becomes more intense in the ore zone. In places, cordierite is completely altered to pinite (Figure 22), or chlorite (Figure 27). Alteration is commonly localized along fractures within cordierite crystals. These fractures in some cases, contain sulphide mineralization, primarily pyrrhotite, chalcopyrite, and galena (Figure 28). Distribution of this late alteration is very spotty, with patches of nearly complete alteration of cordierite and plagioclase, and other areas of little or no alteration.

This alteration could have resulted from hydrothermal fluids related to a later intrusive phase, possibly the granodiorite intrusives to the north. They could have migrated up a zone of weakness, possibly represented by the cordierite-anthophyllite-mica rocks which contain numerous open spaces. An alternative origin could be similar to that proposed for the later alteration around the Broken Hill deposit in Australia (Plimer, 1975). This alteration replaces earlier high-grade metamorphic minerals and was thought to result from metamorphically-generated fluids ascending along permeable sulphide-silicate boundaries.

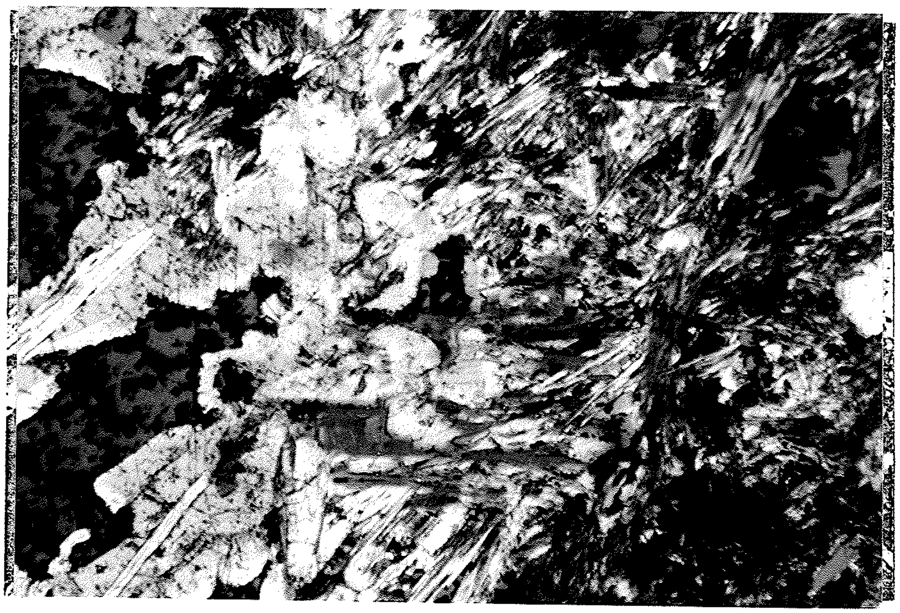


Figure 27: Radiating fibrous chlorite as an alteration of cordierite. Unaltered cordierite at left in contact with pyrrhotite. Combined illumination, crossed polarizers, width of field 1.74 mm (66x).
Location: 70944E, 10291N, 2100 level.

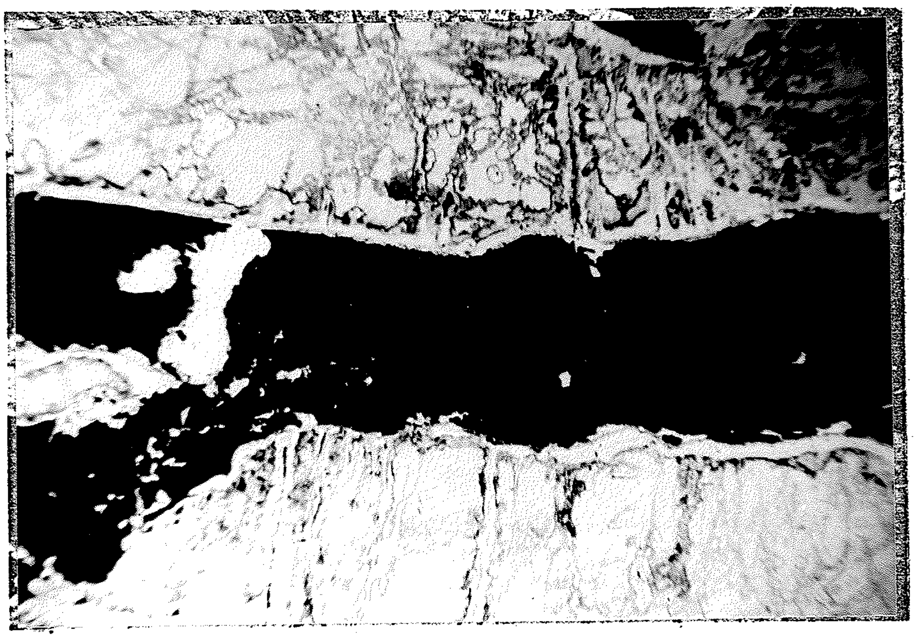


Figure 28: Large cordierite crystal altered along fractures. Sulphide mineralization, mainly chalcopyrite, pyrrhotite and galena deposited along fractures in micro-veinlets, plane light, width of field 4.68 mm (25x). Location: 70516E, 10551N, 2100 level.

CHAPTER IV

DISCUSSION OF THE GENESIS OF THE FOX MINE MINERALIZATION

Previous authors discussing the origin of the Fox ore body have all considered the mineralization to be epigenetic, resulting from the replacement of pre-existing pyritic sulphide accumulations or volcanic rocks with chalcopyrite and sphalerite by metal-bearing hydrothermal solutions. Glass (1972) considered the deposit to be epigenetic because rocks considered to be intrusive appear to predate the mineralization and were apparently replaced by sulphide mineralization. Also the symmetrical outline of the alteration zone with respect to the ore body was cited as further evidence of an epigenetic origin.

Obinna (1974) also advocated a hydrothermal replacement origin. He considered that the ore body and host rocks had both been involved in amphibolite facies metamorphism, but thought that the alteration post dated the metamorphism. Turek et al (1976), in his study of the metal dispersion around the ore body, concluded that his Q-mode factor analysis failed to demonstrate any spatial pattern with respect to the ore body. He suspected that the mineralization was deposited during a period of elevated temperatures, possibly coeval with metamorphism, and subsequently modified by a later metamorphism.

In the hydrothermal replacement hypothesis, mineralization fluids, generally resulting from post-volcanic granitic intrusions, alter and replace pre-existing rocks with massive sulphides (Bateman, 1942). The source of the metals could be either from the granitic magma, or leached from the volcanic rocks themselves (Boyle, 1970). Alternately the massive sulphides could be considered to have been deposited in dilatent zones, possibly related to early phases of deformation of the greenstone belt.

Although there are still many advocates of this hypothesis (Boyle, 1976; Norman, 1977), the majority of literature in recent years has discussed a volcanogenic origin for many Canadian massive sulphide deposits. Recent compilations of Canadian massive sulphide deposits have compared Canadian deposits to those in Cyprus and Japan (Sangster, 1972; Hutchinson, 1965,1973). The authors have considered the Canadian ore bodies as being precipitated on the sea floor from metal-bearing hydrothermal fluids related to the late phases of a volcanic cycle. The distinctive features of Precambrian volcanogenic massive sulphides are: (a) a stratiform and strata-bound configuration, (b) distinctive metal zonation with copper on the stratigraphic foot wall and zinc (±lead) on the hanging wall, (c) chlorite and sericite alteration in the foot wall, often in the form of a pipe, (d) a zone of copper-rich sulphide stringers in the foot wall alteration zone, and (e) association with felsic pyroclastics and quartz porphyry (Sangster, 1972).

In comparing the Fox ore body with any genetic model, difficulties arise in attempting to visualize what the pre-metamorphic rock types were, and what the undeformed configuration of the ore body was. MacDonald (1967) pointed out that metamorphism can result in many epigenetic-appearing features and therefore can lead to a false interpretation of the origin of the deposits. Metamorphism and mobilization of the Fox ore body might have resulted in considerable alteration to its shape.

To fit the Fox Mine into a volcanogenic model, requires the deposit to have been folded isoclinally with the fold apex at the western end of the ore body. The only evidence of such folding is the zoning of the ore body itself, however, the area is considered by several authors to have been isoclinally folded (Glass, 1972; Stanton, 1949). If the deposit was then unfolded, we would observe (a) a copper footwall zone overlain by a zinc hanging wall, (b) a footwall copper-rich disseminated sulphide zone, (c) a hanging wall and footwall alteration zone of cordierite $\pm$ anthophllite rocks, possibly derived from an initial chloritic alteration, and (d) association with a quartz-sericite schist of unknown origin, but possibly an originally felsic volcanic or intrusive rock.

There is no evidence that discounts an epigenetic origin for the Fox Mine. Deposition of sulphides may have occurred at any stage prior to regional metamorphism. The horizontal metal zonation could be explained by differential replacement of various lithologies. The vertical metal zonation, with increasing copper with depth can be explained by hypogene ore-bearing fluids precipitating copper at depth and becoming increasingly zinc rich as they rise. Alternately this zonation could be explained by a primary zonation with copper proximal and zinc distal to an exhalative vent (Sangster and Scott, 1976). This zonation could also be a feature caused by a redistribution of metals during metamorphism.

The Fox ore body has many features in common with massive sulphide deposits in Canada and other countries. Like many other deposits, the Fox deposit is associated with volcanic rocks, exhibits distinct metal zonation, and has an alteration zone that was possibly originally chloritic. The weight of evidence as shown in recent literature favors a volcanogenic sedimentary origin for this class of deposit as a whole (Sangster and Scott, 1976). The author favors a volcanogenic origin for the Fox Mine because of its similarities with other deposits considered to be volcanogenic. The over printing of regional metamorphism and deformation has altered both the shape and mineralogy of the ore body and has obscured much of the evidence for its genesis. It could also be argued that metamorphism of a deposit formed by hydrothermal replacement of pre-existing rocks would result in a similar end product.

Conclusions

The study of the geological setting of the Fox Mine has led to the following conclusions:

(1) The Fox ore body is stratiform and has a strata-bound relationship with Wasekwan Group intermediate metavolcanic rocks, which have undergone repeated deformation and metamorphism.

(2) The ore body exhibits metamorphic features consistent with medium-grade (amphibolite) metamorphism as shown by the enclosing volcanic rocks and is pre-metamorphic in age.

(3) It has undergone deformation and metamorphic mobilization of sulphides which has modified its original shape, and possibly modified its metal zonation.

(4) It is enclosed in a cordierite ± anthophyllite rock which is considered to be the metamorphic product of a primary chloritic alteration.

(5) It exhibits many features, although modified by metamorphism and deformation, which are found in deposits considered by many authors to be volcanogenic in origin.

(6) There is no conclusive evidence to discount an epigenetic origin, subsequently modified by metamorphism and deformation.

REFERENCES

Althaus, E., Karothe, E., Nitsch, K. H., and Winkler, H. G. F., 1970, An experimental re-examination of the upper stability limit of muscovite plus quartz: Neues Jahrb. Mineralogie Monatsh., p. 289-336.

Bachinski, D. J., 1976, Metamorphism of cupriferous iron sulfide deposits, Notre Dame Bay, Newfoundland: Econ. Geol., v. 71, p. 443-452.

Bailes, A. H., 1971, Preliminary compilation of the geology of the Snow Lake-Flin Flon Sheridon area: Man. Mines Br. Geological Paper 1/71, 27 p.

Bateman, A. M., 1942, Economic mineral deposits, John Wiley and Sons, Inc., New York, 898 p.

Boyle, R. W., 1970, The source of metals and gangue elements in hydrothermal deposits: in Problems of hydrothermal ore deposition, ed. Z. Pouba and M. Stemprok: Int. Union Geol. Sci., (Publ.), Ser. A, No. 2, P. 3-6.

____________, 1976, Mineralization processes in Archean greenstone and sedimentary belts: Geol. Surv. Can., Paper 75-15.

Craig, J. R., and Kullerud, G., 1968, Phase relations and mineral assemblages in the Cu-Pb-S system: Am. Mineral., v. 53, p. 145-161.

Deer, W. A., Howie, R. A., and Zussman, J., 1963, Rock-forming minerals, Vol. 2, Chain silicates; Longmans, London, 379 p.

Froese, E., 1969, Metamorphic rocks from the Coronation Mine and surrounding area: *in* ed. A. R. Byers, Symposium on the geology of the Coronation Mine, Saskatchewan: Geol. Surv. Can. Paper 68-5, p. 55-77.

Gilbert, H. P., 1966, Lynn Lake area (Arbour Lake): *in* Man. Min. Res. Div., Report of field activities, 1976, p. 33-37.

Gill, J. E., 1960, Solid diffusion of sulfides and ore formation: XXIst Int. Geol. Congress, Part XVI, p. 209-217.

__________, 1969, Experimental deformation and annealing of sulphides and interpretation of ore textures: Econ. Geol., v. 64, p. 500-508.

__________, 1970, Further notes on the deformation of sulfides: Econ. Geol., v. 65, p. 579-582.

Gilmour, P., 1971, Strata-bound massive pyritic sulfide deposits - A review: Econ. Geol., v. 66, p. 1239-1246.

Glass, D. J., 1972, Editor, Geology and mineral deposits of the Flin-Flon, Lynn Lake, and Thompson areas, Manitoba and the Churchill-Superior Front of the western Precambrian Shield: XXIVth Int. Geol. Congress Guidebook, Excurs. A31 and C31.

Graf, J. L. and Skinner, B. J., 1970, Strength and deformation of sulfides: Econ. Geol., v. 65, p. 206-215.

Guha, J., and Koo, J., 1975, Role of fluid state mobilization during metamorphism of the Henderson ore bodies, Chibougamau, Quebec, Canada: Can. J. Earth Sci., v. 12, p. 1516-1523.

Holdoway, M. J., 1971, Stability of andalusite, and the aluminum silicate phase diagram: Am. J. Sci., v. 271, p. 97-131.

Hopwood, T. P., 1976, "Quartz-eye" bearing porphyroidal rocks and volcanogenic massive sulfide deposits: Econ. Geol., v. 71, p. 589-612.

Hutchinson, R. W., 1965, Genesis of Canadian massive sulphides reconsidered by comparison to Cyprus deposits: Trans. Can. Inst. Min. Metall., v. 68, p. 286-300.

_________________, 1973, Volcanogenic sulfide deposits and their metallogenic significance: Econ. Geol., v. 68, p. 1223-1246.

Hutchison, C. W., 1974, Laboratory handbook of petrographic techniques, John Wiley and Sons Ltd., New York, 527 p.

Iijima, A., 1974, Clay and zeolitic alteration zones surrounding Kuroko deposits in the Holurolo District, Northern Akita, as submarine hydrothermal-diagenetic alteration products: in Geology of Kuroko Deposits, ed. S. Ishihara Mining Geology Special Issue, No. 6, p. 267-289.

Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Can. J. Earth Sci., v. 8, p. 523-548.

Kalliokoski, J., 1965, Metamorphic features of North American massive sulfide deposits: Econ. Geol., v. 60, p. 485-505.

Koo, J., and Mossman, D. J., 1975, Origin and Metamorphism of the Flin-Flon strata-bound Cu-Zn sulfide deposit, Saskatchewan and Manitoba: Econ. Geol., v. 70, p. 48-62.

Lambert, I. B., and Sato, T., 1974, The Kuroko and associated ore deposits of Japan: A review of their features and metallogenesis: Econ. Geol., v. 69, p. 1215-1236.

Large, R. R., 1977, Chemical evolution and zonation of massive sulfide deposits in volcanic terrains: Econ. Geol., v. 72, p. 549-572.

Lawrence, L. J., 1967, Sulphide neomagmas and highly metamorphosed sulfide deposits: Miner. Deposita., v. 2, p. 5-10.

Lusk, J., 1969, Base metal zoning in the Heath Steele B-1 Ore body, New Brunswick, Canada: Econ. Geol. v. 64, p. 509-518.

Luth, W. C., Johns, R. H., and Tuttle, O. F., 1964, The granite system at pressures of 4 to 10 kilobars: Jour. Geophys. Research, v. 69, p. 759-773.

McDonald, J. A., 1967, Metamorphism and its effects on sulphide assemblages: Miner. Deposita., v. 2, p. 200-220.

McRitchie, W. D., 1974, The Sickle-Wasekwan debate: a review: Man. Mines Br. Geol. Paper 1/74.

Milligan, G. C., 1960, Geology of the Lynn Lake District: Man. Mines Br. Publication 57-1, 317 p.

Moore, J. M., Jr., 1977, Orogenic volcanism in the Proterozoic of Canada: in Volcanic Regimes in Canada, ed., W. R. A. Baragar, L. C. Coleman, and J. M. Hall: Geol. Assoc. Canada Spec. Paper No. 16, p. 127-148.

Norman, G. W. H., 1933, Granville Lake District, Northern Manitoba: Geol. Surv. Can., Summary Report, 1933, Part C, p.230-241

________________, 1934, Granville Lake Area, Geol. Surv. Can., Map 301A.

________________, 1936, Granville Lake Sheet (West Half), Geol. Surv. Can., Map 343A.

________________, 1977, Proterozoic massive sulfide replacements at Jerome, Arizona: Econ. Geol., v. 72, p. 642-656.

Obinna, F. C., 1974, The geology and some genetic aspects of Fox Mine Mineralization, Northern Manitoba: Unpub. M. Sc. Thesis, University of Manitoba, 96 p.

Park, C. F., and MacDairmid, R. A., 1970, Ore deposits, 2nd Ed., W. H. Freeman and Company, San Franscisco, 522 p.

Plimer, I. R., 1975, A metamorphogenic alteration zone around the stratiform Broken Hill ore deposits, Australia: Geochemical Journal, v. 9, p. 211-221.

Ramdohr, P., 1969, The ore minerals and their intergrowths, Pergamon Press, Oxford, 1174 p.

Richardson, S. W., 1968, Staurolite stability in a part of the system Fe-Al-Si-O-H: Journ. Petrol., v. 9, part 3, p. 467-488.

Robertson, D. S., 1953, Batty Lake Map Area, Manitoba: Geol. Surv. Can., Memoir 271, 53 p.

Rosen-Spence, A. F. de, 1969, Genese des roches a cordierite-anthophyllite des gisements cupro-zinciferes de la region de Rouyn Noranda, Quebec, Canada: Can. J. Earth Sci., v. 6, p. 1339-1345.

Sangster, D. F., 1972, Precambrian massive sulphide deposits in Canada: a review: Geol. Surv. Can., Paper 72-22, 44 p.

_______________ and Scott, S. D., 1976, Precambrian strata-bound, massive Cu-Zn-Pb sulphide ores of North America: in Handbook of strata-bound and stratiform ore deposits, ed., K. H. Wolf.

_______________, 1978, Isotopic studies of ore-leads of the circum-Kisseynew volcanic belt of Manitoba and Saskatchewan: Can. J. Earth Sci., v. 15, p. 1112-1121.

Sato, T., 1974, Distribution and geological setting of Kuroko deposits: in Geology of Kuroko Deposits, ed. S. Ishihara: Mining Geology

Special Issue, No. 6, p. 1-9.

Simmons, B. D., 1973, Geology of the Millenbach massive sulphide deposit: Can. Min. Metall. Bull., v. 67, p. 67-79.

Spence, C. D., and Rosen-Spence, A. F. de, 1975, The place of sulfide mineralization in the volcanic sequence at Noranda, Quebec: Econ. Geol., v. 70, p. 90-101.

Spry, A., 1969, Metamorphic Textures, Pergamon Press, Oxford, 350 p.

Stanton, M. S., 1949, Geology of the Dunphy Lakes Area: Man. Mines Br. Publication 48-4, 34 p.

Stanton, R. L., 1972, Ore petrology, McGraw Hill, New York, 713 p.

______________, and Gorman, H., 1968, A phenomenological study of grain boundary migration in some common sulfides: Econ. Geol., v. 63, p. 907-923.

Stockwell, C. H., 1964, Age determinations and geological studies, Part II, geological studies: Geol. Surv. Can., Paper 64-17 (Part II).

Turek, A., Tetley, N. W., and Jackson, T., 1976, A study of metal dispersion around the Fox ore body in Manitoba: Can. Min. Metall. Bull., v. 70, p. 104-110.

Upadhyay, H. D., and Smitheringdale, W. G., 1972, Geology of the Gullbridge copper deposit, Newfoundland: volcanogenic sulfides in cordierite-anthophyllite rocks: Can. J. Earth Sci., v. 9, p. 1061-1073.

Vallance, T. G., 1967, Mafic rock alteration and isochemical development of some cordierite-anthophyllite rocks: J. Petrol., v. 8, p. 84-96.

Vokes, F. M., 1971, Some aspects of the regional metamorphic mobilization of pre-existing sulphide deposits: Miner. Deposita., v. 6, p. 122-129.

Walker, R. R., Matulich, A., Amos, A. C., Watkins, J. J., and Mannard, G. W., 1975, The geology of the Kidd Creek Mine: Econ. Geol., v. 70, p. 80-89.

Winkler, H. G. F., 1974, Petrogenesis of metamorphic rocks, 3rd Ed., Springer Verlag, New York, 320 p.

Worobec, A., 1977, Editor, Canadian Mines Handbook, 1977-1978, Northern Miner Press Ltd., Toronto, 280 p.

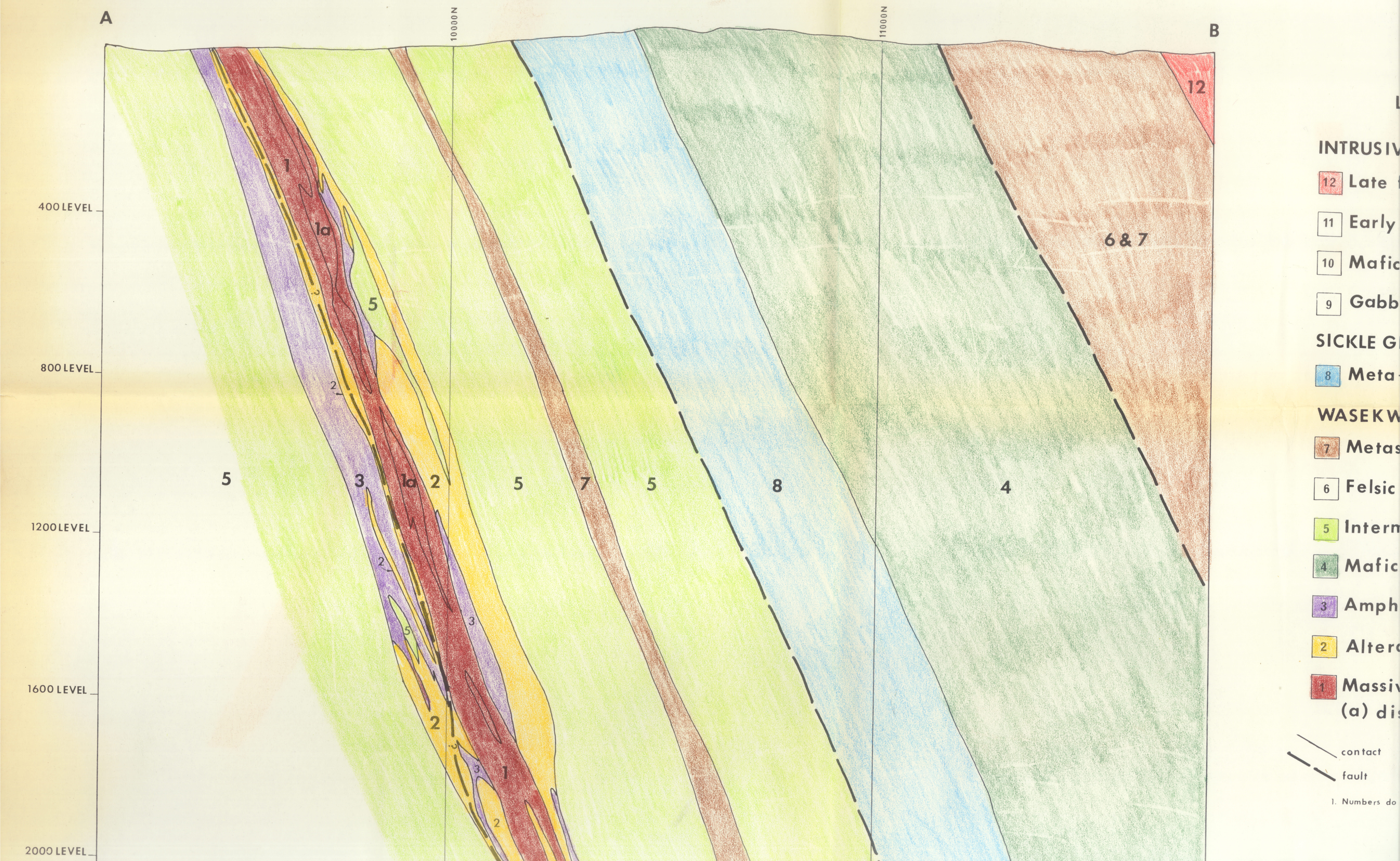
Zwanzig, H. V., 1976, Laurie Lake Area (Fox Lake Project): in Man. Min. Res. Div., Report of Field Activities, 1976, p. 26-32.

______________, 1977, Geology of the Fox Mine area: in Man. Min. Res. Div., Report of Field Activities, 1977.

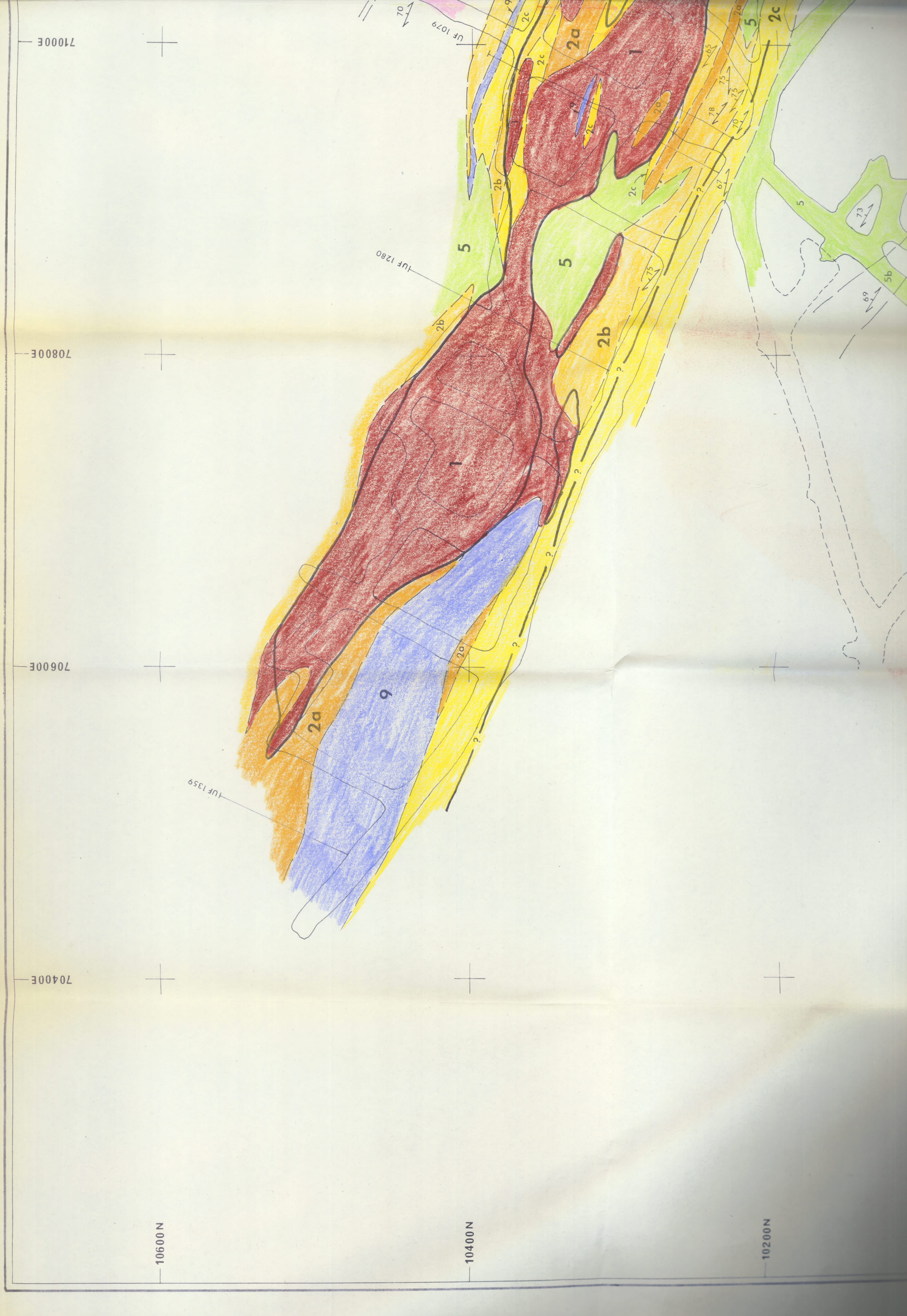
______________, and Keay, J. P., 1977, Geology of the Eager Lake Area: in Man. Min. Res. Div., Report of Field Activities, 1977.

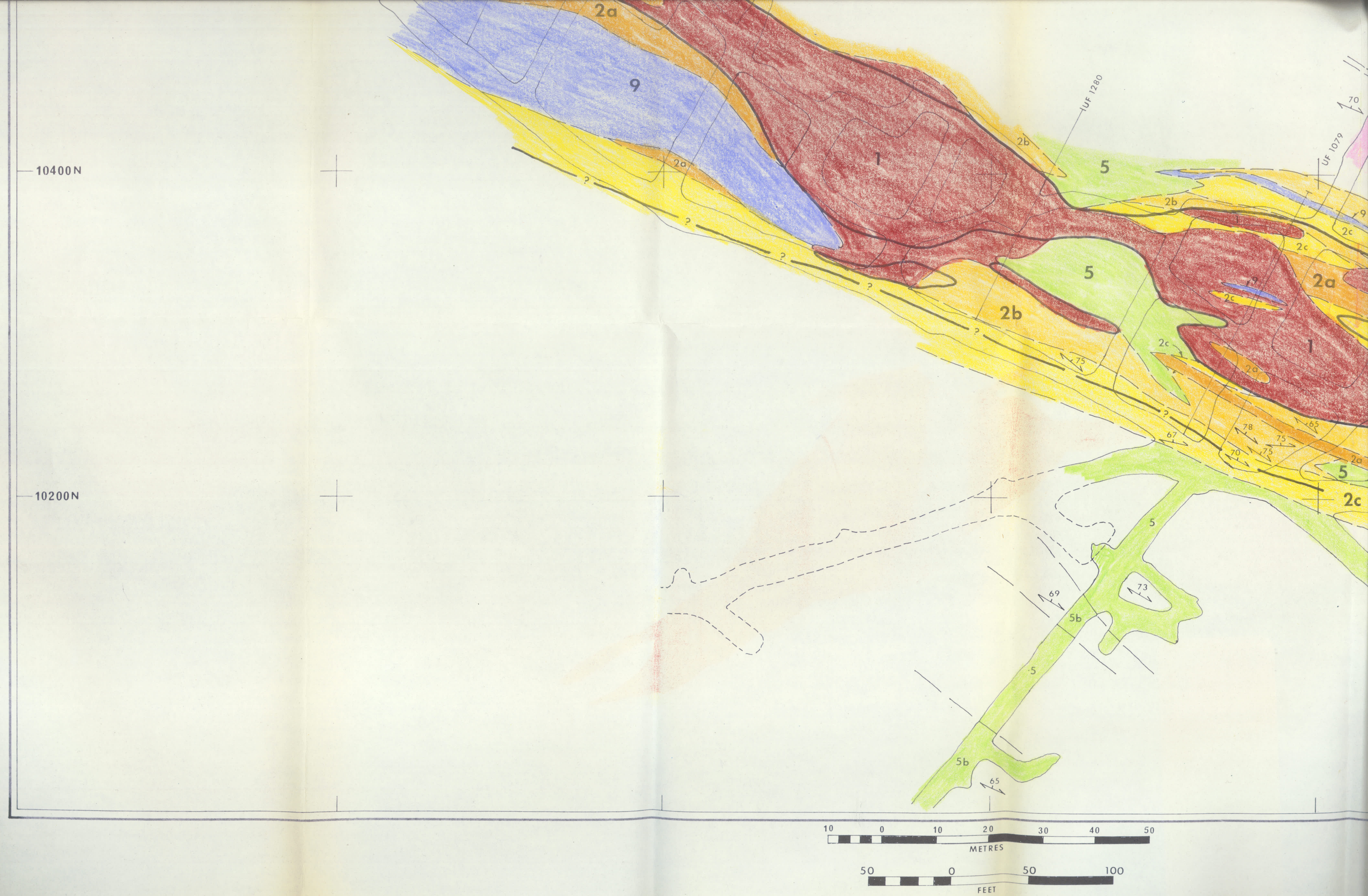
FOX MINE

GEOLOGICAL SECTION A-B



GEOLOGICAL SECTION A-B


71000E
70800E
70600E
70400E
10600N
10400N
10200N
UF 1079
UF 1280
UF 1359
1
2a
2b
2c
5
5b
9


10400N
10200N
1
2a
2b
2c
5
5b
9
UF 1280
UF 1079
METRES
10 0 10 20 30 40 50
FEET
50 0 50 100

FOX MINE GEOLOGY 2100 LEVEL

LEGEND[1]

INTRUSIVE ROCKS

12 Late felsic intrusives

11 Early felsic intrusives

10 Mafic feldspar porphyry

9 Gabbro-diorite

SICKLE GROUP

8 Meta-arkose

WASEKWAN GROUP

7 Metasedimentary rocks

6 Felsic metavolcanic rocks

5 Intermediate metavolcanic rocks
(a) pillowed flows (b) breccia
(c) tuffaceous-volcaniclastic rocks

4 Mafic metavolcanic rocks

3 Amphibolite

2a Cordierite-anthophyllite-cummingtonite

2b Cordierite-muscovite-phlogopite

Alteration

INTRUSIVE ROCKS

12 Late felsic intrusives

11 Early felsic intrusives

10 Mafic feldspar porphyry

9 Gabbro-diorite

SICKLE GROUP

8 Meta-arkose

WASEKWAN GROUP

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6 Felsic metavolcanic rocks

5 Intermediate metavolcanic rocks
(a) pillowed flows (b) breccia
(c) tuffaceous-volcaniclastic rocks

4 Mafic metavolcanic rocks

3 Amphibolite

Alteration zone:

2a Cordierite-anthophyllite-cummingtonite

2b Cordierite-muscovite-phlogopite

2c Quartz-sericite schist

1 Massive sulphides

72 foliation

contact

? possible fault

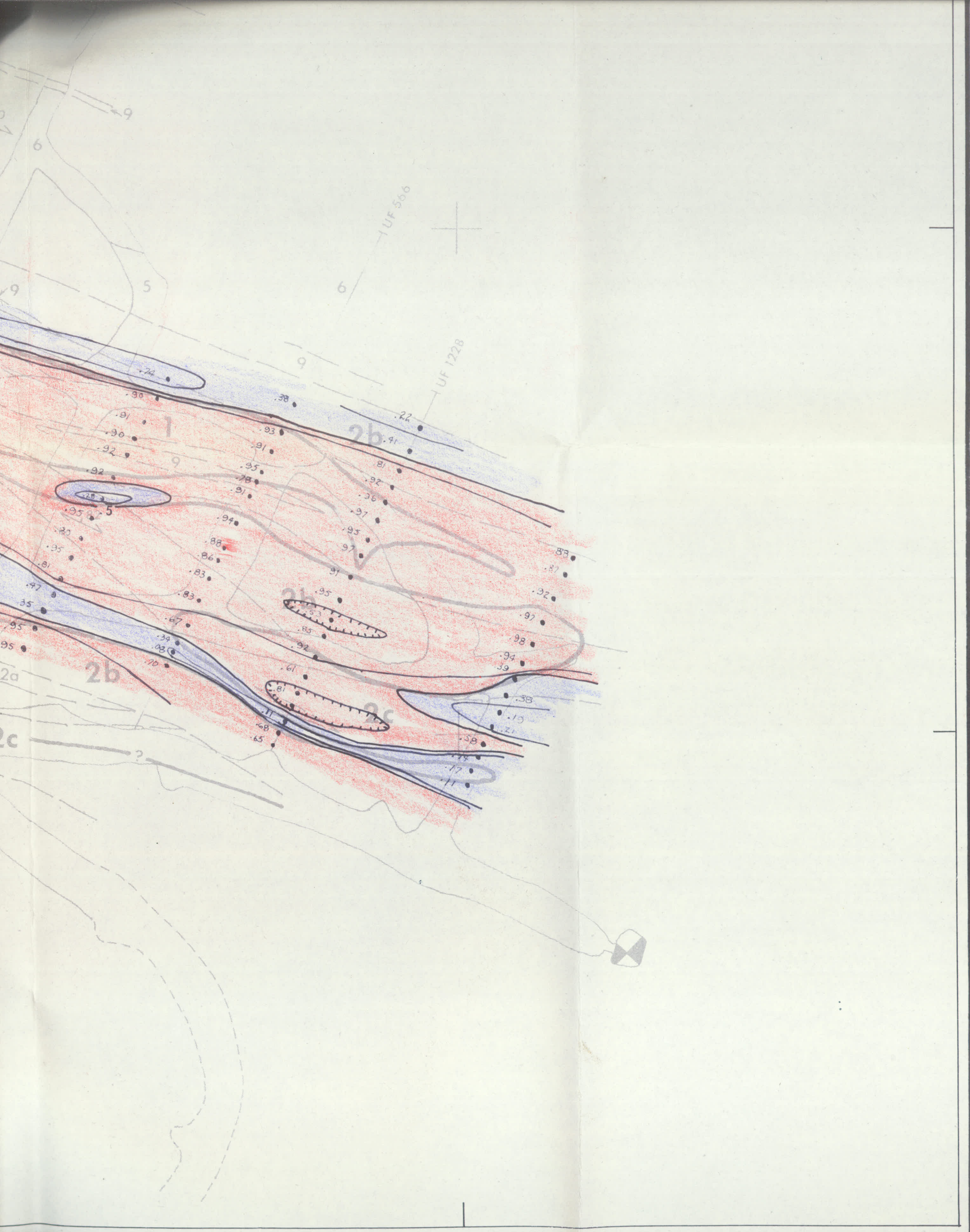
ore outline

underground workings

1. Units are not in stratigraphic order

GEOLOGY BY G. N. LUSTIG 1976

MAP 2



INTRUSIVE ROCKS

- 12 Late felsic intrusives
- 11 Early felsic intrusives
- 10 Mafic feldspar porphyry
- 9 Gabbro-diorite

SICKLE GROUP

- 8 Meta-arkose

WASEKWAN GROUP

- 7 Metasedimentary rocks
- 6 Felsic metavolcanic rocks
- 5 Intermediate metavolcanic rocks
  (a) pillowed flows (b) breccia
  (c) tuffaceous-volcaniclastic rocks
- 4 Mafic metavolcanic rocks
- 3 Amphibolite
- 2a Cordierite-anthophyllite-cummingtonite
- 2b Cordierite-muscovite-phlogopite
- 2c Quartz-sericite schist

Alteration zone (2a–2c)

- 1 Massive sulphides

.72 foliation

contact

? possible fault

ore outline

underground workings

.85• Cu/Cu+Zn values

.5 Cu/Cu+Zn contours

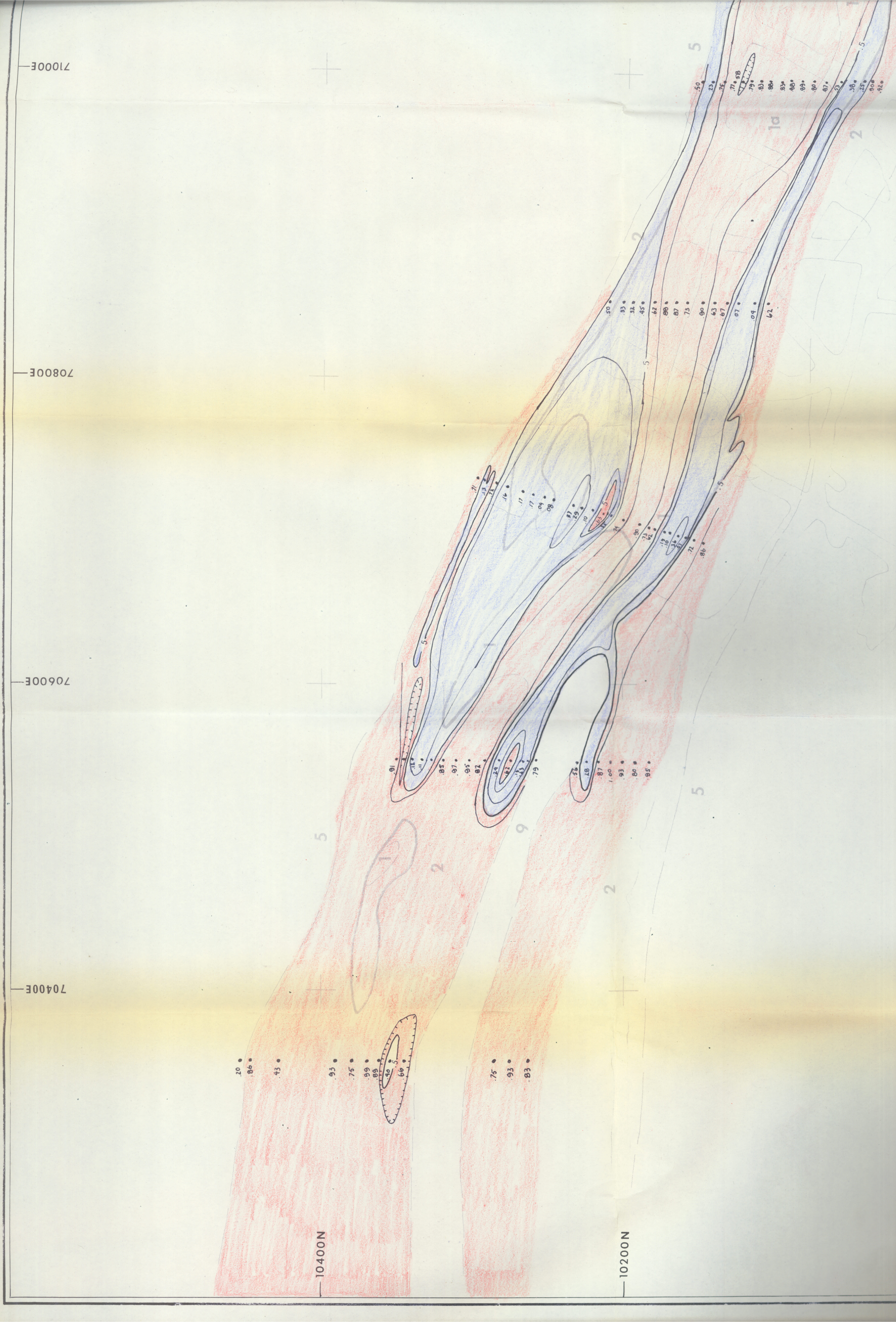
Cu>Zn

Zn>Cu

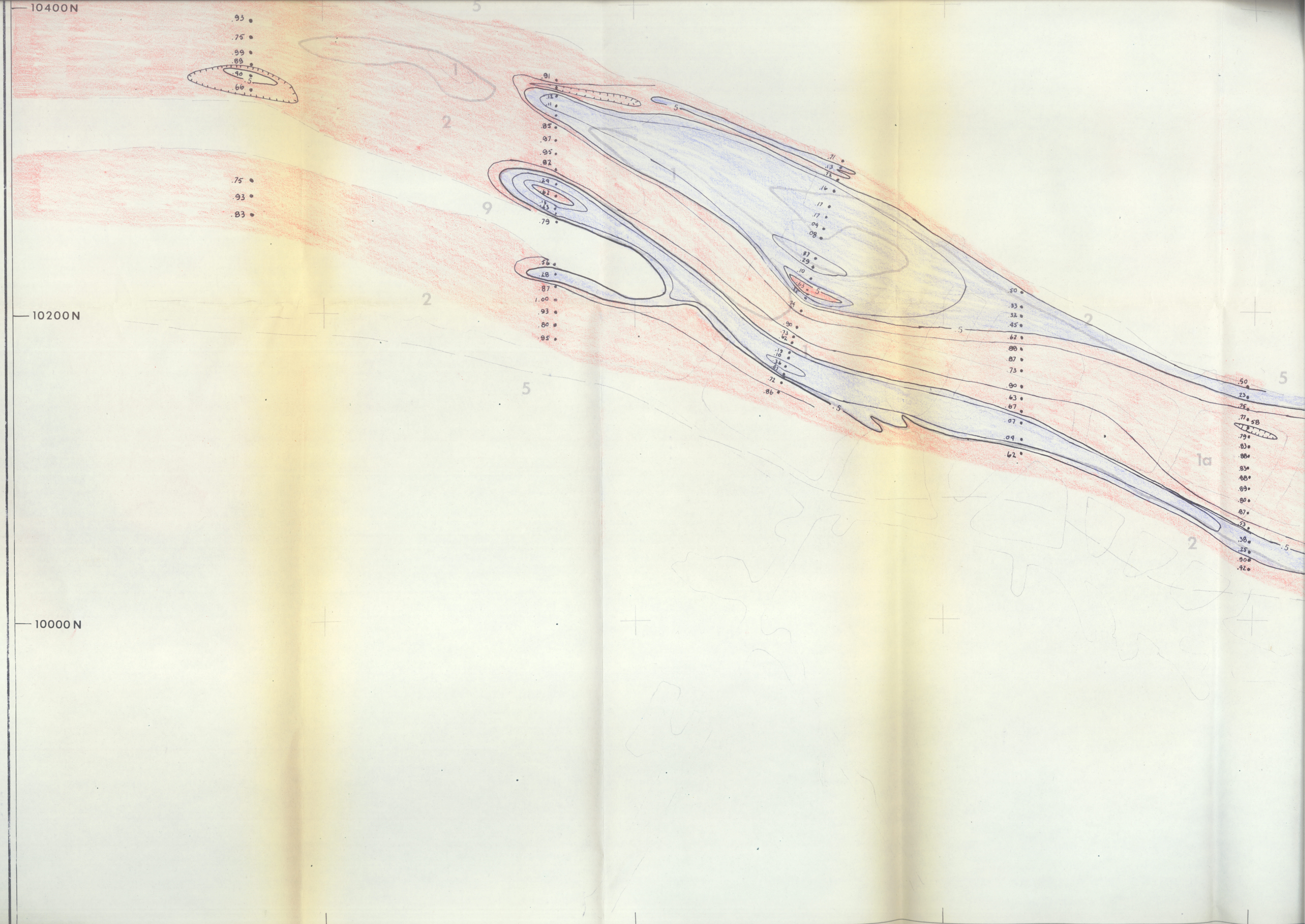
contour interval = .25

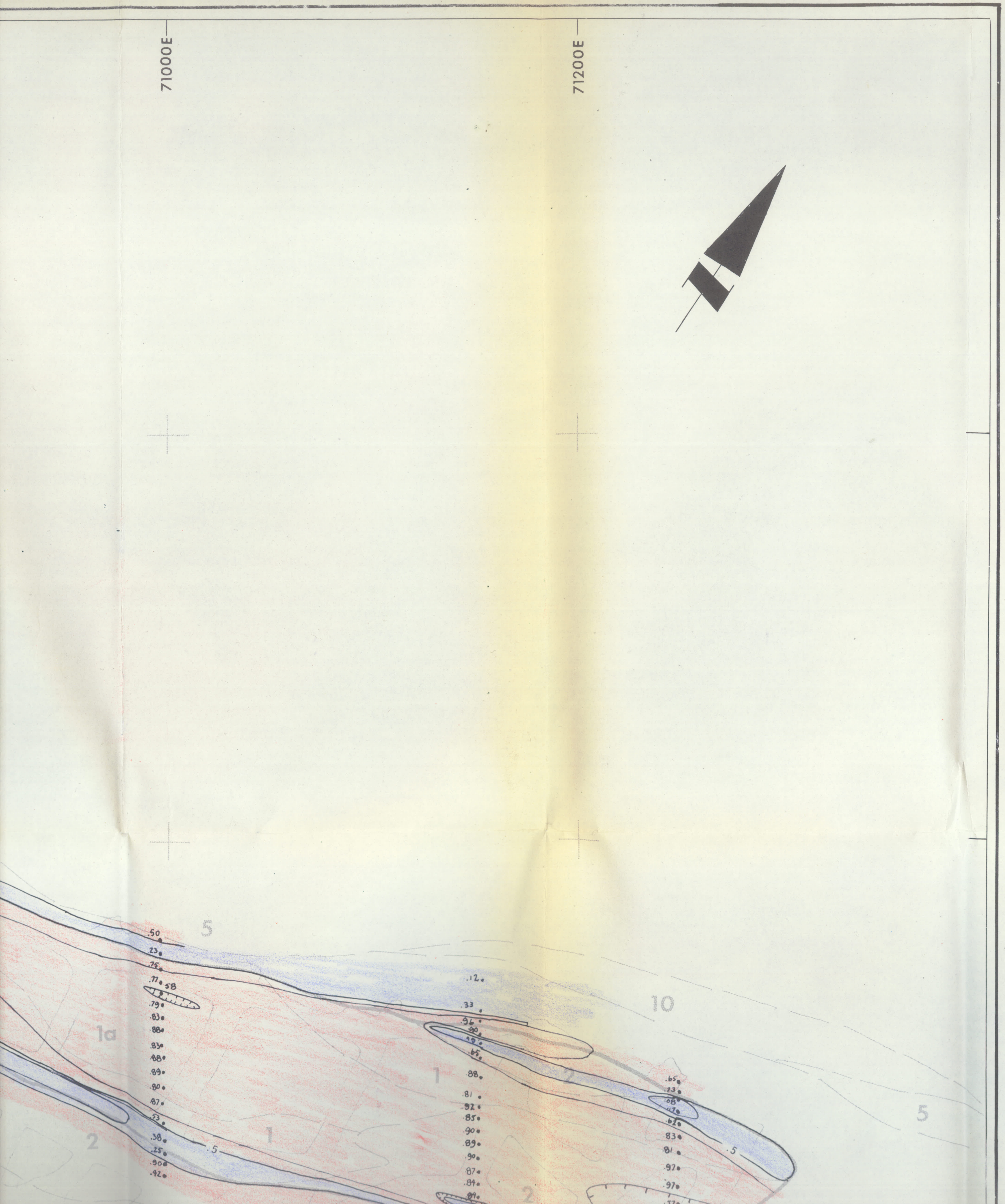
1. Units are not in stratigraphic order

MAP 3



71000E
70800E
70600E
70400E
10400N
10200N


10400N
10200N
10000N



FOX MINE
Cu-Zn ZONATION
1600 LEVEL

LEGEND[1]

INTRUSIVE ROCKS

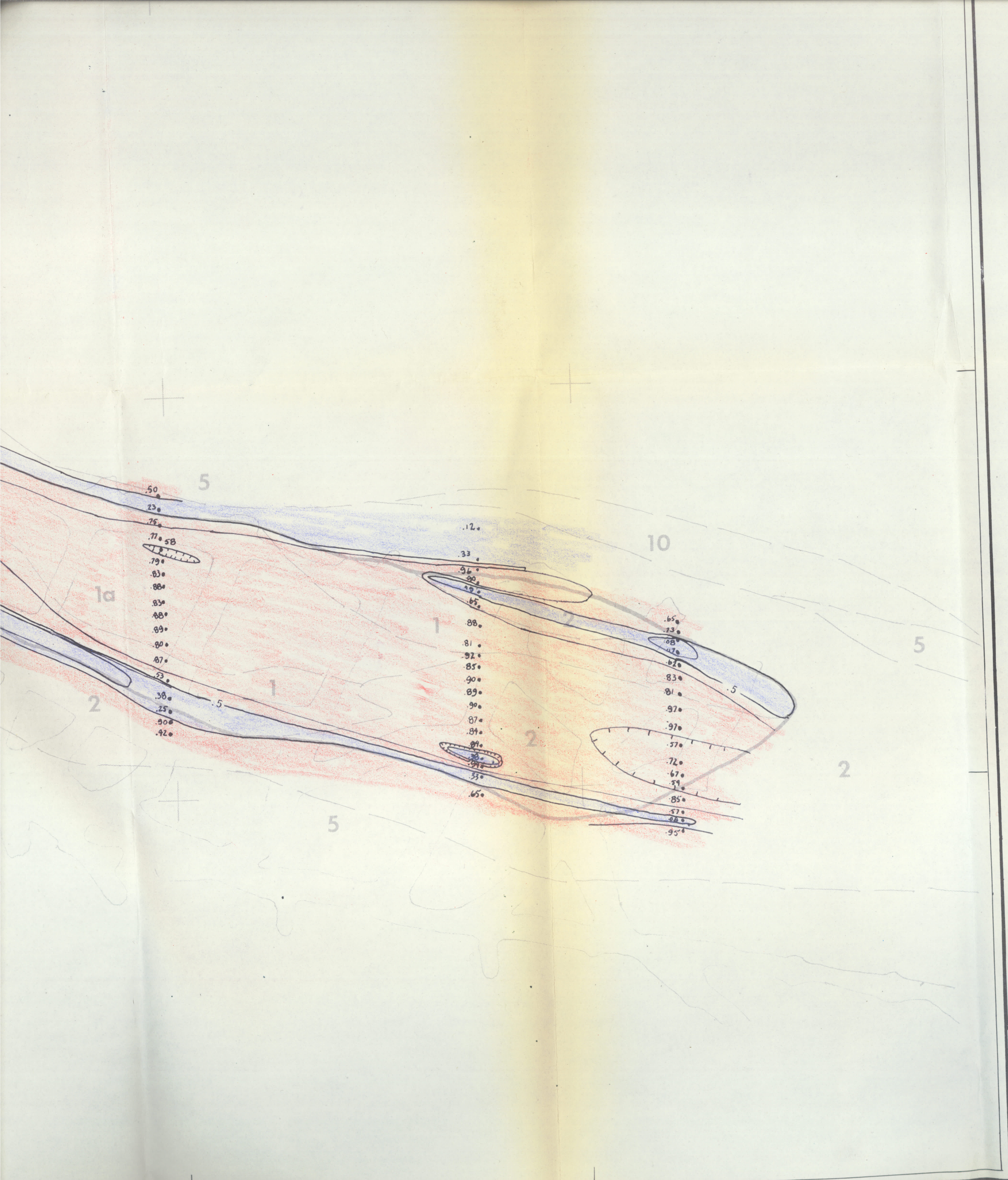
- 12 Late felsic intrusives
- 11 Early felsic intrusives
- 10 Mafic feldspar porphyry
- 9 Gabbro-diorite

SICKLE GROUP

- 8 Meta-arkose

WASEKWAN GROUP

- 7 Metasedimentary rocks
- 6 Felsic metavolcanic rocks
- 5 Intermediate metavolcanic rocks
- 4 Mafic metavolcanic rocks
- 3 Amphibolite
- 2 Alteration zone
- 1 Massive sulphides
  (a) disseminated zone



12 Late felsic intrusives

11 Early felsic intrusives

10 Mafic feldspar porphyry

9 Gabbro-diorite

SICKLE GROUP

8 Meta-arkose

WASEKWAN GROUP

7 Metasedimentary rocks

6 Felsic metavolcanic rocks

5 Intermediate metavolcanic rocks

4 Mafic metavolcanic rocks

3 Amphibolite

2 Alteration zone

1 Massive sulphides
(a) disseminated zone

contact

ore outline

underground workings

.85• Cu/Cu+Zn values

Cu/Cu+Zn contours

Cu>Zn

contour interval=.25

Zn>Cu

MAP 4

1. Units are not in stratigraphic order

10 0 10 20 30 40 50
METRES

50 0 50 100
FEET