<u>Sodic Amphibole in Metavolcanics: Newton Lake Formation</u>

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Abstract

Metamorphic rocks, formed by heat and pressure, are some of the best geological indicators of conditions deep within the earth. The Newton Lake Foramtion, in northeastern Minnesota is an Archean (~2.7 billion years old) metamorphic rock might have formed at a plate margin, when two pieces of earth's crust collided. Metamorphic minerals in the Newton Lake Formation allow evaluation of pressure and temperature conditions, thus permitting comparison between Archean and modern convergent boundaries.

Previous studies have suggested that the collision that produced Newton Lake Formation experienced moderate temperature and pressure conditions (greenschist and amphibolite facies metamorphism), contrasting with rock formed in similar settings today, which experiences lower temperature relative to pressure (blueschist facies)(Condie, 2005). Recent examination of the metavolcanics revealed a sodic (blue) amphibole. This blue mineral is intriguing because the sodic amphibole glaucophane is indicative of high pressure, low temperature metamorphism (blueschist facies). A different blue amphibole, riebeckite, would indicate greenschist or amphibolite facies. Thus, identification of this mineral will help constrain the temperature and pressure conditions that produced the Newton Lake Foramtion, perhaps challenging previous hypotheses about Archean plate tectonics. To answer this question, thin sections were analyzed by transmitted and

reflected light microscopy, electron microprobe and x-ray diffraction, to determine the chemical composition of the amphibole.

These analyses indicate that the metavolcanic rocks experienced at least two episodes of metamorphism and the sodic (blue) amphiboles are most likely riebeckite and magnesio-riebeckite, suggesting that greenschist to amphibolite facies metamorphism, rather than modern style blueschist facies metamorphism, characterizes the Newton Lake.

Acknowledgements

The amount of collaboration on this project was incredible and if not for scientific collaboration, this project would not be what it is. First off, I would like to thank Dr. Jim Welsh for supervising my research at Gustavus Adolphus College and for initiating and pushing me to pursue my interest in geology and scientific research. Secondly, I would like to thank Mr. Barry Frey of the Minnesota DNR, for the introduction of this project as well as all of the help at the MN DNR Core Library in Hibbing Minnesota. Next, I want to thank Dr. Anette von der Handt and the Department of Earth Sciences at the University of Minnesota. Dr. Von der Handt was extremely helpful in assisting this research using the electron microprobe. Fourth, I would like to thank Gustavus Adolphus College physics department specifically Jesse Petricka for assisting in x-ray diffraction. Fifth, I would like the thank Dr. Paul Weiblen for assisting in reflected light microscopy. Sixth, I would like to thank Geology Undergraduate student John Berger, for assisting with technology glitches that arose during this study. Lastly, I would like to thank the Gustavus Adolphus Geology faculty in assisting me in every manner possible throughout my undergraduate work.

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Introduction

Greenstone belts, formed during the Archean Eon (2.5-4.0 billion years ago), comprise significant portions of North America's stable interior. These mafic to ultramafic volcanic sequences and associated sedimentary rocks have experienced multiple mountain-building (orogenic) episodes in their long and complex history. They are a major host for gold and other metallic mineral deposits that often extend to depths well beyond current mining abilities. Numerous greenstone belts are exposed throughout the Canadian Shield. The Wawa Greenstone Belt extends over southern Quebec and Ontario, and westward into Minnesota where it is known as the Vermilion Greenstone Belt.

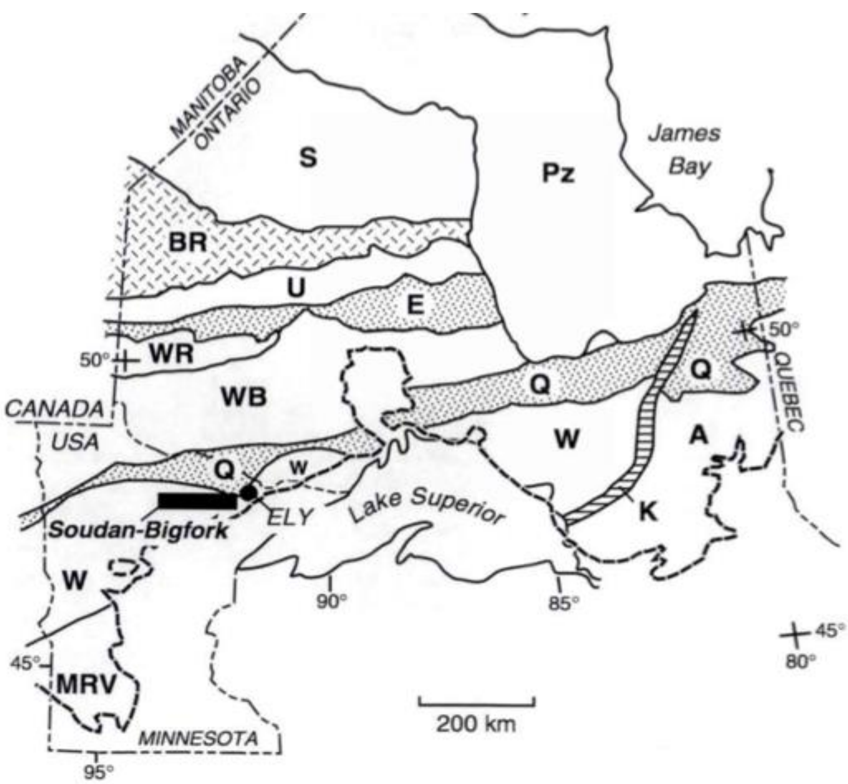

Figure 1: Approximate locations of the Soudan Bigfork area of the Vermillion district in the Wawa subprovince. Subprovince names: S, Sachigo; BR, Berens River; U, Uchi; E, English River; WR, Winnipeg River; WB, Wabigoon; Q, Quetico; W, Wawa; A, Abitibi; MRV, Minnesota River Valley; K, Kapuskasing structural zones; P, Paleozoic rocks in Hudson.

The Vermilion District has been the focus of mineral exploration for more than a hundred years. Low-cost sampling of small rock samples such as glacial clasts and pebbles from gravel pits has revealed several areas with potential for lode gold and massive volcanogenic massive sulfide deposits (Lawler, 1997). Although the Vermilion district was a significant source of iron ore (from banded iron formation) prior to the cessation of mining in 1962, repeated explorations for nonferrous metals over the past 130 years have yielded little success. One core sample drilled by Kerr McGee for Lehmann & Associates in 1984, was upon examination found to contain blue amphibole. Blue amphiboles are rare and may be an indication of high-pressure, low temperature metamorphism such as blueschist facies metamorphism (Wood, 1980). According to previous analysis (Robinson, 1985), greenstone rocks in the Vermilion District (Ely Greenstone) have been subjected to greenschist facies and lower amphibolite facies metamorphism, and blue amphibole had not been previously reported.

The sodic amphibole observed in this core occurs within a 54- foot interval of banded iron formation. Banded iron formations are present within the Vermilion Greenstone Belt (Clement, 1903, Hudak, 2007). Banded iron formations (BIFs) are distinctive units of sedimentary rock that are generally Precambrian in age, the most promiment being the Soudan Iron Formation, which was mined from 1884 to 1962 (Jirsa et al., 2011). A typical BIF consists of repeated thin layers of silver to black iron oxides that range from a few millimeters to a few centimeters in thickness, with the iron portion being composed of either magnetite (Fe_3O_4) or hematite (Fe_2O_3). These layers alternate with bands of iron-poor shales and cherts, often red in color (Katsuta et al., 2012).

There are a number of Na-amphiboles, the most important members of this group are glaucophane and riebeckite. Glaucophane has the general formula

$Na_2Mg_3Al_2(Si_8O_{22})(OH)_2$. In contrast, riebeckite $Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$ contains little Mg and is essentially a Na-Fe amphibole, in which most iron is Fe^{3+} (Ernst, 1963). Glaucophane typically forms in the blueschist facies; riebeckite or magnesio-riebeckite, the magnesium – rich variety of riebeckite, typically forms within the greenschist to amphibolite facies (Ernst, 1963).

Glaucophane forms under a wide range of pressure and temperature conditions. High pressures are not required for the production of glaucophane itself. It is stable under pressure- conditions present in the greenschist and epidote amphibolite facies, in rocks deficient in CaO and rich in Na_2O and MgO relative to Al_2O_3 (Ernst 1963). Riebeckite is often associated with igneous processes in addition to metamorphic conditions, such as those that formed the rocks of the Vermilion District (Papike and Clark, 1968). Like many amphibole minerals, the blue amphibole is occurs as blades and long slender crystals (Wood, 1980). When trying to characterize amphiboles, optical mineralogy cannot be used alone, but rather requires chemical analysis (Papike and Clark, 1968).

Modern and Phanerozoic arcs frequently exhibit blueschist facies metamorphism (Condie, 2005), but Archean convergent boundaries do not typically contain these high pressure–low temperature rocks, although similar tectonic processes, such as subduction, were likely occurring (Condie, 2005). By better characterizing the metamorphic conditions of ancient convergent boundaries, we can learn how ancient plate tectonics might have differed from their modern process.

The purpose of this study is to determine the nature of this unique amphibole, and to better broadly characterize the geologic conditions as represented by the rocks of this core. The blue amphibole is significant in these rocks because blueschist facies have not been identified in greenstone assemblages in Archean rocks in general. Identification of this amphibole will aid in the determination of the metamorphic conditions that affected these rocks.

Geologic Setting

The Vermilion District is situated in northern Minnesota alongside very old and complex geology. Northern Minnesota, Southern Ontario, and Western Manitoba consist of a set of granulite-greenstone terranes that are Archean in age. Much of the metamorphism of these rocks occurred during the Archean (Hudleston, 1988). The Vermilion District is the best exposed and most thoroughly studied of the greenstone and granite complexes in northern Minnesota (Southwick, 1998). Supracrustal rocks that lie within the Vermilion district consist of volcanic-dominated stratigraphic sequences of the Wawa subprovince of the Superior Province of the Canadian Shield. Rocks of the Wawa subprovince in northern Minnesota (figure 1) are divided on the basis of stratigraphic and structural setting into two fault bounded belts: (1) the Soudan belt, to the south, and (2) the Newton belt, to the north. (Jirsa et al., 1992; Southwick et al., 1998).

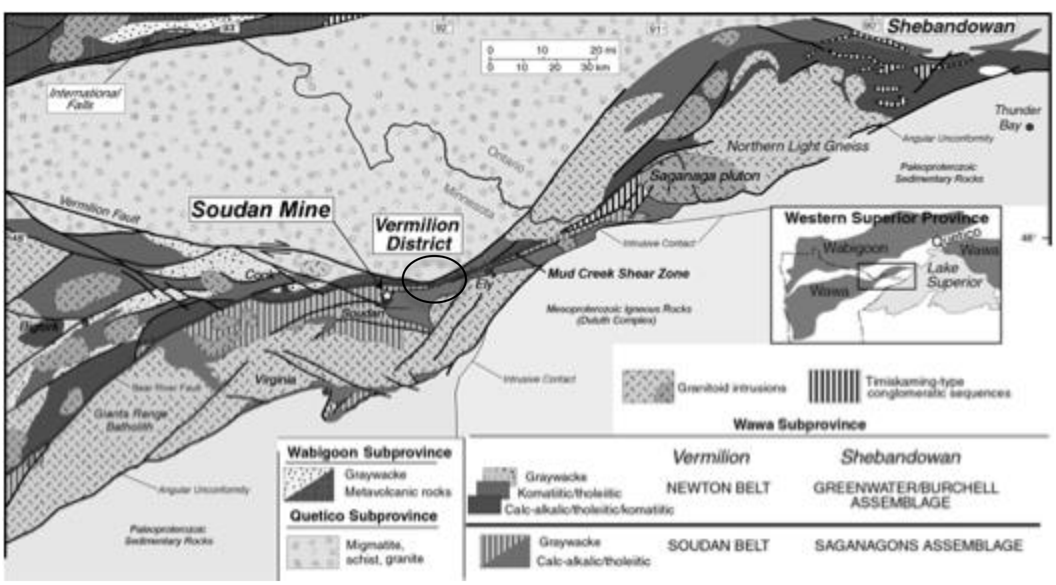

Figure 2: Simplified geologic map of Neoarchean assemblages across the U.S. - Canada border. Inset illustrates major subprovinces of the southwestern Superior Province (Peterson et al., 2001). The circle above refers to the area in question.

The Soudan belt contains large, broad folds involving calc-alkalic and tholeiitic volcanic strata overlain by, and locally interdigitated with, turbidties. The Soudan belt is broken up to into three distinct groups: 1. Upper Greenstone, which is tholeiitic basalt lava flows with some iron-formation. 2. Soudan Iron Formation, consisting of layered cherty iron-formation, epiclastic rocks, and tuff. 3. Lower Greenstone, which consists of Calc-alkalic and tholeiitic basalt-rhyolite lava flows, tuffs, epiclastic rocks and minor iron-formations (Southwick, 1998). According to Southwick, the greenstone belt as a whole has attributes consistent with development in an oceanic volcanic-arc setting that is broadly analogous to our modern arcs in the western Pacific basin.

The Newton belt is broken up into two groups. First is the Bass Lake Sequence which is a tholeiitic basalt lava flow, iron-formation, and felsic porphyries (Hudak, 2004). The second part of the belt is the Newton Formation. This formation consists of tholeiitic and komatiitic basalt flows, intrusions, and clastic strata (Hudak, 2004). Volcanic rocks of the Newton belt differ from those of the Soudan belt in that they contain locally abundant komatiitic flows and peridotitic sills. The two belts are fault-bounded, and the relationship between stratigraphic units within each belt is largely.

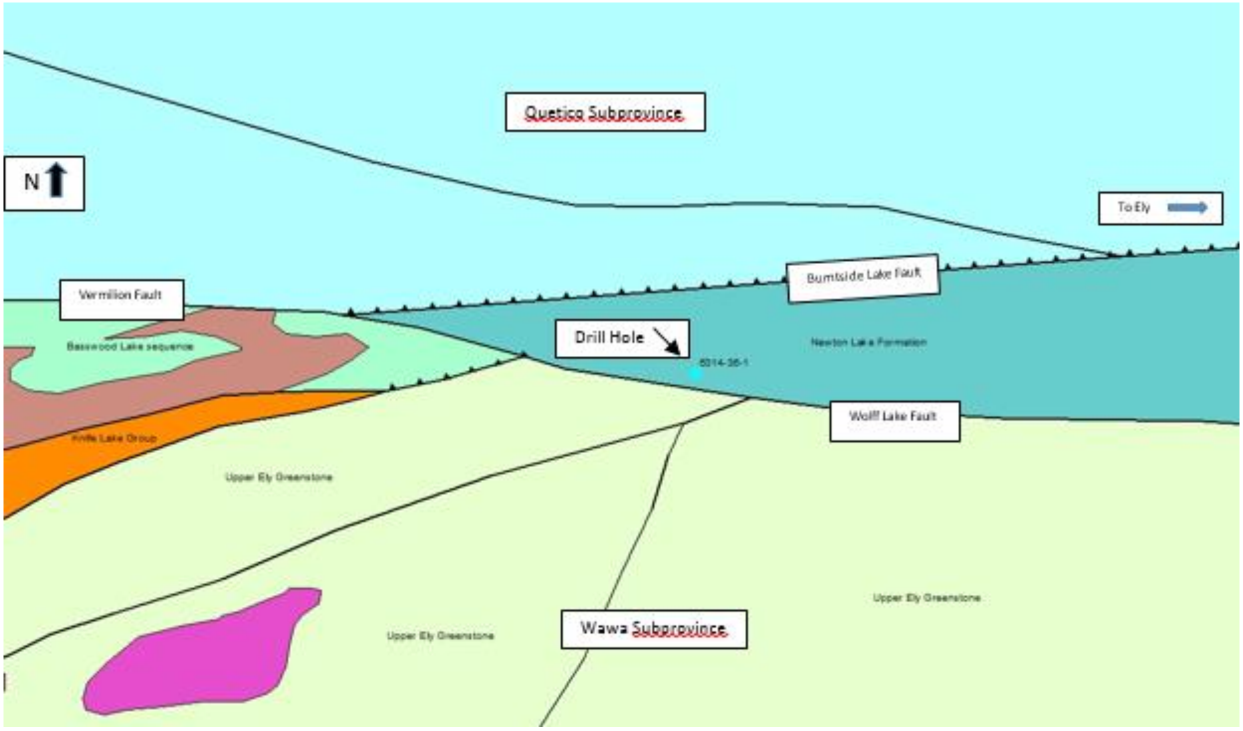

Figure 3: Simplified geologic map of Neoarchean assemblages. Drill hole is bounded by the Burntside lake fault (mud-creek sheer zone) to the north, and the Vermilion- Wolf Lake fault to the south. The drill hole lies near the border of Quetico - Wawa subprovince.

The core analyzed in this study was drilled between Soudan – Ely, in St. Louis County in northeast Minnesota: $^1/_4$SE, $^1/_4$SE, section 36, township 63N, Range 14W. The drill hole is bounded by the Burntside lake fault (mud-creek sheer zone) to the north, and the Vermilion- Wolf Lake fault to the south. The drill hole lies near the border of Quetico- Wawa subprovince, but sits within the Newton Lake Formation. Units that will be seen include (from top down): glacial overburden, greenstone, banded iron formation, and more greenstone.

Methods

I examined the entire 499 feet of rock core. Secondly, I revised/condensed a core log that was previously made by Kerr- McGee during drilling. The next step was to gather the previously made thin sections and to investigate the rock core for areas of other potential areas that might contain sodic amphibole is present or looks to be present. The fourth step was to examine the thin sections with a petrographic microscope to understand the different mineral assemblages that were obtained from the drill core. The fifth step was visiting the University of Minnesota where we identified areas of the thin section where we wanted to test using the electron microprobe.

Chemical analyses of the blue amphibole was performed on a JEOL JXA-8900R electron microprobe at the Department of Earth Sciences, University of Minnesota. The operating conditions were an accelerating voltage of 15 keV, beam current was 20 nA, and the beam diameter was 1 micron. Elements were acquired using analyzing crystals LiFH for Mn Kα, Fe Kα, LiF for Ti kα, PETJ for Ca kα, K Kα, and TAP for Al Kα, Si Kα, Na Kα, Mg Kα, F Kα.

The standards used were apatite, fluorapatite, phosphate for F ka, hornblende, amphibole, silicate for Mg ka, Al ka, K ka, Ca ka, ilmenite, oxide for Ti ka, Fe ka, albite, plagioclase, feldspar, silicate for Na ka, Si ka, and Mn_2SiO_4 (synth) for Mn ka. The counting time was 10 seconds for all elements. Intensity data was corrected for Time Dependent Intensity (TDI) loss (or gain) using a self-calibrated correction for Si ka, Na ka, Mn ka, K ka, Ti ka. The off-peak counting time was 10 seconds for all elements. The off peak correction method was linear for all elements.

Unknown standard intensities were corrected for dead-time. Standard intensities were corrected for standard drift over time. Results were obtained on single points and detection limits are .018 weight percent for Al Kα; .018 weight percent for Mg Kα; .026 wt% for Ca Kα; .05 wt% for Fe Kα; .10 wt% for F Kα. Analytical sensitivity (at the 99% confidence level) ranged from .33 percent relative for Si ka to .78 percent relative for Mg ka to 1.71 percent relative for Na ka to 20.07 percent relative for K ka to 591.60 percent relative for Ti ka. Oxygen was calculated by cation stoichiometry and included in the matrix correction.

X-Ray diffraction was used to quantify the amount of hematite and magnetite as a proxy for Fe^{2+} and Fe^{3+}. This process included powdering rock chips of VG-5 and VG-6 using SPEX Sample Prep Mixer 8000M. After powdering samples were analyzed using a Phillips MPD X' Pert Pro. Reflected light microscopy was used to determine the Fe^{2+} and Fe^{3+} ratio.

Results

Brief description of the core

The condensed version of the core log is located in figure (4).

The topmost 29 feet of the site area are glacial in origin, and consists of sand and gravel figure (4). Directly below the glacial unit is 174 feet of basalt and basalt breccia. This part of the core is massive and pillowed.

The third section of this core is 54 feet in thickness and consists of banded iron formation (oxide facies). This section of the core mainly consist of minerals such as grey chert, black magnetite, green chlorite and blue amphibole figure (4). The chert and magnetite beds are 2-20 mm thick. Some of these beds show quartz alternations that are often brecciated.

The fourth section of rock core (silicate facies) is 68 feet thick. This section also has minor amounts of magnetite and pyrite contacting BIF. Jasper starts to show up towards the bottom of this section of core.

The next section of rock (sulfide facies) is 34 feet in thickness and contains chert, graphite and pyrite association.. This section still has banded iron formation within.

The lowermost unit in this core is 140 feet thick and is made almost completely of greenstone. It should be noted that there is no magnetite present in this section of rock. This section of rock is uniform throughout.

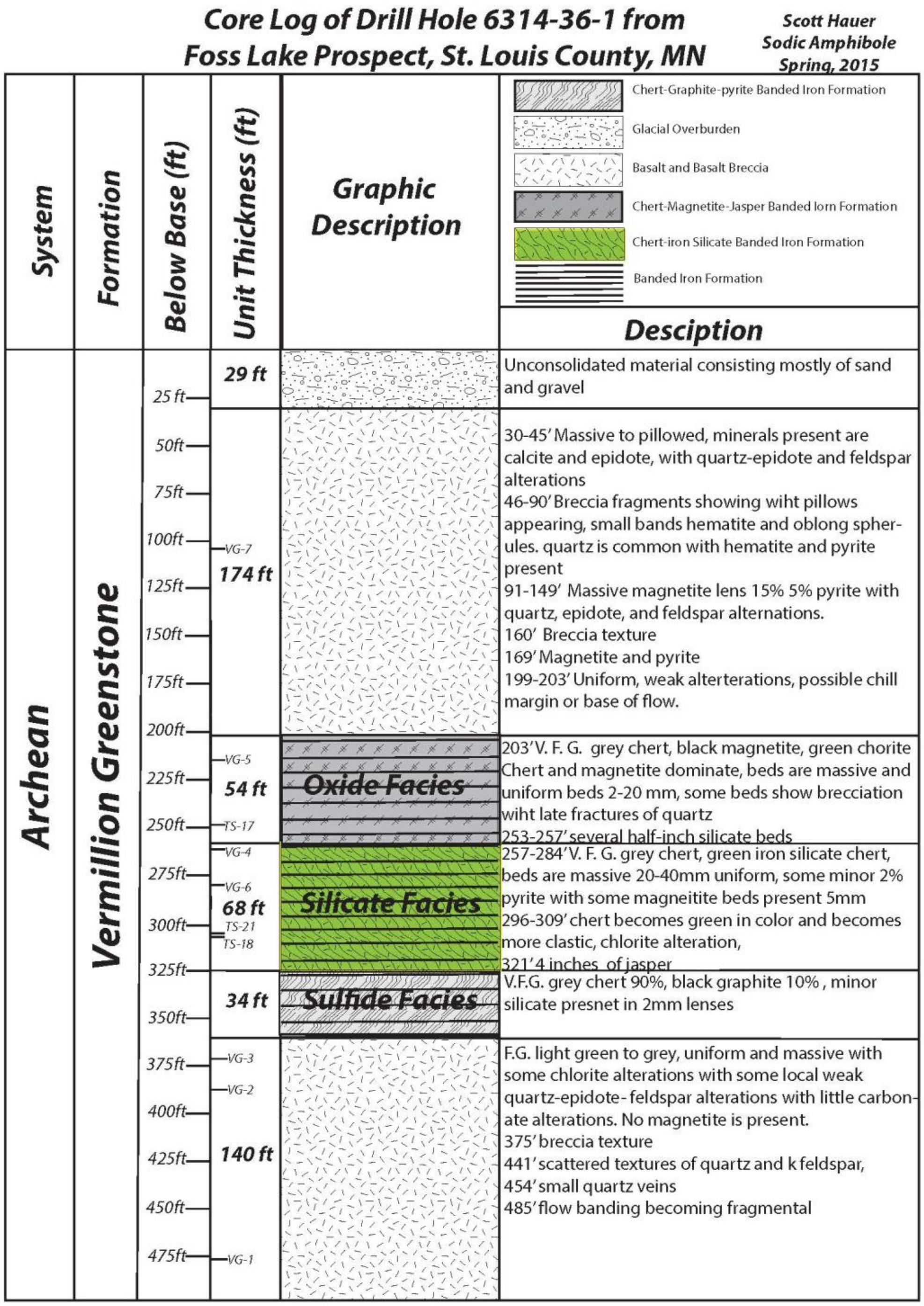

Figure (4): Log of the Vermilion Greenstone core. Condensed and modified from the original by Kerr- McGee Corporation 2-15-85. This log gives basic rock descriptions and locations of samples for thin section.

Description of Blue Amphibole

The blue amphibole that is located in TS-17 is located within the fractures of surrounding rock. Optically this amphibole has blue to greenshich pleochroism. These ampbibole minerals are generally hornblende. This blue mineral in question is located near many iron oxides. Oxides were determined to be 90% magnetite via reflected light microscopy.

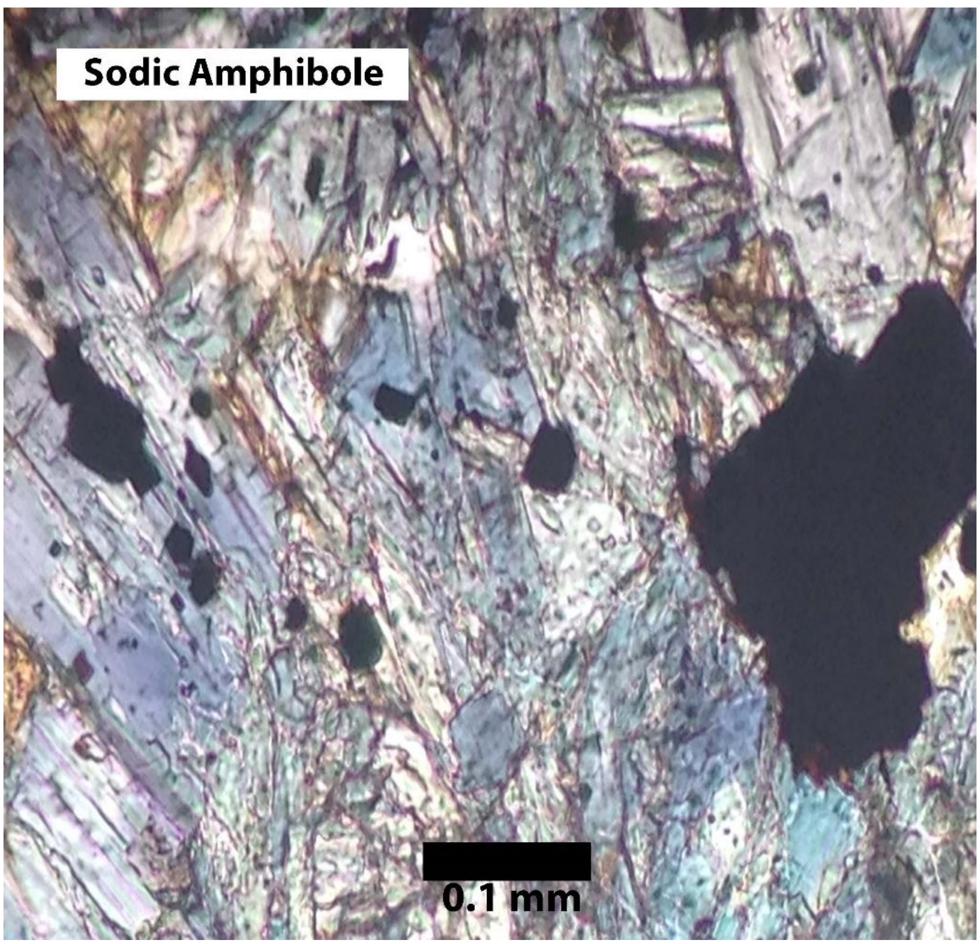

Figure (5): Located above is a microscope image of TS-17 showing sodic amphibole (blue), iron oxides (black), and biotite (pale brown).

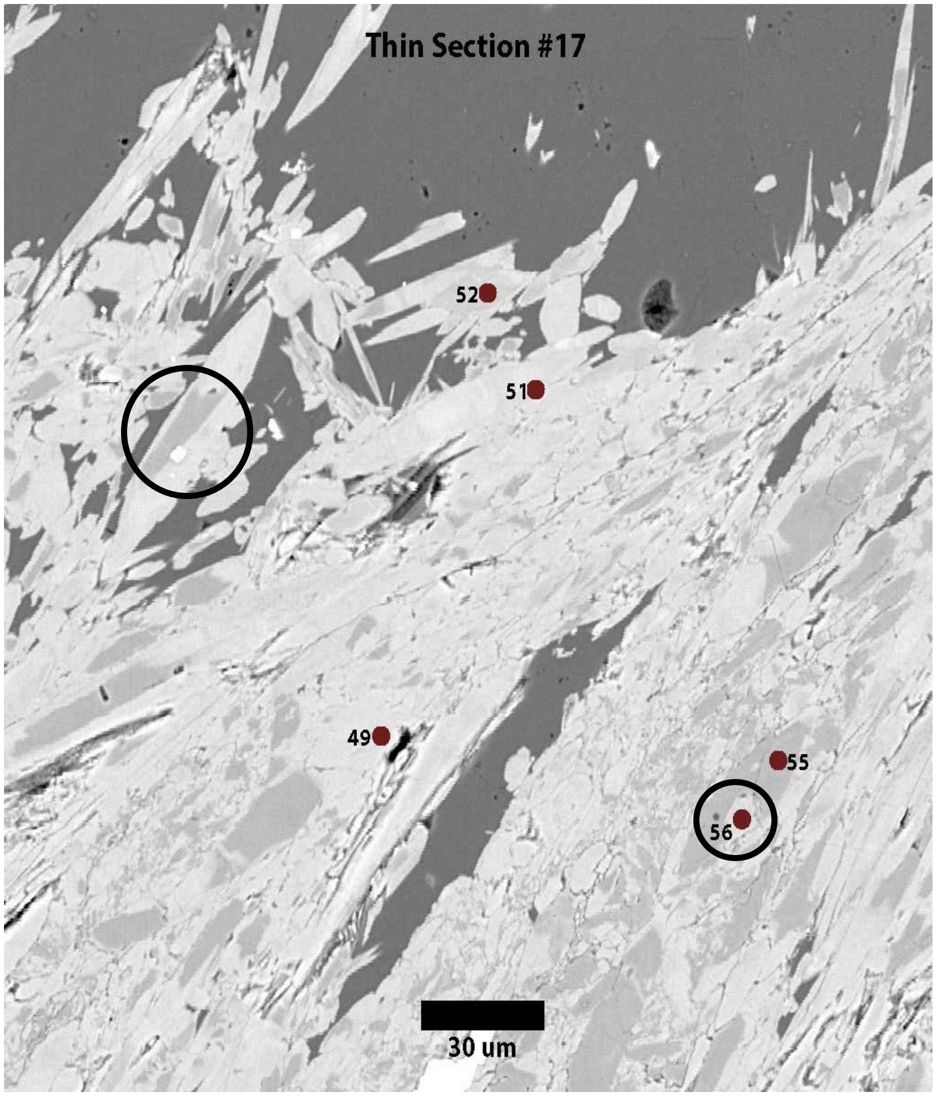

Figure (6): Microprobe image of TS-17 highlighting where the microprobe took an amphibole elemental measurement. Notice the zoning of the amphibole, Locality 49, 51, 52, 55 and 56 are shown.

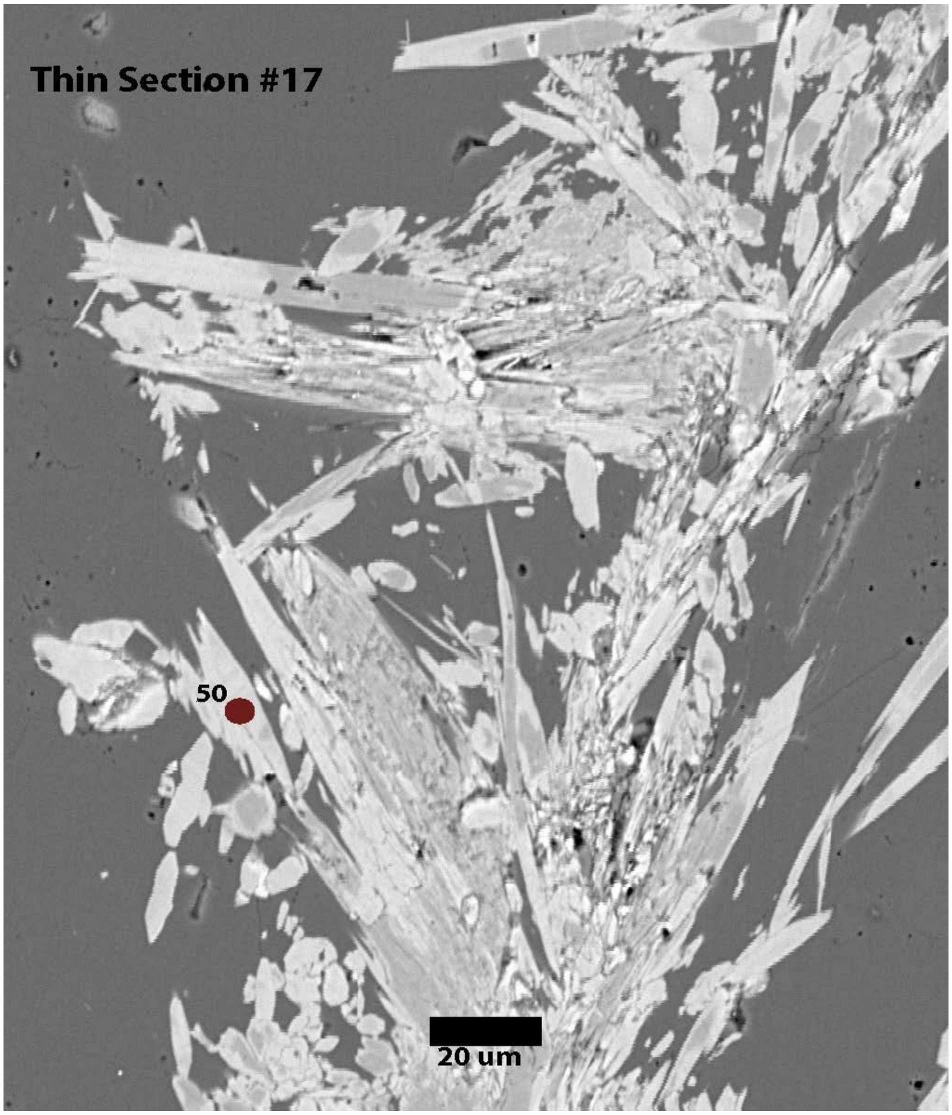

Figure (7): Above is a Microprobe image of TS-17 highlighting where the microprobe took a sodic amphibole elemental measurement. Locality 50 is shown of the left side of the image on a fibrous mineral grain.

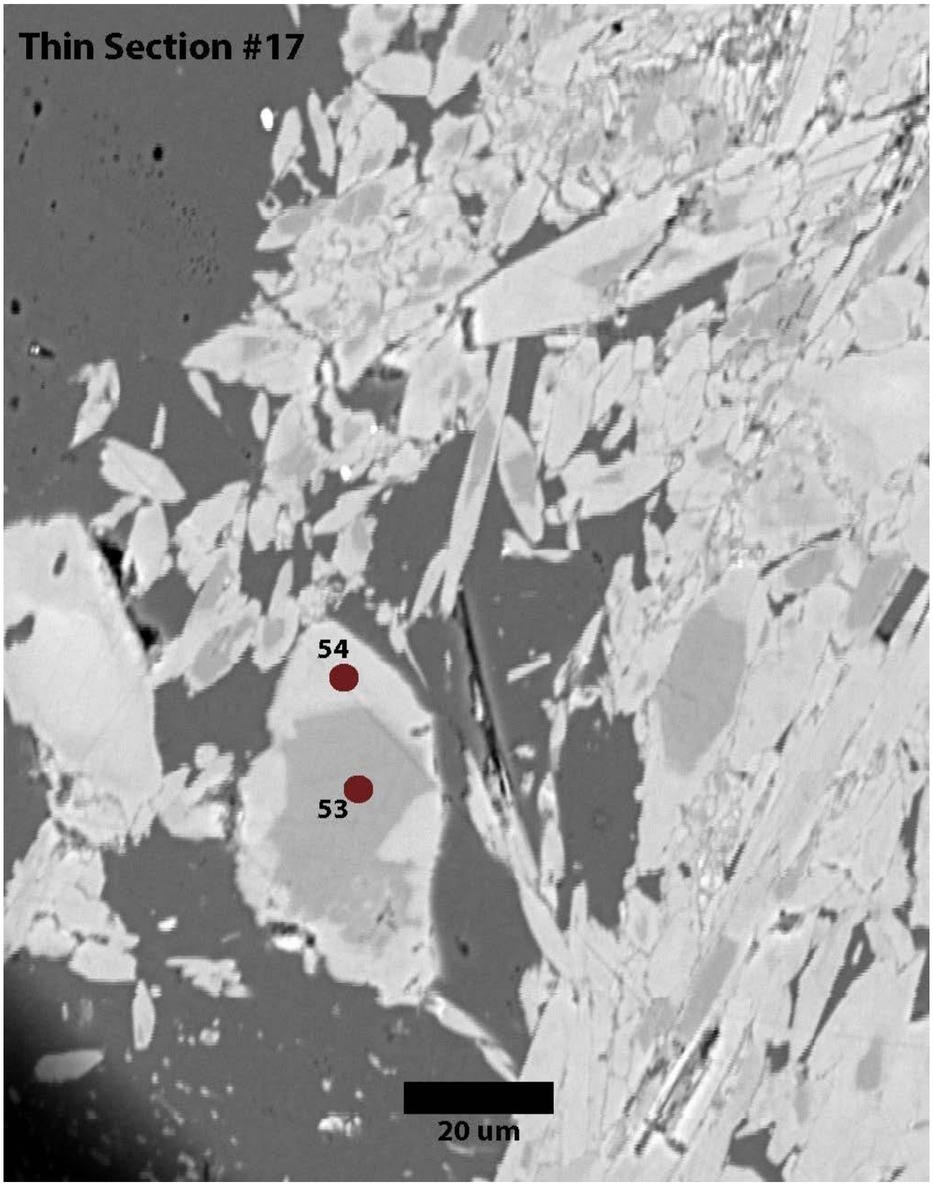

Figure (8): Above is a Microprobe image of TS-17 highlighting where the microprobe took an amphibole elemental measurement. Locality 53 is shown in the internal zoning of an amphibole grain. Locality of 54 is shown on the outside rim of the mineral grain.

Thin sections from various intervals of the core are described in appendix A. This section will focus on will focus specifically on blue amphibole as described in TS-17. Sample TS-17 contained abundant blue amphibole located within fractures and was selected for microprobe analysis. A backscatter image indicated that many of the amphibole grains are zoned, figure (7-8). Several sub-samples of cores and rims were analyzed by microprobe. (Microprobe analyses are given Appendix B.)

Alkali Amphiboles with $(Na+K)_A$ <0.50

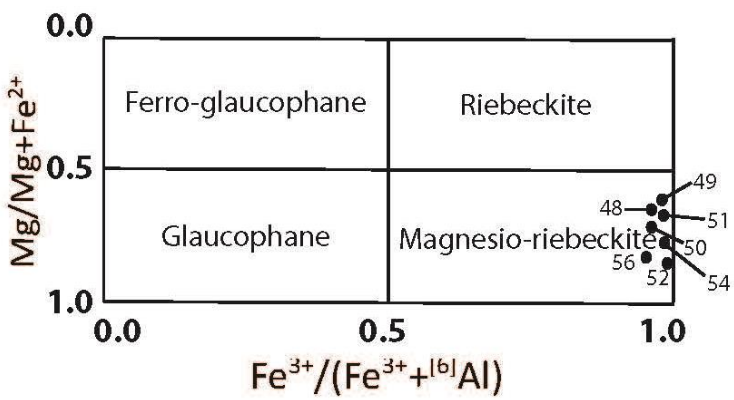

Figure (9): Nomenclature for the sodic amphiboles as a function of Mg, Fe^{2+}, Fe^{3+} and Al content (Deer, Howie and Zussman, 1997). Compositions of alkali amphiboles are superimposed on this figure, as determined by microprobe measurement. Samples numbers correspond to sample sites in figure R-3, R-4, R-5. Total Iron (Fe) was measured by microprobe. Differentiation of iron was estimated using reflected light microscopy, and x-ray diffraction.

Sodic amphiboles tend to occur on the outer portions of the zoned crystals. As figure (9) shows, samples plot near the far right in the riebeckite and magnesio-riebeckite section. These minerals under the microprobe image appear to be slightly lighter in color compared to the calcic amphibole, which forms crystal interiors. Total Iron (Fe) was measured by microprobe. Differentiation of iron was estimated using reflected light microscopy, and x-ray diffraction. Fe^{+2} and Fe^{+3} were estimated using x-ray diffraction by using the magnetite – hematite ratio.

Calcic Amphibole
$Ca_B \geq 1.50$; $Na_B < 0.50$

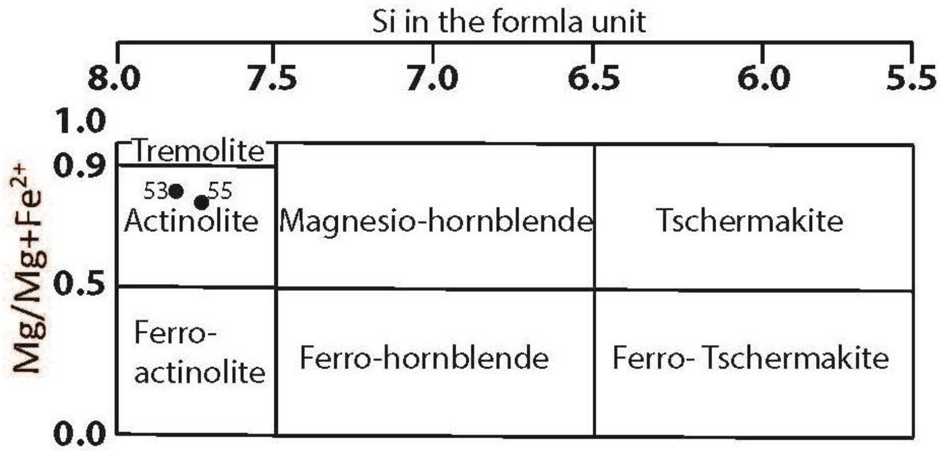

Figure (10): Nomenclature for the calcic amphibole. Above is the plotted calcic amphiboles corresponding to figures R-3, R-4, and R-5. Note, Differentiation of iron was estimated using reflected light microscopy, and x-ray diffraction.

Calcic amphiboles tend to occur on the interior of zoned crystals. As figure (8) shows both minerals that appear as calcic amphiboles and plot in the actinolite section of the diagram. These minerals are high in Si and the Mg/ (Mg + Fe) ratio is near 0.87.

Discussion

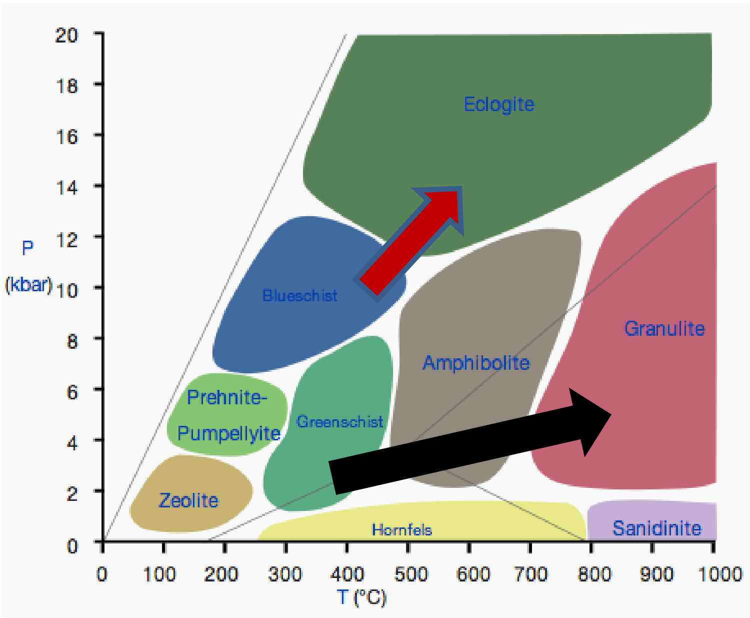

Figure (11): Diagram depicting the metamorphic facies in pressure-temperature space. The domain of the graph corresponds to the circumstances with the Earth's crust and upper mantle (Eskola, 1920).

The greenschist to amphibolite to granulite facies series constitutes the most common facies series (black arrow) of regional metamorphism (Winter, 2012) and represent the simultaneous increase of temperature and pressure along a normal geothermal gradient. Greenschist metamorphism generally occurs in plate convergence zones. Metamorphism of mafic rocks is most evident in the greenschist facies and includes minerals such as, biotite, epidote and actinolite. The transition from the greenschist to the amphibolite facies in mafic rocks involves two major mineralogical changes. The first change is the transition from the mineral albite ($NaAlSi_3O_8$) to oligoclase ($(Ca,Na)(Al,Si)_4O_8$). The second change occurs in amphiboles, where actinolite ($Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$) transforms to hornblende ($(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$) as amphibole 'accepts' increasing amounts of aluminum and alkali earth elements (Mg, Ca, Sr) at higher temperatures (Winter, 2012).

In contrast, the blueschist-eclogite facies (red arrow) figure (11) is associated with the high-pressure, low temperature conditions. These conditions are inferred for modern subduction zones (Winter, 2012), where subducting plates experience increasing pressure as the cold oceanic crust is drawn deep into the Earth's mantle. Blueschist metamorphism of basalt commonly results in the formation of glaucophane ($Na_2(Mg_3Al_2)Si_8O_{22}(OH)_2$). Glaucophane is typically found in relatively low-temperature, high pressure crystalline schists. Glaucophane and ferro-glaucophane are a pair of minerals that reflect low-temperature, high pressure regime regional metamorphism, associated with subduction. These mineral series are stable over a fairly wide range of P-T conditions, but are most commonly plotted in the blueschist zone as seen above. (Deer et al., 1997). Minerals that are commonly associated with blueschist facies often include, glaucophane, lawsonite muscovite, and albite. Riebeckite and magnesio-riebeckite belong to the same solid solution as glaucophane, and represent increasing substitution of Fe^{3+} for Al at higher temperature (Deer et al., 1997).

The zoned amphibole in sample number 55 figure (6) and number 53 figure (8) show a core that is more calcic and aluminum rich, but is low iron. The outer rim (white in appearance) has a much higher sodium and iron content and a lower calcium content. The calcic amphibole at the centers of the amphibole likely formed when pressure and temperature increased from greenschist to amphibolite facies conditions. Zoned amphiboles such as these with Ca- rich cores and Na-rich rims have reported from the Franciscan series of California and from Hokkaido, Washington, in having zoned amphiboles Ca-rich cores and Na-rich rims (Parkinson 1991).

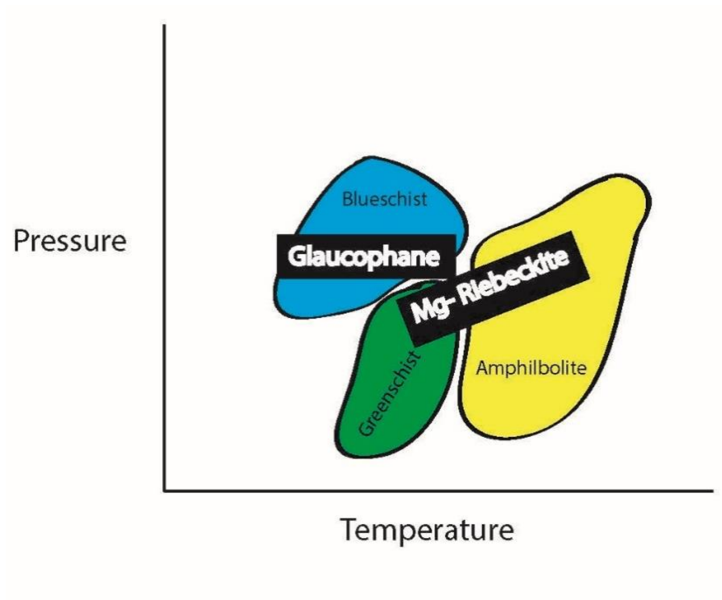

Figure (12): Diagram showing the relationship between sodic amphiboles and metamorphic facies in pressure-temperature space.

Riebeckite and magnesio-riebeckite are two relatively common members of the alkali amphiboles. (Deer et al., 1997). Riebeckite is typically found in igneous rock but is increasingly recognized an important constituent of many high grade schists. On the other hand, magnesio-riebeckite is more commonly found in schists and less commonly in igneous rocks. As shown above figure (9) all of the alkali bearing amphibole minerals within the riebeckite and magnesio-riebeckite composition fields figure (12), indicating upper-greenschist to amphibolite metamorphism.

Zoning results from the mineral's inability to maintain chemical equilibrium in a rock during rapid cooling; the zonation represents a frozen picture of the continuous reaction series for that mineral.

Hornblende/actinolitic hornblende is a common mineral associated with metavolcanics, which indicates that these rocks were subject to upper greenshist to lower amphibolite facies metamorphism. The sodic amphibole in question is located within the fractures of the rock, which appears to be located in the direction of the secondary cleavage.

Many of the amphiboles that have formed in high-grade blueschists facies result from secondary hydration episodes, which occur relatively rapidly and therefore at uniform pressure and temperature during the hydration event. As a result many late stage amphiboles form homogeneous grains, zoning may occur as a result of overgrowth and inter-reaction that may appear to be 'progressive', instead of from a discrete reaction episode (Wood, 1980).

In this instance, these minerals seem to have been exposed to two separate amphibole- forming metamorphic events. As the plate containing the metavolcanics collided with another tectonic plate, metamorphism altered the rocks, producing calcic amphibole. Second, as the aqueous crustal fluids, which were enriched in O_2, and altered the BIF, causing low temperature riebeckite and magnesio- riebeckite to become more stable and would overgrow the earlier Ca amphibole.

Conclusions

This study aimed to determine the nature of sodic amphibole in banded iron formation of the Newton Lake Formation in northeastern Minnesota, in order to better constrain the metamorphic conditions that produced this Archean unit. Electron microprobe imaging revealed that the blue amphibole observed in thin section is composed of two distinct amphibole phases, a calcic amphibole forming crystal cores, and a sodic amphibole forming the crystal rims. Elemental analysis of the calcic amphibole indicates that it is actinolite; the sodic amphibole is magnesio-riebeckite. Both amphiboles likely formed within the upper greenschist to amphibolite facies. The zoning of the amphibole minerals indicates the rocks have been exposed in two separate metamorphic events. As the plates were colliding, metamorphism initially altered the rocks. Second, as the aqueous crustal fluids, which were enriched in O_2, seeped down and altered the BIF, lower temperature riebeckite and magnesio- riebeckite would become more stable and would overgrow the earlier Ca amphibole. This was the main driving force for the creation of the sodic magnesio-riebeckite. Based on the compositions of these amphiboles, the collision that produced these Archean metamorphic rocks had different metamorphic conditions commonly found in regional metamorphic events associated with collisions, rather than the unique high pressure – low temperature regime associated with modern collision zones.

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Appendix A

Thin sections were examined to understand the mineral assemblages in metavolcanic to get an estimate of the metamorphic history of the Archean portion of the core.

VG-1- 477'

Green amphibole present, may be actinolite or hornblende. Most of the thin section is auto -brecciated meaning that there are many little fragments cemented together. Biotite may be present, indicating greenschist metamorphic grade.

VG-2 388'

This thin section is meta-diabase meaning that it is on the border of aphantic and phaneretic. This section had much more coarse mineral grains and fibers. This section shows some bluish green amphibole and has abundant albite.

VG-3 370'

This section VG-3 was dominated by biotite or stilpnomelane, Amphibole was again present with radiating fine-grained fibers possibly being cummingtonite with a pale brown- greenish color.

VG-4 266'

This thin section is from the part of the rock core which has banded iron formation. Sections of dark of chert bands running through it, as well as amphibole. The section mineral that is present is plagioclase. This section is dominated by silica, with minor amounts of iron oxides.

VG-5 215'

VG-5 is from the oxide facies. This section is dominated by grey chert, magnetite, green chlorite and pale blue amphibole. There are late stage quartz filled fractures.

VG-6 281'

VG-6 has much more pleochroism than all the other thin sections. Chlorite and actinolite is dominant in this section. There are deep blue-green amphiboles within this section. This section also has mass amounts of magnetite present.

VG-7 105'

This section can be characterized by meta-basalts. Epidote is present, fine grained amphibole is also a notable mineral characteristic.

TS-17 247'

This section is part of the oxide facies. Sodic (blue) amphibole (25%) is abundant throughout this section. Blue amphibole is fibrous and elongated. Iron oxides are numerous in this section. Other minerals present include grey chert, black magnetite, green chlorite, biotite and lots of quartz.

TH-18 312'

Medium sized crystals of quartz are 2x larger then ones located in TH-19. There is a chert band running through it. This section is located within the silicate facies.

TS-21 310'

This section has biotite, green amphibole, epidote iron oxides, with small crystals, lots of fibrous material. This section is dominated by biotite.

Appendix B

This is the main data set that was used in the results section in order to plot the samples in figure R-8 and figure R-9. Data was collected using an electron microprobe.

Probe #	Sample	Si	Ti	Al	Fe	Mn	Mg	C a	Na
17-01	48.0000	8.3426	0.0000	0.1063	2.5844	0.0061	2.4310	0.3674	1.5218
17-02	49.0000	8.2438	0.0031	0.1197	2.7342	0.0011	2.4512	0.2969	1.6762
17-03	50.0000	8.2330	0.0124	0.1197	2.5743	0.0013	2.5590	0.4205	1.5385
17-04	51.0000	8.2459	0.0000	0.1049	2.7923	0.0011	2.4439	0.2386	1.7463
17-05	52.0000	8.0796	0.0000	0.0726	2.0519	0.0027	3.1184	1.0465	1.0120
17-06	53.0000	7.8114	0.0000	0.2278	0.9756	0.0057	4.1252	1.7456	0.3476
17-07	54.0000	8.2253	0.0093	0.1111	2.5605	0.0011	2.6027	0.4013	1.5807
17-08	55.0000	7.7333	0.0090	0.2881	1.0842	0.0178	4.0388	1.7505	0.3616
17-09	56.0000	8.0543	0.0000	0.1515	2.3169	0.0000	2.9643	0.7146	1.3216