CONTACT METAMORPHISM OF THE VIRGINIA FORMATION IN THE MINNAMAX DEPOSIT
ST. LOUIS COUNTY, MINNESOTA

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA

BY
MARK H. KIRSTEIN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

OCTOBER, 1979

ABSTRACT

The Middle Precambrian Virginia Formation, cut by diabase dikes, was intruded and contact metamorphosed by the Late Precambrian Duluth Complex near Babbitt, Minnesota. Sulfide mineralization of magmatic origin, with minor amounts formed by hydrothermal replacement, is concentrated at the irregular contact zone between the Virginia Formation and the Duluth Complex. Five miles south of Babbitt this mineralization constitutes the Minnamax Copper-Nickel Deposit, which is being investigated and evaluated underground by AMAX Exploration, Inc.

The Virginia Formation consists of pelitic hornfels, calc-silicate pods, and "reaction" rims around the pods. The pelitic hornfels is dark gray, fine-grained, massive, and composed of plagioclase, hypersthene, and cordierite with local occurrences of orthoclase, biotite, and graphite. The calc-silicate pods are light gray, fine- to coarse-grained, are spherical to ellipsoidal and range from 4 inches to 8 feet across. There are three types of pods; homogenous types with no mineral zones developed, layered types with mineral layers developed, and concentric types with mineral zones developed. The primary minerals are diopside, grossular garnet, plagioclase, sphene, wollastonite, and possibly some calcite, and quartz. From strikes and dips of relict bedding in pelitic hornfels and from the broken, fractured, and jumbled nature of calc-silicate

pods deformation of the Virginia Formation appears intense. The "reaction" rims are dark gray, fine-grained, and up to 3 inches wide. They are composed of plagioclase, hypersthene and poikiloblastic clinopyroxene giving a composition intermediate between the pelitic hornfels and calc-silicate pods. The protolith of the pelitic hornfels appears to be a calcareous argillite and the calc-silicates a siliceous dolomitic limestone. The pods are believed to have originally been calcareous concretions in argillite with some being pieces brought up from the calcareous zone at the top of the Biwabik Iron Formation. The "reaction" rims developed after deformation took place, as they surround broken and fractured pods, and formed from diffusion of calcium from the pods into the pelitic hornfels.

The metadiabase dikes are dark gray, fine-grained, and massive. They are composed of lathy plagioclase, augite, and hypersthene. A relict ophitic texture is evident and relict plagioclase phenocrysts have been resorbed.

Sulfides consist of pyrrhotite, exsolved pentlandite, and chalcopyrite in pelitic hornfels and chalcopyrite with exsolved cubanite in calc-silicate pods. Minor ilmenite and magnetite is present in the sulfides. Alteration consists of uralitization of pyroxenes and sericitic and kaolinitic alteration of plagioclase. Quartz, calcite, apophyllite, anhydrite, fluorite, heulandite, laumontite, and prehnite are gangue minerals. This emplacement occurred after the main metamorphic event and formed by hydrothermal replacement.

Based on the primary mineral assemblages present, the rocks fall in the pyroxene hornfels facies. The presence of plagioclase and wollastonite in the calc-silicate pods give a minimum temperature of 600 degrees Celsius at 2 kilobars pressure, and a mole fraction of CO_2 in the vapor phase less than 0.25. An increase of albite in plagioclase can lower the temperature of the reaction forming plagioclase and wollastonite, and could cause the plagioclase and wollastonite to disappear with quartz and calcite stable.

From the presence of laumontite, an upper limit of 350 degrees Celsius at 2 kilobars pressure can be given for the sulfides emplaced hydrothermally. A bottom temperature ranging from 250 to 300 degrees Celsius can be given by the presence of exsolved cubanite in chalcopyrite.

TABLE OF CONTENTS

ILLUSTRATIONS

Figure

TABLES

Table

PLATES

Plate

INTRODUCTION

The Minnamax Copper-Nickel Deposit, being investigated underground by Amax Exploration, Inc., lies five miles south of Babbitt, St. Louis County, Minnesota, at the eastern end of the Mesabi Range (Figures 1 and 2). The deposit formed in the contact zone between the Middle Precambrian Virginia Formation and the Late Precambrian Duluth Complex. This thesis concerns the contact metamorphism of the Virginia Formation and particularly the nature and origin of calc-silicate pods therein. It is based on mapping and sampling of the underground workings at Minnamax.

At the Minnamax Deposit, the Virginia Formation has been metamorphosed to conditions of the pyroxene hornfels facies, was folded and faulted by, and occurs as xenoliths in the Duluth Complex.

At this locality, the Virginia Formation is primarily a pelitic hornfels that is dark gray and fine-grained. Areas rich in calc-silicate pods occur in the pelitic hornfels. These are generally light gray, fine- to coarse-grained, range in length from 4 inches to 8 feet, range in width from 1 inch to 1 foot and are ellipsoidal to spherical (Figure 3).

Metadiabase dikes and sills intrude the Virginia Formation (Figure 4). These dikes and sills are similar in appearance to the pelitic hornfels. They are younger than

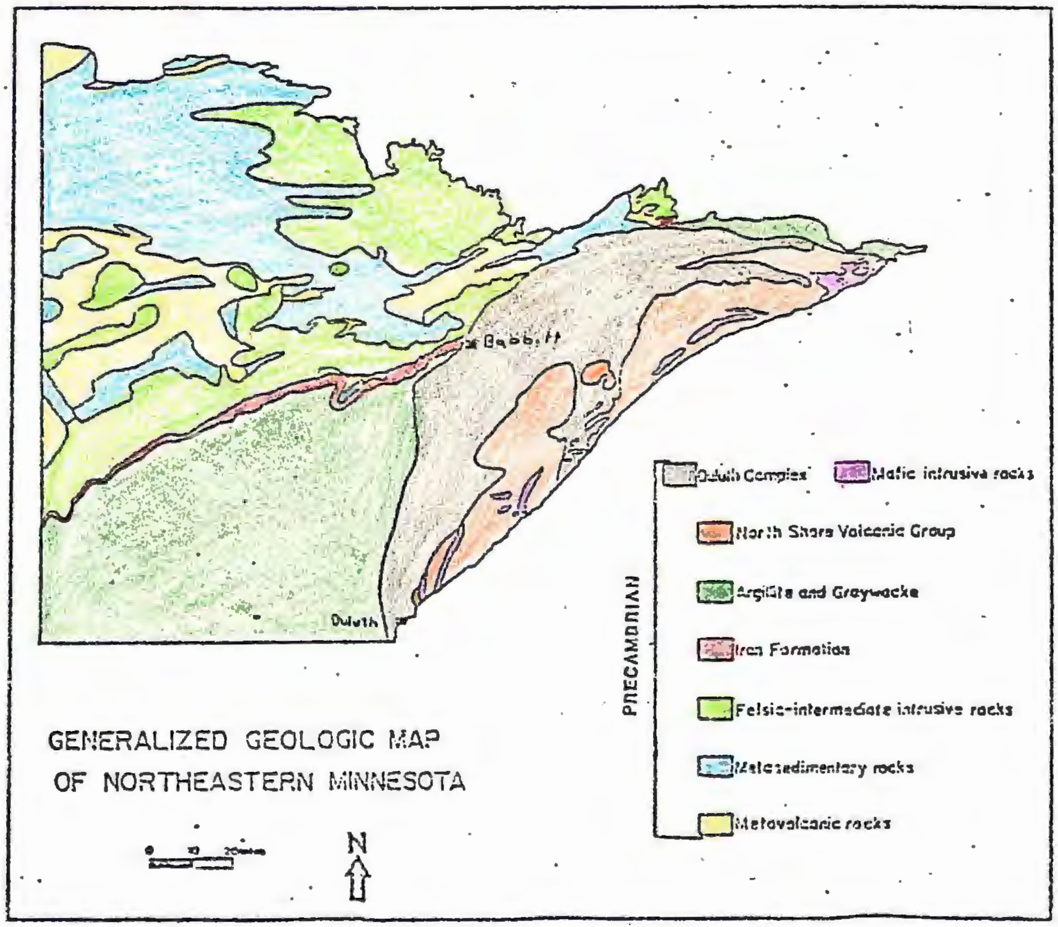

Figure 1. Generalized Geologic Map of Northeastern Minnesota showing major lithologies (After Sims, 1972. al., 1972).

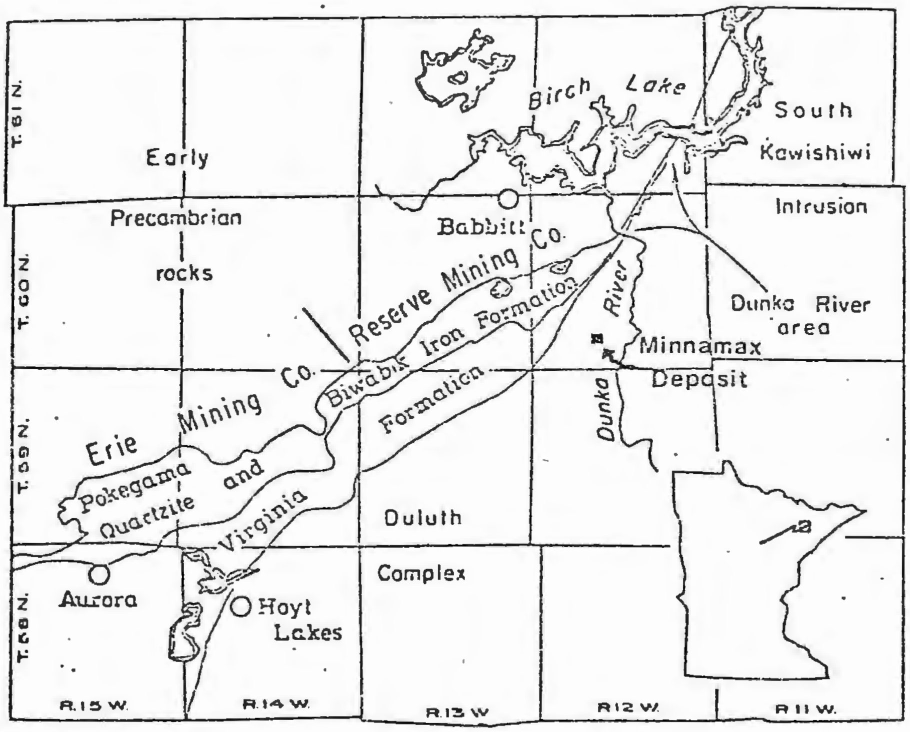

Figure 2. Generalized geologic map of Eastern Mesabi Range (After Bonnichsen, 1968, 1975).

Figure 3. Virginia Formation in the Minnamax Deposit. Dark gray, fine-grained, massive pelitic hornfels surrounds calc-silicate pods. Three types of pods are present: (a) homogenous, (b) layered, and (c) concentric

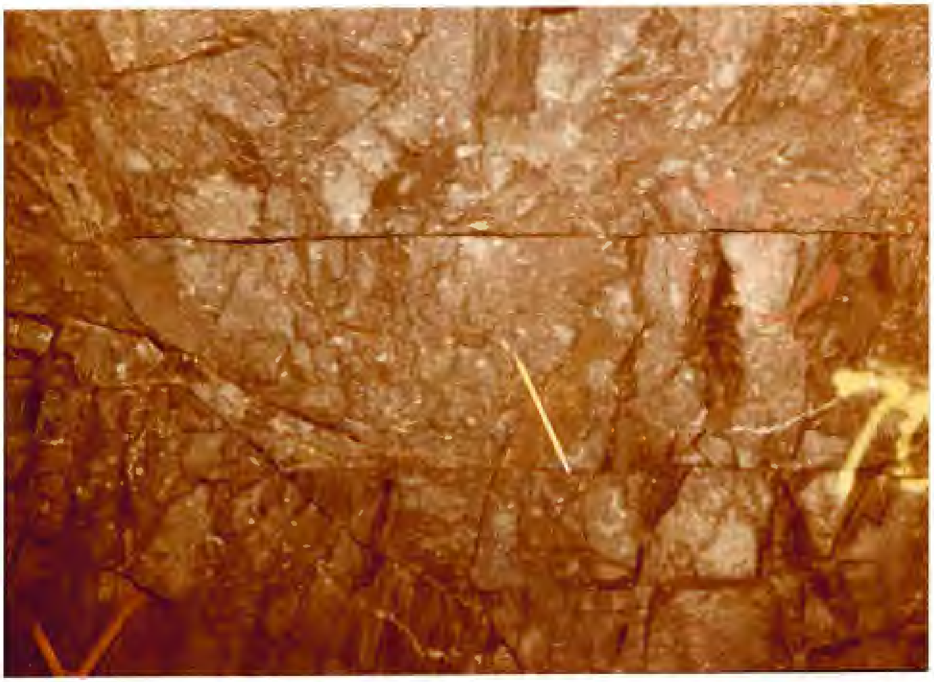

Figure 4. Metadiabase dike showing plagioclase porphyroblasts up to 1 cm across in a fine-grained dark gray matrix.

the Virginia Formation and, by virtue of their metamorphism, are older than the Duluth Complex.

Sulfides occur in all lithologies but are particularly concentrated near the contact between the Virginia Formation and the Duluth Complex. Hydrothermal alteration has occurred where the sulfides were emplaced, thus the sulfides are believed to have been emplaced after the main metamorphic event.

Acknowledgments

The writer wishes to thank Amax Exploration, Inc., and Mr. Jack Malcolm, Manager of the Minnamax Deposit, for allowing complete access to the deposit and its facilities and for financial assistance. The tremendous help given by Stanley Watowich, Tony Nemgar, and James Kulas while at Minnamax is greatly appreciated.

A special thanks goes to Dr. James A. Grant, University of Minnesota-Duluth, who suggested this thesis and gave many unselfish hours serving as thesis advisor.

The helpful criticism and guidance given by Dr. Ralph W. Marsden and James L. Welsh, University of Minnesota-Duluth is also appreciated.

Thanks are due to fellow graduate student William F. Matlack who helped me with several areas of the thesis.

REGIONAL GEOLOGY

General Statement

Rocks ranging in age from Lower to Upper Precambrian are found in Northeastern Minnesota. Major unconformities exist between each age group (Figure 1).

Lower Precambrian Rocks

Lower Precambrian rocks of the Vermilion District are located north of the Mesabi Range and comprise the southern edge of the Superior Province. They consist of metavolcanic rocks, metagraywackes, and granitic rocks. In general, they form alternating belts of granite and greenstone.

The Ely Greenstone consists of mafic to felsic volcanic rocks, commonly pillowed, that have been metamorphosed to greenschist facies. Overlying the Ely Greenstone are dacitic pyroclastics and volcanogenic sediments, consisting of interbedded graywackes and mudstones. These comprise the Knife Lake Group in the east and the Lake Vermilion Formation in the west. Locally an iron formation, the Soudan Iron Formation, occurs between the Ely Greenstone and the volcaniclastic rocks. The Newton Lake Formation, a mafic volcanic succession, conformably overlies part of the Knife Lake Group. Locally mafic to ultramafic sills occur in the Newton Lake Formation (Sims and Morey, 1972).

Three major granitic batholiths intrude the metavolcanic-metasedimentary sequence. The Giants Range batholith intrudes the southern edge of the district, the Vermilion batholith intrudes in the north, and the Saganaga batholith intrudes in the eastern edge of the district. These were emplaced during the Algoman Orogeny, which has been dated at 2,700 m.y. (Goldich, 1972).

Middle Precambrian Rocks

Middle Precambrian rocks, assigned to the Animikie Group, are found southeast of the Vermilion District. The Animikie Group is a sedimentary sequence varying in thickness from 100 feet in the north to 15,000 feet in the south and forming a northeast trending, southeast dipping homocline (Sims and Morey, 1972).

The oldest rock of the Animikie Group is the Pokegema Quartzite. It is composed of quartzites, argillites, argillaceous siltstones, and conglomerates that thicken to the south from 1 inch to 20 feet. (Morey, 1972).

The Biwabik Iron Formation, on the Mesabi Range, and the Gunflint Iron Formation, on the Gunflint Range, consist primarily of ferruginous chert, termed taconite. The Biwabik Iron Formation is as much as 350 feet thick in the central Mesabi Range but thins both east and west to 200 feet (White, 1954). The iron formation can be classified on the basis of texture as coarse-grained "granular" types and fine-grained "slaty" types (Sims and Morey, 1972).

The Virginia Formation, on the Mesabi Range, and the Rove Formation, on the Gunflint Range, lie conformably on top of the iron formation. They consist of a succession of dark gray mudstones, siltstones, and graywackes with lesser quartzite, limestone, and iron formation. Total thicknesses are unknown but it is approximated to be several thousand feet. The lower several hundred feet is carbonaceous (Sims and Morey, 1972).

Northwest-trending mafic dikes, cutting Lower Precambrian rocks but not Middle Precambrian rocks, provide a lower limit of 2,200 m.y. on the age of the Animikie strata (Hanson and Malhotra, 1971). An upper limit of 1,395 m.y. has been given on diabase dikes that cut the biwabik Iron Formation near Nashwauk, Minnesota (Sims and Morey, 1972).

The Penokean Orogeny, that occurred approximately 1,850 m.y. ago, deformed the sediments, with the most intense deformation occurring to the south. In addition, the Penokean Orogeny metamorphosed the sediments, primarily to greenschist facies (Sims and Morey, 1972).

Upper Precambrian Rocks

Keweenawan rocks, formed approximately 1,100 m.y. ago, extend from Duluth, Minnesota to Pigeon River in extreme northeastern Minnesota. They consist of lava flows, assigned to the North Shore Volcanic Group, which are intruded by the Duluth Complex, the Beaver Bay Complex, diabase sills at Duluth, the Hoveland and Reservation River diabase complexes, and the Logan intrusives.

The North Shore Volcanic Group, unconformable on the Lower and Middle Precambrian rocks, consist of lava flows that are primarily basaltic in composition but include intermediate to felsic volcanic rocks. They have the shape of a half-filled dish 150 miles long that is tilted gently to the southeast, toward the Lake Superior Syncline. The lava flows occupy two separate basins which are intruded by the Duluth Complex to the west and separated by the Beaver Bay Complex. The southwestern complex is about 23,000 feet thick and the northeastern complex is about 21,5000 feet thick. The older lavas at Nopeming, and in the Pigeon River-Grand Portage area, overlie quartzite and appear to have been extruded in a subaqueous environment. Younger lavas are entirely subaerial with vesicular upper portions. The lava flows were buried in Late Keweenawan time, subjected to greenschist and zeolite-facies metamorphism, tilted, and eroded (Green, 1972).

The Duluth Complex was emplaced along the major unconformity between Lower and Middle Precambrian rocks and Keweenawan lava flows. The Complex is about 150 miles long and forms and arcuate body with the oldest rocks in the Complex occurring in northern Cook County.

The Duluth Complex is a composite layered intrusion consisting dominately of older anorthosite and younger troctolite with minor granitic bodies. Local areas contain oxide-rich gabbro or two-pyroxene gabbros with evidence of crystal settling (Sims and Morey, 1972).

The Beaver Bay Complex is dominately an ophitic olivine gabbro with minor anorthosite. It connects with the Duluth Complex to the northeast but its relations with surrounding rocks are obscured by glacial drift (Green, 1972).

The Logan intrusions consist mainly of diabase, porphritic diabase, and gabbro, with lesser basalt, granophyre, and intermediate rocks. These occur as sills and dikes (Craddock, 1972).

The Pigeon River intrusions consist of equigranular olivine diabase and are primarily dikes. These dikes are younger than the Logan intrusions (Craddock, 1972).

Early and Middle Keweenawan time probably was a period of crustal extension, leading to vertical fracturing, rising magmas, and downwarping of the crust. The igneous activity and subsidence at this time may represent an aborted continental rift (Craddock, 1972).

Cretaceous and Quaternary

Rocks of Cretaceous age, primarily iron-ore conglomerates, shales and sandstones are found unconformably on top of Middle Precambrian rocks of the western part of the Mesabi Range (Austin, 1972). Their extent may have been reduced due to erosion.

Several periods of Pleistocene glaciation occurred in Northeastern Minnesota, the most recent being of Wisconsin age. The thickness of the drift is less than 100 feet and obscures outcrops and contacts of the underlying rocks. (Wright, 1972).

GEOLOGY OF THE BABBITT AREA

General Statement

The oldest rock in the area is the Giants Range batholith of Archean age. It disappears beneath the Duluth Complex to the east.

The Animikie Group lies unconformably above the Giants Range batholith. The Pokegema Quartzite is very thin and locally missing in the eastern Mesabi Range. The Biwabik Iron Formation is conformably overlain by the Virginia Formation and metadiabase dikes and sills intrude both formations. The regional dip of these rocks is 10 degrees to the southeast. The Duluth Complex intrudes the Biwabik Iron Formation and Virginia Formation from the southeast. It truncates both formations (Figure 2) and has caused contact metamorphism to pyroxene-hornfels-facies.

Biwabik Iron Formation

White (1954), Gunderson and Schwartz (1962), French (1964), Pfleider (1968), Bonnichsen (1968, 1975) and Renner (1969) described the Biwabik Iron Formation in the eastern Mesabi Range as a ferruginous chert 0 to 350 feet thick. It is subdivided into four stratigraphic units, from oldest to youngest: the Lower Cherty, Lower Slaty, Upper Cherty, and Upper Slaty Members (Wolff, 1917).

The rocks in general have a granular texture due to the coarsened fabric from recrystallization. They consist of four main mineral groups; quartz and chert, iron-rich amphiboles, iron-bearing carbonates, and iron oxides and hydroxides. The "slaty" members are fine-grained, laminated, and contain little iron oxide, such as magnetite. The "cherty" members are magnetite rich and contain abundant cherty taconite.

Northeast of Hoyt Lakes, Minnesota (T.59N., R.14W.) the Biwabik Iron Formation shows a transition from relatively unmetamorphosed to metamorphosed taconite. French (1964) delineated four mineralogical zones. Zone (1) occurs up to 10 miles from the Duluth Complex and is dominated by fine-grained unaltered taconite consisting of quartz, iron oxides, iron carbonates, such as siderite, and iron phyllosilicates, such as chamosite, greenalite, minnesotaite, and stilpnomelane. Zone (2) occurs 10 to 2.6 miles from the Duluth Complex and is rather similar to Zone (1) but secondary ankerite has developed. Zone (3), 2.6 to 1.7 miles from the Complex, is characterized by the appearance of cummingtonite and the disappearance of ankerite, siderite, and iron phyllosilicates. Zone (4), within 1.7 miles of the Complex, consists of highly metamorphosed taconite with iron-bearing pyroxenes.

Other mineralogical changes as one approaches the Duluth Complex include the reduction of hematite to magnetite, appearance of ferroan calcite with cummingtonite, conversion of pyrite to pyrrhotite, development of fayalite, and of crystalline graphite from organic matter. The metamorphism is primarily isochemical, except for certain dehydration and decarbonation reactions (Bonnichsen, 1968, 1975).

The Upper Slaty Member in the eastern Mesabi has up to 10 feet of calcareous rocks at the top, which grade into the Virginia Formation. Near the Duluth Complex, these are metamorphosed to marble and calc-silicate hornfels, the latter bearing diopside, idocrase, wollastonite and grossularite (Gunderson and Schwartz, 1962; Bonnichsen, 1968, 1975).

Virginia Formation

Although there is little outcrop of the Virginia Formation, work has been done by White (1954), Gunderson and Schwartz (1962), Bonnichsen (1968, 1975), Pfleider (1968), Handyman (1969), and Renner (1969). The descriptions come primarily from drill core and from exposures in open pit mines on the Mesabi Range. They found the Virginia Formation to be fine-grained, thinly to thickly bedded, dark gray argillite, argillaceous siltstone, and graywacke. It is inferred to be 3000 feet thick.

Iron-rich units near the base of the formation were reported by Pfleider (1968). These units consist of interbedded argillite and gray-brown chert and siderite, are nonmagnetic and laminated. These could be related to the top of the Biwabik Iron Formation, as the contact between the two formations is gradational.

The lower several hundred feet of the Virginia Formation are characterized by calcareous and dolomitic concretions of varying sizes and shapes. Some of these concretions show a well-developed cone-in-cone structure. In addition, carbonaceous layers are also present (White, 1954; Pfleider, 1968). The remainder of this lower unit is composed of dark gray silty argillite and black carbonaceous argillite. These argillites grade upward into fine- to medium-grained graywackes, with beds ranging in thickness from 6 inches to 5 feet (Pfleider, 1968).

Towards the Duluth Complex the Virginia Formation is progressively metamorphosed attaining the pyroxene-hornfels facies. It is very fine-grained, dark gray, and is composed of plagioclase, orthoclase, cordierite, biotite, orthopyroxene, and quartz (Gunderson and Schwartz, 1962; Bonnichsen, 1968, 1975; Handyman, 1969).

Diabase Dikes and Sills

White (1954) and Gunderson and Schwartz (1962) report metadiabase dikes and sills in the eastern Mesabi Range as being dark gray, fine-grained, granofelsic rocks difficult to distinguish from metamorphosed Virginia Formation, although some did show poikiloblasts of plagioclase. The minerals present are labradorite, augite, ilmenite, and lesser orthopyroxene. These minerals show metamorphic effects such as corroded mineral boundaries and resorbed labradorite poikiloblasts.

The metadiabase did not show evidence of contact metamorphism of the surrounding rock, but was thought to have been itself metamorphosed by the Duluth Complex (Gunderson and Schwartz, 1962).

Duluth Complex

Anderson (1954), Gunderson and Schwartz (1962), Taylor (1964), Bonnichsen (1968, 1975), Handyman (1969), and Weiblen and Morey (1977) worked on the Duluth Complex in the area of the eastern Mesabi Range. They found the Duluth Complex to be at least 15,000 feet thick and to be formed from multiple intrusions of mafic magma. An older anorthositic gabbro occurs at the upper part of the complex and a younger layered series of troctolite, olivine gabbro, feldspathic gabbro, and syenogabbro occur in the lower part of the complex.

The anorthositic gabbro is coarse-grained and contains 75-90 percent labradorite, with some bytownite. Augite, olivine, and magnetite-ilmenite constitute the remainder of this unit. The layered series is medium-grained and has olivine as an important constituent along with labradorite, titanaugite, orthopyroxene, and magnetite-ilmenite in varying proportions. The banding shows effects of crystal accumulates from gravity settling and are consistent over large areas (Taylor, 1964).

Sulfide mineralization, consisting of pyrrhotite, chalcopyrite, cubanite, and pentlandite, occurs locally in the lower several hundred feet of the Complex (Hardyman, 1969; Bonnichsen, 1977). Concentrations of sulfides occur at the contact with the Virginia Formation. The sulfides in the

Complex are interstitial, appear to be late syngenetic, and to have specific structural and lithologic controls, such as being concentrated in basins at the base of the Complex (Bonnichsen, 1972).

GEOLOGY OF MINNAMAX

At Minnamax, the metamorphosed Virginia Formation and the metadiabase dikes and sills that intrude it, form the country rock (locally termed the footwall) that was intruded by the Duluth Complex. The regional dip of the Virginia Formation is 5 degrees southeast, steepening to 30 to 50 degrees at the contact with the Duluth Complex (Watowich, 1978). The contact zone is exposed on the 1,700 foot level in four underground drifts totalling approximately 3,800 feet in length.

The Virginia Formation consists of a fine-grained, dark gray hornfels (Figure 3). Relict bedding is found very locally and cannot be followed for more than 3 to 4 feet. The bedding shows complex folding (Figure 5), presumably caused by intrusion of the Duluth Complex.

Calc-silicate pods are present locally in the Virginia Formation. These are light gray, fine- to coarse-grained, spherical to ellipsoidal granofelsic bodies ranging in length from 4 inches to 8 feet and width from 1 inch to 1 foot. They may be classified into three types according to their macroscopic structures: (1) homogenous types with no apparent mineral layering, (2) layered types with well-developed layers up to one-half inch in width, and (3) concentric types with mineral zones that follow the shape of the pod (Figure 3).

Dark gray, fine-grained granofelsic "reaction" rims enclose the calc-silicate pods (Figure 6). These "reaction" rims extend 1 to 3 inches into the pelitic hornfels and follow the shape of the enclosed calc-silicate pod. Mineral zones and layers and fractures abut against these "reaction" rims.

Pre-Complex metadiabase dikes intrude the Virginia Formation. They are dark gray, fine-grained granofelsic rocks that are extremely difficult to distinguish from pelitic hornfels except where relict plagioclase phenocrysts, that are up to 1.5 cm in length, are found (Figure 4).

The Duluth Complex has an irregular contact with the Virginia Formation, which also occurs as xenoliths in the Complex. The rocks of the Complex are dark gray, coarse-grained troctolitic rocks with cumulate textures. They consist of an earlier picrite to olivine gabbro that lacks sulfide mineralization and a later troctolite that has interstitial sulfide mineralization (Figure 7). This later phase is noritic at its base. The primary mineralogy of the Duluth Complex in the Minnamax Deposit consists of labradorite, olivine, augite, minor orthopyroxene, magnetite, and ilmenite (Matlack, personal communication).

Granophyric bodies are present locally in the Virginia Formation. They are light gray, coarse-grained and irregular

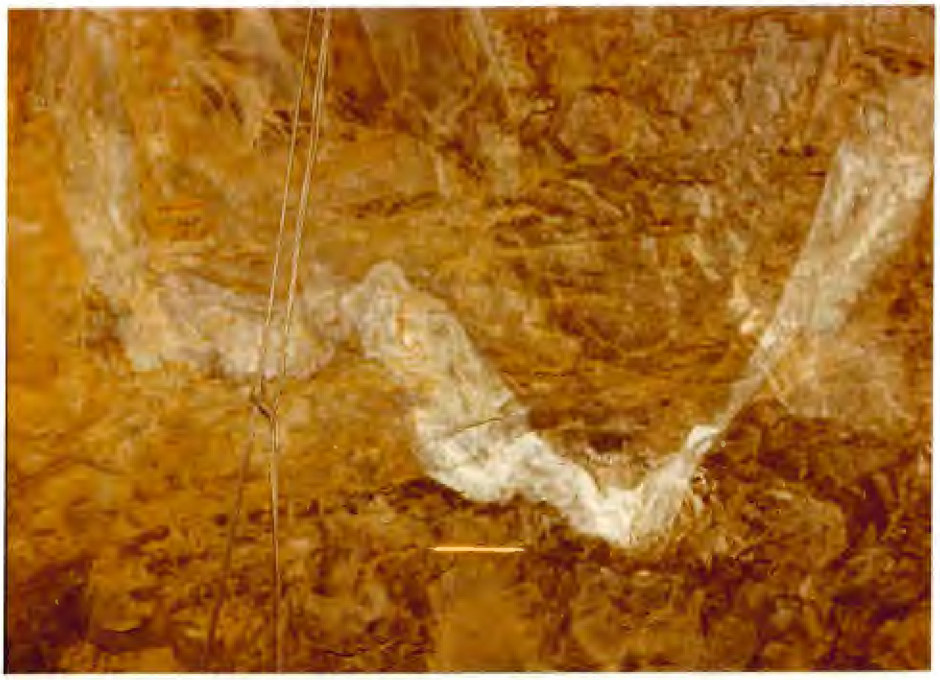

Figure 5. Deformation of Virginia Formation. Contorted relict bedding and calc-silicate pods are evident.

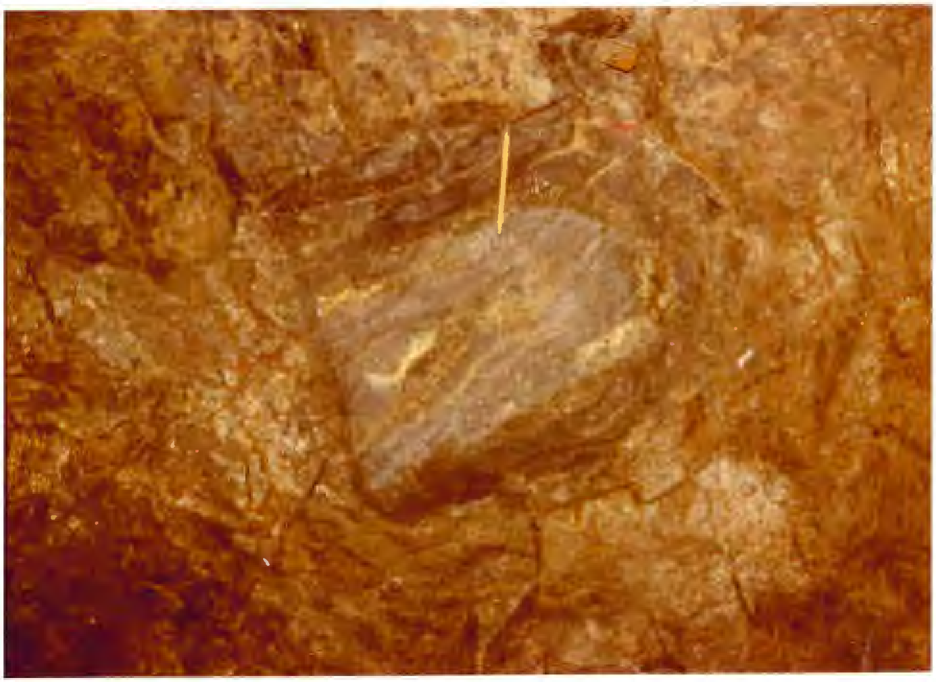

Figure 6. Dark gray "reaction" rim 2 inches across surrounding a calc-silicate pod. Note sulfide mineralization in the pod.

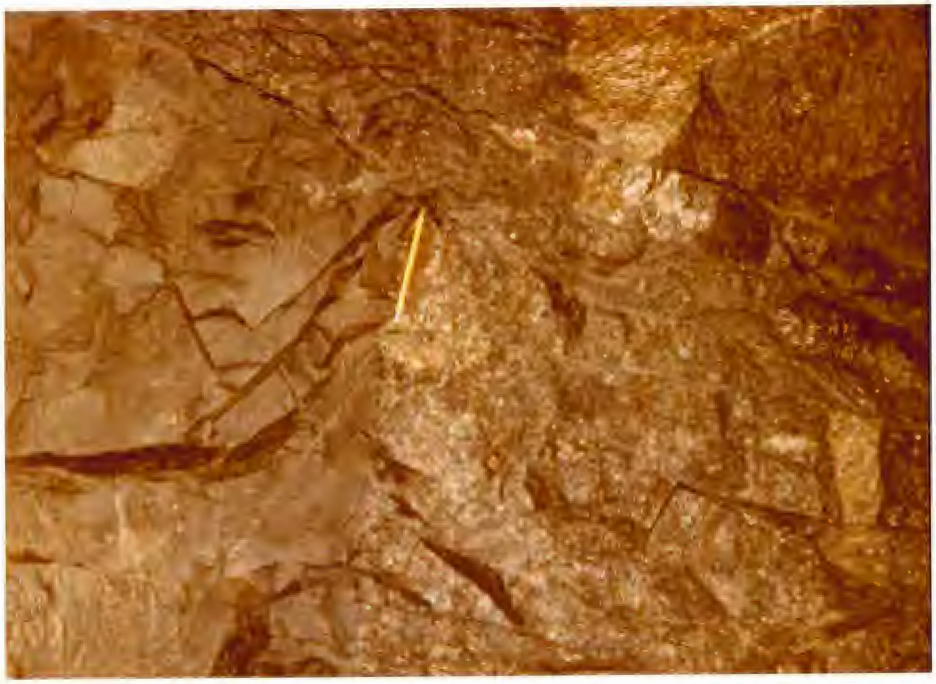

Figure 7. Duluth Complex in the Minnamax Deposit. To the left is the earlier unmineralized troctolitic phase and to the right is the later mineralized troctolitic phase.

in shape, ranging in thickness from 1 to 2 feet. They are composed of plagioclase, potassium feldspar, quartz, and biotite (Matlack, personal communication).

Sulfide mineralization of magmatic origin is concentrated near the contact between the Virginia Formation and the Duluth Complex. These sulfides are disseminated in the Duluth Complex, except in basins near the contact with the Virginia Formation. Sulfides are massive replacement deposits in the Virginia Formation and are absent in metadiabase dikes, except along fractures. Later hydrothermal remobilization of sulfides caused mineralization along faults and fractures in the Virginia Formation and in calc-silicate pods. Pyrrhotite, chalcopyrite, cubanite, and pentlandite constitute the major sulfides present. Chalcocite and bornite are found locally in faults in the Virginia Formation.

STATEMENT OF THE PROBLEM

The purpose of this thesis is to describe the petrography of the country rocks at Minnamax, to interpret their origins and metamorphism, and to study the nature and origin of the mineralization associated with these rocks, Particular attention is paid to the calc-silicate pods in the Virginia Formation.

Related Work On Calcareous Concretions

The vast majority of work on calcareous concretions in the Animikie Group has been in the Thomson Formation, the stratigraphic equivalent of the Virginia Formation in east-central Minnesota. The calcareous concretions are analogous to the calc-silicate pods in the Minnamax Deposit.

Schwartz (1942) and Weiblen (1964) studied concretions in east-central Minnesota. They found the concretions to be composed primarily of quartz and calcite but, near the McGrath Gneiss, concretions with a calcite-epidote core and hornblende-garnet border were reported (Weiblen, 1964).

Two types of concretions were reported: (a) those in coarse graywacke showing bedding continuous with the surrounding rock and, (b) those in fine-grained graywacke-slate which shows two structurally distinct zones, an inner bedded slaty material that is discordant with, and surrounded by, an outer zone with cone-in-cone structure of quartz and calcite (Weiblen, 1964).

Schwartz (1942) noted that the concretions are elongate in the plane of cleavage. Most were found to be flattened ellipsoids with axial ratios of 3:6:8 that ranged in length from 1 inch to 3 feet.

These concretions are surrounded by rock that is poor in lime and are believed to have formed by diagenetic concentration of lime by ground water (Schwartz, 1942).

White (1954), Bonnichsen (1968, 1975), and Pfleider (1968) noted concretions in the Virginia Formation that are also composed of calcite and quartz and, where metamorphosed, contain garnet, wollastonite, and idocrase. Although the origin of the majority of these concretions was thought to be similar to those in the Thomson Formation, White (1954) hypothesized that some of these bodies may be related to the limestone at the top of the Biwabik Iron Formation.

Approaches Used

A total of 12 days was spent at the Minnamax Deposit. Seven days were spent underground collecting samples and mapping 450 feet of drift, at a scale of 1 inch to 10 feet. In addition drill core was studied, of which 10 feet was sampled, to augment the underground sampling.

130 thin sections and five polished sections were made for petrographic study. All rocks were stained for calcium, using Amarand, and for potassium, using sodium cobaltnitrate.

MINERALOGY OF THE COUNTRY ROCKS

General Statement

The country rocks in the Minnamax Deposit, pelitic hornfels, calc-silicate pods, and metadiabase dikes, show effects of contact metamorphism from intrusion of the Duluth Complex. Later sulfide mineralization, and associated development of gangue minerals, has altered the primary mineralogy.

Pelitic Hornfels

The pelitic hornfels is dark gray, fine- to medium-grained (0.5 - 2 mm), equigranular, and granoblastic. Poorly twinned plagioclase (40 - 60 percent), hypersthene (15 - 35 percent), and cordierite (10 - 20 percent) constitute the primary mineralogy (Figure 8). Subpoikiloblastic biotite

(0 - 15 percent), granoblastic orthoclase (0 - 30 percent), and interstitial graphite (0 - 30 percent) are found locally (Figures 9 and 10). The biotite was concentrated along fault zones, with some showing foliation (Figure 11). Minor amounts of apatite occur as inclusions in plagioclase.

"Reaction" Rims

Occurring between the pelitic hornfels and calc-silicate pods are black, granoblastic "reaction" rims, finer-grained than the pelitic hornfels. Untwinned to poorly twinned plagioclase (50 - 70 percent), hypersthene (10 - 20 percent), and poikiloblastic clinopyroxene (10 - 20 percent) make-up the mineral assemblages present in the "reaction" rims (Figures 12 and 13).

Calc-Silicate Pods

The calc-silicate pods in the Virginia Formation are light gray to pink, fine- to coarse-grained, granoblastic, and show local development of poikiloblastic minerals. There is a large variation in mineralogy in the pods (Tables 1 and 2). Of the minerals associated with high-grade metamorphism diopside is ubiquitous and wollastonite, plagioclase, grossular garnet, idocrase, and sphene are common.

Diopside (40 - 60 percent) forms pink to green anhedral grains 0.5 - 2 mm across, with moderate interference colors, a moderate positive 2V, moderate relief, and inclined extinction (Figure 14). It is concentrated at the rims of pods.

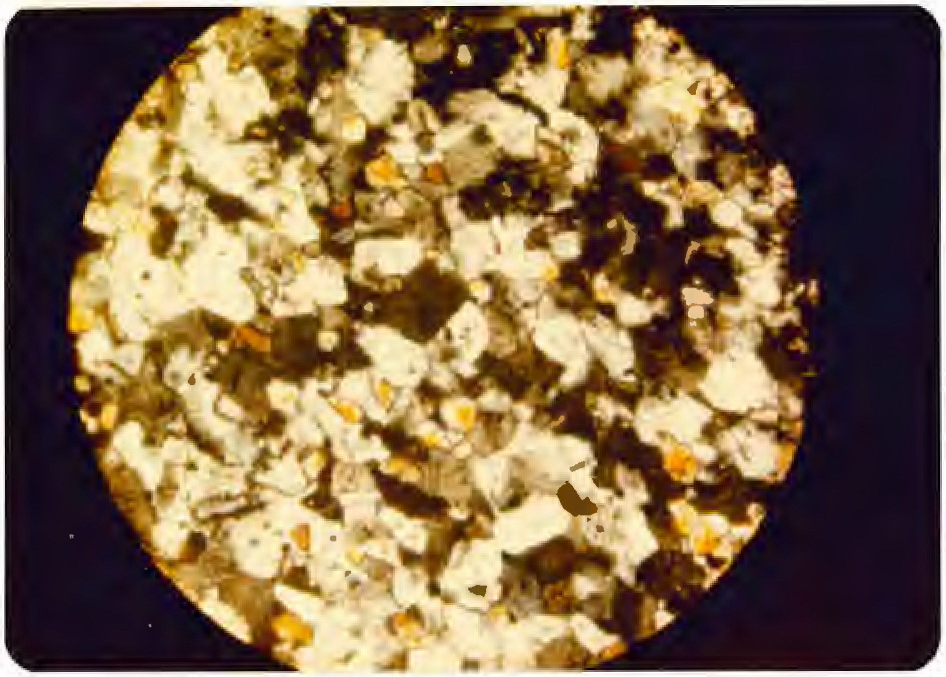

Figure 8. Cordierite with sector twinning, poorly twinned plagioclase and hypersthene in a pelitic hornfels. Sample A-112. Field of view is 2.5 mm in diameter. Crossed polars.

Figure 9. Granoblastic plagioclase, cordierite, and hypersthene. Biotite occurs as subpoikiloblastic grains. Minor ilmenite is opaque. Sample A-95. Field of view is 2.5 mm in diameter. Crossed polars.

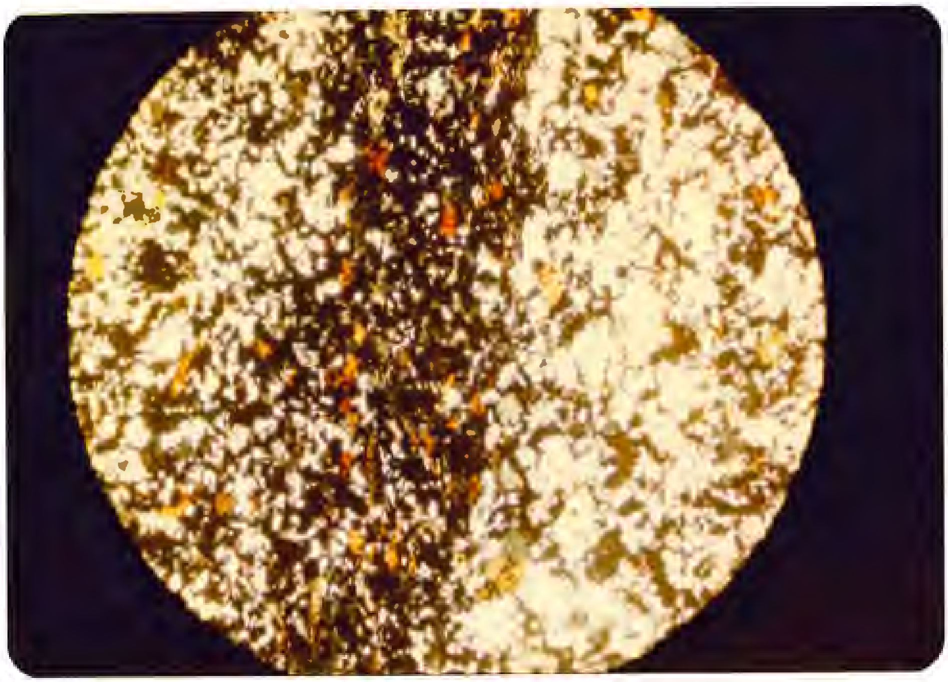

Figure 10. Graphite rich zone in pelititc hornfels. Biotite is associated with the graphite. Plagioclase, hypersthene, and cordierite comprise the remainder of the mineralogy. Sample A-26. Field of view is 2.5 mm in diameter. Uncrossed polars.

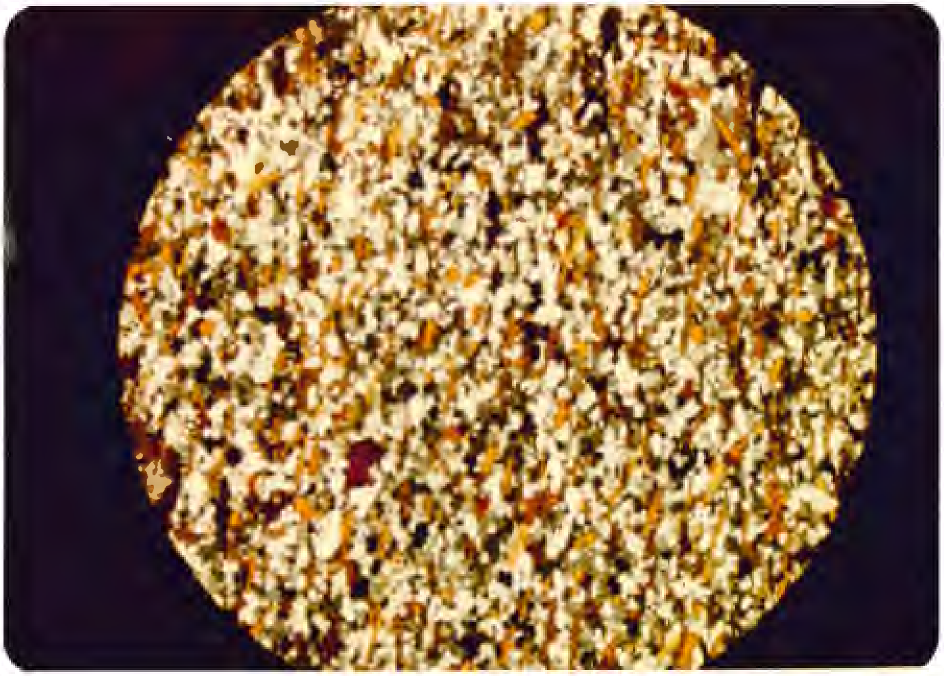

Figure 11. Biotite Schist. Foliated biotite with equigranular poorly-twinned plagioclase, orthoclase, and cordierite. Sample A-101. Field of view is 2.5 mm in diameter. Crossed polars.

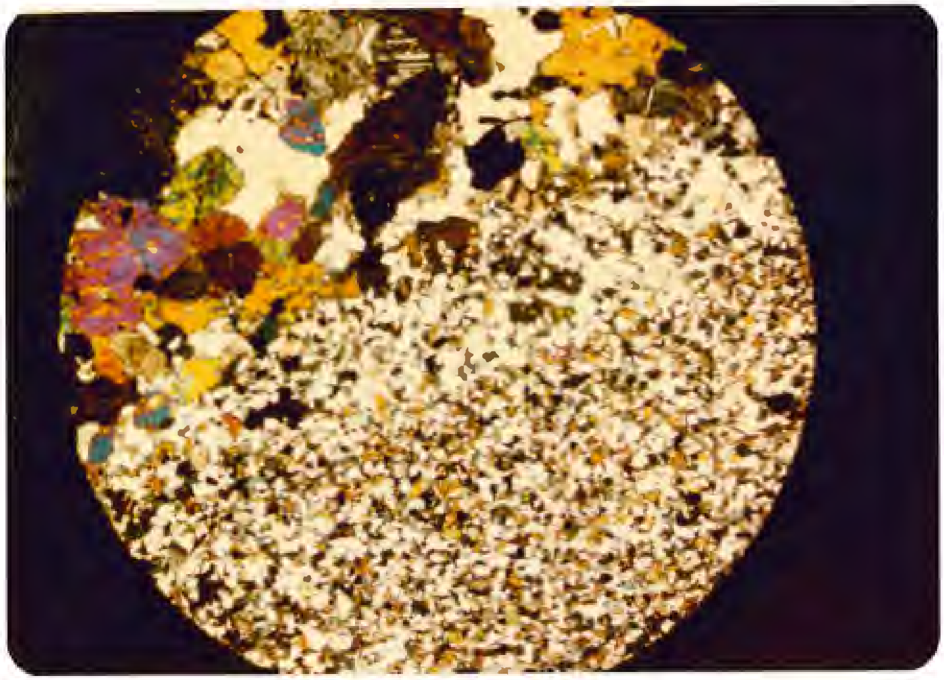

Figure 12. Contact between calc-silicate pod and fine-grained "reaction" rim. Diopside, twinned plagioclase, and poikiloblastic quartz make up the pod. Granoblastic untwinned plagioclase hypersthene and clinopyroxene make up the "reaction" rim. Sample A-100-1. Field of view is 6 mm across. Crossed polars.

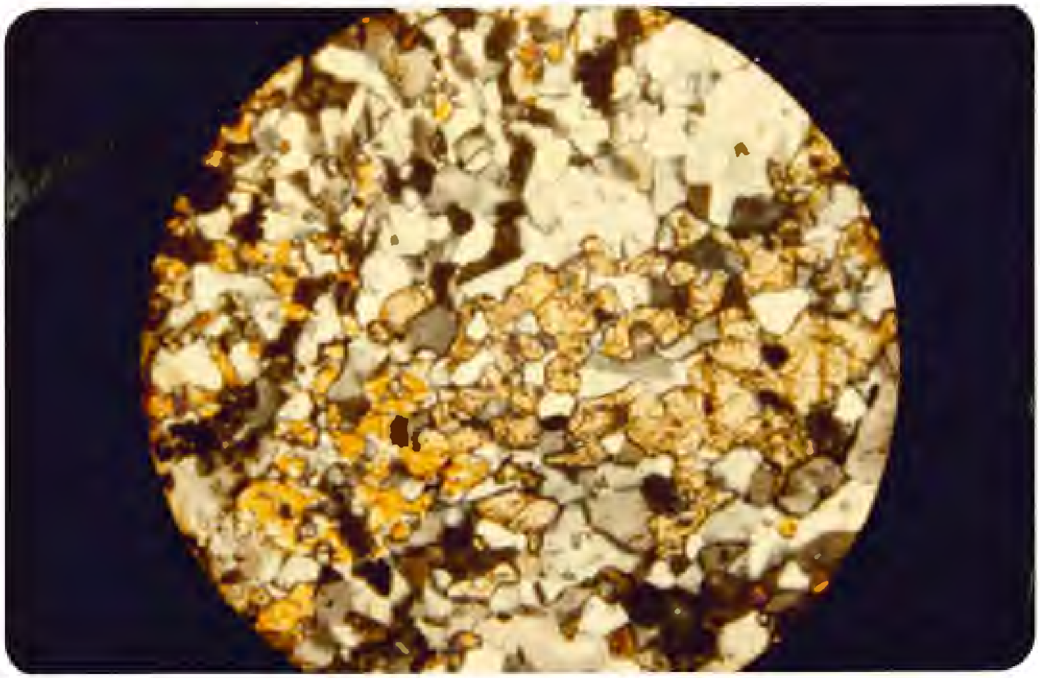

Figure 13. Poikiloblastic clinopyroxene around poorly twinned plagioclase in a "reaction" rim. Hypersthene occurs interstitially. Apatite inclusions occur in plagioclase. Sample A-85. Field of view is 2.5 mm. Crossed polars.

Wollastonite (0 - 50 percent) forms white anhedral grains to subhedral blades 0.5 - 4 mm in length, and rarely poikiloblasts up to 1 cm across (Figures 14 and 15). It is distinguishable from diopside by its lower relief and interference colors, from anorthite by its higher relief and interference colors, and from either by its negative 2V of approximately 40 degrees.

Anorthite (0 40 percent) forms white anhedral to subhedral grains 0.5 - 2 mm across that may show Carlsbad or albite twinning (Figure 14). It has low relief, low interference colors, and a high negative 2V. It is most abundant in the outer zones of the pods associated with diopside.

Grossular garnet (1 - 40 percent) forms light-green to white, anhedral to subhedral grains, 1 to 4 mm across (Figure 15).

Idocrase was found to be a major constituent in the core of one sample. It is light-green, anhedral and poikiloblastic around calcite (Figure 18). It has high relief and is uniaxial negative, with an anomalous Berlin Blue interference color.

Sphene (0 - 3 percent) forms brown anhedral grains that occur interstitially in pods (Figure 14). It is characterized by its very high relief, anomalous brown color under crossed polars and small positive 2V.

Mineral Assemblages Present In Calc-Silicate Pods

Sample Number	Zone 1	Zone 2	Zone 3
A-1	Cc+Gt+Id	Cc+Dp+Gt+Wo	Dp+Pl+Pr+Sp
A-43	An+Ap+Dp+Gt+Sp+Wo		
A-44	Cc+Dp+Gt+Sp+Wo		
A-49	Dp+Pl+Sp+Wo		
A-50	Dp+Q+Sp+Wo		Dp+Pl+Sp
A-52	Cc+Dp+Pl+Pr+Q+Sp+Wo		
A-54	An+Dp+Fl+Wo		
A-57	Cc+Dp+Gt+Hu+La+Q+Wo	Cc+Dp+Gt+Wo	Dp+Gt+Pl+Sp
A-60	An+Ap+Cc+Dp+Fl+Gt+Q+Wo		An+Ap+Dp+Pl+Q+Wo
A-62	An+Dp+Q+Sp+Wo		Dp+Pl+Q+Sp
A-64	An+Cc+Dp+Gt+Q+Wo		Ap+Dp+Fl+Q+Sp
A-67	Ap+Dp+Q+Wo		
A-69	Dp+Q+Sp+Wo		
A-70	Ap+Cc+Dp+Gt+Q+Sp		
A-71	Ap+Cc+Dp+Hu+La+Q		
A-72	Dp+Q+Sp+Wo		Dp+Pl+Q
A-76	An+Ap+Dp+Q+Wo		
A-78	Dp+Q+Sp+Wo		Dp+Pl+Sp
A-82	Dp+Q+Sp+Wo		Dp+Pl
A-83	Dp+Gt+Sp+Wo		
A-84	Dp+Gt+Q+Sp+Wo		Dp+Fl+Q
A-85	An+Dp+Q+Sp+Wo		Dp+Pl+Q
A-86	Dp+Q+Wo		Dp+Pl+Q
A-88	Ap+Dp+Fl+Gt+Q+Wo		
A-89	An+Dp+Q+Wo		Dp+Fl
A-92	Dp+Gt+Q+Sp		
A-93	Dp+Gt+Q+Sp		Dp+Pl+Pr
A-100	An+Dp+Pl+Sp+Wo		Dp+Pl
A-104	An+Cc+Dp+Q+Wo		Cc+Dp+Pl+Q+Wo
A-108	Cc+Dp+Q+Wo		Dp+Gt+Q+Wo
A-109	An+Dp+Gt+Wo		
A-110	An+Cc+Dp+Gt+Wo		Dp+Gt+Wo

Table 1. Primary and Secondary mineral assemblages present in calc-silicate pods. An-anhydrite, Ap-apophyllite, Cc-calcite, Dp-diopside, Fl-fluorite, Gt-grossularite, La-laumontite, Pl-plagioclase, Pr-prehnite, Q-quartz, Sp-sphene, Wo-wollastonite. Zones 1, 2, and 3 refer to the cores, intermediate zones, and outer zones, respectively.

Primary Mineral Assemblages In Calc-Silicate Pods

Sample Number	Zone 1	Zone 2	Zone 3
A-1	Cc+Gt+Id	Cc+Dp+Gt+Wo	Dp+Pl+Sp
A-43	Dp+Gt+Sp+Wo		
A-44	Dp+Gt+Sp+Wo		
A-49	Dp+Pl+Sp+Wo		
A-50	Dp+Sp+Wo		Dp+Pl+Sp
A-52	Dp+Pl+Sp+Wo		
A-54	Dp+Pl+Wo		
A-57	Dp+Gt+Wo	Dp+Gt+Wo	Dp+Gt+Pl+Sp
A-60	Dp+Gt+Wo		Dp+Pl+Wo
A-62	Dp+Sp+Wo		Dp+Pl+Sp
A-64	Dp+Gt+Wo		Dp+Pl+Sp
A-67	Dp+Wo		
A-69	Dp+Sp+Wo		
A-70	Dp+Gt+Sp		
A-72	Dp+Sp+Wo		Dp+Pl
A-76	Dp+Wo		
A-78	Dp+Sp+Wo		Dp+Pl+Sp
A-82	Dp+Sp+Wo		Dp+Pl
A-83	Dp+Gt+Sp+Wo		
A-84	Dp+Gt+Sp+Wo		Dp+Pl
A-85	Dp+Sp+Wo		Dp+Pl
A-86	Dp+Wo		Dp+Pl
A-88	Dp+Gt+Wo		
A-89	Dp+Wo		Dp+Pl
A-92	Dp+Gt+Sp		
A-93	Dp+Gt+Sp		Dp+Pl
A-100	Dp+Pl+Sp+Wo		Dp+Pl
A-104	Dp+Wo		Dp+Pl+Wo
A-108	Dp+Wo		Dp+Gt+Wo
A-109	Dp+Gt+Wo		
A-110	Dp+Gt+Wo		Dp+Gt+Wo

Table 2. Primary mineral assemblages present in calc-silicate pods. Cc-calcite, Dp-diopside, Gt-grossularite, Pl-plagioclase, Sp-sphene, Wo-wollastonite.
Zones 1, 2, and 3 refer to the cores, intermediate zones, and outer zones, respectively.

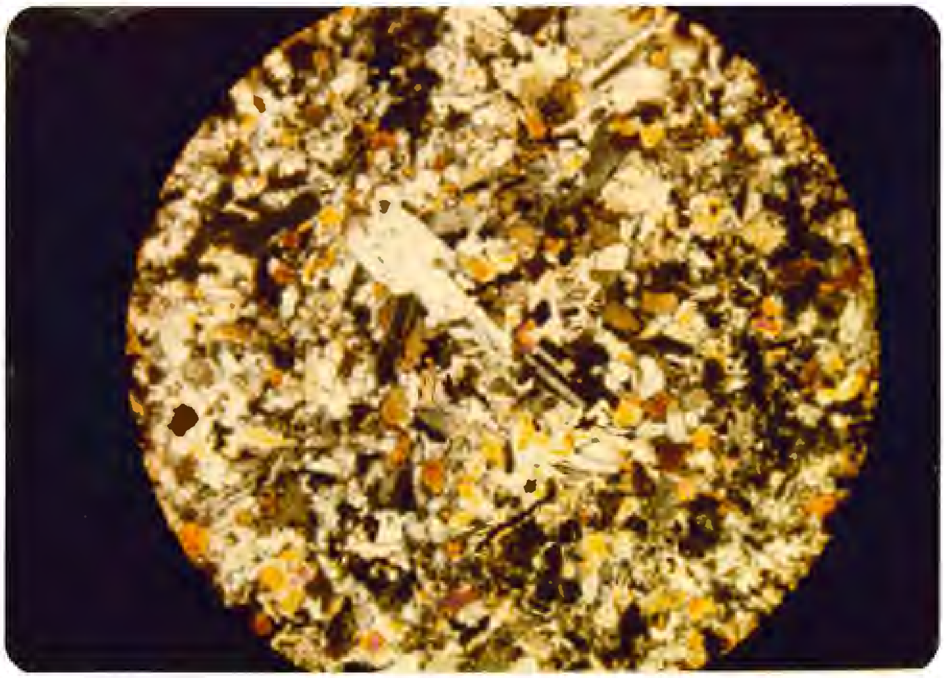

Figure 14. Granoblastic poorly twinned plagioclase, diopside, wollastonite, and sphene in a calc-silicate pod. Some wollastonite is poikiloblastic. Sample A-80. Field of view is 2.5 mm. Crossed polars.

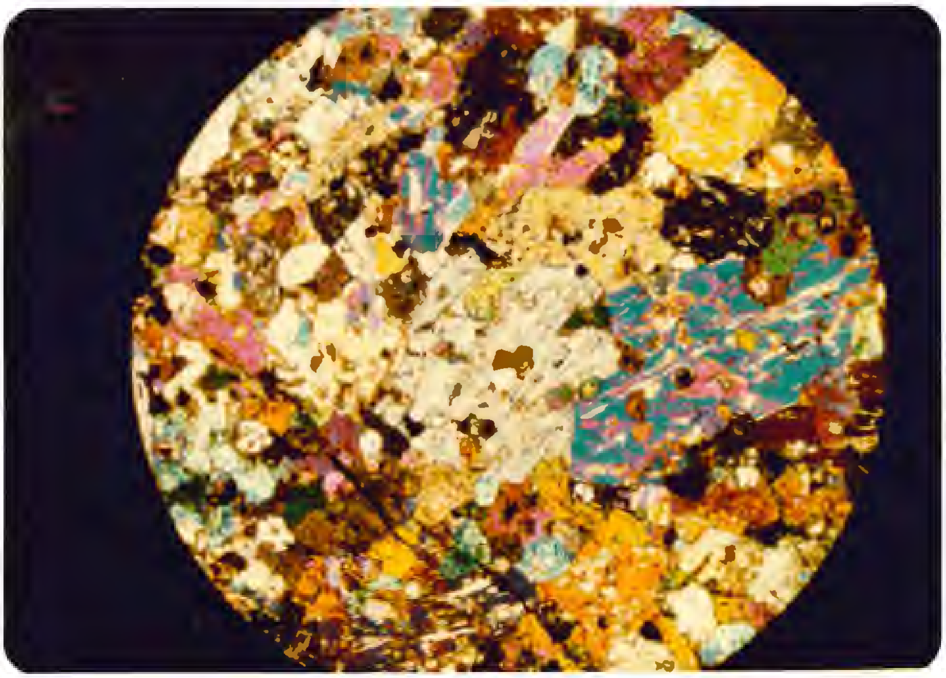

Figure 15. Poikiloblastic wollastonite in a calc-silicate pod. Diopside occurs interstitially and as inclusions in wollastonite. Sample A-100. Field of view is 2.5 mm. Crossed polars.

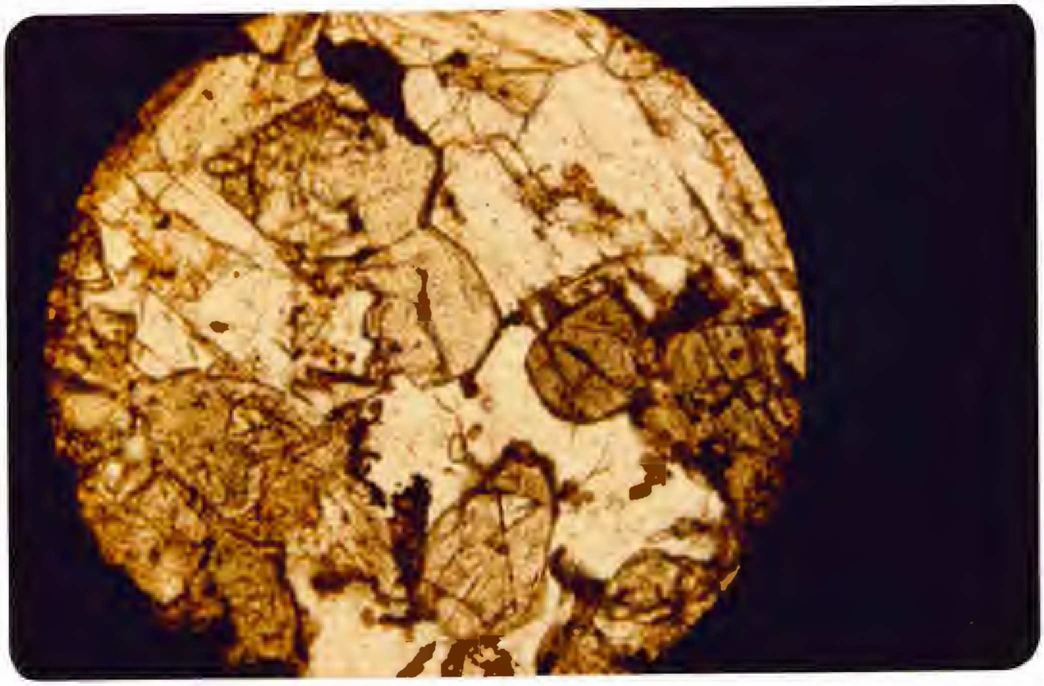

Figure 16. Subhedral garnet with wollastonite, diopside, and subpoikiloblastic quartz in a calc-silicate pod. Sample A-88. Field of view is 2.5 mm. Uncrossed polars.

Figure 17. From left to right (outer zone to core), diopside, altered anorthite (dark), diopside-anorthite, garnet (dark), diopside, garnet and wollastonite zones in a calc-silicate pod. Sample A-1. Field of view is 2.5 mm. Crossed polars.

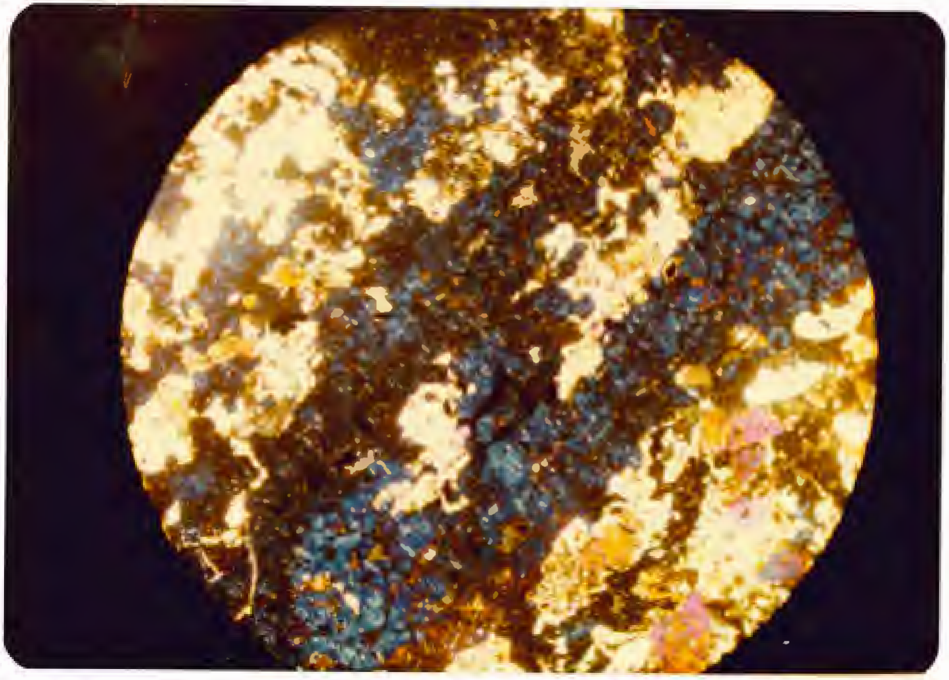

Figure 18. Poikiloblastic idocrase with inclusions of calcite in a calc-silicate pod. Diopside and wollastonite occur on the edge. Sample A-1. Field of view is 2.5 mm. Crossed polars.

Metadiabase

Metadiabase dikes are dark gray, fine- to medium-grained (0.5 - 3 mm), equigranular, and possess a relict ophitic texture (Figure 19). Cloudy white plagioclase relict phenocrysts, up to 1 cm in length, are locally to be found (Figures 4 and 20).

The primary mineralogy consists of labradorite (30 - 70 percent) that is commonly subhedral and lath-like with well developed albite twinning, hypersthene (10 - 15 percent), and augite (0 - 15 percent). Apatite (0 - 2 percent) forms subhedral to euhedral inclusions in labradorite. Ilmenite-magnetite was found in trace amounts and was interstitial.

Sulfides

Later sulfide emplacement, primarily by hydrothermal replacement, has occurred in the calc-silicate pods and surrounding "reaction" rims and pelitic hornfels. The metadiabase dikes are generally barren except along fractures. This sulfide emplacement is locallized, minor, and after the magmatic sulfide emplacement that occurs at the contact between the Virginia Formation and the Duluth Complex.

The most abundant sulfide in the pelitic hornfels is pyrrhotite with exsolved lamellae of pentlandite and minor inclusions of ilmenite and magnetite. Chalcopyrite has replaced pyrrhotite (Figure 21).

Figure 19. Relict ophitic texture in a metadiabase. Hypersthene and augite occur subpoikiloblastically around lathy labradorite. Sample A-133. Field of view is 2.5 mm. Crossed polars.

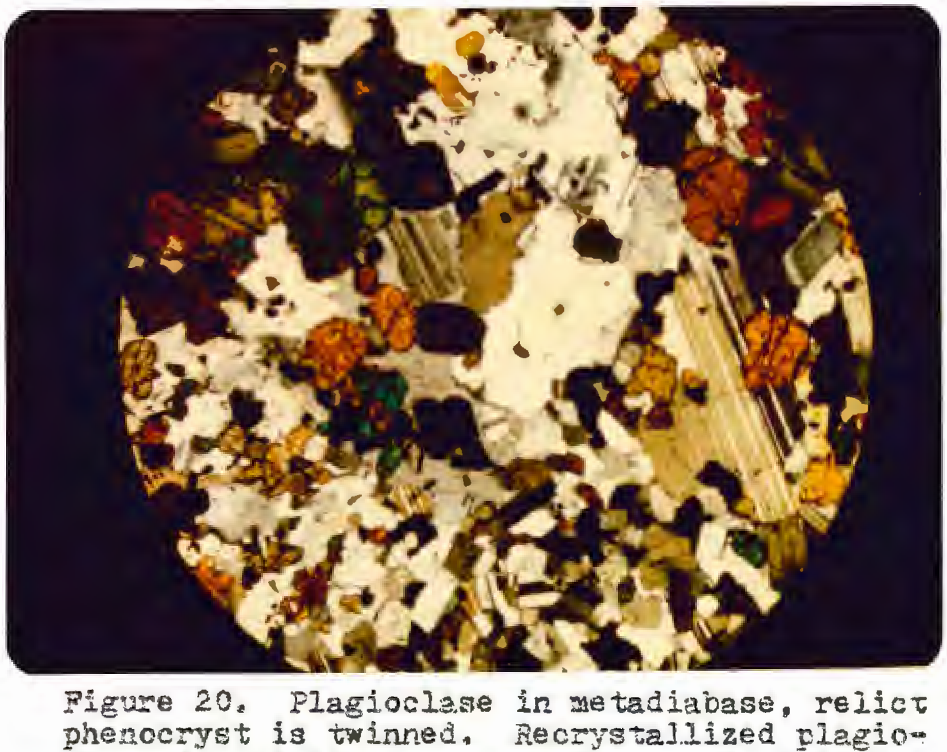

Figure 20. Plagioclase in metadiabase, relict phenocryst is twinned. Recrystallized plagioclase is untwinned. Hypersthene and augite occur interstitially or as inclusions in labradorite. Sample A-98. Field of view is 2.5 mm. Crossed polars.

The calc-silicate pods contain chalcopyrite with exsolved lamellae of cubanite (Figure 22) with minor inclusions of magnetite present. No pyrrhotite was found in the pods.

In metadiabase dikes pyrrhotite appears to be present in small amounts.

Gangue Mineralogy

The type of gangue minerals, and associated alteration, varies as to the lithology. In the pelitic hornfels surrounding the calc-silicate pods, plagioclase showed sericitic alteration (Figure 23) with local uralitization of pyroxene. Biotite is associated with some sulfides (Figure 24). Quartz, found interstitially and as fracture fillings appear to be the primary gangue mineral in the hornfels.

In the calc-silicate pods, plagioclase shows sericitic and kaolinitic alteration (Figure 25). Minor uralitization of diopside is evident (Figure 26).

The primary gangue minerals in the pods are poikiloblastic calcite, quartz, and apophyllite occurring in amounts up to 20 percent (Figures 27 and 28). No signs of disequilibrium can be seen with minerals that are in contact with these gangue minerals. The minerals are easy to distinguish petrographically from one another. Calcite has local development of rhombohedral cleavage, variable relief, and high interference colors. Quartz is clear, has low relief and low interference colors. Apophyllite is white and has an anomalous brown-gray interference color.

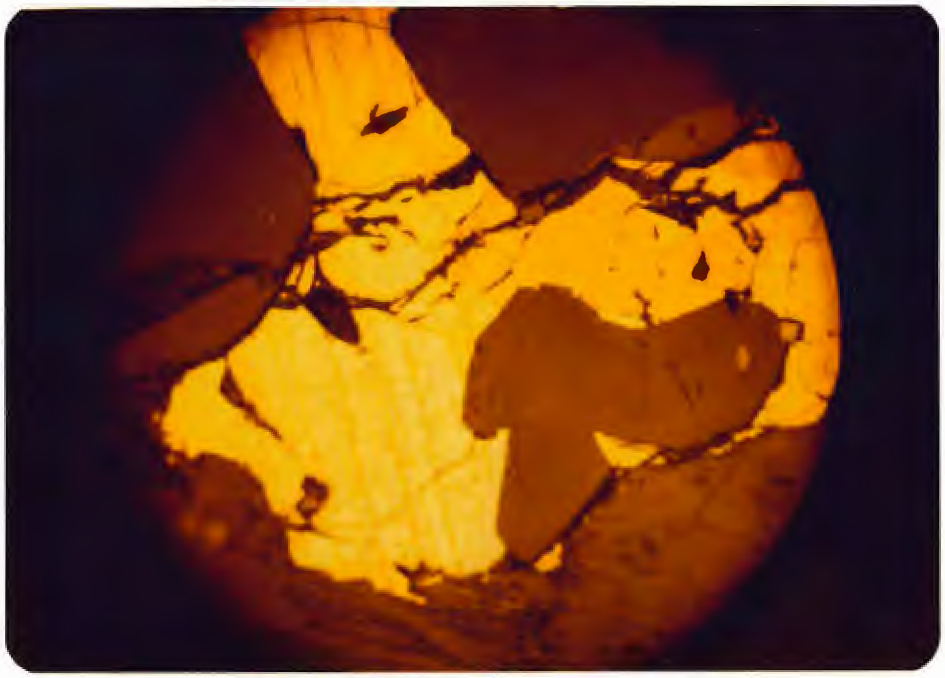

Figure 21. Chalcopyrite replacing pyrrhotite in pelitic hornfels. Sample A-60. Field of view is 2.5 mm. Crossed polars.

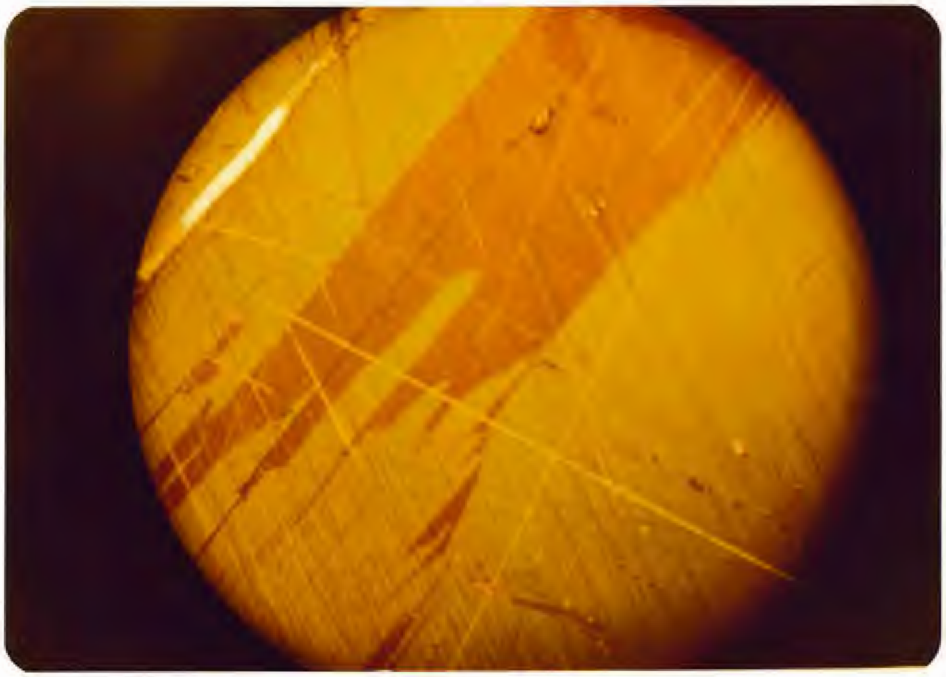

Figure 22. Lamellae of cubanite exsolved in chalcopyrite in a calc-silicate pod. Sample A-118. Field of view is 2.5 mm. Crossed polars.

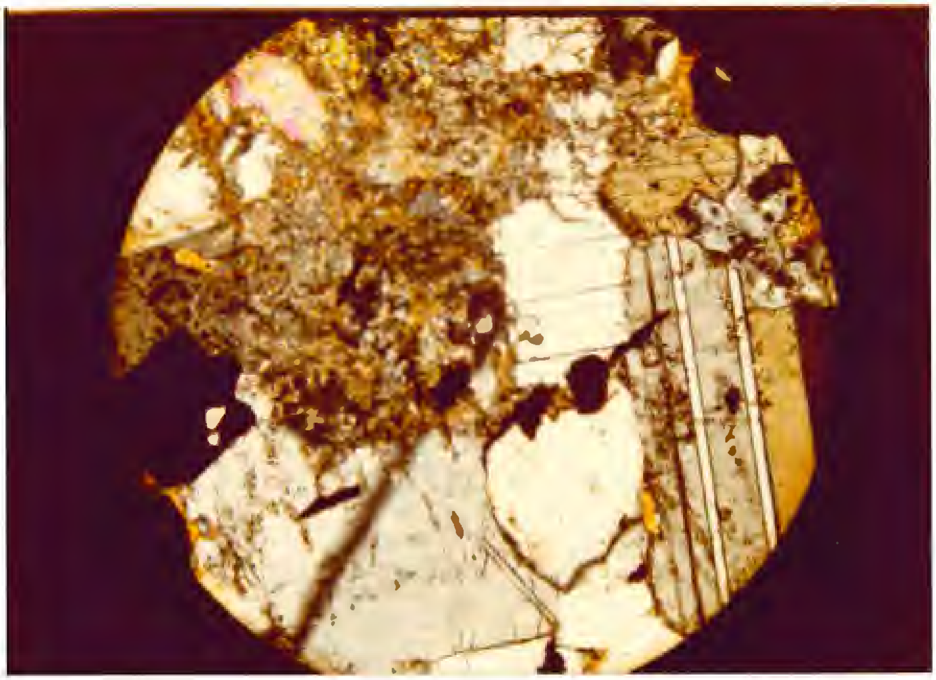

Figure 23. Sericitic alteration of plagioclase in pelitic hornfels. Sulfides are opaque. Sample A-100. Field of view is 2.5 mm. Crossed polars.

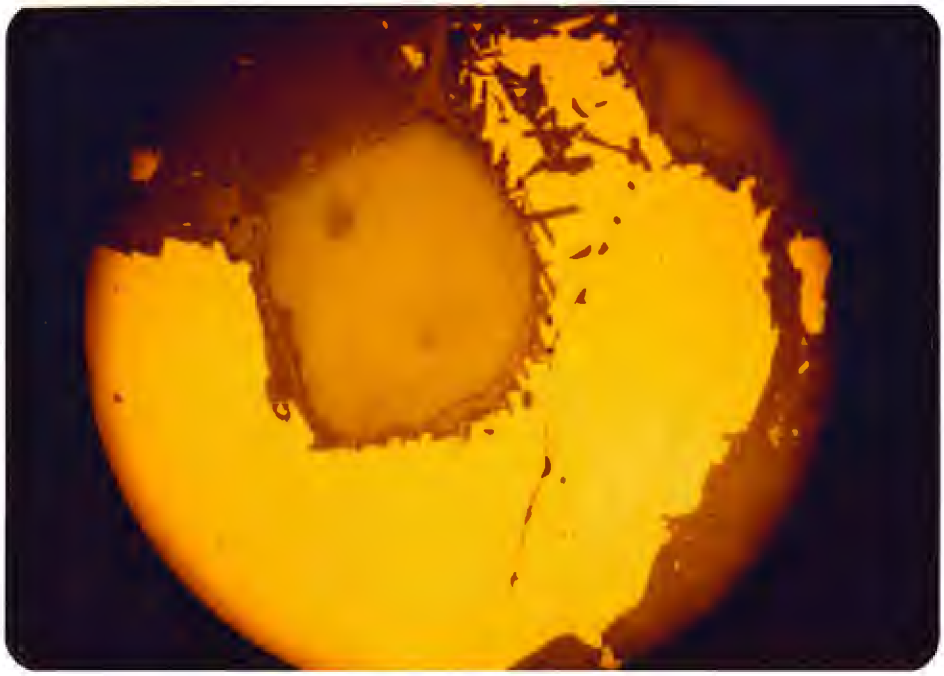

Figure 24. Biotite occurring at grain boundaries between pyrrhotite and plagioclase in pelitic hornfels. Sample A-50. Field of view is 2.5 mm. Uncrossed polars.

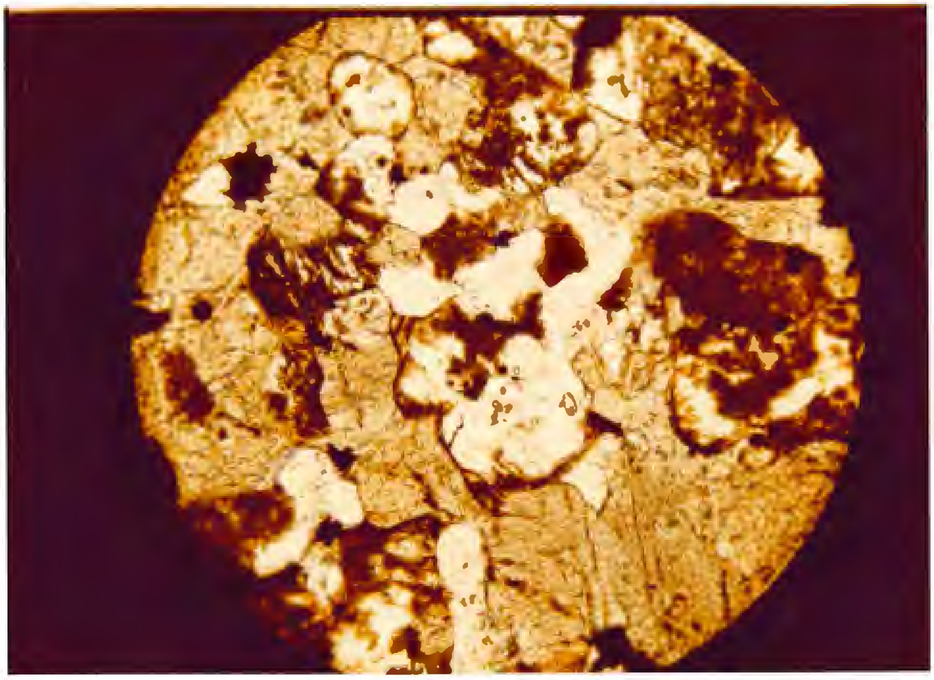

Figure 25. Kaolinitic alteration of plagioclase in a calc-silicate pod. Diopside is unaltered. Sample A-100. Field of view is 2.5 mm. Uncrossed polars.

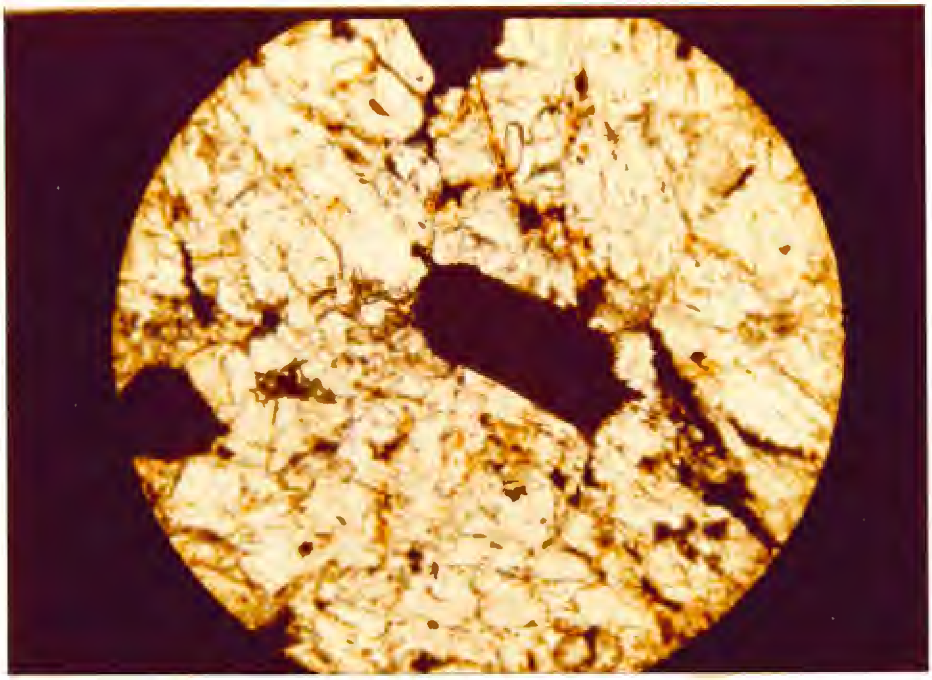

Figure 26. Minor uralitization of diopside with opaque sulfides in calc-silicate pod. Sample A-88. Field of view is 2.5 mm. Uncrossed polars.

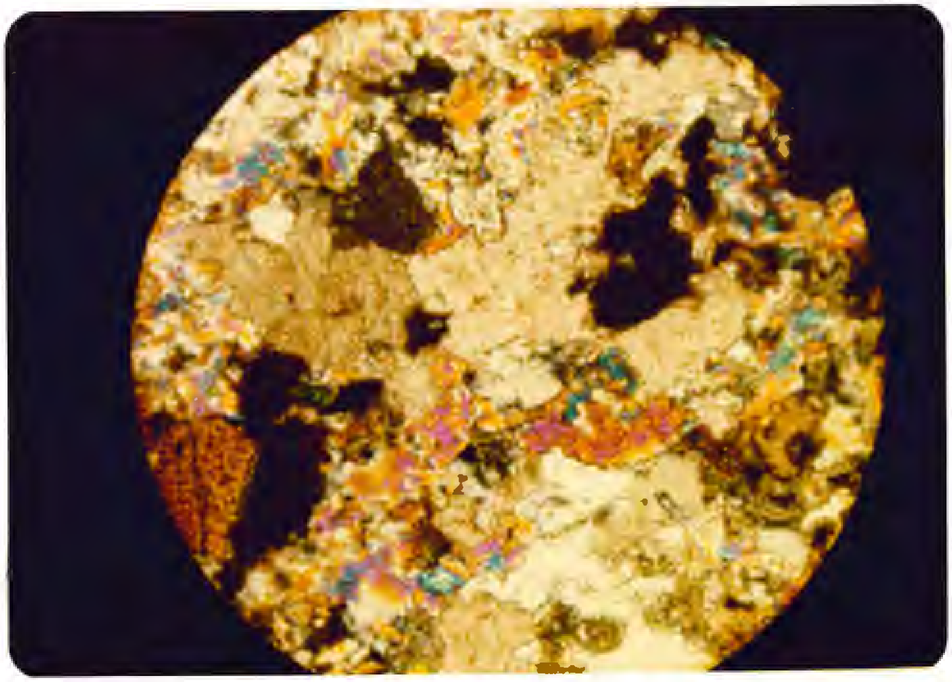

Figure 27. Calcite and quartz occurring poikiloblastically around diopside. Opaques are sulfides. Sample A-104. Field of view is 2.5 mm. Crossed polars.

Gangue minerals that occur in amounts from 0 - 5 percent are anhydrite, fluorite, heulandite, and prehnite. Anhydrite is clear with low relief and moderate interference colors. It is found interstitially as subhedral, radiating crystals and occasionally as euhedral grains up to 1 cm in length. In some samples, it appears to be replacing wollastonite (Figure 29). Fluorite is found as purple subhedral inclusions in quartz (Figure 30). It is associated with fine needles of wollastonite, that also occur as inclusions in quartz and apophyllite. Heulandite (and laumontite) occur as subhedral, platy grains with low relief and low interference colors. They occur as inclusions in quartz (Figure 28). Minor prehnite is found as fracture-fillings associated with anorthite.

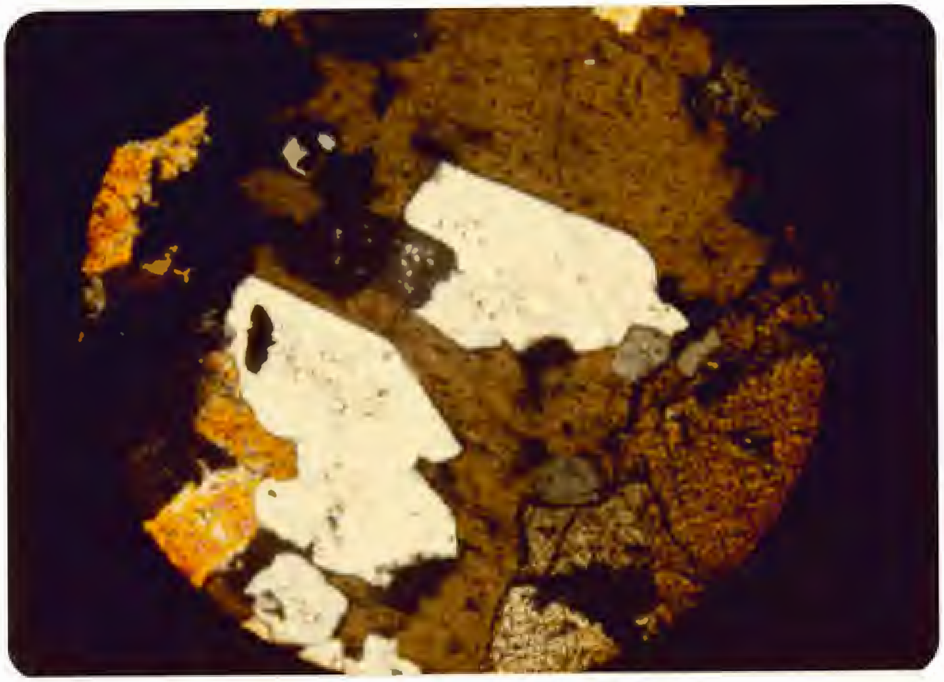

Figure 28. Poikiloblastic apophyllite around quartz and diopside. Inclusions of heulandite and laumontite occur in quartz. Sample A-71. Field of view is 2.5 mm. Crossed polars.

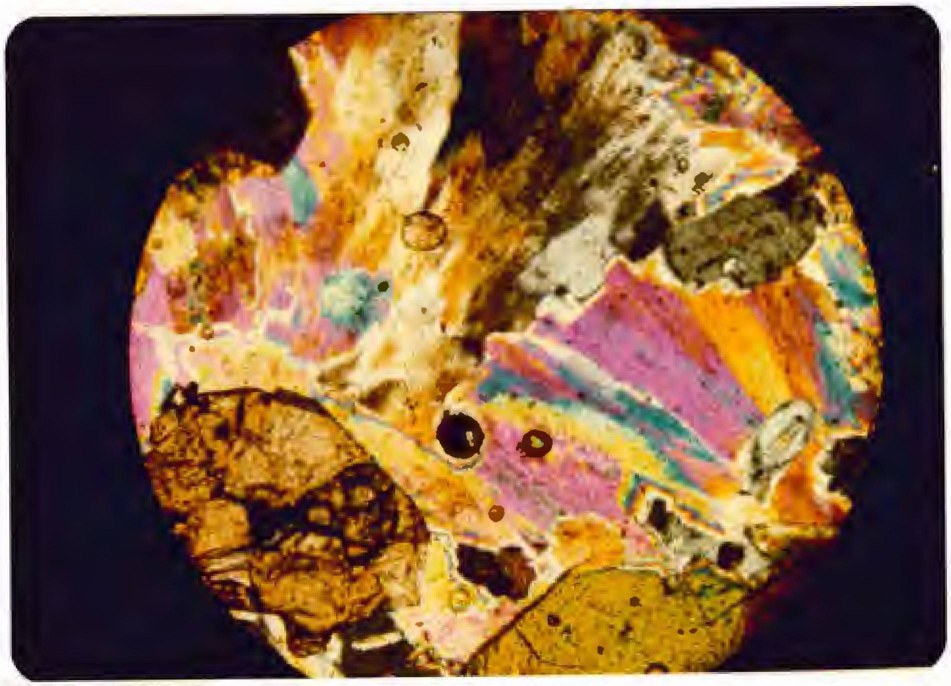

Figure 29. Anhydrite occurring interstitially between diopside and partially replacing wollastonite in a calc-silicate pod. Sample A-80. Field of view is 2.5 mm. Crossed polars.

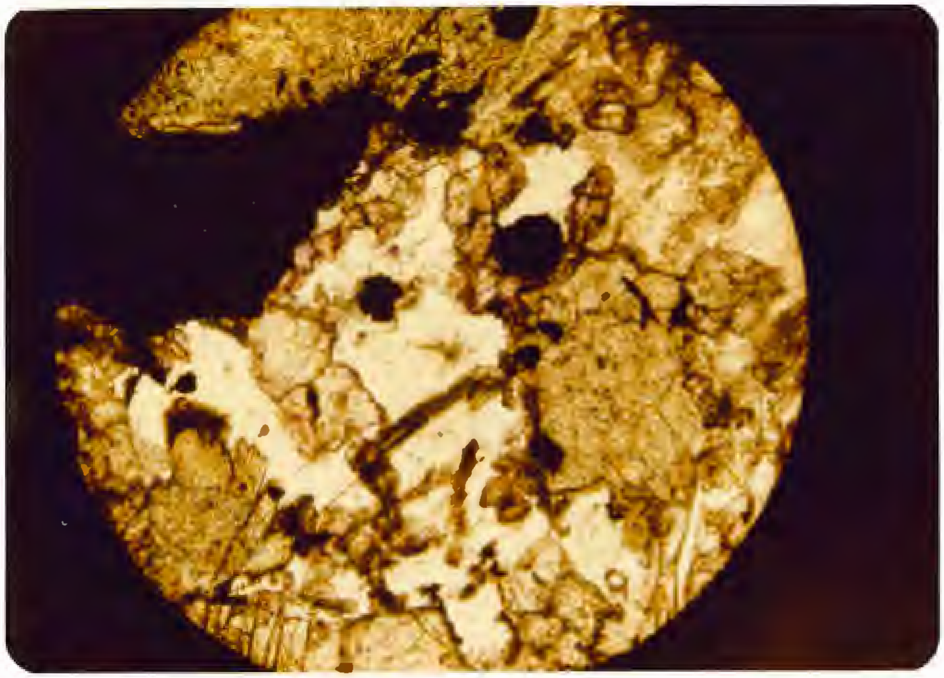

Figure 30. Purple fluorite and needles of wollastonite occurring as inclusions in poikiloblastic quartz in a calc-silicate pod. Quartz is in contact with garnet and wollastonite. Opaques are sulfides. Sample A-88. Field of view is 2.5 mm. Uncrossed polars.

INTERPRETATION OF LITHOLOGIES

Pelitic Hornfels

The mineral assemblage plagioclase-hypersthene-cordierite indicates a composition relatively low in aluminum relative to calcium, iron, and magnesium (Figure 32). The protolith is believed to be a calcareous argillite. Biotite and orthoclase occur in potassium-rich Virginia Formation.

The large variation in strikes and dips of relict bedding in the pelitic hornfels and the jumbled appearance of calc-silicate pods suggest that the Virginia Formation was severly deformed as a result of emplacement of the Duluth Complex.

"Reaction" Rims

The occurrence of "reaction" rims around fractured or broken calc-silicate pods indicates that the intense deformation occurred before the formation of the rims.

The "reaction" rims have a mineral assemblage intermediate between the pelitic hornfels and calc-silicate pods, plagioclase-clinopyroxene-hypersthene (Figure 31). Thus the rims are believed to have formed during the main metamorphic event largely as a result of the diffusion of calcium from the calc-silicate pods into the pelitic hornfels.

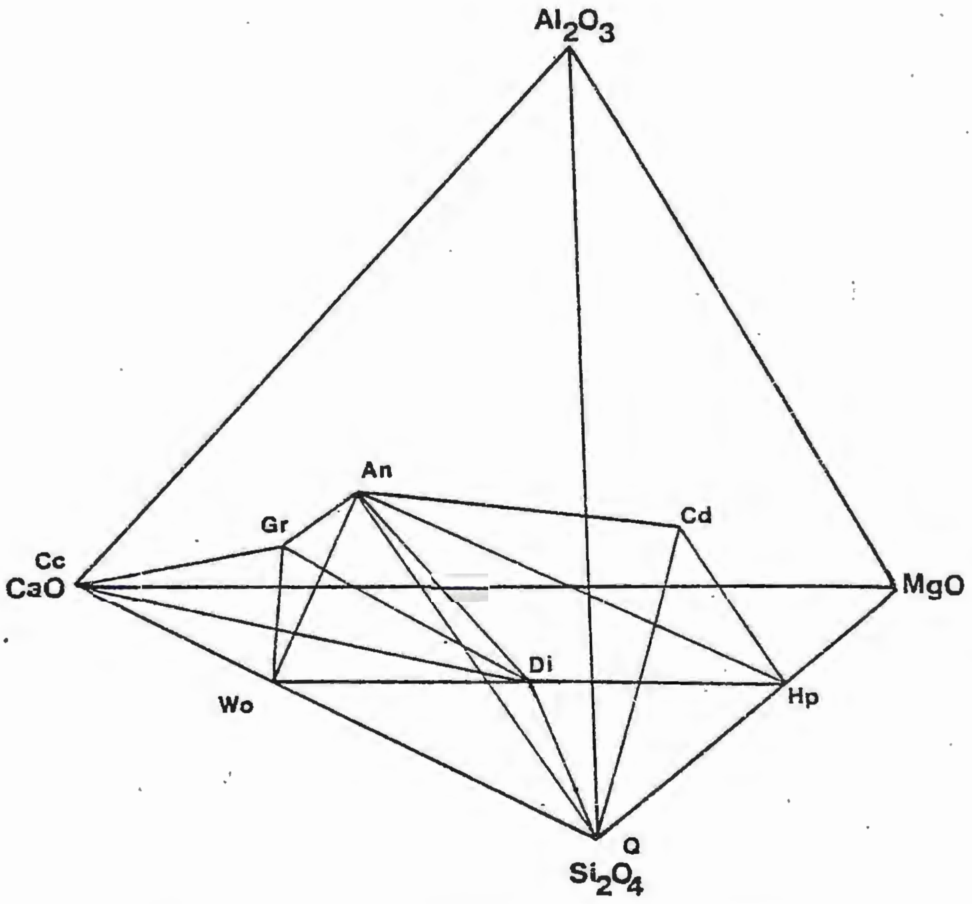

Figure 31. CaO-Al_2O_3-MgO-Si_2O_4 tetrahedron showing primary mineral assemblages in the country rock.

Calc-Silicate Pods

The calc-silicate pods were present before the main metamorphic event, as seen by the formation of the "reaction" rims. These pods are believed to be metamorphic equivalents of the calcareous concretions in the Virginia Formation, described by Pfleider (1968), and in the Thomson Formation, as described by Schwartz (1942) and Weiblen (1964), based on the similarity in shapes and composition. In addition, pieces from the calcareous zone at the contact between the base of the Virginia Formation and the top of the Upper Slaty Member of the Biwabik Iron Formation, that were brought up from intrusion of the Duluth Complex, may be present.

No clear evidence was found to explain why three types of pods, concentric, homogenous, or layered, formed. They all occur together and have no major mineralogical differences.

Although quartz and calcite are known to be gangue minerals associated with the mineralization (p. 35), the extent to which either was present prior to mineralization is not known. Therefore, the assemblages are presented in two tables. Table 1 lists the total mineral assemblages present in the pods, and Table 2 a conservative interpretation of the primary mineral assemblages that were present, on the limiting assumption that all calcite and quartz is related to sulfide emplacement. Thus, conservatively, the dominant primary set of minerals in the pods was diopside-garnet-wollastonite-plagioclase-sphene.

Metadiabase Dikes

The metadiabase dikes intrude the Virginia Formation, but were metamorphosed by the Duluth Complex. A precise age cannot be given. They could be related to Middle Precambrian diabase dikes present in the eastern Mesabi Range (p. 8) or may be related to Keweenawan igneous activity. The typical assemblage therein is plagioclase-augite-hypersthene.

CONDITIONS OF METAMORPHISM

General Statement

The ACF diagram (Figure 32) shows, to a first approximation, the common assemblages in the pelitic hornfels (plagioclase-hypersthene-cordierite). "reaction" rims and metadiabase (plagioclase-clinopyroxene-hypersthene), and calc-silicate pods (plagioclase-clinopyroxene-wollastonite). This indicates metamorphism under conditions of the pyroxene hornfels-facies.

The pressure attained during metamorphism is assumed to be below 3 kilobars. If the whole North Shore Volcanic Group overlay the Virginia Formation at the time of emplacement of the Duluth Complex, then the thickness would be on the order of 20,000 feet (Green, 1972) yielding a lithostatic pressure of approximately 2 kilobars. It is possible that the thickness was less than this due to "shingling" of the lavas, the contribution of the overlying Complex

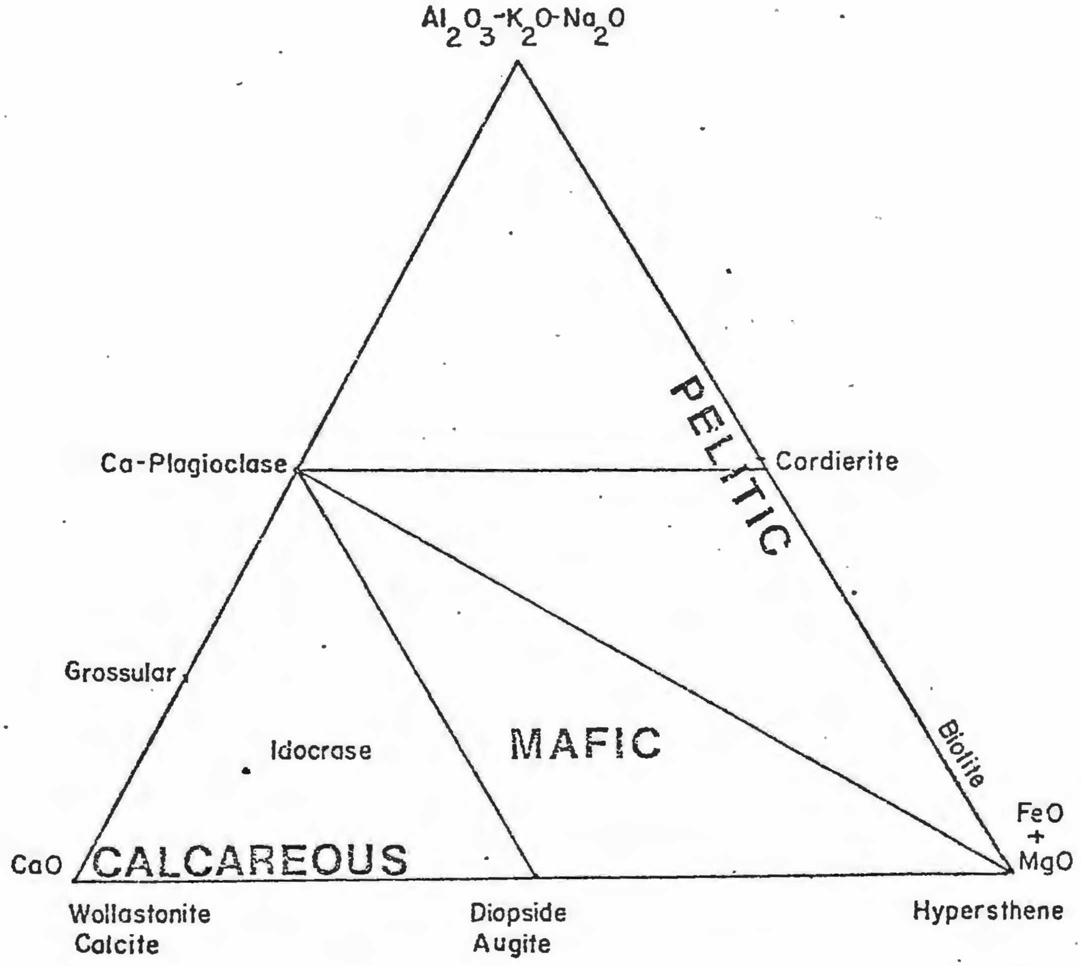

Figure 32. ACF diagram showing mineralogies present in calc-silicate pods, in the calcareous field, metadiabase dikes and "reaction" rims, in the mafic field, and pelitic hornfels, in the pelitic field.

rocks to the lithostatic pressure. Probably 2 kilobars is as close an estimate as is warranted by the available data.

Metamorphic Assemblages in the Calc-Silicate Pods

To examine the variation in assemblages in the pods at the culmination of metamorphism, the minerals that are obviously secondary; fluorite, apophyllite, heulandite, laumontite, prehnite, and anhydrite are omitted. This leaves calcite-diopside-garnet-idocrase-plagioclase-quartz-sphene-wollastonite (Table 1). Diopside (virtually ubiquitous), sphene (common), and idocrase (one sample) involve components other than those in the system $CaO-Al_2O_3-SiO_2-CO_2-H_2O$. Thus the variation in mineral assemblages involves the remaining phases, calcite-garnet-plagioclase-quartz-wollastonite (and vapor). These can be discussed to a first approximation in terms of the above system, assuming the garnet to be pure grossular and the plagioclase pure anorthite.

Figure 33 is a T-X diagram of pertinent stability fields and reactions in this sodium-free system under isobaric conditions of 2 kilobars. If calcite and quartz are secondary-- the conservative case, then the assemblage anorthite + wollastonite + grossular suggests a minimum temperature of 600 degrees Celsius with a mole fraction of CO_2 in the vapor phase being less than 0.25. The major limiting reaction is:

$$\begin{array}{ccccccc} \text{(grossular)} & & \text{(quartz)} & & \text{(anorthite)} & & \text{(wollastonite)} \\ Ca_3Al_2Si_3O_{12} & + & SiO_2 & \rightarrow & CaAl_2Si_2O_8 & + & 2CaSiO_3 \end{array}$$

No gehlenite was found indicating the maximum temperature attained was below 750 degrees Celsius.

It is not certain that quartz and calcite are all secondary, and thus, one may consider quartz-calcite-grossular-anorthite-wollastonite as possible culmination phases (along with a binary H_2O-CO_2 vapor phase). In the system CaO-Al_2O_3-SiO-CO_2-H_2O, in the presence of a vapor, an assemblage of three (or less) solid phases has a variance of three (or more). Such assemblages of high variance are less dubious as approximate equilibrium assemblages than those of lower variance, and will be considered first.

Figure 34 is a schematic T-X_{CO_2} diagram showing isobarically univariant reactions and divariant solid phase assemblages in the model system. 38 out of 46 two and three-phase assemblages in the calc-silicate pods (taken from Table 1) fall in Facies I.(anorthite-grossular-wollastonite), six fit Facies V (grossular-quartz-wollastonite), and two fit Facies IV (calcite-grossular-quartz). No three-phase assemblage anorthite-calcite-wollastonite or anorthite-calcite-quartz has been found. Therefore conditions apparently did not stray to the right of the breakdown of grossular (into Facies II or III).

Figure 35 (Kerrick, et al., 1973) shows how increasing albite in the system lowers the temperature of the reaction that forms wollastonite and plagioclase, and affects

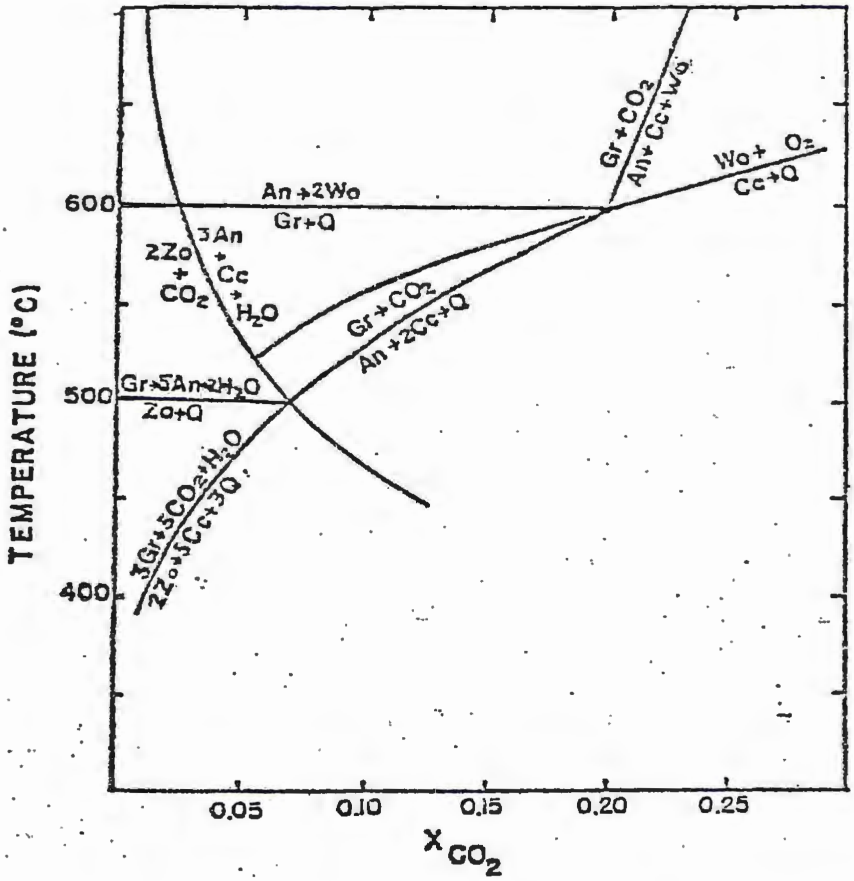

Figure 33. Isobaric T-X diagram for a portion of the $CaO-Al_2O_3-SiO_2-H_2O-CO_2$ system. (Kerrick, et al., 1973).

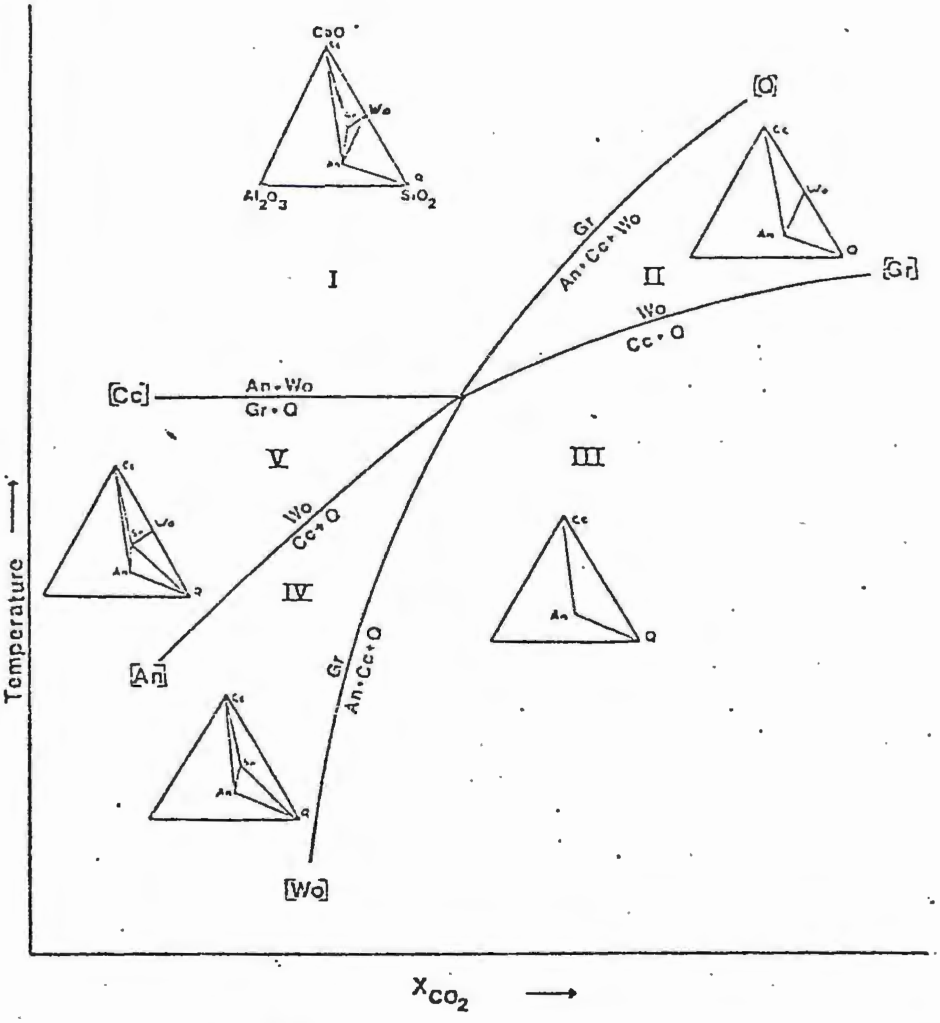

Figure 34. Schematic petrogenetic grid showing isobarically univariant reactions and divariant mineral assemblages relevant to calc-silicate pods.

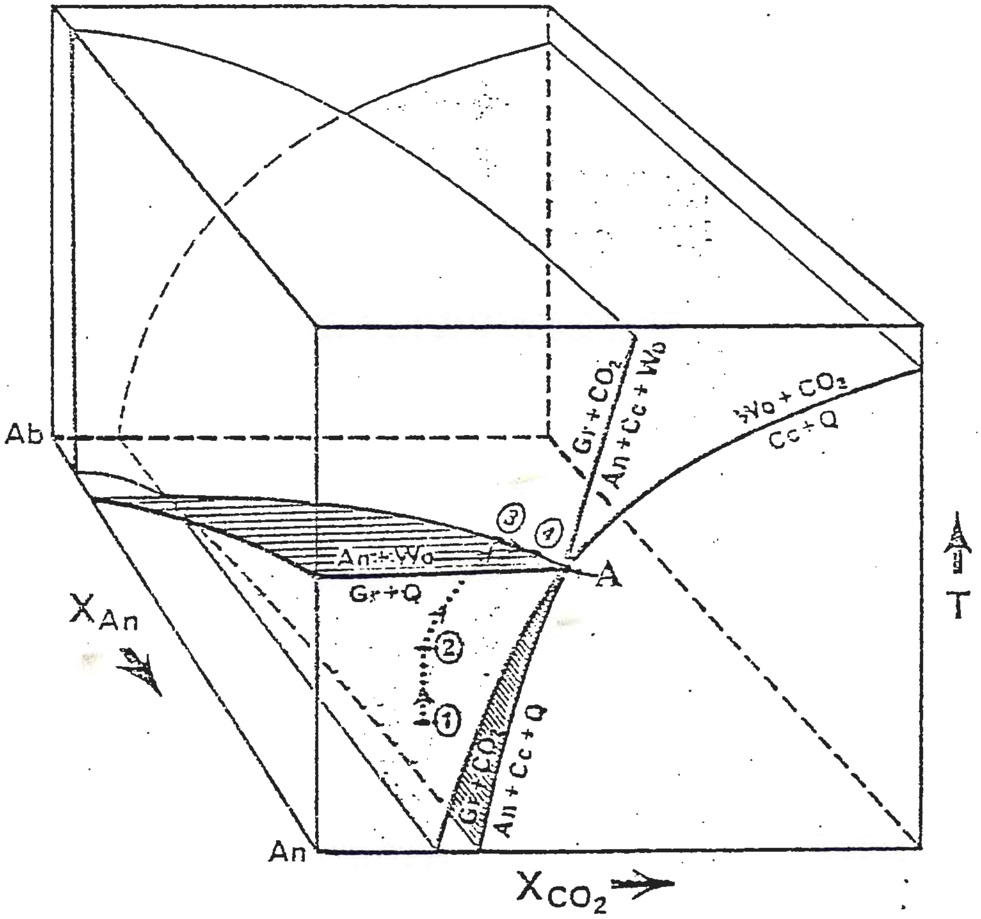

Figure 35. Diagram showing reactions and mineral stability fields with changing CO_2, albite, content of plagioclase and temperature (Kerrick, et al., 1973).

the other reactions involving plagioclase. An isothermal section through this figure indicates that it is possible that the assemblages without plagioclase (grossular-quartz-wollastonite and calcite-grossular-quartz in Facies IV and V) could be isothermal with assemblages of Facies I, but simply lower in sodium.

The occurrence of diopside in all calc-silicate pods, and persistence of silicate minerals throughout pods, suggest a siliceous dolomitic protolith. The modal increase of diopside at the pods' rims suggests diffusion of magnesium into the pods from the pelitic hornfels and calcium out.

Conditions of Sulfide Emplacement

The occurrence of hydrous alteration, with hydrous gangue minerals, and of sulfides replacing silicates indicate that the sulfides in the calc-silicate pods, and surrounding pelitic hornfels, were emplaced by hydrothermal replacement. From textural evidence (the primary metamorphic minerals are being replaced) this sulfide emplacement is believed to have occurred after the main metamorphic event. It should be emphasized that the bulk of sulfide emplacement in the Minnamax Deposit is magmatic.

The paragenetic sequence of mineralization in the pelitic hornfels appears to be early crystallization of magnetite and ilmenite, formation of pyrrhotite, exsolution of pentlandite, and later replacement of pyrrhotite by chalcopyrite. No exsolved cubanite was seen in the samples studied.

In calc-silicate pods, the sequence is crystallization of magnetite and ilmenite, formation of chalcopyrite, and exsolution of cubanite in chalcopyrite.

The minerals associated with the sulfides indicate formation at temperatures lower than the major metamorphism. The most notable examples are grossularite and quartz (Figure 30), in place of plagioclase and wollastonite at higher temperatures and calcite and quartz (Figure 27), which would form wollastonite and CO_2 at higher temperatures (Figure 34).

The occurrence of laumontite can be used to determine the upper temperature limit of sulfides emplaced hydrothermally. Figure 36 (Liou, 1971) shows the stability field of laumontite. Assuming the lithostatic pressure was approximately 2 kilobars, the upper limit of laumontite is 350 degrees Celsius in the sodium-free system. No wairwakite was found in the rocks. In addition, cubanite exsolves in chalcopyrite between 250 to 300 degrees Celsius (Ramdohr, 1969). Thus the maximum temperature during emplacement of the sulfides and associated gangue minerals in the calc-silicate can be given from 250 to 350 degrees Celsius.

CONCLUSIONS

The Virginia Formation in the Minnamax Deposit consists of pelitic hornfels that contains numerous calc-silicate pods. Dark gray "reaction" rims surround all pods. Metadiabase dikes cut the Virginia Formation. These rocks were metamorphosed to the pyroxene hornfels-facies and were intensely deformed by the Duluth Complex. Later hydrothermal replacement by sulfides occurred in the Virginia Formation.

The pelitic hornfels was relatively low in aluminum relative to calcium, iron, and magnesium forming plagioclase-hypersthene-cordierite with graphite. Local occurrences of potassium produced biotite and orthoclase. The protolith is believed to be a calcareous argillite.

Three types of calc-silicate pods are present: (1) Homogenous types with a consistent mineralogy throughout, (2) Layered types that show well developed layers of diopside, and (3) Concentric types with two or more mineral zones developed. The primary minerals are diopside, plagioclase, wollastonite, grossular garnet, idocrase, and sphene. It is uncertain, based on petrographic data, whether some calcite or quartz is primary. Diffusion of magnesium into the pods from the pelitic hornfels gave rise to high concentrations of diopside in the outer zones of the pods. The pods are thought to have been siliceous dolomitic concretions in the Virginia Formation. In addition, some pods may be pieces of dolomitic beds brought up from the top of the Biwabik Iron Formation by the Duluth Complex.

"Reaction" rims are intermediate in composition between the pelitic hornfels and calc-silicate pods, consisting of plagioclase, hypersthene, and poikiloblastic clinopyroxene. These rims formed from diffusion of calcium into the pelitic

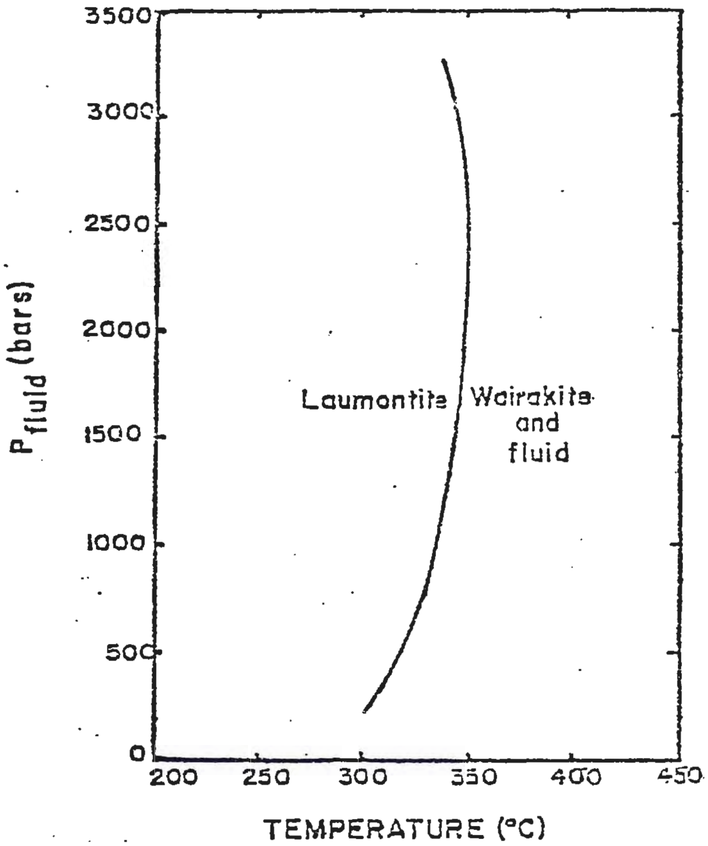

Figure 36. Stability field of laumontite at varying temperatures and pressures (Liou, 1971).

hornfels from the calc-silicate pods. This occurred after the deformation as unbroken rims surrounding pods that are broken or fractured.

Metadiabase dikes consist of labradorite, augite, hypersthene, and minor apatite, and ilmenite-magnetite. A relict ophitic texture is well developed. Relict plagioclase phenocrysts are present as resorbed plagioclase.

Using a sodium-free model, the presence of wollastonite and anorthite in the calc-silicate pods would indicate a minimum temperature of 600 degrees Celsius at 2 kilobars pressure with a mole fraction of CO_2 in the vapor phase being less than 0.25. Consideration of the albitic component in the plagioclase would slightly lower this minimum temperature.

Sulfides, primarily pyrrhotite, chalcopyrite, pentlandite, and cubanite, and associated gangue minerals were emplaced by hydrothermal replacement after the main metamorphic event. An upper limit of 350 degrees Celsius, based on the presence of laumontite, and a bottom limit ranging from 250 to 300 degrees Celsius, based on exsolved cubanite in chalcopyrite, can be given for temperatures of this sulfide emplacement.

REFERENCES CITED

Anderson, G.E., 1956, Copper-nickel Mineralization at the base of the Duluth Gabbro; unpub. M.S. thesis, Univ. Minnesota, Mpls.

Austin, G.S., 1972, Cretaceous Rock; in Geology of Minnesota; A Centennial Volume, Sims, P.K. and Morey, G.B. eds., Minnesota Geological Survey, pp. 509-514.

Bonnichsen, B., 1968. General Geology and Petrology of the Metamorphosed Biwabik Iron Formation, Dunka River Area, Minnesota; unpub. Ph.D. thesis, Univ. Minnesota, Mpls.

______________, 1972, Sulfide Minerals in the Duluth Complex; in Geology of Minnesota: A Centennial Volume, Sims, P.K. and Morey, G.B., eds., Minnesota Geological Survey, pp. 388-393.

______________, 1975, Geology of the Biwabik Iron Formation, Dunka River Area, Minnesota; Econ. Geol., V. 70, pp. 319-340.

Craddock, C., 1972, Late Precambrian Regional Geologic Setting; in Geology of Minnesota: A Centennial Volume, Sims, P.K. and Morey, G.B., eds., Minnesota Geological Survey, pp. 281-291.

French, B.M., 1968, Metamorphism of the Biwabik Iron Formation; Minn. Geol. Survey Bull., V. 45, 103 pages.

Goldich, S.S., 1972, Geochronology in Minnesota; in Geology of Minnesota: A Centennial Volume, Sims, P.K. and Morey, G.B., eds., Minnesota Geological Survey, pp. 27-33.

Green, J.C., 1972, North Shore Volcanic Group; in Geology of Minnesota: A Centennial Volume; Sims, P.K. and Morey, G.B., eds., Minnesota Geological Survey, pp. 299-332.

Grout, F.F., 1933, Contact Metamorphism of the Slates of Minnesota by Granite and by Gabbro Magmas; Geol. Soc. Am., V. 44, pp.989-1040.

Gunderson, J.N., and Schwartz, G.M., 1962, The Geology of the Metamorphosed Biwabik Iron Formation, Eastern Mesabi District, Minnesota; Minn. Geol. Survey, Bull., V. 43, 139 pages.

Hanson, G.N., and Malhotra, R., 1971, K-Ar Ages of Mafic Dikes and Evidence for Low-grade Metamorphism in Northeastern Minnesota; Geol. Soc. Am. Bull., V. 82, pp. 1107-1114.

Hardyman, R.E., 1969, The Petrology of a Section of the Basal Duluth Complex, St. Louis County, Northeastern Minnesota; unpub. M.S. thesis, Univ. Minnesota, Mpls., 132 pages.

Kerrick, D.M., Randazzo, A.F., and Crawford, K.E., 1973, Metamorphism of Calcareous Rocks in Three Roof Pendants in the Sierra Nevada, California; Jour. Petrology, V. 14, pp. 303-326.

Liou, J.G., 1971, P-T Stabilities of Laumontite, Wairwakite, Lawsonite, and Related Minerals in the System $CaAl_2Si_2O_8$-SiO_2-H_2O; Jour. Petrology, V. 12, pp. 379-409.

Pfleider, E.P., Morey, G.B., and Bleifuss, R., 1968, Mesabi Deep Drilling Progress Report No. 1; in Annual Mining Symposium, 29th, Pfleider, E.P. and Berger, F.E., eds., Univ. Minn. Proc., pp. 59-92.

Ramdohr, P., 1969, The Ore Minerals and Their Intergrowths; Pergamon Press, New York, 1174 pages.

Renner, J., 1969, The Petrology of the Contact Rocks of the Duluth Complex, Dunka River Area, Minnesota; unpub. M.S. thesis, Univ. Minnesota, Mpls.

Schwartz, G.M., 1942, Concretions of the Thomson Formation, Minnesota; Am. Jour. Sci., V. 240, pp. 491-499.

Sims, P.K., and Morey, G.B., 1972, Resume of Geology of Minnesota; in Geology of Minnesota: A Centennial Volume, Sims, P.K. and Morey, G.B., eds., Minnesota Geological Survey, pp.3 - 20.

Taylor, R.B., 1964, Geology of the Duluth Gabbro Complex near Duluth, Minnesota; Minn. Geol. Survey Bull., V. 44, 63 pages.

Watowich, S.N., 1978, A Preliminary Geological Overview of the Minnamax Copper-Nickel Deposit in the Duluth Gabbro; 39th Ann. Minnesota Mining Symposium, 51st Ann. Meeting, Minn. Section, AIME, pp. 19-1-11.

Weiblen, P.W., 1964, A Preliminary Study of the Metamorphism of the Thomson Formation; unpub. M.S. thesis, Univ. Minnesota, Mpls.

Weiblen, P.W., and Morey, G.B., 1975, The Duluth Complex - A Petrologic and Tectonic Summary; 36th Ann. Minn. Mining Symposium: Dept. of Conferences and Continuing Education, Univ. Minnesota, Mpls., pp. 72-95.

White, D.A., 1954, Stratigraphy and Structure of the Mesabi Range, Minnesota; Minn. Geol. Survey Bull., V. 38, 92.pages.

Wolff, J.F., 1917, Recent Geologic Developments on the Mesabi Range, Minnesota; Am. Inst. Mining Metall. Engineers Trans., V. 56, pp. 142-169.

Wright, H.E., Jr., 1972, Quaternary History of Minnesota; <u>in</u> Geology of Minnesota: A Centennial Volume, Sims, P.K. and Morey, G.B., <u>eds</u>., Minnesota Geological Survey, pp. 515-547.