MINERALOGY AND METAMORPHISM OF THE STROMATOLITE-BEARING LAYERS OF THE BIWABIK IRON FORMATION

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Under the supervision of Professor James Welsh

ABSTRACT

The 1.85 billion year old Biwabik Iron-formation of northeastern Minnesota contains some of the earliest forms of life on the planet, present in structures called stromatolites. Samples of the iron-formation were collected directly above and below stromatolite bearing horizons, to determine silicate mineralogy, so as to ultimately understand the effects of metamorphism on the stromatolites. Degree of metamorphism adjacent to the stromatolite horizons was found to range from late diagentic to moderate metamorphic grade.

ACKNOWLEDGMENTS

Special thanks should be given to the advisor of this thesis Professor James Welsh for his continued help and support. Thanks should also be given to the other professors of the Gustavus Adolphus Geology department. The author would also like to thank Professor Russell Shapiro whose research on stromatolites helped launch this work, and provided many of the samples. Thanks should also be extended to the mining companies who allowed us to gather samples and the workers of the Hibbing core library whose help in wading through the cores was greatly appreciated. Thanks should also be given to Macalester College for allowing us the use of their equipment and time, and specifically to Jeff Thole who’s help with the X-ray analyis is greatly appreciated.

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INTRODUCTION

The Biwabik Iron Formation is a 1.85 billion year old banded iron formation (Schultz and Cannon, 2007). It is the middle member the Animikie Group located in northeastern Minnesota. The Biwabik Iron Formation is bounded by the Virginia Formation above and the Pokegama Quartzite below. The Animikie Group was deposited in a shallow marine environment during the penokean orogeny (Schultz and cannon, 2007) and (Ojakangas, 1983). Due to its deposition in a shallow marine environment the formation also preserves two layers of stromatolite, ancient microbial mounds that lived on the shallow shelves. After burial and preservation of the stromatolite layers the Biwabik was contact metamorphosed by the intrusion of the Duluth Gabbro Complex (French 1968).

Stromatolites although of little economic significance may provide important insights into how life on this and ultimately other planets begin (Shapiro et. al. 2008). However because stromatolite fossils have been preserved in such ancient rocks, their remains have consistently undergone some level of metamorphism. The exact effect of metamorphism on the primary structures of stromatolites is largely unknown. The Biwabik Iron Formation therefore provides a unique opportunity to study stromatolites at varying degrees of metamorphism. This study will focus on describing the silicate minerals surrounding the stromatolites, to ultimately provide an estimate of the metamorphic grade of the stromatolites at various locations.

GEOLOGIC SETTING

The Biwabik Iron-formation is located in northeastern Minnesota in an area called the Mesabi Range, which extends for approximately 120 miles in an east-northeast direction, from Grand Rapids on the west and Birch Lake on the east, and approximately 90 miles north of Duluth (Fig.1).

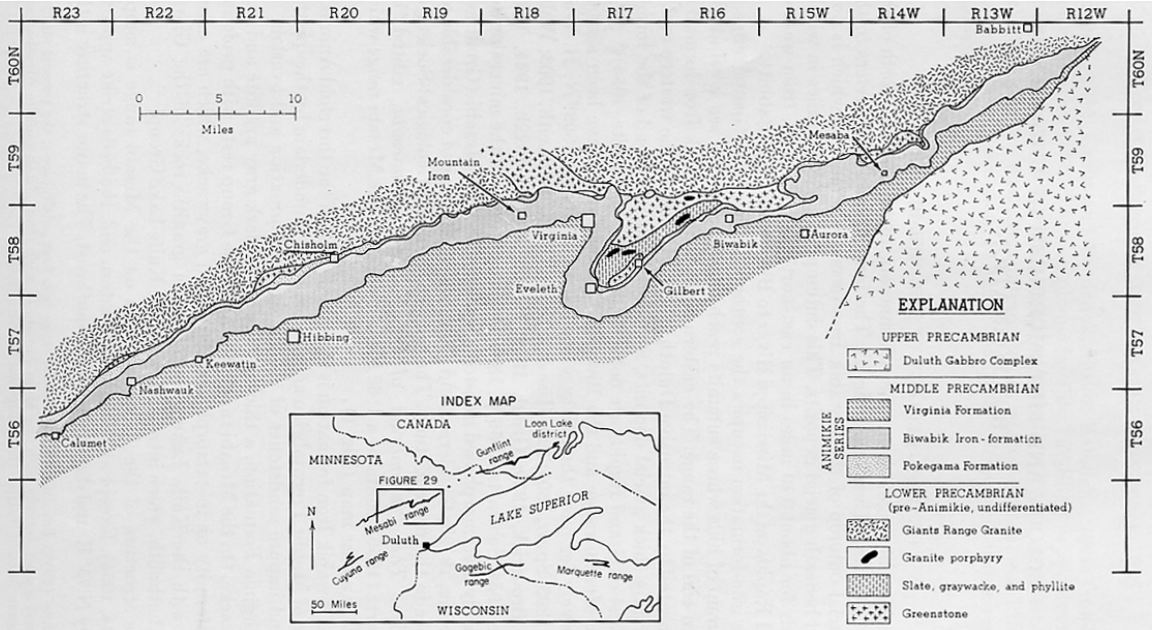


Fig.1. Geologic map of the Mesabi Range. Inset the gives the location of the Mesabi Range in Minnesota (Franch 1968).

The Biwabik Iron-formation occurs at the southern slope of the Giants Range Batholith. The iron-formation is 500 meters thick, and is part of the 2700 meter thick Animikie Group which consists of the Pokegama Quartzite at the base, followed by the Biwabik Iron Formation, and finally the Virginia Formation (Fig 2). It ranges in outcrop width from a quarter mile to three miles (French, 1968). The group is of Early Proterozoic age and the iron formation itself has an age of approximately 1.85 billion years old (schulz and Cannon, 2007). The Animikie Group is correlative with the Menominee Group of Michigan and Wisconsin (Schulz and Cannon, 2007).

The Biwabik Formation is correlative to the Gunflint Formation of Ontario, and the Ironwood Formation located in Wisconsin and the Upper Peninsula of Michigan (Schulz and Cannon, 2007). Its western edge is overlain by thick sequences of glacial deposits. The eastern edge of the Biwabik is intruded by the Duluth Complex but was once most likely continuous with the Gunflint Formation. The Biwabik Iron Formation is fairly simple structurally. Most beds strike N75E and dip gently to the southeast, though two broad folds are present in the Virginia Horn area (French, 1968).

The petrology and mineralogy of the Biwabik Iron Formation is representative of most Precambrian banded iron-formations around the world. The mineralogy of the iron-formation changes as distance from the Duluth Complex decreases. The mineral assemblages vary from unaltered to low grade iron-rich metamorphic minerals in the west to high grade iron-rich minerals in the east (French, 1968). The major minerals present in the formation are quartz, hematite, magnetite, iron silicates, and carbonates. The iron silicate minerals present are minnesotaite, greenalite, stilpnomelane, and cummingtonite/grunerite. The major carbonate groups consist of calcite and siderite (Gruner, 1946)

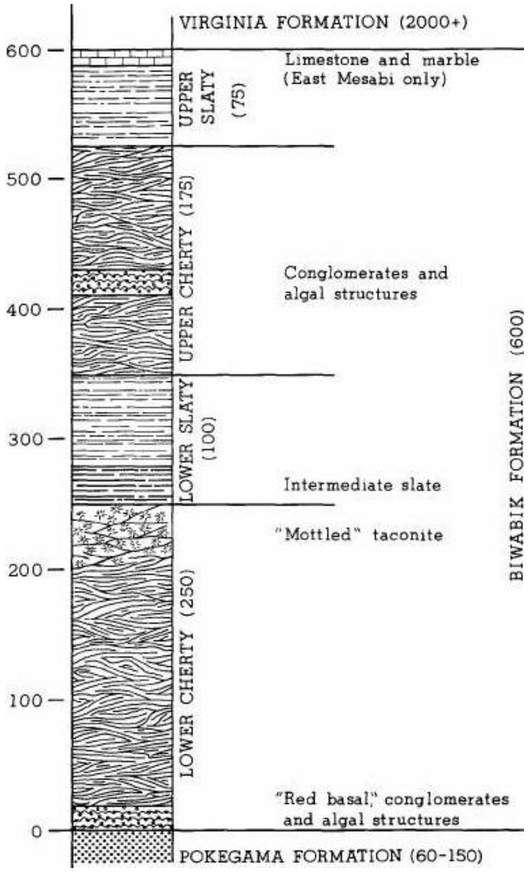


Fig.2. Generalized stratigraphic section of the Biwabik Iron Formation (French 1968)

The Biwabik Iron-formation was deposited in response to the tectonic events of the Penokean orogeny, which began 1.88 billion years ago when an oceanic arc made up of what is now part of Wisconsin and southern Minnesota collided with the southern margin of the Superior craton (Schulz and Cannon, 2007). Due to tectonic loading a broad shallow basin was formed on the margin of the Superior craton. Initially, siliciclastic material began depositing in the basin followed by iron formation and finally deeper water sedimentation which led to the deposition of the Virginia Formation (Schulz and Cannon, 2007).

The most recent study of the depositional environment of the Animikie basin, was done by Ojakangas (1983). In his model the Biwabik Iron Formation was deposited on a tidally dominated shallow marine shelf. The cherty iron formation was most likely deposited in a shallower high energy region while the slaty iron formation was being deposited further out in deeper calmer water. The iron-rich waters were likely due to upwelling from deeper parts of the basin (Ojakangas, 1983).

PREVIOUS WORK

Important early studies of the Mesabi Iron Range include the works of Van Hise and Leith (1901), Gruner (1924, 1926), White (1954) and Gundersen and Schwartz (1962). Van Hise and Leith (1901) contributed the earliest descriptive work on The Mesabi Range. Gruner (1924) carried out further work on the iron-bearing rocks of the Mesabi Range, especially those in the western portion of the formation. In 1946 Gruner expanded his work to include a much more detailed examination of the mineralogy of the iron-bearing rocks of the Mesabi Range. The iron formation is comprised of a vast array of minerals both primary and metamorphic in origin. The major minerals of the western

Biwabik Formation are quartz, magnetite, hematite, minnesotaite, stilpnomelane, greenalite, goethite, siderite, dolomite, and calcite. The eastern edge of the Biwabik has been contact metamorphosed by the Duluth Complex and contains metamorphic pyroxenes and amphiboles (Gruner, 1946).

White's (1954) work focused on the stratigraphy and structure of the formation. He subdivided the iron formation into two facies: one a cherty taconite which is characterized by a granular quartz rich texture of rounded iron silicate clasts, and a slaty taconite which is darker, fine grained, and contains much more carbonaceous material. These two facies alternate starting with the Lower Cherty at the base followed by the Lower Slaty, the Upper Cherty, and finally the Upper Slaty at the top of the formation (White, 1954). Gundersen and Schwartz (1962) produced detailed work on the more highly metamorphosed eastern Mesabi district.

Perhaps the most useful work on the mineralogy and metamorphism of the Biwabik comes from French's (1968) work on the metamorphism of the Biwabik Iron Formation. French describes the rocks of the western end as being chiefly composed of quartz, magnetite, hematite, iron carbonates, and iron silicates. The western edge is considered by French (1968) to be mineralogically "intermediate between the carbonate and silicate facies of iron formations." French (1968) interprets the metamorphism of the Biwabik Iron-formation to range from diagenetic to low grade in the west to high grade contact metamorphism in the east. Of the diagenetic to low grade metamorphic index minerals stilpnomelane, greenalite, and minnesotaite are the most important. Of the three silicates stilpnomelane is the most abundant followed by minnesotaite and then greenalite. The metamorphism of the eastern of the end of the iron range was further elaborated on by Bonnichsen (1969), who studied the high grade contact metamorphosed rocks of the Dunka River area. These rocks exhibit higher metamorphic grade minerals such as: orthopyroxene, fayalite, and amphiboles of the cummingtonite-grunerite series.

IRON SILICATE MINERALOGY

Iron silicate minerals are present throughout the Biwabik Iron Formation, and can be used as indicators of metamorphic grade. The layer silicate minerals greenalite, stilpnomelane, and minnesotaite form under conditions ranging from primary or diagenetic to low grade metamorphism. Amphiboles of the cummingtonite-grunerite series form under moderately metamorphosed conditions. Finally in high grade banded iron formations orthopyroxenes and fayalite become the characteristic iron silicates (Klein, 2005). Figure three shows the iron silicate mineral assemblages with increasing metamorphic grade foe the lower metamorphic grades (Klein, 1974). Figure 4 gives the relative stability field for most minerals found in metamorphosed iron formations.

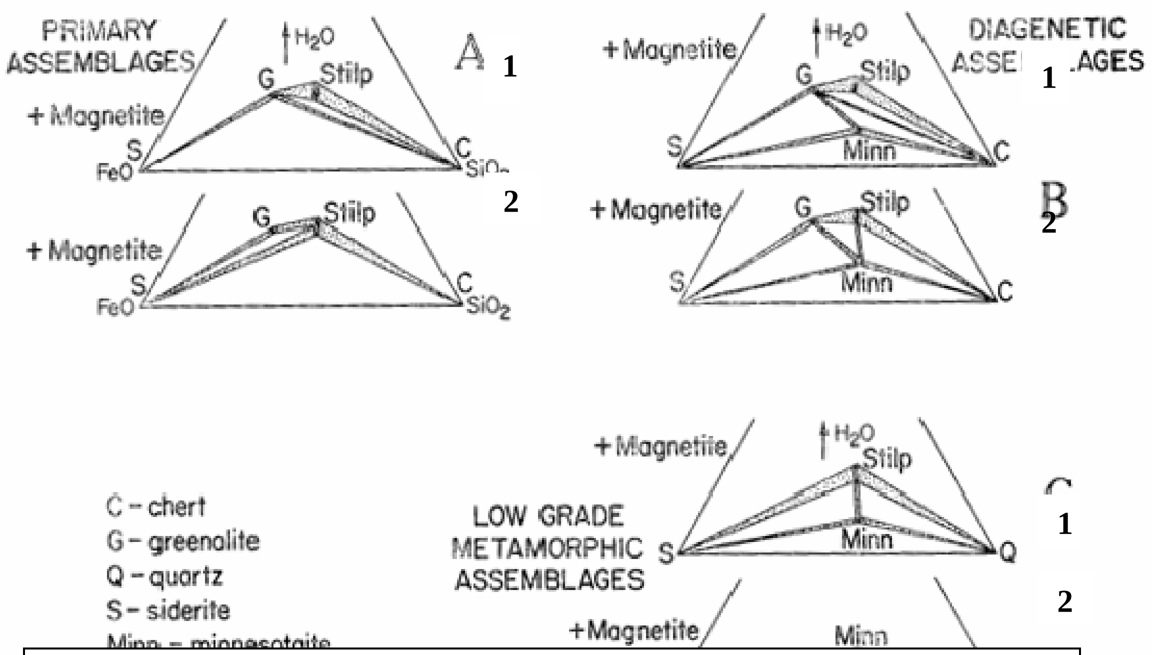


Fig.3. Chemographic diagram showing change in iron silicate mineral assemblages with increasing metamorphic grade (Klein 1974)

Diagenetic to Low Grade Metamorphic Iron Silicates

Greenalite $Fe_6Si_4O_{10}(OH)_8$ may be formed during primary deposition, diagenisis or low grade metamorphism. It is the only mineral thought to be potentially primary in origin, and maybe contained in primary features, such as ooids, granules and as cements. It is microcrystalline and appears light to olive green in color under plain light (Klein, 2005).

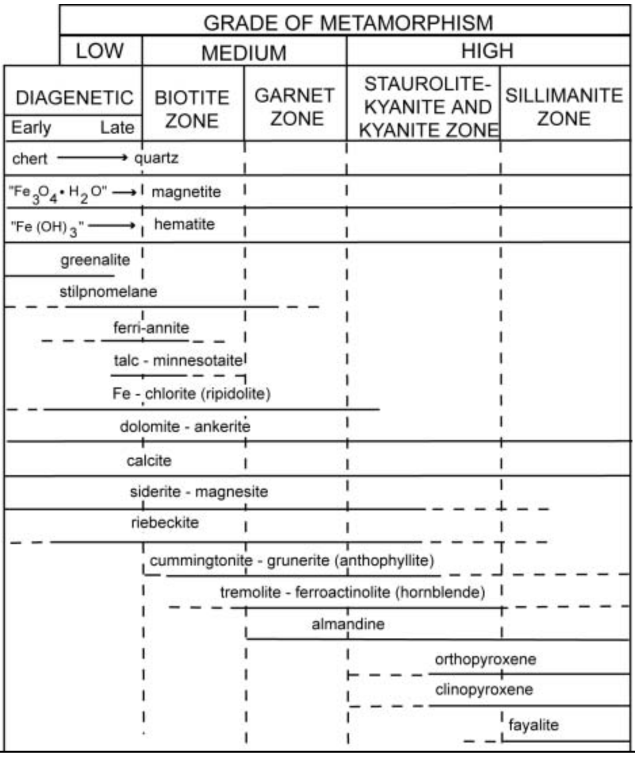


Fig.4. Stability fields of minerals in metamorphosed iron formations (Klein 2005)

Stilpnomelane $Fe_{2\text{-}7}(Si,Al)_4(O,OH)_{12}*xH_2O$ is generally the most abundant of the three iron silicates found in iron formations around the world. Stilpnomelane is thought to first occur during diagenesis but is also formed during low grade metamorphism. In thin section it appears as light to dark brown needles or sheaves and is typically lightly to strongly pleochroic in nature. Stilpnomelane commonly occurs with greenalite in cross cutting relationships. It also occurs in radiating clusters (Klein, 2005).

Minnesotaite $(Fe^{2+}, Mg)\ Si_4O_{10}(OH)$ Is thought to be of low grade metamorphic origin. It is usually not as abundant as stilpnomelane but is still nearly ubiquitous in mineral assemblages of this kind. Minnesotaite appears as fine grained, colorless to light green sprays, and is lightly pleochroic in nature. Minnesotaite is thought to form by reactions such as the combination of chert and greenalite to form minnesotaite, the breakdown of greenalite to form minnesotaite and magnetite, or by the reaction of siderite and chert to producing minnesotaite and carbon dioxide (Klein, 2005).

Moderate Metamorphic Grade Iron Silicates

Minerals of the cummingtonite-grunerite series are the primary mineral assemblages of moderately metamorphosed iron formations. Cummingtonite and grunerite appear in thin section as colorless to light green minerals. They occur as fine grained needles which are often strongly intergrown. Cummingtonite and grunerite are thought to form by the combination of siderite and quartz to form grunerite and carbon dioxide and the breakdown of minnesotaite to form grunerite and water.

METHODS

Sampling

Samples were collected in the summer of 2008, many by Russell Shapiro. Specifically samples were collected from immediately above and below the stromatolite horizons, to ensure the mineral assemblages present would be indicative of the metamorphic conditions of the stromatolites. Hand samples from the Biwabik were taken from the mines: MINNTAC, Polymet 5 pit, LTV 2 east pit, North Shore 38 pit, Mink Mountain, and Kakabeka Falls. Drill core samples from the Biwabik and the Pokegama formations were taken from drill cores stored in the Minnesota Drill core library located in Hibbing Minnesota. Core samples were taken from Minnesota Geologic Survey core 2 and 5 as well as VHB-001. Location of samples can be seen in Fig. 5.

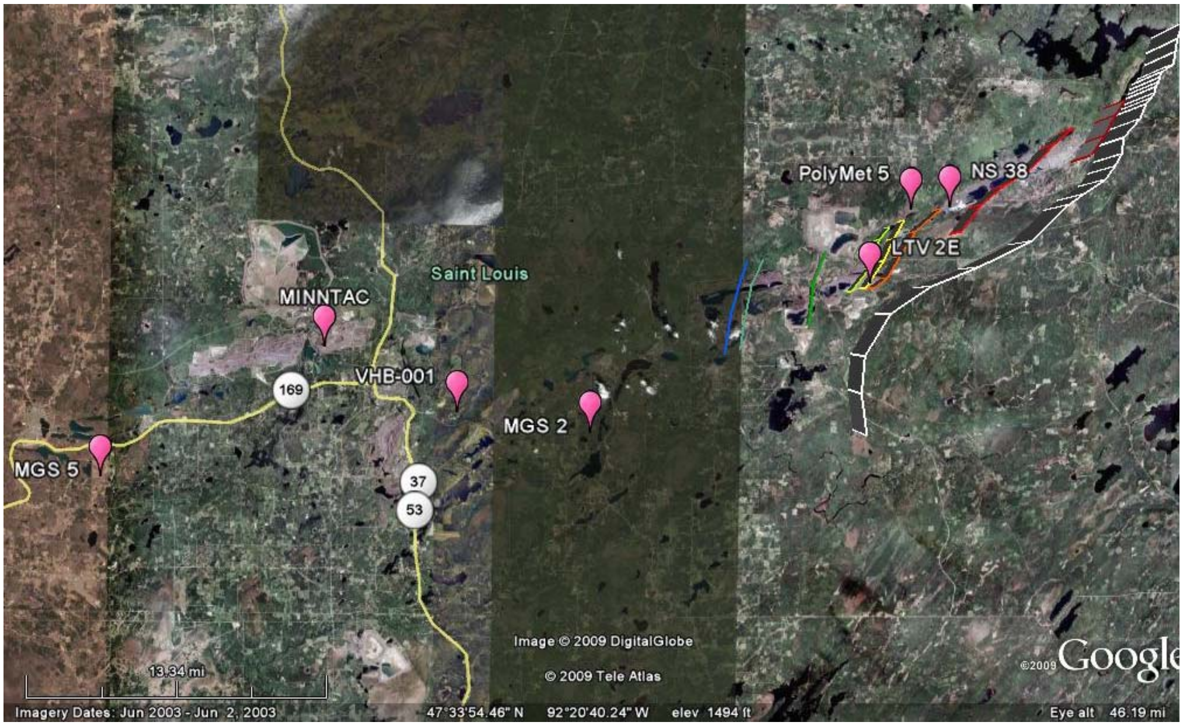


Fig. 5. Map of Mesabi Range showing contact of the Duluth complex, boundaries of metamorphic zones and location of samples (Shapiro et. al. 2008). Polymet five corresponds to the samples LTV5.

Fig. 6 gives a generalized cross section of the Biwabik at the areas sampled.

Samples were taken from the pictured areas above and below the stromatolite layers.

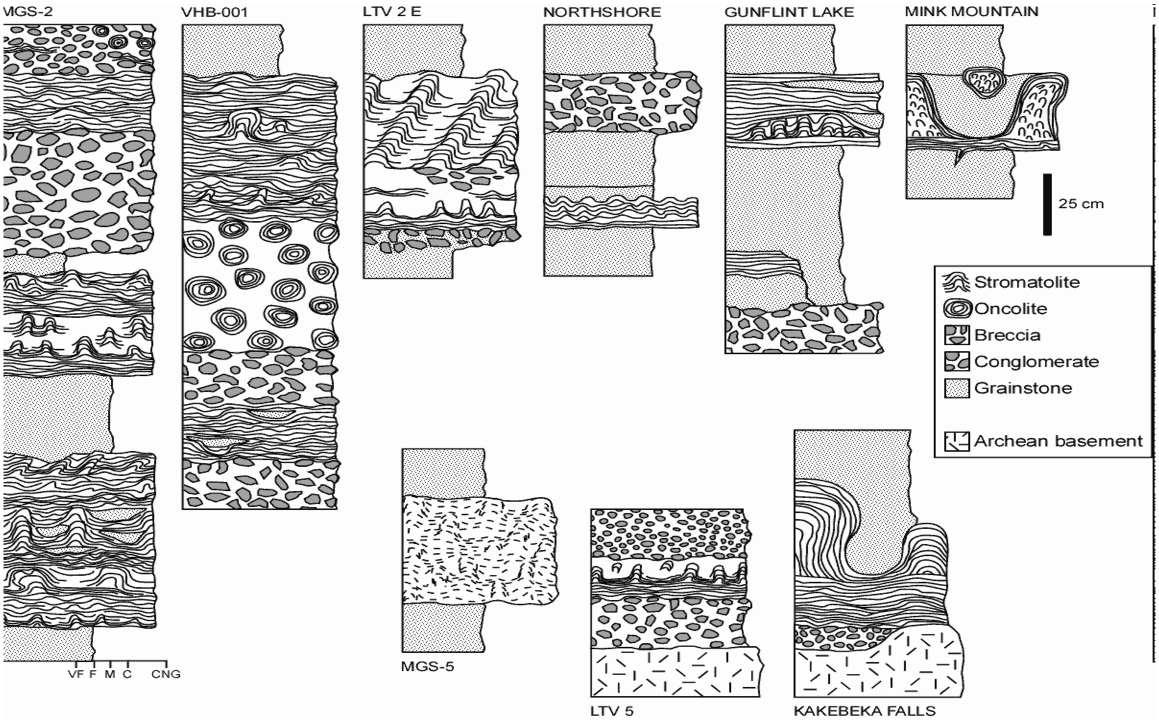


Fig.6. Generalized cross section of the Biwabik iron formation at the localities samples. Samples were taken from above and below the upper and lower stromatolite bearing layers (Shapiro et. al. 2008)

Analytical Methods

Thin sections were made from the hand samples and core samples collected in the field. The thin sections were used to determine preliminary mineralogy and assess the textural relationship of the minerals contained. Further determination of mineralogy was obtained by the use X-ray powder diffraction at Macalester College. Several samples were hand ground using mortar and pestle until sufficiently small grain size was obtained. The results were then matched to minerals with corresponding peaks.

RESULTS

Description of Thin Sections

All thin sections were viewed and the minerals contained were identified and described. Nearly all of the thin sections contain varying amounts of quartz, iron oxides, carbonate, and iron silicates. Because the first three mineral groups are not useful in determining metamorphic grade they will not be described in detail. Thin sections are described from west to east. Table 1 gives the approximate location of each thin section along with its sample number and the iron silicates present.

Sample #	Sample	Location	Unit	Fe Silicates
MGS-5-1207	Core	3 miles southeast of Chisholm	Pokegama	G
MGS-5-1212	Core	3 miles southeast of Chisholm	Pokegama	M, S
MGS- 2-1747	Core	5 miles east of Gilbert	Biwabik	G, M, S
VHB-001-1060	Core	Between Virginia and Gilbert	Biwabik	S
L5-B-1-1	Hand	LTV area 5	Biwabik	G
L2E-B1-1	Hand	LTV 2 east site	Biwabik	CG
L2E-B5-1	Hand	LTV 2 east site	Biwabik	G, M, S
NS38-B-1-1	Hand	North Shore Mine	Biwabik	CG
NS38-B-5-1	Hand	North Shore Mine	Biwabik	CG

Table 1. Table containing sample number, location and minerals present in thin section. G=greenalite, M=minnesotaite, S=stilpnomelane, CG=Cummingtonite/Grunerite

MGS-5-1207: This sample was collected from the Pokegama Formation, above the stromatolite horizon. The thin section contains quartz grains held together by greenalite cement as can be seen in Fig. 7. The greenalite is light green in color, weakly pleochroic, with low birefringence, and microcrystalline in texture.

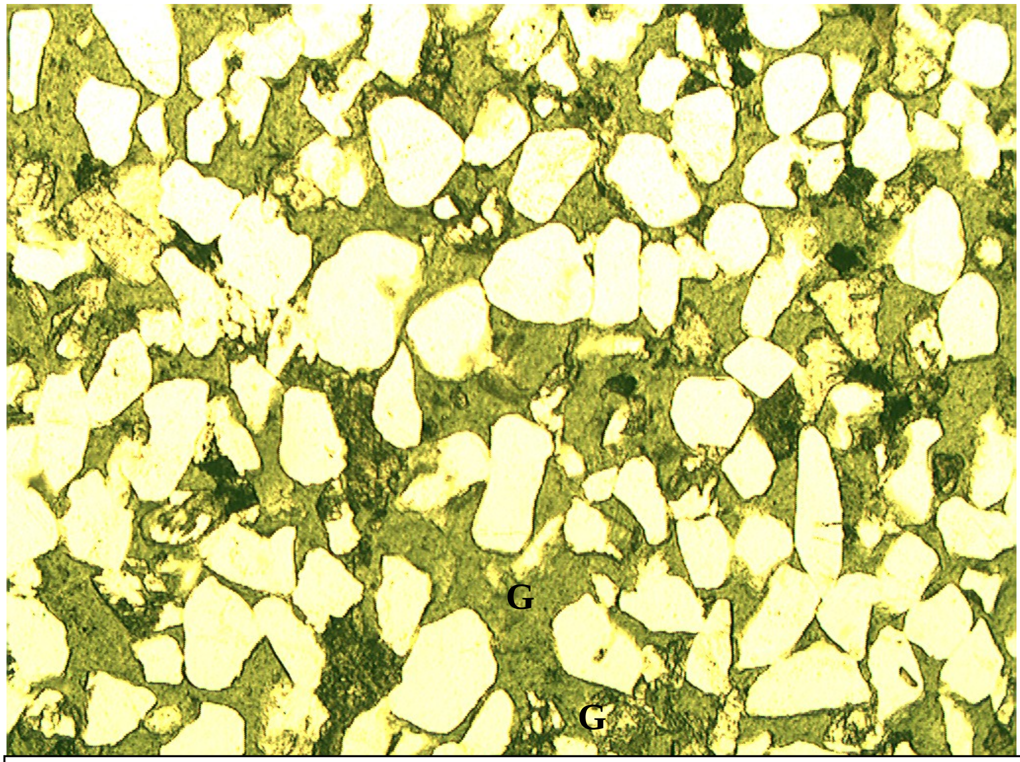


Fig.7. MGS-5-1207: Quartz grains surrounded by greenalite cement at 10X power. G=greenalite

MGS-5-1212: This thin section also from the Pokegama Formation is from a sample 5 feet below MGS-5-1207, and below the stromatolite horizon. In this sample, clasts are predominantly carbonate held together by chert. Iron silicates are not abundant in this section, but include greenalite, minnesotaite, and stilpnomelane. Greenalite occurs mostly as partial replacement in clasts. Minnesotaite most commonly occurs as small radiating clusters intergrown with greenalite, and is recognized by its strong pleochroism and high birefringence (Fig.8). Stilpnomelane is mostly fine grained, locally exhibiting tiny radiating clusters. It is identified by its brown color and pleochroism.

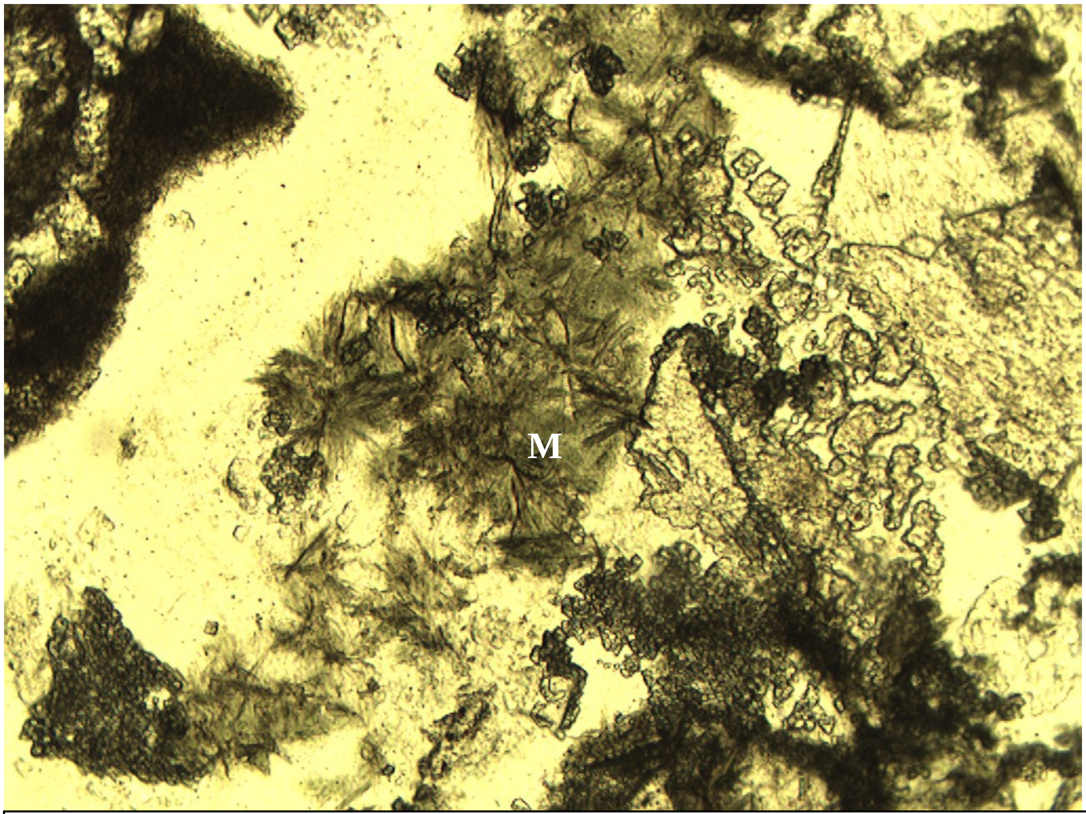
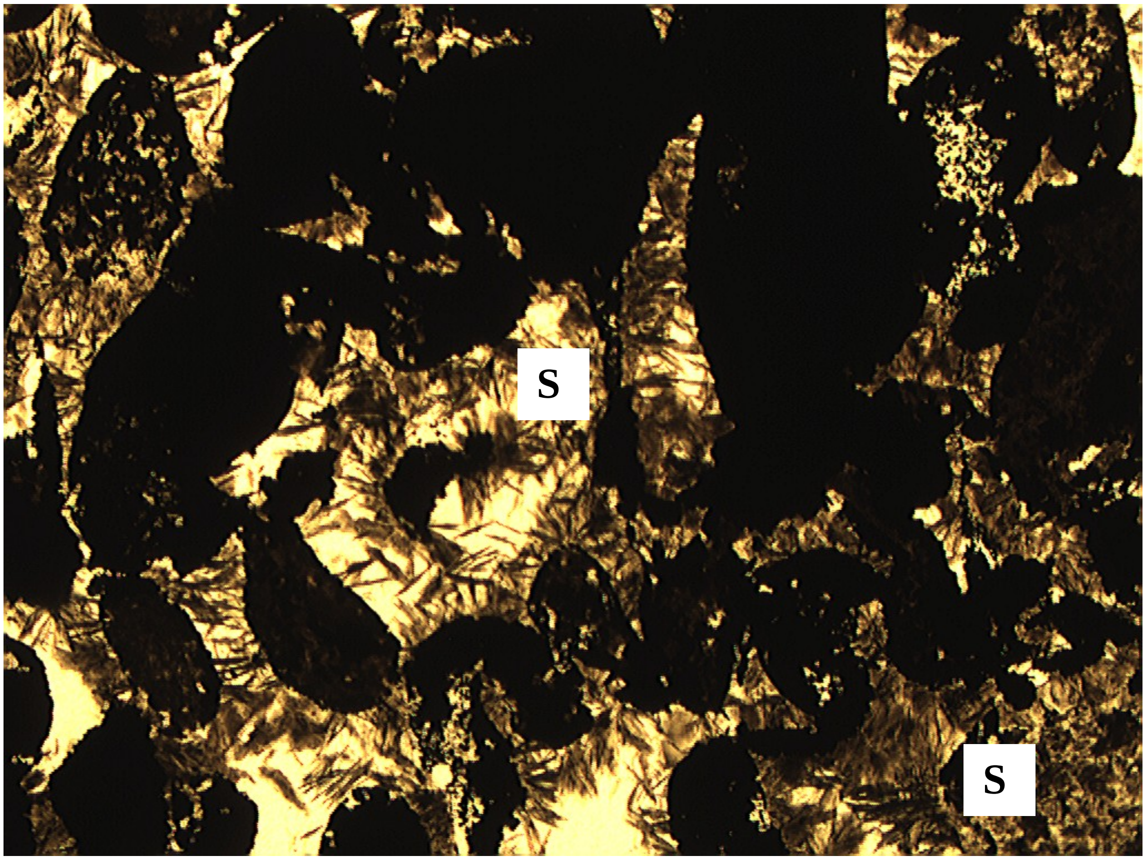


Fig.8. MGS-5-1212: Fine grained fibrous, radiating minnesotaite under 10 X power. M=minnesotaite

MGS-2-1747: This thin section located adjacent to the lower stromatolite layer contains brown radiating stilpnomelane, and fine grained fibrous radiating minnesotaite that tends to be associated with magnetite grains.

VHB-001-1060: The thin section contains olive brown stilpnomelane with a radiating acicular habit (Fig.9) and smaller amounts of radiating fibrous minnesotaite. Minnesotaite displays an olive green to light brown pleochroism.



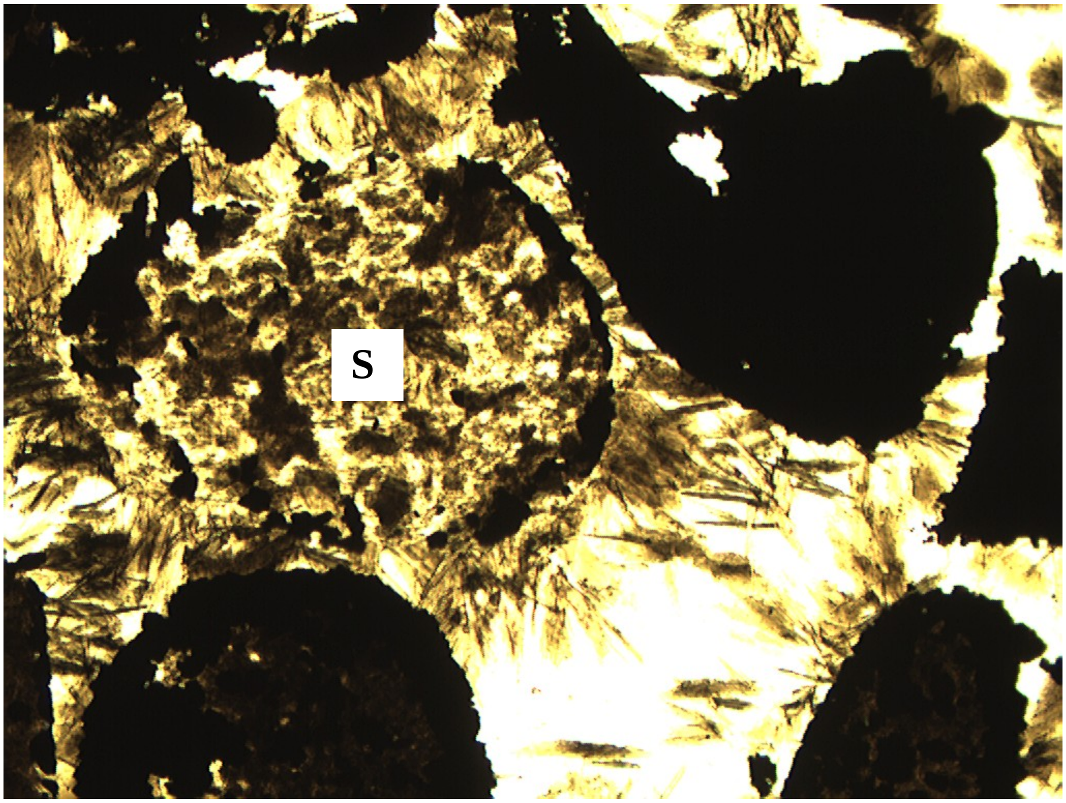


Fig.9. VHB-001-1060: Olive brown, radiating, acicular stilpnomelane in 4X power above and 10X power below. S=stilpnomelane

L5-B-1-1: This sample was collected from an intraformational conglomerate horizon collected from the upper stromatolite layer. It contains clasts of quartz, carbonate, granules of greenalite, and intraclasts of fine sandstone and siltstone. The greenalite granules are dark green to olive green in color and are microcrystalline in character (Fig.10.).

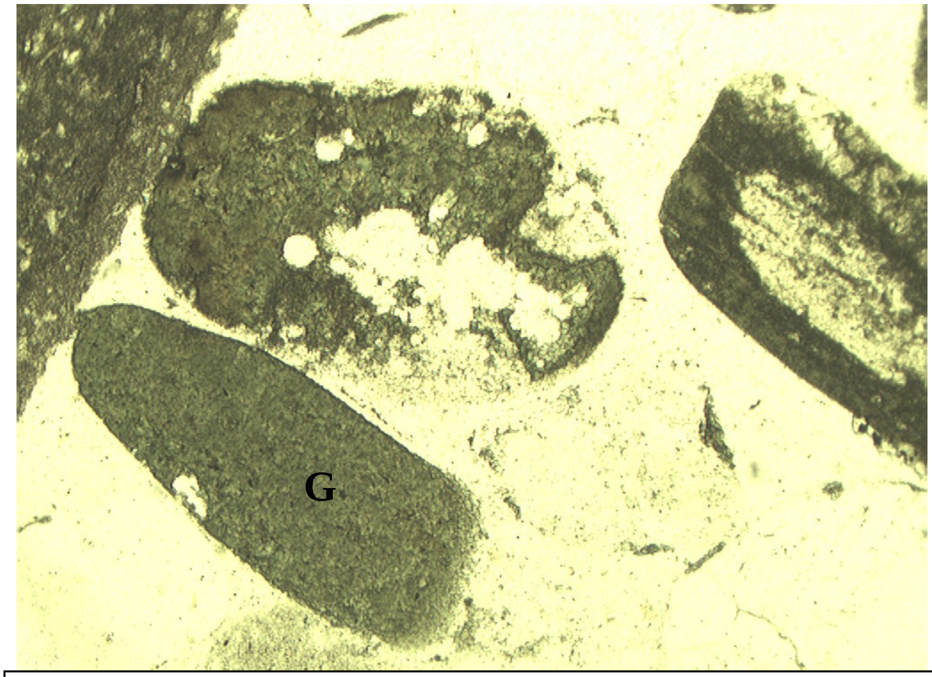


Fig.10. L5-B1-1: Dark green microcrystalline greenalite granules under 10X power. G=greenalite

L2E-B1-1: The thin section contains radial masses of amphibole colorless to pale green in color, most likely of the cummingtonite grunerite series.

L2E-B5-1: This sample comes from the same locality as the previous sample. It contains numerous radiating clusters of an acicular pale brown to nearly colorless amphibole, probably cummingtonite. These clusters typically radiate from somewhat amorphous dark brown centers. A few of these dark brown clusters are pleochroic and may be stilpnomelane. It appears that the amphibole may be forming from the breakdown of stilpnomelane or possible hematite. Also present are small micaceous looking greenish pleochroic grains of moderate to high birefringence, probably minnesotaite, which also appears to be in the process of breaking down.

NS38-B-1-1: This sample taken adjacent to the upper stromatolite, contains a small amount of a radiating amphibole of the cummingtonite-grunerite series.

NS38-B-5-1 contains a considerable amount of fibrous radiating amphibole of the cummingtonite grunerite series (Fig. 11). The mineral is pale green in color suggesting chemical makeup intermediate between cummingtonite and grunerite.

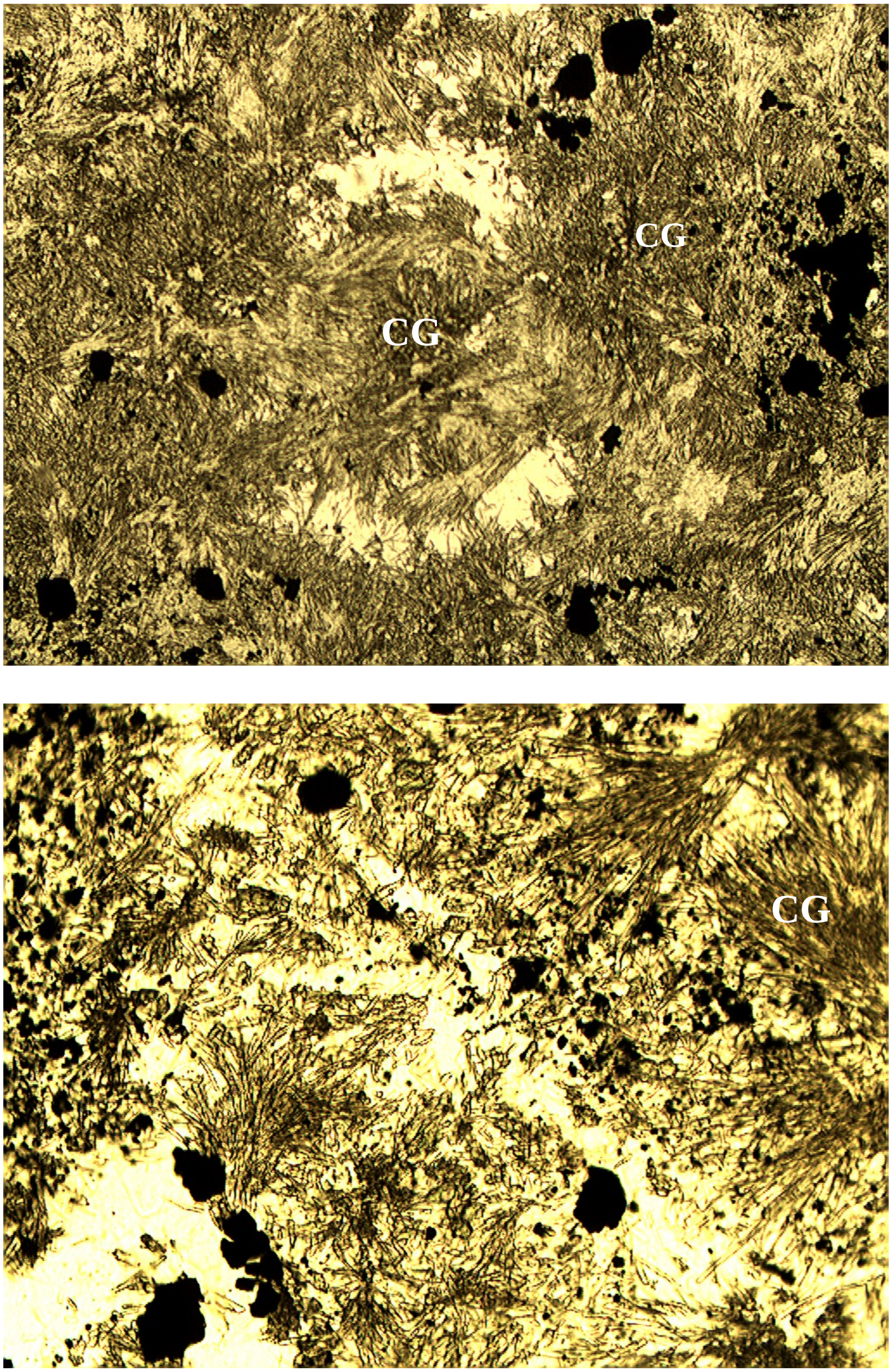


Fig.11. NS38-B-5-1: Intergrown, fibrous, radiating masses, of cummingtonite-grunerite in 4X on previous page and 10X power below. CG=cummingtonite/grunerite

X-Ray Analysis

X-ray analysis was conducted to verify that the iron silicates seen and described in thin section were indeed the minerals they were identified as. Minerals were identified by the method of X-ray powder diffraction using the XRD at Macalester College. Five samples were powdered and ran through the machine to verify the minerals they contained. The five samples were chosen because they contain key iron silicate minerals in great enough abundance to make identification possible. The samples ran through the XRD were: VHB-001-1060, MGS-5-1207, MGS-5-1212, MGS-2-1747, and finally NS38-B5-1. VHB-001-1060 was run three times once with all of the magnetite content present, once with the magnetite content removed, and once at a lower angle to verify the presence of stilpnomelane. The first two were run to determine whether concentration would have an appreciable effect on the analysis.

VHB-001-1060: This sample was run three separate times once with magnetite removed, once without, and once at a lower angle. Both of the first two readouts showed the same minerals present quartz and iron oxide. Figure 12 gives the XRD readout for the third run which used a lower 2 theta angle which confirmed the presence of stilpnomelane.

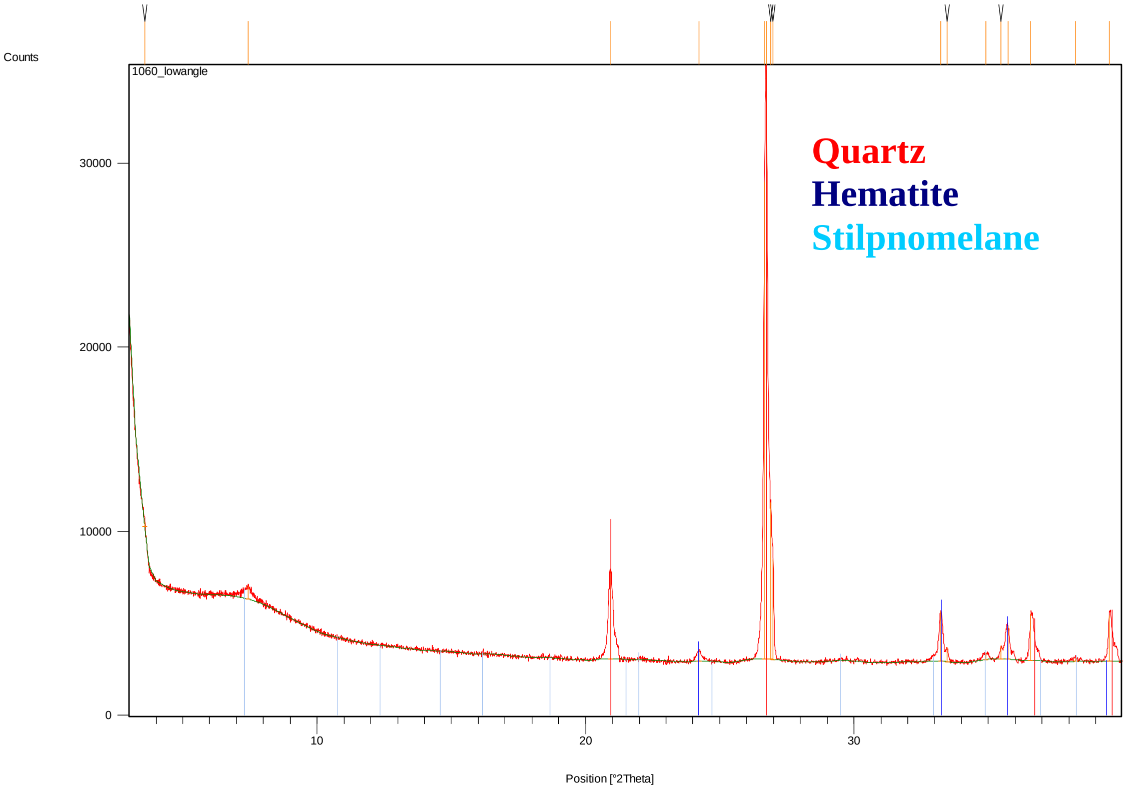


Fig.12. X-ray diffraction analysis results of count versus 2 theta of sample VHB-001-1060 showing the presence of quartz and hematite.

MGS-5-1207: The peaks produced by the X-ray analysis for this sample confirmed the presence of the iron silicate greenalite as well as major amounts of Quartz (Fig.13). This sample was described in thin section to contain greenalite cement.

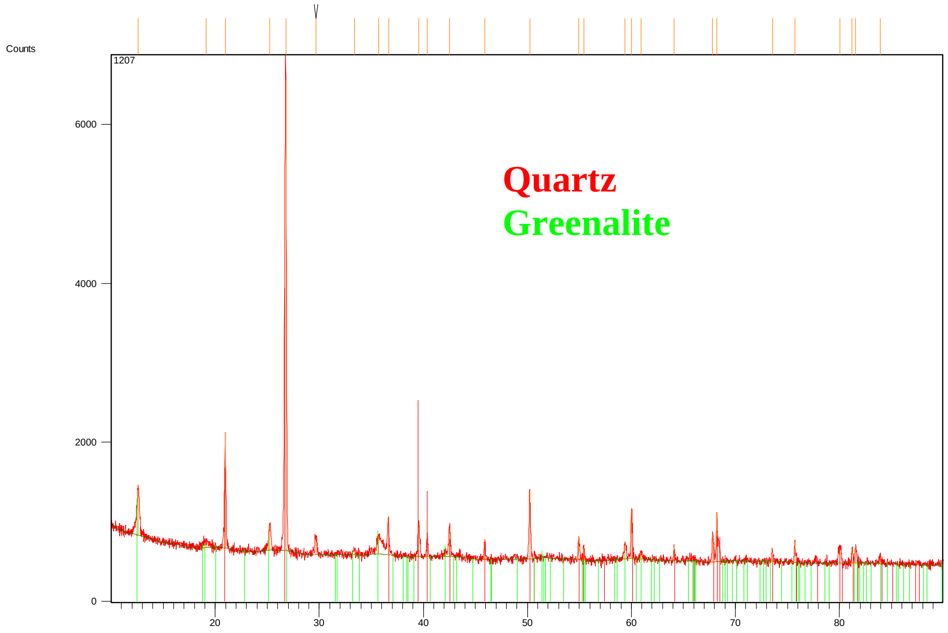


Fig.13. Count versus 2 theta readout for sample MGS-5-1207 showing the presence of quartz and greenalite.

MGS-5-1212: This sample was confirmed by X-ray diffraction to contain quartz, calcite, and siderite (Fig.14). No iron silicates described in thin section were verified by the peaks produced by the XRD.

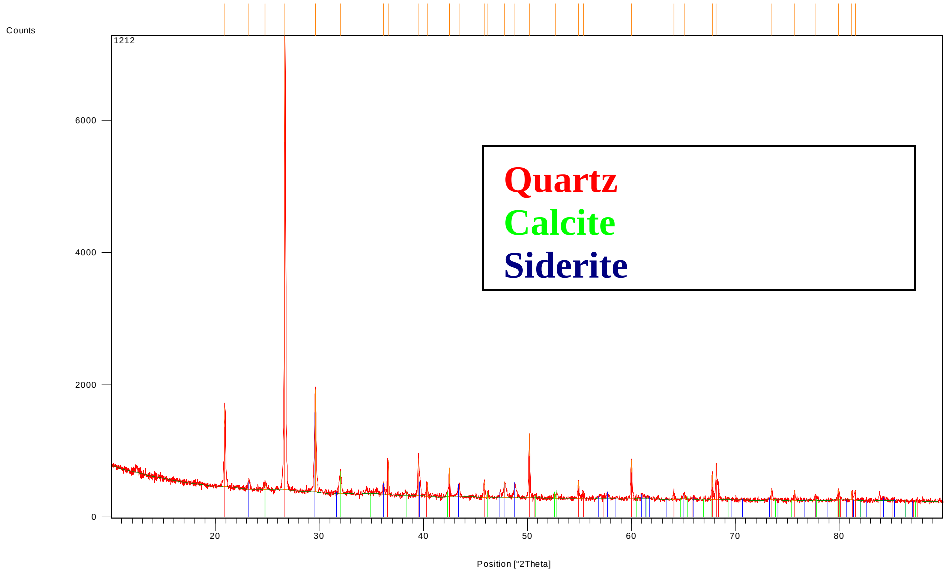


Fig.14. Graph of count versus 2 theta for sample MGS-5-1212 verifying the presence of quartz, calcite, and siderite.

MGS-2-1747: This core sample was confirmed by the XRD to contain quartz and greenalite (Fig.15). Minnesotaite and stilpnomelane were also described in thin section but were not verified by X-ray analysis.

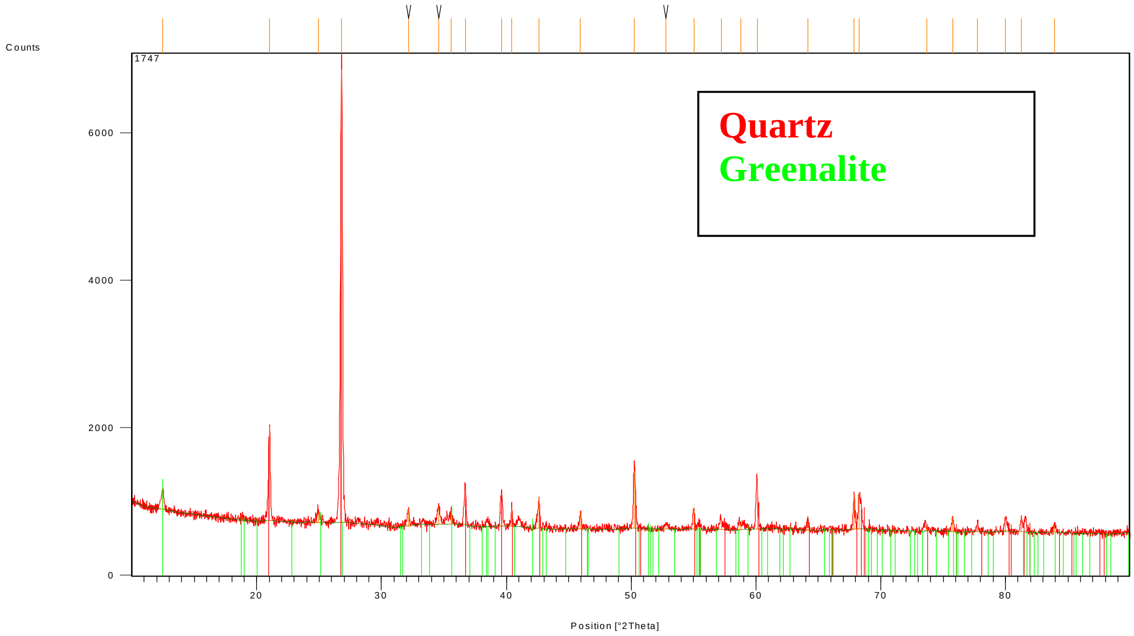


Fig.15. Count versus 2 theta readout for the sample MGS-2-1747 confirming the presence of quartz and greenalite.

NS38-B-5-1: The peaks produced by the XRD confirmed that this sample from the eastern side of the iron formation contains the minerals quartz, iron oxides, and cummingtonite (Fig.16). Confirmation of the presence of cummingtonite by X-ray analysis coincides with the optical description of an amphibole mineral present in the thin section.

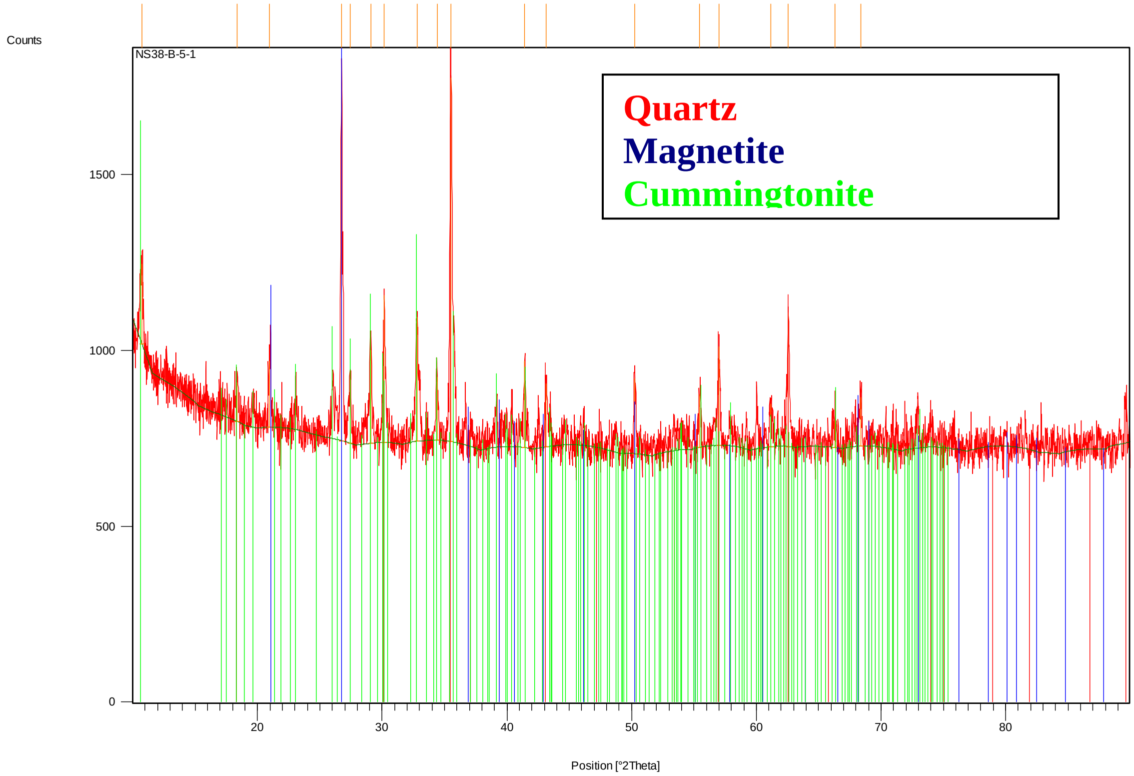


Fig.16. Graph of count versus 2 theta for sample NS38-B-5-1 confirming the presence of magnetite, Quartz, and cummingtonite.

X-ray analysis was used to verify the presence of minerals described in thin section with limited success. The XRD was unable to pick out any peaks corresponding to minnesotaite. The failure to identify minnesotaite was most likely due to very small concentrations of the mineral or to the fact that the major peaks were outside the scanning range.

DISSCUSSION

Based on thin section and X-ray analysis it has been concluded that the samples and the adjacent stromatolites range in metamorphic grade from possibly upper diagenetic to moderate metamorphic grade, which is consistent with the earlier studies done by French (1968). The core samples *MGS-5-1207*, *MGS-5-1212*, *VHB-001-1060*, and *MGS-2-1747* contain the minerals greenalite, stilpnomelane, and minnesotaite. Based on the mineral assemblages present the samples from these cores are most likely of upper diagenetic chlorite zone greenschist facies.

L2E-B-1-1 and *L2E-B-5-1* from the LTV mine contain a colorless to pale green amphibole of the cummingtonite/grunerite series. *L2E-B-5-1* may also contain traces of minnesotaite and stilpnomelane in the process of breaking down. The presence of cummingtonite/grunerite and the potential breakdown of stilpnomelane and minnesotaite suggest this sample is also of moderate metamorphic grade most likely of the upper biotite zone of the greenschist facies or higher.

The sample *L5-B-1-1* appears to be anomalous in nature. It contains granules of greenalite in a location were the metamorphic grade should be much too high for greenalite to exist. The greenalite in the sample may be confused for a chlorite mineral which can exist at higher metamorphic grades.

NS38-B-1-1 and *NS38-B-5-1* both from the North Shore mine contain an amphibole of the cummingtonite/grunerite series. Presence of this amphibole suggests moderate metamorphic grade of lower amphibolite facies.

CONCLUSION

The Biwabik iron formation preserves two layers of stromatolites that have undergone various degrees of metamorphism. This study attempts to aid in deciphering the effects of metamorphism on stromatolites by providing the metamorphic grade of the stromatolites at various locations. The Degree of metamorphism adjacent to the stromatolites was determined using thin section and XRD analysis. The minerals adjacent to the stromatolite horizons in this research were found to range from upper diagenetic to moderate emetamorphis grade metamorphism of lower amphibolite facies It is anticipated that the information obtained from this study will be useful for future interpretation of stromatolite textures.

Suggestions for further research on this topic include the use of a scanning electron microscope or electron micro probe to better analyze chemical compositions and to further verify the minerals present in thin section. Further verification may also be possible by concentrating mineral samples to increase the relative abundances of minerals such as minnesotaite and stilpnomelane.

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