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Ontario Geoscience Research Grant Program

Grant No. 96 -
Nature and Origin of Mineralization
Inside the Sudbury Basin

by
D.H. Rousell

1983

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E.G. Pye, Director
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ONTARIO GEOSCIENCE RESEARCH GRANT PROGRAM

Final Research Reports, 1982

Preface

This publication includes one final report on a research project that terminated March 31, 1981 and was funded under the Ontario Geoscience Research Grant Program. A requirement of the Program is that recipients of grants are to submit final reports within six months after termination of funding. Many of the research projects supported in 1978-79 (the first year of the Grant Program) were planned for three years. As a result, an unusually large number (19) of final reports were received this year. Unlike previous years, each report has been put on a separate Open File.

A final report is defined as a comprehensive summary stating the findings obtained during the tenure of the grant, together with supporting data. It may consist, in part, of reprints or preprints of publications and copies of addresses given at scientific meetings.

It is not the intent of the Ontario Geological Survey to formally publish the final reports for wide distribution but rather to encourage the recipients of grants to seek publication in appropriate scientific journals whenever possible. The Survey, however, also has an obligation to ensure that the results of the research are made available to the public at an early date. Although final reports are the property of the applicants and the sponsoring agencies, they may also be placed on an open file. This report is intended to meet this obligation.



E.G. Pye
Director
Ontario Geological Survey

May, 1982

ABSTRACT

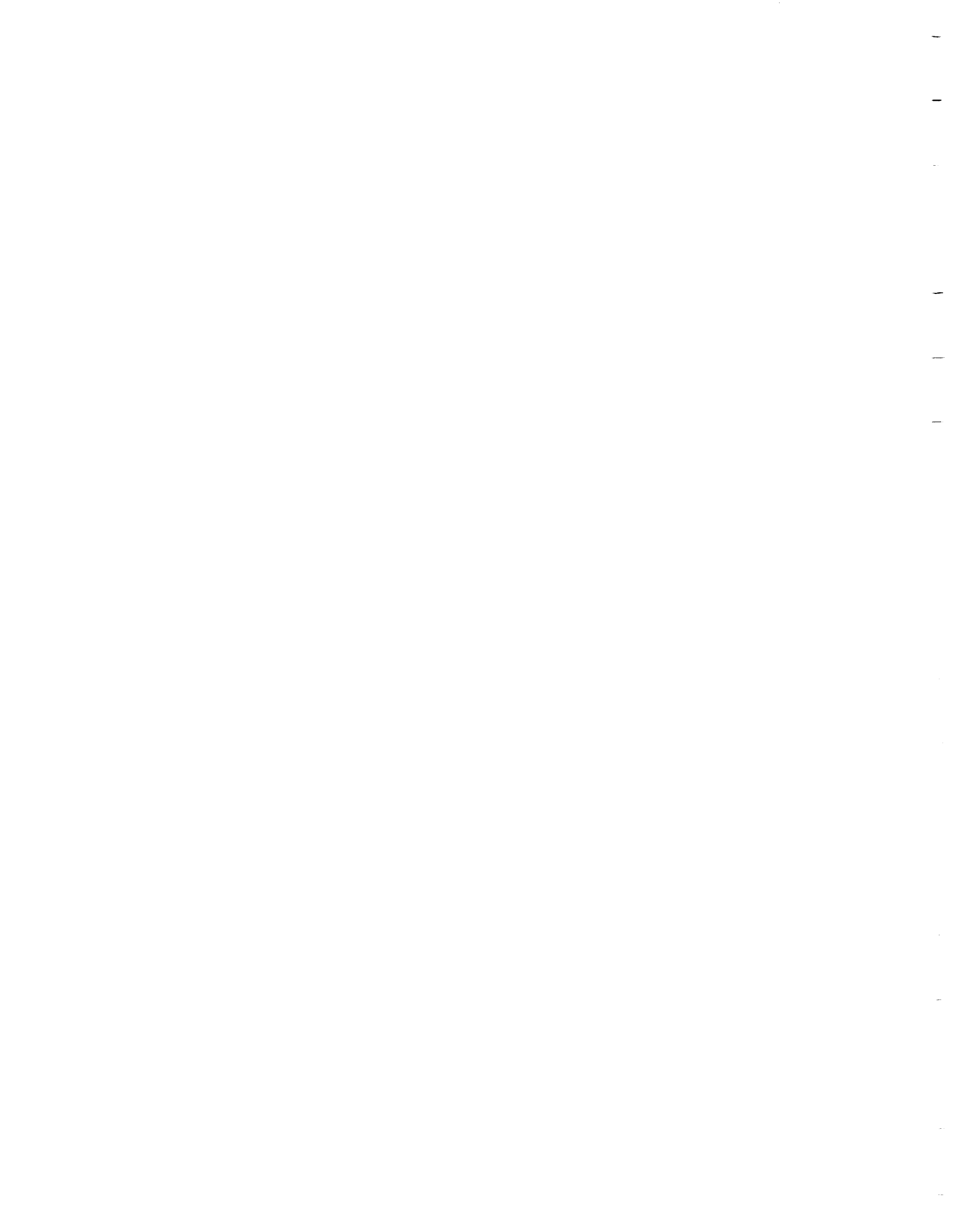
Rocks of the Whitewater Group, of Aphebian age, constitute the fill of the Sudbury Basin and consist of three formations which are, from oldest to youngest: Onaping, a massive heterogenous breccia; Onwatin, argillite and siltstone; and Chelmsford, mainly greywacke. Mineralization in these rocks and in the upper portion of the Nickel Irruptive is as follows: 1) Sulphides are disseminated throughout the Onaping Formation. Pyrrhotite, the major sulphide mineral, occurs as fragments; others are chalcopyrite, sphalerite, galena, pyrite and marcasite. 2) Zn, Pb, Cu, Ag and Au mineralization in a carbonate-chert unit at the base of the Onwatin Formation (Vermilion-Errington mines). 3) Pyrite and minor base metals in the Onwatin Formation. 4) Mineralized quartz veins including Moore Lake (Pb, Zn, and Cu). Material from two former gold "mines" (Gordon Lake and Creighton) yielded no Au values. Quartz-carbonate veins in a mafic sill contain Cu, An, As and Au. 5) Anthraxolite veins in the Onwatin Formation.

The mineralization can be explained in terms of the volcanic theory of basin formation, but evidence favors the meteorite impact theory. The sulphide fragments in the Onaping Formation may have been formed by the brecciation of sulphide-rich pods located in the upper mantle and at the base of the transient crater; some of the sulphides may have been derived from Huronian target rocks. The Vermilion-



Errington deposits may represent sedimentary exhalative deposits of the Remac type; mineral-rich brines, trapped at the base of the transient crater, rose upward and precipitated the mineralized carbonate-chert about local events and under anoxygenic conditions. These conditions continued throughout the deposition of the upper Onwatin Formation but pyrite was the only sulphide that formed.

The quartz veins were emplaced during the time of tectono-metamorphism of the basin. Metamorphism remobilized and concentrated carbonaceous material in the Onwatin Formation to form the anthraxolite veins.



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ONTARIO GEOSCIENCE RESEARCH GRANT PROGRAM

Grant No. 96-

Nature and Origin of Mineralization
Inside the Sudbury Basin

by

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1

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INTRODUCTION AND GEOLOGICAL SETTING

The Sudbury Basin is renowned for the nickel-copper mines located at or near the outer rim. The rocks inside the Basin also host a variety of mineral occurrences including two former base metal mines. Apart from progress reports related to this study (Rousell 1981a, 1982), little new information on the mineralization has appeared in twenty-five years and many of the occurrences are poorly known. The purpose of this investigation is to determine the nature and the origin of the mineralization in terms of recent models of ore formation and Basin evolution.

The Sudbury Basin is situated near the junction of three structural provinces of the Canadian Shield: it lies within the Southern Province, with the Superior Province to the northwest and the Grenville Province to the southeast (Fig.1). The basin is elliptical in plan view, 58 km long and 26 km wide, with the long axis trending N65 E. The outer segments may be divided into three ranges: East, North and South.

Rocks of the Whitewater Group, of Aphebian (Early Proterozoic) Age, comprise the fill of the Basin and have no known equivalents outside the Basin. The group consists of three formations which are, from oldest to youngest, the Onaping, Onwatin and Chelmsford Formations. Contacts between the formations are gradational and conformable. A distinctive breccia, consisting

mainly of quartzite fragments as much as 80 m in length, occurs at the base of the Onaping Formation (Stevenson 1961, 1972; Peredery 1972). Igneous rocks underlie, penetrate and locally form the matrix of the basal breccia. These igneous rocks may be related to the micropegmatite phase of the Nickel Irruptive (Stevenson 1963), the oxide-rich phase of the Nickel Irruptive (Peredery and Naldrett 1975), or they may represent melt rocks formed by meteorite impact (Peredery 1972). Above the basal unit, the Onaping Formation consists of a massive upward-fining breccia containing fragments which include devitrified glass, quartzite, granite, gneiss and gabbro. The Onwatin Formation is composed of argillite and siltstone. A mineralized carbonate-chert unit (Vermilion member), the distribution of which is not fully known, occurs at the base of the Onwatin Formation. The Chelmsford Formation consists largely of greywacke with minor argillite and siltstone and represents a proximal turbidite sequence (Cantin and Walker 1972, Rousell 1972). The rocks of the Whitewater Group contain abundant carbonaceous material and this imparts a dark color to them.

The Nickel Irruptive was emplaced between the Onaping Formation and the footwall rocks, outcrops in the form of an elliptical ring and outlines the Basin perimeter. The nickel-copper ores, consisting mainly of pyrrhotite, pentlandite and chalcopyrite are within a distinctive inclusion-bearing facies

known as the sublayer (Souch et al. 1969, Naldrett et al. 1972, Pattison 1979). The Sublayer occurs between the Nickel Irruptive and the footwall and in radiating dykes known as offsets.

The Basin was formed approximately 1.9 Ga ago (Gibbins and McNutt 1975a) and its origin is controversial (Stevenson and Stevenson 1980, Rousell 1981b). It was long regarded as being of volcanic origin and is still regarded as such by some. Dietz (1962) proposed that the basin was excavated by meteorite impact; data supporting this theory include that of Dietz (1964, 1972), Dence (1972), French (1972), Peredery (1972), Pattison (1979) and Morrison (1982).

The Sudbury Basin was deformed by an orogenic event 1.6 to 1.8 Ga ago (Gibbins and McNutt 1975b). The basin, once less elliptical than its present form in plan view, was flattened by a 'push' directed toward the northwest. A penetrative tectonic foliation and lineation were developed in the Onaping Formation and locally in the Nickel Irruptive of the South and East Ranges (Brocum and Dalziel 1974, Rousell 1975). In the South Range, isoclinal similar folds, overturned to the northwest, are present in the basal breccia of the Onaping Formation (Stevenson 1960) and at the contact of the Onaping and Onwatin Formations (Martin 1957). Further to the northwest the deformation intensity decreased and rocks of the Onwatin and Chelmsford Formations developed a cleavage and formed open concentric folds with vertical axial planes. Still further to

the northwest the deformation was slight as only a local and weak foliation is present in the Onaping Formation of the North Range. A later episode of deformation produced kink bands in the Onaping Formation of the South Range (Rousell 1980) and still later episodes of brittle deformation formed a complex joint pattern (Rousell and Everitt 1981).

The location of all mineral occurrences inside the basin that are known to the writer are shown on Figure 1. The mineralization may be grouped as follows:

- (1) disseminated sulphides in the Onaping Formation;
- (2) sulphides in a carbonate-chert unit (Vermilion member);
- (3) pyrite and local base metals in the Onwatin Formation;
- (4) anthraxolite veins in the Onwatin Formation; and
- (5) mineralized quartz (carbonate) veins. The mineralization is diagrammatically represented in the columnar section of Figure 2.

DISSEMINATED SULPHIDES IN THE ONAPING FORMATION

Disseminated sulphides are present throughout the entire Onaping Formation including the igneous rocks that occur below and locally form the matrix of the basal quartzite breccia. The sulphides occur mainly in the form of discrete fragments but there are also sulphide patches and sulphide grains within rock fragments. The sulphide fragments are tectonically elongated

in the South and East Ranges. Several of the occurrences are exposed in trenches and pits and one by an adit approximately 37 m in length (locally known as 'Morley's mine' - Fig. 1). The sulphide content of these occurrences is variable and some were apparently reported on the basis of accessibility. Muir (1980) and Lafleur (1981) noted that sulphides in the North Range are most abundant in the upper portion (black member) of the formation. The sulphide fragments seldom exceed 0.5 cm in length and the volume percent is generally less than 10 percent. Polished section examination indicates that pyrrhotite is the major sulphide mineral with individual grains 0.5 mm or less in diameter. Chalcopyrite is common and is frequently enclosed by pyrrhotite but, in general, comprises less than 1 percent of total sulphides. Sphalerite, galena, marcasite and pyrite occur in minor amounts. The most abundant sulphide minerals in the Sudbury Ni-Cu mines (Hawley 1962) and in the Nickel Irruptive (Duke and Naldrett 1976) are: pyrrhotite, chalcopyrite and pentlandite; and pyrite, chalcopyrite, pyrrhotite and pentlandite, respectively. Thus the sulphide mineralization in the Onaping Formation resembles that in the mines in that pyrrhotite and chalcopyrite are the commonest sulphide minerals, differs from that in the Nickel Irruptive in that the order of abundance is essentially reversed, and differs from both in the apparent absence of pentlandite.

Desborough and Larson (1970) identified the following sulphide minerals in specimens of the Onaping Formation from the South Range and the Onaping Falls area (near Morley's Mine, Fig. 1) in the North Range: pyrrhotite, nickel marcasite, "pure" pyrite, nickel pyrite, sphalerite and chalcopyrite. Pyrrhotite is the most abundant sulphide mineral and it is locally replaced by nickel pyrite and nickel marcasite. The nickel and cobalt contents of grains of pyrrhotite, pyrite and marcasite were determined in three specimens by means of electron microprobe analysis. The Ni content of pyrrhotite is of particular interest; the range for eight grains is 0.1 to 0.35 weight percent and the average is 0.28 weight percent nickel. The ranges of nickel content of pyrrhotite from seven specimens from the Nickel Irruptive (Duke and Naldrett 1976) and from several Sudbury Ni-Cu mines (Hawley 1962) are 0.5 to 1.2 weight percent and 0.76 to 2.65 weight percent, respectively. The corresponding average nickel contents are 0.81 and 1.62 weight percent, respectively. Thus the nickel content of pyrrhotite is apparently low in the Onaping Formation, higher in the Nickel Irruptive and still higher in the Ni-Cu ores.

Table 1 sets out chemical data for 28 specimens of the Onaping Formation in terms of range and average values (see Rousell 1982, for complete analyses). Average values of Zn and Pb, obtained by omitting the maximum value (Table 1), are

used for comparison with other published data. Relatively high metal values are present in an exposure of the top of the Onaping Formation located immediately west of Errington No. 2 shaft (Zn - 2.32 weight percent, Pb - 6250 ppm, Ba 2839 ppm and As - 302 ppm); and from an outcrop of the base of the formation near Foisey (Zn - 650 ppm, Pb - 960 and As - 152 ppm). Elsewhere metal values in the formation appear to be modest. Trace element data from the Onaping Formation reported by Arengi (1977) and Sadler (1958) are also given in Table 1 in terms of range and average values. Arengi's (1977) data indicate somewhat higher average Zn, Ni and Cr values and Sadler's (1958) data show higher average values of Cu, Ni and Pb compared to the average values obtained in this study.

The average abundance of certain elements in various common rock types and the earth's crust have been determined by several investigators (see Krauskopf 1967, 1979). It is difficult to compare the Onaping Formation with a particular rock type because of the heterogeneous nature of the unit (Peredery 1972) and because of a lack of geochemical data. Based on the chemical analyses of six selected specimens, Stevenson (1972) concluded that the Onaping Formation ranges in composition from rhyodacite near the base to dacite toward the top. This corresponds most closely to the 'intermediate' rock type (Table 1). The average values of Cu, Zn, Co and Cr

in the Onaping Formation are at least twice as great as the average values of these elements in intermediate rocks; Ni and Pb values are not appreciably different. The average As value in the Onaping Formation is notably high and is approximately 13 times greater than the average value of intermediate rocks and 16 times greater than the average value of the crust. The data of Arengi (1977) and Sadler (1958) indicate average Ag values that are approximately 100 times greater than the average Ag values of intermediate rocks; however, the material analyzed by the writer yielded much lower Ag values (Table 1).

SULPHIDES IN A CARBONATE-CHERT UNIT

The Vermilion Mine, the Sturdy property and the three shafts of the Errington Mine are located in the southwestern corner of the Basin (Fig. 1). These Zn-Pb-Cu-Ag-Au deposits occur over a length of 11 km, are in a carbonate-chert unit located at the base of the Onwatin Formation and are on the site of a magnetic high (GSC 160) that extends to the north-east and beyond the mines. Burrows and Rickaby (1930) discussed the early history of the operations, Martin (1957) described the geology of the mines and excellent coloured plans and sections are presented by Thomson (1956, after Martin 1957).

These properties have had a chequered history of exploration and development and have changed hands several times. Mineralization was first discovered by James Stobie in 1897 at Stobie Falls

on the Vermilion River (near Errington No. 1 shaft, Fig. 1 and no longer exposed). Several small shafts, in the vicinity of Errington No. 1 shaft indicate early activities. After considerable diamond drilling the Errington No. 1 shaft was sunk in 1926 (approx. 152 m) followed by the sinking of No. 2 shaft (approx. 457 m) and No. 3 shaft (approx. 125 m). The Vermilion Lake orebody, situated beneath Vermilion Lake, was discovered in 1929 by diamond drilling. An extensive surface installation was constructed that included a mill and flotation plant. Operations ceased in 1931 because of a fall in metal prices. In 1952 the Errington Mine was dewatered and the properties reopened. The Vermilion Lake Mine shaft was completed in 1953 (approx. 381 m). Operations apparently stopped in 1957 (S.N. Charteris, pers. commun.). One of the reasons for the lack of success was due to problems of recovery because of the fine-grained nature of the ore. Giant Yellowknife Mines Limited, the present owners of the property, completed a drilling program in 1979 at the Vermilion Mine in order to obtain fresh material for recovery tests.

The ore occurs in a distinct unit called the "Vermilion Formation" (Martin 1957). Arengi (1977) relegated the unit to member status because diamond drill hole data indicated lateral discontinuity; the writer concurs with this view.

Figure 4 is a diagrammatic representation of the Vermilion member and it is based on the description by Martin (1957). The basal argillite (0-30 m thick) is a massive, siliceous and carbonaceous rock containing pyrite as fine disseminated grains and thin layers; upper and lower contacts are gradational. The argillite is supposedly replaced by the overlying carbonate from the top down and the former may be thin or absent when the latter is thick. The carbonate rock, as much as 30 m in thickness, hosts most of ore and varies from fine to coarse grained, locally exhibits pisolitic texture and may be prominently layered (see photograph in Thomson 1956, p.50 and Fig. 3A). A cherty carbonate zone marks the gradation from carbonate to chert breccia. Carbonate replaces chert breccia and locally this process is almost complete. The chert breccia consists of black chert fragments, generally less than 5 cm in length, set in a matrix of white recrystallized chert. The uppermost unit of the member (approx. 6 m thick) consists of interbedded argillite, limestone and dolomite.

The ore sulphides consist of pyrite, sphalerite, galena, chalcopyrite, marcasite and pyrrhotite. There are two types of ore: disseminated ore and massive pyrite ore (Fig. 3B). The disseminated ore occurs in the carbonate rock and the mineralization is fine-grained and intimately mixed. The massive pyrite ore is generally high in Zn and low in Cu, occurs mainly at the base of the carbonate rock and apparently replaces the

underlying argillite; massive pyrite is also present at the base of the Vermilion member. Chalcopyrite locally replaces pyrite and pyrrhotite and also replaces chert breccia and chert carbonate. The highest copper values tend to be at the top and bottom of the deposits. Quartz veins in the ore zone display coarse sphalerite, galena and chalcopyrite; the veins are barren outside the ore zone.

The rocks in the mines are strongly folded and faulted and the structure is complex. The folds are isoclinal, doubly plunging and overturned to the northwest with the axial planes dipping steeply to the southeast. Some of the folds are asymmetrical with a long southeastern limb and a short northwestern limb; the orebodies are located on the southeastern limbs and hinges of the folds. The folds appear to be of the similar type. The carbonate rocks of the Vermilion member probably behaved in a ductile manner and flowed toward the fold hinges; the brittle chert brecciated. The rocks are offset by reverse faults, disposed parallel to the axial plane of the folds, with as much as 150 m dip-slip movement.

Some investigators stressed that the ore bodies lie in a major fault or shear zone (Burrows and Rickaby 1930, Thomson 1956) implying a genetic connection between faulting and ore. In general, the rocks of the South Range lack primary layering but possess a tectonic foliation oriented parallel to the faults.

Thus it is difficult to recognize faults on the surface except at the southwestern rim of the basin where lithologic contacts are offset. Deformation in the basin increases in intensity toward the southeast (Rousell 1975). The rocks in the mines are probably no more intensely faulted than are those to the southeast.

Burrows and Rickaby (1930) located five outcrops of ore on a map of the Errington property; only two of these are now exposed. One, located between Errington No. 2 and No. 3 shafts (Fig. 1) consists of a lenticular gossan, as much as 2 m wide, enclosed by slate of the Onwatin Formation. Mottled grey and white dolomite, with an average grain diameter of 0.5 mm, comprises approximately 90 percent of the rock together with minor quartz and sulphides. A chemical analysis of a specimen (W82, Table 2) indicates a 0.9 weight percent Zn content. The Vermilion member is well exposed at the northwestern edge of a ridge occupied by the Errington No. 1 shaft (Fig. 3C). Chert breccia consists of black chip-like fragments of chert, as much as 5 cm in length, set in a matrix of white, very fine-grained quartzite with individual grains approximately 0.05 cm in diameter. This rock is not mineralized (W81-1, Table 2). A dense, fine-grained siliceous rock is associated with the chert breccia. Most of the exposure consists of a medium to coarse grained, massive dolomitic rock containing abundant

sulphides including sphalerite, pyrite, galena and chalcopyrite. Chemical analyses of this material (W81-2, W81-3, Table 2) indicates a high Zn content together with Pb, Cu and As values.

Table 2 sets out chemical analyses of a specimen from the Errington No. 3 dump (W68) and the average of 4 specimens from the Vermilion Mine dump (Arengi 1977). The Zn, Pb and Cu values indicate that much of the material in these dumps is mineralized.

The Vermilion member is covered by surficial deposits outside the ore zone and the lateral extent of the member can only be traced by drilling. According to Arengi (1977), argillaceous limestone, 1-4 m thick, was encountered in three drill holes in the North Range (northeast of the mafic sill and southwest of Proulx, Fig. 1); in the South Range a drill hole (between Foisey and Papineau, Fig. 1) penetrated approximately 30 m of argillaceous limestone and cherty limestone and two other drill holes, southwest of the above hole and northeast of Errington No. 3 shaft, penetrated 2 m of these rocks. Average metal values for four specimens from the South Range drill holes are given in Table 2 and indicate low metal values.

PYRITE AND BASE METALS IN THE ONWATIN FORMATION

The Onwatin Formation is rich in pyrite. This pyrite occurs as abundant silt-size grains arranged parallel to the bedding plane and as massive stratiform lenses (Fig. 3D), generally 1 to 3 cm thick, but locally as thick as 20 cm. The presence of pyrite along cleavage planes indicates remobilization. Pyrite cubes, as much as 2 cm in diameter, occur in local masses and are the result of recrystallization. This type of occurrence is common north of Vermilion Lake and many are exposed in trenches and pits.

Chemical data for eleven specimens of the Onwatin Formation are given in Table 1 in terms of range and average values (see Rousell, 1982, for complete analyses). All specimens, except one, are from the western portion of the Basin as the formation is poorly exposed elsewhere. Apart from modest Zn values (1250 ppm)ⁱⁿ a specimen from an exposure between Errington No. 2 and Errington No. 3 shafts, none of the other specimens contain an appreciable metal content. In the Onwatin Formation the average values of Co, Ba, As and Ag are greater, Zn values are somewhat less (omitting 1250 ppm from average) and Cu, Ni, Pb and Cr values are approximately the same as the average values in shale (Table 1).

Table 1 gives the range and average values of Sadler's (1958) chemical data for (1) Onaping-Onwatin transition zone and basal Onwatin argillite and (2) Onwatin Formation; and Arengi's (1977) chemical data for the Onwatin Formation. All these values are higher than the average values of shale, particularly Ag. The transition zone - basal argillite is very high in Cu, Ni, Co and Pb; Sadler's (1958) data on the Onwatin Formation indicates high Cu and Pb values; and Arengi's (1977) data indicates high Cu and Cr values and very high Zn values compared to average values in shale.

The specimens chemically analyzed by Sadler (1958) and Arengi (1977) yielded considerably higher metal values than the specimens of the Onwatin Formation analyzed by the writer. Much of the material of these investigators came from drill holes which apparently intersected relatively mineral-rich zones.

ANTHRAXOLITE VEINS

An anthraxolite vein (Fig. 3E) occurs in the Onwatin Formation at a locality north of Errington No. 1 shaft (Fig. 1). The anthraxolite is a black, dense, platy material and contains considerable pyrite and some quartz. The anthraxolite consists of approximately 95 percent carbon (Burrows and Rickaby 1930). The vein is exposed in an inclined adit 30 m in length and two smaller inclined adits. The deposit generated considerable

local interest before the turn of the century as it was thought the material could be used as a fuel; however, it proved unsuitable due to the high ash content. Another similar anthraxolite vein occurs north of the Vermilion Mine (Fig. 1).

QUARTZ (CARBONATE) VEINS

In the South Range sulphide-bearing quartz veins occur at the contact of the Nickel Irruptive and the Onaping Formation (Foisey and Papineau properties) and in the basal felsic breccia of the Onaping Formation (Moore Lake occurrence). Gold-bearing quartz veins are present in the lower part of the Onaping Formation. In the North Range mineralized quartz (carbonate) veins occur in the basal felsic breccia of the Onaping Formation (Proulx property), in shear zones in the Onaping Formation (Lafleur 1981) and in a mafic sill located at the Onwatin-Chelmsford contact. Quartz veins are prominent in the South Range but are relatively scarce in the North Range. Mineralized quartz veins have not been reported in the East Range.

Figure 5 is a stereographic plot of poles to 47 quartz veins all but four of which are from the South Range. In general, the veins dip steeply and the rose diagram of the strikes indicates two dominant trends, $N53^{\circ}E$ and $N83^{\circ}E$. In the southwestern portion of the South Range the lithologic contacts and the foliation strike approximately $N53^{\circ}E$; in the eastern part of the South Range the strike of the contacts and foliation turn (at Foisey property,

Fig. 1) and strike approximately $N83^{\circ}E$. In the former locality quartz veins strike at $N53^{\circ}E$ and in the latter locality at $N83^{\circ}E$. Accordingly, quartz veins in the South Range strike parallel to lithologic contacts and the foliation.

Sulphide-Bearing Quartz Veins

There are a number of quartz veins in the vicinity of the Foisey property (Fig. 3F). The most mineralized vein is approximately 1 m in thickness and is within the igneous rock which forms the matrix of the basal felsic breccia of the Onaping Formation. Black sphalerite, together with some galena and chalcopryrite, form local blebs as much as 3 cm across. Polished section examination indicates that sphalerite, galena and chalcopryrite comprise approximately 90 percent, 9 percent, and 1 percent of the total sulphides, respectively. Sphalerite occurs as masses over 1 cm across, galena occurs as tiny (0.01 mm) inclusions in the sphalerite and as individual grains 0.01 mm in diameter and chalcopryrite occurs as grains 0.01 mm in diameter within the sphalerite. Chemical analyses of a specimen of the vein (W3-1A, Table 3) indicates high values of Zn and Pb and the presence of minor amounts of Ag and Au. An analysis of the igneous country rock (W3-2, Table 3) indicates a low metal content.

The geological setting of the Papineau property is somewhat similar to that of the Foisey property but the sulphide mineralogy is different. Quartz veins and blebs as much as 5 m in thickness are very numerous in this locality and they are within an igneous rock (micropegmatite?) that is below the basal breccia of the Onaping Formation. At the Papineau shaft a 2.5 m wide quartz vein contains massive arsenopyrite and some pyrite. Mauve-coloured carbonate material contains chalcopyrite, malachite and azurite. Polished section examination reveals that over 90 percent of the sulphides consist of arsenopyrite and less than 10 percent is chalcopyrite. Chemical analyses of two specimens from the vein (W10-A and W10-B, Table 3) indicate relatively high Cu values, moderately high Au and Co values and traces of Ag. Specimen W10-B gave the highest Au value of any specimen analyzed in the present study. A few tens of metres north of the shaft is a trench 65 m long and 3 m wide. Broken vein material contains arsenopyrite and a chemical analysis of this material (W11, Table 3) indicates relatively high Au, Co and Ba values.

The Moore Lake occurrence consists of several quartz veins, approximately 10 cm in width, within the basal breccia of the Onaping Formation. Galena occurs in masses as much as 5 cm in width together with black sphalerite, pyrite, and minor chalcopyrite. The presence of these minerals was confirmed by polished section examination. A chemical analysis of a specimen from

the vein (W52-2, Table 3) shows high Pb and Zn values and the highest Ag value of any chemically analyzed specimen in the study. The country rock contains considerable pyrite but a chemical analysis (W52-1, Table 3) indicates low metal values.

The Proulx property is located in the North Range and on the south shore of Nelson Lake (formerly Trout Lake). Burrows and Rickaby (1930) briefly described the occurrence. A shaft was sunk to a depth of at least 20 m and two quartz veins 1.5 and 2.4 m in thickness contain appreciable amounts of sphalerite, galena, and chalcopyrite. The country rock is the basal felsic breccia of the Onaping Formation. At present there is no trace on the surface of the shaft or of quartz veins.

Lafleur (1981) reported the presence of north-northwesterly trending shear zones in the Onaping Formation in Dowling Township. Some shears extend more than 20 m along strike and contain galena, sphalerite, chalcopyrite and pyrite. Chemical analyses of five samples from one set of veinlets (near Morley's Mine, Fig. 1) contained as much as 8.88 percent Zn, 11.8 percent Pb and 0.42 percent Cu (Lafleur 1981).

Gold-Bearing Quartz Veins

The Gordon Lake and Creighton "gold mines", apparently abandoned around the turn of the century, occur in the southwestern portion of the basin (Fig. 1). Both are briefly described by Blue (1893).

A prominent outcrop of quartz-rich rock on the west side of the Gordon Lake Road^(Fig. 3F) is presumably the site of the "mine" (Fig. 1). The quartz-rich rock is penetrated by a 10 m long adit and there is a 22 m long trench. The rock is pale pink, medium grained, and contains numerous quartz veins and blebs as much as 30 cm wide. The quartz-rich unit is approximately 12 m in thickness, dips steeply to the southeast, and is internally folded. In thin section the pink quartz rock consists of strained quartz grains, together with some plagioclase grains, in a fine grained mosaic of recrystallized quartz. Locally the quartz is highly fractured. Pyrite and limonite are abundant. A light green rock consisting of carbonate, quartz, and chlorite occurs beneath the quartz-rich unit. The writer tentatively interprets the quartz rock as a quartzite fragment from the basal breccia of the Onaping Formation that has been emplaced in its present position in the Onaping Formation by faulting. Chemical analyses of three specimens from the property (W44-1, W44-2, W44-3, Table 3) indicate no Au nor significant amounts of any other metal.

During the time of operation of the Creighton Mine gold values were apparently between \$4 and \$20 per ton of ore (Blue 1893); in 1893 the price of gold was \$20 per ounce. An abandoned shaft (surface dimensions 5.5 m by 3 m) is located on the property and there is a large dump. Quartz vein material

extends over a width of 12 m with as much as 4 m of continuous exposure. The vein is exposed for 100 m along strike until it disappears into a swamp. The country rock, the Onaping breccia, contains some disseminated sulphides and the quartz vein contains some pyrite and limonite. Table 3 gives a chemical analysis of the country rock (W61-1) and analyses of three specimens of the quartz veins (W61-2, W61-3, and W61-4). No Au was detected and the values of the other metals are low. Similar results were obtained from a specimen from a quartz vein near the Creighton Mine (W60).

Sulphide-Bearing Quartz-Carbonate Veins in a Mafic Sill

A mafic sill as much as 30 m in thickness, and exposed at three localities over a length of 4 km, occurs at the contact between the Onwatin Formation and the Chelmsford Formation in the North Range (Fig. 1). The rocks are strongly altered but primary pyroxene is locally preserved. The sill is the locus of mineralized quartz-carbonate veins and these have been explored by numerous pits and trenches. The veins are as thick as 1.7 m and are irregular, and vein material is commonly intimately mixed with the mafic rocks. The carbonate is buff-coloured, weathers to a chocolate brown, and is probably ankerite or siderite. Pyrite, commonly in the form of cubes, locally weathers to limonite and hematite. Arsenopyrite is a prominent mineral,

occurs in local masses a few centimetres across, and as narrow veinlets in quartz and in the mafic rock. Chalcopyrite is locally present and weathers to malachite.

Table 3 sets out chemical analyses of two specimens of the mafic rock and four specimens of quartz-carbonate veins. Both specimens of the mafic rock (W35-1, W39-2) contain disseminated pyrite but neither have significant metal values; W39-2 contains traces of Au. Specimen W36-1 is from a vein with massive arsenopyrite and has a high As content and contains appreciable Au and some Ag. Specimen W37 is from a vein with visible chalcopyrite and displays high Cu and Zn values and a modest Pb content. Specimens W39-1 and W65 apparently represent material from barren veins although W39-1 has a moderately high As content.

ORIGIN OF MINERALIZATION

Previous suggestions as to the origin of the mineralization inside the Sudbury Basin are limited to the Vermilion-Errington deposits; it was assumed that the Basin was of volcanic origin. Compelling evidence suggests that the Basin was formed by meteorite impact and that the processes that led to the formation of the Ni-Cu ores were triggered by this event. No attempt has been made to explain the mineralization inside the Basin in terms of this theory.

The mineralization inside the Basin may be separated on the basis of time of formation as follows: (1) mineralization that formed essentially instantaneously and immediately after the initial Sudbury event (sulphide fragments in the Onaping Formation); (2) mineralization that formed after the deposition of the Onaping Formation and before the deposition of the Chelmsford Formation (Vermilion-Errington deposits, pyrite in Onwatin Formation); and (3) mineralization formed during a tectono-metamorphic event (anthraxolite veins, quartz-carbonate veins). The first two groups must be a direct result of whatever process formed the basin.

In the following discussion previous ideas are reviewed, the mineralization is related to other sediment-hosted mineral deposits and the mineralization is considered in terms of the volcanic and meteorite theories of basin origin and a later tectonic event.

Sulphides in the Onaping Formation

According to Sangster and Scott (1976) sulphide fragments are not uncommon in felsic pyroclastic rocks associated with Precambrian massive sulphide deposits. These fragments may form by several processes including brecciation of original sulphide layers, by slumping or later volcanic explosions or brecciation

by explosion of sulphides in volcanic pipes. Sulphides in the Onaping Formation consists mainly of pyrrhotite fragments and the formation is considered by some (eg. Stevenson 1972) to represent a felsic pyroclastic rock. Accordingly, sulphide-rich material must have been present prior to brecciation and incorporation into the unit.

Pattison (1979), among others, proposed that the Ni-Cu ores of the Basin formed as a result of meteorite impact. Figure 6 is a diagrammatic representation of the evolution of the Basin according to this theory. Figure 6A shows the target area just prior to impact. The outline of the maximum transient crater is indicated and it apparently penetrated as deep as the upper mantle where sulphide-rich pods were presumably present. Metasedimentary and tuffaceous rocks of the Elsie Mountain and Stobie Formations (Huronian Supergroup), exposed to the south of the Basin, locally contain as much as 10 percent sulphides (Fig. 6A); mainly pyrrhotite and some pyrite and chalcopyrite (Innes 1972).

The sulphide-rich pods, together with silicate rocks, formed an impact melt that travelled up the crater wall (Fig. 6B); the sulphides separated from the melt due to density differences and produced the Ni-Cu ore bodies in the sublayer (Fig. 6E). Some of the sulphide material in the pods and in the Huronian rocks may have been brecciated and, together with silicate material, incorporated in the airborne ejecta. This material,

presumably in a molten or semi-molten state (Peredery 1972), fell back into the crater to form the Onaping Formation.

Vermilion-Errington Deposits and Mineralization in the Onwatin Formation

The Vermilion-Errington deposits were originally thought to lie in a major shear zone and to represent irregular pods scattered throughout masses of chert-carbonate rock. The mineralization was interpreted in terms of the classical hydrothermal concept; that is, the sulphides were supposedly derived from mineral-bearing solutions emanating from the Sudbury Nickel Irruption and at lower temperatures than the Ni-Cu ores, also derived from the irruption (Burrows and Rickaby 1930).

Further studies, after the reopening of the mines in 1952, led to the realization that the deposits were stratigraphically and structurally controlled. The ore occurs mainly on the south limb of folds that are the site of thrust faults and "Maximum dragging and brecciation of the Vermilion formation occurs in such locations, and the best structural conditions to catch mineralization of epigenetic origin" (Martin 1957, p. 368). Martin (1957) further stated that some or most of the chert, carbonate and pyrite may be the result of hot-spring activity during the last phase of Onaping volcanism. Thomson (1956) suggested that the host rocks may be sedimentary in origin,

that the chert breccia might be the result of slumping or later deformation and that these brecciated horizons were amenable to mineralization.

Card and ^{Hutchinson}~~Hutchison~~ (1972) elaborated on these earlier concepts and considered the deposits in terms of regional volcanic-tectonic cycles. The Onaping Formation is regarded as a product of explosive volcanism during a second cycle. During the later phases of this cycle two metal- and sulphur-rich phases supposedly formed: a melt which differentiated at depth to form the Nickel Irruptive and the Ni-Cu ores outside the basin, and a volatile phase which escaped to the surface to form the Vermilion-Errington deposits inside the basin.

Arenqi (1977) assumed that the basin was formed by meteorite impact and suggested that the deposition of the Onaping Formation (fall-back breccia) resulted in a flat crater floor. Disruption of the floor, possibly due to the emplacement of the Sudbury Nickel Irruptive, gave rise to local highs on which carbonate banks developed (Vermilion member); basal argillites and siltstones of the Onwatin Formation were deposited between the banks.

Sangster (1970) divided Canadian stratabound Pb-Zn deposits into two types: the Mississippi Valley type and the Remac type (after the Reeves-MacDonald Mine, Kootney arc structural province, B.C.; later referred to as Alpine type, Sangster and Scott 1976). The former deposits occur in relatively undeformed platform carbonates and are located between or at the margins of basins.

The ores are younger than the host carbonate and were emplaced in permeable zones formed by processes such as brecciation, fracturing and dolomitization. The rocks of the Remac deposit are highly deformed; the ore is fine- to medium-grained and banded and the carbonate host is composed of alternating light bands and dark graphite-bearing bands of dolomite. In general, the stratigraphic succession for Kootney arc Pb-Zn deposits from bottom to top, is: quartzite, thin-bedded limestone and dolomite, local chert and black carbonaceous shales (see Høy 1982). The succession suggests the rocks were deposited in the centre of a basin and in a deep-water euxinic environment rich in H_2S ; metal-bearing solutions precipitated sulphides in the form of a layer on the seafloor and syngenetic with the host rocks (Sangster 1970).

The stratigraphic succession associated with the Vermilion-Errington deposits, namely basal argillite, banded carbonate with mineral layers and bitumen, chert and black carbonaceous pyritic shale (Onwatin Formation) suggests these deposits may be of the Remac type. The basal argillite, interpreted by Martin (1957) to be a volcanic mud leached by hot acids, may represent an alteration halo. The Vermilion-Errington deposits may be sedimentary-exhalative deposits (Carne and Cathro 1982) and the 'volatile phase' of Card and Hutchinson (1972) might actually represent metal-rich brines. Moreover, the process

could have been triggered by meteorite impact. The impact site might have been a shallow sea; seawater penetrated to the bottom of the deep transient crater and became trapped by the fall-back breccia. The crater then filled with seawater and the outer rim gave rise to a closed basin much larger than the present remnant basin (compare Fig. 6C and 6F). The abundant carbonaceous material, perhaps derived from a floating algal mat, suggests that bottom waters were stagnant and anoxygenic (Fig. 6D). The trapped brines, (possibly augmented by a 'volatile phase' formed as a result of pressure release due to impact), rose upward, deposited minor quantities of Zn, Pb and Cu as they passed through the Onaping Formation and, on reaching the basin floor, precipitated the Vermilion member about local vents. Minor amounts of metals were precipitated between the vents in the basal argillites and siltstones of the Onwatin Formation. Reducing conditions apparently prevailed throughout the deposition of the upper Onwatin Formation but pyrite was the only sulphide that formed.

Further evidence of the origin of the Vermilion-Errington deposits may be obtained by comparing them to other sediment-hosted Cu-Pb-Zn deposits. Figure 7 is a plot of metal ratios of a number of these deposits (from Gustafson & Williams 1981); the symbols refer to the lithology of the host rocks and the deposits are listed in Table 4. The Vermilion-Errington deposits are indicated as B to E (see Table 2 for data) with

the average at F (Zn = 64.5, Pb = 20.6 and Cu = 14.9 percent).

In Figure 7A, a plot of Cu-Pb-Zn ratios, the solid line encloses the field of North American Precambrian massive sulphide deposits and the broken line encloses the field of Canadian and Japanese Phanerozoic massive sulphide deposits; both are in volcanic or volcano-sedimentary host rocks (after Sangster and Scott 1976). The Mississippi Valley-type carbonate-hosted deposits tend to be rich in Pb or Pb and Zn and lack Cu. The Alpine-type carbonate deposits are either Cu-rich or Pb-Zn rich. The sandstone-hosted deposits are either rich in Cu with minor amounts of Pb or Zn or are Pb-rich with minor Zn. Shale-hosted deposits are Cu-rich or contain Pb and Zn with minor Cu and deposits in gneiss contain mainly Pb with variable amounts of Cu and Zn. The Vermilion-Errington deposits, Precambrian in age, fall outside the field of North American Precambrian massive sulphide deposits. The latter deposits are notably deficient in Pb (Sangster 1972); the Vermilion-Errington deposits contain appreciable lead. This suggests, but does not prove, that the Vermilion-Errington deposits are not related to volcanic processes. Figure 7A also illustrates the separation between Pb-Zn deposits and copper deposits. Note that the Vermilion-Errington deposits contain nearly as much Cu as Pb.

Figure 7B is a plot of $\text{Cu-Pb+Zn-Ag} \times 10^3$ ratios. The Ag content is extremely variable in Cu and Pb-Zn sediment-hosted deposits and in volcanogenic massive sulphide deposits. There is a lack of Ag in Mississippi Valley type deposits. The Ag content of the Vermilion-Errington deposits is moderately high and exceeds that of almost all alpine type deposits plotted on Fig. 7B.

Mineralization and Basin Deformation

Rocks of the Onaping Formation in the South Range are characterized by a tectonic foliation and numerous quartz veins whereas those of the North Range are undeformed and quartz veins are scarce. The strike of the quartz veins in the South Range is parallel to the strike of the tectonic foliation; the veins are not geometrically related to a prominent northwesterly trending joint set (Rousell and Everitt, 1981). Accordingly, the veins were apparently emplaced during the major deformation of the basin (approx. 1.7 Ga) rather than during a later episode of brittle deformation.

The exact time of emplacement of the mineralized mafic sill and the enclosed quartz-carbonate veins is not known. A similar mafic sill occurs in the Onwatin Formation south of the Chelmsford outcrop belt. Cleavage in the Onwatin Formation passes into sill rocks suggesting this sill was emplaced before or during basin deformation.

Tectono-metamorphism remobilized and concentrated carbonaceous material in the Onwatin Formation to form the anthraxolite veins, folded and faulted the Vermilion-Errington deposits, tectonically elongated the sulphide fragments in the Onaping Formation and locally remobilized and recrystallized pyrite in the Onwatin Formation.

CONCLUSIONS

The disseminated sulphides occur throughout the Onaping Formation. A detailed investigation is needed in order to determine if there are local mineral-rich horizons. The genetic connection between pyrrhotite in the Onaping Formation and that in the Ni-Cu ores, the Nickel Irruptive and the Huronian rocks remains unresolved.

The Vermilion-Errington deposits contain an appreciable amount of metals. The deposits occur at the only locality in the basin where the Vermilion member outcrops; elsewhere, the base of the Onwatin Formation is covered by alluvium. Prospecting by means of geophysical methods and diamond drilling might locate deposits similar to those of the Vermilion and Errington mines.

The quartz veins containing base metals appear to be too small to be of economic significance. The present study indicates that the two "gold" mines contain little if any gold.

Arsenic contamination has been reported in water wells in the Dowling area (southwestern end of the basin). Arsenopyrite occurs in quartz veins but these veins are small and local. The Onaping Formation and the Onwatin Formation both have high background values of arsenic and these country rocks may be the source of the arsenic contamination.

Available evidence suggests that the Sudbury Basin formed as a result of meteorite impact. If so, the foregoing represents a description of the mineralization of the fill of an Aphebian astrobleme. To the writer's knowledge, the fill of other terrestrial astroblemes lack mineralization.

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Figures

- Figure 1. Geological map showing the location of mineral occurrences inside the Sudbury Basin. Ni, Nickel Irruptive; OP, Onaping Formation; OW, Onwatin Formation; and CH, Chelmsford Formation. Inset map indicates the regional setting of the basin.
- Figure 2. Diagrammatic representation of mineralization inside the Sudbury Basin.
- Figure 3.
- A. Layered carbonate rock of the Vermilion member from the dump at the Errington No. 2 shaft. Bar is 5 cm.
 - B. Massive pyrite ore from the dump at the Errington No. 2 shaft. Light grey carbonate rock (upper left) contains chalcopyrite blebs up to 1 cm in length. Bar is 3 cm.
 - C. Outcrop of the Vermilion member at Errington No. 1 shaft.
 - D. Pyrite lense in the Onwatin Formation (Highway 144, Dowling).
 - E. Anthraxolite vein exposed by an adit (north of Errington No. 2 shaft, Figure 1).
 - F. Quartz vein at Foisey property.
 - G. Gordon Lake "gold" mine.
- Figure 4. Diagrammatic representation of the stratigraphy and mineralization in the Vermilion member.
- Figure 5. Lower hemisphere equal-area plot of poles to 47 quartz veins in the Whitewater Group. Rose diagram indicates the preferred orientations of the strikes of the veins.

Figure 6. Schematic representation of the evolution of the Sudbury Basin by meteorite impact (after Dence 1972 and Pattison 1979) and the formation of mineralization inside the basin.

Figure 7. Metal ratios of sediment-hosted stratiform deposits. Host rocks are indicated by symbols. Data for Errington and Vermilion mines (Table 2) are from Thomson (1976). The rest of the data, except as indicated below, are from Gustafson and Williams (1981); names of the deposits are listed in Table 4 with the numbers identical to those used by these authors.

- A. Cu-Pb-Zn ratios. Metal values of Mississippi Valley type deposits are from Sangster (1976). Solid line - field of North American Precambrian massive sulphide deposits in volcanic or volcano-sedimentary host rocks; and broken line - field of Canadian and Japanese Phanerozoic massive sulphide deposits in volcanic or volcano-sedimentary host rocks (after Sangster and Scott 1976).
- B. Cu-Pb+Zn-Ag $\times 10^3$ ratios. Plots of volcanogenic massive sulphide deposits (unnumbered) are for comparative purposes.

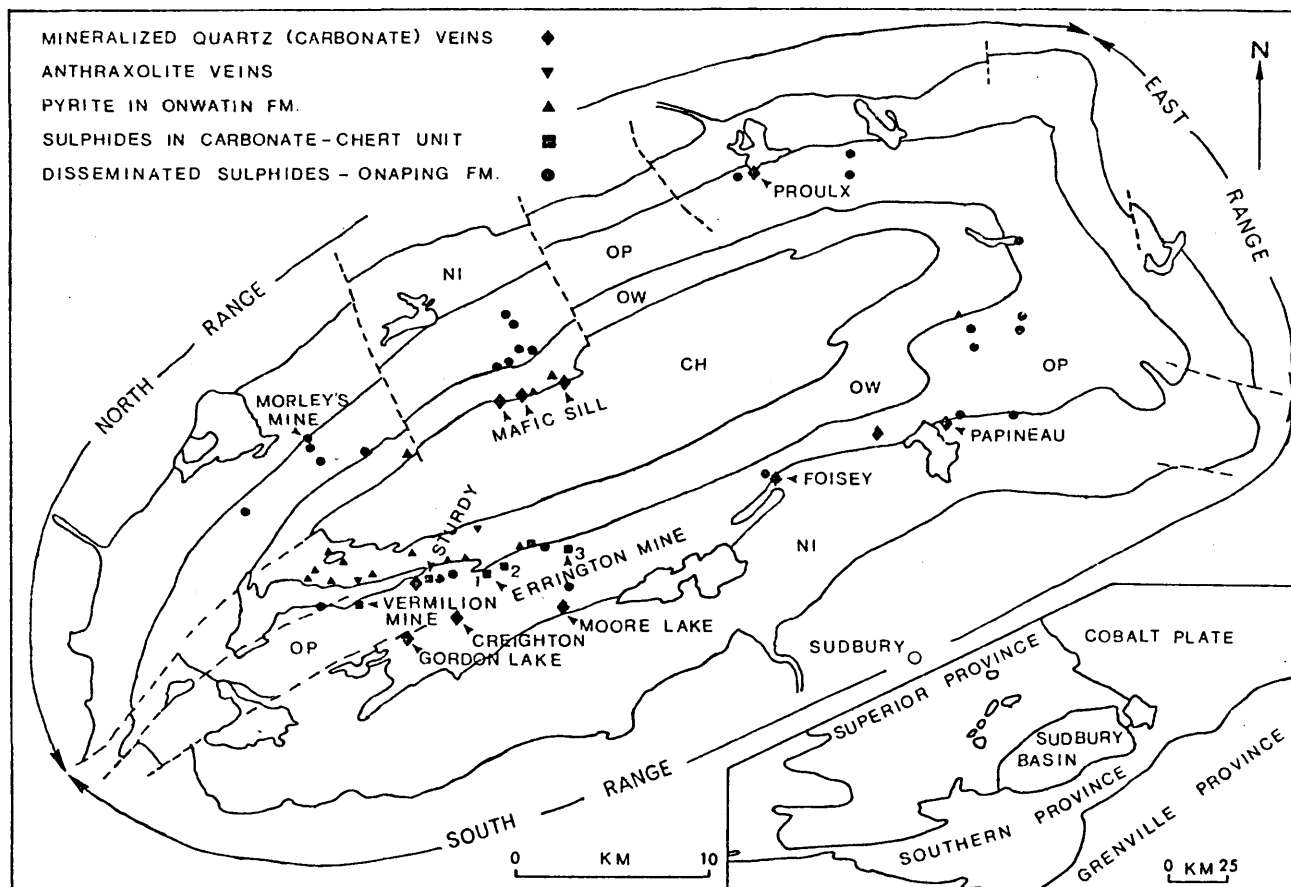


Figure 1. Summary of chemical data from the Onaping and Onwatin Formations and average values of the crust, intermediate igneous rocks and shale.

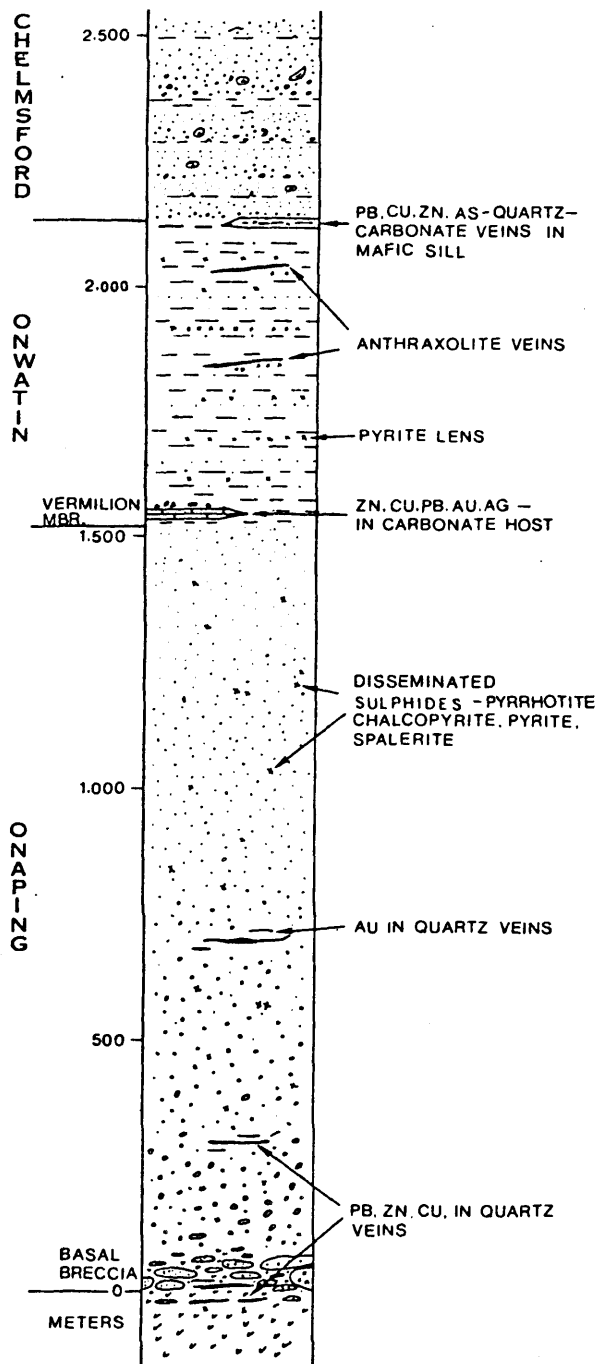


Figure 2.
Diagrammatic representation of mineralization inside the Sudbury Basin.

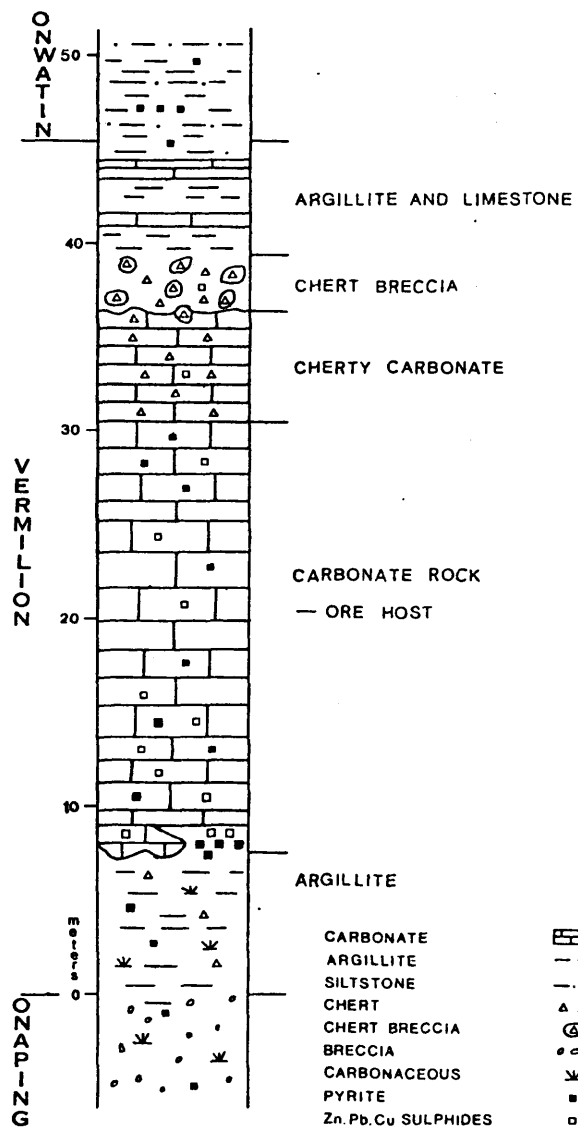


Figure 4.
Diagrammatic representation of the stratigraphy and mineralization in the Vermilion member.

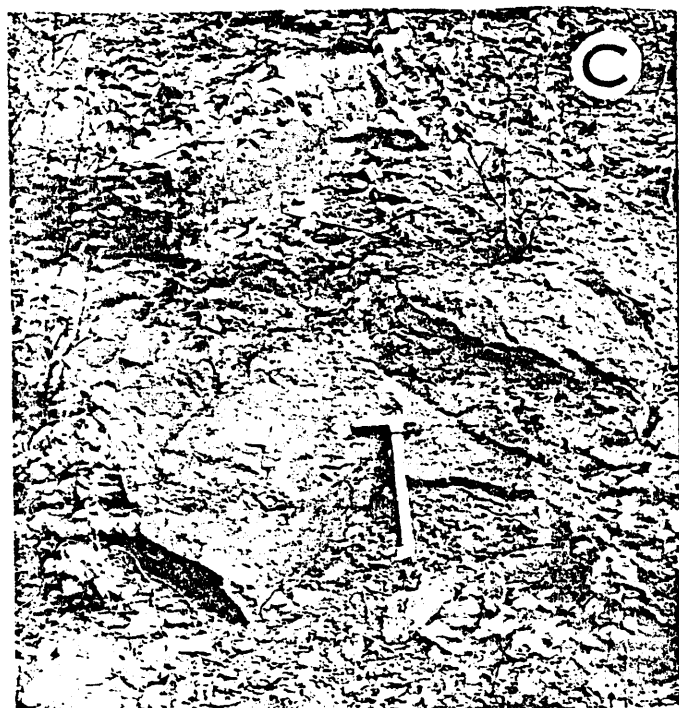


Figure 3.

- A) Layered carbonate rock of the Vermilion member from the dump at the Errington No. 2 shaft. Bar is 5 cm.
- B) Massive pyrite ore from the dump at the Errington No.2 shaft. Light grey carbonate rock (upper left) contains chalcopyrite blebs up to 1 cm in length. Bar is 3 cm.
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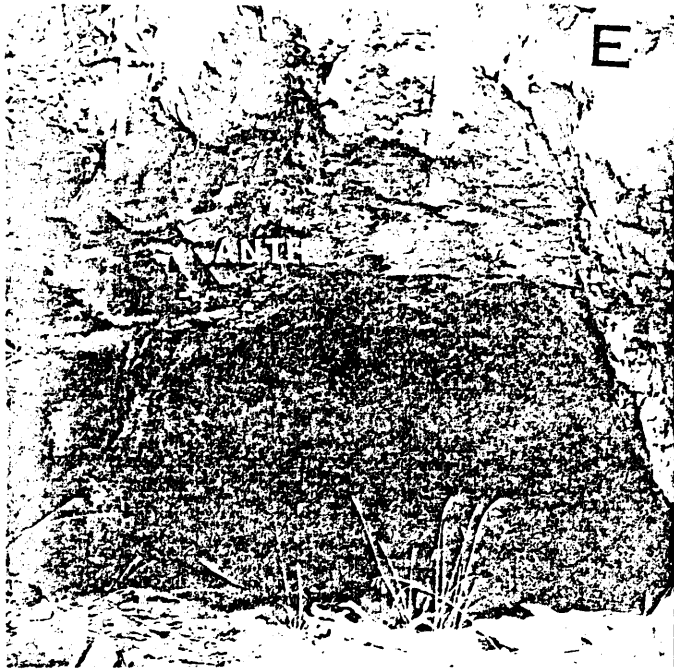
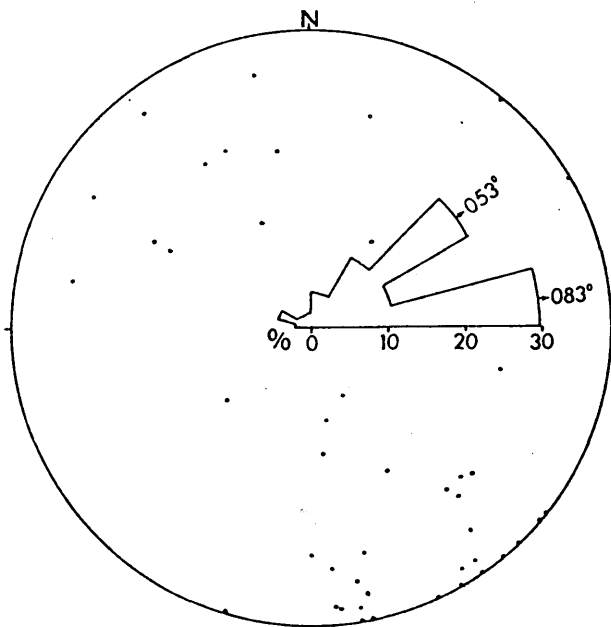


Figure 3 continued.

- E) Anthraxolite vein exposed by an adit (north of Errington No. 2 shaft, Figure 1.
- F) Quartz vein at Foisey property.
- G) Gordon Lake "gold" mine.



POLES TO 47 QUARTZ VEINS

Figure 5. Lower Hemisphere equal-area plot of poles to 47 quartz veins in the Whitewater Group. Rose diagram indicates the preferred orientations of the strikes of the veins.

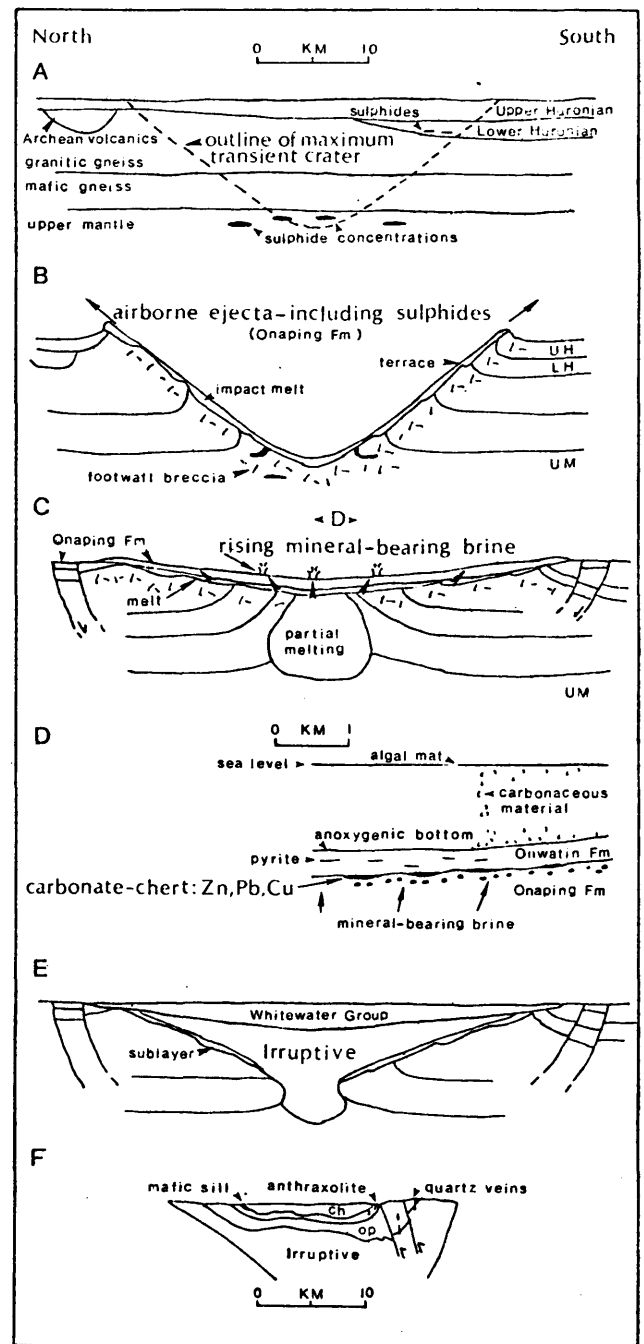


Figure 6. Schematic representation of the evolution of the Sudbury Basin by meteorite impact (after Dence 1972 and Pattison 1979) and the formation of mineralization inside the basin.

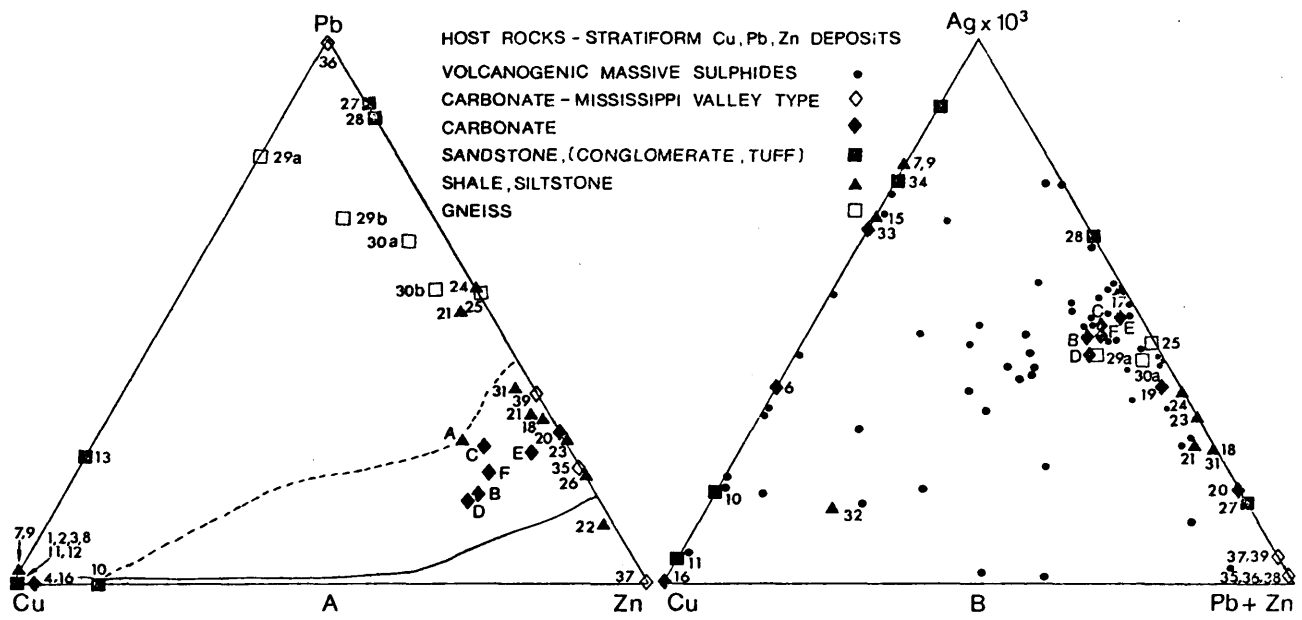


Figure 7. Metal ratios of sediment-hosted stratiform deposits. Host rocks are indicated by symbols. Data for Errington and Vermilion mines (Table 2) are from Thomson (1976). The rest of the data, except as indicated below, are from Gustafson and Williams (1981); names of the deposits are listed in Table 4 with the numbers identical to those used by these authors.

- A. Cu-Pb-Zn ratios. Metal values of Mississippi Valley type deposits are from Sangster (1976). Solid line - field of North American Precambrian massive sulphide deposits in volcanic or volcano-sedimentary host rocks; and broken line - field of Canadian and Japanese Phanerozoic massive sulphide deposits in volcanic or volcano-sedimentary host rocks (after Sangster and Scott 1976).
- B. Cu-Pb+Zn-Ag x 10³ ratios. Plots of volcanogenic massive sulphide deposits (in numbered) are for comparative purposes.

Tables

- Table 1. Summary of chemical data from the Onaping and Onwatin Formations and average values of the crust, intermediate igneous rocks and shale.
- Table 2. Chemical analyses of specimens from the Vermilion member and average values of published data from the Vermilion-Errington deposits.
- Table 3. Chemical ^{analyses} of specimens from quartz (carbonate) veins.
- Table 4. List of ore deposits plotted on Figure 7.

Table 1. Summary of chemical data from the Onaping and Onwatin Formations and average values of certain common rocks.

	ppm									ppb
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	Au
Onaping Fm. ²	15	ND	11	20	ND	41	9	ND	ND	ND
Range	325	2.32*	147	200	6250	2839	146	302	4.1	70
Average N = 28	85	955	48	47	272	553	80	28	0.3	
Average N = 27 ³		129			16					
Onaping Fm. ⁴	6	249	84	22	ND	240	205	-	ND	-
Range	103	900	211	121	45	2210	1440	-	17.1	-
Average N = 7	58	376	106	60	16	771	447		10	
Onaping Fm. ⁵	28	40	70	23	39	-	50	-	<1	-
Range	282	160	155	43	83	-	86	-	42	-
Average N = 7	154	97	118	33	60		76		7	
Transition ⁶	245	53	120	38	50	-	80	-	<1	
Range	600	418	350	144	110	-	282	-	11	
Average N = 11	394	163	223	70	70		134		<4	
Onwatin Fm. ²	ND	10	26	ND	ND	287	46	ND	ND	ND
Range	105	1250	155	125	120	4828	128	162	0.6	10
Average N = 11	49	155	63	50	22	1465	94	37	0.33	-
Average N = 10 ⁷		46								
Onwatin Fm. ⁸	15	51	46	11	18	-	72	-	<1	
Range	600	5610	271	165	135	-	167	-	7.5	-
Average N = 11	168	1320	144	55	62		129		<2	
Average N = 7 ⁹		120								
Onwatin Fm. ¹⁰	11	326	59	24	ND	250	136	-	ND	
Range	724	7420	244	81	150	1340	307	-	25	
Average N = 6	230	1917	133	49	53	778	225		17	
Average N = 5 ¹¹		695								
Crust ¹²	50	70	75	22	12.5	500	100	1.8	0.07	3
Intermediate ¹³	32.5	66	35	8.5	15	-	36	2.2	0.06	4
Shale ¹²	50	90	80	20	20	600	100	10	0.1	3

- Notes: 1. * - percent, ND - not detected, dash - not analyzed and N - number of samples.
 2. Rousell 1982.
 3. Average omitting 2.32 wt.% for Zn and 6250 ppm for Pb.
 4. Data from two DDH's located in the central part of the North Range (Arengi 1977).
 5. Data from four DDH's and three outcrops; six analyses from the northeastern part of the South Range and one from the East Range (Sadler 1958).
 6. Onaping-Onwatin transition zone and basal argillite of Onwatin Fm; data from three DDH's located in northeastern part of the South Range (Sadler 1958).
 7. Average omitting 1250 ppm Zn.
 8. Data from several DDH's and outcrops in North and South Ranges (Sadler 1958).
 9. Average omitting 5610, 5610, 1480 and 1340 ppm Zinc.
 10. Data from two DDH's located in the central part of the North Range and one from a DDH located in the central part of the South Range (Arengi 1977).
 11. Average omitting 7420 ppm Zn.
 12. Krauskopf (1979).
 13. Krauskopf (1967).

Table 2. Chemical analyses of specimens from the Vermilion member and average values of published data.

Spec. No.	ppm										ppb Au	
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag			
W68	1300	3.0*	28	14	525	45	26	42	4		30	
W81-1	70	45	ND	40	ND	ND	0.6	27	-		-	
W81-2	9000	3.8*	20	60	1.6*	ND	4	7800	-		-	
W81-3	2000	4.1*	100	35	8000	460	30	1100	-		-	
W82	120	9000	10	20	175	25	ND	77	-		-	
Vermilion mine dump ³	1.03*	3.45*	62	193	1.43*	215	68	-	71		-	
Vermilion member ⁴	34	390	62	30	111	248	70	-	11		-	
	- wt. % -				wt. %				ppm	ppb		
Errington No.2 shaft ⁵	1.10	3.82			0.97				49.4		656	
Errington No.3 shaft ⁵	1.05	4.79			1.96				69.4		531	
Vermilion No.4 shaft ⁵	1.26	3.92			.97				43.8		781	
Vermilion-north zone ⁵	0.34	3.73			1.30				51.3		625	
Average	0.94	4.07			1.30				53.5		648	

- Notes:
- * - percent and dash - not analyzed.
 - W68 - Errington No. 3 dump, W81 - outcrop at Errington No. 1 and W82 - outcrop between Errington No. 2 and No. 3.
 - Average of four samples (Arengi 1977).
 - Average of four samples from two DDH's in the central part of the South Range (Arengi 1977).
 - Average values of ore (Thomson 1956).

Table 3. Chemical analyses of specimens from quartz veins.

Spec. no.	ppm									ppb
	Cu	Zn	Ni	Co	Pb	Ba	Cr	As	Ag	
W3-1A Foisey	160	8.5*	22	200	6750	464	59	1400	8	60
W10-A Papineau	5000	1	6	160	25	77	18	1.3*	2	869
W10-B Papineau	3000	1	40	580	80	125	29	10.1*	3	2400
W11 Papineau	150	ND	10	305	3	1477	4	45	<1	820
W36-1 mafic sill	60	10	40	230	ND	46	31	18.6*	7	1610
W37 mafic sill	1.0*	2500	40	280	420	1	17	ND	2	ND
W39-1 mafic sill	3	5	10	165	ND	6	16	4400	ND	10
W65 mafic sill	135	50	25	40	ND	62	10	28	1	ND
W44-1 Gordon Lake	ND	25	15	87	310	221	17	ND	1	ND
W44-2 Gordon Lake	ND	ND	32	155	ND	21	12	35	ND	ND
W52-2 Moore Lake	50	1.93*	56	160	2.73*	70	37	4.5*	264	ND
W60 Creighton	20	150	132	120	10	1546	492	82	ND	ND
W61-2 Creighton	5	3	22	215	ND	59	15	1	ND	ND
W61-3 Creighton	40	7	38	133	11	662	18	24	ND	ND
W61-4 Creighton	40	95	54	68	15	19	9	ND	ND	ND

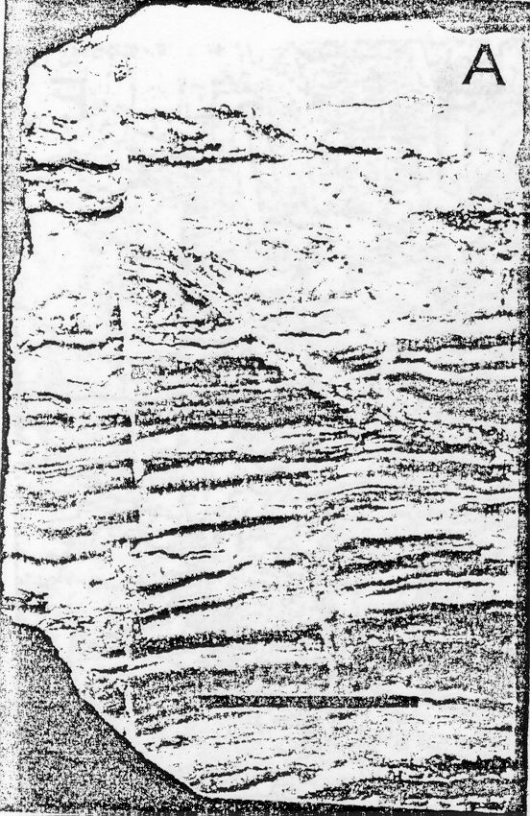
Notes: 1. * - percent and ND - not detected.

Table 4. List of ore deposits plotted on figure 7.

- | | |
|--|---|
| 1. Mifulira, Zambia | 28. Largentière, France |
| 2. Rokana, Zambia | 29a. Aggeneys (Black Mountain, open pit)
South Africa |
| 3. Chibuluma, Zambia | 29b. Aggeneys (Black Mountain, underground)
South Africa |
| 4. Shaba, Zaire | 30a. Aggeneys (Broken Hill, open pit) S.A. |
| 6. Redstone River, Canada | 30b. Aggeneys (Broken Hill, underground) SA |
| 7. White Pine, USA | 31. Faro, Canada |
| 8. Spar Lake, USA | 32. Vangorda, Canada |
| 9. Creta, USA | 33. Gortdrum, Ireland |
| 10. Boleo, USA | 34. Mallow, Ireland |
| 11. Corocoro, Mexico | 35. Tri State, USA |
| 12. Nacimiento, USA | 36. Old Lead, USA |
| 13. Dzhe zkazgan, USSR | 37. Upper Mississippi Valley, USA |
| 15. Lubin, Poland | 38. Upper Silesia, Poland |
| 16. Mt. Isa (Cu), Australia | 39. Pine Point, Canada |
| 17. Mt. Isa (Pb-Zn), Australia | A. Kupferschiefer regional ratio |
| 18. McArthur River (H.Y.C.), Australia | B. Errington No. 2 |
| 19. Tynagh, Ireland | C. Errington No. 3 |
| 20. Silvermines, Ireland | D. Vermilion No. 4 |
| 21. Rammelsberg, Germany | E. Vermilion north zone |
| 22. Meggen, Germany | F. Average of B, C, D and E |
| 23. Lady Loretta, Australia | |
| 24. Sullivan, Canada | |
| 25. Broken Hill, Australia | |
| 26. Howard's Pass, Canada | |
| 27. Laisvall, Sweden | |



A



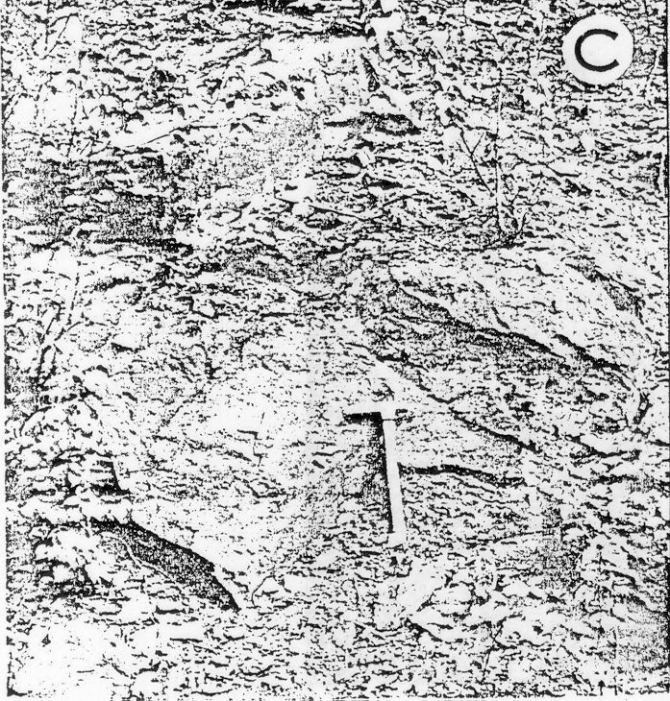
B

Cr

100 μm



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E

ANTH

