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# ORE MINERALOGY AND POLYMETAMORPHOSED NATURE OF THE ARCHEAN Zn-Cu-Fe MASSIVE SULFIDE DEPOSITS AT THE GARON LAKE MINE, MATAGAMI, QUEBEC, CANADA.

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## Abstract

Massive Zn-Cu-Fe sulfide deposits at the Garon Lake Mine occur in three sulfide lenses in a group of metamorphosed rhyolite crystal tuffs, metasediments and basalts. The major ore minerals are sphalerite, chalcopyrite, pyrrhotite and pyrite. Minor associated silicates are actinolite, tremolite, chlorite, albite and quartz. Rounded detrital pyrite, magnetite and chert grains and diagenetic pyrite are the only preseved premetamorphic features. Middle amphibolite facies regional metamorphism is marked by sulfide-silicate foliation, and syntectonic porphyroblasts of pyrite. After the intrusion of a granodiorite pluton, pyrite was fractured, and the other sulfides developed wedge-shaped twins. These minerals were subsequently involved in porphyroblasitic and polygonal granoblastic growth and annealing. Cordierite and anthophyllite developed from chloritized wallrocks. During retrograde changes, some pyrrhotite was converted to pyrite, marcasite and magnetite. On the evidence of textures and mineralogy, the deposit is synsedimentary-diagenetic and of distal type.

## Introduction

The important consequence of Archean massive sulfide deposits is that these deposits have been metamorphosed. This may have resulted in features that can mask their true origin. Because of this, the origin of many massive and conformable sulfide deposits has long been a subject of controversy and discussion.

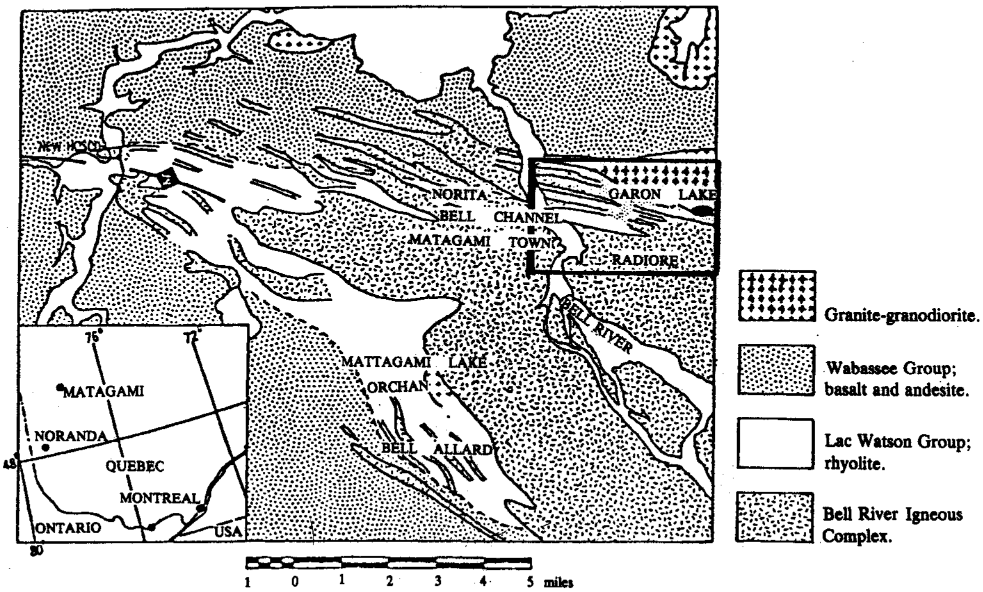

**Fig. 1.** Regional geology and location of mines in the Matagami district. The location of Matagami in Quebec is shown as inset (lower left), and the Garon Lake Mine area is shown as an inset (right). The geology is simplified from Sharpe (1968), and MacGeehan (1978).

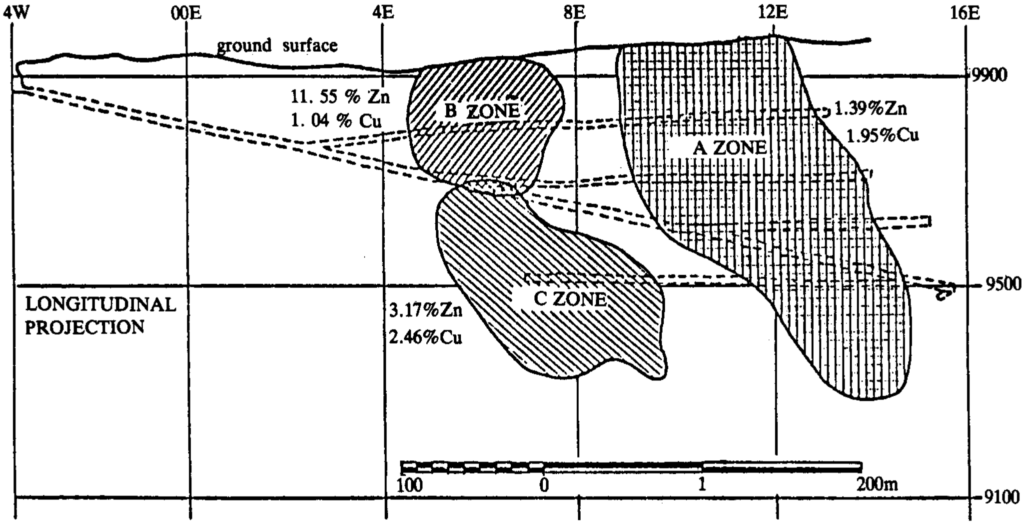

**Fig. 2.** Geological map showing the detailed outcrop, projected drill-hole intersections and some interpreted geology adjacent to the Garon Lake Mine. QFXT and RCHT represent quartz feldspar rhyolite crystal tuff and cherty rhyolite crystal tuff (after MacGeehan, 1979). The metavolcanic rocks in this map may be considered as metabasalt and metarhyolile (author).

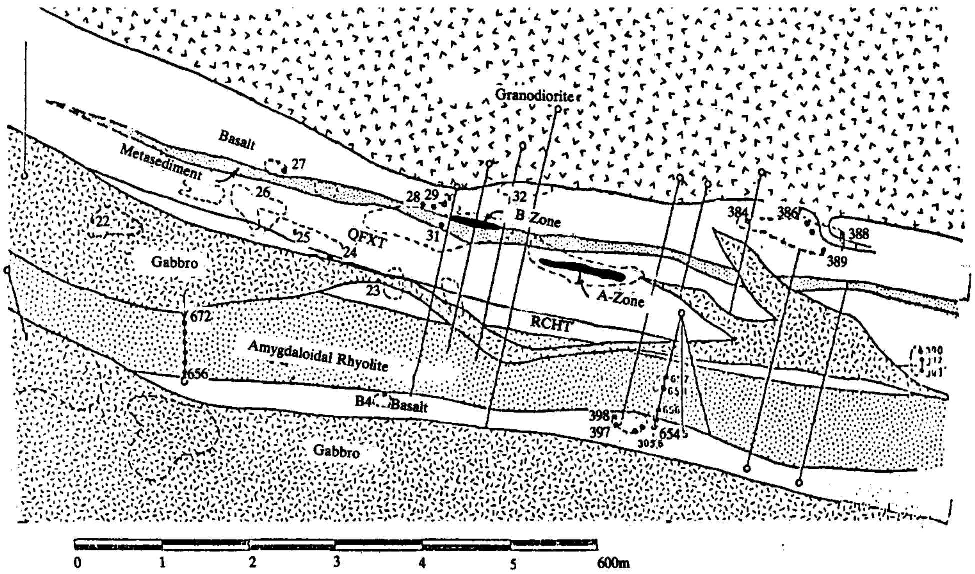

**Fig. 3.** Longitudinal vertical projection of the three sulphide lenses, showing the economic or mineable perimeter of each orebody (after Macleen and MacGeehan, 1976).

This paper emphasizes the importance of recognizing the polymetamorphosed character of Zn-Cu-Fe sulfide deposits found at the Garon Lake Mine. It also provides evidence for establishing the time of ore formation with respect to the wallrocks, thereby restricting the number of processes that can be used in formulating a genetic model for the ore.

## Location, Geology and Exploration

The Garon Lake Mine is located in Isle Dueu township, two miles east of the town of Matagami in northern Quebec (Fig. 1).

The mine lies within a series of metavolcanic rocks between the northern margin of the Bell River Complex and a large intrusion of granitic rocks (Fig. 1 and 2). The volcanic rocks are composed of basalts, rhyolites and volcanic derived sediments. The volcanic rocks and sulfides have been subjected to regional metamorphism of the middle amphibolite facies, and a moderate regional metamorphic foliation has developed in the volcanic rocks and ores. These have been intruded by a granite-granodiorite

| Sulfide zone | Dimensions meters | Type of ore | Wallrock (Metavolcanic rocks) | Shape of orebody | Tonnages Tons | %Zn | %Cu | Zn/Cu |
|---|---|---|---|---|---|---|---|---|
| A-zone | 120×250 | Coarse-grained with large porphyroblasts of pyrite. | Rhyolite crystal tuff. | Elliptical. | 309,000 | 1.39 | 1.95 | 0.7 |
| C-zone | 200×100 | Intermediate between A and B | Rhyolite crystal tuff. | Elliptical. | 54,000 | 3.17 | 2.46 | 1.3 |
| B-zone | 133×260 | Zinc-rich | Basalt and metasediments. | Circular | 88,000 | 11.55 | 1.04 | 11.1 |

(Modified after Maclean and MacGeehan, 1976).

**Table 1. Characteristic of Three Sulfide Zones in the Garon Lake Mine.**

Aftabi (1980)

| Minerals | Premetamorphic | Regional metamorphism | Contact metamorphism | Retrograde changes and oxidation |
|---|---|---|---|---|
| Pyrrhotite | mainly as undeformed massive matrix, and rarely as fine dispersed grains (Po). | foliated and corrugated (Po) with tremolite and actinolite. Few pyrrhotite grains were incorporated along the sphalerite grain boundaries or exsolved during, metamorphim (Po). | wedge shaped twinned, annealed and recrystalized pyrrhotite with 120° triple junctions. | blade shaped grains (Po) formed as a result of Po oxidation to pyrite and irregular shaped magnetite. |
| Pyrite | deterital grains, Py (prediagenetic), and diagenetic grains (Py) | nucleation and development of syntectonic porphyroblasts (Py). | broken Py and enlargement of them as Py, plus small undeformed cubes of pyrite. | late generations of pyrite as colloform (Py), undeformed cubes and pyritohedrons (Py) and dirty porous pyrite (Py). |
| Sphalerite | undeformed massive matrix and bands. | foliated sphalerite with Po and biotite. | wedge shaped twinned, annealed and recrystalized sphalerite with 120° triple junctions. | ——— |
| Chalcopyrite | undeformed massive matrix. | foliated chalcopyrite. | well-formed wedge shaped twinned, annealed and recrystalized chalcopyrite with 120° triple junctions. | ——— |
| Bornite | —— | formed due to the breakdown of chalcopyrite to pyrite and IIS, and subsequent cooling. | | |
| Marcasite | —— | —— | —— | lath-shaped twinned and untwinned grains formed from the oxidation of pyrrhotite (Po), |
| Magnetite, chert, quartz and calcite | all four minerals as deterital grains. | elongation in quartz, and magnetite grains appear as porphyroblasts. | recrystalization of all as granoblastic texture; in particular quartz, magnetite and chert. | late irregular shaped magnetite formed due to the oxidation of pyrrhotite (Po), and calcite occurs as veinlets. |

**Table 2. Genetic Relationships of Sulfides, Magnetite, Chert, Quartz and Calcite in the Garon Lake Mine.**

pluton particularly close to the north side of the Garon Lake Mine.

The mine is composed of three stratiform sulfide lenses (Maclean and MacGeehan, 1976) shown in Fig. 3 and Table 1.

The sulfides were discovered by electromagnetic and magnetic surveys in 1956 and explored by diamond drilling in 1957 and subsequent years. The mine was operated from 1971 to 1975. The total tonnage of the deposit is 415,000 tons of ore grading 1.83% Cu and 3.59% Zn.

Samples were taken from A, B and C lenses. Some samples were also chosen from drill cores. (Maclean and MacGeehan, 1976).

## Ore Mineralogy

A study of many samples at the Garon Lake Mine indicates that the sulfide ores are composed of the following, in order of abundance, pyrrhotite (60%) pyrite (28%) sphalerite (6%), chalcopyrite (5%) marcasite, and bornite. Gangue minerals are mainly silicates, and chert. Other minor minerals are magnetite and calcite.

Silicate minerals incorporated in the sulfides are mainly tremolite, actinolite, anthopyllite, chlorite, albite and quartz.

The sulfide minerals occur in a wide variety of textural relationships. Because of these textural variation and because of the relation of each mineral to the others, they are described separately. In addition, a paragenetic table (table 2) and also photos have been made to illustrate their textural relations.

Pyrite occurs as five textural varieties, but the first variety is composed of large, rounded, circular and barrel shaped grains in a matrix of fine grained well-shaped cubes pyrite, sphalerite, chalcopyrite, pyrrhotite and silicates (Fig 4a). They occur in all three sulfide lenses, but most commonly in the C-zone, and form about 5% of all pyrite. Some grains contain inclusions of sphalerite, chalcopyrite and silicates. These rounded or reworked pyrite grains are the oldest type of pyrite because all the other types can be shown to be formed later. In addition, some of these grains have been overgrown and form the cores to syntectonic porphyroblasts (Fig.4b). Maclean and Aftabi, (1982) and Maclean (1984) reported similar pyrite grains in the Matagami district. Pyrite grains of the second type are dispersed, small cubes and pyritohedrons that make up

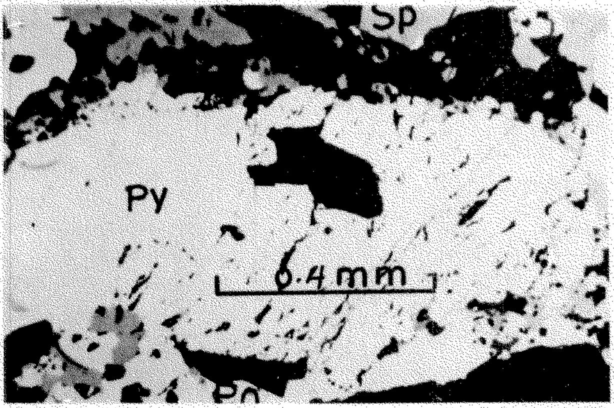

**Fig. 4a**
A large detrital pyrite grain (py) in a matrix of sphalerite and pyrrhotite.

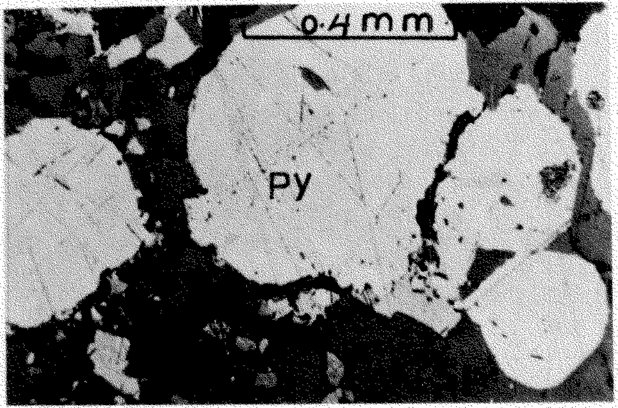

**Fig. 4b**
Overgrowth of pyrite on rounded pyrite grains (py). Matrix is sphalerite. The black rounded minerals on the top and bottom of photo are detrital chert.

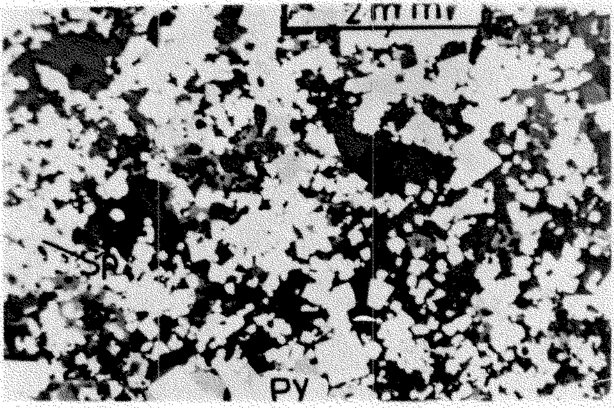

**Fig. 4c**
Diagenetic pyrite (py) in the matrix of sphalerite, quartz and calcite.

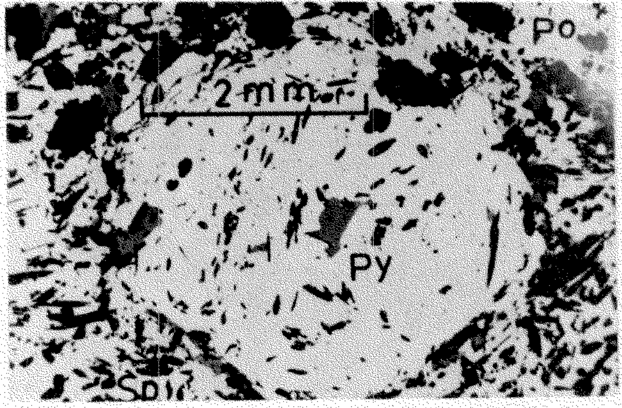

**Fig. 4d**
Syntectonic porphyroblasts of pyrite (py) wrapped around by foliated tremolite in a pyrrhotite-rich matrix (po).

approximately 5% of the pyrite (Fig. 4c). They are discrete crystals, free of inclusions and without preferred orientation. In most samples, they are dispersed in a matrix of sphalerite, pyrrhotite, chalcopyrite, quartz, chert and calcite. Where seen, they do not appear to be affected by shearing of fracturing, but this is probably due to their small size. Where pyrite and chert of other silicates are layered, these small grains form a matrix to the rounded grains. These are probably of the same age as the rounded pyrite grains and occur most commonly in the A-zone and B-zone. Some of these pyrite grains show atoll-texture (Aftabi, 1980, p. 30-31) and probably are similar to those reported by Brigs, et al (1977).

The third type of pyrite grains are predominate in these ores (70%) .They are porphyroblastic snowballed pyrite (Fig. 4d) that push aside tremolite grains and thus are syntectonic pyrite, formed during regional metamorphism. Similar porphyroblastic pyrite grains are also reported by Froese (1982), Bonavia and Maclean (1986) and Humphreys (1986).

Some of the pyrite porphyroblasts are fractured (Fig. 4e) during the emplacement of the granodiorite pluton.

Pyrite grains of the fourth type form very large crystals with sharp corners up to 5 cm in a pyrrhotite-rich matrix and formed during contact metamorphism (Fig. 4f).

The last variety of pyrite is a colloform pyrite (Fig. 4g), associated with pyrrhotite and marcasite in the C-zone. This type of pyrite resembles "birds eye pyrite" described by Ramdohr (1969) and Meyers, (1980). In general the grain size of pyrite ranges from 0.15 to 50 mm.

Pyrrhotite makes a matrix to all sulfide minerals. Most of the pyrrhotite grains show foliation, deformation twinning and annealing. The grain size of pyrrhotite grains ranges from 0.11 to 0.25 mm. under microscopic examination, it is difficult to dicern whether the pyrrhotite was formed by metamorphism of pyrite. In fact, no textural evidence supports this.

Chalcopyrite and sphalerite are frequently associated with each other, and usually display mutual boundaries. Their grain size ranges from 0. 1 to 0. 32 mm. In most cases both minerals are the matrix to all types of pyrite grains. In addition, sphalerite grains are frequently foliated and show deformational twinning (Fig. 4h). Sphalerite grains sometimes contain exsolution of chalcopyrite and smeared bead shaped grains of pyrrhotite along their grain boundaries (Fig. 4h).

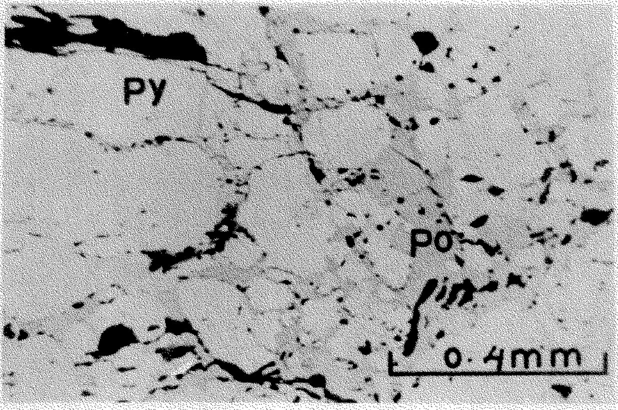

**Fig. 4e**
Fracturing and fragmentation of pyrite porphyroblasts (py). Filled by chalcopyrite and pyrrhotite.

**Fig. 4g**
Conversion of pyrrhotite (po) grains to superb or bird eye colloform pyrite during retrograde metamorphism.

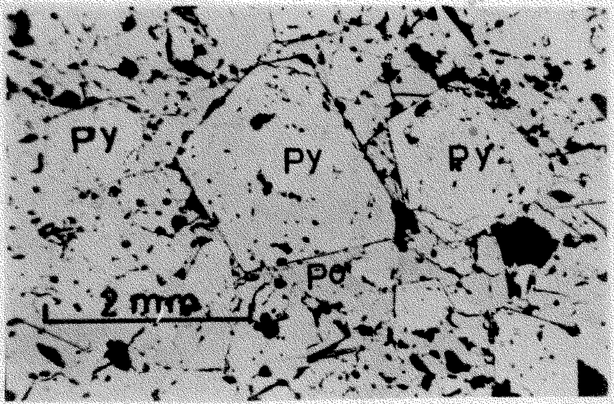

**Fig. 4f**
Well-crystallized porphyroplasts of pyrite (py) with sharp corners in a matrix of pyrrhotite (po).

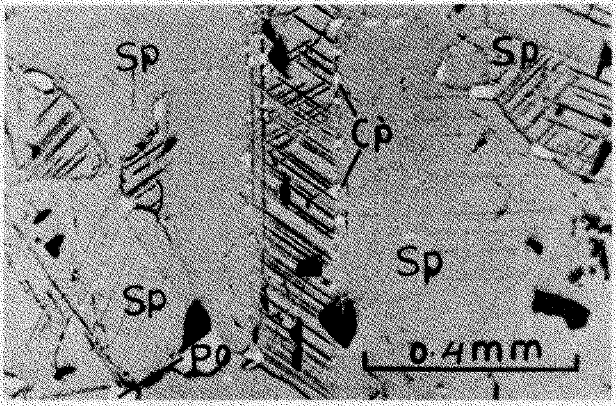

**Fig. 4h**
Chalcopyrite incorporated as lammelae and blebs along the twin planes of sphalerite, whereas pyrrhotite is incorporated as bead shaped grains along the grain boundaries of sphalerite.

Marcasite is a minor sulfide mineral formed by conversion of pyrrhotite grains during retrograde changes.

Bornite is another minor mineral formed by the isolated breakdown of chalcopyrite to intermediate solid solution(ISS) and pyrite during regional or contact metamorphism at 550°C (Cabri, 1973; Maclean; Cabri and Gill, 1972). During subsequent cooling the intermediate solid solution (ISS) could locally invert to chalcopyrite and bornite.

In addition to sulfide minerals, minor amounts of quartz, magnetite, calcite and chert are dispersed within sulfide minerals, The important thing is that some of magnetite, chert and quartz grains occur as deterital grains.

## Ore Geochemistry

The iron content of pyrrhotite and the FeS content of sphalerite grains were determined for measuring the limits of temperature and pressure of crystallization of the pyrite-pyrrhotite-chalcopyrite-sphalerite assemblages.

The iron content of annealed pyrrhotite was measured by X-ray diffraction which is 46.51 + 0.6 at.% Fe. This coincides with the compositional field of monoclinic pyrrhotite given by Scott and Kissin (1973) and Kissin (1974). According to Maclean and MacGeehan, (1976) and Aftabi, (1980), the porphyroblastic texture of pyrite and the evidence of metamorphism in the wallrocks indicate that orebodies have been subjected to high temperature (600°C) and high pressure (5kb). Under this condition, it is possible for pyrite to be converted to pyrrhotite plus sulfur in an open system ($FeS_2 \rightarrow FeS + S$). Although pyrrhotite would be high temperature hexagonal during these events, it is well known that it inverts easily to the low temperature monoclinic form (Scott and Kissin, 1973 and Kissin 1974). There is evidence in the ore that sulfur was not lost. The most cost convincing sign is the association of rounded detrital pyrite grains embedded in the pyrrhotite without any corroding (Fig. 4a and 4d).

There is also no evidence in the wallrocks of additional sulfur or sulfide-silicate reactions as has been suggested by McDonald (1967), Vokes (1969), Sangster (1972), Sangster and Scott (1976) and Rockingham and Hutchinson (1980). Based on quantitative mineralogical data (Aftabi, 1980), the percentage of pyrrhotite at the Garon Lake Mine is three times higher than the Geco Mine in Canadian Shield, even though the metamorphism at the Garon Lake Mine (middle amphibolite) is lower than the Geco Mine (High grade ampibolite). As a result, the pyrrhotite in the Garon Lake Mine is mainly primary in origin, and since it does not retain its high temperature composition during metamorphism, it can not be used as a geothermometer at the Garon Lake Mine.

The FeS content of sphalerite grains were measured by microprobe at McGill University. The mean content of FeS in all textural varieties of sphalerite (non-deformed, twinned and annealed) that co-exists with pyrrhotite (monoclinic), pyrite and chalcopyrite at the Garon Lake Mine is 10.6 + 0.6 mole%. This value is very close to the sphalerite-pyrite-monoclinic-pyrrhotite boundary given by Scott and Kissin (1973) for 1 bar confining pressure and temperatures between 75°C and 200°C at 10 kb pressure (Lusk and Ford, 1978).

The pressures attained during metamorphism are difficult to evaluate by other methods, but estimates from host rocks silicates of middle amphibolite facies assemblages (Aftabi, 1980 and Maclean and Aftabi, 1982) are around 5 kb for contact metamorphism assemblages, but in general the limits are not well defined. The maximum temperature of metamorphism of the mine has been estimated from silicate assemblages to be between 450°C and 600°C (Aftabi, 1980). The 9.9 kb pressure obtained from the sphalerite geobarometer would require about 30 km thickness of overlying rocks in the mine area during Archean time which appears to be very high. Texturally, there is no evidence of pyrrhotite being exsolved after the deformational twins of sphalerite grains (Fig. 4h) or during subsequent annealing, and cooling, whereas, chalcopyrite did exsolve along the deformational twins as lamellae and blebs. According to Hutchinson and Scott (1978), extensive exsolution of chalcopyrite in sphalerite may be responsible for the inhomogeneity of FeS in sphalerite, and may demonstrate a high temperature of formation. However, they have concluded that chalcopyrite exsolution can not by itself account for low FeS contents, which can give anomalously high estimates of pressure.

The maximum amount of chalcopyrite exsolved from sphalerite in the Garon Lake Mine ores is around 1% and would therefore, have very little effect on pressure estimate.

## Mineralogical Changes in the Ore

The possible mineralogical changes that may have occurred during metamorphism and retrograde changes are thought to be probably as follows:

$$FeS_2 \xrightarrow[\text{middle amphibolite facies}]{\text{regional metamorphism}} FeS_{1-x} + S$$

$$FeS_2 \xrightarrow[\text{hornblende hornfels facies}]{\text{thermal metamorphism}} FeS + S$$

(probably high temperature pyrrhotite)

$$S + FeS \xrightarrow{\text{cooling after the peak of thermal metamorphism}} FeS_2$$

(as a new generation of pyrite)

$$6\,FeS + 2O_2 \longrightarrow Fe_3O_4 + 3FeS_2 \text{ (pyrite) or Marcasite}$$

## Textural Model for the Process of Ore Formation

In view of the geology, ore mineralogy and textural relations, a model is proposed for the process of ore

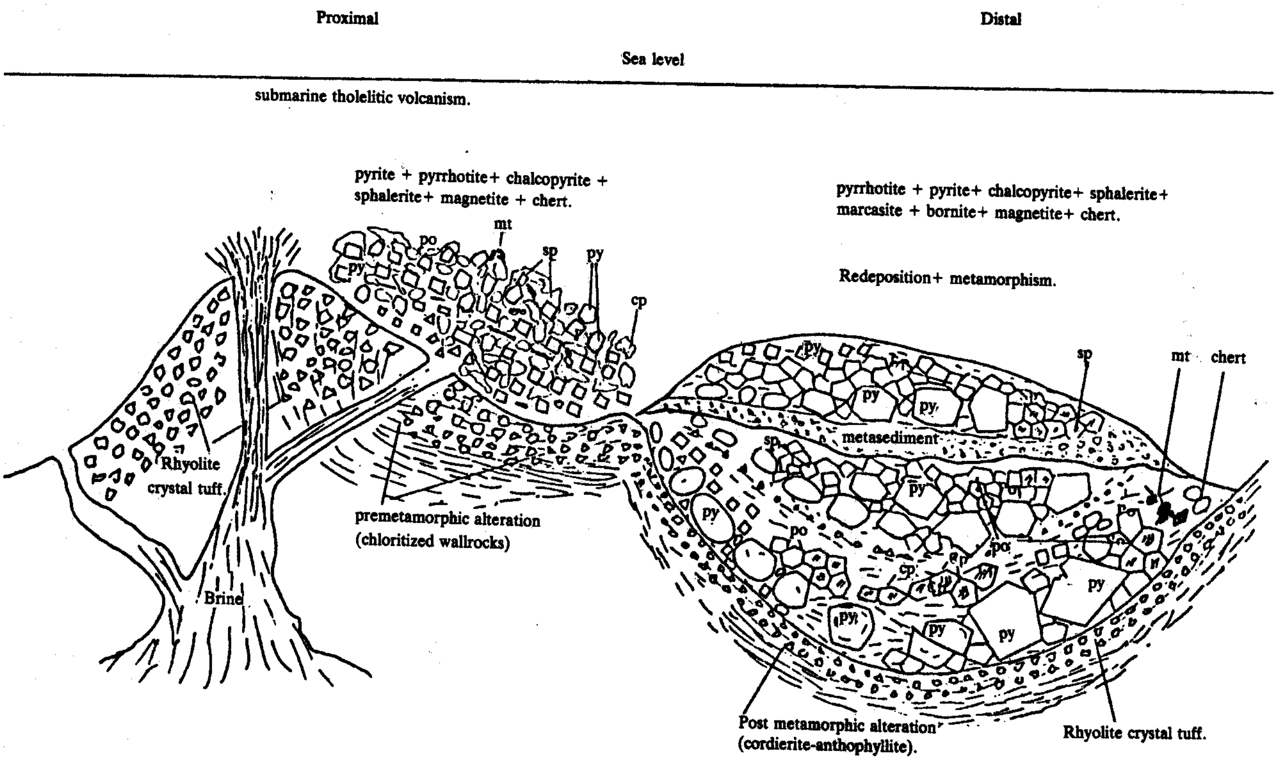

**Fig. 5.** Texturally proposed model for the process of massive sulfide ore formation at the Garon Lake Mine. The proximal ores are shown as they had formed, or recrystalized during diagenesis. The distal ores are shown in their metamorphosed condition. po = pyrrhotite, py = pyrite, cp= chalcopyrite, sp= sphalerite, mt =magnetite-

formation at the Garon Lake Mine, from the stage of volcanism and mineralization to sedimentation and metamorphism (Fig. 5). According to this model metal-bearing brines came from a volcanic conduit at some distance from the mine, probably a domal area. There was interaction between the solutions and rhyolitic tuffaceous and massive rhyolite, which caused them to be chloritized. In addition, the interaction between the solutions and seawater deposited zinc, copper and iron sulfides as proximal masses on the slope of the rhyolite crystal tuff.

Texturally, the sulfides (pyrite, pyrrhotite, chalcopyrite and sphalerite) were deposited as proximal lenses with chert and magnetite as gel-like material probably similar to the recent deposits of sulfides on the Red Sea floor (Bischoff, 1969). During compaction and diagenesis pyrite developed crystal faces and the other sulfides formed the matrix. It is generally thought that instability at the initial depositional site resulted in slumping or mass gravity sliding of the sulfide lenses. The presence of detrital pyrite, magnetite, chert and quartz grains indicate that all the sulfide minerals were transported and redeposited as sediments. Since the detrital pyrite grains are not well-sorted, it is suggested that the sulfide bodies were not transported very far. There is also evidence of detrital pyrite grains within the alteration zone, indicating that the original chloritized wallrocks were transported simultaneously with the sulfides and metamorphosed to cordierite-anthophyllite rock (Maclean and MacGeehan, 1976 and Aftabi, 1980).

The proximal sulfide deposits and some of the altered rocks were transported and deposited as distal lenses. The sulfides and their enclosing rocks were later folded and metamorphosed to the middle amphibolite.

## Conclusion

On the basis of field work and textural and mineralogical data, the recognition of a polymetamorphosed massive sulfide deposit at the Garon Lake Mine is based on the following temporal relationship of the ores and wallrocks with metamorphism:

1) The presence of detrital pyrite, chert and magnetite grains, and of diagenetic pyrite indicates the processes of sedimentation, diagenesis and subsequent redeposition of sulfides and sediments from their original proximal source.

2) The marked sulfide-silicate foliation, and nucleation of pyrite porphyroblasts are the best examples of features developed during middle amphibolite facies regional metamorphism.

3) The development of fractured pyrite porphyroblasts, marks the emplacement of the granodiorite and subsequent thermal metamorphism.

4) The presence of low temperature sulfide assemblages such as, marcasite, colloform «birds eye» pyrite is the result of retrograde changes.

5) The mean P–T condition obtained from silicate assemblages is more than 5 kb and at a temperature around 600°C. The sphalerite geobarometer shows 9.9 kb pressure which is well-supported by sulfide textures.

6) As a result of the various textural relations outlined in this study, a synsedimentary-diagenetic origin of the distal type is suggested for the Garon Lake Mine.

## Guidelines for Exploration

1)Detrital pyrite, magnetite and chert grains preserved in massive sulfide ores indicate that they could be distal type deposits.

2) Pyrrhotite rich massive sulfide ores can be primary, and there should be substantial evidence of a sulfur loss before deducing a breakdown of pyrite.

3) Porphyroblasts of pyrite, coarse grained sphalerite, pyrrhotite and chalcopyrite, and deformation annealing textures are indicative of metamorphosed ores.

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