



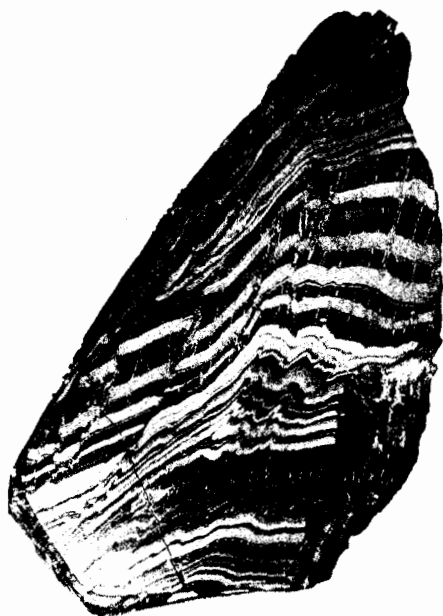
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49th Annual Meeting

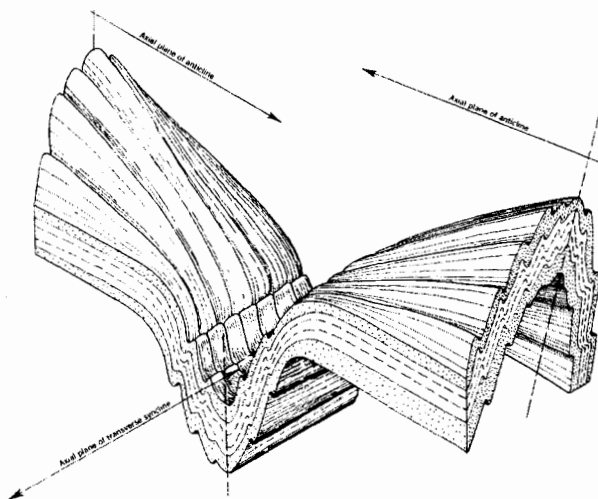
Proceedings Volume 49
Part 2- Field Trip Guidebook



Quinnesec Mine, Menominee Iron District



Wauseca pyritic slate



Refolded fold style of Iron River-Crystal Falls allochthon

Iron Mountain, Michigan
May 7-11, 2003

INSTITUTE ON LAKE SUPERIOR GEOLOGY

**49TH ANNUAL MEETING
MAY 7-12, 2003
IRON MOUNTAIN, MICHIGAN**

HOSTED BY:

**Laurel G. Woodruff and William F. Cannon
Co-chairs
U.S. Geological Survey**

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and

**John Gartner, Coleman Engineering Company
Local committee representative**

**Proceedings
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Part 2 – Field Trip Guidebook

Compiled and edited by William F. Cannon, USGS

Illustrations prepared by Connie L. Dicken and Stacy Saari, USGS

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Wauseca Pyritic Member of Dunn Creek Slate. A sulfide facies iron-formation from the Iron River-Crystal Falls district, Michigan. Original photograph appears in USGS Professional Paper 570.

Schematic illustration of cross-folding in the Iron River-Crystal Falls district as depicted in USGS Professional Paper 570.

Quinnesec Mine in the Menominee Iron District at Quinnesec, Michigan. Photograph by Elizabeth Heinen.

PALEOPROTEROZOIC STRATIGRAPHY AND TECTONICS ALONG THE NIAGARA SUTURE ZONE, MICHIGAN AND WISCONSIN

G.L. LaBerge¹, W.F. Cannon², K.J. Schulz², J.S. Klasner³, R.W. Ojakangas⁴

¹ University of Wisconsin-Oshkosh (retired) and U.S. Geological Survey, ² U.S. Geological Survey, ³ Western Illinois University (retired) and U.S. Geological Survey,

⁴ University of Minnesota Duluth (retired)

INTRODUCTION

The Niagara suture zone formed during the Penokean orogeny at about 1875 Ma by collision of island arcs of the Wisconsin magmatic terranes with the southern margin of the Superior craton and its epicratonic cover of the Marquette Range Supergroup. The Niagara fault, generally considered the principal suture boundary, has an arcuate trace across northern Wisconsin defined primarily from geophysical data, sparse outcrops, and widely spaced drill core data (fig. 1). In more detail, the Niagara fault is but one of a family of subparallel anastomosing faults that bound structural panels of Paleoproterozoic rocks, which together comprise the Niagara suture zone (fig. 2). The rocks within these panels have a distinctive structural style marked by tight folds with widely varying but commonly steeply plunging axes. These probably formed by refolding of simpler, gently plunging folds, which are widely recorded in correlative strata north of the suture zone. A blanket of glacial material over most of the region, the on-lap of Paleozoic rocks in northern Michigan and a thick cover of Keweenaw rocks of the Midcontinent rift system in northwestern Wisconsin and eastern Minnesota have obscured the suture zone over most of its length in the southern Lake Superior region. The area described in this guide is the only area where extensive exposures allow direct observations of stratigraphic and structural features along the collision zone.

The purpose of these field trips is to examine exposures along and on both sides of the Niagara suture zone. Stops were chosen to illustrate: 1) the Paleoproterozoic sedimentary sequence developed on the continent margin; 2) igneous rocks that constitute parts of the Wisconsin magmatic terranes; and 3) some of the structural features produced as a result of the collision of the island arcs with the continent margin, and their influence on interpretations of the stratigraphy.

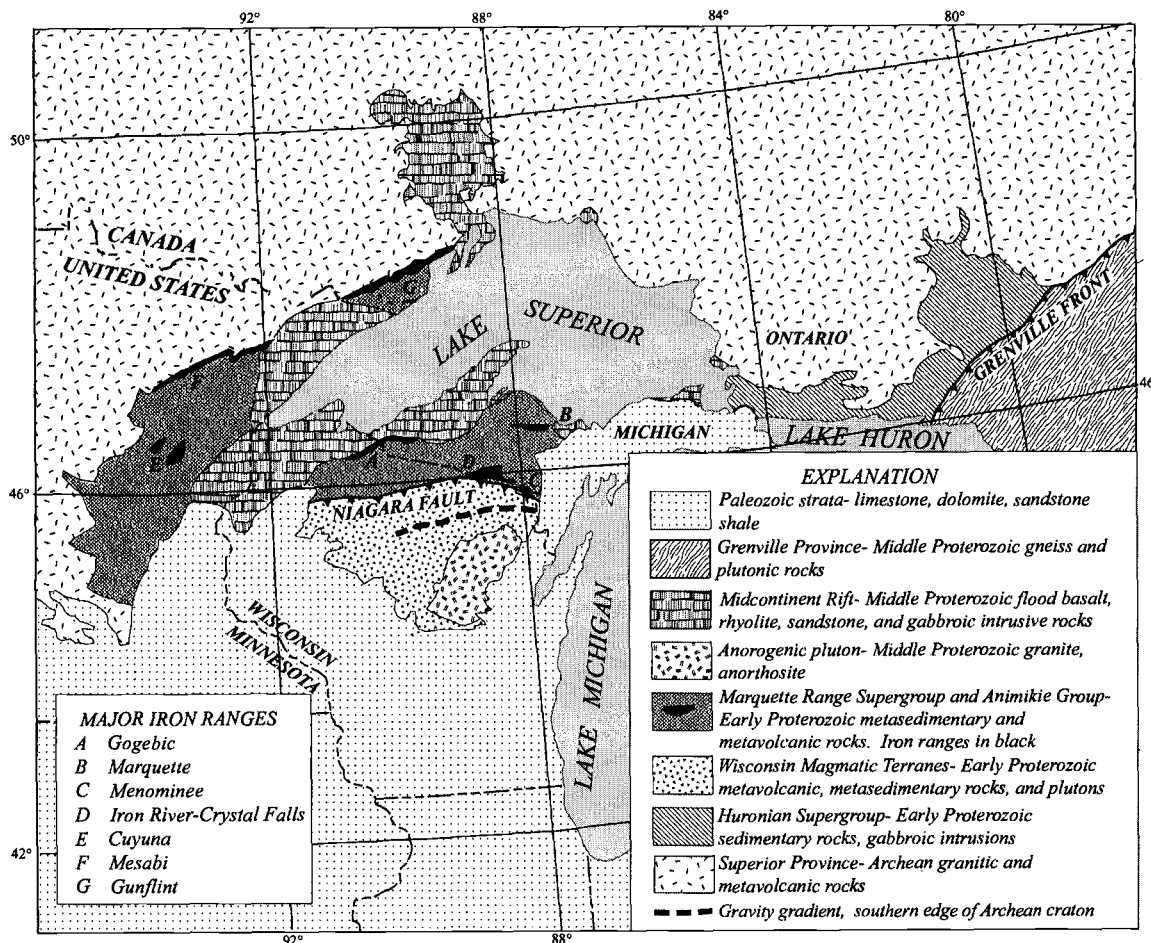


Figure 1. Generalized geologic map of the Lake Superior region showing the major iron ranges.

The southern part of the upper peninsula of Michigan and adjacent parts of northeastern Wisconsin contain exposures of Archean rocks with overlying Paleoproterozoic metasedimentary and metavolcanic rocks of the Marquette Range Supergroup, as well as a wide variety of volcanic, sedimentary, and intrusive rocks of the Wisconsin magmatic terranes. The modern geologic framework of the area has been established largely by mapping by the U.S. Geological Survey conducted from the 1940's through the 1980's (Bayley, and others, 1966; Dutton, 1971; James and others, 1968; Sims, 1990; Sims and Schulz, 1993). Beginning in the late 1970's, the importance of the Niagara fault zone as a suture between oceanic terranes on the south and a continental assemblage on the north was documented (Cambray, 1978; Greenberg and Brown, 1983; Larue and Sloss, 1980; Larue, 1983). This led to a period of study of the structural geology of the region in order to decipher the structural events consequent to suturing (Larue and Ueng, 1985; Sedlock and Larue, 1985; Ueng and Larue, 1987). This guidebook draws heavily on these previous studies, supplemented in places by our own observations.

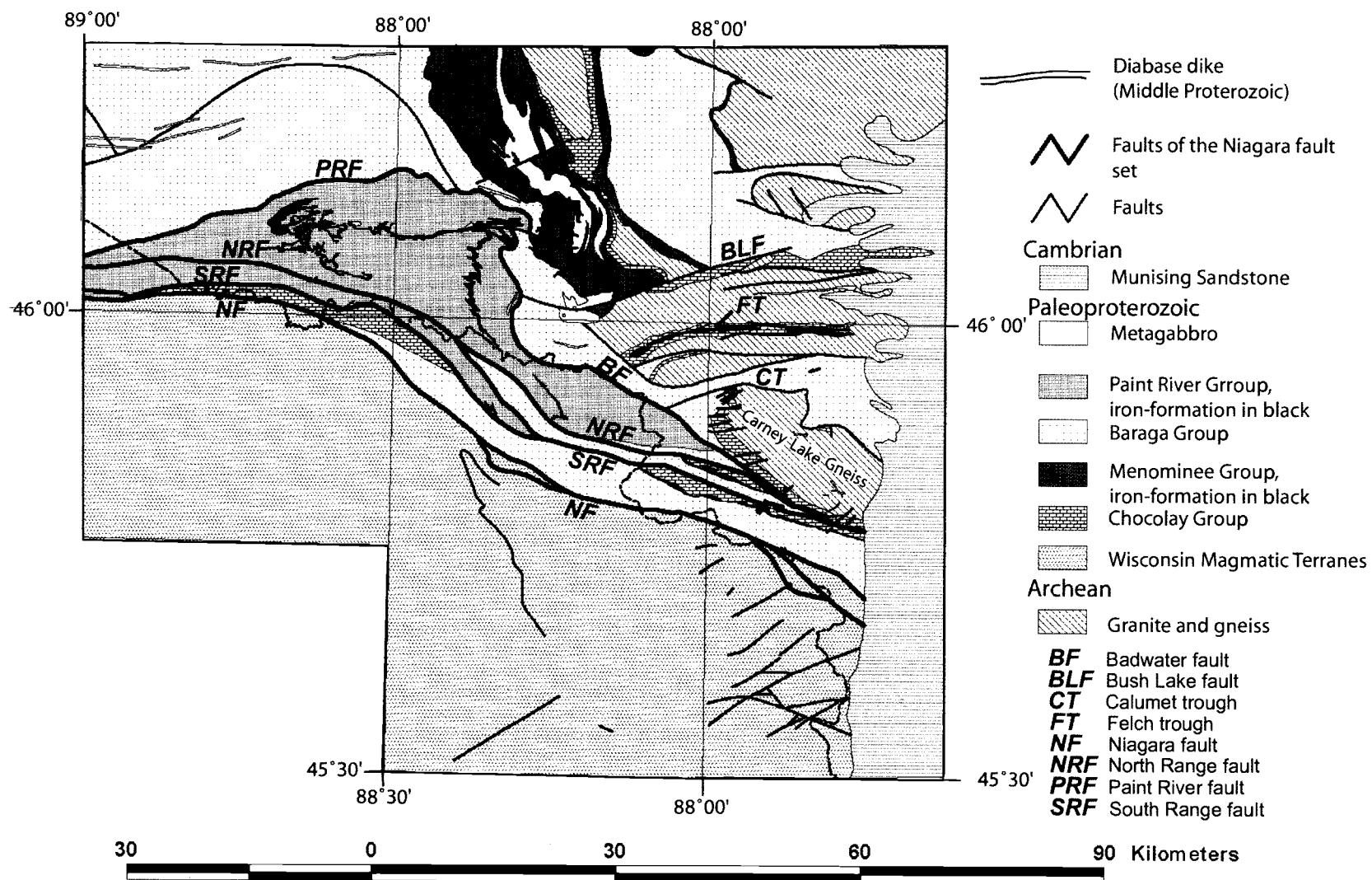


Figure 2. Geologic map of the Niagara suture zone and surrounding terranes showing the location of named features referred to in the text.

CONTINENT MARGIN SEQUENCE

A thick succession of dominantly sedimentary rocks that were deposited on Archean basement is widely distributed in northern Michigan, Wisconsin and Minnesota, and, to a lesser extent, in northern Ontario. The succession records a wide variety of geologic environments and includes the extensive and economically important iron-formations in the Lake Superior region.

STRATIGRAPHY

Archean

Carney Lake Gneiss: The only extensively exposed Archean unit in the field trip area is the Carney Lake Gneiss (fig. 2). The Carney Lake, like other Archean rocks farther north, is exposed in the core of a Penokean structural uplift. It bounds the Menominee Range on the north and is the basement on which the Paleoproterozoic iron-bearing sequence of the Menominee Range was deposited. The Carney Lake Gneiss is seen at stops 2-2 and 2-3, where it is exposed beneath the unconformity at the base of the Paleoproterozoic Fern Creek Formation. According to Treves (1966) granitic gneiss forms about 85 percent of the unit. Inclusions of amphibolite, biotite schist and some quartzite constitute about 10 percent, the remainder being granodiorite and syenite dikes. Amphibolite inclusions are more abundant in the northern part of the complex, whereas biotite schist is more common in the southern part. According to Davis and others (1960) the Carney Lake Gneiss is about 2,700 million years old. Foliation and tabular inclusions define a complex internal folding pattern in the gneiss, which is mostly a result of Archean deformation.

Paleoproterozoic

The Paleoproterozoic continent margin sequence is comprised of sedimentary and volcanic rocks at least several kilometers thick in the Menominee and Iron River - Crystal Falls districts and probably much thicker in much of the area. The stratigraphic relationships are shown in figure 3, which compares the stratigraphy in the field trip area with that in other well-studied areas to the north and east. Originally referred to as "Huronian" by Van Hise and Leith (1911), and later as "Animikie Series" by James (1958), the sequence was renamed the Marquette Range Supergroup, comprised of the Chocelay, Menominee, Baraga and Paint River Groups, by Cannon and Gair (1970). The stratigraphic succession of the first three groups is well established. However, the stratigraphic position of the Paint River Group, along with the Badwater Greenstone, is less certain. The Paint River Group was originally considered the youngest of four stratigraphically superposed groups by James (1958), but more recent interpretations generally consider it to be an allochthon structurally emplaced over the Baraga Group. The Paint River Group may be a distal, deeper water equivalent of the Menominee and Baraga Groups, which has been thrust onto the continental margin during Penokean compressive deformation.

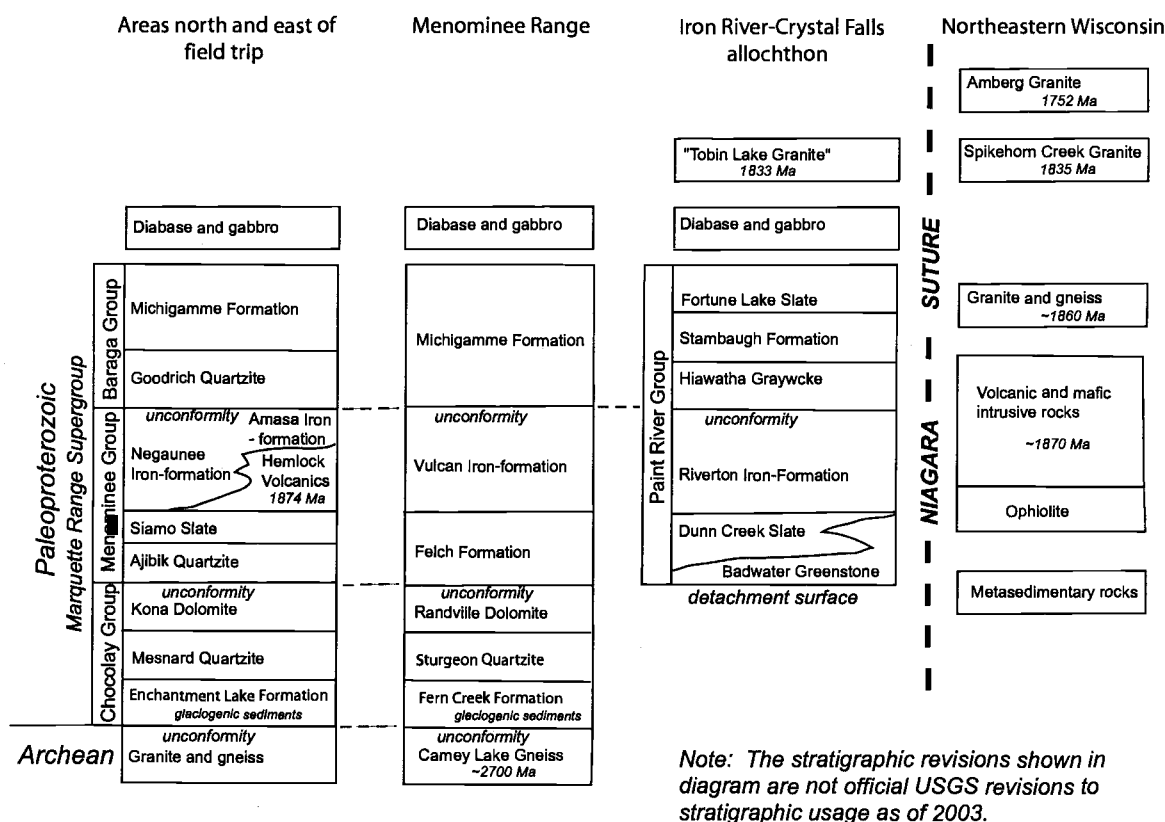


Figure 3. Correlation chart of Paleoproterozoic strata in Menominee and Iron River-Crystal Falls and surrounding terranes. Includes changes to previous usage not yet officially adopted by the USGS.

Chocollay Group

Fern Creek Formation: Francis J. Pettijohn (1943) described and named the Paleoproterozoic Fern Creek Formation, verified it as a basal sedimentary unit resting unconformably upon Archean granitic basement of the Carney Lake Gneiss, and suggested a glacial origin. Additional descriptions were made by Trow (1948), by Freedman and others (1961) and by Bayley and others (1966). Prior to Pettijohn's work, the relationships of these sedimentary rocks to the granitic rocks of the region were debated by Bayley (1904), Lamey (1937), and Dickey (1936).

Two other basal Paleoproterozoic formations in the region, the Enchantment Lake Formation and the Reany Creek Formation, are present in the Marquette Trough, 50-55 miles north of the Fern Creek exposures. It has been suggested by several workers that these rock units are also glaciogenic and correlative with the Fern Creek Formation (e.g., Gair and Thaden, 1968; Puffett, 1969; Gair, 1981; Ojakangas, 1984). The two exposures of the Fern Creek Formation seen on these field trips (stops 2-2 and 2-3) are of more than local significance. Correlation with the Gowganda Formation in the Huronian Supergroup ca 120 miles to the east in Ontario and with the Snowy Pass Supergroup 900 miles to the WSW in Wyoming has been proposed by various workers (e.g., Puffett, 1969; Young, 1970, 1973, 1983; Ojakangas, 1984, 1985, 1988; Roscoe and Card, 1993). Young (1970) suggested that all of these units, and others in Quebec

and the NW Territories, are remnants of a continental-scale glaciation. Furthermore, correlation with glaciogenic units on the Fennoscandian Shield in Finland and adjacent Karelia, Russia, has also been proposed (Marmo and Ojakangas, 1984; Ojakangas, 1985, 1988; Ojakangas and others, 1991; Ojakangas and others, 2001).

It must be emphasized that the correlations are greatly strengthened by the presence of similar stratigraphic sequences in all of the above-named areas and regions. This is as follows, moving stratigraphically upward: glaciogenic rocks, paleosols (or remnants thereof), orthoquartzites, and carbonates (Ojakangas, 1997; Ojakangas and others, 2001). Mafic dike swarms dated at 2.2 – 2.15 Ga cut all the aforementioned sedimentary sequences. It is possible that the glaciogenic units of North America and the Baltic region (Marmo and Ojakangas, 1984) were formed on a single supercontinent, Kenorland, at about 2,300 Ma (Ojakangas, 1988). The breakup of Kenorland occurred at 2.2 – 2.1 Ga with the emplacement of the Nipissing mafic sills and dike swarms of the Canadian Shield and the Jatulian mafic rocks of the Fennoscandian Shield.

The Fern Creek Formation is exposed in only a few small areas adjacent to the Archean Carney Lake Gneiss (figs. 2, 4). These exposures likely represent erosional remnants of more widespread glaciogenic deposits preserved in topographic lows on the Archean bedrock surface. Post-glacial weathering, erosion, and sorting by wind and water resulted in the stratigraphic sequence of glaciogenic deposits, paleosol (sericitic schist), and quartz sand (now the Sturgeon Quartzite) that will be seen at stop 2-2 (Fern Creek locality) and stop 2-3 (Sturgeon River locality). Two other localities – Black Creek (sec. 6, T. 39 N., R. 28 W.), and Pine Creek (sec. 32, T. 41 N., R. 29 W.) (Freedman and others 1961) – are relatively inaccessible and not as well exposed. These four small areas of exposure are located along a 17-mile portion of the northwest-trending contact between the Carney Lake Gneiss and these basal Paleoproterozoic units (fig. 4). The two field stops are within 5 miles of each other.

Sturgeon Quartzite: At most places in the Menominee district a thick, light colored, vitreous quartzite forms the basal Paleoproterozoic unit on the Carney Lake Gneiss (Bayley and others, 1966). The type exposures of the Sturgeon Quartzite are along the Sturgeon River in the Felch district, about six miles north of the Menominee district (see fig 2). In the Menominee district the quartzite forms a continuous belt along the southwest margin of the Carney Lake Gneiss. It is well exposed at stops 2-2 and 2-3.

The Sturgeon Quartzite ranges from 1,000 to 2,000 feet thick, is composed primarily of white, gray, green or pink vitreous quartzite, commonly showing ripple marks and cross-bedding. It is composed almost entirely of quartz. Trow (1948) showed that the cross-bedding data suggest that the quartz sand of the Sturgeon was derived from the northwest, and Pettijohn (1957) showed that many of the Paleoproterozoic quartzites of the Lake Superior region had a source area to the west or northwest. The Sturgeon Quartzite is considered to have formed during a marine transgression onto the Archean craton, possibly to the northwest. Bayley and others (1966) interpreted the quartzite to be conformable and gradational with the Fern Creek Formation, and to be conformable with the overlying Randville Dolomite.

Randville Dolomite: The Randville Dolomite overlies the Sturgeon Quartzite in the Menominee and Felch districts. It takes its name from exposures near Randville, north of Iron Mountain. The dolomite occurs in three southeast-trending belts in the Menominee

district because of repetition by faulting (Bayley and others, 1966). It is estimated to be about 2,000 feet thick. Classic exposures of deformed stromatolitic dolomite are present at stop 2-6.

The Randville is composed mainly of massive clastic dolomite with thick- and thin-bedded sandy dolomite, dolomitic and quartzose slate, and pebbly dolomite conglomerate (Bayley and others, 1966). Domal stromatolites 1-3 inches high and 3-12 inches in diameter are common and widespread in the formation. They form reefs as much as 50 feet thick and are of great aerial extent. The stromatolites are usually in thin-bedded sandy dolomite and conglomeratic dolomite of shallow water origin. The clastic dolomite consists mainly of rounded carbonate fragments that range in size from sand to cobbles. Internally the fragments consist of fine-grained dolomite. Bayley and others (1966) stated that the presence of stromatolites, oscillation ripple marks, mud cracks and clastic beds indicates deposition in very shallow water. Larue (1981) reported that remnants of anhydrite and gypsum crystals, along with the bedding features, suggest deposition of the Randville Dolomite in a paleo-sabkha environment. Thus, the Chocoley Group may record continuous deposition from a glacial environment (the Fern Creek Formation) to an arid sub-tropical environment (the Randville Dolomite).

Menominee Group

Felch Formation: The Felch Formation is a sericitic slate and quartzite that overlies the Randville Dolomite. It consists of thin-bedded sericitic slate and phyllite and intercalated thin-bedded quartzite, with the quartzite layers more prevalent near the top of the formation (Bayley and others, 1966). It is about 100 feet thick in the Menominee district, but thickens to about 500 feet in the Felch district to the north. Bayley and others (1966) considered the Felch Formation to be correlative with the Ajibik Quartzite and Siamo Slate of the Marquette district and the Palms Formation of the Gogebic district. They state that although the Felch Formation is structurally concordant on the Randville Dolomite, both local and regional relationships suggest that the Felch Formation is unconformable on the Randville Dolomite. However, the Felch Formation is conformable and gradational with the overlying Vulcan Iron-formation.

Vulcan Iron-formation: The Vulcan Iron-formation is the major iron-bearing unit of the Menominee district. The iron-formation is divided into four units, two composed mainly of granular iron-formation and two composed of slate and slaty iron-formation. In succeeding order the units are the Traders Iron-bearing Member, the Brier Slate, the Curry Iron-bearing Member, and the Loretto Slate. The Traders and Curry Members contain layers of granular jasper alternating with layers of magnetite and hematite. The Brier and Loretto Members are mainly laminated siliceous iron-rich slate, which locally contains laminae of detrital quartz, feldspar, micas, zircon and tourmaline. According to Dutton (1958), the iron-formation is about 1,000 feet thick, of which about 730 feet is ferruginous slate (Brier Slate = 330 feet, Loretto Slate = 400 feet) and 270 feet is granular iron-formation (Traders = 100 feet, Curry = 170 feet). The Vulcan is seen at stops 2-4 and 2-5.

Baraga Group

In the area of the field trips, rocks of the Baraga Group are mostly in the Menominee Range, where they consist of a variety of rock types generally combined into the Michigamme Formation. The belts underlain by the Michigamme Formation are very poorly exposed, which accounts, at least in part, for the lack of detailed mapping of what may well be otherwise discernible map units. According to Bayley and others (1966) the Michigamme Formation consists chiefly of slate, especially quartzose, micaceous, and graphitic varieties, subgraywacke, quartzite, conglomerate, dolomite, dolomitic quartzite, and some iron-formation. More recent exploration drilling also has identified units of mafic volcanic rocks. An unconformity between the Michigamme and underlying Vulcan Iron-formation is indicated by the presence of widespread basal conglomerate, containing clasts of iron-formation and other Menominee and Chocolay Group lithologies, and by regional truncation of pre-Baraga Group units beneath the basal Michigamme units. The Michigamme Formation is the youngest Paleoproterozoic unit preserved in the Menominee Range.

The Michigamme Formation extends westward and is present widely, although poorly exposed, in fault panels lying between the Wisconsin magmatic terranes and the Iron River-Crystal Falls allochthon. Dutton (1971) has provided a detailed description of these rocks, which are equally as varied lithologically as their equivalents in the Menominee Range. Farther north, the Michigamme Formation is structurally beneath the Iron River-Crystal Falls allochthon and is widely exposed north and east of the allochthon. This area also has considerable lithologic diversity, but graded-bedded graywackes, pelitic schist and slate, and impure quartzite become more dominant toward the north and interlayered mafic volcanic rocks and iron-formation become volumetrically minor.

Total thickness of the Michigamme Formation is not known, but it is probably several thousand feet or more. Dutton (1971) stated that the Michigamme might be as much as 20,000 feet thick in the Florence, Wisconsin area. Barovich and others (1989) used Nd isotope data to show that the Michigamme Formation in the field trip area was derived from a Paleoproterozoic source. Sims and others (1993) suggest that the source was the Wisconsin magmatic terranes to the south, with deposition in a foredeep environment during docking of the Wisconsin magmatic terranes with the continent margin.

Paint River Group

Rocks assigned to the Paint River Group consist of about 6,500 feet of sedimentary strata, which overlie as much as 15,000 feet of volcanic rocks. They form the bedrock of the Iron River-Crystal Falls district (James and others, 1968). Five formations were assigned originally to the Paint River Group. Here, we add a sixth formation, the Badwater Greenstone, as discussed in more detail below. The stratigraphic position of the Paint River Group has been problematical for more than half a century. The group was interpreted to be part of the Michigamme Formation in older reports (e.g. Leith and others, 1935), but was interpreted to be a separate group (younger than the Michigamme) by James and others (1968) and Cannon and Gair (1970). However, as discussed below, more recent studies have suggested that the Paint River Group may be a fault-repeated sequence correlative with the Baraga and/or Menominee Groups (cf. Sims and others, 1993). Below, we provide evidence that the Paint River Group is an

allochthon structurally emplaced over the Michigamme Formation and consists of deep-water distal equivalents of the Menominee and Baraga Groups.

The 6,500 feet of Paint River Group sedimentary strata have some special characteristics. Larue and Sloss (1980) point out that presence of turbidites indicates that they were deposited in a subsiding basin. Likewise, Cannon (1986) noted "the group consists of a very unusual sequence of extremely ferruginous slate, greywacke, and carbonate iron-formation. The abundance of pyritic and graphitic slate, the absence of more oxidized facies of iron-formation, and the drastic lateral facies changes of some units suggest that the group was deposited in deep, anaerobic water in a tectonically unstable environment."

Badwater Greenstone: The Badwater Greenstone is a thick sequence of massive and pillowed basalt, with the pillows and fragmental units (agglomerates) along with minor interbedded slate and iron-formation (James and others, 1968). It is seen at stop 3-7. The Badwater is estimated to be 3,000 to 8,000 feet thick, but may be up to 15,000 feet thick in the Iron River area (James and others, 1968). The relative age of the Badwater Greenstone has been uncertain for many years, but most recent interpretations (e.g., Sims and others, 1993) consider it to be correlative with the lithologically and chemically similar Hemlock Formation. As such, it would be equivalent to part of the Menominee Group deposited about 1875 Ma. We here suggest that the Badwater be placed within the Paint River Group in contrast to its previous assignment to the Menominee or Baraga Groups for reasons discussed more fully below.

Dunn Creek Slate: The Dunn Creek Slate is composed of 400 to 1,500 feet of strata between the Badwater Greenstone and the Riverton Iron-formation (James and others, 1968). It is seen at stop 3-5. The Dunn Creek is a lithologically varied unit comprised of a sequence of well-bedded to laminated argillite and cherty argillite, with units of somewhat coarser impure quartzite, and thin cherty iron-formations. The term "slate" is a misnomer in that most of the rock has, at best, a moderately developed cleavage, and true slates are rare. The upper part of the formation is a distinctive highly graphitic argillite and argillite breccia unit, the Wauseca Pyritic Member (stop 3-3), which is present throughout the Iron River-Crystal Falls district and forms the footwall of the Riverton Iron-formation (James and others, 1968). The Wauseca is an example of sulfide facies iron-formation as defined by James (1954). It contains from 15 to 25% Fe and from 10 to 30% S. In the Iron River area parts of the Wauseca Member contain carbon that has not been altered to graphite, suggesting that the rocks have undergone little, if any metamorphism. Tyler and others (1957) showed that some of the carbonaceous material in the Iron River area is, in fact, coal, and as such, this is one of the oldest known occurrences of coal in the world. The lower part of the Dunn Creek Slate is poorly exposed, but evidently varies considerably in character within the district (James and others, 1968). The basal contact of the Dunn Creek with the Badwater Greenstone is poorly known, but probably conformable. The great lateral changes in thickness of the Dunn Creek suggest that it was deposited over a surface with considerable relief and that the relief was buried before the later phases of deposition so that thin units of the Wauseca Member are continuous over the entire district. The Dunn Creek is conformable with and locally gradational with the basal units of the Riverton Iron-formation. This contact is seen at stop 3-3. The Riverton is also seen at stops 3-3 and 3-4.

Riverton Iron-formation: The 10 to 800-foot-thick Riverton Iron-formation is conformable and gradational with the underlying Dunn Creek Slate, and is the main iron-bearing unit in the Iron River-Crystal Falls district. It is described in detail by James and others (1968). Where it is oxidized it consists primarily of thin-bedded chert and iron-rich carbonate, layers of stilpnomelane and disseminated graphite. However, in most areas the iron-formation is altered, with the iron oxidized to limonite and goethite, and the chert being variably leached (James and others, 1968). The best natural exposure of the unoxidized phase of the Riverton is on the apron of the dam on the Paint River in Crystal Falls, Michigan (stop 3-6).

Hiawatha Graywacke: The Hiawatha Graywacke ranges in thickness from 0 - 500 feet and disconformably overlies the Riverton Iron-formation. The basal part of the formation is a breccia of chert fragments in a graywacke matrix, which is well exposed along the Paint River in Crystal Falls (James and others, 1968). The chert fragments are commonly an inch or more in size, but locally range up to as much as 2 feet in length. Above the basal breccia unit, most of the Hiawatha Graywacke is a dark gray massive medium grained greywacke in which clastic grains are readily visible. In the western part of the Iron River area the graywacke is particularly coarse and contains a large amount of clastic feldspar (James and others, 1968). They suggested that the change from chemical to clastic deposition was the result of structural disturbance that halted iron-formation deposition.

Stambaugh Formation: The Stambaugh Formation is about 100 feet thick and is composed of a lower laminated cherty unit overlain by massive chloritic slate and some graywacke (James and others, 1968). Much of the unit is moderately to strongly magnetic, a feature that was very helpful in resolving the structure in the district.

Fortune Lakes Slate: The Fortune Lakes Slate is the uppermost formation of the Paint River Group and the youngest Precambrian unit in the district (James and others, 1968). It also underlies the largest area and, because of poor exposure, is the least known formation. It is at least 4,000 feet thick and is composed dominantly of slates with interbedded graywacke and minor iron-formation. Graded-bedded graywacke composes about 25 percent of the formation. Graded units range in thickness from 1-30 feet (James and others, 1968).

Stratigraphic Synthesis of the Marquette Range Supergroup

The foundation for modern stratigraphic terminology of the Paleoproterozoic strata of the southern Lake Superior region was established by James (1958), who defined the four-fold group designation still in use and introduced the term Animikie Series for the presumably stratigraphically superposed sequence of Chocolay, Menominee, Baraga, and Paint River Groups. The term "Marquette Range Supergroup" was introduced by Cannon and Gair (1970) to replace "Animikie Series" in compliance with the North American Stratigraphic Code; an assemblage of groups is a supergroup, not a series, and the name "Animikie" was already a well established group name in Minnesota and Ontario. In more recent years, two principal changes have been proposed. First is the recognition that the Menominee Group contains thick volcanic formations that are temporal equivalents of the major iron-formations. This relationship is best documented in the eastern Gogebic range where the Emperor Volcanic Complex (Trent, 1976) interfingers with the Ironwood Iron-formation and is unequivocally part of the Menominee

Group succession (Klasner and others, 1998). Likewise, the Hemlock Formation, a thick succession of volcanic rocks long considered a part of the Baraga Group, was reassigned to the Menominee Group (Cannon, 1986). Although relationships are not as definitive as in the Gogebic Range because of structural complications and poor exposures, the correlation is supported by interbedded iron-formations within the Hemlock and an extensive iron-formation (Amasa/Fence River) overlying the Hemlock, which are believed to be the westward continuation of the Negaunee Iron-formation from the Marquette Range. Also, the Amasa Formation is unconformably overlain by a conglomerate lithologically indistinguishable from basal conglomerate of the Goodrich Quartzite of the Marquette Range. Taken together, the weight of evidence suggests that both the Emperor and Hemlock volcanic rocks were erupted simultaneously with iron-formation deposition and interfinger with the Ironwood and Negaunee Iron-formations. Both the Emperor/Ironwood assemblage and the Hemlock/Amasa assemblage are unconformably overlain by a conglomerate marking the base of the Baraga Group and thus seem properly assigned to the Menominee Group.

A second principal change to stratigraphic correlation is the recognition that the Paint River Group is likely an allochthon structurally emplaced over the Baraga Group and is therefore not necessarily a younger sequence. As we propose here, certain lithologic similarities between Paint River units and Menominee and Baraga Group units suggest that the Paint River is equivalent to both the Menominee and Baraga Groups. The five formations originally assigned to the Paint River Group lie in their entirety within the Iron River-Crystal Falls basin (referred to as the Iron River-Crystal Falls district by James and others, 1968). Over the years there have been differences in opinion concerning the relative ages of the strata within the Iron River-Crystal Falls basin, the underlying Badwater Greenstone, and nearby Baraga and Menominee Group strata. Leith and others (1935) interpreted the sedimentary rocks of the district to be roughly equivalent to the Michigamme Formation, but they were uncertain about the stratigraphic position of what they called the Paint River and Pentoga belts of greenstone (Badwater Greenstone of current usage). James (1958), however, proposed that the strata of the Iron River-Crystal Falls district comprised the uppermost - the Paint River Group - of four stratigraphic groups that make up the Marquette Range Supergroup. The Badwater Greenstone was considered to be part of the Baraga Group. Larue and Sloss (1980) discussed sedimentation of the Marquette Range Supergroup and accepted James' interpretation, whereas others questioned the stratigraphic position of the Paint River Group. For example, Cambray (1978) suggested that the Paint River Group is stratigraphically equivalent to the Menominee Group. More recently, Sims (1990, 1992), and Sims and Schulz (1993) proposed that the Paint River Group is the stratigraphic equivalent of the Baraga Group and they correlated the Badwater Greenstone with the Hemlock Formation in the Menominee Group.

As shown in figure 3, there is some lithologic similarity between units of the Paint River Group and other nearby successions, the most obvious being a thick and extensive banded iron-formation overlain disconformably by clastic rocks including ferruginous conglomerate. In this regard, the Riverton Iron-formation/Hiawatha Graywacke succession of the Paint River Group is similar to the Vulcan/Michigamme succession of the Menominee Range and the Negaunee/Goodrich succession of the Marquette Range. We suggest that the Riverton/Hiawatha disconformity is equivalent to the Menominee/Baraga unconformity elsewhere and that the Riverton and older formations of the Paint River Group are equivalent to Menominee Group units, whereas the Hiawatha and younger parts are equivalent to the Baraga Group. Thus, the thick clastic,

in part turbiditic, units of the upper part of the Paint River Group are correlatives of rocks of similar depositional setting in the Baraga Group. The Badwater Greenstone may be the equivalent of the Hemlock Formation in the Menominee Group. We here suggest that the Badwater Greenstone should be placed in the Paint River Group rather than the Menominee Group. Structural evidence presented below indicates that the Badwater is part of the allochthonous sequence, as indicated by the widespread occurrence of steeply plunging folds characteristic of the allochthon, and is an integral part of the Paint River succession, being the volcanic base on which younger units were deposited with apparent conformity. It thus is more aptly included with the Paint River Group rather than in other groups from which it is structurally separated and thus has unknown stratigraphic relations.

Structure

The area of the field trips spans the Paleoproterozoic suture separating the Archean Superior craton and Paleoproterozoic epicratonic rocks on the north from Paleoproterozoic oceanic and island arc rocks of the Wisconsin magmatic terranes on the south. The most commonly accepted model for accretion is northward emplacement of volcanic arcs over a south-directed subducting slab, eventually leading to the culmination of Penokean deformation as the arcs collided with the southern edge of the Superior craton.

The Niagara fault zone, a zone of intense shearing as much as several kilometers wide in some areas, is the feature which most completely separates volcanic rocks on the south from epicratonic sedimentary rocks on the north and is generally considered to be the surface trace of the suture. However, it is but one of a series of anastomosing faults that bound structural panels in which volcanic and sedimentary rocks are intermixed. These panels compose a belt as much as 25 km wide, which we refer to as the Niagara suture zone. Available structural data indicates that these panels were thrust northward during collision and are allochthonous with regard to Archean basement rocks and, in some cases with regard to lower parts of the sedimentary succession. The allochthons are characterized by a complex structural history in which refolding of early folds has resulted in diversely and commonly steeply plunging folds.

Terminology

Because various names have been applied over the years to structural elements composing what we now refer to as the Niagara suture zone, the following discussion correlates the terms used here with previous terminology. Both Bayley and others (1966) and Dutton (1971) defined the structural panels of the region and the map geometry has remained essentially unchanged since their work. They, however, did not use the term "Niagara fault", although they did recognize and map the fault as a major boundary between the dominantly volcanic rocks to the south and dominantly sedimentary rocks to the north. They did name other faults and also applied names to various structural blocks. We have retained their names throughout most of this report. With recognition of the significance of the Niagara fault as a suture, Larue and Ueng (1985) introduced the term "Florence-Niagara terrane" to encompass the eight structural panels defined by Bayley and others (1966) and Dutton (1971) as a roughly ten-kilometer-wide zone of rocks exhibiting very intense internal deformation unique to the tectonics of the suture zone. An additional terrane, the Crystal Falls terrane, was proposed by Ueng and Larue

(1987) and considered to be part of the terrane-boundary tectonic assemblage because of its complex, although less intense deformational history. In this report we have used the term "Niagara suture zone" to encompass both the Florence-Niagara terrane and Crystal Falls terrane. The suture zone is bounded on the south by the Niagara fault zone. The rocks of the suture zone all show a complexity and intensity of folding much greater than exhibited by correlative strata farther north. The northern boundary of the suture zone is the Badwater fault and Paint River fault, both probably originally thrusts, which transported Paleoproterozoic strata northward. We use the term "Iron River-Crystal Falls allochthon" as an equivalent to the "Crystal Falls terrane" of Ueng and Larue (1987) and "Iron River-Crystal Falls basin" of many older reports.

Niagara Fault Zone

The Niagara fault zone is a zone of highly strained rock most commonly up to a few hundred meters wide although there are few places where it is exposed and its width can be estimated. Its location (see fig. 1) is relatively well defined in the regions covered by this field guide, but lack of outcrops to the west make its location somewhat problematic. In those regions its location is based largely on interpretation of aeromagnetic maps on which the fault is expressed as a discontinuity of structural patterns. On geologic maps it is generally portrayed as a single line separating mostly metasedimentary rocks on the north from metavolcanic rocks on the south, but it is likely to have numerous splays extending southward into the volcanic terranes, only some of which have been seen in outcrop.

On the field trips we will examine two of the best-exposed areas of the fault zone. Highly sheared rocks of the fault zone are well exposed in Piers Gorge (stop 2-1). Although this locality is about a kilometer south of the mapped fault, there is little doubt that shearing seen here is a splay of the Niagara fault. Rocks within the fault zone are severely flattened and stretched and foliation strikes generally WNW and dips steeply south. High strain has resulted in rotation of fold axes to parallelism with the direction of maximum elongation (Sedlock and Larue, 1985). Based on stretch lineations, which plunge 60° SW, Sims and Schulz (1993) suggest that tectonic transport was northeastward, perpendicular to the trace of the fault, and onto the exposed part of the continental margin to the north. They infer that the fault zone dips about 70° to the south. The fault zone is also seen at stop 3-1 at the Pine River dam. There, very highly strained rocks of the Michigamme Formation are well exposed.

Although the Niagara fault has been widely accepted as a paleosuture, gravity studies by Attoh and Klasner (1989) suggest that the Archean cratonic rocks continue southward at depth to a steep gravity gradient that trends northeastward across north-central Wisconsin (fig. 1). By that interpretation the Niagara fault is a major thrust, which has transported arc rocks for at least a few tens of kilometers northward over the southern edge of the Superior craton. Based on gravity model studies, Klasner and Osterfeld (1984) had previously suggested that magmatic domes, such as the Dunbar Dome, are allochthonous, detached at depth and thrust northward in the hanging wall of the Niagara fault, which flattens at depth toward the south.

Niagara suture zone

Both the Menominee and Iron River-Crystal Falls districts lie near the southern edge of the exposed continental margin of the Penokean orogen and both lie within the Niagara suture zone as we define it here. The continental rocks north of the Niagara fault are highly faulted and divided into a series of structural blocks. Sedlock and Larue (1985) refer to these blocks as "fault bounded tectonostratigraphic terranes", but we prefer to use the term "structural panels" because they do not fit the strict definition of a tectonostratigraphic unit, which is defined in the Glossary of Geology as a "mixture of rock stratigraphic units resulting from tectonic deformation." Rather these are fault-bounded slices of rocks or rock-stratigraphic sequences that have a unique structural signature. Although both districts are part of the Niagara suture zone, they are distinctly different from each other structurally. Thus they will be discussed individually below.

Menominee District

The Menominee district lies within the Niagara suture zone at the southern edge of a series of uplifted blocks of Archean basement (figs. 1, 2). Those rocks north of the Menominee range contain fault-bounded troughs of tightly appressed Paleoproterozoic strata—the Felch and Calumet troughs (fig. 2)—down-faulted between blocks of Archean rocks. Studies by Klasner and others (1989) and Klasner and Sims (1993) suggest that these Archean blocks were uplifted and thrust northward along Bush Lake fault, a master fault that, they suggest, carried now eroded Paleoproterozoic and Archean rocks onto the continental hinterland to the north. A series of south-verging thrusts occurs in the Felch and Calumet trough areas. These may have developed as back-thrusts during the northward thrusting event, or they may have developed later during the Mazatzal orogeny (Holm and others, 1999; Romano and others, 2000).

The general structure of the Menominee iron district (fig. 4) is a south-facing homocline of Paleoproterozoic strata in which stratigraphic repetitions are created by three major faults and by folding internal to fault slices (Bayley and others, 1966). The faults cut the folds longitudinally, approximately along the fold axes, repeating the Paleoproterozoic sequence three times and forming three "ranges". Farthest north, the Carney Lake Gneiss forms the core of a broad anticlinal structure. The Paleoproterozoic strata lie unconformably on the gneiss and dip steeply to the south or are overturned (as at stop 2-3) and dip steeply north and face south. Farther south, the Paleoproterozoic strata are repeated twice by major faults to form the two ranges of the district. These faults were named the North Range fault and South Range fault by Bayley and others (1966) (fig. 4). The faults have steep dips at the present level of exposure and consistently show south-side-up displacement. Most recent interpretations (e.g., Sims and Schulz, 1993) consider them to have been thrust faults, which were steepened by continued shortening of the thrust panels. The rocks in the hanging wall (south side) of these faults have no indications of Archean basement rocks, in contrast to the area immediately to the north where the Carney Lake Gneiss is an integral part of the structure. The north range and south range panels may be allochthons detached from basement and thrust northward over the more autochthonous sequence of the northern part of the district. The Menominee range is bounded on the south by the Niagara fault (stop 2-1), along which it is in contact with volcanic rocks of the Wisconsin magmatic terranes.

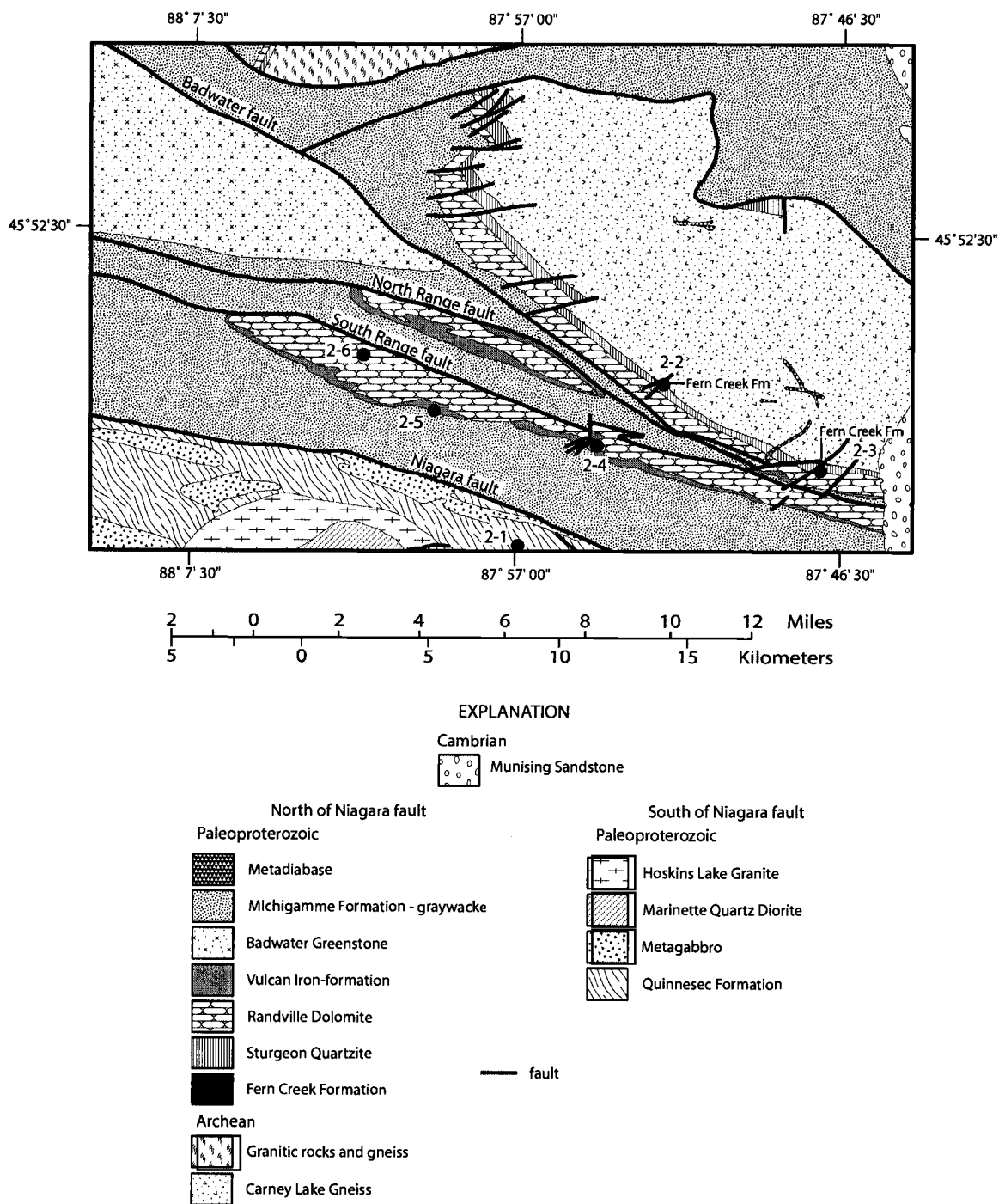


Figure 4. Geologic map of part of the Menominee Iron Range showing the location of field trip stops. Geology is from Bayley and others (1966).

These faults continue to the northwest into the Florence, Wisconsin area and along the south side of the Iron River-Crystal Falls district, where Dutton (1971) mapped four fault-bounded structural "blocks". He named the blocks, from north to south, the Brule River block, the Keyes Lake block, the Pine River block, and the Popple River block. The

Menominee Range and contains, in its western portions, an extensive dolomite (Saunders Formation) generally accepted as the equivalent of the Randville Dolomite of the Menominee Range. The occurrence of these shelf-deposited rocks in the southernmost and structurally highest thrust panel of the continental foreland indicates that the continental shelf originally extended substantially south of the present Niagara fault.

Iron River - Crystal Falls District

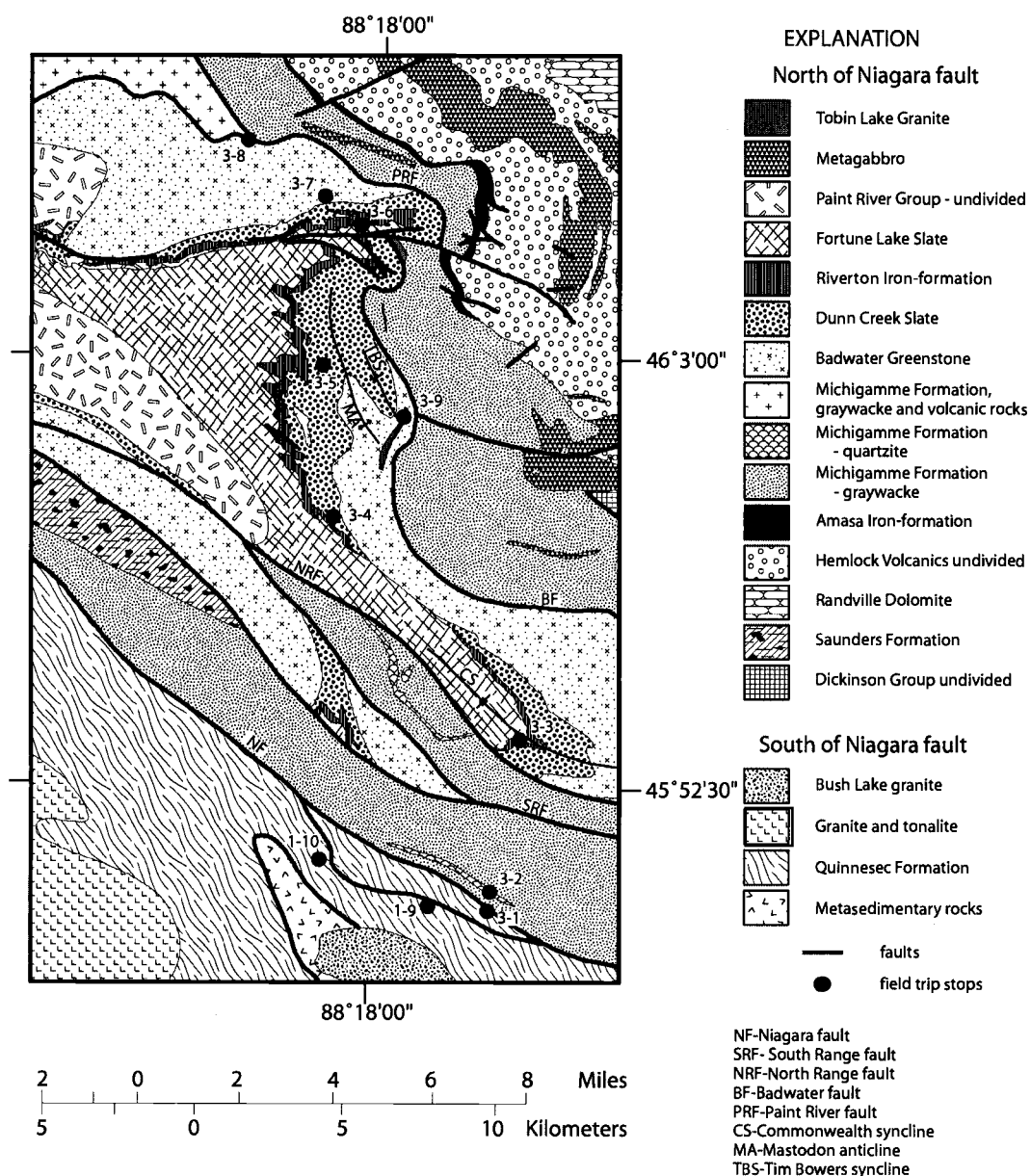


Figure 5. Geologic map of the Florence area and eastern part of the Iron River-Crystal Falls district showing the location of field trip stops. Geology is from Dutton (1971) and James and others (1968).

The Iron River-Crystal Falls District (fig. 1, 2, 5) is a triangular-shaped basin of tightly folded strata of the Paint River Group. Structural studies by James and others (1968) showed that sedimentary strata of the Iron River-Crystal Falls basin are tightly and multiply folded. Dips of less than 60 degrees are rare. For the most part the trends of the fold axes are parallel or sub-parallel to the principal axis of the triangular district. Stratigraphically overturned beds are common. There are a dozen or more faults having displacements measured in thousands of feet. In addition, James and others (1968, page 87) noted "It is the opinion of one of the authors (FJP) that the folds in the Michigamme Slate are unrelated to those in the Badwater Greenstone and Dunn Creek slate...", suggesting that the Michigamme has a different structural signature than the Badwater Greenstone and overlying Dunn Creek Slate. Francis J. Pettijohn (FJP) further suggested that a north-trending fault separates the Michigamme from the Badwater and Paint River Group strata along the eastern edge of the district. More recent structural studies (Ueng and Larue, 1987) identified four phases of deformation, including two major folding events that resulted in the extremely complex fold interference pattern characteristic of the district. This refolded fold geometry is exceptionally well displayed at stop 3-6.

Uncertainty concerning the stratigraphic position of the Paint River Group and Badwater Greenstone, as discussed above, led Sims (1990) and Sims and Schulz (1993) to propose that a thrust (detachment) fault (the Badwater thrust fault) lies at the base of the Badwater Greenstone and that the Badwater and overlying Paint River Group strata are allochthonous, tectonically emplaced above Baraga Group strata of the continental margin. Although the Badwater thrust fault was not directly observed, they based their interpretation on unpublished geochemical data by K. J. Schulz, and the presence of "extensive thrust faulting" of continental margin strata.

To test this interpretation, Klasner and others (1999) compared the structural signature (primarily orientation of fold axes) in the Paint River Group strata and Badwater Greenstone with the structural signature in underlying Baraga Group strata. Based on measurement of 123 fold axes throughout the Iron River-Crystal Falls basin, they found that most fold axes plunge steeply (approximately 85 degrees) north (fig. 6A). There are at least three other trends in the plot of the fold axes, indicating that the rocks in the Paint River Group are multiply deformed. In contrast, fold axes in the area north and east of the Iron River-Crystal Falls basin plunge at low angles to the west-northwest or east-southeast (see fig. 6B). These measurements were made mainly in Michigamme Formation strata of the Baraga Group. The striking difference in structural history of these two regions supports the proposal of Sims (1990) that a thrust fault separates these two regions. Thus, the Paint River Group, including the Badwater Greenstone, appears to be allochthonous, having been thrust onto the autochthonous Baraga Group strata.

The metamorphic grade of rocks surrounding the Paint River Group ranges from greenschist to amphibolite (James and others, 1968; Bayley and others, 1966; Dutton, 1971), but Paint River Group rocks of the Iron River-Crystal Falls district reach only greenschist or lower metamorphic grade. This feature, too, suggests that there is a fault with considerable displacement separating the Paint River Group from surrounding rocks.

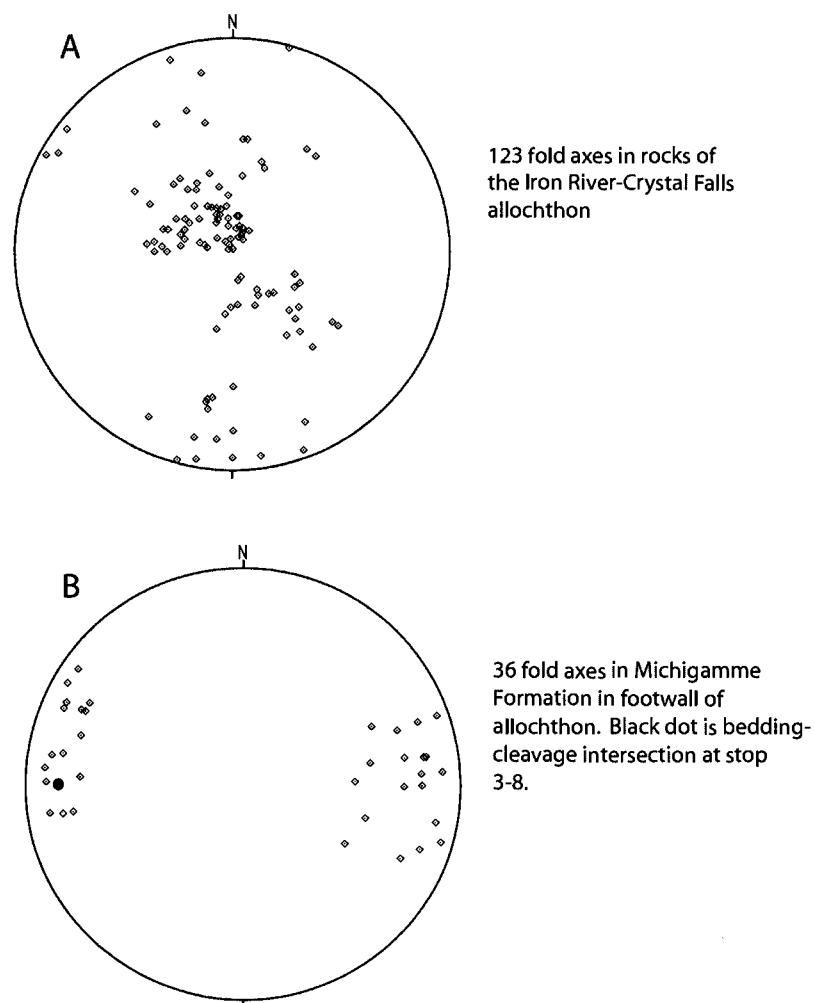


Figure 6. Stereoplots (lower hemisphere equal area projections) showing the orientation of fold axes within the Iron River-Crystal Falls allochthon (A) and in the Michigamme Formation north and east of the allochthon (B).

A north-northeasterly-oriented cross section constructed from underground mapping in mine workings (James and others, 1968) in the Iron River area provides an example of the complexity of folding typical of this district. The structure seen here suggests that the initial folding in the Iron River-Crystal Falls basin may have been recumbent (fig. 7A). The cross section shows a recumbent syncline in Hiawatha Graywacke and overlying Riverton Iron-formation. In the third dimension this fold plunges steeply into the section (to the NW). It is strongly overprinted by other folds of diverse orientations. The syncline closes toward the southwest and the overturned upper limb in which the stratigraphically older Riverton Iron-formation lies above Hiawatha Graywacke suggests a northward structural vergence. The orientation of fold axes measured in outcrops near the mine are shown in figures 7B and 7C.

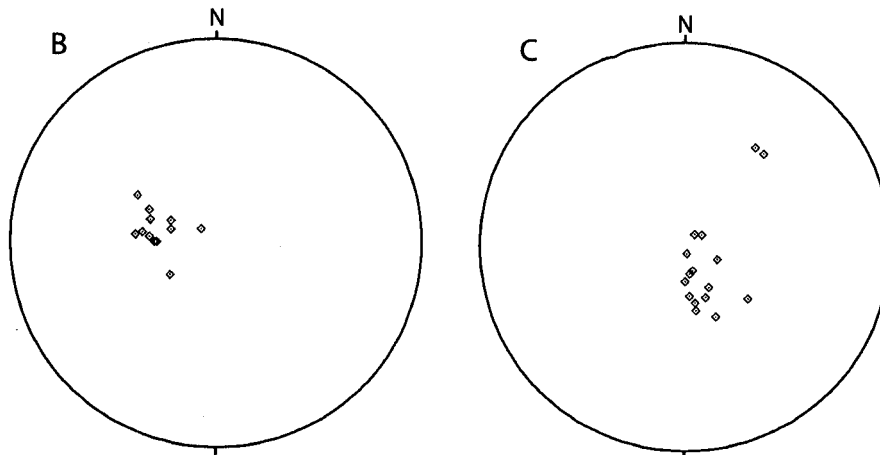
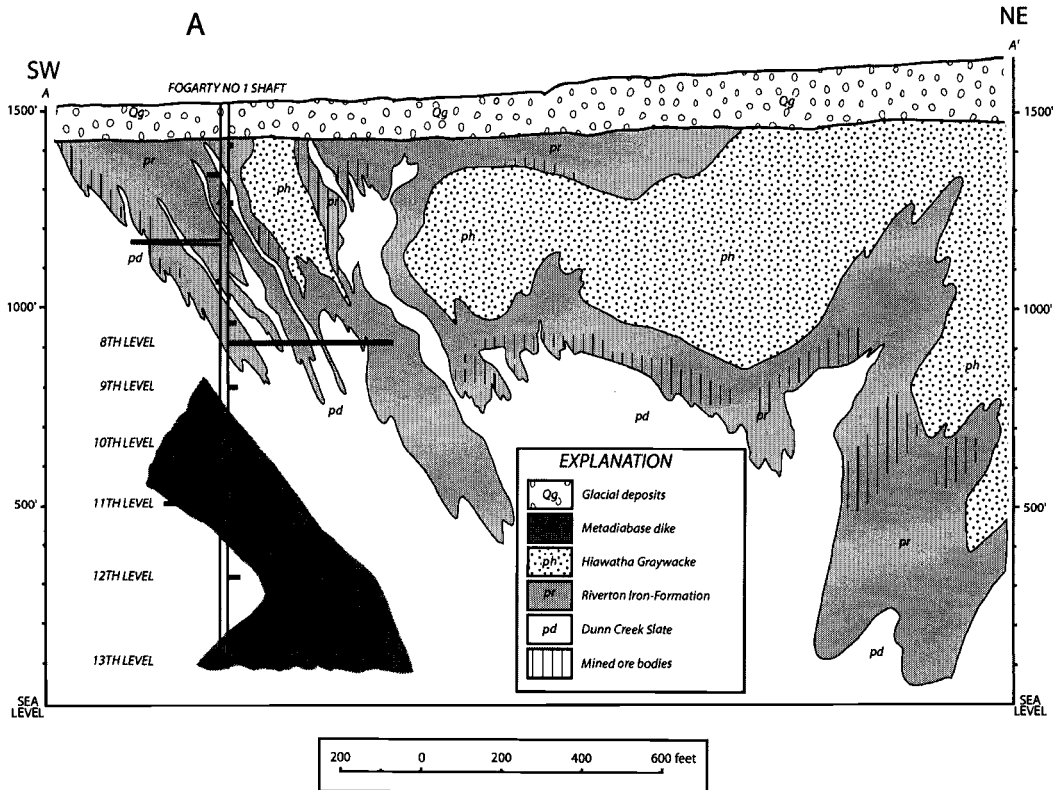


Figure 7. A- Geologic cross section through the Buck Mine in Iron River, Michigan, about 12 miles west of Crystal Falls. Cross section is in sec. 1, T. 42 N., R. 35 W., and sec. 6, T. 42 N., R. 34 W. Reproduced from James and others (1968) to show large refolded recumbent syncline, the very tight folding, and wide diversity of axial surfaces of folds. Lower hemisphere equal area stereograms of fold axes in outcrops of Riverton Iron-formation (B) and Hiawatha Graywacke (C) near the mine.

History of Iron Mining

Iron ore was discovered in the Menominee district in 1848 by two explorers, J.W. Foster and S.W. Hill, according to Winchell (1895). However, iron mining did not begin until 1870, when N.P. Saxton started digging pits and trenches on the site of the Breene Mine, with the first ore being shipped in 1873 (Bayley and others, 1966). All the major mines had been located by 1878. Production continued until 1958, with a total production from the district of approximately 85,000,000 tons (Bayley and others, 1966). Seven mines produced nearly 77,000,000 tons of ore, with a majority of the production from the district coming from three mines, the Chapin (27,500,000 tons), the Penn (21,700,000 tons) and the Aragon (11,200,000 tons) (Dutton, 1958). Production from the Chapin Mine ended in 1934 with a major collapse of the workings. The subsidence from this collapse formed the lake on the north side of Iron Mountain. A causeway across the lake now carries the traffic on Highways U.S.-2 and U.S.-141. Ore from the district was hauled by rail to Escanaba, MI, from where it was carried by boat to steel mills on the lower Great Lakes. All of the ore shipped from the district was high-grade natural iron ore. Although the iron-formation in the Menominee district was studied as a possible source of beneficiating ore (a "taconite ore"), no commercial operation has been undertaken.

Harvey Mellen, a United States land surveyor, first discovered iron ore in the Iron River-Crystal Falls district in 1851 (James and others, 1968). Mining commenced in 1881 and the first ore was shipped in 1882. Except for the early years of mining, when many mines were operated as small open pits, nearly all of the ore was recovered by underground mining (James and others, 1968). Mine exposures and maps of the numerous mines greatly helped resolve the complex structure of the district. A major hazard to mining was caused by the pyritic slate of the Wausau Pyritic Member of the Dunn Creek Slate, which would burn spontaneously when exposed to air in the mines. During the 92-year period from 1882-1974, approximately 205,000,000 tons of iron ore were shipped from the district. Although there were 121 mines in the district, a majority of the ore came from about a dozen mines.

In the Florence district, iron ore was recovered from six relatively small mines between 1880 and 1960. Only about 8,000,000 tons of predominantly soft hematite and limonite ore with a high phosphorous content was produced (Dutton, 1971). The Florence mine was the most productive mine in the district with 3,680,000 tons shipped between 1880 and 1931. Nearly all of the production from the district was from the Riverton Iron-formation (Dutton, 1971).

PEMBINE-WAUSAU MAGMATIC TERRANE

Introduction

The volcanic and plutonic rocks that are widely distributed in northeastern Wisconsin south of the Menominee and Iron River-Crystal Falls iron-bearing districts in Michigan are the easternmost exposures of a major east-trending belt of volcanic and plutonic

rocks known as the Pembine-Wausau terrane, the northernmost of the two Wisconsin magmatic terranes (Sims and others, 1989). The occurrences in Marinette and Florence Counties, Wisconsin represent the best-exposed portion of this suite of rocks in the Lake Superior region and include a dismembered ophiolite sequence (Schulz, 1987). The Wisconsin magmatic terranes represent complex magmatic arcs accreted to the southern margin of the Archean Superior Craton during the Paleoproterozoic Penokean orogeny (Sims and others, 1989).

The Pembine-Wausau terrane is mainly composed of tholeiitic and calc-alkaline volcanic rocks that formed between 1860 and 1889 Ma (Sims and others, 1989). A more restricted calc-alkaline volcanic succession was deposited between 1835 and 1845 Ma on the older rocks along the southern margin of the terrane in Marathon County. Granitoid rocks constitute nearly half of the exposed rocks in the terrane and range in age from about 1870 to 1760 Ma. These intrusive rocks are mainly granodiorite and tonalite but include gabbro, diorite and granite (Sims and others, 1993). An older suite of granitoids ranging in age from about 1870 to 1840 Ma is broadly syn-orogenic whereas younger post-collisional alkali-feldspar granite suites were emplaced at about 1835 Ma and 1760 Ma. The magmatic rocks of the Pembine-Wausau terrane are separated from epicratonic rocks of the Marquette Range Supergroup to the north by the Niagara fault zone (see Bayley and others, 1966, and Dutton, 1971) and from the Marshfield magmatic terrane to the south along the Eau Claire shear zone (Sims and others, 1989).

General Geology

Volcanic rocks are relatively well exposed in the northern and eastern part of Marinette County and eastern Florence County in northeastern Wisconsin, where they form an arcuate belt around the large Dunbar gneiss-granitoid dome (fig. 8) (Sims and Schulz 1993). The supracrustal rocks, formally named the Quinnesec Formation by James (1958), consist of metamorphosed basalt, andesite, dacite, and rhyolite lava flows and volcanoclastic rocks, and locally, sedimentary rocks including greywacke, graphitic slates, and iron-formation. Pyritic to pyrrhotitic massive sulfide bodies are also present locally (Hollister and Cummings, 1982; LaBerge, 1983). Gabbro sills are common, particularly in the northern part of the sequence (Bayley and others, 1966). Serpentinite bodies, commonly with some associated gabbros, are also present locally.

Jenkins (1973) noted that at least four lithologically distinct volcanic units could be defined in northeastern Wisconsin with three of the units sufficiently different from the lithologies of the type area of the Quinnesec Formation (Prinz, 1958; Bayley and others, 1966) to warrant their separate designation. He proposed the informal names McAllister formation, Beecher formation, and Pemene formation, listed in the order of progressively more silicic units, and Jenkins (1973) suggested that this also represents the order of decreasing age. More recently, DePangher (1982) proposed that the Quinnesec Formation be designated the Quinnesec Group consisting of five lithostratigraphic units having formational status. For the purposes of this field guide, the informal nomenclature proposed by Jenkins (1973) will be used for the volcanic rocks in the area.

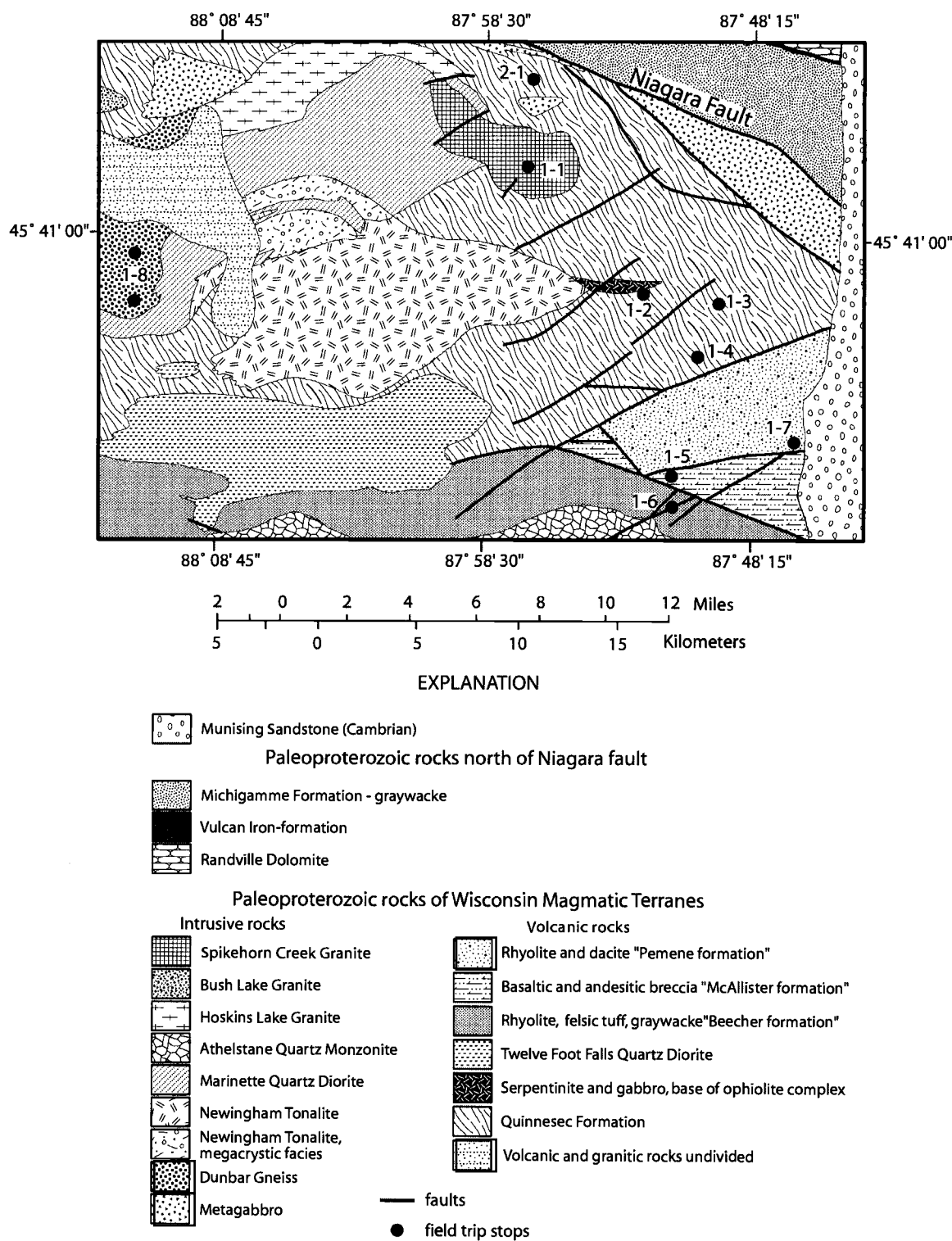


Figure 8. Generalized geologic map of part of northeastern Wisconsin showing the location of field trip stops.

The units of the Dunbar gneiss-granitoid dome intrude the volcanic rocks in northern Marinette County, and the Athelstane Quartz Monzonite intrudes them in the south.

Small intrusive bodies ranging from hornblendite and gabbro to quartz diorite, granite and calc-alkaline lamprophyre are widespread, particularly in the southeastern parts of the exposed volcanic sequence. To the north and northeast, the volcanic sequence is truncated by the Niagara fault (Bayley and others, 1966; Dutton, 1971), which marks a major discontinuity in the rocks of the region. North of this fault, rocks of the Michigamme Formation and other units of the Marquette Range Supergroup occur, along with basement uplifts of Archean gneissic rocks.

The supracrustal rocks and associated subvolcanic intrusives are variably altered to greenschist facies mineral assemblages throughout the eastern outcrop area but contain assemblages as high as amphibolite facies adjacent to the Dunbar dome and further to the west. The rocks are regionally folded on northwest-trending axes, but they commonly lack a strong penetrative cleavage in the east. As a result, primary textures and structures are generally well preserved in the eastern outcrop area. Units generally face outward from the margins of the Dunbar dome and Athelstane intrusion.

Contacts between the various volcanic units are not exposed, but are interpreted to be high-angle faults (Jenkins, 1973; Sims and Schulz, 1993). Because of uncertainties in the amount of displacement on these faults and the complexity of folding, detailed correlations between units have not been possible. Present geologic data support the interpretation of the Quinnesec Formation (as used by Jenkins) as the oldest volcanic unit. The relative ages of the other units, however, remain uncertain. The units may have been structurally emplaced and may not be in their original stratigraphic position. The regional structure suggests that the McAllister formation may be younger than the Beecher formation but older than the Pemene formation. Further work is required to resolve the age and stratigraphic relationships of these units.

Until relatively recently the age of the volcanic rocks in northeastern Wisconsin was a point of controversy. Van Hise and Bayley (1900) and Bayley (1904) originally interpreted the "Quinnesec schists" as Archean because of the striking similarity of these rocks to Archean rocks elsewhere in the Lake Superior region. Van Hise and Leith (1911) subsequently assigned the Quinnesec to a post-Michigamme (i.e. Paleoproterozoic) age on the basis of the interpretation of Hotchkiss and others (1915) that the Michigamme Formation graded upward into volcanic rocks in Florence County, Wisconsin. Dutton (1971) later reinterpreted the relationship in this area and placed a fault between the volcanic units to the south and the Michigamme Formation to the north. Bayley and others (1966) and Dutton (1971), favored an Archean age, although acknowledging that definitive field evidence was lacking to establish the age of the Quinnesec Formation.

Banks and Rebello (1969) reported a U-Pb zircon age of $1,866 \pm 39$ Ma for a felsic volcanic sample from south of the Dunbar dome. This age, which is not resolvable from the ages of the rocks of the Dunbar dome (Sims and others, 1984), is now generally taken as that of the volcanic sequence in northeastern Wisconsin, although this locality is isolated from the main areas of outcrop. More recently, an age of $1,870 \pm 56$ Ma was obtained for the basalts of the Quinnesec Formation by whole-rock Sm-Nd isotopic systematics (Beck and Murthy, 1991). Thus, the age of the volcanic rocks in northeastern Wisconsin is now established as Paleoproterozoic and not Archean as once thought. Their age is generally similar to that obtained for the massive sulfide deposits near Crandon, Monico and Ladysmith to the west (Sims, 1976) and to ages of

other volcanic and plutonic rocks of the Pembine–Wausau magmatic terrane (Sims and others, 1989).

Volcanic Units

The four volcanic units that comprise the supracrustal sequence in Marinette and Florence Counties, as well as some of the granitoid bodies that intrude them, are briefly described below. Further information can be found in Sims and others (1989), Sims and others (1992), and Sims and Schulz (1993). Although the rocks are mostly metamorphosed at greenschist facies, the prefix "meta" is generally omitted below for simplicity.

Quinnesec Formation: The Quinnesec Formation is the dominant volcanic unit exposed in northeastern Wisconsin. Its stratigraphic thickness is not known because of uncertainties in the degree of folding and faulting but is probably on the order of several thousand meters. The Quinnesec Formation consists predominantly of basalt lava flows and diabase in the north, but includes pillowed and fragmental andesite in the south. The basalt is commonly pillowed, with the pillows locally variolitic. The pillowed flows are in some areas overlain by thick (tens of meters) sections of pillow breccia and hyaloclastite breccia (N. ½, sec. 11, T. 37 N., R. 21 E., Faithorn 7.5 minute quadrangle). Andesite increases in abundance southward in the formation, and is generally plagioclase and clinopyroxene-phyric and amygdaloidal. Fresh, glacially polished outcrops around the new location of the Kremlin mine pit east of Pembine (S. ½, sec. 26, T. 37 N., R. 21 E., Faithorn 7.5 minute quadrangle) provide excellent exposures of andesite breccia. Felsic tuff and breccia are also present locally in the Quinnesec, particularly in the northern portion near the Menominee River. Felsic fragmental units are also present in the LaSalle Falls area along the Pine River in Florence County (Bayley and others, 1966; Dutton, 1971).

Compositionally, the Quinnesec basalts are tholeiitic, with generally low TiO_2 and other high-field-strength element abundances, and flat to extremely light rare-earth element (REE) depleted patterns (Sims and others, 1989). In addition, some of the basalts and the andesites have very low TiO_2 and REE abundances, but relatively high Cr and Ni contents. The trace element characteristics of the mafic volcanic rocks overlap those of mid-ocean ridge basalt (MORB) and primitive island-arc tholeiite suites whereas the andesites show compositional affinities with boninites (fig. 9), although none of the andesites are as high in MgO as true boninites. The felsic volcanic rocks have low potassium compositions with relatively low REE abundances and flat REE patterns. They are similar in composition to tholeiitic plagiogranite/rhyolite (Schulz, 1987; Sims and others, 1989). The compositional data suggest that the original basaltic magmas that gave rise to the Quinnesec rocks were derived from a variably incompatible-element-depleted mantle source. This is supported by a large positive epsilon Nd value of 4.2 for the basalts (Beck and Murthy, 1991), indicative of derivation from a mantle with long-term depletion in light rare-earth elements.

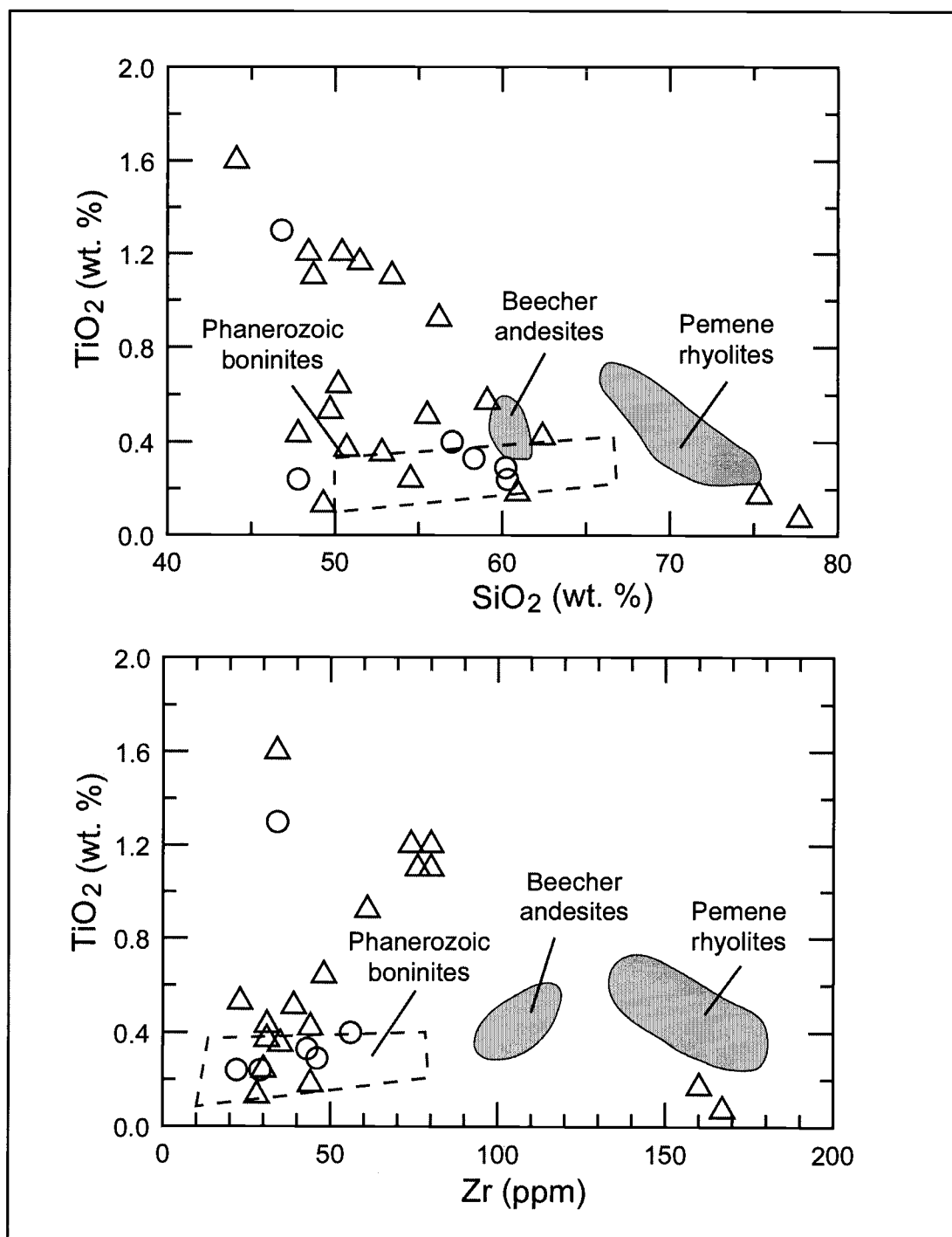


Figure 9. Plots of TiO_2 versus SiO_2 (upper) and Zr (lower) for volcanic rocks (triangles) and related gabbros and diabase (circles) from the Quinnebec Formation, northeastern Wisconsin. Note that several of the samples plot in the field of Phanerozoic boninites. Fields also are shown for Beecher andesites and Pemene rhyolites.

Sedimentary rocks appear to be rare within the Quinnebec Formation. Where present, they consist mostly of chert, graywacke, slate and iron-formation. Iron-formation occurs as thin units interlayered with volcanoclastic sedimentary rocks and tuffs, and consists of

interlayered chert and siderite (Cummings, 1978). A small massive sulfide deposit, containing pyrrhotite and chalcopyrite, in a felsic tuff, and in a fine-grained black slate that occurs between the felsic tuff and a mafic unit is exposed at Pine Rapids (locally known as "LaSalle Falls") on the Pine River (LaBerge, 1983).

In addition to volcanic rocks, the Quinnesec Formation also contains a number of gabbroic and ultramafic rocks (Sims and Schulz, 1993). Numerous large gabbro bodies are present, particularly near the Niagara fault zone. These bodies are more or less conformable with the basaltic flows and probably represent synvolcanic sills, although Bayley and others (1966) considered the gabbroic sills to be "post-Animikie" in age. Gabbro and anorthositic gabbro comprise the bulk of the sills. Some sills also contain peridotite (serpentinite) and pyroxenite layers and magnetite-rich gabbro. Trace element and isotopic data for the gabbros show they are comagmatic with the basalts of the Quinnesec Formation (Schulz, unpublished data).

Several serpentinized peridotite bodies of varying sizes occur within the volcanic succession, but the largest and best-exposed occurs south of Timms Lake (Morgan County Park) east of Pembine, Wisconsin. The body trends east from outcrops in the NE. $\frac{1}{4}$, sec. 19, T. 37 N., R. 21 E., for a distance of about 4.5 km to the North Branch Pemebonwon River in the NE. $\frac{1}{4}$, sec. 22, T. 37 N., R. 21 E. The body produces a large magnetic anomaly. Serpentinized peridotite is dominant in the western part of the body where it is locally cut by coarse grained (1-5 cm) dikes of pyroxenite now replaced by amphibole. The serpentinite generally shows few primary textures, although primary compositional layering is suggested locally by differential weathering of bands in some outcrops. Veins of carbonate and cross-fiber asbestos are common. Layered and massive gabbro, along with local masses of strongly foliated-lineated gabbro, are dominant in the eastern part of the body. The gabbroic rocks are cut by numerous mafic dikes, some of which appear to be sheeted, with diabasic to microdioritic textures. The strongly foliated-lineated gabbro masses appear as screens between the dikes. The foliation in the gabbro screens is at a high angle to the contacts of the body with the Quinnesec basalts. The strong deformational fabric of the gabbro screens is not present in most of the associated rocks of the body, including the dikes. This suggests that the deformation of the gabbro in the screens occurred prior to emplacement of the dikes and to the regional deformation. The trend of the mafic dikes is about parallel to the trend of the serpentinite-gabbro body (~E-W) and generally at a high angle to the foliation of the gabbro screens. The dikes do not appear to extend into the surrounding pillow basalts. These features suggest that the serpentinite-gabbro body may be fault-bounded and tectonically emplaced within the Quinnesec Formation. The compositions of the gabbros and diabasic dikes within this body range from MORB to depleted island-arc tholeiite and high-magnesium andesite with boninitic affinities; these mafic rocks are similar in composition to the basalts in the Quinnesec Formation (fig. 9).

The lithologies and their arrangement in this ultramafic-gabbroic body, along with those of the Quinnesec Formation generally, are similar to those that characterize Phanerozoic ophiolite sequences (fig. 10). This includes (from bottom to top): mafic-ultramafic plutonic rocks, a dike (sheeted?) complex, extrusive pillowed and massive basalt lava flows, and overlying arc-related volcanoclastic rocks. Tectonized ultramafic rocks representing suboceanic mantle have not been recognized. Also, based on the present exposure, the ultramafic-mafic cumulates and dike complex, although present, are much less extensive than in the ideal ophiolite sequence (fig. 10). This may be a function of

limited exposures in the region and/or lack of preservation of the lower part of the ophiolite sequence during later magmatic and tectonic events. Incomplete sequences are common in ophiolites found in many orogenic belts (Moore, 2002). The lithologic association observed in the Quinnesec and the compositions of rocks, ranging from MORB to depleted island-arc tholeiite and high-magnesium andesite of boninitic affinity, and plagioclase-rhyolite, are similar to Cenozoic suprasubduction zone ophiolites like those of the Coast Ranges in California (Shervais and Kimbrough, 1985; Shervais, 2001).

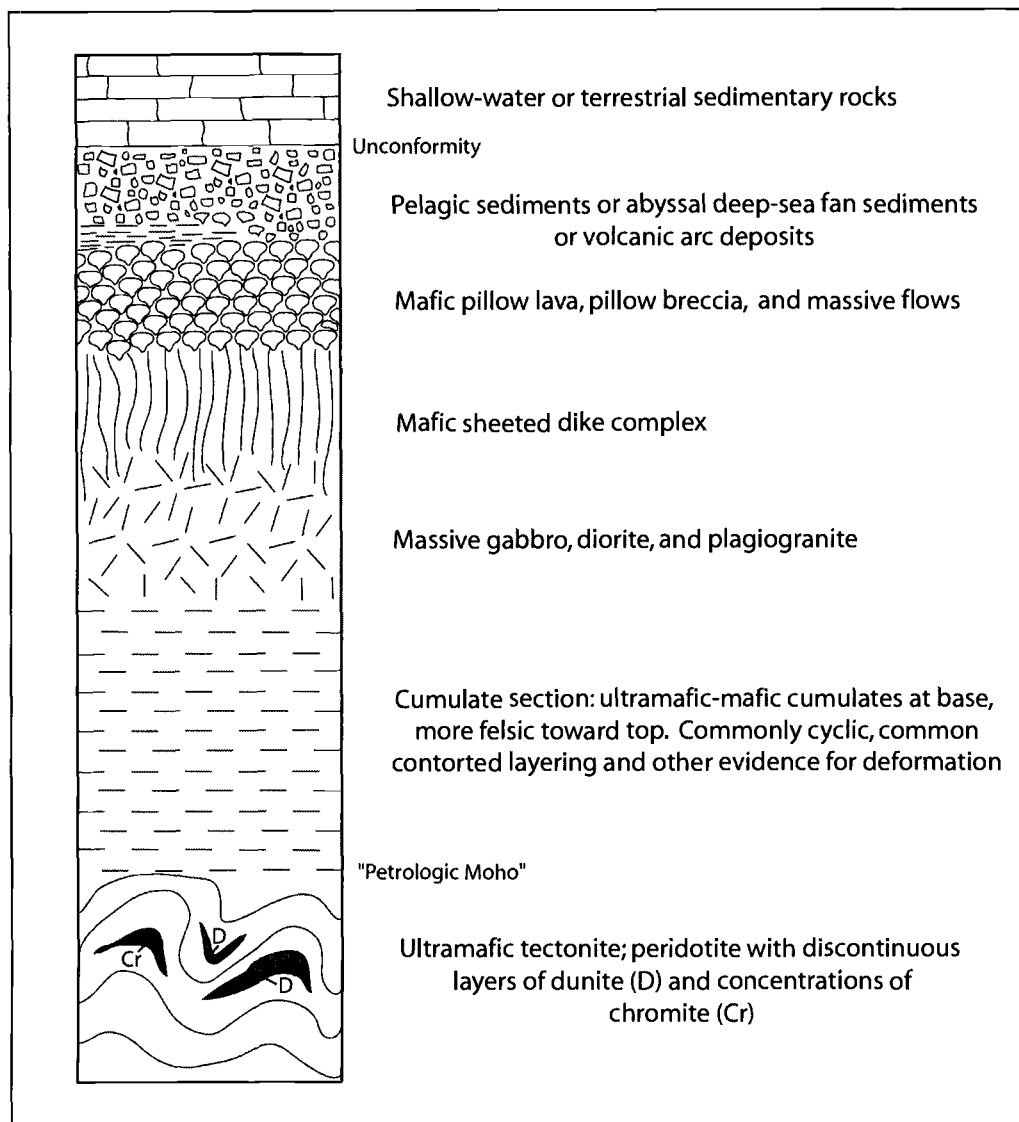


Figure 10. Schematic cross-section of a complete ophiolite (after Moore, 2002).

The Quinnesec Formation is intruded by units of the Dunbar dome including the Marinette Quartz Diorite and the Spikehorn Creek Granite, as well as by the Newingham Tonalite and Twelve Foot Falls Quartz Diorite (Sims and Schulz, 1993) and numerous

small lamprophyre dikes and plugs locally. To the southeast the Quinnesec is in apparent fault contact with the Pemene formation (Sims and Schulz, 1993).

McAllister formation: The McAllister formation appears to be in fault contact with the adjoining volcanic units in the area (Jenkins, 1973). It occurs in a roughly east-west belt between the Pemene formation to the north and the Beecher formation to the south (Sims and Schulz, 1993). It ranges in thickness from about 300 meters in the west to 3,000 meters in the east with units facing north and generally striking N.70-80° W and dipping near vertical. The McAllister consists of calc-alkaline basaltic to andesitic volcanic breccia with a lithic tuff matrix, and locally pillowed and massive lavas. Fragments in the breccia are distinctive in that they generally contain large pyroxene crystals that are now replaced by hornblende. Amygdules are also common in many fragments. Vertically, the McAllister formation shows no consistent gradation in fragment size. However, laterally, fragment size increases from west to east (Jenkins, 1973). Near the Menominee River, blocks more than 15 cm in diameter are common, suggesting the source area for this dominantly fragmental unit may be located to the east in Michigan.

Beecher formation: The Beecher formation extends in a north-facing, east to southeast-trending belt south of the McAllister formation and north of the Athelstane Quartz Monzonite (Sims and Schulz, 1993). The formation is at least 3,000 meters thick with a lower and upper unit. The thicker (2,000 - 3,000 m) lower unit consists dominantly of calc-alkaline plagioclase- and pyroxene-phyric andesite and dacite lava flows and lesser volcanoclastic rocks. The thinner (up to 300 m) upper unit consists of interbedded felsic ash, crystal tuff, lapilli tuff, and coarser fragmental rocks, some with distinctive rounded pink to white felsite fragments. Some units show grading whereas others are unsorted. Black slates are also present locally in the upper part of the formation.

The lower part of the Beecher formation, where intruded by the Athelstane Quartz Monzonite, faces away from the intrusion and has a well developed foliation and steeply plunging lineation. Dikes of Athelstane Quartz Monzonite extend only a short distance into the Beecher formation.

Pemene formation: The Pemene formation is interpreted to be the youngest volcanic unit in eastern Marinette County. It occupies a broad oval area whose outline is well expressed in the local topography in the northern part of the Miscauno Island 7.5 minute quadrangle. The Pemene is at least 2,000 meters thick and consists predominantly of thick (45 - 300 m) calc-alkaline rhyolite lava flows typically composed of a flow-top hyaloclastite breccia, an underlying flow-banded unit, and a microspherulitic central core. The microspherulitic core constitutes the bulk of each flow and contains plagioclase phenocrysts, commonly in glomeroporphyritic clusters, and locally phenocrysts of blue quartz. The flow-banded unit, where present, has gradational upper and lower contacts and laminar to highly-contorted banding. The top of each flow has a layer of hyaloclastite breccia 3 to 75 m thick that probably formed by quench fragmentation as the hot rhyolite flows came in contact with cold external water. Exposures in the NE ¼, NW ¼, sec. 13, T. 36 N., R. 21 E., (Miscuano Island 7.5 minute quadrangle) provide an excellent cross sectional view of one of these rhyolite flows. Here, large open outcrops show a transition from massive microspherulitic rhyolite upward into flow-banded rhyolite breccia with clasts to about 30 cm (a "crackle breccia"?). This in turn grades upward into a spectacular fine hyaloclastite consisting of black rhyolite fragments, some with fine internal banding and white rinds (figs. 11 and 12). Thin sedimentary units with graded

bedding are present between some rhyolite flows. The general characteristics of the Pemene rhyolites is similar to those of other submarine rhyolite lava flow and dome complexes such that on the Island of Ponza, Italy (Scutter and others, 1998).

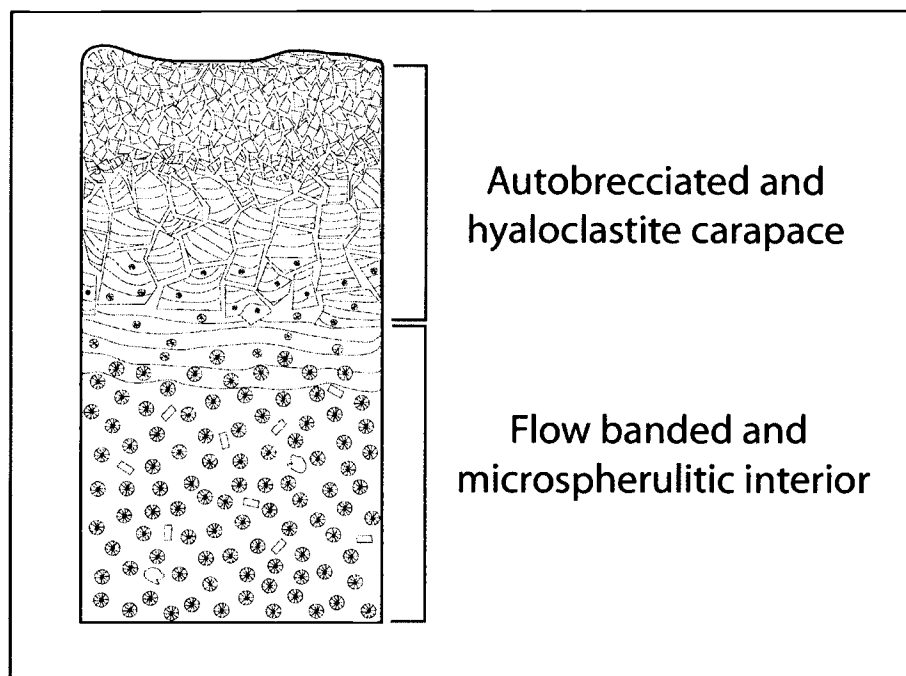


Figure 11. Schematic cross-section of the upper part of a subaqueous rhyolite lava flow in the Pemene formation.

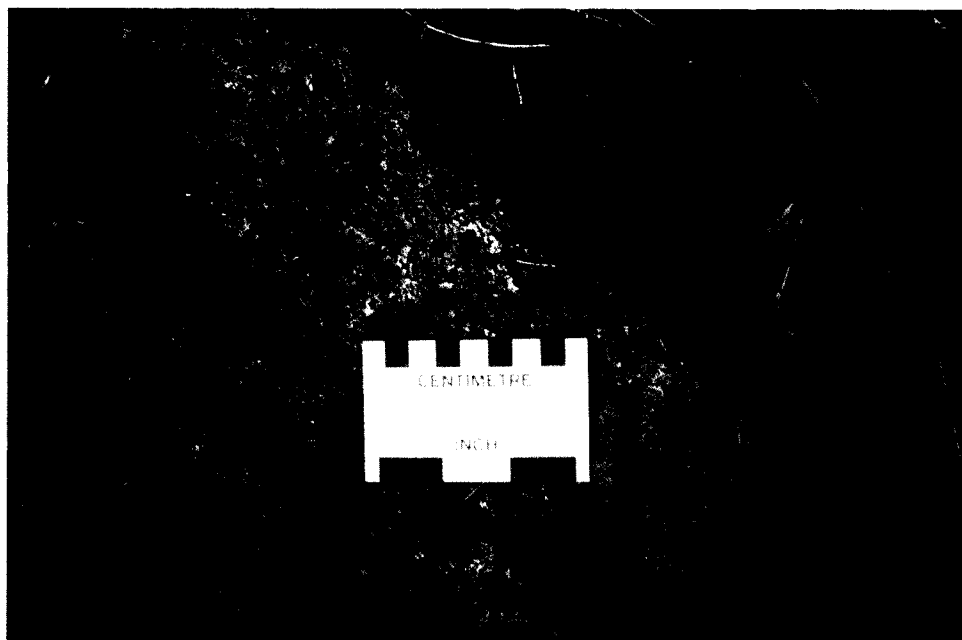


Figure 12. Photograph of the rhyolite hyaloclastite in the upper carapace of a subaqueous Pemene rhyolite lava flow.

The Pemene formation shows little evidence of a penetrative structural fabric. The flows show a southward dip in the north and dip nearly vertically in the south. Jenkins (1973) interpreted the structure of the Pemene as an east-trending, asymmetric, doubly plunging syncline.

Major Intrusive Rocks

A variety of intrusive rocks are present within the supracrustal sequence in northeastern Wisconsin. They range from synvolcanic gabbro, diabase, diorite, and tonalite to syntectonic intermediate to felsic granitoids (including those related to the Dunbar dome), lamprophyric dikes and plugs, and post-tectonic granites and diabase dikes.

Twelve Foot Falls Quartz Diorite: The Twelve Foot Falls Quartz Diorite comprises a large "sill-like" intrusion some 20 km by 5 km in size to the west of Beecher, Wisconsin (Sims and Schulz, 1993). It is composed of gray, generally medium to coarse-grained quartz diorite containing subhedral crystals of sodic andesine, subhedral hornblende, and anhedral bluish quartz. In composition it is similar to calc-alkaline andesites in the McAllister and Beecher formations (Sims and others, 1992).

Athelstane Quartz Monzonite: The Athelstane Quartz Monzonite intrudes the Beecher formation and extends for an unknown distance to the south and west (Sims and Schulz, 1993). It consists dominantly of medium- to coarse-grained quartz monzonite and locally contains numerous metavolcanic inclusions. The Athelstane Quartz Monzonite is dated at $1,836 \pm 15$ Ma (Banks and Cain, 1969). The Amberg Granite, which intrudes the Athelstane Quartz Monzonite west and north of Amberg (Sims and Schulz, 1993), is dated at $1,756 \pm 19$ Ma (Van Schmus, 1980).

Dunbar Dome

Note. Only a brief summary of the geology of the Dunbar dome is presented here for the purposes of the present trips. More comprehensive accounts are available in a guidebook by Sims and others (1984), and in U.S. Geological Survey Professional Paper 1517 by Sims and others (1992).

The Dunbar dome is one of several granitoid domes in northern Wisconsin that have cores of gneiss, migmatite and granitoid rocks and are mantled by metavolcanic and metasedimentary rocks in the Pembine-Wausau magmatic terrane (Sims and others, 1985). Where ages have been determined, both the core of the domes and mantle or cover rocks are of Paleoproterozoic age. The Dunbar dome is a complex antiformal structure consisting of a central core of Dunbar Gneiss, Marinette Quartz Diorite, and Hoskin Lake Granite, and three lateral protuberances (lobes) from the core composed of Bush Lake Granite on the west, Spikehorn Creek Granite on the east, and Newingham Tonalite on the south (Sims and others, 1992). The intrusive and structural evolution of the dome spanned the relatively short time of about 30 Ma, from syn-tectonic events at about 1865 Ma to post-tectonic at about 1835 Ma.

Conclusions

The volcanic and associated intrusive rocks in northeastern Wisconsin south of the Niagara fault, the Pembine ophiolite, are interpreted to record the evolution of a

Paleoproterozoic suprasubduction zone ophiolite-island arc sequence. Shervais (2001) has shown that suprasubduction zone ophiolites tend to display a consistent sequence of events during their formation and evolution in response to similar tectonic processes. This sequence includes the following (after Shervais, 2001):

- (1) Birth, which entails the initiation of ophiolite formation during extension above a newly forming or reconfigured intraoceanic subduction zone. Rocks formed during the initial phase of ophiolite formation include layered and isotropic plutonic gabbros, sheeted dikes, and a "lower" volcanic section consisting of low-K tholeiitic basalt and basaltic andesite with MORB and primitive arc tholeiite affinities. Gabbros formed during this stage are often ductilely deformed (foliated or boudinaged) in response to syn-magmatic extension.
- (2) Youth, during which continued melting of previously depleted asthenospheric mantle occurs in response to increased fluid flux from the subducting slab. Rocks formed during the second phase of ophiolite formation include intrusive mafic-ultramafic sills and additional dikes, and an "upper" volcanic unit characterized by basalt and andesite with highly depleted incompatible trace element compositions (i.e., low-Ti basalt, high-Mg andesite and boninite).
- (3) Maturity, during which the subduction zone stabilizes and the rate of crustal spreading slows. Rocks formed during this phase include hornblende diorite, quartz diorite, tonalite, and volcanic rocks ranging from basalt to rhyolite, all with transitional to calc-alkaline compositions. Volcanism typically becomes more silicic with time. In many cases, these rocks have not been considered part of the subjacent ophiolite, but rather have been attributed to post-ophiolite arc volcanism.
- (4) Death, which results from the demise of active spreading and subduction. In the case where death results from collision with an active ocean spreading center, dikes and lavas with oceanic basalt compositions may crosscut and overlie the older ophiolite-arc section.
- (5) Resurrection, which accompanies emplacement by obduction onto a passive continental margin or accretionary uplift with renewed subduction. In the case where death is the result of collision with a passive margin, death and resurrection of the ophiolite sequence may occur essentially simultaneously.

The rocks of the Quinnesec Formation appear to record the first two stages of suprasubduction zone ophiolite evolution. The presence in the upper part of the Quinnesec Formation of basalt and andesite lavas and dikes derived from highly refractory mantle is particularly diagnostic of a relationship to the early stages of intraoceanic subduction and formation in a forearc setting (Shervais and Kimbrough, 1985; Beccaluva and Serri, 1988). This further implies that the Quinnesec Formation and associated rocks did not form in a back-arc basin near the margin of the Superior Craton, but probably formed as an intraoceanic ophiolite-arc system above a southward dipping (in present coordinates) subduction zone.

The calc-alkaline volcanic rocks of the McAllister, Beecher and Pemene formations and associated intrusives such as the Newingham Tonalite and Twelve Foot Falls Quartz Diorite appear compatible with the third stage (maturity) of suprasubduction zone ophiolite evolution. Shervais (2001) notes that for a suprasubduction zone ophiolite to reach maturity requires that the ocean basin being subducted be large enough to complete the first two stages without disappearing. This suggests that the

Paleoproterozoic ocean basin that was subducted was probably significant in size (at least many hundreds of kilometers).

It appears likely that growth of the Pembine ophiolite-arc system was terminated by its collision with and obduction onto the passive margin of the Superior craton. Since subduction appears to be largely driven by slab pull, the southward subduction of oceanic lithosphere attached to the Superior continental margin would have pulled the continental lithosphere along with it as it descended into the subduction zone below the ophiolite-arc system. With detachment of the subducting oceanic lithosphere, the buoyancy of the continental lithosphere would have led to its rapid uplift along with the leading edge of the ophiolite-arc system (Shervais, 2001). This interpretation suggests that the volcanic and associated rocks of northeastern Wisconsin are allochthonous, as is also suggested by gravity and magnetic data for the region (Klasner and others, 1985; Attoh and Klasner, 1989). This stage is recorded by the deformation of the ophiolite-arc sequence and by the intrusion of the syn-tectonic units of the Dunbar dome. It is possible that the shallow-water sedimentary rocks (carbonates) along the west margin of the Dunbar dome (Sims and Schulz, 1993) represent Chocolay Group rocks of the Marquette Range Supergroup that were uplifted from the continental margin basement below during formation of the Dunbar dome.

FIELD TRIP 1

PEMBINE-WAUSAU MAGMATIC TERRANE

Klaus J. Schulz, USGS, Reston, VA and Gene L. LaBerge, University of Wisconsin-Oshkosh (retired), Oshkosh, WI and USGS



Pillowed flows of high-Mg andesite of the Quinnebec Formation, part of the Pembine ophiolite complex, Quiver Falls, Wisconsin

FIELD TRIP 1

PEMBINE-WAUSAU MAGMATIC TERRANE

Klaus J. Schulz, USGS, Reston, VA and Gene L. LaBerge, University of Wisconsin-Oshkosh (retired), Oshkosh, WI and USGS

The Paleoproterozoic volcanic and associated intrusive rocks exposed in the eastern part of Marinette County in northeastern Wisconsin are the easternmost exposures of the Pembine-Wausau terrane, the northernmost of the two Wisconsin magmatic terranes (Sims and others 1989). The volcanic rocks are composed of tholeiitic and calc-alkaline volcanic and volcanoclastic rocks that formed at about 1870 Ma (Sims and others, 1989). They are cut by a variety of intrusive rocks ranging from syn-volcanic gabbros, diorites, and tonalities to syn- and post-tectonic granitoids (i.e., Dunbar Gneiss and related rocks). The magmatic rocks of the Pembine-Wausau terrane are separated from the epicratonic sedimentary rocks of the Marquette Range Supergroup in Michigan by the Niagara fault zone. The lithologic units present in eastern Marinette County and their chemistry strongly suggest that these rocks represent a Paleoproterozoic suprasubduction zone ophiolite, the Pembine ophiolite (Schulz, 1987; Sims and others, 1989). The ophiolite and associated island-arc rocks were accreted to the southern margin of the Archean Superior Craton during the Penokean Orogeny.

On this field trip we will examine the major lithologies that comprise the Pembine ophiolite. This includes examples of ultramafic rocks (serpentinite), layered and massive gabbros cut by mafic dikes, pillow basalts and andesites, and several overlying calc-alkaline arc-related volcanic and volcanoclastic rocks (fig. 1-1).

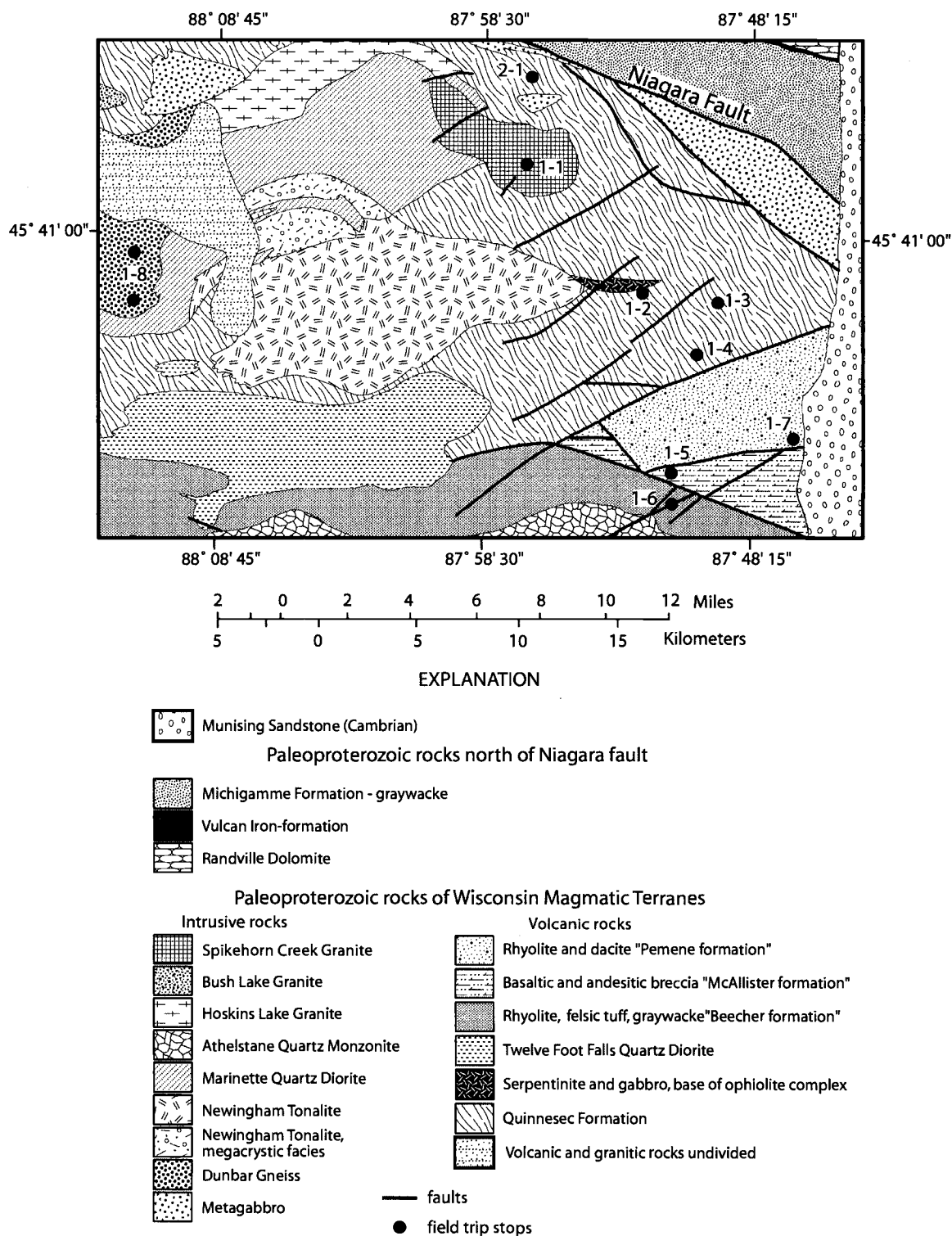


Figure 1-1. Generalized geologic map of part of northeastern Wisconsin showing the location of field trip stops 1-1 through 1-8. See figure 3-2 (p. 67) for location of stops 1-9 and 1-10.

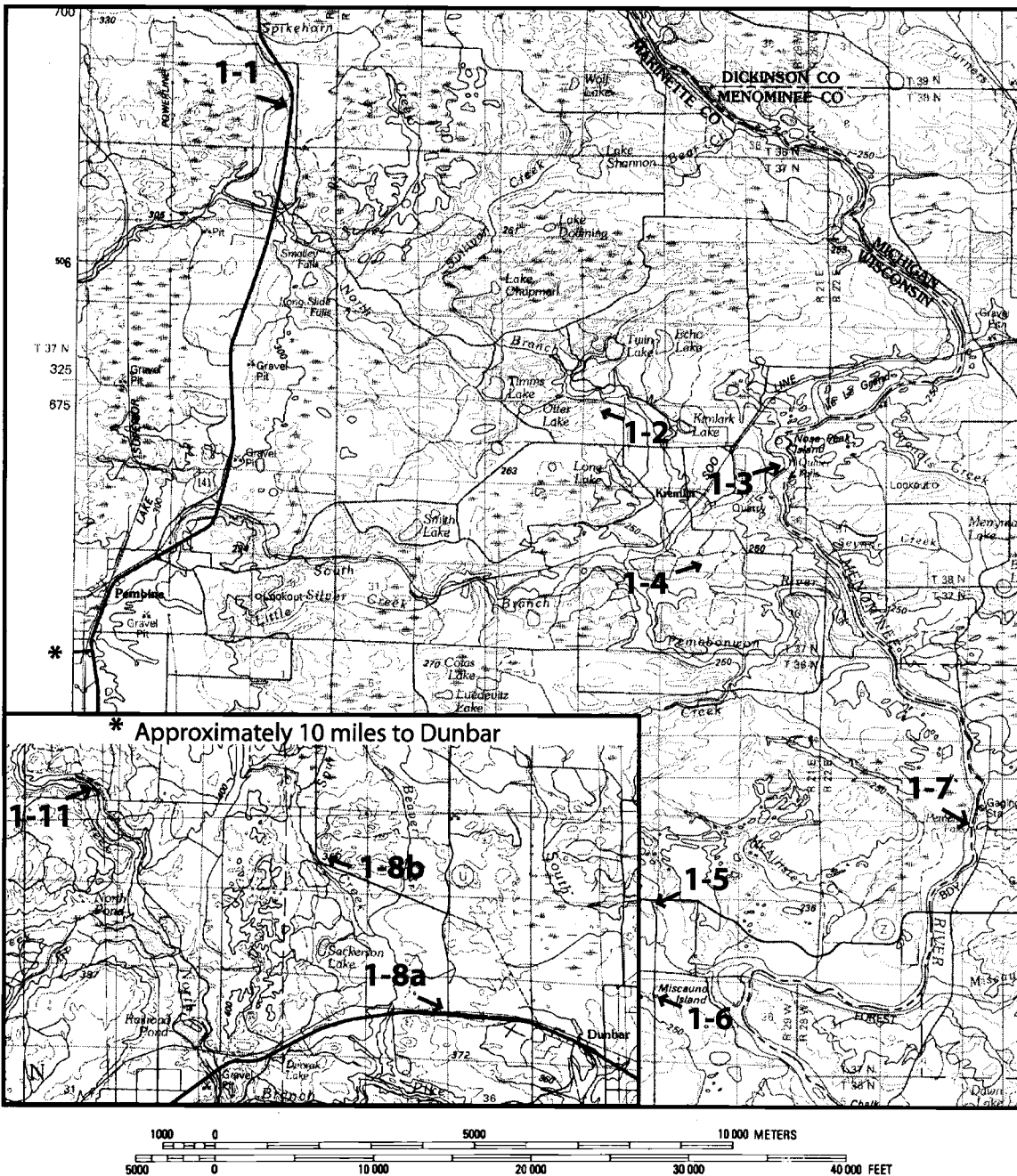


Figure 1-2. Part of the Escanaba 1:100,000-scale topographic map showing the location of field trip stops 1-1 through 1-7 and supplemental stops 1-8 and 1-11.

Stop 1-1. Spikehorn Creek Granite (west side U.S. Highway 141, SW $\frac{1}{4}$, NE $\frac{1}{4}$, sec. 36, T. 38 N., R. 20 E.).

The outcrop on the west side of U.S. Highway 141 (fig. 1-2) is representative of the Spikehorn Creek Granite, a gray to pinkish gray, fine- to medium-grained massive granite with scattered potassium feldspar grains as much as 2 cm in diameter. The granite is composed of plagioclase (sodic oligoclase) with weak normal zoning,

microcline microperthite, quartz, biotite, sphene, and opaque oxides. Accessory minerals include zircon, allanite, apatite (rare), and fluorite (rare). The granite has sharp intrusive contacts with the Quinnesec volcanic rocks and the Marinette Quartz Diorite.

The Spikehorn Creek Granite is a post-tectonic diapiric intrusion on the northeast side of the Dunbar dome with an age of $1,835 \pm 6$ Ma (Sims and others, 1992). It is similar in composition and age to the LittleTobin Lake Granite, which intrudes the Badwater Greenstone north of the Niagara Fault zone (Schneider and others, 2002; see also field trip 3, stop 3-9). Both the Spikehorn and Little Tobin Lake granites represent "stitching" plutons, emplaced after collision of the Pembine-Wausau magmatic terrane with the passive margin of the Superior Craton. As such, the age of these granites provides a minimum age for the Penokean Orogeny.

Stop 1-2. Exposures of Serpentinite, Gabbro, and Mafic Dikes (i.e., Ophiolite) East of Pembine (NW ¼, NW ¼, sec. 22, T. 37 N., R. 21 E.)

Follow the red flags and trail north to outcrops of serpentinite on the south side of the North Branch Pemebonwon River. The serpentinite in the surrounding outcrops shows variable features including layering (fig. 1-3), brecciation, and carbonate and serpentine veining. Chromite is clearly evident in some samples. Some serpentinite is highly magnetic whereas other samples are not; this may reflect original variations in the proportion of olivine and pyroxene in the ultramafic rocks. Locally, dikes of pyroxenite (now altered to talc-serpentine) have been observed cutting the serpentinite.



Figure 1-3. Photograph of nearly vertical layering in ultramafic (serpentinite) rocks at stop 1-2.

As we walk south we will first see further exposures of serpentinite followed after a few hundred meters by a series of outcrops with variable proportions of layered gabbro, foliated-lineated gabbro, massive diabase and quartz diabase (dikes?), all cut by reddish-brown-weathering mafic dikes (figs. 1-4 and 1-5). The foliation in the foliated gabbro is variable in strike between N.15 W. to N.15 E. and dips steeply either E or W. The mafic dikes generally strike about E-W parallel to the overall trend of the serpentinite-gabbro body and dip steeply. The dikes do not appear to extend outside the body into the surrounding pillow basalts. The serpentinite-gabbro body appears to be fault-bounded and tectonically emplaced within the Quinnesec Formation.

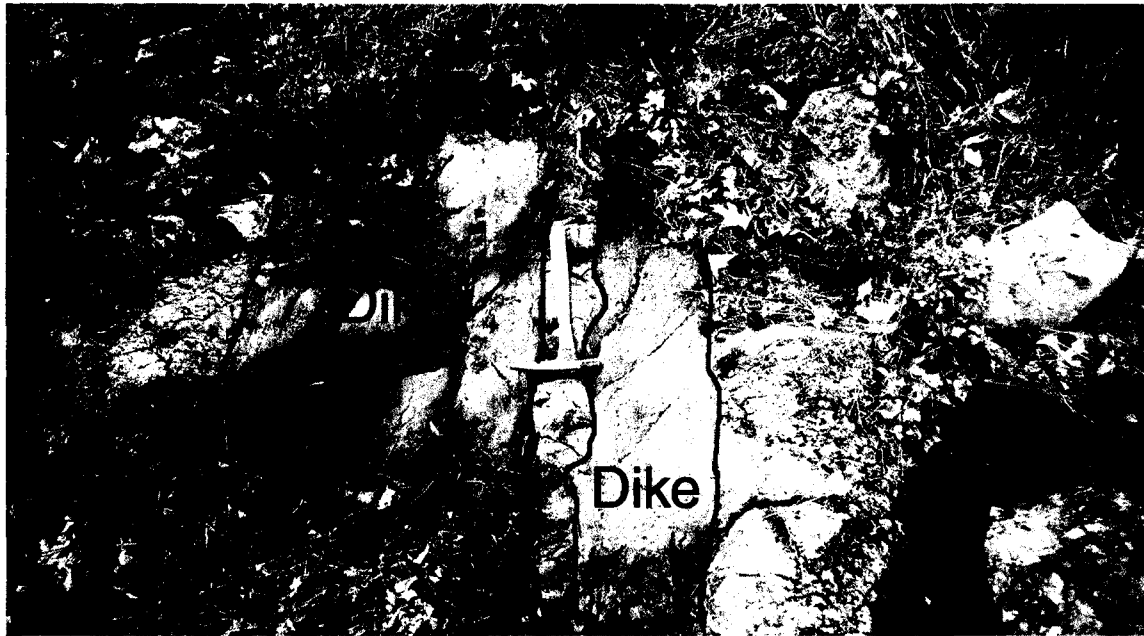


Figure 1-4. Photograph of rusty weathering mafic dikes with gabbro screens at stop 1-2 (Note, dike margins are highlighted).

The lithologies and their arrangement in this ultramafic-gabbroic body along with those of the Quinnesec Formation generally are similar to those that characterize recent ophiolite sequences (Moore, 2002). This includes (from bottom to top): mafic-ultramafic plutonic rocks, a dike (sheeted?) complex, extrusive pillowed and massive basalt lava flows, and overlying volcanoclastic sedimentary rocks. The compositions of the gabbros and mafic dikes within this body range from MORB to depleted island-arc tholeiite and high-magnesium andesite with boninitic affinities; the mafic rocks are similar in composition to the gabbros and basalts in the Quinnesec Formation (Sims and others, 1989; Schulz, 1987 and unpublished data). The lithologic association and chemistry are similar to recent suprasubduction zone ophiolites like those of the Coast Ranges in California (Shervais and Kimbrough, 1985; Shervais, 2001). These data, along with the presence of overlying calc-alkaline island-arc volcanic and volcanoclastic rocks, suggest formation of the Quinnesec as a suprasubduction zone ophiolite associated with forearc extension during the early stages of subduction and island arc formation.



Figure 1-5. Close-up photo of rusty weathering mafic dike cutting foliated gabbro at stop 1-2. Note cleavage development along the upper margin of dike (dike contacts are highlighted).

Stop1-3. Pillow basalt of the Quinnesec Formation, Quiver Falls on the Menominee River (NE ¼, SW ¼, sec. 24, T. 37 N., R. 21 E.)

Basalt and andesite pillow lavas and pillow breccias are common in the Quinnesec Formation. A three-dimensional view of pillows can be seen in this exposure along the banks of the Menominee River at Quiver Falls (fig.1-6). Here, south-facing elongate closely packed basalt pillows can be seen with excellent preservation of features due to the low degree of deformation. Locally, the basalt here is also highly variolitic (fig. 1-7) with large (1-2 cm) round pinkish siliceous-appearing varioles. Chemically the basalt is characterized by relatively high MgO (9.8 wt.%), and very low TiO₂ (0.35 wt.%), Zr (35 ppm), and REE (flat pattern at ~6 x chondrites) contents. It is similar in composition to some of the massive diabasic gabbro seen at stop 1-2.



Figure 1-6. Photograph of pillow basalt in the Quinnesec Formation at Quiver Falls on the Menominee River (stop 1-3).



Figure 1-7. Photograph of variolitic basalt at Quiver Falls on the Menominee River (stop 1-3).

Stop 1-4. Andesite Breccia at the New Kremlin Mine Pit (S ½, sec. 26, T. 37 N., R. 21 E.)

The fresh glacially polished outcrops around the new Kremlin mine pit at this stop provide excellent exposures of andesite breccia in the upper part of the Quinnesec Formation. The Kremlin mine processes the Quinnesec rocks for roofing granules. The andesite breccia consists of angular to sub-rounded volcanic fragments ranging from about 5 cm to at least 40 cm across in a matrix of 0.5 to 2.0 cm hyaloclastite fragments. The sub-rounded fragments and hyaloclastite matrix suggest that the unit may represent pillow breccias and/or subaqueous debris flows. Note the black pyroxene phenocrysts in some of the andesite clasts. Locally to the west, similar rocks are interlayered with rhyolite flows and tuffs.

Stop 1-5. McAllister Formation on Marek Road (NE ¼, NE ¼, sec. 22, T. 36 N., R. 21 E.)

The McAllister formation consists of calc-alkaline basaltic to andesitic volcanic breccia with a crystal lithic tuff matrix, and locally pillowed and massive lavas. This outcrop is typical of the McAllister volcanic breccia. Fragments in the breccia are distinctive because they generally contain large pyroxene crystals that are now replaced by hornblende. Amygdules are also common in many fragments. The size of fragments in the McAllister formation increases from west to east. Near the Menominee River, blocks over 15 cm in diameter are common suggesting the source area for this dominantly fragmental unit may be located to the east in Michigan.

Stop 1-6. Beecher Formation on Marek Road (NW ¼, NW ¼, sec. 26, T. 36 N., R. 21 E.)

The Beecher formation consists of two units: a thick (~2,000-3,000 m) lower unit consisting dominantly of calc-alkaline plagioclase- and pyroxene-phyric andesite and dacite lava flows and lesser pyroclastic rocks, and a thinner (~300 m) upper unit, which consists of interbedded felsic ash, tuff and coarser fragmental rocks. The exposures at this stop are in the upper unit and show bedded crystal tuff (fig. 1-8), lapilli tuff, and coarser units, some with distinctive rounded pink to white felsite fragments (fig. 1-9). Some units are graded whereas others are unsorted. Graded bedding in some layers indicates tops to the northeast. Jenkins (1973) suggested that at least some of the rocks of the Beecher formation were deposited subaerially.



Figure 1-8. Photograph of bedded crystal tuff in the upper unit of the Beecher formation, stop 1-6.

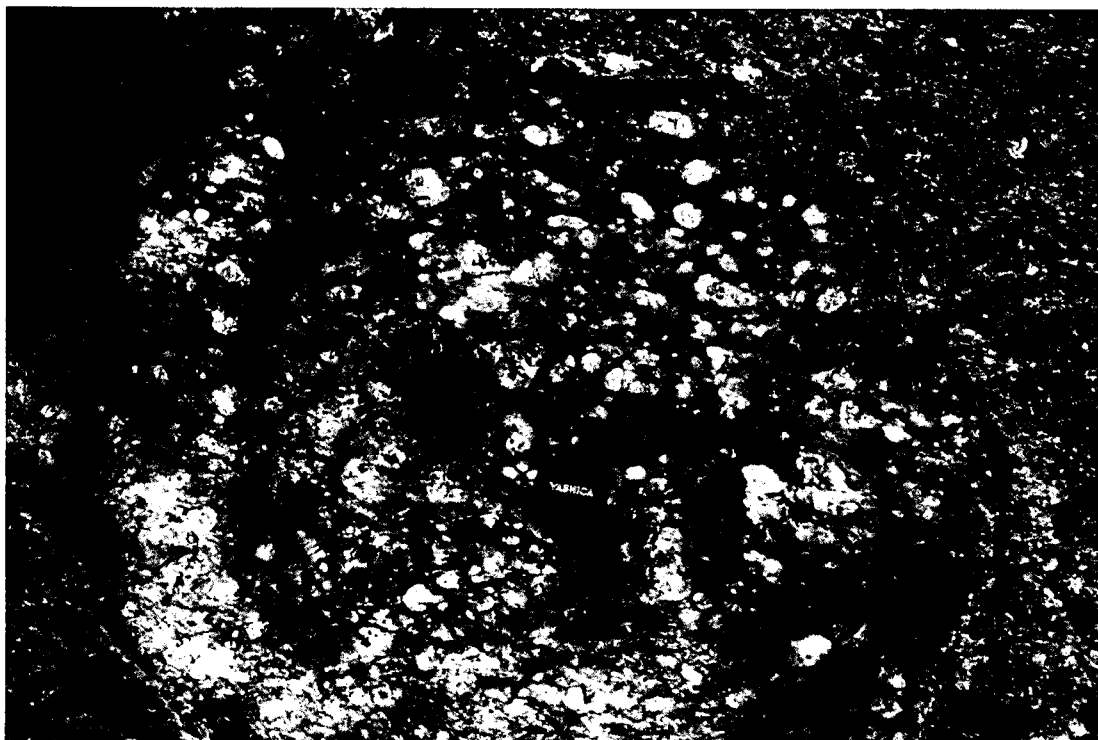


Figure 1-9. Photograph of a distinctive fragmental unit with rounded pink to white felsite fragments in the upper part of the Beecher formation, stop 1-6.

Stop 1-8. Pemene Formation at Pemene Falls on the Menominee River (NW corner, sec. 23, T. 37 N., R. 25 W.)

Exposed along the bank of the Menominee River at Pemene Falls is rhyolite of the Pemene Formation. The rocks are dark gray to reddish gray, contain few feldspar phenocrysts, and are generally microspherulitic. Phenocrysts, many of which are glomeroporphyritic, consist mainly of euhedral to subhedral albite; however, phenocrysts of blue quartz are present locally. The microspherules consist of radial intergrowths of quartz and albite. This phase of the Pemene probably represents the devitrified interior portion of a rhyolite flow.

In areas to the west, Pemene rhyolite lava flows show internal gradations from massive microspherulitic rhyolite at their centers to flow-banded rhyolite and finally autobreccia and hyaloclastite carapaces. This suggests the Pemene rhyolite flows were deposited subaqueously. Locally, felsic dikes are found cutting the rhyolite.

Supplemental Stop 1-8. Dunbar Gneiss West and North of Dunbar, Wisconsin

Stop 1-8a. Dunbar Gneiss on the West Side of the Intersection of County Road U with U.S. Highway 8 (SW ¼, SW ¼, sec. 26, T. 37 N., R. 18 E.).

The low outcrops here are composed mainly of megacrystic granite gneiss that contains rafts of layered amphibolite (fig. 1-10). This lithology is similar to that dated from an outcrop to the north with a U-Pb zircon concordia upper intercept age of $1,862 \pm 5$ Ma (Sims and others, 1992). Lineation in the amphibolite plunges generally about $20-25^\circ$ N. $85-90^\circ$ E. Locally, the amphibolite is refolded by folds having N. 50° W. steep axial surfaces. The granite gneiss has a pervasive N. 70° W. foliation. The granite gneiss (Dunbar Gneiss) is tonalitic in composition, and is interpreted as a plutonic protolith (Sims and others, 1992).

Stop 1-8b. Migmatitic Dunbar Gneiss (Center sec. 15, T. 37 N., R. 18 E.).

The exposures on the east side of the road are of migmatitic Dunbar Gneiss. The gneiss here consists mainly of compositionally layered rocks, biotite gneiss, and lesser amphibolite, intruded by megacrystic biotite gneiss, granite pegmatite, and aplite. All rocks are deformed with foliation striking N. $50-55^\circ$ W. at 90° . The foliation is defined by biotite and hornblende alignment and is generally parallel to compositional layering.

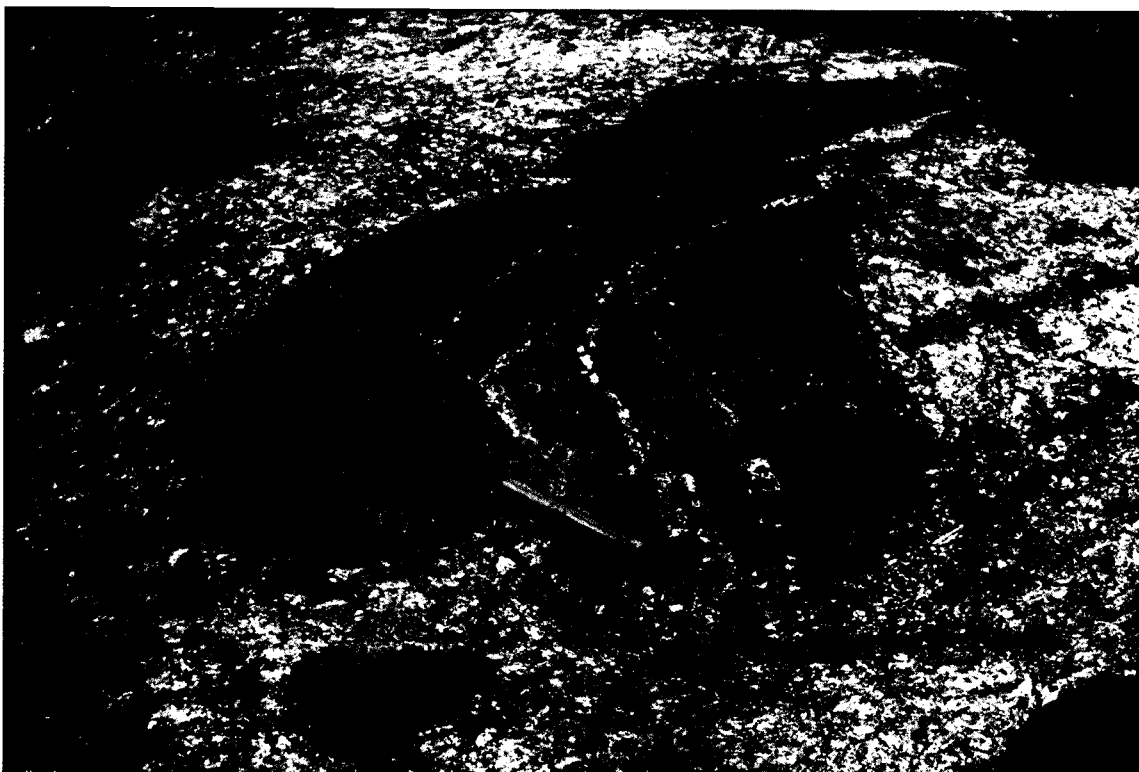


Figure 1-10. Photograph of an outcrop of megacrystic Dunbar Gneiss with folded amphibolite rafts at stop 1-8a.

Supplemental Stop 1-9. Sulfide deposit at "LaSalle Falls" on the Pine River. (NW ¼, SE ¼, sec. 30, T.39 N., R.18 E. See figure 3-1 and 3-2 for location.)

The Pembine-Wausau terrane is host to a number of volcanogenic massive sulfide deposits, two of which are known in northeastern Wisconsin (Cummings, 1978; LaBerge, 1983). The deposit on the Pine River is the only known naturally exposed massive sulfide deposit in Wisconsin.

The deposit at Pine Rapids (locally known as LaSalle Falls) on the Pine River occurs in the Quinnesec Formation about one mile south of the Niagara Fault zone (fig. 3-2). LaSalle Falls is formed where the Pine River flows over a resistant unit of rhyolite breccia onto an easily eroded unit of sulfide-bearing schist that occurs between the rhyolite and a unit of mafic volcanic rocks. Removal of the easily eroded schist has formed a narrow gorge on the Pine River for several hundred feet below the falls. The rocks strike nearly east-west and dip 60-70° S with a prominent lineation that plunges 50-60°, S 40° W.

The deposit was discovered during an airborne geophysical survey in the 1970's, and has been drilled. The main part of the geophysical anomaly extends downstream within the river channel between exposures of rhyolite on the north and basaltic rocks on the south. Drill cores show that the rhyolite consists of coarse fragments in a relatively sulfide-rich matrix, a typical "stringer ore". Rhyolite exposed at the falls is very pitted, due to breakdown of the sulfide-rich (pyrrhotite-chalcopyrite) matrix material. Exposures

immediately below the falls, at the stratigraphic level of the main EM anomaly, consist of approximately 18 m of sulfide-bearing schist and cherty units. The sedimentary unit is mainly laminated chloritic and sericitic schist with pyritic lenses up to 3 mm thick. Garnets are common in some layers. Sprays of black tourmaline are present in the mafic volcanic rocks on the south side of the river.

The structure in the area is somewhat puzzling. Based on regional geology, Dutton (1971) and Bayley and others (1966) concluded that the Quinnesec Formation faces north near the Niagara Fault. Sims and others (1984) also reported that the Quinnesec faces northward away from the Dunbar Dome, which lies south of "LaSalle Falls". In addition, although deformation has obscured facing direction indicators, such as pillows, in most areas, north-facing pillows are exposed in the SW $\frac{1}{4}$, NE $\frac{1}{4}$, sec. 26, T. 34 N., R. 17 E., about two miles west of "LaSalle Falls". However, the lithologic sequence and pattern of mineralization at "LaSalle Falls" suggests that the rocks hosting the mineralization face southward. The zone of "stringer ore" is north of the main sulfide zone, and the sequence is "overlain" (?) by mafic volcanic rocks to the south.

Supplemental Stop 1-10. Pine River Pegmatite bodies. (NW $\frac{1}{4}$, NE $\frac{1}{4}$, sec. 22, T. 39 N., R. 17 E.) See figures 3-1 and 3-2 for location.)

(WARNING: - Because this exposure is near the Pine River WILD RIVERS AREA, no collecting is permitted at this locality.)

Dutton (1971) reported the occurrence of pink tourmaline in a pegmatite dike from this area. The pegmatites are located approximately 150 feet west of the Pine River and approximately 300 feet south of Highway 101 in Florence County (fig. 3-1). The location is about a mile south of the Niagara Fault.

The pegmatite bodies are up to a few meters wide and cut felsic volcanic rocks of the Quinnesec Formation. The pegmatites are sub-parallel to the foliation in the volcanic rocks, strike nearly north-south, and dip about 50 degrees west. A number of small lithium-rich pegmatite bodies in the area contain spodumene, lepidolite, and elbaite tourmaline as well as quartz, albite and microcline. Some pegmatites contain abundant pink tourmaline crystals 0.5 - 1.0 cm wide and 2.5 - 5.0 cm long, commonly oriented roughly perpendicular to the upper contact of the pegmatite. Some tourmalines are color zoned, with a pink core and blue-green rind. The pegmatites are composed dominantly of aplitic quartz-feldspar with some lepidolite. The pegmatites represent highly evolved granitic melts related to the nearby Bush Lake Granite associated with the Dunbar gneiss-granitoid dome (Sims and others, 1992).

Supplemental Stop 1-11. Metasedimentary Rocks on the Northwest Side of the Dunbar Dome (SW $\frac{1}{4}$, SE $\frac{1}{4}$, sec. 7, T. 37 N., R. 18 E.)

Metasedimentary rocks are exposed intermittently on the west side of the Dunbar dome and adjacent to and northwest of the Bush Lake lobe (Sims and Schulz, 1993). Although included by Dutton (1971) in the Quinnesec Formation, subsequent mapping, geophysical data, and core drilling by a private company show that these strata underlie the Quinnesec. The exposed metasedimentary rocks are metamorphosed at amphibolite grade and are mainly quartz-rich schist, impure marble, calc-silicate rocks, and biotite schist. Drilling and electromagnetic data indicate that a graphitic schist lies along the

west side of the Bush Lake lobe stratigraphically below the exposed metasedimentary rocks.

The large exposure at this stop on the south side of Macintire Creek consists of interbedded calc-silicate rocks and biotite schist that are cut by granite pegmatite and aplite dikes, identical to those exposed within the western part of the Dunbar dome. At another outcrop area to the north (NW $\frac{1}{4}$, SW $\frac{1}{4}$, sec. 11, T. 38 N., R. 17 E.), a succession at least 100 m thick of marble, calc-silicate rocks, and thin interbeds of biotite schist and ferruginous quartzite is exposed. The marble at this location has structures suggestive of stromatolites.

In many respects the metasedimentary rocks exposed on the west side of the Dunbar dome resemble those of the Chocalay Group of the Marquette Range Supergroup, as exposed in the Menominee iron range to the north (Bayley and others, 1966). These metasedimentary rocks may compose a tectonic slice of continental-margin rocks that is interleaved with granitoid rocks of the Dunbar dome and volcanic rocks of the Quinnesec Formation. Alternatively, they may have been uplifted from beneath the over-thrust Quinnesec Formation during the formation of the Dunbar dome.

FIELD TRIP 2

MENOMINEE IRON DISTRICT

Gene L. LaBerge, University of Wisconsin-Oshkosh (retired) and USGS; John S. Klasner, Western Illinois University (retired) and USGS; William F. Cannon, USGS; Richard W. Ojakangas, University of Minnesota Duluth (retired)



The Quinnesec Mine near Quinnesec, Michigan produced about 500,000 tons of siliceous iron ore between 1887 and 1935 from open pits and stopes in the Vulcan Iron-formation. The workings seen here are on the overturned northern limb of a syncline. The locality is also noted for the excellent exposures of the basal Cambrian unconformity. The roof of the working in the upper right is the base of the Munising Sandstone, which lies with an angular unconformity on the overturned Vulcan Iron-formation. Photograph by Elizabeth Heinen.

FIELD TRIP 2

MENOMINEE IRON DISTRICT

Gene L. LaBerge, University of Wisconsin-Oshkosh (retired) and USGS; John S. Klasner, Western Illinois University (retired) and USGS; William F. Cannon, USGS; Richard W. Ojakangas, University of Minnesota Duluth (retired)

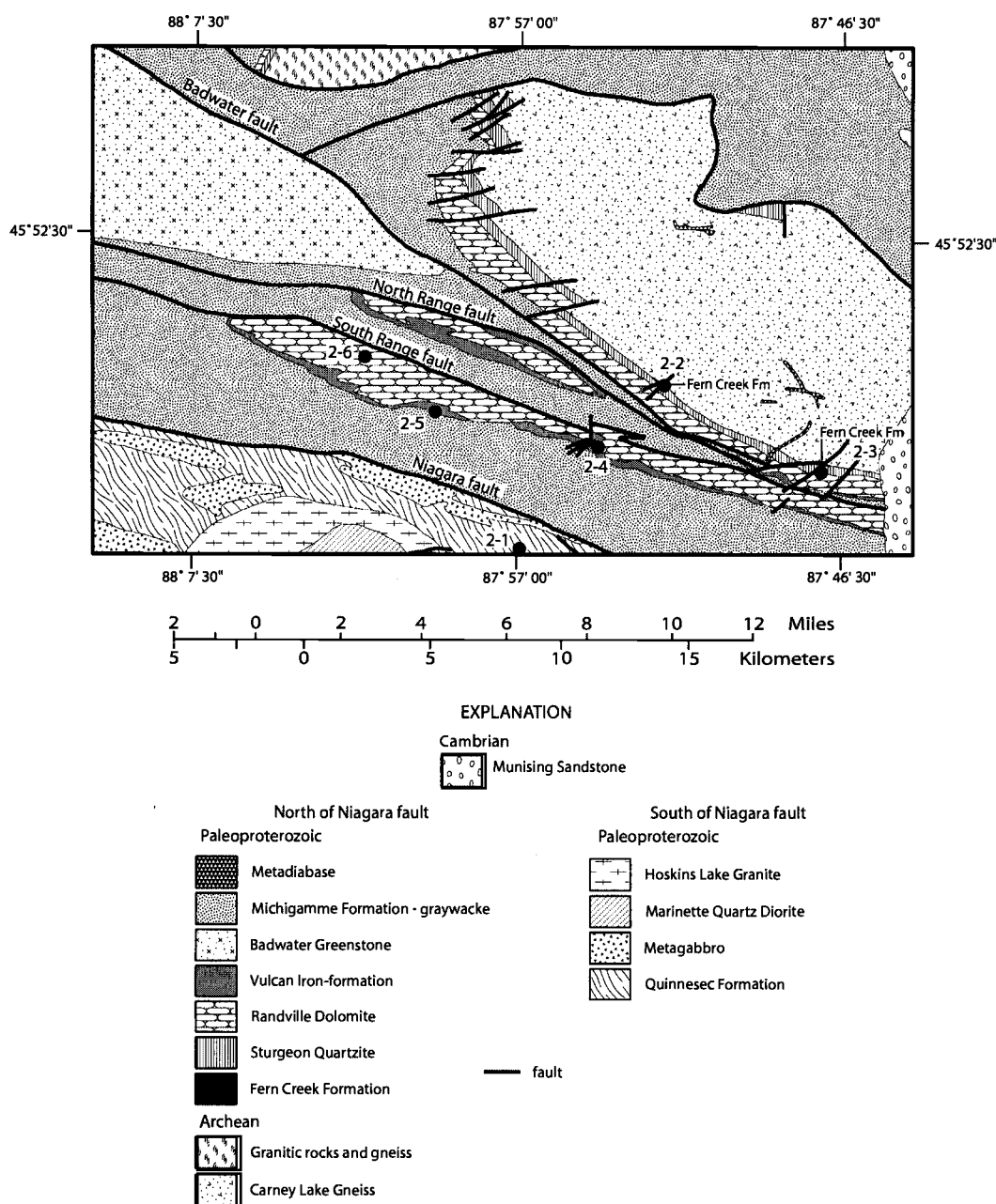


Figure 2-1. Geologic map of part of the Menominee Iron-district showing the location of field trip stops. Geology simplified from Bayley and others (1966) and Sims and Schulz (1993).

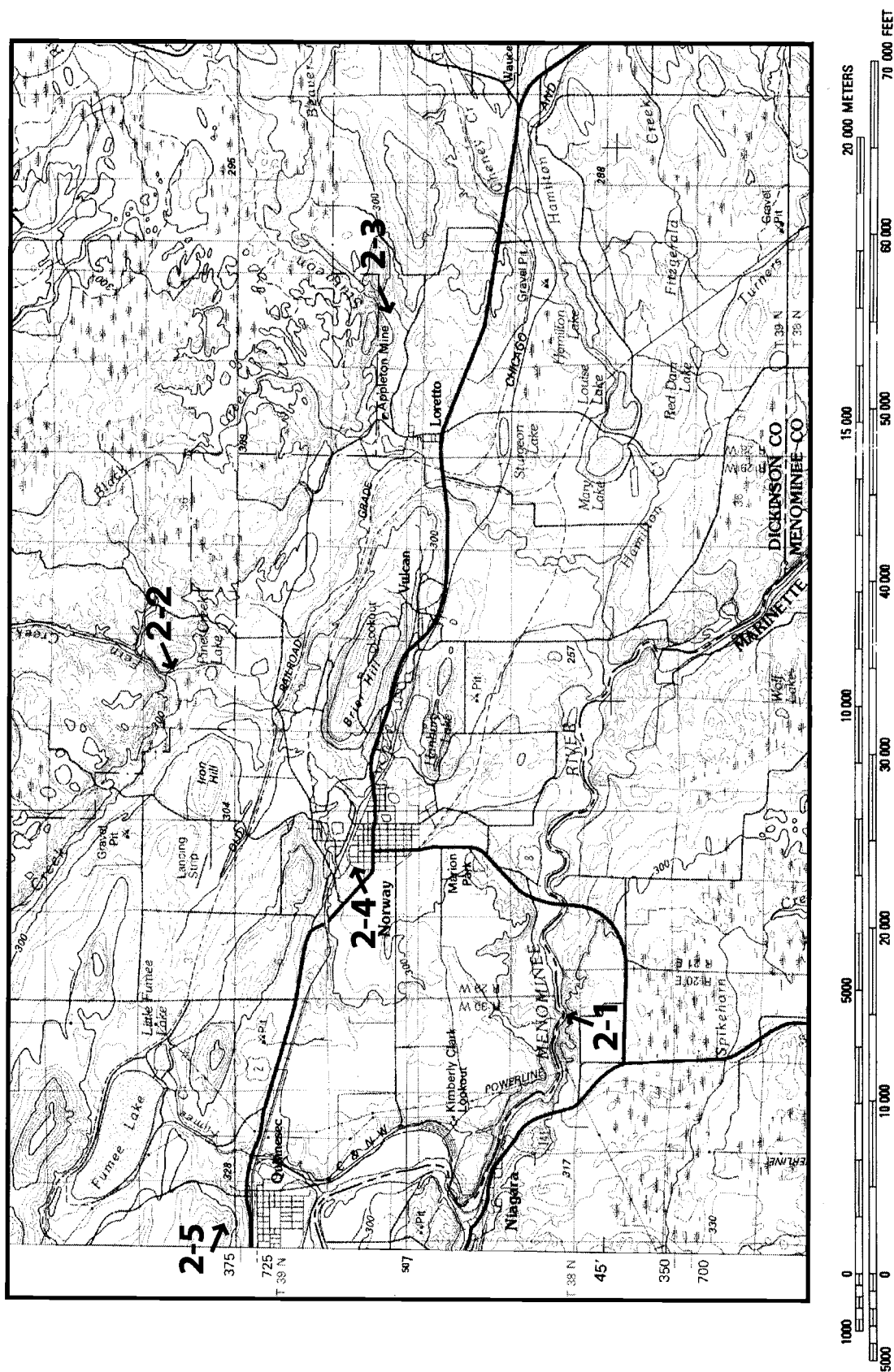


Figure 2-2. Part of the Escanaba 1:100,000-scale topographic map showing the location of field trip stops 2-1 through 2-5. See figure 3-2 for the location of stop 2-6.

This trip examines rocks of the Menominee iron-bearing district, with emphasis on units of the Paleoproterozoic Marquette Range Supergroup. Archean rocks of the Carney Lake Gneiss are seen at two stops and volcanic rocks of the Wisconsin magmatic terranes, intensely deformed in the Niagara fault zone, are also seen. The geologic map of the field trip area is shown in figure 2-1 and a road map of the field trip stops is in figure 2-2.

Stop 2-1. Piers Gorge on the Menominee River. (SE 1/4, NE 1/4, sec. 24, T. 39 N., R. 30 W.)

Rocks exposed along the Menominee River at Piers Gorge are almost certainly a branch of the Niagara fault zone and represent one of the few exposures of the fault zone. This location is about one kilometer south of the mapped trace of the Niagara fault. The hill lying north of the gorge, but still south of the mapped fault, is underlain by metagabbro that is much less deformed than the rocks in the gorge. These relationships indicate that strain along the fault was distributed very heterogeneously and concentrated in discrete zones of very high strain surrounding islands of weakly deformed rocks. The rocks in the gorge are highly foliated and lineated quartz-sericite schists and chloritic schists, probably developed from felsic and mafic volcanic rocks. Felsic and mafic volcanic rocks with only weak foliation, along with mafic sills with little internal deformation, are exposed on both sides of this strongly foliated zone. Metagraywacke of the Marquette Range Supergroup is exposed in Norway, about 2 miles north of this locality, and volcanic and plutonic rocks of the Wisconsin magmatic terranes are exposed along the Menominee River in this area.

The foliation here strikes N 80°-85° W and dips 80°-85° N. and has a stretch lineation that plunges 60°-65°, N 85° W.

As the recognized boundary between the dominantly sedimentary rocks of the Marquette Range Supergroup to the north and the Wisconsin magmatic terranes to the south, the Niagara fault zone is commonly referred to as a suture. However, it lacks some features (such as a *mélange*) that are typical of suture zones. Geophysical evidence (Attoh and Klasner, 1989; and LaBerge and Klasner, 2001) suggests that thinned continental crust of the Superior craton has been overridden by the Wisconsin magmatic terranes, and extends in the subsurface for 10-50 miles south of the Niagara fault zone. If this is the case, the Niagara fault zone may be the frontal thrust on which oceanic rocks of the Wisconsin magmatic terranes overrode the continent margin assemblage of the Marquette Range Supergroup. Continued compression of the suture zone resulted in the steepening of the thrust surfaces into their present, nearly vertical orientation.

Stop 2: Fern Creek locality – Archean basement, Fern Creek Formation, and Sturgeon Quartzite. (N 1/2, sec. 34, T. 40 N., R. 29 W.)

Take County Road 573 to the northeast off of U.S. 2, about 1 mile northwest of the town of Norway. Proceed about 2 miles and turn north (left) just beyond the bridge over Pine Creek, onto a secondary road. Proceed about 1½ miles to Fern Creek, which crosses the secondary road at a sharp bend in the road. Proceed about ¼ mile farther to a small intermittent creek that also crosses the road. Park near here. See figure 2-3 for a detailed map, and Figure 2-4 for a generalized rock column.

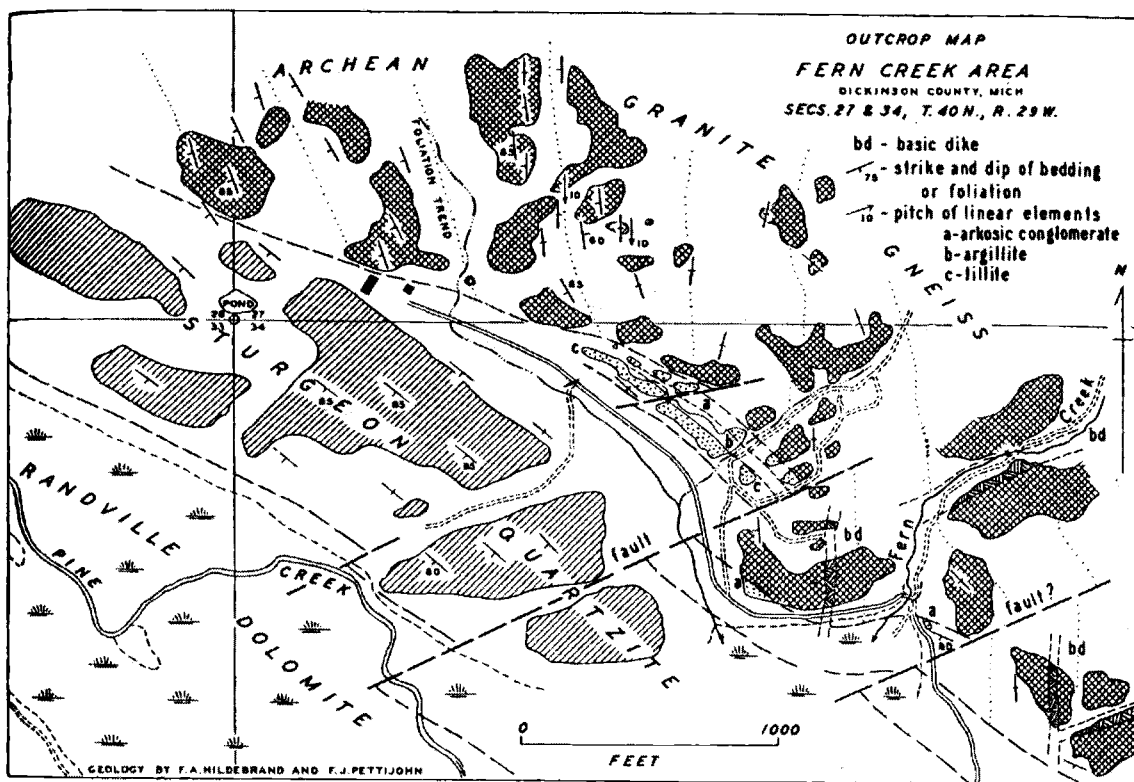


Figure 2-3. Location map of stop 2-2. (from Pettijohn, 1943.)

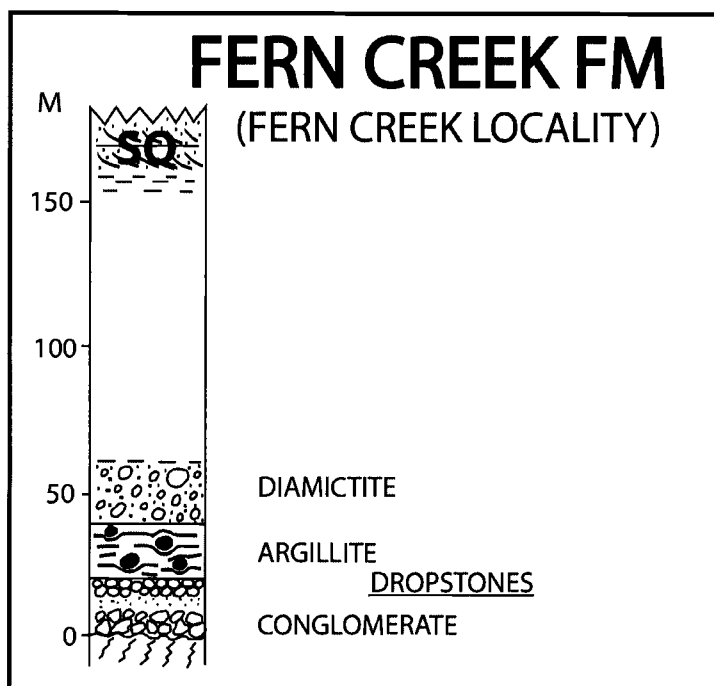


Figure 2-4. Generalized stratigraphic column at Fern Creek locality. SQ at the top of the column designates the Sturgeon Quartzite.

Note that the road is situated in a NW-trending valley about 175 m wide, between two prominent topographic highs. The Carney Lake Gneiss forms the prominent bluff and upland on the northeast side of the road, and the Sturgeon Quartzite forms a prominent ridge on the southwest side of the road. The valley is situated on the Fern Creek Formation, of which the lowest 60 to 70 m are somewhat exposed.

The Archean-Paleoproterozoic contact, a major unconformity representing a few hundred million years of erosion, is now subvertical, as are the Fern Creek Formation and the Sturgeon Quartzite. Our first substop is at this unconformity, and then we will move up-section through the subunits of the Fern Creek Formation and end in the Sturgeon Quartzite.

Substop 1. From the road, move about 100 m up the small creek bed to the subvertical unconformity, where we can observe both the Carney Lake Gneiss and the overlying basal gneiss-fragment (i.e., arkosic) conglomerate of the Fern Creek Formation. Note the angular to subangular nature of the clasts, obviously locally derived. Minor beds of red arkosic sandstone are also present. The entire sequence has stratigraphic tops toward the south.

Interpretation: High-velocity fluvial and in-situ rubble/debris flow deposits.

Substop 2. Reverse direction and head back toward the road, moving up the stratigraphic section. This poorly exposed subunit, 60-75 feet thick, is a laminated fine-grained argillite with scattered larger stones. Many of these stones show clear evidence of having been "dropped" into the fine-grained sediment from above, causing a bowing downward and/or a penetration of the underlying laminae. Others do not show these relationships and are therefore called "lonestones" rather than "dropstones" (fig. 2-6). Note the E-W slaty cleavage that crosses the bedding, which strikes about N 50° W.



Figure 2-5. Thin-bedded argillite and siltstone with dropstone. Note that the stone has both pierced and bowed down the underlying laminae.



Figure 2-6. Large (35 cm) limestone (beneath hammer) in vertical laminated siltstone/sandstone beds. Some smaller limestones are also present.

Interpretation: Deposition of fine-grained sediment in a body of water (marine?) near a melting glacier, with the larger clasts dropped in from icebergs and/or a floating ice shelf.

Substop 3. The next subunit is a diamictite, a matrix-supported conglomerate with rather sparse clasts set in a massive graywacke matrix (fig. 2-7). Note the total lack of bedding and the presence of a crude schistosity that causes the rock to break into thick slabs.

Interpretation: Deposition directly by glacial ice (i.e. tillite) or by the "raining out" of detritus from icebergs or a floating glacier onto a basin floor lacking currents to generate lamination (i.e., "rainout till").

Substop 4. Cross the road, following the marked trail about 100 m across a low-lying area without outcrops, to the base of the ridge that lies southwest of the road. The first low-lying exposure at the base of the ridge is poorly exposed and is composed of argillite/sericite schist and sericitic quartzite, about 5 m thick. The low-lying area may be totally or in part underlain by this sericitic rock, which is softer than the rocks of substops 1-3 and the overlying vitreous quartzite. The prominent ridge is composed of the Sturgeon Quartzite (fig. 2-8). It is well cemented with silica and is totally recrystallized, making it a very resistant rock unit. It is composed almost totally of well-sorted, fine- to

medium-grained quartz sand; few grains are coarser than 1 mm. Original grain boundaries are easily seen only in the sericitic quartzite.



Figure 2-7. Diamictite with scattered stones and crude schistosity.

Interpretation: The sericite schist is a paleosol and the sericitic quartzite is a reworked paleosol that was developed upon the Fern Creek Formation during a long period of extensive weathering in a subtropical or tropical climate. The overlying Sturgeon Quartzite is the product of the reworking and sorting of the weathered detritus by wind and water. The quartzite here is about 325 m thick, and elsewhere in the region it has a maximum thickness of 600 m (Freedman and others, 1961). It obviously represents the transported resistant quartz sand fraction of a very broad, deeply chemically weathered surface that was largely developed upon granitic rock over a long period of time. There is no diagnostic evidence within the quartzite itself of a terrestrial (fluvial) versus a marine environment of deposition. However, an apparently conformable relationship with the overlying thick Randville Dolomite (300-430 m), which is stromatolitic and contains detrital quartz grains and thin interbeds of quartzite, is strongly suggestive of a shallow marine environment for the Sturgeon Quartzite. In addition, diopside-rich quartzite high in the formation suggests a gradational contact with the Randville Dolomite (Freedman and others, 1961). Detrital quartz grains in the sericitic schist show a marked elongation and alignment (Bayley and others, 1966), indicative of shearing along this softer zone beneath the quartzite.



Figure 2-8. Ripples in Sturgeon Quartzite

Stop 2-3: Sturgeon River Dam locality. Archean basement, Fern Creek Formation, and Sturgeon Quartzite. (E ½, sec. 8, T. 39 N., R. 29 W.).

From Stop 2, backtrack about 1½ miles to County Road 573. Turn left (east) and proceed about 3½ miles. Turn left (east) on Swede Settlement Road, which leads toward the power station/dam and proceed for about 1½ mile. Turn left (north) on a smaller road that leads to the power station/dam. Proceed about ½ mile to locked gate. Park here. If approaching this stop from the village of Loretto, take County Road 573 north out of Loretto for about ½ mile. Then turn right (east) on Swede Settlement Road, which leads toward the power station/dam, and proceed for about 1½ miles. Turn left (north) on a smaller road that leads to the power station/dam. Proceed about ½ mile to locked gate. Park here. As of this writing in 2003, the dam is slated for removal in the relatively near future.

Here the Sturgeon River has cut a deep gorge through the Sturgeon Quartzite; the formation was named for this locality. This small area has been well studied, especially because of the presence of the Archean-Paleoproterozoic contact at the dam. The area has been described by Credner (1869), Brooks (1873), Rominger (1881), Irving (1890), Bayley (1904), Lamey (1937), Pettijohn (1943), and Trow (1948).

Substop 1. Walk past the gate to the end of the road at the powerhouse and dam. We will traverse back up the road to the vehicles, thus observing the rock units in stratigraphic sequence. The dam was constructed on Sturgeon River Falls, which was held up by a thick mafic dike that can be seen in the woods off the east end of the dam. The unconformity between the Archean Carney Lake Gneiss and the Paleoproterozoic Fern Creek Formation can be seen in a small ground-level exposure adjacent to the dam

(fig. 2-9). The lowest bed in the Fern Creek is a diamictite at this spot, whereas a short distance to the west on the river bottom by the power station, the lowest unit is arkosic sandstone with rare oversized stones.

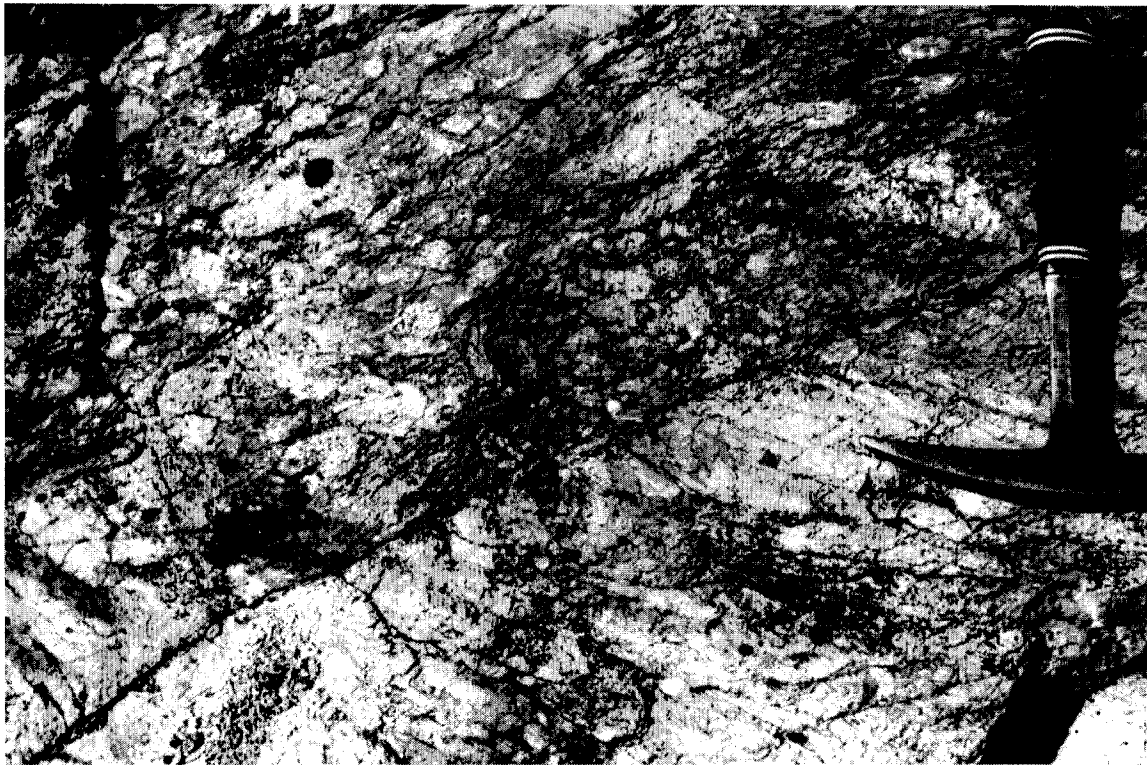


Figure 2-9. Unconformity at Sturgeon River dam. Hammer head rests on Archean Carney Lake Gneiss and hammer handle is on basal diamictite of the Fern Creek Formation. Nearby in river bottom, the basal unit is arkosic sandstone with rare dropstones, illustrated in figure 2-11.

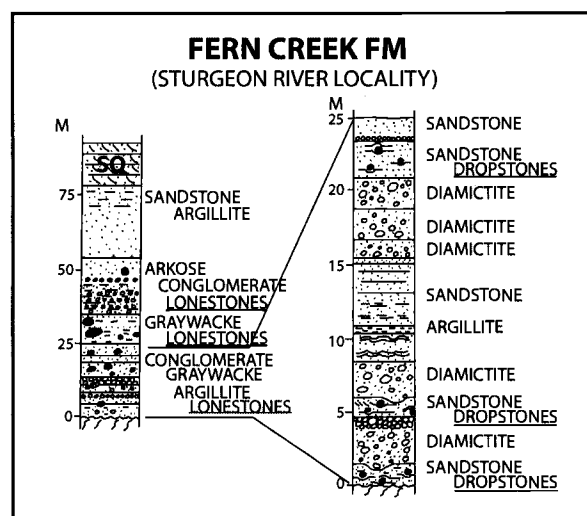


Figure 2-10. Stratigraphic column at Sturgeon River locality. SQ at the top of the column designates the Sturgeon Quartzite.

Figure 2-10 is a measured column of the Fern Creek Formation. The lower 25 m are well exposed when there is no water in the channel. Note that this portion of the formation consists of five beds of diamictite (matrix-supported conglomerate) as thick as 2.5 m, three arkosic sandstone beds as thick as 2.6 m with rare oversized stones, stacked arkosic sandstone beds with minor intercalated siltstone and argillite laminae, an argillite bed 4.5 cm thick, and a 15 cm conglomerate. Because the water level is commonly high, figures 2-11 and 2-12 are included here to illustrate some important features.



Figure 2-11. Granitic dropstone in lowest sandstone of the stratigraphic column. Note that the stone has pierced and bowed down the underlying laminations.

Interestingly, the well-exposed section seen in the river bottom is not found on the west bank of the river; only 1½ m of conglomeratic rock is present there. Apparently the more complete section is preserved in a topographic low on the Archean surface. However, faulting may be a factor as well, for weathered pyrite is present along a fault between the Archean basement and the Fern Creek west of the powerhouse.

The middle 25 m of the Fern Creek Formation is relatively poorly exposed; figure 2-10 shows this portion consisting of conglomerate, graywacke sandstone with oversized stones, and arkosic sandstone with oversized stones.



Figure 2-12. Second, third, and fourth beds of stratigraphic column of Figure 2-10. View is to west. Beds 2 and 4 are diamictites below and above arkosic sandstone with rare dropstones.

Interpretation: This is a glaciogenic sequence. The diamictites may be thin tills deposited beneath glacial ice, but more likely are debris flow deposits as suggested by one diamictite bed that grades upward into sandstone. Some of the conglomeratic beds are difficult to clearly classify as either matrix-supported or clast-supported. One 20 cm bed at the 15 m level in the section is graded from medium sand to clay, suggestive of a turbidity current mechanism. Several of the oversized stones in the sandstone and greywacke beds show either a bowing down of the underlying laminae or an actual penetration, indicating that the stones were dropped into the basin from above and are indeed dropstones. Other lonestones may be dropstones, too, but clear evidence is lacking. The likely mechanism for deposition of dropstones is release from melting icebergs or from a floating glacier.

Substop 2: The 25 m section between 50 and 75 m on Figure 2-9 is intermittently exposed on the west bank of the river, but this area is usually inaccessible because of high water. It includes beds of sericitic quartzite interbedded with sericite schist. The sericitic nature of this interval is illustrated by a small road-level outcrop between the road and the river just north of the quartzite ridge. This is a sericitic quartz pebble conglomerate with sericite clay chips, some reddish rather than yellow-green in color.

Interpretation: This sericitic portion of the column is interpreted as a reworked paleosol that formed on the Fern Creek Formation during a warm climatic period that followed glaciation. Trow (1948) first suggested that this might be a paleosol.

Substop 3: Sturgeon Quartzite ridge. Note that the bedding is slightly overturned towards the south, and that cross-bedding indicates that stratigraphic tops are to the

south. Cross-bedding is of both trough and planar types. According to Trow (1948), the general cross-bedding indicates a paleocurrent trend from the northwest toward the southeast.

Interpretation: Abundant asymmetrical ripple marks have low ripple indices (wave length/ripple height) indicative of deposition by water rather than by wind. The beds are generally of even thickness, indicative of a shallow marine rather than a fluvial environment of deposition. See text for substop 4 of stop 2-2 for additional interpretation of the genesis of the Sturgeon Quartzite. The Sturgeon has long been correlated with the Mesnard Quartzite of the Marquette Trough.

Stop 2-4. Brier Slate Member of the Vulcan Iron-formation in Norway, MI. (Modified from Dutton, 1958). (E ½, SE ¼, sec. 5, T. 39 N., R. 18 W.)

Three iron mines, the Aragon, Cyclops, and Norway mines were developed in the northern part of the city of Norway, MI, and subsidence of these abandoned mines has limited development in this part of the city. The Aragon mine was the third largest producer of iron ore in the Menominee district (Dutton, 1958), and the head frame of the mine still stands about 5 blocks east of this stop. Figure 2-13 shows the location of several interesting geological features, but the trip will visit only the Brier Slate Member type locality.

According to Dutton (1958), outcrops along the ridge north of Norway are Randville Dolomite with a rather extensive, but incomplete, cover of breccia composed of dolomite fragments that are slightly to thoroughly silicified. (This breccia is similar to that at the top of the correlative Bad River Dolomite in the Gogebic district, some 120 miles west-northwest of here.) The silicification is believed to be the result of surficial weathering in post-Randville - pre-iron-formation time. The dolomite dips about 60 degrees southward, and the convexity of stromatolites in the dolomite indicate that the beds also face southward. Small outliers of Cambrian sandstone overlying the Randville Dolomite are also present (e.g., at Rochon St. and Curry Lane along the ridge).

The Randville is overlain by the Felch Formation, the basal unit of the Menominee Group. One of the few exposures of the Felch Formation is at this locality in Norway (Dutton, 1958). The Felch Formation consists of sericitic slate and thin layers of quartzite. The uppermost part of the formation is a ferruginous quartzite that is a marker bed throughout the district. The quartzite is a transitional unit between the dominantly clastic, non-ferruginous strata of the Felch Formation and the iron-rich chemical sediments of the Vulcan Iron-formation (Dutton, 1958).

Three members of the Vulcan Iron-formation were exposed in Norway in 1958, according to Dutton (1958). Exposures of the basal, thin-bedded oxide facies Traders Member are present at the northeastern end of a southwesterly trending area of outcrops. The Traders is presently exposed north of Sixteenth Ave. and Main St., in the old Cyclops mine workings, which is being used as a landfill by the city of Norway. The Brier Slate Member (this stop) is exposed on an outcrop knob at Eleventh Ave. and the Aragon location, southwest of the Traders Member location. In fact, the Brier Slate was named for exposures here. Several small-scale folds that plunge about 45 degrees easterly are exposed along the old railroad cut on the north side of the outcrop. According to Dutton (1958), the oxide facies, oolitic and granular iron-formation of the

Curry member of the Vulcan Iron-formation was exposed at the southwest end of the outcrop area.

The Michigamme Formation unconformably overlies the iron-formation and is exposed in several low roadcuts along U.S. Hwy-8 on the southern outskirts of Norway.

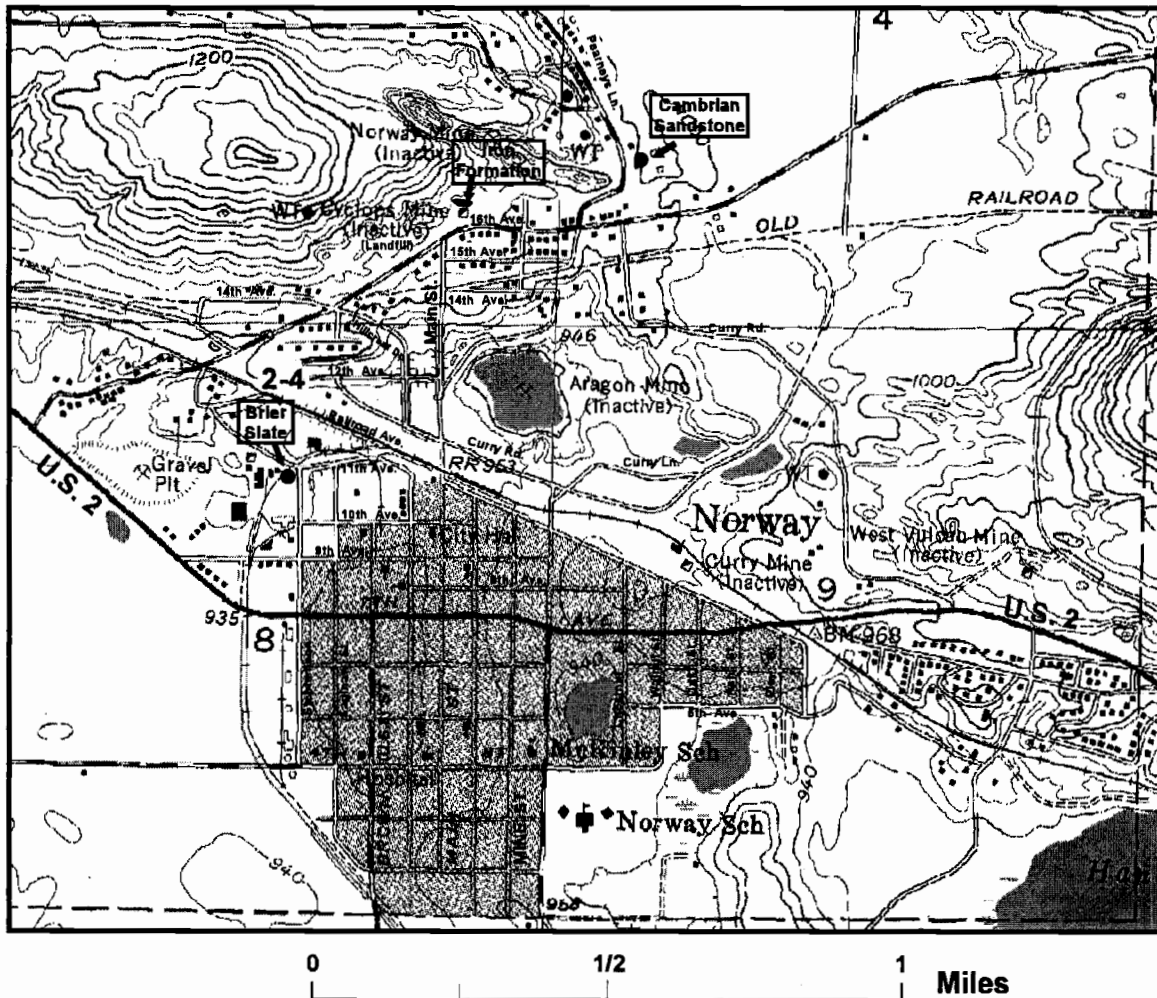


Figure 2-13. Part of the Norway 7 1/2' quadrangle showing the location of stop 2-4 and some other features of geologic interest.

Stop 2-5. Quinnesec mine, just northwest of Quinnesec, MI. (Modified from Dutton, 1958) (SW 1/4, SE 1/4, sec. 34, T. 39 N., R. 30 W.)

(NOTE: For safety reasons a security fence surrounds this property. For permission to enter contact Joe Massie, Quinnesec, MI, Ph (906-774-4471).

The abandoned workings of the Quinnesec mine are mainly in the Traders iron-bearing member of the Vulcan Iron-formation. The mine lies on the overturned north, limb of a second order syncline (fig. 2-14). The Precambrian strata at the mine dip about 60 degrees north, but face southward, inasmuch as the Brier slate member of the Vulcan is

along the south side of the excavated approach to the mine, and the Felch Formation is along the north wall of the workings.

Note the Cambrian sandstone overlying the mine workings along the north side of the hill, providing an unusual view of an unconformity (fig. 2-15). The basal portion of the sandstone contains numerous angular slabs of oxidized iron-formation, iron ore, and slate in a sandy matrix. Clearly, this area was a small island as the Cambrian sea advanced over the area. The clasts of iron ore in the basal conglomerate also indicate that the ore here was formed before the Cambrian sea covered the area.

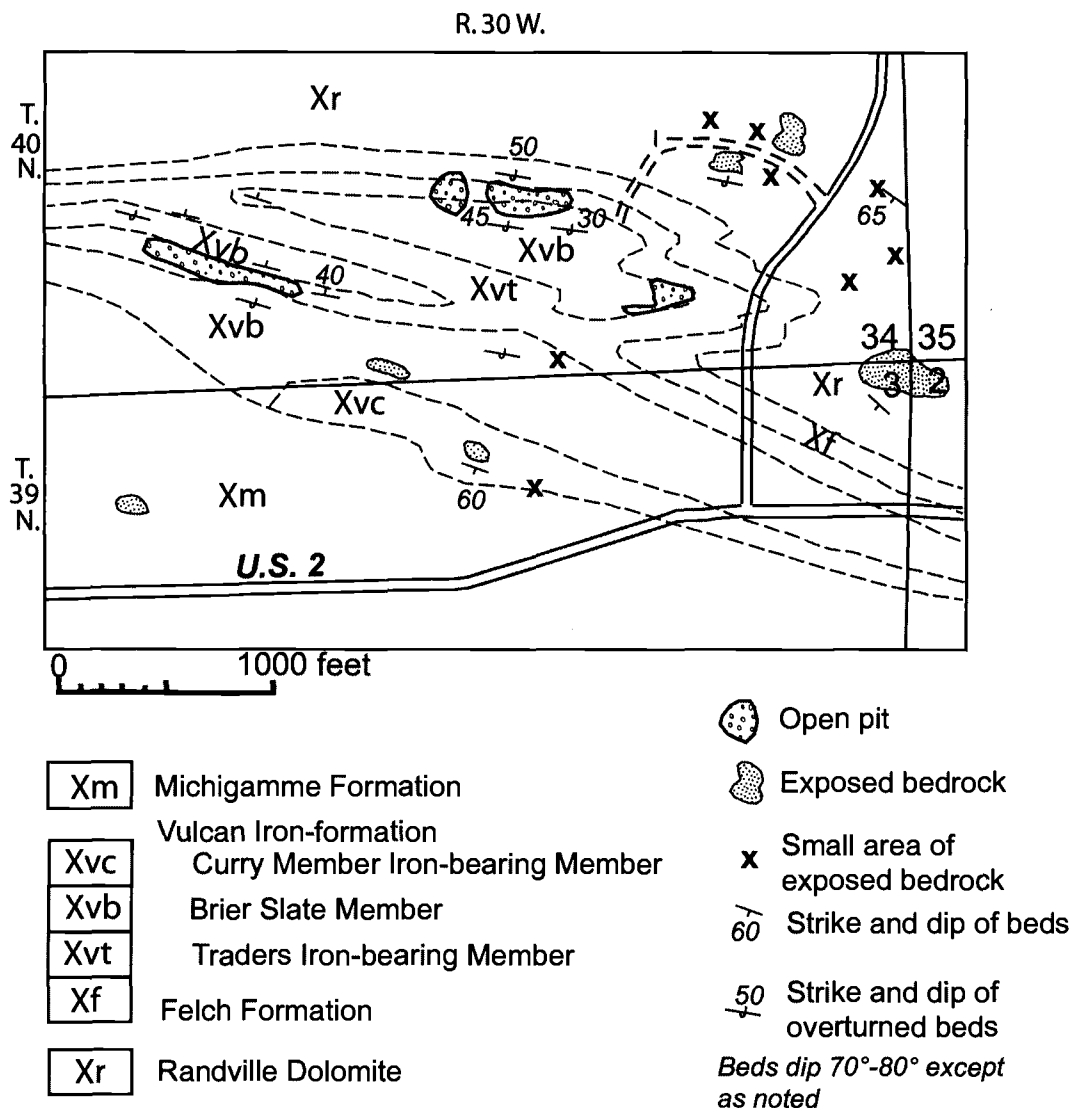


Figure 2-14. Map of the Quinnesec mine and vicinity at stop 2-5 showing that the workings were developed in the overturned northern limb of a small syncline. Map from Bayley (1957).



Figure 2-15. Abandoned workings at Quinnesec mine. Ore bodies were mined from the Traders Iron-bearing member of Vulcan Iron-formation. View looking west shows beds dipping north, but facing south. Roof of workings is base of the Munising Sandstone of Cambrian age and provides an excellent view of the basal Cambrian unconformity. Photo by Elizabeth Heinen.

Stop 2-6. Randville Dolomite along Margaret St. on Lake Antoine in Iron Mountain, MI. (Modified from Dutton, 1958) (SE ¼, NE ¼, sec. 29, T. 39 N., R 30 W.)

This exposure of the Randville Dolomite on the south shore of Lake Antoine was formerly the site of a small quarry for the production of road material. Operation of the quarry was halted during the late 1930's through the influence of geologists and other interested people who wanted the site preserved for future geologic examination (Dutton, 1958).

The glacially scoured outcrop shows a variety of sedimentary and structural features. The rocks are dipping nearly vertically, and face southward. Sedimentary features preserved here include abundant stromatolites (fig. 2-15), typically 3-4 inches high and 4-8 inches in diameter. The old quarry face provided a vertical view of the stromatolites - now largely obscured by graffiti. Thin layers of quartz sand are interbedded with the dolomite, and ripple marks and mud cracks are present in places. These features suggest a very shallow water environment of deposition, and several authors (e.g. Larue, 1981) have suggested that the Randville Dolomite may have been deposited in a paleo sabkha environment.

Structural features exposed here include deformed stromatolites. Several layers of stromatolites that are strongly skewed in a right-lateral direction are present. The dolomite evidently recrystallized readily, allowing ductile deformation of the stromatolites. Possible fracture cleavage is oriented so that it is nearly "axial planar" to the deformed stromatolites, and is roughly parallel with the regional structure.



Figure 2-16. Randville Dolomite at stop 2-6. Laminated dolomitic layers are interbedded with stromatolitic dolomite. Stromatolite mounds are deformed and show an asymmetry indicating a right lateral sense of shear. View is looking down at a horizontal surface and beds dip vertically.

FIELD TRIP 3

STRATIGRAPHY AND STRUCTURE OF THE IRON RIVER- CRYSTAL FALLS BASIN

William F. Cannon, USGS, Reston, VA; John S. Klasner, Western Illinois University (retired) and USGS; Gene L. LaBerge, University of Wisconsin-Oshkosh (retired) and USGS



Tightly folded Riverton Iron-formation near Stager Lake, Michigan. Tight complex folds such as these are typical of the structural style of the Iron River-Crystal Falls allochthon.

FIELD TRIP 3

STRATIGRAPHY AND STRUCTURE OF THE IRON RIVER-CRYSTAL FALLS BASIN

William F. Cannon, USGS, Reston, VA; John S. Klasner, Western Illinois University (retired) and USGS; Gene L. LaBerge, University of Wisconsin-Oshkosh (retired) and USGS

The Iron River-Crystal Falls iron district was mined extensively for high-grade "soft" iron ores from 1882 until the early 1970's producing more than 200 million tons of ore. Because of the high economic interest in the region, the availability of many underground mine workings, and extensive diamond drilling, a detailed stratigraphy and structure was deciphered in what otherwise would have been a largely unknown terrane, mostly concealed by the nearly continuous cover of glacial deposits. The most detailed study of the region was conducted by a large group of USGS and affiliated geologists beginning in 1943 and continuing for about 10 years. Surface exposures were mapped in detail, as were most underground mine workings. Ground magnetic surveys helped delineate the surface trace of certain units and the extensive collection of exploration drill core was examined. One of the earliest aeromagnetic surveys was conducted here when the technique was still classified shortly after World War II. The work of the USGS was aided immeasurably by the cooperation of the numerous mining companies active in the area. The results of that painstaking work were summarized in USGS Professional Paper 570 (James and others, 1968), which remains the only comprehensive account of the geology of the region. Much of the descriptive material in this guide is taken from that work. Additional detailed studies of the Florence area, Wisconsin were done by Dutton (Dutton, 1971) and also were instrumental in determining the geological relationships along the southern extent of the Iron River-Crystal Falls basin, including areas visited in the first three stops of this trip (figs. 3-1 and 3-2).

The Iron River-Crystal Falls basin is a triangular structure, with an area of about 300 square miles, underlain by strata of the Paint River Group. It is surrounded, except on part of the eastern side, by volcanic rocks of the Badwater Greenstone. Our current interpretation of the area is that the Paint River Group, as originally defined, and the Badwater Greenstone, are an allochthon, and were thrust northward during the Penokean orogeny, driven by arc collision south of the Niagara fault. This trip traverses from the Niagara fault, as seen at Pine River Flowage in northern Wisconsin, northward across the complexly deformed fault panels of the Niagara suture zone, and onto the structurally simpler rocks north of the Iron River-Crystal Falls allochthon. Most stops examine the lithology and structure of rocks of the Paint River Group. Principal observations are the preponderance of steeply plunging folds in all panels of the suture zone rocks, the extraordinarily complex fold patterns, particularly in the Iron River-Crystal Falls allochthon, and the contrast with the simpler, gently plunging folds north of the suture zone.

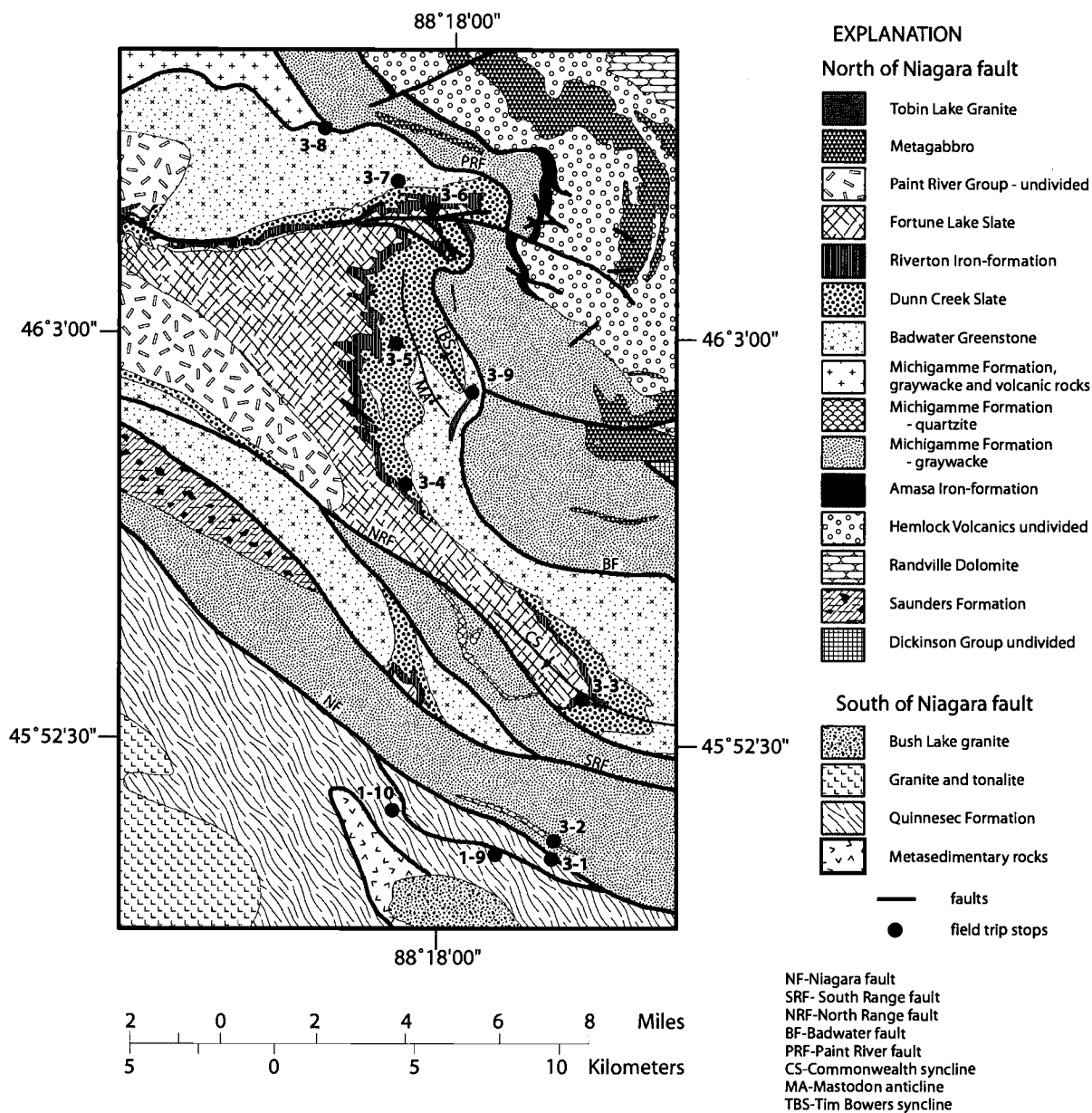


Figure 3-1. Geologic map of the eastern part of the Iron River-Crystal Falls basin showing the location of stops for field trip 3.

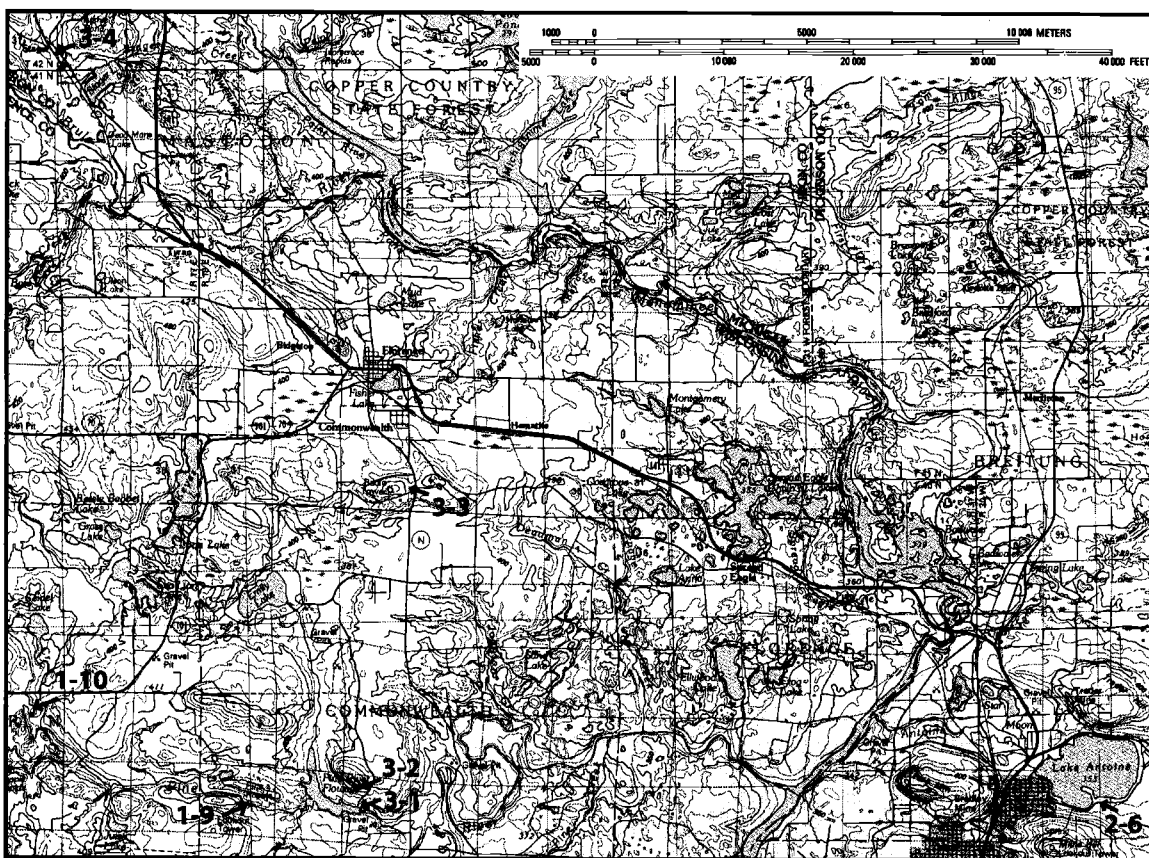


Figure 3-2. Part of the Iron Mountain 1:100,000-scale topographic map showing the location of field trip stops 3-1 through 3-4 and 1-9, 1-10.

Stop 3-1. Michigamme Formation at Pine River Flowage (NE 1/4, SW 1/4, sec. 28, T. 39 N. R. 18 E.)

This outcrop lies within the Pine River structural block as defined by Dutton (1971). Large exposures are along the gorge of the Pine River just downstream from the Pine River dam. The Pine River block is composed almost entirely of the Michigamme Formation consisting mostly of graywacke and lesser quartzite and conglomerate (stop 3-2). Although penetrative deformation is intense and there are many small-scale folds well exposed at this stop, the overall structure of the block seems to be a uniformly south-facing succession as indicated by cross beds and graded beds.

The outcrops seen here are very close to the Niagara fault whose location here is well constrained by rather abundant outcrops (see fig. 3-3). The rocks exposed below the dam are no more than 500 feet northeast of the volcanic rocks of the Quinnesec Formation, part of the Wisconsin Magmatic Terranes. The Michigamme Formation in this vicinity was well described by Dutton (1971) and the following is extracted from his report. "The rock is gray and well-bedded in layers one-fourth to one-half inch thick. The percentage of minerals in the rocks is approximated as quartz from 20 to 50; sericite and muscovite from 20 to 70; biotite from 10 to 25; and chlorite, if present, from 5 to 40. Dark red garnets are abundant in the schist near the quartzite; they locally are concentrated in layers and lenses, but they may be minor or absent. Some garnets have been rotated

after formation as much as 25 degrees, as shown by the angular discordance between general foliation and the layers of very fine opaque grains within the garnets. Deflected foliation at the boundary surfaces of the garnets also indicates direction but not amount of rotation."

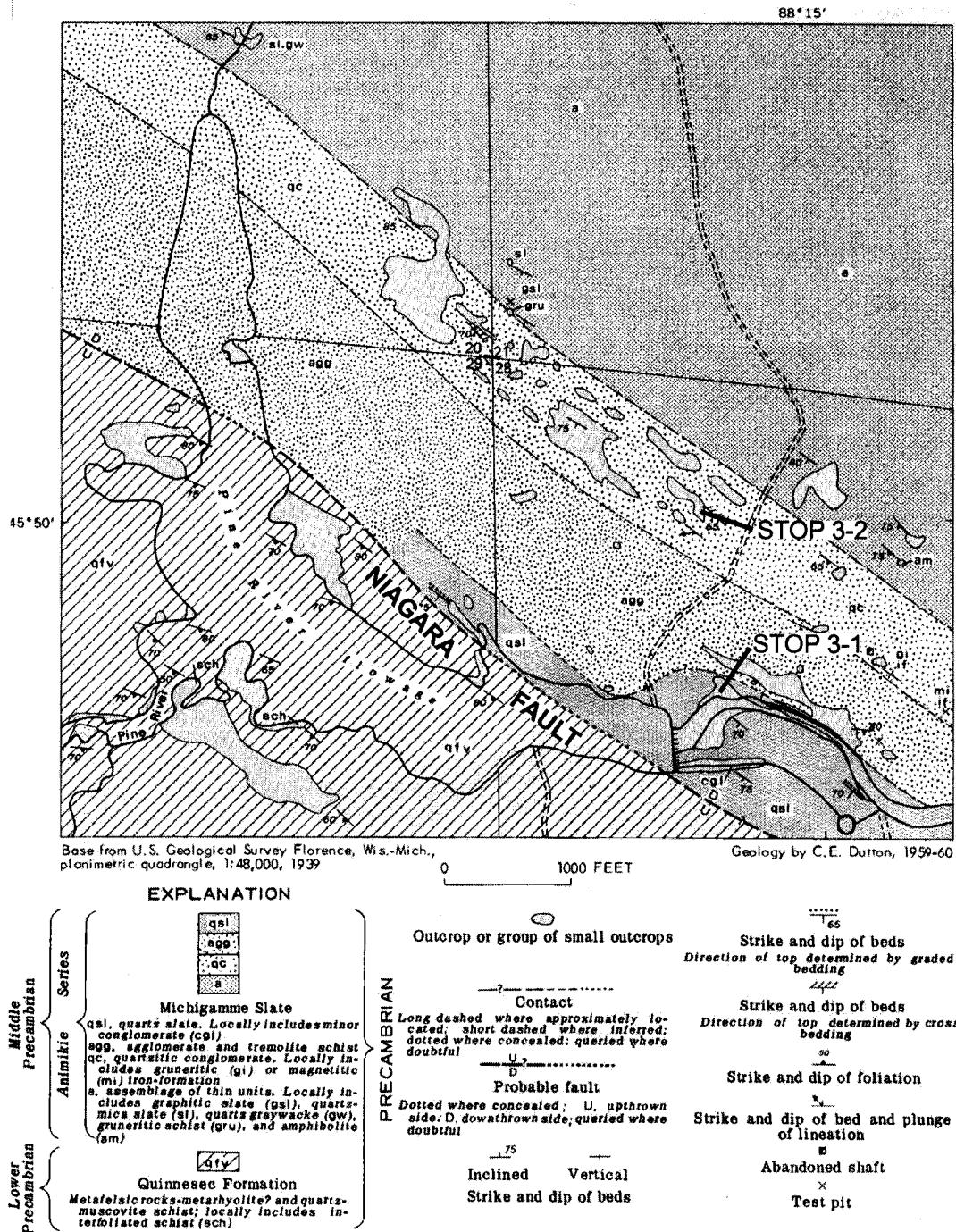


Figure 3-3. Geologic map of part of the Florence area, Wisconsin showing the location of field trip stops 3-1 and 3-2. Map originally published by Dutton (1971, figure 3).

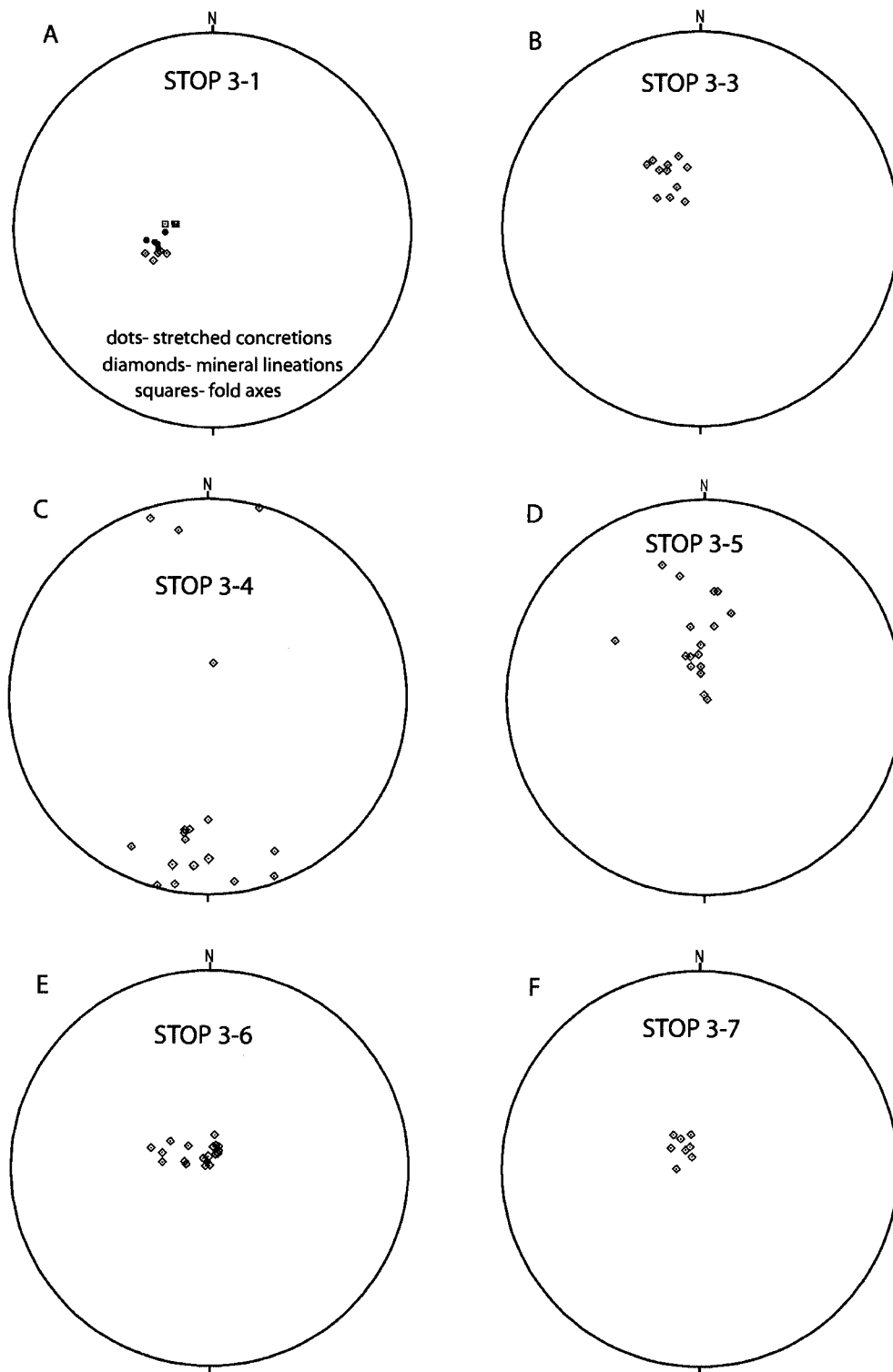


Figure 3-4. Lower hemisphere equal area stereoplots showing orientation of fold axes and related structures at various stops for field trip 3.

The rocks near the dam are a strongly foliated and lineated chlorite-garnet schist. Primary layering is well preserved but has been transposed parallel to S_1 foliation. Dextral drag folds in the transposed layering have steeply plunging axes (see fig. 3-4,A) that are parallel to mineral lineations on foliation surfaces. Axes of maximum elongation in deformed clasts and concretions plunge 60 degrees toward the south, parallel to the mineral lineation. These highly strained rocks have an S_1 foliation that dips steeply south as do the elongation (stretching) axes. These steep, south plunging structures seem to be characteristic of the Niagara fault zone. Similarly oriented, steeply south plunging structures occur south of the Niagara Fault zone, probably in splays of the Niagara fault in volcanic rocks of the Wisconsin magmatic terrane that crop out a few miles south of the Pine River Dam (Sims and others, 1985). The structural fabric in this region reflects overthrusting--with a right-lateral component--of the Wisconsin magmatic terrane from the south onto the continental margin and later steepening of the thrusts to their present orientation.

Stop3-2. Quartzite and Conglomerate of the Michigamme Formation near Pine River Dam. (NE $\frac{1}{4}$, NW $\frac{1}{4}$, sec. 28, T. 39 N., R. 18 E.)

The quartzite conglomerate exposed here (fig. 3-3) is the most prominent and best-exposed unit in the Pine River Block (Dutton, 1971). Leith and others (1935) considered it to be a separate formation (the "Breakwater Quartzite"). However, according to Dutton (1971), it appears to be a lens within the Michigamme Formation and he did not give it a separate stratigraphic name.



Figure 3-5. Conglomerate in Michigamme Formation at stop 3-2 showing strongly stretched and aligned pebbles. Photograph from Dutton (1971), figure 5.

The quartzite conglomerate is about 700 feet thick and extends northwestward about 3 miles from near the center of sec. 28, T. 39 N., R. 18 E., to the NE corner, sec. 24, T. 39 N., R. 17 E., (Dutton, 1971). Cross-bedding indicates that stratigraphic tops are toward the southwest. Layers and lenses of quartzite with flat (or flattened and stretched) pebbles and cobbles (fig. 3-5) of recrystallized chert and iron-formation are the dominant lithology. (Note: This locality is only about one half mile north of the Niagara fault.) The matrix within the pebbly units is composed of quartz, fine-grained hematite or magnetite, or both. The unit was studied in detail by Nilsen (1965), who showed that it consists of two conglomeratic subunits separated by a quartzite and pebbly quartzite subunit. His paleocurrent analysis indicates a predominant current flow toward the southeast in a shallow, near-shore basin.

Structurally, there appears to be a cleavage-parting parallel with bedding. Bedding strikes N55°W, parallel to the strike of the Niagara fault, and dips 65° SW. Stretched pebbles plunge steeply southwest.

Stop 3-3. Riverton Iron-formation and Wauseca Pyritic Member of Dunn Creek Slate (SW ¼, SW ¼, sec. 34, T. 40 N., R. 18 E.)

This stop is along the axis of the Commonwealth syncline named by Dutton (1971) and is within Dutton's Brule River block, now included as the southeastern extension of the Iron River-Crystal Falls allochthon. Roadcuts on Highway N about 2 miles southeast of Florence, Wisconsin were made after Dutton's mapping of the area, but reveal geology very much as inferred on his maps. The roadcuts consist of alternating units of black, pyritic slate of the Wauseca Pyritic Member, the uppermost member of the Dunn Creek Slate, and cherty carbonate and silicate iron-formation of the overlying Riverton Iron-formation. Individual lithologic units of slate and iron-formation are generally a few tens of feet thick and the contact between them is well exposed in many places along the roadcut. The interleaving of the two units is probably a result of repetition by tight folding, although contacts cannot be traced around fold hinges within the limits of the roadcut. The lithologies could be stratigraphically interlayered, but such broad-scale inter-bedding is not known elsewhere in the district where a few feet, at most, of transitional beds occur between the two units where exposed in many mine workings. We think it more likely that folds with amplitudes greater than the height of the roadcut cause the repetitions with a geometry like those displayed in parts of figure 7 (p. 19) at the Buck mine in which fold amplitudes are many times greater than fold wave-lengths. Small-scale tight folds showing this type of geometry are common within individual lithologic units in this roadcut. The Wauseca consists of multiply deformed, black, ferruginous, and highly pyritic slate with thin - up to a few inches thick - beds of chert. The Wauseca was classified as a sulfide facies iron-formation by James (1954) and was his principal example for defining this facies. Foliation is generally parallel to the bedding and axial planar folds in bedding. It is roughly oriented N55°W, 85°NE, and is parallel to the trend of the Brule River block. The rock is folded isoclinally with axes that plunge variably but most plunge steeply northwest (see stereoplot on fig. 3-4,B). These small folds are most likely parasitic to the Commonwealth syncline.

The Wauseca Pyritic Member has some anomalous chemical characteristics. Ongoing studies by the USGS of the geochemistry of black slates in the region found that a composite of 30 feet of black slate in this roadcut contained 1230 parts per million arsenic and 14 parts per million selenium, both values being the highest that we have

detected in northern Wisconsin and the upper peninsula of Michigan. Studies are continuing to determine to what degree the Wauseca might contribute to a regional arsenic anomaly in surficial materials.

Stop 3-4. Riverton Iron-formation along eastern limb of Iron River-Crystal Falls basin (NW $\frac{1}{4}$, sec. 31, T. 42 N., R. 32 W.).

Typical Riverton Iron-formation is exposed in cuts along two sub-parallel abandoned railroad spurs, the northern of which is drivable as a single-track road. The exposures are approximately in the middle of the Riverton, which in this area strikes NNE and dips steeply to the west into the Iron River-Crystal Falls basin. Detailed maps of the area are included in USGS Professional Paper 570 by James and others (1968) and detailed lithologic descriptions of the Riverton are in the same publication. In general, the Riverton, where unaffected by secondary oxidation, which is widespread in the district, is thin-bedded and consists mostly of interbedded chert and siderite. Iron silicate minerals, mostly stilpnomelane, are only locally important. Thin partings of argillaceous and carbonaceous material are common and some pyritic layers are also widespread.



Figure 3-6. Tight folds in the Riverton Iron-formation at stop 3-4.

The rock seen here is generally only weakly oxidized so preserves many of the original sedimentary minerals and structures. Like all of the Iron River-Crystal Falls allochthon,

metamorphic grade is extremely low and no metamorphic effects are detectable in hand specimens. Small-scale folds are very well developed. Most plunge gently to moderately toward the north or south (fig. 3-4,C).

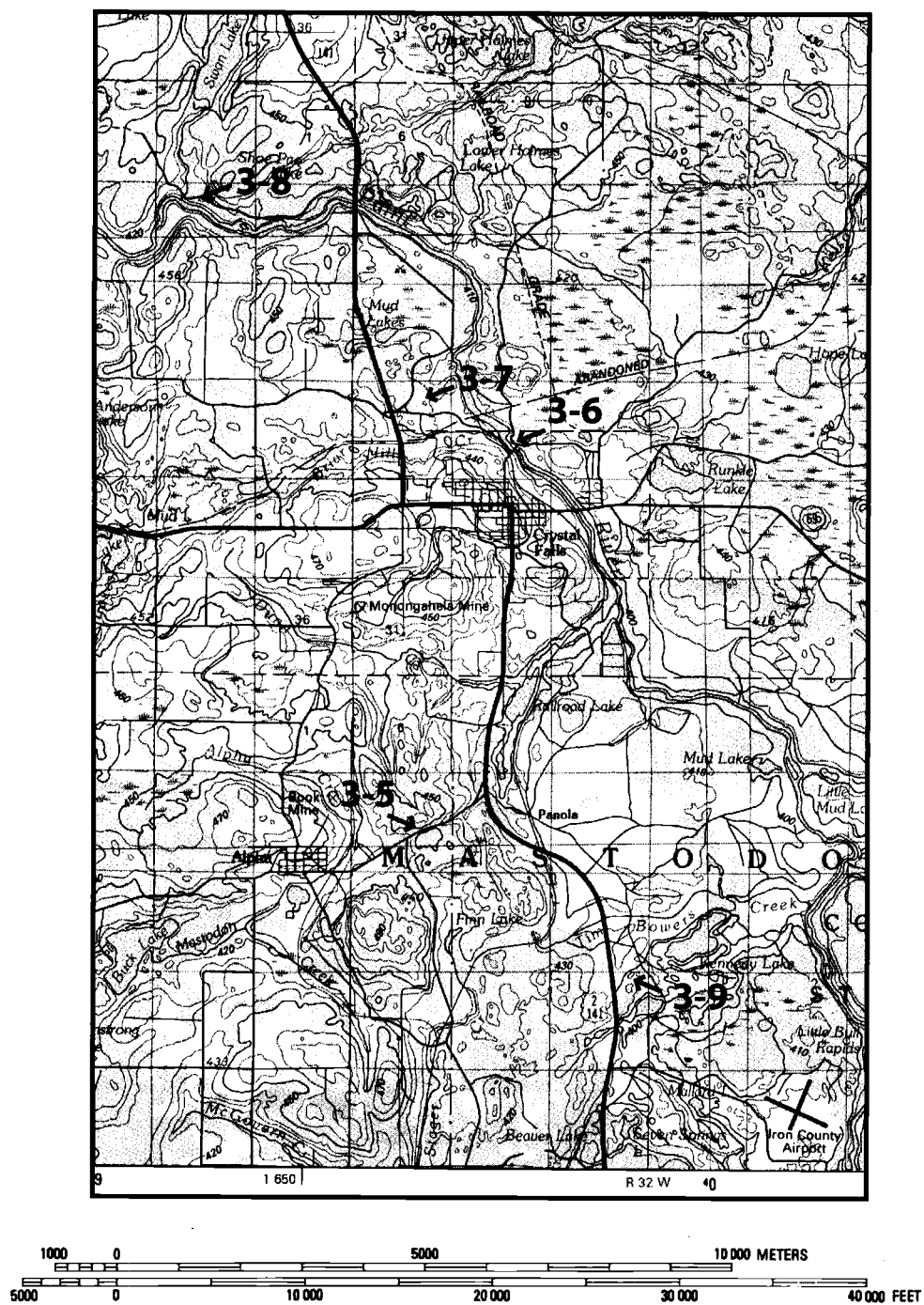


Figure 3-7. Part of the Iron River 1:100,000-scale topographic map showing the location of field trip stops 3-5 through 3-9.

Stop 3-5. Dunn Creek Slate near Alpha, MI (NW ¼, SE ¼, sec. 7, T. 42 N., R. 32 W).

The Dunn Creek Slate is the lowermost unit of the Paint River Group as defined by James (1958). It lies, probably conformably, on the Badwater Greenstone and has a gradational upper contact with the Riverton Iron-formation. It is a unit of greatly varied lithology and thickness considering the entire Iron River-Crystal Falls basin, and is defined more as a stratigraphic interval than by a distinctive lithology. James and others (1968) described the variations in lithology and thickness. The area near the village of Alpha contains the best exposures and probably the greatest stratigraphic thickness of the Dunn Creek. The detailed mapping of the area by the USGS as part of the Iron River-Crystal Falls study presented in James and others (1968) also produced a series of more detailed reports published by the Geological Survey of Michigan. The report on the Alpha area (Pettijohn and others, 1969) subdivided the Dunn Creek into three mappable units based on a unit of distinctive laminated slate that forms the middle part of the formation and separates upper and lower units of gray to black, cherty, in part sideritic, slate. The mapping of these units was very useful in tracing the northward extension of the Mastodon anticline, but for reasons not known to us these internal units were not shown on maps in Professional Paper 570. According to Pettijohn and others (1969) the exposures seen at this stop are in the lower unit of the Dunn Creek Slate and lie about 1500 feet west of the trace of the axial plane of the Mastodon anticline. This outcrop is located on the north side of Highway N about one mile east of Alpha, MI (fig. 3-7). The outcrop consists of black ferruginous slate with more massive, openly folded, cherty layers. There is a slaty foliation parallel to bedding in places. Elsewhere foliation is axial planar to the open folds in the massive layers and is generally oriented N40°W, 75°NE. A stereoplot of fold axes from the broader region in this area (fig.3-4,D) shows that the folds plunge steeply to gently north-northwest. Fold axes reported by Pettijohn and others (1969) also plunged from 40-80 degrees northwest. It is clear from the relationships mapped in this area that even regional folds like the Mastodon anticline have steep plunges within the allochthon.

**Stop 3-6. Riverton Iron-formation at the Paint River Dam in Crystal Falls, MI.
(Center, sec. 20, T. 43 N., R. 32 W.)**

The Riverton Iron-formation is 500-800 feet thick in the Crystal Falls area and is mostly inter-laminated chert and siderite. Exposures just below Paint River Dam provide the best example in the district both of the primary lithology of the Riverton and of the extraordinary structural complexity of the deformation characteristic of the Iron River-Crystal Falls allochthon. A sketch map of the outcrop, published by James and others (1968), is reproduced here to provide a view of the entire outcrop, some of which is flooded periodically, depending on the rate of flow of the Paint River. The exposure shows the typical chert-siderite lithology, which comprises the bulk of the Riverton Iron-formation throughout the district. There are also good examples of a silicate iron-formation, a lithologic type unique to the Crystal Falls area. These were described by James and others (1968) as follows: "... at the apron of the Paint River dam in Crystal Falls the chert-siderite iron-formation contains layers that consist dominantly of stilpnomelane. These layers, which are from a fraction of an inch to several inches thick, are readily distinguished in the outcrop from the chert and siderite by their inferior hardness and by their peculiar closely spaced cross fracture that resembles that of some coal." Some beds are also relatively rich in pyrite.

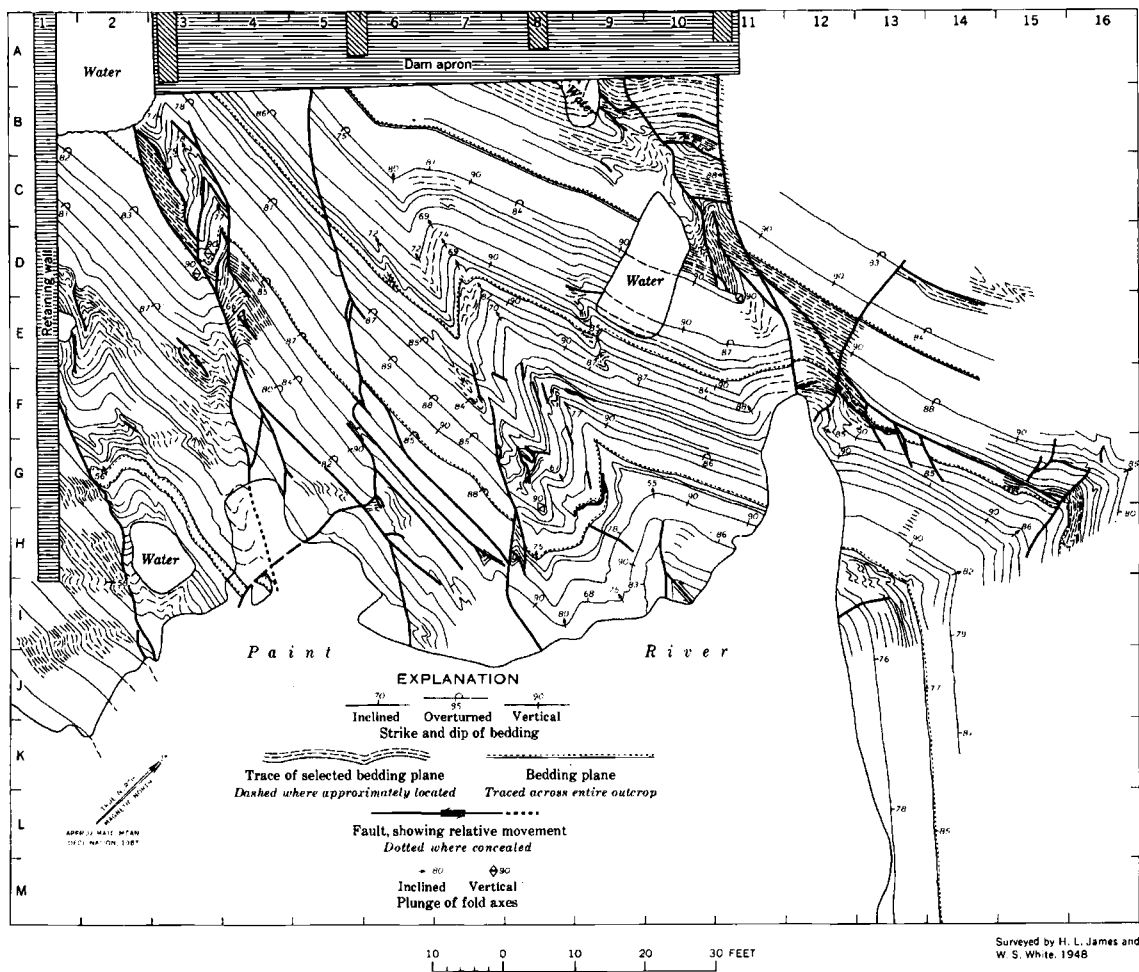


Figure 3-8. Sketch map of Riverton Iron-formation at Paint River Dam, Crystal Falls, Michigan. (James and others, 1968, fig 21)

Figure 3-4, E shows that most folds plunge steeply to the west (note that north is toward the upper right in figure 3-8). Plunges are steep, varying from 55 degrees to vertical. But, on the most northeasterly part of the outcrop folds plunge toward the north at about right angles to the other folds. These abrupt variations in fold geometry are characteristic of the district as revealed in the many underground mines that were mapped during the period of mining in the early to mid-1900's. In addition to the fold axes that we have measured, this exposure was studied in detail by Ueng and Larue (1987), who recognized 4 phases of deformation and provide a detailed discussion of the structural history. To generalize their conclusions, the folds that plunge steeply to the west formed in an initial major folding phase and those that plunge steeply to the north are a second phase.

Stop 3-7. Badwater Greenstone north of Crystal Falls (sec. 18, T. 43 N., R 32 W.)

NOTE: All outcrops in this area are on private land and should not be visited without prior permission of property owners.

The Badwater Greenstone is a thick succession of submarine mafic volcanic rocks that underlies the Dunn Creek Slate, probably conformably, although evidence is scant. As discussed above, we propose to include the Badwater in the Paint River Group because structural evidence indicates that it is part of the Iron River-Crystal Falls allochthon. Thus it has definable stratigraphic relationships to the overlying Paint River strata but is in fault contact with all other surrounding units. James and others (1968) described rocks of the Badwater as "...somewhat varied in detail, but in general they are massive fine-grained dark-greenish-gray rocks that consist chiefly of chlorite, actinolite, hornblende, albite, clinozoisite-epidote, and carbonate. Ellipsoidal and agglomeratic structures are common. The rocks almost certainly originated as sub-marine flows and fragmental volcanics and are dominantly, if not entirely, of primary basaltic composition." The formation contains minor sedimentary rocks consisting of carbonate-rich slate and thin iron-formation. James estimated that the Badwater is as much as 15,000 feet thick in places, but its thickness varies greatly within the district.

At this stop the Badwater Greenstone is a strongly deformed pillow basalt and pillow breccia. The basalt is weakly to strongly foliated, and has stretched volcanic clasts and pillows. Foliation is generally oriented N80°W, 85°NE. Stretched clasts and pillows plunge steeply northwest as shown in figure 3-4, F. These steeply plunging structures, similar to those inherently part of the Niagara suture zone rocks from here southward to the Niagara fault, are the principal evidence that the Badwater Greenstone is part of the Iron River-Crystal Falls allochthon and is structurally detached from more simply deformed rocks to the north that will be seen at stop 3-8.

Stop 3-8. Michigamme Formation north of Crystal Falls, MI (SW ¼, NE ¼, sec. 12, T. 43 N., R. 33 W.)

The Michigamme Formation, a thick sequence of clastic rocks, dominantly graded bedded graywackes and thinner-bedded siltstones, underlies a very large area north and east of the Iron River-Crystal Falls allochthon. Broad, open folds with steeply dipping, more or less east-west trending, axial planes and shallowly-plunging fold axes characterize deformation. At this locality scattered outcrops of varicolored slate are located on the north side of the Paint River, about six-tenths of a mile west from the Highway-141 bridge and display well this characteristic fold geometry. Prominent slaty cleavage is oriented N75°W, 80°NE, and intersections of bedding and cleavage indicate that fold axes plunge 15 degrees west. Outcrop-scale folds with this orientation are also present here. This nearly horizontal, westerly plunge of the fold axes is characteristic of fold axes found in the Michigamme Formation along the north and east sides of the Iron River-Crystal Falls district, and contrasts sharply with the steeply plunging orientation of fold axes and stretch lineations found in the Badwater Greenstone and overlying Paint River Group strata. This contrast in structural style between the rocks here and those at all other stops seen to this point indicate that there is a fundamental structural boundary between the Badwater Greenstone and other rocks of the allochthon and the Michigamme Formation. The outcrops visible south of the River are Badwater Greenstone, indicating that the boundary lies immediately south of these Michigamme

outcrops, probably beneath the river. We have proposed the name Paint River fault for this structure and interpret it to be the basal detachment of the allochthon.

Stop 3-9. Little Tobin Lake Granite (NE ¼, sec. 21, T. 42 N., R. 32 W.)

A dike-like body of granite, called the little Tobin Lake dike by James and others (1968), intrudes the Badwater Greenstone and forms a body about 2 miles long and a quarter of a mile wide (fig. 3-1). The rocks are gray to reddish gray and fine- to medium-grained and are composed dominantly of microcline microperthite, albite, and mica. In this area the Badwater is intensely folded on the Mastodon anticline and the adjacent Tim Bowers syncline, both of which are traversed by the dike, which maintains a nearly straight trace. The dike clearly seems to be emplaced after the major folding of the Paint River Group. It yielded a U-Pb zircon date of 1833 ± 6 Ma (Schneider and others, 2002), which places a younger limit on the age of emplacement of the Iron River-Crystal Falls allochthon. Several other smaller bodies of granite lie between here and Crystal Falls, about 5 miles to the north. These, too, are apparently post-tectonic and occur both within the allochthon and in the structurally lower Michigamme Formation. James and others (1968) states "The granitic bodies all have been sheared to some extent, and all have been metamorphosed". Perhaps these granites record a younger, circa 1650 Ma deformation as has been proposed for this area by Romano and others (2000).

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FIELD TRIP 4

LIFE CYCLE OF AN IRON DEPOSIT—THE REPUBLIC MINE FROM ORE GENESIS TO MINE RESTORATION

William F. Cannon, USGS, Reston, VA; John G. Meier, Cleveland Cliffs Iron Co., Ishpeming, MI; Thomas Waggoner, Geologic Consultant, Negaunee, MI



The Republic pit in 1973, approximately at mid-point of production.



The Republic Wetlands Preserve in 2002, constructed on the former tailings basin of the Republic mine.

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Brief history of mining and geologic studies

Mining: The Republic Mine in western Marquette County, Michigan produced more than 75 million tons of iron ore during two generations of mining. The Republic Iron Company was organized in Marquette, Michigan in October 1870 and mining at what is now the site of the closed Republic Mine began in 1871. Operated by the Republic Iron Company, the mine was producing 235,000 tons of hard, specular hematite by 1880. Mining operations were conducted in open pits and 14 shafts. The greatest shaft depth was 2,910 feet. The Cleveland-Cliffs Iron Company acquired the mine in 1914 and operated it until 1926 when it closed. Shipments from the stockpile continued until 1937. The total ore shipped from 1872-1937 was more than 8.5 million tons. After that, the mine sat idle until the early 1950s.

In 1952, construction of the modern-day facilities began and the open pit mine was in production by 1956, mining low-grade iron ore that was concentrated at the mine's plant and pelletized at the former Eagle Mills pellet plant in Negaunee Township. In the early 1960's an expansion of the mine, including pelletizing and additional concentrating equipment, took place. This expansion was completed in 1964, at which time Republic was producing more than 2 million tons of iron ore pellets annually. A unique part of the mining operation at Republic was the in-pit crushing system, which performed coarse crushing near the floor of the pit and transported the crushed ore from the pit to the plant, a vertical lift of 647 feet, via a 2,814-foot conveyor in an inclined tunnel in the footwall of the ore body.

In 1981, with the iron ore and steel industry in a deep recession, operations at Republic were suspended. When hope faded that market conditions would improve to allow pellet production to resume, Republic was permanently closed in early 1996. More than 45 million tons of pellets were produced at the Republic plant between 1964 and 1981. Including pellets produced at the Eagle Mills plant and some produced at the Humboldt plant with Republic ore, Republic accounted for more than 63 million tons of pellets since 1956. When the mine closed in 1981, Republic employed more than 700 people.

In addition to being a major iron-producing area for more than a century, the geologic relationships shown in the mine area and other nearby exposures have played an important role in developing concepts of the origin of iron-formations of various sedimentary facies, their alteration through regional metamorphism, and a rather complex history of iron concentration that led to the formation of the high-grade ores on which the initial mining was based. This trip visits some of these exposures and provides a review of the rich history of studies of the geology of iron deposits in this part of the Lake Superior region.

Geologic studies: The first recorded geologic observations at Republic were made by Government Land Office surveyors in 1846 while surveying the township and range grid of the area. They clearly recognized the importance of the ore that was readily visible on what was then a prominent hill along the Michigamme River.

Five years later the area was visited by J.W. Foster and J.D. Whitney, U.S. Government Geologists, who provided the following description (Foster and Whitney, 1851): "The largest mass observed by us in this region occurs on the left bank of the Machi-gamig, in section 7, of township 46, range 29, and traces of it are to be observed in several of the adjoining sections. It here rises in a nearly vertical cliff to the height of one hundred and thirteen feet, and is somewhat variable in purity. For the most part it has a slaty cleavage, and, on close inspection, is observed to be composed of alternating bands of micaceous specular iron and quartz, tinged red by the peroxide of iron: but there are occasional belts which display a granular texture, and apparently possess a greater degree of purity. These laminae are nearly vertical, exhibiting few contortions, and range with so much uniformity, that the observer would be inclined to refer both the slates and the iron to a common origin. Interlaminated with it is a band of rock composed mainly of white, granular quartz, with traces of feldspar, through which are disseminated particles, as well as rounded masses, of specular iron. It is difficult to pronounce whether this is a conglomerate or breccia."

During the ensuing 20 years, the wave of exploration and development along the Marquette Range reached Republic. In 1871, shortly before mining was initiated, the ore was described by Swineford (1871). His description of Smith Mountain, as it was then called, was "The mountain rises to a height of nearly, if not quite, 1,000 feet above the waters of the Michigammi River, which runs near its base, and the explorations made last summer reveal the existence of an immense body of ore, which can be traced over a mile by outcrops alone. The writer visited this mountain last summer and has no hesitation in saying the he believes it to be by far the most valuable property yet discovered. The ore is a very pure magnetic, similar to that of the Washington and Champion. The elevation is such that the ore can be mined at a comparatively trifling cost, and it would be an easy matter to mine and ship a hundred thousand tons in the first year after commencing operations." He further states "It was originally discovered by S.C. Smith, Esq., of Marquette, from whom it takes its name, and who threw away an immense fortune in its sale at a nominal price." Apparently Mr. Swineford had a rather optimistic eye, both in estimating topographic relief and ore reserves.

In 1873, T.M. Brooks published a comprehensive survey of the iron-bearing rocks of the Marquette range including both descriptions and an atlas. At Republic he determined the detailed internal stratigraphy of the iron-formation and produced the first detailed map of the deposit. He recognized the synclinal character of the host rocks and described the several lithologic types of iron-formation and ores exposed in the area. Like Swineford, Brooks was very impressed by the large ore exposure and wrote "The immense mass of pure specular ore, which was naturally exposed near the center of the north $\frac{1}{2}$ of the southeast $\frac{1}{4}$ of Sec. 7, T. 46, R. 29, could leave no reasonable doubt in the mind of the experienced observer, that this deposit of ore was one of the largest, if not the largest, in the Marquette region. This outcrop, the extent of which is shown on the map of the Republic Mountain, being there marked "pure specular ore", is, so far as I know, the largest outcrop of any equally rich ore, ever found in the United States."

A more detailed and accurate description of the geology was published in 1897 by Henry Lloyd Smyth as Chapter VI of the classic USGS Monograph 28 by Van Hise and Bayley on the geology of the "Marquette Iron-bearing District" (Van Hise and Bayley, 1897). By that time, the original mines were well established and an understanding of the processes of ore-formation was being developed by Van Hise and Bayley. Smyth's observations at Republic were an important part of that research and are discussed in more detail below. Among Smyth's contributions were recognition of the detailed stratigraphic sequence of the Early Proterozoic strata, which has not been significantly modified since, with the exception of some changes in nomenclature, and delineating the plunging synclinal geometry of the strata. With regard to the ore deposits, Smyth's maps were the first (and only) ones that showed a distinct separation between dominantly specularite ores and dominantly magnetite ores. He correctly surmised that the hard ores formed by secondary concentrations within the iron-formation, in part through leaching of original siliceous beds, and also recognized the detrital character of iron enrichments in the basal conglomerates of the Goodrich Quartzite.

Much later, in the early 1950's, Harold James of the USGS published two fundamental papers in which Republic played a major role. His work on zones of regional metamorphism (James, 1955) was strongly influenced by the Republic area, which was at the center of a zone of sillimanite grade metamorphism of his Republic metamorphic node. The Republic area was the sole locality where several lithologic types of iron-formation were within this high-grade zone and was the principal example upon which he defined the very high-grade metamorphic effects on iron-formation. A fundamental outcome of that study was that even very intense metamorphism does not change the original oxidation state of a majority of the iron, an idea contrary to widely held concepts at that time. The relationships upon which he based that conclusion are clearly displayed in a glacially polished outcrop at the Kloman Mine (fig. 4-1, stop 4-1). James's studies of the importance of sedimentary conditions in determining the mineralogic character of iron-formations, published as his famous "Sedimentary facies of iron-formation" (James, 1954), also drew heavily on relationships seen in the Republic area, and again the exposures at Kloman mine were instrumental in showing the relationship between bedding characteristics and mineralogy of iron-bearing phases.

The most recent comprehensive geologic study of the Republic area was conducted by Cannon (1975) who mapped the geology of the iron-bearing sequence and surrounding rocks, including detailed mapping in the open-pit. Because the pit was developed in the same stratigraphic unit that contained the high-grade ores mined previously underground, exposures of those high grade ores and their relationships to host rocks were abundant in the pit and were a fundamental component of Cannon's study of the origin of hard iron ores of the Marquette Range (Cannon, 1976). Unfortunately those exposures are now flooded in the abandoned pit.

Geology of the Republic area

The Republic area has many similarities to the Marquette Iron Range to the north and east and is generally considered to be an extension of it. Paleoproterozoic strata of the Marquette Range Supergroup are preserved in a syncline, the Republic trough, between uplifted blocks of Archean gneisses. The stratigraphic units defined in the Marquette Iron Range, can be applied in the Republic trough as well, and to some extent can be traced directly into the Marquette Range. The Paleoproterozoic units in the Republic area consist of a basal clastic sequence of the Ajibik Quartzite and Siamo Slate which were

mapped as a single unit by Cannon (1975) because very limited exposure does not allow accurate mapping of a contact between them. These are overlain by the Negaunee Iron-formation, the principal iron-bearing unit. The Goodrich Quartzite lies unconformably on the Negaunee. The unconformity was well exposed in the Republic pit before flooding. The basal part of the Goodrich is a ferruginous conglomerate, which grades upward into quartzite. The youngest strata are biotite-garnet schist with beds of impure quartzite, which make up the Michigamme Formation. The Michigamme also contains a basal unit of silicate-magnetite iron-formation. Several sills of diabase were intruded into the strata, mostly in the iron-formation, and have been folded with it.

The fundamental structure of the area is a narrow, deep, northwest-plunging syncline of Paleoproterozoic strata of the Marquette Range Supergroup flanked by Archean gneisses. Gravity studies indicate that along Highway 95, where the trough is about 3,000 feet wide, it is about 5,000 feet deep (Klasner and Cannon, 1974). Axes of minor folds measured in the Republic pit, which follows the iron-bearing beds around the keel of the trough, plunge about 45° to the northwest. The tight compression within the syncline has produced intense small scale folding in some units, such as the schists of the Michigamme Formation seen at stop 4-2 (fig. 4-1). This deformation apparently also has caused severe attenuation of the iron-formation along the limbs of the syncline as shown by the drastic thinning seen in traversing from the Republic pit at the keel of the structure along strike onto the nearly vertical limbs. The contact between the Paleoproterozoic strata and Archean basement gneisses is interpreted to be a fault along both limbs of the syncline. The fault on the southwestern limb was well exposed in the pit and completely truncates the Negaunee and Ajibik/Siamo strata producing the fish-hook shape of the taconite orebody. Bedding in the iron-formation near the fault, as well as shear foliation in Archean rocks along the fault, generally dips from 75° - 85° to the southwest indicating that the fault is a high-angle reverse fault at the present exposure level. The fault along the northeast limb is not as well documented by exposures, but beds on the northeast limb are commonly overturned and dip about 85° to the northeast suggesting that the northeast limb fault is also a high angle reverse fault. Thus the Republic trough has an unusual geometry in being a syncline that widens somewhat below the present surface.

The intense Penokean deformation recorded in the Paleoproterozoic strata of the Republic trough is not present within the surrounding Archean gneisses where intense multiple folding events documented by Taylor (1967), Cannon (1975), and Hoffman (1987) appear to be entirely a result of late Archean tectonism. Cannon (1973) used metadiabase dikes as structural markers to indicate the general absence of penetrative Penokean deformation in the areas of Archean rocks. These dikes, which occur in northeast- and northwest-trending swarms, are metamorphosed by Penokean metamorphism of the Republic node and, in places, have sheared margins caused by Penokean deformation, but everywhere maintain their vertical, planar dike geometry and have essentially no internal tectonic fabric. Relict diabasic textures are commonly well preserved even in the most highly metamorphosed dikes. Thus it appears that Penokean deformation within areas of Archean basement rocks was largely confined to zones of shearing, which separate larger blocks of rock that remained rigid. The Republic trough, therefore, is a graben with respect to Archean rocks. The synclinal form of the trough of Paleoproterozoic strata is a result of those strata being molded around the structural form created by differential movement of individual discrete blocks of Archean basement rocks.

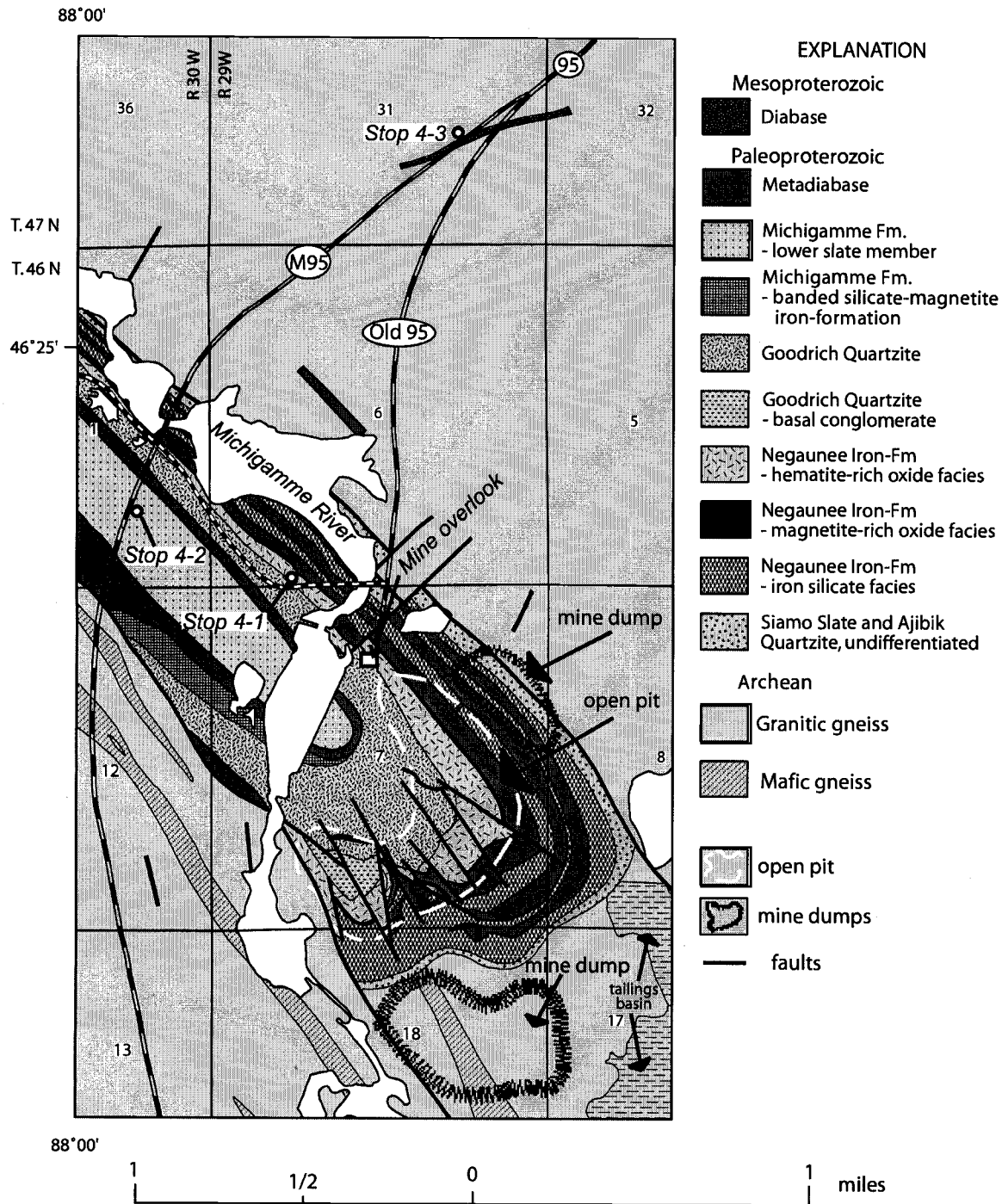


Figure 4-1. Geologic map of the Republic area, Michigan showing the location of field trip stops. Geology from Cannon (1975).

Economic geology

The iron ores produced at Republic were of two different types: early production was of high-grade ores that occur within the upper part of the Negaunee Iron-formation and lower part of the overlying Goodrich Quartzite. These are locally known as "hard ores" because of their compact, coarse crystalline nature. The more recent production of iron concentrate and pellets was from lower-grade material typical of upper stratigraphic units of the Negaunee Iron-formation.

Concentrating-grade ore (taconite): The modern open pit of the Republic mine was developed to mine the uppermost parts of the Negaunee Iron-formation consisting mostly of hematitic jasper (fig. 4-2). The ore horizon varied from 400-600 feet thick in the pit. The ore horizons dip approximately vertically along in the northern part of the pit, which lies along the northeast limb of the Republic syncline, but dips flatten to about 45 degrees in the southern part of the pit near the synclinal axis. Coarse-grained specular hematite was the most important ore mineral but some magnetite was also produced from a thin unit of banded chert-magnetite iron-formation that formed a continuous unit no more than a few tens of feet thick stratigraphically below the hematitic jasper. Some iron production also came from highly ferruginous conglomerate of the Goodrich Quartzite, mostly present as a lens as much as several hundred feet thick in the southwest part of the pit. Essentially all of the iron was deposited as primary sedimentary accumulations.

The iron content of the ore was no greater than typical of the Negaunee elsewhere in the region. The economics of the deposit were controlled principally by the structural geometry of the ore beds and by the oxide mineralogy and grain size. Lower units of the Negaunee, never mined, consist of silicate (mostly grunerite)- magnetite iron-formation, which was not amenable to concentration by the techniques used at Republic. These rocks, along with three diabase sills, underlie the prominent ridge along the northeast and southeast flanks of the pit where they dip nearly vertically. The uppermost diabase sill forms the footwall of the orebody (figs. 4-3, 4-5). The unusual strength and stability of this metadiabase allowed the development of a high footwall of the pit, which stood several hundred feet high as a vertical to slightly overhanging rock face. This situation was an important economic factor in that it eliminated the need for the large amount of waste rock removal that would have been necessary to maintain a more typical footwall pit slope.

In addition to the occurrence of the hematite and magnetite iron-formation, other geologic factors were critical in enhancing the economics of the Republic mine. The geometry of the syncline created the moderately-dipping and thick sequence of iron-formation along the keel, which was required to extract ore with an economically permissible amount of removal of underlying iron-silicate and diabase, and overlying Goodrich Quartzite waste rock. Also, the high degree of metamorphic recrystallization was vital in enhancing the liberation and concentration of iron minerals, in that grinding to very-fine grain size was not required to allow separation of iron-minerals from chert by the flotation process used at Republic.



Figure 4-2. Wavy-bedded jaspilite typical of the ore zone for the Republic open pit. Lighter layers are specular hematite and darker layers are lenticular beds of metamorphosed jasper.



Figure 4-3. The Republic open pit in 1973. View looking SE along the NE limb of the Republic syncline. The high wall on the left side of the pit is the upper contact of a metadiabase sill, now dipping vertically.

Hard ores: The first phase of mining at Republic was based on high-grade (60-65% Fe) concentrations of specular hematite and magnetite, which were referred to as hard ore (fig. 4-4), in contrast to the earthy masses of iron oxides and hydroxides, the soft ores, widely mined in the eastern parts of the Marquette district. The origin of hard ores has been investigated since the geologic studies of Van Hise and Bayley (1897), who were the first to recognize a connection between the Negaunee-Goodrich unconformity and occurrence of hard ore. They proposed that oxidation of siderite and leaching of silica from the iron-formation by groundwater formed hematite concentrations. They envisioned tectonism as important in producing a permeable crushed zone at the unconformity to accentuate groundwater flow. Later, Van Hise and Leith (1911) proposed the classic theory that the hard ores formed by surficial weathering and leaching of the Negaunee Iron-formation, during the uplift preceding deposition of the Goodrich Quartzite, and are paleosupergene concentrations; this weathered and leached material was later deformed and metamorphosed to produce the present hard ore. This theory was widely accepted and most recently supported by Gair (1975) based largely on observations in the Cliffs Shaft mine in Ishpeming. Others have proposed that the hard ores are at least partly hydrothermal (Roberts and Bartley, 1943; Crump, 1948; Anderson, 1968; Marsden, 1968).

A comprehensive reexamination of the hard ores of the Marquette Range by Cannon (1976), including critical relationships then exposed in the Republic pit, suggested that there are two types of hard ore, each formed by a substantially different set of processes. He recognized a distinction between dominantly specular hematite ores,

which commonly possessed Penokean tectonic fabrics, and dominantly magnetite ores, which generally are massive and appear to post-date tectonism. The hematite ores show geologic relationships that are fully consistent with the original paleosupergene origin proposed by Van Hise and Leith and are still believed to record an interval of oxidative weathering and leaching during the stratigraphic hiatus between the Negaunee Iron-formation and Goodrich Quartzite. The geologic map of the Republic area published by Smyth (*in* Van Hise and Bayley, 1897) clearly distinguished hematite and magnetite types of ores, which occur in distinct and to some extent separate ore lenses. Cannon documented that a similar duality of ore types is widespread in the western Marquette range, most particularly at the Greenwood and Champion mines. The magnetite ore is invariably post-tectonic, commonly contain euhedral quartz crystals in vugs, and occurs within hematitic host rocks. Cannon proposed that the magnetite ores formed from a hydrothermal fluid that was reducing with respect to the hematitic host rock. He suggested that fluids released by metamorphic devolatilization of the iron-formation, which was rich in both hydrous and carbonate minerals in its primary state, was the origin of the hydrothermal fluids. Metamorphism of the Republic node is known to have begun during the closing phases of Penokean deformation but to have outlasted and reached its peak after deformation. Thus, the magnetite hard ores were interpreted to have been deposited shortly after formation of the Republic syncline and to be precipitates from reduced metamorphic fluids carrying ferrous iron from stratigraphically lower parts of the iron-formation to the upper parts where reaction with hematitic beds caused precipitation of magnetite.

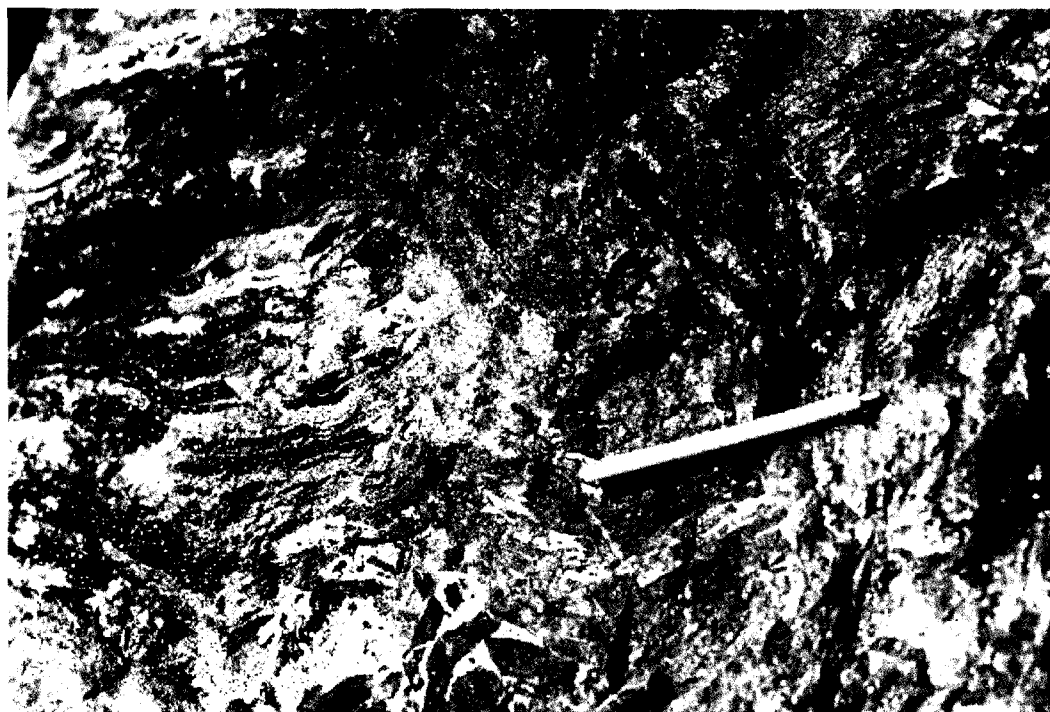


Figure 4-4. Former exposure in Republic pit showing wavy-bedded jaspilite on left and magnetite hard ore on right. The hard ore truncates jaspilite bedding at a nearly right angle. Within a few centimeters of the contact, much of the jasper is converted to milky quartz and partly removed from the rock, creating vugs into which quartz crystals have grown. The loss of volume resulted in brecciation of the iron-formation, which was later healed and largely obliterated by magnetite deposition. Magnet is about 12 cm long.

The Republic pit and mill

In 1947 Cleveland Cliffs Iron Co. began research on devising a viable metallurgical concentrating scheme to upgrade the banded specular chert iron-formation at Republic to a suitable grade of concentrate. The crude ore composition was 38% Fe, 42.5% SiO₂, 0.033% P, 0.90% MgO, 0.53% CaO, 0.72% Al₂O₃, 0.03% Na₂O, and 0.04% K₂O. A concentration process was needed to produce a product with roughly 65% Fe and 5% SiO₂. The Company settled on a hot anionic flotation of the specularite after the crude was ground to 90% passing 325 mesh size. After the board of directors approved a new mining operation at Republic, the company teamed with three partners who would consume the pellet product (i.e. Wheeling Pittsburgh, J & L Steel Corp., and International Harvester Co.). Operations started with site clearing in 1952 followed by construction of a concentrator capable of producing an initial 600,000 long tons (lt) of concentrate. Pelletization (agglomeration) was initially conducted at the Eagle Mills pellet plant located southwest of the City of Marquette starting in 1956. In 1962, a pelletizing facility located at the mine was brought on line with production increasing to 2.6 million lt of pellets per year.

The open pit was developed by a conventional bench-berm system from surface to an ultimate depth of +940 feet. A unique feature of the Republic Mine was the development of the vertical to slightly overturned footwall on the northeast side of the pit that was referred to as the highwall (fig. 4-5). This distinctive design required steel mesh screen held in place by rock bolts to prevent spalled rock from falling into work areas.

During the middle 1970s the pit crusher was relocated from the pit crest to an adit/chamber located in the high wall on the +1130 bench (lower left of fig. 4-5). A 2800-foot-long gallery at 11% grade had been driven from surface to the chamber to house the conveyor used to move the ore from the crusher to the plant stockpile (upper right of fig. 4-5).

Mining was conducted using conventional shovel-truck equipment to get the ore to the crusher. Initial haulage units were 34 tons Euclid trucks. However, by the time the mine was idled in 1981, 80-ton units were standard.

Republic crude was extremely hard and initial production drilling used the Linde Jet Piercing machine in which fuel oil and oxygen were combusted to heat and spall the rock for drilling. During the 1970s the mining equipment industry developed rotary machines capable of delivering 90,000 lbs. of down pressure to the bit, which allowed the mine to change over to conventional blast hole drilling. Blasting required the use of ammonium nitrate and fuel oil (ANFO) at a high usage exceeding one pound per ton whereas other mines could get the required results for half the powder factor.

Rock stability at the mine was enhanced by dewatering wells on the pit perimeter that drew down water keeping it from the pit faces and further stabilizing the pit walls. This was especially important on the northwest side of the pit where the Michigamme River had been partly diverted to allow pit development.

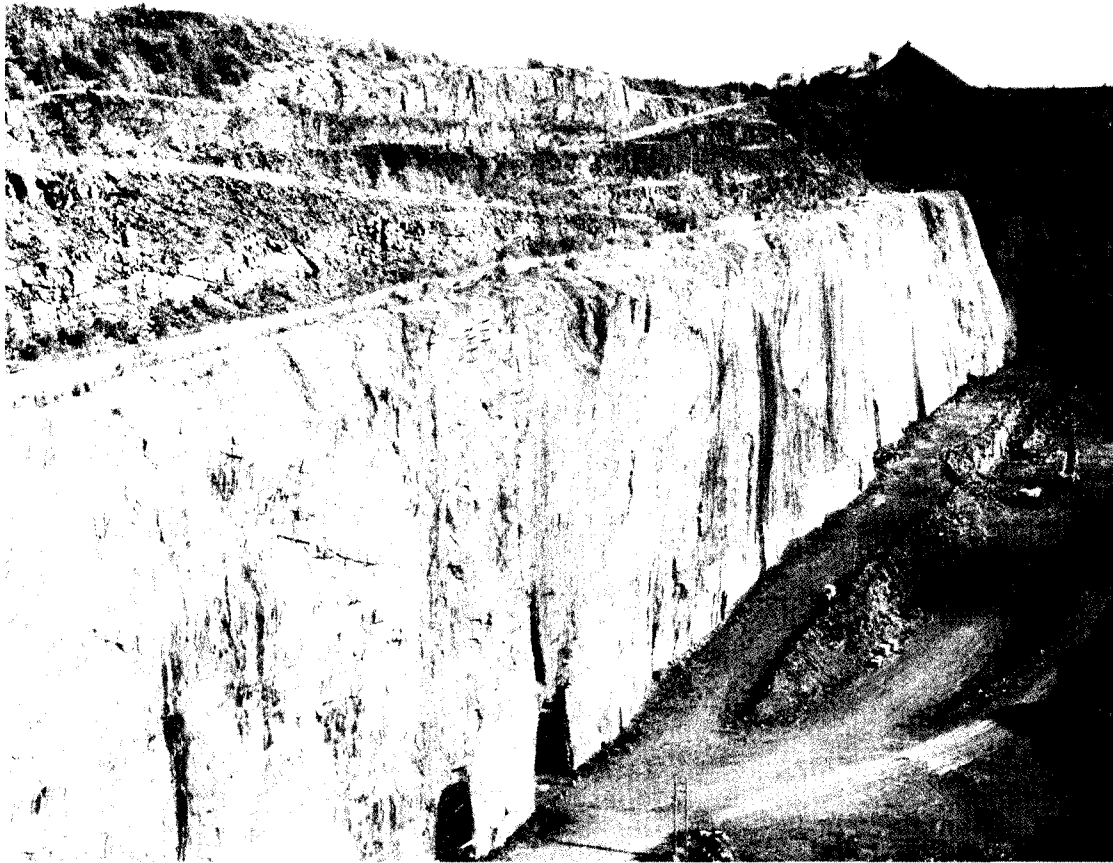


Figure 4-5. The highwall at Republic. View is looking southeast. The steep rock face is the upper contact of a metamorphosed diabase sill, which was emplaced at the base of the oxide-facies ore unit. Other rock faces in upper left are underlying beds of magnetite-grunerite iron-formation, which were removed as waste. The units now dip vertically or are slightly overturned so that, in places, the highwall projects slightly outward over the pit. The two portals in lower center are the access to the primary crusher. Crushed ore was moved to stockpile (on horizon in upper right) by conveyor through an inclined tunnel. The highwall was about 300 feet high at the time of this photograph near the end of pit operation.

Crude ore underwent three crushing stages to provide a product less than ½-inch size, which was fed to the grinding section. Grinding consisted of a conventional rod mill with a steel rod charge to effect size reduction. The crude was then sent to a ball mill containing small steel balls to complete the grinding to a size suitable to liberate ore minerals from gangue. The crude was discharged at 90% passing 325 mesh. Flotation using a fatty acid reagent separated the iron from the gangue by floating the iron minerals (anionic). The coarse nature of the product required further grinding to make it suitable for pelletizing. Concentrate was reground in ball mills, heated, and the pulp was sent hot to roughers, cleaners and scavengers. The final product was dewatered, balled, and finally sent to the Allis Chalmers Grate Kiln system to be heated to 2440° F to produce a tough pellet capable of withstanding handling and transport to the furnace. The product was carried to Marquette by rail and then shipped via lake cargo vessels to steel furnaces in the lower Great Lakes. Scrubber and electrostatic precipitators

removed 99% of the particulate matter from the discharge air. Tailings from the process were settled in vast settling ponds located southeast of the plant that have subsequently been converted to viable wetlands.

From 1956 to 1981 the mine produced 62 million tons of pellets recovered from 145 million tons of crude ore.

Considerable resources remain in the ground at currently subeconomic status. The resources, as estimated by Cleveland Cliffs Iron Co., include both specular hematite ore, the traditional ore mined at Republic, and magnetite-silicate iron-formation, which was not amenable to concentration by the process used at Republic. The estimated resources in million of long tons (MLT) of ore are:

<i>Ore type</i>	<i>Resource</i>	<i>Grade</i>	<i>Fe Recovery</i>	<i>Fe in concentrate</i>	<i>SiO₂ in conc.</i>
<i>Spec. hematite</i>	<i>63 MLT</i>	<i>38% Fe</i>	<i>44% Wt. Rec.</i>	<i>65.0% Fe</i>	<i>5.00%</i>
<i>Mag.-Silicate</i>	<i>60 MLT</i>	<i>27% Fe</i>	<i>33% Wt. Rec.</i>	<i>67.0% Fe</i>	<i>5.80%</i>

Talc is common in footwall ore in the area of the axial keel of the syncline. MgO analyses range from 1% to 4.7%. Schistose conglomerates contain sericite, chlorite, epidote and tourmaline. Most ore in the pit contained 0.20% TiO₂ but the southwest Park City area had elevated values in the .50 to 1.65% TiO₂ as rutile associated with hematite

Mine closure and restoration

From tailings basin to the Republic Wetlands Preserve: The Republic Mine in Marquette County, Michigan ceased operations in 1981, but was not officially closed until 1996. Plans were made to reclaim a substantial portion of the Republic Mine as a wetland mitigation project to serve the needs of the nearby Empire and Tilden mines and other Cliffs-managed properties. The Cleveland-Cliffs Iron Company and its partners in the two active mines agreed to proceed with what is called the Republic Wetlands Preserve (RWP). The Michigan Department of Environmental Quality and the U.S. Environmental Protection Agency were involved from the inception of the project.

Northern Ecological Services, Inc. (NES) and Cliffs Mining Services Company (CMSC) formed the project team involved in the planning, design, construction, and monitoring of the RWP project. Approximately 650 acres of wetlands were created/restored on iron tailings and reuse water basins at the Republic Mine (fig. 4-6). Another 1,650 acres of wetlands and uplands were included in the RWP, bringing the total acreage to 2,300 acres.

Water levels in the tailings basins were managed to create optimal conditions for wetland vegetation, with dormant seeding and fertilizing being done, as well as aerial application of seed and fertilizer on less accessible areas. Over 250,000 trees were planted in the wetlands.



Figure 4-6. Wildlife trail in a forested and emergent wetland developed on the former tailings basin at the Republic Mine, now the Republic Wetlands Preserve.

In 2002, phase I of the RWP completed its fifth, and final, year of monitoring and the wetland plant growth and wildlife use is nothing short of spectacular. Peregrine falcons, a federal endangered species, have been documented on a number of occasions using the RWP. A pair of bald eagles nests there, as well as osprey and common loons, all state-threatened species. There is also a great blue heron nesting colony, with approximately 60 nests active each year. Over 100 species of birds have been documented using the site. The land has been transformed from former mined lands to a diverse component of the landscape in about five years' time.

The wetland credits that have not been used to compensate for unavoidable wetland impacts at the Empire and Tilden mines are in the process of being placed in a wetland mitigation bank to be used for future mine-related projects in Marquette County. In summary, the RWP is a classic example of how the mining industry and government regulators can work together to reclaim former mine land and create a valuable natural asset that benefits area wildlife and satisfies the mitigation requirements.

FIELD TRIP STOPS

Several previous ILSG field trips have visited the Republic area. The following descriptions are taken largely from guidebooks prepared by Cannon and Klasner (1972) and Cannon and others (1975).

Stop 4-1. Negaunee Iron-formation at Kloman mine.

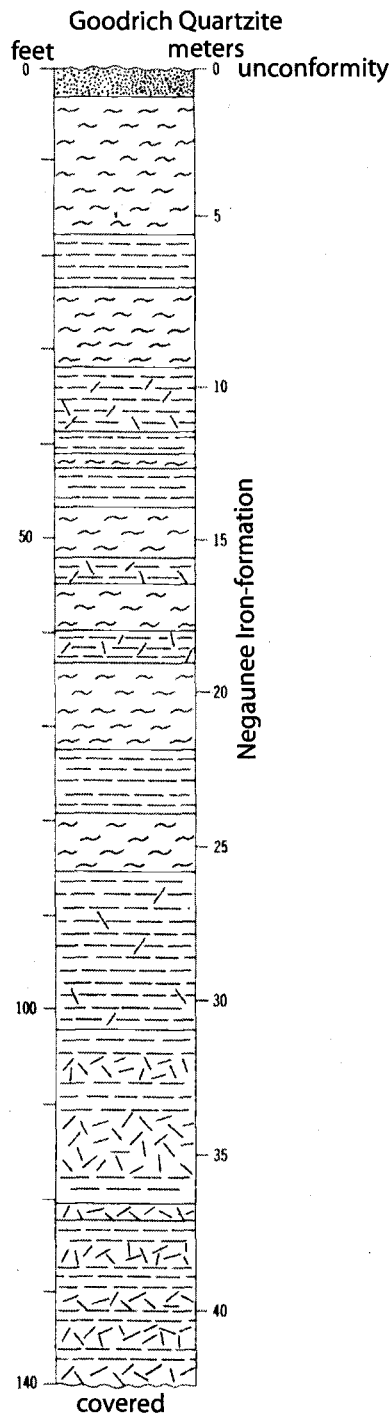
The Kloman (also known as Columbia) Mine was a small, early mine that produced about 95,000 tons of hard ore between 1873 and 1883. The ore body lay along the

contact with the Negaunee Iron-formation and Goodrich Quartzite. The pit is visible inside of the fenced area but is not available for examination because of safety concerns. The principal interest at this stop is the large, glacially polished outcrop of the Negaunee Iron-formation lying just northeast of the fenced area.

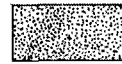
Here the Negaunee exhibits a small-scale interbedding of several different lithologic types of iron-formation. A detailed section is shown here as originally presented by Cannon and Klasner (1972) and much of the description is likewise taken from that earlier field guide. The outcrop is on the northeast limb of the Republic syncline. Beds strike about N 45° W and dip vertically. As a point of reference to the detailed section the large eye-bolt set into the outcrop corresponds to the bed at 42 feet on the section. The Negaunee as seen here shows a marked lateral facies change from the Republic open pit only about 3,000 feet along strike. Whereas the ore horizon in the pit is entirely jaspilite, with a few tens of feet of chert-magnetite iron-formation at the base, the same horizon here contains many units of chert-magnetite and chert-magnetite-silicate iron-formation interbedded with the jaspilite.

A close correspondence between bedding characteristics and mineralogy suggests that the present mineralogy, although a product of sillimanite-grade metamorphism, still reflects original differences in the sediments, particularly in oxidation state of the iron. Hematite-bearing units are typically wavy-bedded and contain red or maroon jasper, much of which has abundant bright red granules, possibly originally oolites. This is in contrast to the magnetite-rich and silicate-bearing units, which are typically even-bedded. Presumably the wavy-bedded hematitic rocks were deposited in relatively shallow water, above wave base, where currents were sufficiently intense to produce disturbed bedding and oolites, and the water was sufficiently oxygenated to result in a thoroughly oxidized sediment. The even-bedded magnetite and silicate rocks, on the other hand, are presumed to have formed in deeper water, below wave base, where a combination of quiet bottom conditions and relatively unoxygenated water allowed the accumulation of ferrous iron minerals in uniform layers. If this is so, the rocks here indicate deposition in progressively shallower water with several fluctuations either in depth of water or depth of wave action to produce the interlayering of lithologic types in the transition zone between the dominantly ferrous sediments at the base of the section and the ferric sediments at the top of the section.

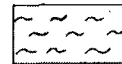
The correspondence between bedding characteristics and mineralogy is convincing evidence that these rocks represent a primary oxide facies of iron-formation and that the specularite and magnetite are metamorphic derivatives of primary hematite and magnetite or some precursor minerals with similar oxidation states. Some minerals that are considered primary may have formed by diagenetic or early metamorphic changes; however, the oxidation state of each bed must reflect the composition of bottom or interstitial waters, for adjacent beds are commonly of markedly different oxidation states. The relationships shown in this outcrop were instrumental in the recognition that some hematitic iron-formation is a primary facies of iron-formation (James, 1954).



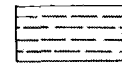
EXPLANATION



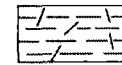
Hard ore: massive specularite with variable amounts of magnetite and little or no chert.



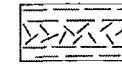
Wavy-bedded jaspillite: discontinuous beds of jasper or jasper-mantled chert, much with granular texture, interbedded with specularite layers with minor to moderate amounts of magnetite. Beds typically 1 to 2 inches thick.



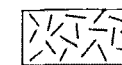
Even-bedded chert-magnetite iron-formation: typically in beds 1/2 to 1 inch thick. Chert is white or gray and interbedded magnetite is fine-grained and massive.



Even-bedded chert-magnetite-silicate iron-formation: similar to chert-magnetite iron-formation but with a selvage of grunerite at chert-magnetite contacts.



Even-bedded chert-silicate iron-formation: interlayered chert and grunerite with thin laminae of magnetite within grunerite layers



Silicate-magnetite iron-formation: grunerite with laminae and disseminations of magnetite; non-cherty.

Figure 4-7. Detailed stratigraphic section across the outcrop of Negaunee Iron-formation at the Kloman mine (from Cannon and Klasner, 1972).

The rocks here were metamorphosed to sillimanite grade during the Penokean orogeny (James, 1955), as indicated by the coarse grain size of chert and by mineral assemblages in nearby pelitic and mafic rocks. Of particular interest at this outcrop is the

lack of equilibration of oxidation states between adjacent units in spite of the intense metamorphism. Dominantly hematitic units are in sharp contact with dominantly magnetitic units, and although hematitic beds are nowhere in direct contact with silicate-bearing beds, they are separated by only thin beds in many places. These relationships attest to the inability of metamorphic fluids to induce widespread oxidation or reduction of solid phases and are a classic illustration of rocks in which the chemical potential of oxygen during metamorphism was buffered by the solid phases.

Stop 4-2. Michigamme Formation garnet-amphibole schist.

A roadcut on the east side of Highway 95 shows tightly folded schist of the Michigamme Formation, which here is mostly an iron-rich meta-argillite, now consisting of biotite-garnet-amphibole (grunerite) schist containing a few inch-thick layers of impure quartzite. Although the rock is in the sillimanite zone of metamorphism, sillimanite is not present here because of the lack of appropriately aluminous compositions. Blades and rosettes of light-colored iron-amphibole are common and have been mistaken for sillimanite in field examination of this outcrop by many geologists. It is interesting to note that Harold James who defined the Republic metamorphic node, and the sillimanite zone at its core, in his classic paper on zones of regional metamorphism (James, 1955) never observed sillimanite in outcrops. The only occurrence was in a glacial erratic boulder of Michigamme-type schist, which he presumed was transported only a short distance. The zone was defined more on the basis of assemblages in mafic rocks than on the distribution of sillimanite. Later, detailed mapping of the region (Cannon and Klasner, 1976) did find sillimanite (fibrolite) in one outcrop of the Michigamme Formation several miles northeast of this locality. An additional sillimanite occurrence was reported in drill core about three miles northwest of here by Haase (1979).

This outcrop is approximately on the axis of the Republic syncline. Minor folds with amplitudes much greater than wavelengths and greatly attenuated limbs are common and reflect the gross geometry of the Republic trough, which along the highway is estimated to be about 5,000 feet deep by gravity models (Klasner and Cannon, 1974) but is only about 3,000 feet wide. The folding is markedly non-cylindrical at outcrop scale, and domains of homogeneous strain are very small, being measurable in a few tens of square feet. Although most minor folds plunge northwest in accord with the plunge of the Republic syncline, the plunge of minor folds vary from about 15 to 65 degrees. The non-cylindrical nature of the folding may be a reflection of an earlier folding, which has been strongly overprinted by the development of the Republic syncline. The style of folding is especially well shown near the north end of the roadcut (fig. 4-8) where a 1- to 3-inch-thick quartzite bed is repeated many times by folds. Axes of adjacent folds, only a few inches apart, have plunges that diverge by as much as 60 degrees.

At the next stop (stop 4-3) we will see a major contrast between the high degree of penetrative Penokean structures seen here and their near absence in nearby Archean basement rocks.



Figure 4-8. Vertical face about 1 meter high showing tight folds in Michigamme Formation at stop 4-2. Folds are shown by a thin quartzite layer (light) in biotite-garnet schist. Note thickened hinge regions and attenuated limbs. Fold at right is completely dismembered, a geometry reflecting the Republic syncline itself.

Stop 4-3. Archean gneiss and younger dikes.

This roadcut on the west side of Highway 95 near the intersection with Old Highway 95 shows a widespread variety of granitic gneiss, which makes up part of the southern complex, the basement on which Paleoproterozoic strata were deposited. The most abundant rock type in the southern complex is a coarsely megacrystic granite, named the Bell Creek Gneiss by Cannon and Simmons (1973). Rock typical of this unit is exposed in the northern and southern parts of this roadcut. The rocks near the center are finer-grained and somewhat sheared granite. The relationships in the southern part of the outcrop are sketched in figure 4-9 and illustrate two major periods of orogeny that affected the Archean rocks; the older being an intense Late Archean folding and the younger being non-penetrative deformation during the Penokean orogeny. The oldest rock is the granitic gneiss, which was deformed and metamorphosed in the Archean event. Northwest-trending planar structures are shown mostly by preferred orientation of large microcline megacrysts and, in places, by a subtle compositional layering expressed as variations in abundance of the megacrysts. A northeast-trending porphyritic dike of metadiabase truncates the northwest-trending structures. The dike trends subparallel to the roadcut exaggerating its true thickness. Typically, such dikes are no more than a few tens of feet thick. This dike truncates the granite foliation, but is massive, although metamorphosed to a grade typical of this part of the Republic

metamorphic node. Thus, it must have been emplaced after the Archean deformation but before the Penokean metamorphism. Its massive nature, including preserved diabasic texture in thin section, and its straight trace indicates that it was not deformed during the Penokean orogeny, even though its emplacement must predate the orogeny. Such dikes are very common throughout the southern complex and consistently show these same relationships of retaining planar dike geometry and relict diabasic textures. Deformation, presumably of Penokean age, is seen in some dikes as sheared margins, but even in those cases, the planar dike geometry is not altered. Good examples of this can be seen in other roadcuts north of here heading toward Humboldt. The occurrence of such planar metadiabase dikes at literally hundreds of localities throughout the southern complex is prime evidence that the complex was not penetratively deformed during the Penokean orogeny. Rather, Penokean deformation of the Archean basement appears to have been accomplished by relative movement between discrete, rigid, fault-bounded blocks. This indicates that the intense deformation of Paleoproterozoic strata, such as just seen at stop 4-2, does not extend into the basement. The fault blocks of Archean rocks appear to have provided a rigid form around which the Paleoproterozoic strata were molded. In the case of the Republic trough, the structure with respect to Archean rocks is a deep, narrow graben between two high-angle reverse faults. The syncline developed in the Paleoproterozoic rocks as a result of their compression between the two bounding fault uplifts. Estimates of metamorphic pressures by Hasse (1979) and Attah and Klasner (1989) indicate that the Republic area was buried beneath roughly eight kilometers of strata during Penokean deformation and was heated to temperatures of 550° to 600°C at peak metamorphic conditions, which slightly postdated the major deformation. Under those conditions the Archean granitic gneisses apparently did not deform plastically, but rather retained considerable strength so that the shape of the individual fault-bounded basement blocks controlled the geometry of structures in the overlying strata.

A final feature in this roadcut is a Mesoproterozoic diabase dike related to the Midcontinent rift and part of the Baraga dike swarm of reversed magnetic polarity dikes intruded at roughly 1.1 Ma. The dike has a chilled contact against both the granitic gneiss and metadiabase dike and is virtually unmetamorphosed.

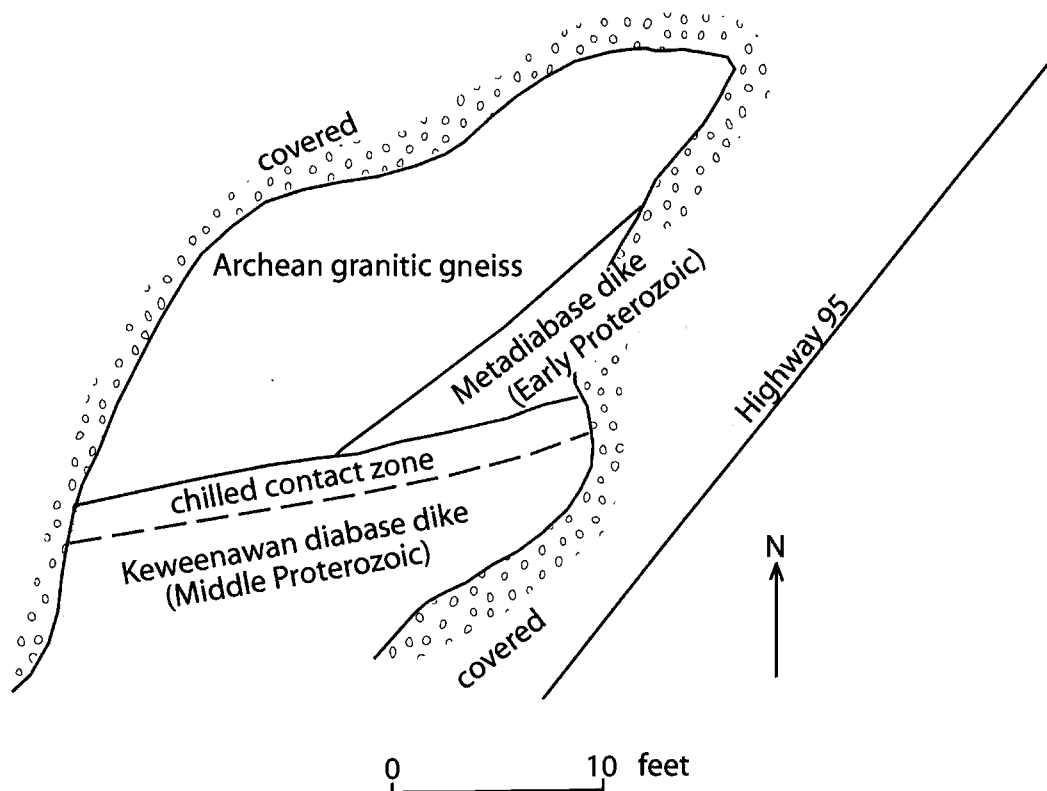


Figure 4-9. Sketch map of southern part of roadcut showing relationships between Archean granitic gneiss and diabase dikes of two different ages.

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49TH ANNUAL



**INSTITUTE ON LAKE SUPERIOR
GEOLOGY**

IRON MOUNTAIN, MICHIGAN MAY 7 – 11, 2003



**Proceedings Volume 49
PART 1 – PROGRAMS AND ABSTRACTS**



INSTITUTE ON LAKE SUPERIOR GEOLOGY

**49TH ANNUAL MEETING
MAY 7-11, 2003
IRON MOUNTAIN, MICHIGAN**

HOSTED BY:

**LAUREL G. WOODRUFF AND WILLIAM F. CANNON
Co-Chairs
U.S. GEOLOGICAL SURVEY**

With assistance from Michigan Technological University

and

John Gartner, Coleman Engineering Company

**Volume 49
Part 1 – Proceedings and Abstracts**

**Compiled and edited by Laurel Woodruff, U.S. Geological Survey and
Theodore Bornhorst, Michigan Technological University**

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49TH INSTITUTE ON LAKE SUPERIOR GEOLOGY

VOLUME 49 CONSISTS OF:

PART 1: PROGRAM AND ABSTRACTS

PART 2: FIELD TRIP GUIDEBOOK

OVERVIEW: PALEOZOIC STRATIGRAPHY AND TECTONICS ALONG
THE NIAGRA SUTURE ZONE, MICHIGAN AND WISCONSIN

TRIP 1: PEMBINE-WAUSAU MAGMATIC TERRANE

TRIP 2: MENOMINEE IRON DISTRICT

TRIP 3: STRATIGRAPHY AND STRUCTURE OF THE IRON RIVER –
CRYSTAL FALLS BASIN

TRIP 4: LIFE CYCLE OF AN IRON DEPOSIT – THE REPUBLIC MINE
FROM ORE GENESIS TO MINE RESTORATION

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Mark Jirsa (through 2003)
Minnesota Geological Survey
2642 University Avenue
St. Paul, MN 55114-1057
USA
Jirsa001@tc.umn.edu

In 2004 contact: Peter Hollings
Lakehead University
Department of Geology
Thunder Bay, ON P7B 5E1
CANADA
peter.hollings@lakeheadu.ca

ILSG website: <http://www.ilsgeology.org>

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INSTITUTES ON LAKE SUPERIOR GEOLOGY

#	YEAR	PLACE	CHAIRS
1	1955	Minneapolis, Minnesota	C.E. Dutton
2	1956	Houghton, Michigan	A.K. Snelgrove
3	1957	East Lansing, Michigan	B.T. Sandefur
4	1958	Duluth, Minnesota	R.W. Marsden
5	1959	Minneapolis, Minnesota	G.M. Schwartz & C. Craddock
6	1960	Madison, Wisconsin	E.N. Cameron
7	1961	Port Arthur, Ontario	E.G. Pye
8	1962	Houghton, Michigan	A.K. Snelgrove
9	1963	Duluth, Minnesota	H. Lepp
10	1964	Ishpeming, Michigan	A.T. Broderick
11	1965	St. Paul, Minnesota	P.K. Sims & R.K. Hogberg
12	1966	Sault Ste. Marie, Michigan	R.W. White
13	1967	East Lansing, Michigan	W.J. Hinze
14	1968	Superior, Wisconsin	A.B. Dickas
15	1969	Oshkosh, Wisconsin	G.L. LaBerge
16	1970	Thunder Bay, Ontario	M.W. Bartley & E. Mercy
17	1971	Duluth, Minnesota	D.M. Davidson
18	1972	Houghton, Michigan	J. Kalliokoski
19	1973	Madison, Wisconsin	M.E. Ostrom
20	1974	Sault Ste. Marie, Ontario	P.E. Giblin
21	1975	Marquette, Michigan	J.D. Hughes
22	1976	St. Paul, Minnesota	M. Walton
23	1977	Thunder Bay, Ontario	M.M. Kehlenbeck
24	1978	Milwaukee, Wisconsin	G. Mursky
25	1979	Duluth, Minnesota	D.M. Davidson
26	1980	Eau Claire, Wisconsin	P.E. Myers
27	1981	East Lansing, Michigan	W.C. Cambray
28	1982	International Falls, Minnesota	D.L. Southwick
29	1983	Houghton, Michigan	T.J. Bornhorst

30	1984	Wausau, Wisconsin	G.L. LaBerge
31	1985	Kenora, Ontario	C.E. Blackburn
32	1986	Wisconsin Rapids, Wisconsin	J.K. Greenberg
33	1987	Wawa, Ontario	E.D. Frey & R.P. Sage
34	1988	Marquette, Michigan	J. S. Klasner
35	1989	Duluth, Minnesota	J.C. Green
36	1990	Thunder Bay, Ontario	M.M. Kehlenbeck
37	1991	Eau Claire, Wisconsin	P.E. Myers
38	1992	Hurley, Wisconsin	A.B. Dickas
39	1993	Eveleth, Minnesota	D.L. Southwick
40	1994	Houghton, Michigan	T.J. Bornhorst
41	1995	Marathon, Ontario	M.C. Smyk
42	1996	Cable, Wisconsin	L.G. Woodruff
43	1997	Sudbury, Ontario	R.P. Sage & W. Meyer
44	1998	Minneapolis, Minnesota	J.D. Miller & M.A. Jirsa
45	1999	Marquette, Michigan	T.J. Bornhorst & R.S. Regis
46	2000	Thunder Bay, Ontario	S.A. Kissin & P. Fralick
47	2001	Madison, Wisconsin	M.G. Mudrey, Jr. & B.A. Brown
48	2002	Kenora, Ontario	P. Hinz & R.C. Beard
49	2003	Iron Mountain, Michigan	L.G. Woodruff & W.F. Cannon

CONSTITUTION OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

(Last amended by the Board—May 8, 1997)

Article I **Name**

The name of the organization shall be the "Institute on Lake Superior Geology".

Article II **Objectives**

The objectives of this organization are:

- A. To provide a means whereby geologists in the Great Lakes region may exchange ideas and scientific data.
- B. To promote better understanding of the geology of the Lake Superior region.
- C. To plan and conduct geological field trips.

Article III **Status**

No part of the income of the organization shall insure to the benefit of any member or individual. In the event of dissolution, the assets of the organization shall be distributed to _____ (some tax free organization).

(To avoid Federal and State income taxes, the organization should be not only "scientific" or "educational, but also "non-profit")

Minn. Stat. Anno. 290.01, subd. 4

Minn. Stat. Anno. 290.05(9)

1954 Internal Revenue Code s.501(c)(3)

Article IV **Membership**

The membership of the organization shall consist of persons who have registered for an annual meeting within the past three years, and those who indicate interest in being a member according to guidelines approved by the Board of Directors.

Article V **Meetings**

The organization shall meet once a year. The place and exact date of each meeting will be designated by the Board of Directors.

Article VI **Directors**

The Board of Directors shall consist of the Chair, Secretary-Treasurer, and the last three past Chairs; but if the board should at any time consist of fewer than five persons, by reason of unwillingness or inability of any of the above persons to serve as directors, the vacancies on the board may be filled by the Chair so as to bring the membership of the board to five members.

Article VII **Officers**

The officers of this organization shall be a Chair and Secretary-Treasurer.

A. The Chair shall be elected each year by the Board of Directors, who shall give due consideration to the wishes of any group that may be promoting the next annual meeting. His/her term of office as Chair will terminate at the close of the annual meeting over which he/she presides, or when his/her successor shall have been appointed. He/she will then serve for a period of three years as a member of the Board of Directors.

B. The Secretary-Treasurer shall be elected at the annual meeting. His/her term of office shall be four years, or until his/her successor shall have been appointed.

Article VIII **Amendments**

This constitution may be amended by a majority vote (majority of those voting) of the membership of the organization.

BY-LAWS OF THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

I. Duties of the Officers and Directors

- A. It shall be the duty of the Annual Chairman to:
 - 1. Preside at the annual meeting.
 - 2. Appoint all committees needed for the organization of the annual meeting.
 - 3. Assume complete responsibility for the organization and financing of the annual meeting over which he/she presides.
- B. It shall be the duty of the Secretary-Treasurer to:
 - 1. Keep accurate attendance records of all annual meetings.
 - 2. Keep accurate records of all meetings of, and correspondence between, the Board of Directors.
 - 3. Hold all funds that may accrue as profits from annual meetings or field trips and to make these funds available for the organization and operation of future meetings as required.
- C. It shall be the duty of the Board of Directors to plan locations of annual meetings and to advise on the organization and financing of all meetings.

II. Duties and Expenses

- A. Regular membership dues of \$5.00 or less on an annual basis shall be assessed each member as determined by the Board of Directors..
- B. Registration fees for the annual meetings shall be determined by the Chair in consultation with the Board of Directors. The registration fees can include expenses to cover operations outside of the annual meeting as determined by the Board of Directors. It is strongly recommended that registration fees be kept at a minimum to encourage attendance of students.

III. Rules of Order

The rules contained in Robert's Rules of Order shall govern this organization in all cases to which they are applicable.

IV. Amendments

These by-laws may be amended by a majority vote (majority of those voting) of the membership of the organization; provided that such modifications shall not conflict with the constitution as presently adopted or subsequently amended.

Last Amended – May, 1996

MEMBERSHIP CRITERIA FOR THE INSTITUTE ON LAKE SUPERIOR GEOLOGY

Approved May 8, 1997

A. Membership in the Institute on Lake Superior Geology requires either participation in Institute activities, or an indication on a regular basis of interest in the Institute. Those individuals registering for an annual meeting will remain as members for 4 years unless: 1) they indicate no further interest in the Institute by responding negatively to the statement on meeting circulars "Remove my name from the mailing list"; or 2) two successive mailings in different years are returned by the postal service as address unknown.

B. Those individuals who have not registered for an annual meeting in the past 4 years must indicate an interest in the Institute by postal, electronic, or verbal correspondence with the Secretary-Treasurer at least once every two years. Such individuals will be removed from the membership if they indicate no further interest in the Institute or two successive mailing in different years are returned by the postal service as address unknown.

C. The Secretary-Treasurer will maintain a list of current members. The list will include the date of the beginning of continuous membership, dates of returned mail, dates of last contact (expression of interest), and the date membership expires, barring a change of status initiated by the member. Those individuals who have become members of ILSG by Section B will have an expiration date listed at 2 years from the upcoming meeting. For example, a member who expresses interest in September of 1997 (the next annual meeting is May, 1998) will have an expiration date of May, 2000, unless the member contacts the Secretary-Treasurer or attends an annual meeting.

D. "Member for Life" status is granted to individuals who have been (nearly) continuous participants of the ILSG meetings for 15 years, Goldich Medal recipients, or those who have served as meeting chairs. This status will be further maintained unless the individuals indicate no further interest in the Institute, or 4 mailings in different years are returned by the postal service as address unknown, or they are deceased.

E. All members will be mailed the First Circular for the Annual Meeting and the ILSG Newsletter. The Chair of the annual meeting may opt to send the first circular to additional individuals. All returned mail should be reported to the Secretary-Treasurer.

F. The Secretary-Treasurer can designate any individual who is on the ILSG membership list (mailing list) as of January 1, 1997 as a member for life based on participation in ILSG activities.

G. Members are strongly encouraged to send address corrections to the Secretary-Treasurer to avoid unintentional lapse of membership.

GOLDICH MEDAL GUIDELINES

(Adopted by the Board of Directors, 1981; amended 1999)

Preamble

The Institute on Lake Superior Geology was born in 1955, as documented by the fact that the 27th annual meeting was held in 1981. The Institute's continuing objectives are to deal with those aspects of geology that are related geographically to Lake Superior; to encourage the discussion of subjects and sponsoring field trips that will bring together geologists from academia, government surveys, and industry; and to maintain an informal but highly effective mode of operation.

During the course of its existence, the membership of the Institute (that is, those geologists who indicate an interest in the objectives of the ILSG by attending) has become aware of the fact that certain of their colleagues have made particularly noteworthy and meritorious contributions to the understanding of Lake Superior geology and mineral deposits.

The first award was made by ILSG to Sam Goldich in 1979 for his many contributions to the geology of the region extending over about 50 years. Subsequent medallists and this year's recipient are listed in the table below.

Award Guidelines

- 1) The medal shall be awarded annually by the ILSG Board of Directors to a geologist whose name is associated with a substantial interest in, and contribution to, the geology of the Lake Superior region.
- 2) The Board of Directors shall appoint the Goldich Medal Committee. The initial appointment will be of three members, one to serve for three years, one for two years, and one for one year. The member with the briefest incumbency shall be chair of the Nominating Committee. After the first year, the Board of Directors shall appoint at each spring meeting one new member who will serve for three years. In his/her third year this member shall be the chair. The Committee membership should reflect the main fields of interest and geographic distribution of ILSG membership. The outgoing, senior member of the Board of Directors shall act as liaison between the Board and the Committee for a period of one year.
- 3) By the end of November, the Goldich Medal Committee shall make its recommendation to the Chair of the Board of Directors, who will then inform the Board of the nominee.
- 4) The Board of Directors normally will accept the nominee of the Committee, inform the medallist, and have one medal engraved appropriately for presentation at the next meeting of the Institute.
- 5) It is recommended that the Institute set aside annually from whatever sources, such funds as will be required to support the continuing costs of this award.

Nominating Procedures

- 1) The deadline for nominations is November 1. The Goldich Medal Committee shall take nominations at any time. Committee members may themselves nominate candidates; however, Board members may not solicit for or support individual nominees.
- 2) Nominations must be in writing and supported by appropriate documentation such as letters of recommendation, lists of publications, curriculum vita's, and evidence of contributions to Lake Superior geology and to the Institute.
- 3) Nominations are not restricted to Institute attendees, but are open to anyone who has worked on and contributed to the understanding of Lake Superior geology.

Selection Guidelines

- 1) Nominees are to be evaluated on the basis of their contributions to Lake Superior geology (*sensu lato*) including:
 - a) importance of relevant publications;
 - b) promotion of discovery and utilization of natural resources;
 - c) contributions to understanding of the natural history and environment of the region;
 - d) generation of new ideas and concepts; and
 - e) contributions to the training and education of geoscientists and the public.
 - 2) Nominees are to be evaluated on their contributions to the Institute as demonstrated by attendance at Institute meetings, presentation of talks and posters, and service on Institute boards, committees, and field trips.
 - 3) The relative weights given to each of the foregoing criteria must remain flexible and at the discretion of the Committee members.
 - 4) There are several points to be considered by the Goldich Medal Committee:
 - a) An attempt should be made to maintain a balance of medal recipients from each of the three estates—industry, academia, and government.
 - b) It must be noted that industry geoscientists are at a disadvantage in that much of their work is not published.
 - 5) Lake Superior has two sides, one the U.S., and the other Canada. This is undoubtedly one of the Institute's great strengths and should be nurtured by equitable recognition of excellence in both countries.
-

GOLDICH MEDAL COMMITTEE

Serving through the meeting year shown in parentheses

Frank Luther (2003)

University of Wisconsin, Whitewater

Ron Sage (2004)

Ontario Geological Survey (retired)

David Meineke (2005)

Meriden Engineering, Hibbing, Minnesota

Steve Kissin, as out-going senior member of Institute Board of Directors, is liaison between Goldich Medal Committee and the Board through the 2004 meeting

2003 GOLDICH MEDAL RECIPIENT

Klaus J. Schulz

U.S. Geological Survey
Reston, Virginia

GOLDICH MEDALISTS

1979 Samuel S. Goldich

1980 *not awarded*

1981 Carl E. Dutton, Jr.

1982 Ralph W. Marsden

1983 Burton Boyum

1984 Richard W. Ojakangas

1985 Paul K. Sims

1986 G.B. Morey

1987 Henry H. Halls

1988 Walter S. White

1989 Jorma Kalliokoski

1990 Kenneth C. Card

1991 William Hinze

1992 William F. Cannon

1993 Donald W. Davis

1994 Cedric Iverson

1995 Gene LaBerge

1996 David L. Southwick

1997 Ronald P. Sage

1998 Zell Peterman

1999 Tsu-Ming Han

2000 John C. Green

2001 John S. Klasner

2002 Ernest K. Lehmann

CITATION

Klaus J. Schulz 2003 Goldich Medal Recipient

Klaus Schulz has had a long and productive career spanning more than 30 years as a geologist in the Lake Superior region. He was introduced to the geology through his education in the area, he completed graduate studies in the region, performed several summers of field work for mining companies in a number of different areas, and has conducted extensive research as a scientist with the U.S. Geological Survey. This extensive and diverse experience has made him a real authority on the geology of the Lake Superior region.

Klaus received his B.S. degree in geology from the University of Wisconsin-Oshkosh in 1971. He completed his Masters degree at the University of Minnesota-Duluth in 1974, with a thesis project in the Vermilion district of northern Minnesota. He received his Ph.D. from the University of Minnesota in 1977 with a dissertation on the petrology of volcanic rocks in the Vermilion district. Klaus spent the next two years as a National Research Council Research Associate with NASA at the Johnson Space Center in Houston, where he studied Archean basaltic and ultramafic magma types as analogs of early planetary crust. In 1982, after three years as a faculty member at Washington University in St. Louis, Klaus resigned his teaching position and joined the U.S. Geological Survey in Reston, VA, fulfilling a long-standing dream of his. During the next twenty years with the USGS Klaus was a research scientist and administrator with a strong interest in the geology of the Lake Superior region.

The traits that have made Klaus a success were evident early in his career. In his undergraduate days at Oshkosh, Klaus distinguished himself as an avid reader of the geological literature. As a junior in 1970, he wrote an outstanding research paper discussing the similarities between Archean greenstone belts and modern island arcs. He worked several summers doing fieldwork for Bear Creek Mining Company in central Wisconsin and northern Michigan, and for U.S. Steel Corp. in the Vermilion district of northern Minnesota. This combination of field work and a thorough knowledge of the literature has continued to be a hallmark of his professional career, and has led to a number of significant contributions to the geology of the Lake Superior region.

In the summer of 1971, Klaus and William Spence discovered the Lake Ellen kimberlite near Crystal Falls, Michigan, while working as exploration geologists in the area. Klaus was very much involved in the recognition of the rock as a kimberlite. This was the first kimberlite discovered in the Lake Superior region.

His Masters thesis involved considerable mapping in the Ely greenstone belt in Minnesota, and geochemical studies for his Ph.D. dissertation showed that the Newton Lake Formation was a high-magnesium basalt, similar to komatiites. This was the first documented occurrence of komatiitic rocks in the Lake Superior region.

In the early 1980's, his field mapping and geochemistry of rocks in the Pembine area of the Wisconsin magmatic terranes demonstrated the presence of ophiolitic rocks. Again, this was the first documented ophiolite in the Lake Superior region, and showed that the Wisconsin magmatic terranes were, at least in part, an oceanic island arc. His subsequent model for the evolution of the Marquette Range Supergroup on the continental margin during the Penokean orogeny is an extension of his familiarity with the rocks in the region combined with his encyclopedic knowledge of the geologic literature on the evolution of continental margins.

Klaus also contributed to the GLIMPCE program, which ultimately provided significant insight into the structure and origin of the Mid-continent rift, and into its magmatic origin and metallogeny.

He has authored and co-authored more than 120 publications, maps, abstracts and field guides, including field guides for the 1984, 1992, and 2003 Institute meetings.

Klaus' contributions have provided a better understanding of the Archean, the Early Proterozoic, the Middle Proterozoic, and the Phanerozoic history of the Lake Superior region. And he continues to be an active contributor on a global stage, taking the knowledge and experience that he has gained in the Lake Superior region and applying it to international projects.

Therefore, it is my distinct pleasure and honor to present Klaus Juergen Schulz as the 2003 recipient of the Goldich Medal "For Outstanding Contributions To The Lake Superior Region".

Submitted by Gene L. LaBerge

EISENBREY STUDENT TRAVEL AWARDS

The 1986 Board of Directors established the ILSG Student Travel Awards to support student participation at the annual meeting of the Institute. The name "Eisenbrey" was added to the award in 1998 to honor Edward H. Eisenbrey (1926-1985) and utilize substantial contributions made to the 1996 Institute meeting in his name. "Ned" Eisenbrey is credited with discovery of significant volcanogenic massive sulfide deposits in Wisconsin, but his scope was much broader—he has been described as having unique talents as an ore finder, geologist, and teacher. These awards are intended to help defray some of the direct travel costs of attending Institute meetings, and include a waiver of registration fees, but exclude expenses for meals, lodging, and field trip registration. The annual Chair in consultation with the Secretary-Treasurer determines the number of awards and value. Recipients will be announced at the annual banquet.

The annual Chair, who is responsible for the selection, will consider the following general criteria:

- 1) The applicants must have active resident (undergraduate or graduate) student status at the time of the annual meeting of the Institute, certified by the department head.
- 2) Students who are the senior author on either an oral or poster paper will be given favored consideration.
- 3) It is desirable for two or more students to jointly request travel assistance.
- 4) In general, priority will be given to those in the Institute region who are farthest away from the meeting location.
- 5) Each travel award request shall be made in writing to the annual Chair, and should explain need, student and author status, and other significant details. The form below is optional. Successful applicants will receive their awards during the meeting.

INSTITUTE ON LAKE SUPERIOR GEOLOGY



Eisenbrey Student Travel Award Application

Student Name: _____ Date: _____

Address: _____

email: _____

Department Head-Typed

Educational Status: _____

Department Head-Signature

Are you the senior author of an oral or poster paper? YES _____ NO _____

Will any other students be traveling with you?

Who? _____

Statement of need (use additional page if necessary)

Please return to:

STUDENT PAPER AWARDS

Each year, the Institute selects the best of the student presentations and honors presenters with a monetary award. Funding for the award is generated from registrations of the annual meeting. The Student Paper Committee is appointed by the annual meeting Chair in such a manner as to represent a broad range of professional and geologic expertise. Criteria for best student paper—last modified by the Board in 2001—follow:

- 1) The contribution must be demonstrably the work of the student.
- 2) The student must present the contribution in-person.
- 3) The Student Paper Committee shall decide how many awards to grant, and whether or not to give separate awards for poster vs. oral presentations.
- 4) In cases of multiple student authors, the award will be made to the senior author, or the award will be shared equally by all authors of the contribution.
- 5) The total amount of the awards is left to the discretion of the meeting Chair and Secretary-Treasurer, but typically is in the amount of about \$500 US (increase approved by Board, 10/01).
- 6) The Secretary-Treasurer maintains, and will supply to the Committee, a form for the numerical ranking of presentations. This form was created and modified by Student Paper Committees over several years in an effort to reduce the difficulties that may arise from selection by raters of diverse background. The use of the form is not required, but is left to the discretion of the Committee.
- 7) The names of award recipients shall be included as part of the annual Chair's report that appears in the next volume of the Institute.

Student papers will be noted on the Program.

2003 STUDENT PAPER AWARDS COMMITTEE

Theodore Bornhorst - Michigan Technological University, Houghton, MI -- Chair

Kevin Sikkila – Wisconsin Department of Transportation, Superior, WI

Anne Argast – Indiana University – Purdue University Fort Wayne, Fort Wayne, IN

Tim Flood – St. Norbert College, De Pere, WI

2003 SESSION CHAIRS

Peter Hinz – Ontario Geological Survey, Kenora, ON

Eric Jerde - Morehead State University, Morehead, KY

James Miller - Minnesota Geological Survey, Duluth, MN

Mike Mudrey, Jr. – Wisconsin Geological and Natural History Survey, Madison, WI

2003 BOARD OF DIRECTORS

Board appointment continues through the close of the meeting year shown in parentheses, or until a successor is selected

Laurel Woodruff Co-Chair 2003 meeting (2006)

U.S. Geological Survey, St. Paul, MN

Peter Hinz (2005)

Ontario Geological Survey, Kenora, ON

Michael G. Mudrey, Jr. (2004)

Wisconsin Geological and Natural History Survey, Madison, WI

Stephen A. Kissin (2003)

Lakehead University, Thunder Bay, ON

Peter Hollings-Secretary-Treasurer (2006)

Lakehead University, Thunder Bay, ON

Mark A. Jirsa-Secretary-Treasurer-“emeritus” (in transition)

Minnesota Geological Survey, St. Paul, MN

2003 LOCAL COMMITTEES

General Co-Chairs

Laurel G. Woodruff – U.S. Geological Survey, St. Paul, MN

William F. Cannon – U.S. Geological Survey, Reston, VA

Program and Abstracts Editors

Laurel G. Woodruff -- U.S. Geological Survey, St. Paul, MN

Theodore J. Bornhorst – Michigan Technological University, Houghton, MI

Field Trip Guidebook Editor

William F. Cannon – U.S. Geological Survey, Reston, VA

Acting Local Committee, Iron Mountain

John Gartner – Coleman Engineering, Iron Mountain, MI

Connie Dicken – U.S. Geological Survey, Reston, VA

Sally LaBerge – Oshkosh, WI

2003 BANQUET SPEAKER

Susan Martin

Department of Social Sciences
Michigan Technological University
Houghton, Michigan

**The indigenous people of the Lake Superior Basin: Understanding the links
among environment, geology and religious belief**

Report of the Chair of the 48TH Annual Meeting

Peter Hinz, Co-Chair ILSG 2002

The 48th Annual Institute on Lake Superior Geology was hosted by the Ontario Geological Survey on May 9-12, 2001. Principal local committee members were Peter Hinz and Richard C. Beard, co-chairs, Carmen C. Storey, and Kevin O'Flaherty Program co-chairs, Charles E. Blackburn, Field Trip Co-ordinator, M. Kathleen McGowan-Hinz, Treasurer, and Christine C. Blackburn, Secretary. Other principal individuals are listed in the Proceedings Volume.

Attendance at ILSG 2001

A total of 97 professionals and student professionals attended the meeting, 39 of whom pre-registered by the April 2, 2001 deadline. A total of 8 students were registered, 7 of whom requested and received travel assistance.

Eisenbrey Student Travel Awards 2001

Seven students requested and received travel assistance from the Eisenbrey Student Travel Award Fund established to support student participation at the Annual Institute. Details, including criteria and application forms, are available at the ILSG website.

Bogdan Nitescu	University of Toronto, Toronto, ON
Claire Sturm	Oberlin College, Oberlin, OH
Elizabeth Fein	Oberlin College, Oberlin, OH
Justin Johnson	Lakehead University, Thunder Bay, ON
Becky Rogala	Lakehead University, Thunder Bay, ON
William Jahn	University of Minnesota - Duluth, Duluth, MN
Daniela Vallini	University of Western Australia, Nedlands, WA

Meeting Summary

The 48th Annual Institute on Lake Superior Geology Annual Meeting was held at the Best Western Lakeside Inn and Convention Centre, the same location as the 1985 meeting. The one-and-a-half days of technical sessions were preceded by: Field Trip 1 – Tanco Rare-Element Pegmatite, Southeastern Manitoba led by staff of the Tantalum Mining Corporation of Canada Ltd.; followed by Field Trip 2 – Quaternary Geology of Southeastern Manitoba led by E. Nielsen and Gaywood Matile (Manitoba Geological Survey); and Field Trip 3- Structure and Sedimentology of the Seine Conglomerate, Mine Centre Area, Ontario lead by Dyanna Czeck (Department of Geology, Oberlin College) and Philip Fralick (Department of Geology, Lakehead University)

Due to the small number of talks submitted, the Technical Session Chairs were unable to group talks into session themes. The meeting began with an anecdotal history of mining in northwestern Ontario presented by Kevin O'Flaherty, followed by regional scale talks on the Western Superior Province. The remainder of the technical sessions included a broad range of talks focusing on ground water, petrography, sedimentology, mineralogy and structural topics. The final session ended at noon, allowing for an early departure of Field Trip 6 to Red Lake. Post meeting trips included: Field Trip 4 – Industrial Minerals and Paleozoic Geology of Southeastern Manitoba; Field Trip 5 – Separation Rapids Rare-Element Pegmatite Field, Ontario; and Field Trip 6 – Geology of the Red Lake Camp. All field trips ran smoothly considering the frigid conditions of early May in northwestern Ontario. ILSG Secretary -Treasurer, Mark Jirsa was the lone participant of Field Trip 6 successful in obtaining samples from Goldcorp's Red Lake Mine in Red Lake. He was able to do this by cunningly embedding the samples in the back of his neck. Upon returning to Kenora the samples were proudly displayed in a baggy kindly supplied by the staff of Red Lake's Margaret Cochenour Memorial Hospital emergency room.

Annual Banquet and Goldich Award

At the Annual Banquet Ted DeMatties presented the citation for Ernest K. Lehmann, recipient of the Goldich Medal for 2002 for his contributions to the Institute and Lake Superior Geology. L. Harvey Thorliefson, Geological Survey of Canada, provided a scintillating discussion on The Search for Diamonds in Canada for the after dinner address. Laurel Woodruff and Bill Cannon of the U.S. Geological Survey invited participants to the 49th Annual Meeting in Iron Mountain, Michigan.

2002 Best Student Paper Awards

- 1) Becky Rogala - Lakehead University, Thunder Bay, Ontario (\$400, oral presentation)
New information from the Sibley Group
- 2) Elizabeth Fein - Oberlin College, Oberlin, Ohio (\$50, poster; Co-authors C.L. Sturm and D.M. Czeck) *Anisotropy of magnetic susceptibility in the Ottetail pluton, Northern Ontario*
- 3) Claire Sturm - Oberlin College, Ohio (\$50, oral; Co-authors D.M. Czeck and E. Fein)
Petrographic study of the Ottetail pluton, Superior Province, Northwestern Ontario

2002 Eisenbrey Student Travel Awards

- 1) Bogdan Nitescu - University of Toronto, Toronto, ON (\$250)
- 2) Claire Sturm - Oberlin College, Oberlin, Ohio (\$200)
- 3) Elizabeth Fein - Oberlin College, Oberlin, Ohio (\$200)
- 4) Justin Johnson - Lakehead University, Thunder Bay, ON (\$150)
- 5) Becky Rogala - Lakehead University, Thunder Bay, ON (\$150)
- 6) William Jahn - University of Minnesota, Duluth, MN (\$150)
- 7) Daniela Vallini - University of Western Australia, Nedlands, WA (\$400)

2002 Goldich Medal Recipient

Ernest K. Lehmann

MTU Archives Donation

A check for \$100 was sent to Michigan Technological University Archives, as required by Board agreement (\$1 per participant per meeting), for maintenance of ILSG proceedings archives.

Proceedings including Part 1 (Programs and Abstracts) and Part 2 (Field Trip Guidebook) are available from the Institute:

Institute on Lake Superior Geology
c/o Mark Jirsa, Secretary - Treasurer
Minnesota Geological Survey
2642 University Avenue
St. Paul MN 55114-1057
Phone: 612.627.4539 Fax: 612.627.4778
e-mail: jirsa001@tc.umn.edu

48th ANNUAL INSTITUTE ON LAKE SUPERIOR GEOLOGY BOARD OF DIRECTOR'S MEETING

Board of Directors

Peter Hinz (2002 General Chair)
Michael Mudrey (2001 Co-chair)
Steve Kissin (2000 Co-chair)
Laurel Woodruff: Proxy for Ted Bornhorst (1999 Co-chair and liaison with Goldich committee)
Mark Jirsa (Institute Secretary-Treasurer)

Guests

Phil Fralick (2000 Co-chair)
Carmen Storey (2003 Program Chair)
Kevin O'Flaherty (2003 Program Chair)
Bill Cannon (proposed 2003 Co-chairs)
Rod Johnson (Goldich Committee)
Frank Luther (Goldich Committee)

The following is based on the secretaries' notes and recollection; any omissions or misstatements are unintentional. Motions by the Board of Directors are generally paraphrased—"approved" or "accepted" implying that a motion was made, seconded, and passed unanimously. The expression "generally agreed" carries less formality, but indicates a directive that will be pursued. Some issues that were resolved after the Board meeting, but during the conference are included here for closure.

MINUTES

1. Accepted report of the Chairs for the 47th ILSG, Madison, Wisconsin; as printed in the Proceeding Volume (Mudrey), and minutes of last Board meeting, May 10, 2001 (Jirsa)
2. Received, discussed, and accepted 2001-2002 ILSG Financial Summary (Jirsa).
3. Discussed and approved 2003 (49th annual) meeting location—Iron Mountain, Michigan, and tentative co-chairs Laurel Woodruff and Bill Cannon, USGS. As currently envisioned, Ted Bornhorst will handle logistics of field trips.
4. Approved Peter Hinz as on-going ILSG Board member.
5. Discussed replacing Rod Johnson as the "member from industry" on Goldich Committee (end of term 2002) with several candidates including Dave Meineke of Meriden Engineering, Hibbing, Minnesota. Dave later accepted the position and was welcomed, and Rod was thanked for his service to the Institute, during the annual banquet. Dave's term will end after Goldich selection for the meeting of 2005.
6. Discussed replacement of Mark Jirsa as ILSG Secretary-Treasurer (end of 4-year term 2002). A new member to the Institute, Peter Hollings, Lakehead University in Thunder Bay, was installed as "Secretary-Treasurer in-training," pending a vote by the general membership (as required in By-Laws). Because of his newness to the Institute, the board generally agreed that Peter would serve 2 years of the 4-year term concurrently with Mark in a period of transition. At the end of the 2 years (following the 2004 meeting), the finances and records of the institute, and responsibilities of the position would fall to Peter.

This was presented to the membership after the Board meeting, and was generally accepted.

7. Other business:

- a) Discussed the offer by Mike Mudrey to take over as ILSG webmaster—It was generally agreed that Mike could do that, assuming Ted was busy with other obligations and probably would not mind the relief. Subsequent discussions indicate

that Ted would like to continue in this endeavor, and has already paid in advance for 5 years of web service to continue. It remains in Ted's hands.

b) Discussed efforts by Graham Wilson to list ILSG publications as part of his MINLIB project and website (www.turnstone.ca) —Steve Kissin volunteered to contact Graham and see if there is anything that the ILSG can and should do to assist.

c) Discussed the prospect of extending a “free ride” to annual Goldich Medal recipients. It was generally agreed that registration costs should be paid by the annual meeting committee, and that lodging, meals, and travel costs could be paid, at the discretion of the annual meeting chairs.

d) Discussed the ILSG Newsletter—Peter Hinz has offered to write it beginning in 2004 or so. He can coordinate with Ted Bornhorst about that transition. The topic of whether the Newsletter should remain paper, or be changed to a wholly electronic format was discussed and tabled. Most seemed to think we should eventually switch to a web-based newsletter, perhaps with email notification. This raised a further issue that members must be encouraged to notify the secretary-treasurer of changes in email address or other status.

e) Questionable sampling—An issue was raised that at least one group of regular meeting participants has a tradition of using guidebooks to locate places for massive sampling programs. In this one case, samples are sold to Wards or other rock and mineral specimen dealers. The problems are 1) some of the localities discussed in guidebooks are on private land (and therefore trespassing is likely), and 2) taking large amounts of sample from some localities limits the use of these sites to future generations. It was generally agreed that ILSG would print in their guidebooks a Policy Statement that warns of this “questionable sampling practice.” Mark Jirsa will create such language for inclusion in future guidebooks.

f) Discussed digital submission of abstracts—Peter Hinz warns from experience that this practice can easily turn into a nightmare for preparers, particularly if the submitters don't follow (or the host organization doesn't specify) rigid guidelines for submission formats. This includes both text and illustration formats. **Adjournment**

Respectfully submitted on January 27, 2003 to Peter Hinz, Chair of the 48th annual meeting, for incorporation into the Report of the Chair to appear in Proceedings Volume 49.

Mark Jirsa, Secretary-Treasurer, Institute on Lake Superior Geology



PROGRAM



The following companies made generous contributions to the 49th Annual Meeting. We thank them and John Gartner of the Local Committee for their commitment to the Institute on Lake Superior Geology. For almost 50 years this organization has thrived through the sustained interests of individuals, corporations, universities, and government agencies in the international geologic community. This dedication to an exchange of scientific ideas and a passion for field trips (even in driving rain or snow) has enabled the ILSG to fulfill one of its primary objectives: to promote better understanding of the geology in the Lake Superior region.

Kleiman Pump & Well Drilling, Inc.
P.O. Box 704
Iron Mountain, Michigan 49801-0704

Prime Meridian Resources Ltd.
N7478 Niagara Lane
Fond du Lac, WI 54935

Coleman Engineering Company
635 Circle Drive
Iron Mountain, MI 49801

WEDNESDAY MAY 7, 2003

8:00 a.m. FIELD TRIP 1: WISCONSIN MAGMATIC TERRANE (#1 IN GUIDEBOOK)

Klaus Schulz, *U.S. Geological Survey*

Gene LaBerge, *University of Wisconsin – Oshkosh, emeritus*

8:00 a.m. FIELD TRIP 2: THE REPUBLIC MINE – LIFE CYCLE OF AN IRON ORE DEPOSIT FROM GENESIS TO RECLAMATION (#4 IN GUIDEBOOK)

William Cannon, *U.S. Geological Survey*

John Meier, *Cleveland Cliffs Iron Company*

6:00 p.m. Return of Trips 1 and 2

4:00 p.m. - 8:00 p.m. Registration

7:00 p.m. - 9:00 p.m. Ice Breaker Social and Poster Setup

THURSDAY MAY 8, 2003

8:00 a.m. - 9:00 a.m. REGISTRATION

Note: Technical Sessions are in White Spruce, Pine Mountain Resort

♦ Denotes Student Presentation

8:15 a.m. INTRODUCTORY REMARKS

Laurel G. Woodruff and William F. Cannon, Co-Chairs

TECHNICAL SESSION I

Session Chair: Jim Miller, Minnesota Geological Survey, Duluth, MN

8:30 a.m. Harold Bernhardt - Menominee Range Historical Foundation Museum

A brief history of iron mining on the Upper Peninsula's Menominee Iron Range

9:00 a.m. Cannon, W.F., LaBerge, G.L. and Klasner, J.S.

Niagara suture zone, northern Michigan and Wisconsin—tectonics in the 1.85 Ma arc-continent collisional boundary

9:30 a.m. Schulz, K.

A Paleoproterozoic suprasubduction zone ophiolite-island arc complex in northeastern Wisconsin

10:00 a.m. COFFEE BREAK AND POSTER SESSION

10:40 a.m. Schneider, D.A., Holm, D.K., O'Boyle, C., Hamilton, M. and Jercinovic, M.

Paleoproterozoic development of a gneiss dome corridor in the southern Lake Superior region, USA

11:00 a.m. Holm, D.K., Van Schmus, W.R., MacNeill, L.C., Boerboom, T.J., Schweitzer, D. and Schneider, D.A.

Late Paleoproterozoic (1900-1600 Ma) tectonic history of the northern mid-continent, U.S.A.: Implications for crustal stabilization

11:20 a.m. Medaris, L.G., Jr. and Dott, R.H., Jr.

The Sioux Quartzite revisited: sedimentology, metamorphism, geochemistry and the origin of pipestone

11:40 p.m. Smyk, M.C.

The Lake Nipigon Geoscience Initiative – planned activities and objectives

12:00 p.m. **Lunch Break – Poster Session and ILSG Board Meeting** (by invitation)

TECHNICAL SESSION II

Session Chair: Mike Mudrey, Jr., Wisconsin Geological Survey, Madison, WI

1:30 p.m. ♦ **Heggie, G. and Hollings, P.**

Geochemistry and mineralization of the Seagull Intrusion, Northern Ontario

1:50 p.m. ♦ **Johnson, J.R., Hollings, P. and Kissin, S.A.**

Mineralization of the Norton Lake Cu-Ni-PGE deposit

2:10 p.m. **Miller, J. D., Jr.**

Petrology and PGE potential of the Greenwood Lake Intrusion, central Duluth Complex, Lake County, Minnesota

2:30 p.m. ♦ **Joslin, G.D., Miller, J.D., Jr. and Rowell, W.F.**

Stratiform Pd-Pt-Au mineralization in the Sonju Lake Intrusion, Lake County, Minnesota

2:50 p.m. ♦ **Marma, J., Brown, P. and Hauck, S.**

Magmatic and hydrothermal PGE mineralization of the Birch Lake Cu-Ni-PGE Deposit in the South Kawishiwi, Duluth Complex, northeast Minnesota

3:10 p.m. **COFFEE BREAK AND POSTER SESSION**

3:30 p.m. **Waggoner, T.**

A hydrothermal component of Iron Formations –A Marquette Range perspective

3:50 p.m. **Tsu-Ming Han**

Mode of occurrence of trona and thermonatrite and their possible origin in the Negaunee Iron-Formation of the Marquette Range, Lake Superior District, USA

4:10 p.m. **Blaske, A.R.**

Geology of the Mississippi-Valley type mineralization at Bellevue, Michigan

4:20 p.m. ♦ **Larson, P.**

Mean transport length in tills of the southern portion of the Laurentide ice sheet: implications for drift exploration in the Lake Superior region

4:50 p.m. ♦ **Marlow, L., Mooers, H. and Larson, P.**

Glacial Lakes Aitkin and Upham: their origin and environmental history

5:10 p.m. **Trow, J.**

Five gold possibilities in some Keweenawan copper sulfides in Ontario and Michigan

6:00 p.m. **ICE BREAKER – MIXER – CASH BAR**

7:00 p.m. **ANNUAL BANQUET AND AWARD PRESENTATION**

- **Announcement of 50th Annual Meeting Location**
- **2003 Goldich Award Presentation to Klaus Schulz**
- **2003 Banquet Address**
Dr. Susan Martin, Michigan Technological University
The indigenous people of the Lake Superior Basin:
Understanding the links among environment, geology
and religious belief

Meeting participants who are not registered for the banquet are welcome to the banquet address

FRIDAY MAY 9, 2003

TECHNICAL SESSION III

Session Chair: Eric Jerde, Morehead State University, Morehead, Kentucky

8:20 a.m. **INTRODUCTORY REMARKS**

Laurel G. Woodruff and William F. Cannon, Co-chairs

8:30 a.m. **Hollings, P., Fralick, P. and Kissin, S.**

Geochemistry and geodynamic implications of the 1537 Ma Redstone Point anorogenic granite, Ontario, Canada

8:50 a.m. ♦ **Buttram, R.M. and Bjornerud, M.**

Textural constraints on the origin of rapakivi textures in the Wolf River Batholith

9:10 a.m. ♦ **Sandin, N.A. and Bornhorst, T.J.**

Sequence of Precambrian mafic dikes in Marquette County, Michigan, with emphasis on the Sugarloaf Mountain and Republic areas

9:30 a.m. **Jerde, E.A.**

Gabbro/granophyre relations of the Crocodile Lake Intrusion: a possible vent for the Hovland Lavas?

9:50 a.m. ♦ **Vislova, T.**

Evaluation of initial magma compositions for the Bald Eagle Intrusion and associated rocks

10:10 a.m. **COFFEE BREAK AND POSTER SESSION**

10:30 a.m. ♦ **Charkoudian, K., Tikoff, B. and Bauer, R.**

Stike-slip separation of the Burntside trondhjemite and the Wakemup Bay tonatlite, Northern Minnesota

10:50 a.m. ♦ **Garbowicz, A. and Bjornerud, M.**

Paleostress inferences from slip vectors in the eastern part of the Wisconsin segment of the Midcontinent rift

11:10 a.m. ♦ **Potter, E.G. and Mitchell, R.H.**

The rare and exotic mineralogy of the Western Subcomplex of the Deadhorse Creek Diatreme, Northwestern Ontario

11:30 a.m. **Brown, B.A., Mudrey, M.G., Jr., Czechanski, M.L., Reid, D.D. and Hunt, T.C.**
Highway construction, mine reclamation, and land-use planning challenges in the historic Upper Mississippi Valley lead-zinc district of southwest Wisconsin

11:50 a.m. **Wattrus, N.**
High-resolution multibeam bathymetry in Lake Superior

12:10 p.m. **LUNCH BREAK – POSTERS REMOVED AFTER LUNCH**

TECHNICAL SESSION IV

Session Chair: Peter Hinz, Ontario Geological Survey, Kenora, ON

1:40 a.m. ♦ **Vallini, D.A., McNaughton, N.J., Rasmussen, B., Fletcher, I. and Griffin, B.J.**
Using xenotime U-Pb geochronology to unravel the history of Proterozoic sedimentary basins: a study in Western Australia and the Lake Superior region

2:00 p.m. **Kissin, S.A., Vallini, D.A., Addison, W.D. and Brumpton, G.R.**
New zircon ages from the Gunflint and Rove Formations, northwestern Ontario

2:20 p.m. ♦ **Richardson, A., Fralick, P. and Hollings, P.**
Sibley Basin sediment provenance using zircon and whole rock geochemical methods: Possible source areas of the Pass Lake Formation

2:40 p.m. ♦ **Rogala, B., Fralick, P. and Borradaile, G.**
A magnetostratigraphic and secular variation study of the Sibley Group

3:00 p.m. **COFFEE BREAK**

3:20 p.m. **Argast, A.**
What does sediment chemistry tell us about rocks like those from the Fern Creek Formation?

3:40 p.m. **Bartnik, P. J. and Evans, B. W.**
Geology and hydrogeology in the Kingsford, Michigan area

4:00 p.m. **Presentation of Student Paper Awards**
Ted Bornhorst, Michigan Technological University: Student Paper Committee

SATURDAY MAY 10, 2003

8:00 a.m. **FIELD TRIP 3: MENOMINEE IRON RANGE (#2 IN GUIDEBOOK)**
Gene LaBerge, *University of Wisconsin – Oshkosh, emeritus*
John Klasner, *University of Western Illinois, emeritus*
William Cannon, *U.S. Geological Survey*

6:00 p.m. **Return of Trip 3**

SUNDAY MAY 11, 2003

8:00 a.m. **FIELD TRIP 4: Iron River – Crystal Falls Iron District (#3 IN GUIDEBOOK)**
Gene LaBerge, *University of Wisconsin – Oshkosh, emeritus*
John Klasner, *University of Western Illinois, emeritus*
William Cannon, *U.S. Geological Survey*

6:00 p.m. **Return of Trip 4**

POSTER PRESENTATIONS

Brown, B.A., Czechanski, M.L., Mudrey, M.G., Jr. and Reid, D.D.

Wisconsin mineral resource GIS and related digital map and database products – a progress report

Boerboom, T.

Bedrock geologic maps of Keweenaw volcanic and intrusive rocks in the Lakewood, French River, and Knife River 7.5' quadrangles, North Shore of Lake Superior, Minnesota

Easton, R.M.

Geology and mineral potential of Proterozoic mafic intrusions in the northern Grenville Province of Ontario

Hart, T.R.

Keweenaw mafic and ultramafic intrusive rocks of the Lake Nipigon and Crystal Lake areas, northwestern Ontario

Hauck, S.A., Oreskovich, J.A. and Severson, M.J.

Geology, drill holes, mineral leases, and geophysics in the Duluth and Beaver Bay Complexes, northeastern Minnesota: Integration of various GIS databases to tell a story of the history of past and current Cu-Ni-PGE mineral exploration

❖ **Heiling, C.D.**

Peperites of the Gafvert Lake Volcanic Complex, St. Louis County, Minnesota

❖ **Hocker, S.M., Hudak, G.J., Odette, J.D. and Newkirk, T.T.**

Chemistry of alteration mineral phases at the Five Mile Lake volcanic-hosted massive sulfide prospect, NE Minnesota

❖ **Keatts, M.J., Jirsa, M. and Holm, D.**

Results of $^{40}\text{Ar}/^{39}\text{Ar}$ single-grain analyses of Precambrian mafic intrusions in northern and north-central Minnesota

❖ **McKenzie, M.A., Holm, D.K., Schneider, D.A. and Jercinovic, M.**

Results of EMP monazite geochronology in E-C Minnesota: Evidence for large-scale geon 17 metamorphism associated with post-tectonic plutonism

❖ **Metsaranta, R., Fralich, P. and Hollings, P.**

A geochemical investigation of Mesoarchean metavolcanic and metasedimentary rocks from the Birch – Uchi greenstone belt

Nicholson, S.W. and Cannon, W.F.

Stratigraphy and structure of Keweenaw rocks of the St. Croix horst, northwestern Wisconsin

Stott, G.M., Davis, D.W., Parker, J.R., Straub, K.J. and Tomlinson, K.Y.

Archean tectonostratigraphic assemblages of eastern Wabagoon Subprovince, northwestern Ontario



ABSTRACTS

WHAT DOES SEDIMENT CHEMISTRY TELL US ABOUT ROCKS LIKE THOSE FROM THE FERN CREEK FORMATION?

Argast, Anne, Department of Geosciences, Indiana University Purdue University Fort Wayne, Fort Wayne, IN 46805-1499, Argast@ipfw.edu

Bulk chemical analyses are accepted and powerful tools for the study of metamorphic and igneous rocks. Bulk chemical analyses are less accepted and less widely used for the study of sedimentary rocks. This is at least partly the result of a widely-held view that chemical data are unreliable indicators of sedimentary events due to the post-burial diagenetic alteration of the sediment. In recent years, this view has been reinforced with studies indicating the potential for extreme diagenetic alteration of sediments, with km-scale transport proposed in some systems (e.g., Wintsch and Kvale, 1994).

Potassium is often singled-out as an especially mobile component in diagenetic systems. For example, Awwiller (1993), working in the Gulf Coast Tertiary, postulates an increase from 2.0 to 3.8 wt. percent K_2O in mudrocks, due significantly to the transport of K as part of 10^3 pore volumes of fluid passing through the system in the depth range from 1500 to 4000 m below the surface.

An alternate view (Argast and Donnelly, 1987) maintains K_2O is a generally conservative element in diagenetic settings, and that observed variations in K_2O content preserve compositional characteristics present at and before accumulation. Depending on your point-of-view, the chemistry of diagenetically and metamorphically altered sedimentary rocks may (or may not) provide useful information about provenance, weathering and other qualities of the sedimentary system.

Unconsolidated sediments, delivered as turbiditic pulses of siliciclastic debris eroded from the Himalaya Mountains, accumulated on the Bengal Fan (DSDP 218) and now at subbottom depths from 12 to 729 m, produce chemical trends very similar to those previously noted in lithified (and metamorphosed) sedimentary rocks. The similarity in chemical trends across this broad range of conditions and environments suggests sedimentary chemical trends arise from fundamental conditions imposed upon the system before burial, and are not necessarily the result of extensive diagenetic alteration at depth.

The Fern Creek Formation (Early Proterozoic, Lower Chocoy Group) is well exposed along the Sturgeon River near the dam northeast of Loretto, Michigan. These rocks have been interpreted as glaciogenic in origin, and the diamictites they contain used as evidence for glacially-derived dropstone units. Others have interpreted the Fern Creek Formation as nonglaciogenic in origin with the sediments accumulated in fluvial environments grading upward into lagoonal or estuarine environments. Field and textural qualities (to be discussed as part of a post-meeting fieldtrip in the Menominee Iron Range) support a glaciogenic origin.

Bulk rock chemistry also supports a glaciogenic origin (Argast, 2002) . The chemical data, including the absence of a correlation between K_2O and Al_2O_3 , show sediments from the Fern Creek Formation were deposited without extensive sorting or demixing of hydraulically coarser- and finer-grained fractions. Other data, including the Na_2O/K_2O and $(2Ca + Na + K)/Al$ atomic ratio suggest sediment accumulated with abundant original feldspar. The chemical index of alteration (CIA) ranges from 50 to 61, similar to the average CIA of 57 in Gowganda diamictite matrices. The accessory suite is complex and includes poorly rounded zircons. These attributes are consistent with an origin as a glacial till.

Several minerals enriched in rare earth elements (REE) and/or thorium were identified in the Fern Creek Formation. These include monazite, huttonite (monoclinic $ThSiO_4$) and a fluor-hydroxy-REE mineral. Th concentrations as high as 53 ppm were noted in one bulk analysis. Efforts to obtain a chemical date on these minerals have so far been unsuccessful.

The Carney Lake Gneiss is a chemically-compatible possible source for the Fern Creek Formation.

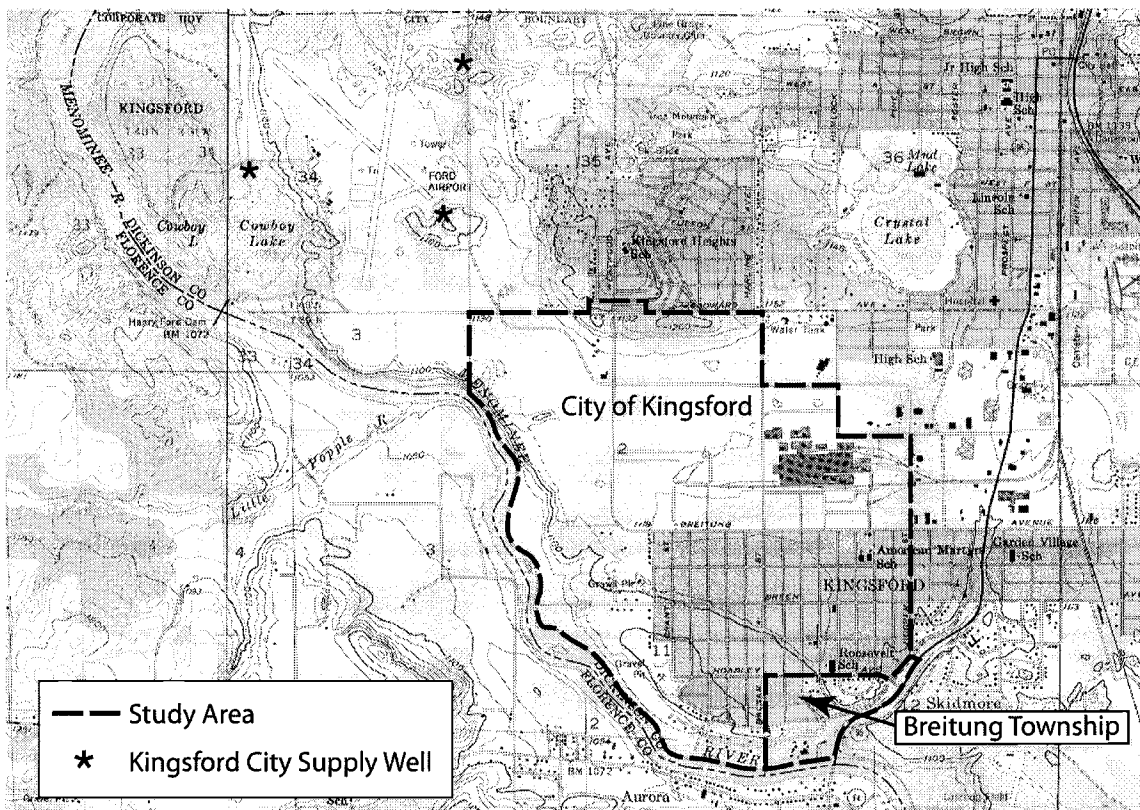
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- Argast, S. and Donnelly, T.W., 1987, The chemical discrimination of clastic sedimentary components: *J. Sed. Pet.*, v. 57, p. 813-823.
- Awwiller, D.N., 1993, Illite/smectite formation and potassium mass transfer during burial diagenesis of mudrocks: a study from the Texas Gulf Coast Paleocene-Eocene: *J. Sed. Pet.*, v. 63, p. 501-512.
- Wintsch, R. P. and Kvale, C. M., 1994, Differential mobility of elements in burial diagenesis of siliciclastic rocks: *J. Sed. Res.*, v. 64A, p. 349-361.

GEOLOGY AND HYDROGEOLOGY IN THE KINGSFORD, MICHIGAN AREA
BARTNIK, PATRICK J., pbartnik@arcadis-us.com, ARCADIS G&M, Inc., Kingsford,
Michigan, 49802; and

EVANS, BRUCE W., bevans@arcadis-us.com, ARCADIS G&M, Inc., Milwaukee,
Wisconsin, 53202

Investigations have been undertaken in a portion of the City of Kingsford, Michigan and Breitung Township, Michigan (the study area) to determine the geologic and hydrogeologic characteristics of glacial sediments and bedrock. The study area is located in Dickinson County in the south-central Upper Peninsula of Michigan.



The ARCADIS investigations were largely completed between April 1997 and January 2001, but are continuing. During the investigations, over 300 soil borings were completed, along with 47 test pits and 9.5 miles of geophysical study. The topography is characterized by three distinct landform terraces (Upper, Lower, and Riverside), which range in elevation from approximately 1,120 feet above mean sea level (ft msl) to approximately 1,045 ft msl. The Upper Terrace contains several isolated glacial kettles. The elevation of the Menominee River is approximately 1,037 ft msl. The geology is

comprised of unconsolidated glaciofluvial and glaciolacustrine deposits of clay, silt, sand, and gravel that exhibit complex horizontal and vertical spatial variability. These sediments overlie the Middle Precambrian Michigamme Slate and the Lower Precambrian metavolcanic Quinnesec Formation. Depth to groundwater in the unconsolidated deposits ranges from about 10 feet below land surface (bls) near the Menominee River to more than 50 feet bls in the Upper Terrace. Groundwater flow follows irregular pathways toward the Menominee River, but generally flows from northeast to southwest. Vertical hydraulic gradients range from +0.863 ft/ft in upland areas to -0.012 ft/ft near the Menominee River. Hydraulic conductivities range from 10^{-3} centimeters per second (cm/sec) to 10^{-1} cm/sec for coarser-grain material to 1.03×10^{-3} cm/sec to 3.94×10^{-5} cm/sec for the very fine-grain sand and sandy silt. The bedrock is generally considered impermeable. Groundwater flow velocities range from approximately 3 ft/day to 280 ft/day in coarser-grain units, and from approximately 0.1 ft/day to 3 ft/day in the very fine-grain sand and sandy silt.

To aid in the understanding of the complex geology within the study area, three-dimensional modeling of the geology was undertaken using the topographic surface, bedrock surface, and glacial sediments. Thirteen geologic units identified from the borehole data were categorized in to 3 units, based on permeability and anticipated effects on groundwater flow. The modeling and visualization of the geology were completed using a Geostatistical Software Library (GSLIB), developed at Stanford University, FORTRAN programs, and Environmental Visualization System (EVS) software developed by the C Tech Development Corporation.

GEOLOGY OF THE MISSISSIPPI-VALLEY TYPE MINERALIZATION AT BELLEVUE, MICHIGAN

BLASKE, Allan R., Blaske Geoscience, 8313 Hartel, Grand Ledge, MI 48837

The Bayport Limestone is exposed in quarrying operations at Bellevue, in southwestern Eaton County, Michigan. Mining has been active around Bellevue since the mid-1800's. Approximately 25 feet of the Bayport is exposed in the quarrying operations, and consists of a gray to buff colored thin-bedded limestone.

The Bayport limestone is late Mississippian in age, and comprises the upper portions of the Grand Rapids Group. It is underlain by the Michigan Formation, also of the Grand Rapids Group. The early Mississippian Marshall Sandstone and Coldwater Shale lie below the Grand Rapids Group. The Bayport is overlain by the early Pennsylvanian Saginaw Formation (within the Michigan Basin), but covered only by glacial sand and gravel at the quarry site.

Mineralogy of the deposit is simple, consisting predominantly of pyrite, marcasite, and calcite. Pyrite is most commonly found as encrustations of cubic crystals, formed directly on limestone. Marcasite is generally lighter in color than the pyrite, and often in iridescent, platy crystal groups. Marcasite is by far the dominant iron sulfide. Two generations of calcite are observed. Early calcite is found as small crystals lining cavities as drusy coatings. The second generation of calcite is found in large, euhedral crystals and cleavable masses. Trace amounts of sphalerite, barite, and fluorite are present. Fluorite was the earliest to form, as small brown crystals directly on the limestone. Pyrite was formed in association with the early calcite. Marcasite and sphalerite are later than the early calcite and pyrite. Second generation calcite began slightly after the marcasite. Tiny crystals of marcasite can also be found on the large calcite, indicating that formation of marcasite continued to the end of mineralization. Barite appears later than the sulfides, but before the end of the calcite formation.

Mineralization is present predominantly in brecciated zones and vein structures within the Bayport Limestone. The most common type of breccia consists of small, angular clasts surrounded by open-space filling of sulfides and calcite. A second type of breccia consists of larger, rounded clasts, with the interstitial spaces filled with a muddy limestone and pyrite. Orientation and size of the mineralized zones within the limestone is not known, due to lack of exposure within the quarry and insufficient historical mapping. Fine-grained iron sulfide is also observed as replacement structures, along apparent solution fronts within the massive limestone.

The geochemistry of the sulfides indicates the simplicity of the mineralization. 36-element ICP analysis of pyrite and marcasite separates, as well as a composite breccia sample, indicate very low concentrations of trace elements. Copper, lead and zinc are found at concentrations of less than 60 ppm; nickel is less than 30 ppm; and cadmium and cobalt less than 5 ppm. Barium is also low, generally less than 20 ppm. Manganese is high in the breccia (385 ppm), and lower in the sulfide separates (64 to 109 ppm), while chromium is high in the sulfides (150 ppm) and low

in the breccia (31 ppm). Arsenic is present in the breccia (7 ppm), but low in the iron sulfides at less than 5 ppm.

Sulfur isotopic compositions were analyzed on separated samples of pyrite, marcasite, and sphalerite. Sulfur isotopic compositions ($\delta^{34}\text{S}$) of the sulfide phases from the Bayport Limestone are 14.5‰ for the pyrite, 12.8‰ for the marcasite, and 19.8‰ for the sphalerite. These compositions indicate that the mineralizing fluids were basinal brines from within the surrounding Mississippian and Pennsylvanian formations. Unpublished data obtained from the USGS (Westjohn, D. B., pers. comm.) as part of the RASA program indicate a large range of $\delta^{34}\text{S}$ in samples collected from the underlying Marshall Sandstone and Michigan Formation, as well as the overlying Saginaw Formation and the Jurassic Red Beds. Pore water, whole-rock, sulfide, and sulfate sulfur isotope compositions for the underlying formations exhibit average $\delta^{34}\text{S}$ near 20‰, while the average $\delta^{34}\text{S}$ within the overlying formations is near 17‰.

Temperature of the mineralization has been determined using fluid inclusions in calcite (Panter, K. S., 2001). Calcite afforded the only mineral phase with inclusions for microthermometric study. Temperatures of homogenization indicate a bimodal distribution, with a low temperature mean of approximately 58°C, and a high temperature mean of approximately 138°C. The mean temperature of all inclusions analyzed was 107°C. These temperatures are similar to those observed using isotopic compositions in authigenic minerals in the Mississippian and Pennsylvanian sandstones (Westjohn, D. B., 1994). Fluid salinities based on freezing point depression range from 2.6 to 9.5 equivalent weight percent NaCl.

The quarries at Bellevue are located within 5 to 6 miles to the north and west of the known northwest end of the Albion-Scipio Oil Field Trend. This oil field (dolomitized fracture and solution cavities) structure is located within the Trenton-Black River (Middle Ordovician) rocks, some 4,000 feet deeper than the Bayport Limestone. The structure is related to faulting within the basement rocks. Evidence of the structure, however, is present in the lower Mississippian Sunbury Shale Formation, (approximately 3,000 feet higher than the Middle Ordovician rocks), the Coldwater Shale (overlying the Sunbury), and the Marshall Sandstone (overlying the Coldwater). If movements associated with this structure are evident in the formations immediately below the Bayport Limestone, it seems likely that the Bayport Formation would also be affected by faulting associated with the structure. Faulting associated with the Trend is likely responsible for small structures in the Bayport, allowing for brecciation, subsequent fluid migration, and precipitation of the mineralization.

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BEDROCK GEOLOGIC MAPS OF KEWEENAWAN VOLCANIC AND INTRUSIVE ROCKS IN THE LAKEWOOD, FRENCH RIVER, AND KNIFE RIVER 7.5' QUADRANGLES, NORTH SHORE OF LAKE SUPERIOR, MINNESOTA

BOERBOOM, Terrence J., Minnesota Geological Survey, St. Paul, MN, *boerb001@umn.edu*

The Minnesota Geological Survey, with partial funding by the U.S. Geological Survey STATEMAP geologic mapping program, has recently published detailed bedrock geologic maps of three quadrangles located along the North Shore of Lake Superior northeast of Duluth, Minnesota (Fig. 1; Boerboom and others, 2002a, b). Field mapping was completed at a scale of 1:12,000, and compiled at a scale of 1:24,000. This mapping has shown that some flow sequences can be traced inland as far as 10 to 12 kilometers, and has identified hundreds of individual flows within the larger flow units. Several mafic to felsic, subcordant to discordant sills and intrusions have also been mapped.

Prior to this mapping, the only published bedrock geologic maps for this area were at a scale of 1:200,000 (for example Miller and others, 2001), and other work was concentrated along the shoreline of Lake Superior. Brannon (1984) sampled 160 successive volcanic flows, starting above the Lester River sill and ending in Two Harbors, as part of an exhaustive geochemical study. Green and others (1977) included this area as part of a more broad coastal zone management study. Schwartz and Sandberg (1940) published a paper on the diabase sills near Duluth that included some of the sills mapped during this study. Sandberg (1938) mapped the stratigraphy of the flows exposed at the shoreline from Duluth to Two Harbors, identifying some 180 lava flows. Although all of these studies made some incursions inland from the shore, none of them provided systematic mapping away from the shoreline proper.

Bedrock exposure in the map area varies greatly, from nearly continuous outcrop along the shoreline and many of the short streams along the slope into Lake Superior, to variably abundant outcrop in the hills inland from the lakeshore. Throughout the map area, there are many closely spaced streams that have eroded into the bedrock perpendicular to the strike of the volcanic stratigraphy. Hence, many of the individual flows could be traced for a great distance along strike by tying them together from one streamcut to the next, in combination with the shoreline outcrops. In contrast, the more resistant intrusive rocks are typically exposed on the tops and slopes of high hills. The northeast part of the map area is poorly exposed and thus much of the bedrock geology in that area is constrained largely by aeromagnetic data.

Green (2002) has proposed a subdivision of the North Shore Volcanic Group into a series of informal sequences and formations that are separated by major lithological and geochemical breaks or by intrusions. Within the area of the maps shown here, these include the Larsmont basalts, Sucker River basalts, the Lakewood lavas, and the Lakeside lavas (Fig. 2). The detailed bedrock geologic maps shown here subdivide these informal formations into multiple layers comprised of lava flows of similar composition and texture in which multiple flow contacts have been documented.

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Figure 1. Index map showing location of mapped quadrangles. Work is currently in progress on the Two Harbors and Castle Danger quadrangles.

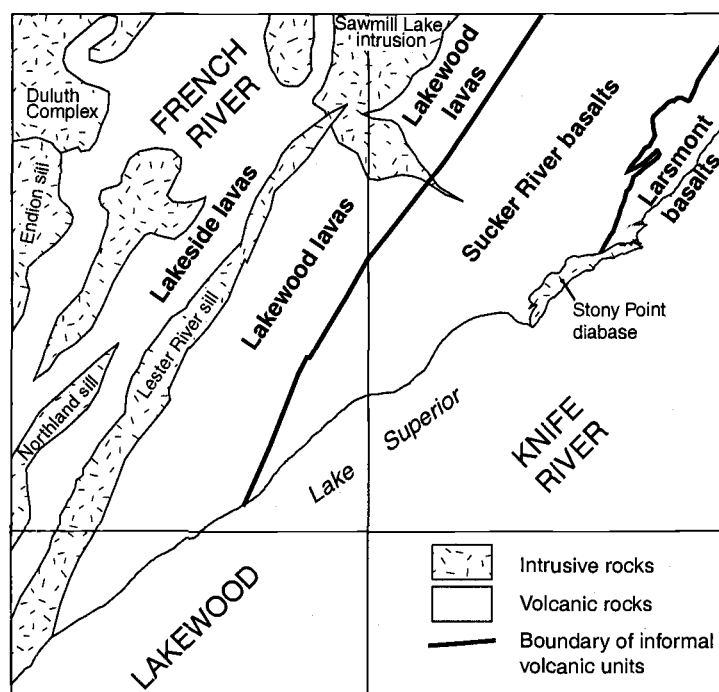
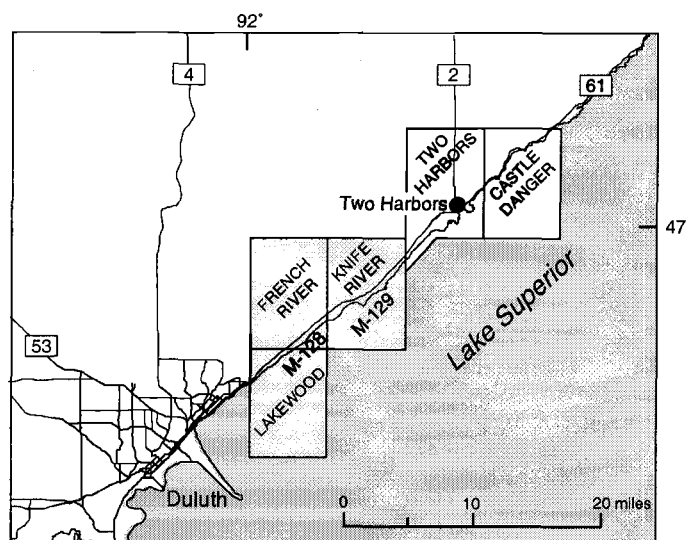


Figure 2. Index map showing the relative positions of the informal volcanic units of Green (2002).

WISCONSIN MINERAL RESOURCE GIS AND RELATED DIGITAL MAP AND DATABASE PRODUCTS – A PROGRESS REPORT

BROWN, B.A.¹, CZECHANSKI, M.L.¹, MUDREY, M.G., Jr.¹, and REID, Daniel D.² (1) Wisconsin Geological and Natural History Survey, Univ. of Wisconsin-Extension, 3817 Mineral Point Road, Madison, WI 53705, babrown1@facstaff.wisc.edu, (2) Wisconsin Dept of Transportation, 3502 Kinsman Blvd, Madison, WI 53704-2507

A new Mines, Pits and Quarries (MPQ) database containing information on 1,302 significant nonmetallic mining sites throughout Wisconsin has been completed by the Wisconsin Geological and Natural History Survey (WGNHS) in cooperation with the U.S Geological Survey (USGS). Locations were digitized from county-based digital orthophotography wherever available and by site visits. Data tables were linked to existing USGS databases (MAS/MILS and MRDS) and to Wisconsin Department of Transportation (WDOT) aggregate test data; this linkage of all previous digital and analog databases is the first updated inventory since 1980. Future versions will be augmented with current site information, collected under the nonmetallic reclamation program of Wisconsin Department of Natural Resources, and additional historic sets such as the Road Material Survey sites of the WGNHS/WDOT.

Georeferenced maps layered with digital geology, topography, orthophotography, soil, and so forth provide a valuable land-use planning resource. Concern for safety and construction problems in the reconstruction of U.S. Highway 151 through the historic Upper Mississippi Valley Base-Metal Mining District, southwest Wisconsin, made possible the scanning and georeferencing of the Wisconsin Mineral Development Atlas. The Mineral Development Atlas is a detailed set of 1,450 section-scale maps (1 inch equal 200 feet) of mine workings, drill-hole location and ancillary data dating from 1900 until mining ceased in 1979. These maps were maintained by the WGNHS and the University of Wisconsin-Platteville and were scanned by the WDOT.

All Wisconsin water well construction reports for 1936-1988 are now available on CD-Rom. They provide an extensive data set for geologic mapping as well as environmental and water resource analysis. New WGNHS map products are being produced in digital form and a variety of analog maps including the 1:24,000 USGS geologic quadrangle maps of the lead-zinc district are being converted to digital as resources allow.

This presentation will provide an interactive demonstration of these data sets and GIS layers, a review of available map data such as regional geophysics, and an update on the status of geologic mapping at the WGNHS.

HIGHWAY CONSTRUCTION, MINE RECLAMATION, AND LAND-USE PLANNING CHALLENGES IN THE HISTORIC UPPER MISSISSIPPI VALLEY LEAD-ZINC DISTRICT OF SOUTHWEST WISCONSIN

BROWN, B.A.¹, MUDREY, M.G., Jr.¹, CZECHANSKI, M.L.¹, REID, Daniel D.², and HUNT, T.C.³, (1) Wisconsin Geological and Natural History Survey, Univ. of Wisconsin-Extension, 3817 Mineral Point Road, Madison, WI 53705, babrown1@facstaff.wisc.edu, mgmudrey@wisc.edu, (2) Wisconsin Dept. of Transportation, 3502 Kinsman Blvd, Madison, WI 53704-2507, (3) Reclamation Program, Univ. of Wisconsin-Platteville, 712 Pioneer Tower, Platteville, WI 53818

The Upper Mississippi Valley Lead-Zinc District of Wisconsin, Illinois, Iowa, and Minnesota produced nearly 10 million tons of lead-zinc ore from the 1820s until the last mine closed in 1978. The district will probably never be mined again, but problems related to mineralization and past mining activity pose significant problems for highway construction and post-mining land use. Specific hazards and engineering problems include (1) Highly altered and unstable rock and shallow abandoned mine workings encountered during highway construction, (2) leachate from roaster-pile waste and (3) locally degraded groundwater from lead-zinc sulfide mines. As rural residential development increases, the abandoned workings, particularly poorly sealed shafts, can be a hazard. Most low-sulfide waste rock has been recycled as aggregate, and carbonate-rich tailings overgrown with vegetation make it difficult to find any surface evidence of small, older mine sites that may cause problems.

High sulfate in groundwater samples was noted in 1978 following closure and flooding in an area where large mines had operated for more than 50 years and a drawdown cone had developed over a 20-square mile area. A well-replacement program near Shullsburg restored potable water supplies. Onsite reclamation consisted of establishing vegetation on the tailings and crushing the coarse waste rock for aggregate. Leachate from zinc roaster waste piles produced over 100 years resulted in highly acidic and metal-rich surface water near Mineral Point. The roaster piles were successfully reclaimed by surface grading and contouring along with neutralization and fertilization to allow vegetation to establish. This was accomplished at a fraction of the cost of removal of the roaster waste piles.

Previously undiscovered sulfide mineralization and associated rock alteration exposed during highway construction along U.S. Highway 151 near Mineral Point resulted in the unanticipated need for engineering redesign of major roadcuts and structures. The need to identify areas of potentially unstable slopes led to scanning of the Wisconsin Mineral Development Atlas, which has proven to be invaluable in identifying areas of mineralization, alteration, and abandoned workings in the path of construction. These detailed maps (1 inch to 200 feet) of mine workings and exploration drillhole locations are now being used by county and regional planners and zoning authorities to identify and incorporate potential mining related hazards into land-use planning.

TEXTURAL CONSTRAINTS ON THE ORIGIN OF RAPAKIVI TEXTURES IN THE WOLF RIVER BATHOLITH

R. Michele Buttram and Marcia Bjornerud
Geology Department, Lawrence University, Appleton, WI 54912

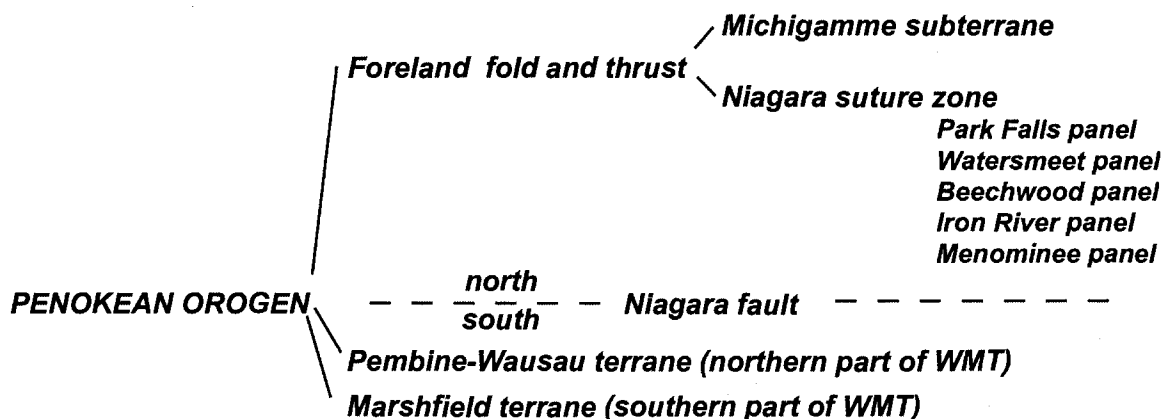
The Wolf River Batholith of north-central Wisconsin, a 1.47 Ga composite anorogenic pluton, includes some of the world's finest examples of 'rapakivi' granite, in which large potassium feldspar crystals are mantled by plagioclase. Although rapakivi granites have been described for more than a century, the origin of this distinctive texture, both in the Wolf River complex and elsewhere, remains controversial. Some workers argue that rapakivi mantles are coronae formed at a peritectic or eutectic point under equilibrium crystallization conditions. Others maintain that rapakivi textures record disequilibrium associated with magma mixing and or sudden changes in pressure.

While most previous investigations have focused on the chemistry of rapakivi granites, this study examined the physical character of the Wolf River rocks – specifically, the size, shape, orientation and distribution of the rapakivi-type feldspar crystals. Among the most striking characteristics of these rocks is the large size of the feldspars (up to 7 cm in length). Statistical analyses show that there is no significant difference in size or aspect ratio between crystals with and without the rapakivi mantle. However, the K-feldspar cores of the rapakivi-type crystals tend to be rounder (less euhedral) than non-rapakivi grains, suggesting that they experienced significant resorption prior to the growth of the plagioclase mantle. A weak grain shape fabric and random juxtaposition of rapakivi and non-rapakivi grains must also be explained by any viable model for the origin of the texture. Our data appear to be most consistent with the magma mixing model, which is compatible with earlier geochemical studies of the Wolf River complex.

Niagara suture zone, northern Michigan and Wisconsin—tectonics in the 1.85 Ma arc-continent collisional boundary

W.F. Cannon, (*U.S. Geological Survey, Reston, VA 20192, wcannon@usgs.gov*) **G.L. LaBerge**, (*University of Wisconsin-Oshkosh (retired) and U.S. Geological Survey*), **John S. Klasner** (*Western Illinois University (retired) and U.S. Geological Survey*)

The Niagara suture zone, as used here, is a belt varying in width from about 6 km to 40 km lying north of the Niagara fault. It separates the accreted volcanic arcs of the Wisconsin magmatic terranes (WMT) on the south from the autochthonous and parautochthonous continental margin rocks on the north. It consists of Paleoproterozoic metasedimentary and metavolcanic rocks of the epicratonic Marquette Range Supergroup and Archean basement rocks upon which they were deposited. The Archean rocks constitute the southern margin of the Superior craton, which was rifted and eventually separated during extensional phases of the Penokean orogenic cycle, and then thrust northward during Penokean convergence. The suture zone is marked by very high strain and widespread multiple steeply to vertically plunging folds. The suture zone is one of numerous subdivisions of the Penokean orogen whose hierarchy of component parts is shown below.



The map pattern shown here was derived from published detailed maps in the east (Bayley and others, 1966; Dutton, 1971; James and others 1968; and James and others, 1961) and from our recent work in the west, where outcrops are scarce but access to recent exploration drill information as well as proprietary detailed aeromagnetic and electromagnetic data have aided in clarifying the geologic relationships (Cannon and others, 1998).

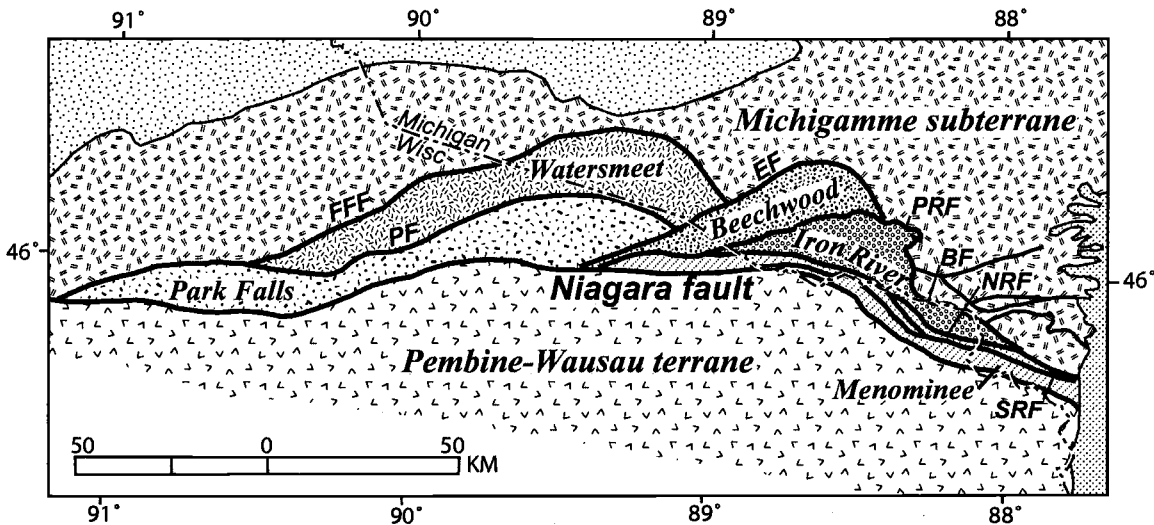
Each of the five fault panels of the Niagara suture zone has a unique set of characteristics.

Watersmeet panel- Paleoproterozoic strata are mostly pelitic schists and gneisses containing ferruginous strata and locally dolomite near the base. They were deposited on a basement of Archean gneiss. Both basement and cover were deformed into gneiss domes. High-pressure metamorphism produced kyanite-bearing assemblages.

Park Falls panel- Generally similar to Watersmeet panel except that metamorphism was lower pressure and sillimanite-bearing assemblages are predominant.

Beechwood panel- Consists of Paleoproterozoic graywacke and shale and mafic volcanic rocks in roughly equal parts. Archean basement is not exposed. Folds are ENE-trending and have subhorizontal axes. Rocks are in greenschist facies.

Iron River panel- Rocks are the Paint River Group, including the Badwater Greenstone. Archean basement is not exposed. Strata are multiply folded creating a complex fold interference map pattern. Most fold plunge steeply. Metamorphosed to greenschist or sub-greenschist facies.



Map showing the five structural panels (Park Falls, Watersmeet, Beechwood, Iron River, and Menominee) that constitute the Niagara suture zone. Faults that bound the panels are Flambeau Flowage fault (FFF), Powell fault (PF), Elmwood fault (EF), Paint River fault (PRF), Badwater fault (BF), North Range fault (NRF), and South Range fault (SRF).

Menominee panel- Rocks are entirely of Paleoproterozoic age. No Archean basement is exposed. Strain was extreme. Commonly all structural elements, including fold axes, are subvertical. Metamorphism is lower to upper greenschist facies and largely post-tectonic.

These panels, and the Niagara suture zone that they constitute, differ from the Michigamme subterrane to the north. There was little penetrative deformation of Archean basement in the Michigamme subterrane. Paleoproterozoic strata were moderately to weakly deformed. Folds, for the most part, are simple and gently plunging. Metamorphic grade is variable and mostly post-tectonic. Thus, the Niagara suture zone documents a range of tectonic styles unique to the very high strains in a belt no more than a few tens of kilometers wide, along which differential movement between the accreting arcs on the south and the craton margin on the north was concentrated.

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Strike-slip separation of the Burntside trondhjemite and the Wakemup Bay tonalite, Northern Minnesota

Karoun Charkoudian, Basil Tikoff

Department of Geology and Geophysics, University of Wisconsin, Madison WI, 53706

Robert Bauer

Department of Geological Sciences, University of Missouri, Columbia, MO, 65211

INTRODUCTION The Vermilion fault is a local tectonic boundary in the southern Canadian Shield juxtaposing the Quetico subprovince (granites and schists) with the Wawa greenstones. The Burntside trondhjemite and the Wakemup Bay tonalite are small, elliptical, Archean granites separated by 35 km of right lateral offset on the Vermilion fault in northern Minnesota. The Vermilion fault is interpreted as initially active as a normal fault, juxtaposing the shallow Wawa greenstone to the south with the deeper granites and migmatized schists to the north (figure 1, stage 1). It was later reactivated as a strike-slip fault, separating the Burntside trondhjemite from the Wakemup Bay tonalite (figure 1, stage 2). Although the Vermilion fault is the regional boundary between the Quetico and Wawa subprovinces, the Haley fault lies to the south of the Vermilion fault and contains Quetico schists that belong on the north side of the Vermilion fault (figure 1).

The purpose of this study is to compare emplacement setting, fabrics, composition, and shape of the two plutons to determine if they constitute a piercing point on the Vermilion fault. In addition, we have determined the dip on the Vermilion fault, constrained the emplacement history of the Wakemup tonalite, and determined a potential cause for the isolated fault block that now contains the Wakemup Bay pluton (figure 1, stage 2).

The Burntside trondhjemite is a small lenticular pluton that intruded the schist that lies to the north of the Burntside Lake fault, a continuation of the Vermilion fault at its eastern end. The Wakemup Bay pluton is a biotite-bearing tonalite that intruded the schist that lies just to the north of the Haley fault.

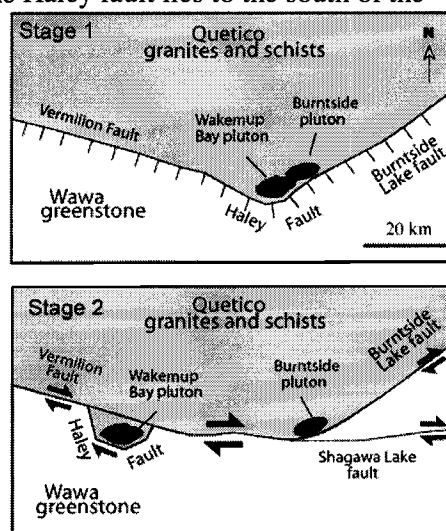


Figure 1

AMS ANALYSIS The Anisotropy of Magnetic Susceptibility (AMS) is a rapid, non-destructive technique, commonly used in granitic studies to obtain magnetic fabrics. Principle AMS ellipsoid axes are defined as $k_{\max} > k_{\text{int}} > k_{\min}$. The magnetic foliation is defined as the $k_{\max}$ - k_{int} plane, and the magnetic lineation is defined as the orientation of $k_{\max}$.

The bulk susceptibility varies widely in both the Wakemup Bay tonalite (500-8500 μSI) and the Burntside trondhjemite (500-3500 μSI). This range of susceptibility is attributed to the large variation in magnetite content throughout these bodies. The AMS foliations parallel the measured field foliation in both plutons. Lineations in the Wakemup Bay tonalite dip shallowly to the E and W, and lineations in the Burntside trondhjemite dip shallowly to the ENE and WSW. Magnetic lineations consistently parallel the long axis of the plutons.

GRAVITY STUDY The Burntside and Wakemup plutons were selected for a gravity study because they both contain a single surrounding lithology (biotite schist) with a significant and consistent density contrast ($\Delta\text{density} = -0.08$ to -0.1 g/cc). In addition, the gravity data allows us to model the dip of the Vermilion fault.

A Lacoste and Romberg gravity meter model G was used for both areas. After corrections, a forward model approach was used to interpret the depth of the Burntside pluton and Vermilion fault geometry using WinGLink, a geophysical interpretation software program. The Burntside pluton is a thick body between 2-3 km in thickness. The Vermilion fault is a steeply-north dipping to vertically oriented feature. Using a gravimetric three-dimensional iterative technique on the Wakemup Bay pluton resulted in a good first-order picture of the pluton. Most of the pluton is very thin, less than 0.5 km thick. There are two root zones of up to 4 km depth, both of which lie on the southern portion of the Wakemup pluton, furthest away from the Vermilion fault.

INTERPRETATION We interpret the Burntside and Wakemup plutons as part of the same granitic complex prior to strike-slip faulting on the Vermilion fault. These igneous bodies are similar in composition and both have undergone solid-state deformation. The plutons have similar structural settings. The Wakemup Bay pluton intrudes an F3 fold hinge and the Burntside pluton has refolded F2 folds at its southern end. Given the separation, the folding episodes may or may not correlate exactly.

The gravity inversion and AMS study on the Wakemup pluton provide constraints on pluton emplacement. The pluton has an average thickness of 0.5 km. Because the pluton contains a roof of wallrock, this estimate reflects the true thickness of the pluton. The AMS foliation and lineation parallel the fold limbs and fold hinge, respectively, of a km-scale F3 fold. Therefore we interpret the Wakemup as syntectonically intruding an F3 fold hinge.

We use a forward gravity model to estimate the dip on the Vermilion fault, which dips between 70° N and vertical. This interpretation requires that the section of the Vermilion fault south of the Burntside pluton was not active as a south-side down normal fault.

We propose the following tectonic model (figure 1). The Burntside pluton and the Wakemup Bay pluton were initially part of the same granitic complex. The Vermilion fault was initiated as a normal fault (figure 1, stage 1), which juxtaposed the amphibolite facies Quetico sub-province with the greenschist facies Wawa belt. The Wakemup tonalite, with a thick root on its south side, acted as a promontory in the fault system. The Vermilion fault was then reactivated as a strike-slip fault (figure 1, stage 2), cutting through the thinnest (NW) section of the Wakemup Bay pluton. This created the fault-bounded block that contains the Wakemup Bay pluton. Therefore, it is evident that the pluton shape has played a crucial role in controlling Vermilion fault orientation, both for the early normal faulting and later strike-slip faulting.

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GEOLOGY AND MINERAL POTENTIAL OF PROTEROZOIC MAFIC INTRUSIONS IN THE NORTHERN GRENVILLE PROVINCE OF ONTARIO

R.M. EASTON, Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5, mike.easton@ndm.gov.on.ca

Since 1998, mafic intrusions near the Grenville Front in Ontario have been prime exploration targets for Cu-Ni-PGE mineralization. To assist in this effort, the Ontario Geological Survey has conducted detailed mapping in high potential areas of the Grenville Province between 1999 and 2002. This poster summarizes the results of these mapping efforts.

East Bull Lake intrusive suite, including the River Valley intrusion: Country rocks to East Bull Lake intrusive (EBLI) suite rocks in the area are inferred to be mainly Archean in age, and are grouped into 4 gneiss associations. Metamorphic grade is upper amphibolite facies; country rocks to the mafic intrusions are commonly migmatitic.

The Paleoproterozoic EBLI suite consists of several mafic layered intrusions emplaced between 2490 and 2468 Ma (James et al. 2002) that occur over a distance of ~250 km, roughly centered on the present site of Sudbury. The largest of these bodies in the Grenville is the River Valley intrusion, which underlies roughly 100 km² of Dana and Crerar townships. Previous maps correlated mafic rocks west of Crerar Township with the River Valley intrusion. This study indicates that at least 3 separate intrusions are present, each emplaced into different country rocks, and with different stratigraphy and mineral potential.

EBLI suite rock types range in composition from anorthosite to melanorite, troctolite and rarely peridotite; leucogabbro and gabbro dominant. The crystallization order of primary phases is most commonly plagioclase (An₈₀₋₆₂), olivine (Fo₇₆₋₅₉), orthopyroxene (En₇₅₋₅₈), titanomagnetite, and clinopyroxene. In Dana Township, the River Valley intrusion locally exhibits primary mineralogy and well preserved igneous textures. Phase layering varies from cm- to m-scale, which is discernable in outcrop, and dm or larger, which is identified by detailed mapping. Isomodal layering is most common; mineral and size graded layers are less common. Cryptic layering is well documented for the River Valley intrusion. Pearce-element ratio and chondrite-normalized REE diagrams illustrate that each body formed from one or more cogenetic magmas (James et al. 2002). A high-Al, low-Ti tholeiitic composition can explain the dominant leucocratic rock compositions in the EBLI suite (James et al. 2002).

Within the EBLI suite, contact-type Cu-Pd-Pt mineralization (1 to 10 g/t Pd+Pt+Au) occurs in the matrix of an inclusion and/or fragment-bearing gabbro to leucogabbro at the base or side of the intrusions where the primary igneous contact is preserved. A second, similar, zone of mineralization may occur 100-200 m above the contact. Examples occur throughout the EBLI suite, however, the most consistent grades have been reported from the River Valley intrusion in Dana Township. Chalcopyrite and lesser pyrrhotite form 1-3 % sulfide, either finely disseminated or as local cm-sized patches. PGE mineralization is commonly associated with sulphide. Study of the East Bull Lake intrusion indicates that mineralization originates from the intrusion and subsequent dynamic mixing of S-saturated, inclusion-bearing, second-stage (PGE enriched, i.e. 20-100 ppb PGE) magmas that entered the magma chamber carrying liquid sulfide droplets (James et al. 2002). Reef-style mineralization has yet to be documented within the EBLI suite.

Geological history between Sudbury and River Valley: Archean rocks in this area record a sequence of events similar to that observed in the Levack Gneiss complex and high-grade portions of the Quetico subprovince, but unlike the Pontiac subprovince. The following geological history is inferred. After deposition of greywackes south of the Temagami greenstone belt, invasion by tonalitic to granodioritic plutons, probably accompanied by burial, formed the migmatitic gneisses now represented by the Pardo and Red Cedar Lake gneiss associations, likely between 2685 and 2675 Ma. This was followed by a second period of tonalitic to granodioritic magmatism, deformation and metamorphism at mid-crustal levels between 2670 and 2660 Ma. The Crerar gneiss association represents the products of this latter activity. Subsequent felsic magmatism at roughly 2640 Ma was accompanied by emplacement of pegmatite veins.

A logical extension of this work is to interpret the gneiss associations as a southward-deepening section of the crust. As interpreted, Archean metawackes exposed immediately north of the Grenville Front represent high-levels of the crust. The Pardo gneiss, immediately south of the Grenville Front, represents the middle part of a 10-15 km thick upper crustal layer dominated by supracrustal and intrusive rocks. The Red Cedar Lake gneiss and the Street gneiss association represent the basal portion of this upper crustal layer, with the former derived from a metasedimentary rock sequence and the latter from a greenstone sequence. Intrusive rocks of the Crerar gneiss association are part of a 10-15 km thick middle crustal layer. This crustal section is roughly equivalent to that observed across the Wawa gneiss domain. Emplacement of EBLI suite bodies occurs at several levels within this crustal section.

Flett Township mafic Intrusions: Evidence for a mafic and A-type granite magmatic province in the northern Grenville Province was discovered while examining mafic intrusions near Temagami that occur in Tomiko domain, near its contact with the Grenville Front tectonic zone. Proterozoic country rocks consist of gneissic granite, with minor mafic and quartzose gneiss and metaconglomerate. The Fall Lake intrusion consists of little metamorphosed gabbro and leucotroctolite. The Fanny Lake intrusion consists of olivinite and troctolite. Igneous texture is well preserved, but metamorphic coronas occur around primary olivine and clinopyroxene. Geochemistry indicates that both bodies are slightly alkalic, compositionally similar to the Sudbury diabase dike swarm dated at 1238 ± 4 Ma, and have affinities to within-plate basalts.

The Fall Lake intrusion yielded pristine baddeleyite, with 3 concordant or just slightly discordant grains giving an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1235 ± 2 Ma. The Fanny Lake sample yielded baddeleyite, with some grains having thin zircon overgrowths, consistent with the presence of corona textures in the body. Two concordant grains without overgrowths gave an average $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1238 ± 2 Ma.

Both intrusions are spatially associated with the A-type Mulock granite, dated previously at 1244^{+4}_{-3} Ma. Intrusions of similar age include the Sudbury dike swarm, Mercer anorthosite, and the West Bay and Powassan granitoid plutons. The new age data provides further evidence for the presence of a bimodal magmatic province active from 1270-1235 Ma in the Laurentian margin of the Grenville Province. The tectonic setting is interpreted as an extensional rift that formed inboard of a continental arc active on the southern margin of North America between 1450-1300 Ma. This setting resembles that of the Cenozoic Columbia River Basalt Group.

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PALEOSTRESS INFERENCES FROM FAULT SLIP VECTORS IN THE EASTERN PART OF THE
WISCONSIN SEGMENT OF THE MIDCONTINENT RIFT

Amy Garbowicz, Marcia Bjornerud,
Geology Department, Lawrence University, Appleton, WI 54912

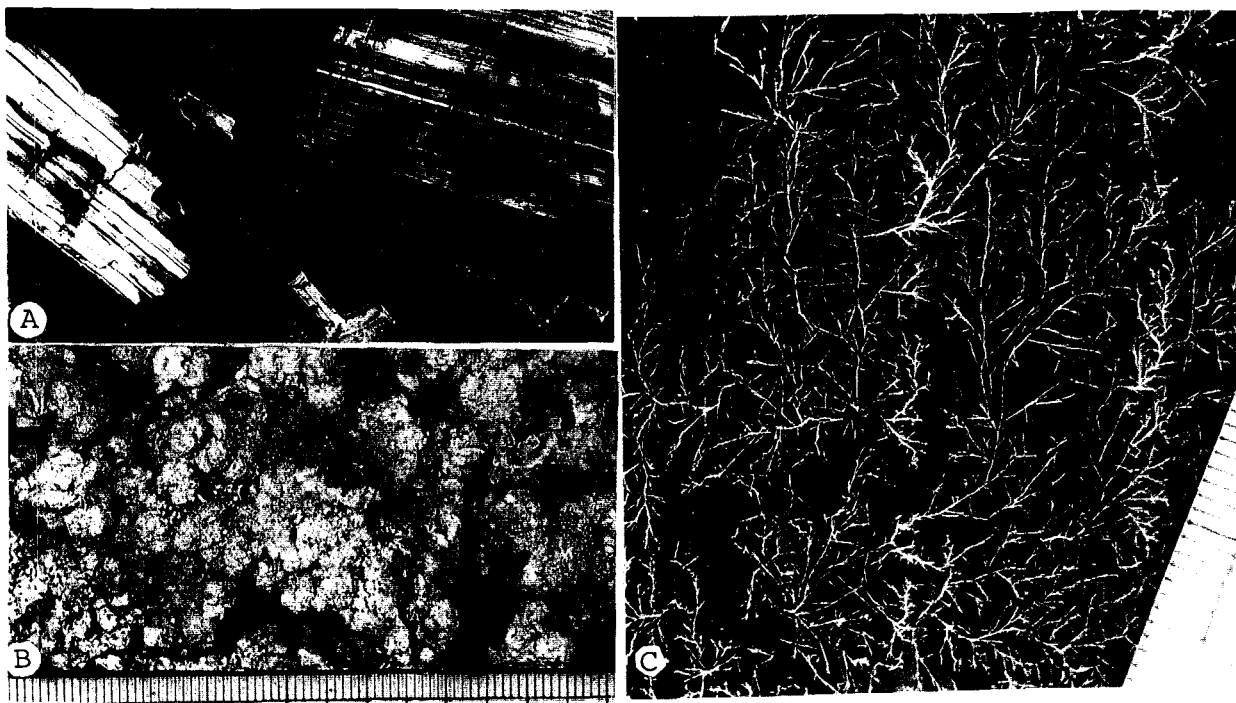
Building accurate models for both the opening and closing of the Midcontinent Rift requires an understanding of the evolution of regional stresses over time. This study focused on slickenfibers as paleostress indicators in the portion of the Rift exposed near the southern shore of Lake Superior in northeasternmost Wisconsin. The orientations of slickenfibers were used to determine slip vectors on outcrop-scale faults within rift-related igneous and sedimentary rocks. Rocks sampled span the entire range of the Keweenaw Supergroup, from the Tyler Formation to the Freda Sandstone, with most of the sampling in the Porcupine Volcanics, the Kallander Creek Volcanics, and the Mellen Gabbro. The mineral composition of the slickenfibers was used as a proxy for their age, based on the known regional sequence of secondary mineralization within the Rift. Chlorite and epidote slickenfibers were grouped together and considered older since these were among the first minerals precipitated by hydrothermal fluids following the main magmatic interval. Slickenfibers of calcite and zeolite were considered to be younger. Some individual faults were observed to have multiple generations of slickenfibers with different compositions, indicating either reactivation or continuous slip over a protracted period of time. Data from the field were analyzed using *Fault Kinematics* (by R. Allmendinger, Cornell University), a program that calculates best-fit paleostress tensors from fault slip information. The calculated tensors all indicate normal stress regimes (maximum principal stress subvertical), even for the latest generations of slickenfibers. This contrasts with the results of studies on the Keweenaw Peninsula, which have documented two distinct stress regimes. There, early normal faulting gives way to reverse faulting, possibly as a response to far-field stresses associated with the Grenville Orogeny. The absence of reverse-slip vectors in the northeastern Wisconsin segment of the Midcontinent Rift may reflect the misorientation of this part of the rift with respect to those far-field stresses.

Mode of Occurrence of Trona and Thermonatrite and their Possible Origin in the Negaunee Iron-Formation of the Marquette Range, Lake Superior District, USA

Tsu-Ming Han (Retired)

Research Laboratory, Cleveland-Cliffs Inc.

A white colored substance is often seen on the surface of the silicate-bearing Negaunee Iron-Formation of low metamorphic grade on the Marquette Range, Michigan. This substance is mostly of a mixture containing hydrous sodium carbonates (trona and thermonatrite). It occurs as thin coatings along bedding (Figure 1-A), and in fractures cutting across the bedding; as coatings and colloform clusters on bedding planes (Figure 1-B); and as contour patterns distributed between the fractures of bedding surfaces. Furthermore, nearly pure trona was developed quickly as dendrites and minute dots on the cut surfaces of some hand specimens in storage (Figure C). To the writer's knowledge, these minerals have not been previously reported from Precambrian BIF of the equivalent metamorphic grade in other districts.



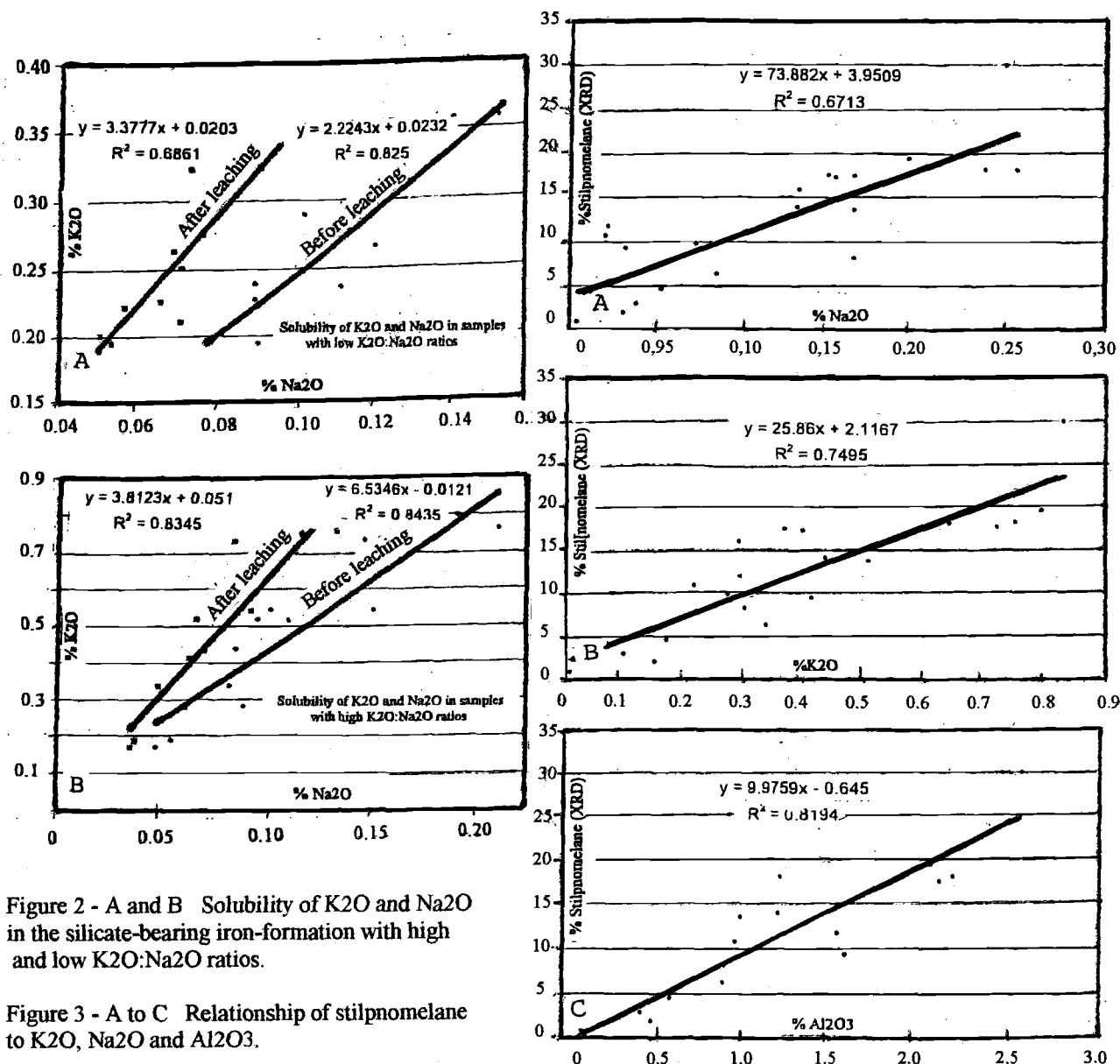
Figures 1 – Mode of occurrence of trona and thermonatrite.

A–As white coatings along bedding. B–As colloform clusters on a bedding plane.
C– As dendrites on the cut surface of a hand specimen in storage.

The iron-formation is composed of magnetite, siderite, ankerite, and stilpnomelane..
Minnesotaite is also locally present in noticeable quantities. K is more than Na in these minerals as is the case in nearly all of the Precambrian iron-formations of low metamorphic grade. As a

general rule, stilpnomelane contains more K and Na than the minnesotaite. However, the K₂O:Na₂O ratio in these minerals and in the iron formations may vary substantially.

Based on the results from the highly purified water leaching tests on more than twenty different samples, the Na in the iron-formation is water-soluble whereas the K is practically insoluble (Figures 2A and B). The XRD and analytical data show a good correlation between the amount of stilpnomelane and the amounts of Na₂O, K₂O and Al₂O₃ (Figures 3A to C).



It may be logically concluded that most of the sodium was derived from the stilpnomelane, which was leached out by meteoric water. The mixture of the hydrous sodium carbonates was then developed through evaporation under the atmospheric conditions.

Keweenawan Mafic and Ultramafic Intrusive Rocks of the Lake Nipigon and Crystal Lake areas, northwestern Ontario

Hart, Thomas R., Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, Ontario P3E 6B5; tom.hart@ndm.gov.on.ca

The Keweenawan diabase sills in the Lake Nipigon and Crystal Lake areas, northwest of Lake Superior, consist of two distinct geochemical and geographical groups with each area also hosting a number of unique intrusions that suggest different tectonic processes. Mapping by Smith and Sutcliffe (1987) in the Crystal Lake area identified a series of 6 Logan diabase sills >5 m thick that gently dip to the southwest, and intrude into the early Proterozoic Rove Formation. Northeast trending dykes of the Pigeon River swarm range from olivine to quartz diabase in composition, and include dykes that crosscut the Logan sills and dykes that appear to merge with the sills. The layered gabbro – anorthosite – troctolite Crystal Lake Gabbro crosscuts and contains inclusions of Pigeon River dykes. Samples of the Logan sills can be subdivided into a low TiO_2 -Th/Yb - Zr/Y group and a high TiO_2 -Th/Yb - Zr/Y group (OGS 2002). The high TiO_2 group was identified as being quartz normative, and comparable to the type Logan sills by Sutcliffe (1991). Samples identified as Pigeon River dykes exhibit a high degree of variability suggesting that they represent at least three unrelated intrusions. One subset of the Pigeon River dykes is comparable to the low TiO_2 group of Logan sills, and another subset is comparable to the Crystal Lake Gabbro. Most of a third subset of dyke samples are located along Highway 61 close to the Pigeon River, and contain lower trace element abundances and ratios than the other intrusions in the area. Gabbro samples from the Crystal Lake Gabbro intrusion display some overlap with the low TiO_2 group of Logan sills but also includes samples with higher Zr/Y, Th/Yb, and Th/Ta ratios. The Logan diabase sills are confined to the area to the south of Thunder Bay, with the Nipigon diabase sills located to the north.

The initial Keweenawan intrusive event in the Lake Nipigon area is probably represented by the relatively flat lying to shallowly dipping peridotites located in the Disraeli, Leckie – Seagull - Fox Mountain, Hele, and Kitto areas that form intrusions a few kilometres in diameter. The peridotites are composed of orthocumulate to mesocumulate textured wehrlite to lherzolite, containing 1 to 2% reddish brown mica and commonly a discontinuous olivine gabbro border phase (e.g. Sutcliffe 1987; Hart et al. 2002). The Disraeli, Seagull and Hele peridotites are characterized by higher MgO and Zr/Y and Th/Yb values but lower Th/Ta ratios than the Nipigon diabase sills. A series of 0.5 to 3.0 m thick sills are located stratigraphically below the Nipigon sills, as exposed along Highway 17 at Kama Hill. These sills have MgO, Th/Yb and Th/Ta values intermediate between the peridotites and Nipigon sills, and subdivided into higher Th/Ta and lower Th/Ta subgroups may be possible with additional sampling. These sills have Th/Ta and La/Yb ratios comparable to the high TiO_2 group of Logan sills, but generally have lower trace element abundances. The Kitto peridotite also has Th/Yb, Th/Ta and Zr/Y ratios that overlap with these sills rather than the other peridotites. The olivine tholeiite Nipigon diabase sills are up to 200 m thick, and are chilled against the peridotite intrusions. Previous work indicates that some sills were formed by multiple pulses of magma (e.g. Sutcliffe, 1987; Hart et al. 2002), but the chemistry of the sills over the

entire Lake Nipigon area displays little variation. Geochemical differences between the peridotites and Nipigon diabase sills are comparable to the variations observed in the Osler Group volcanic rocks (e.g. Sutcliffe, 1991). The Nipigon sills have TiO₂ values comparable to the low TiO₂ group of Logan sills but higher Th/Ta and lower La/Yb ratios. The differences in the geochemistry of the diabase sills between the Lake Nipigon and Crystal Lake areas is similar to the differences observed in the volcanic rocks of a number of flood basalt provinces (e.g., Mantovani et al. 1985). The regional extent of the geochemical groups within the Keweenawan intrusions is not known. An initial examination of troctolites from the Babbitt deposit of the Duluth Complex (Ripley et al. 1999) indicates Th/Ta, Th/Yb, and Zr/Y ratios comparable to the Nipigon peridotites rather than the intrusions of the Crystal Lake area.

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GEOLOGY, DRILL HOLES, MINERAL LEASES, AND GEOPHYSICS IN THE DULUTH AND BEAVER BAY COMPLEXES, NORTHEASTERN MINNESOTA: INTEGRATION OF VARIOUS GIS DATABASES TO TELL A STORY OF THE HISTORY OF PAST AND CURRENT CU-NI-PGE MINERAL EXPLORATION

Steven A. Hauck, Julie A. Oreskovich, and Mark J. Severson, Economic Geology Group, Natural Resources Research Institute (NRRI), University of Minnesota, Duluth, 5013 Miller Trunk Highway, Duluth, MN 55811-1442, shauck@nrri.umn.edu

Mineral exploration in the Duluth Complex began in 1948 on Spruce Road when two prospectors found sulfide mineralization. Subsequent core drilling, geological mapping, and airborne and ground geophysics by more than 28 exploration companies (including the NRRI, MGS - Minnesota Geological Survey, and the DNR - Dept. of Natural Resources, Division of Lands and Minerals), over the next 52 years led to the discovery of copper-nickel±platinum-group element (PGE) mineralization along the basal contact of the Duluth Complex (Fig. 1). Ten Cu-Ni-PGE or PGE-Cu-Ni deposits were defined by drilling during these years. Over 2,142 drill holes have been drilled into the Duluth and Beaver Bay complexes with 1,666 of these holes being drilled along the basal contact. Over 954,000 ft. of drill core from the basal contact has been relogged by NRRI, and their results are discussed in many publications. Geophysical exploration began as early as 1956, by Bear Creek Mining Company, and continues today. The State of Minnesota (MGS), with funding from the Legislative Commission on Minnesota Resources, flew high resolution aeromagnetics over this area as well as the rest of the state. The MGS has also collected and produced a gravity map covering both complexes. Peak exploration (1966-1978) began with the leasing of State of Minnesota mineral rights in 1966 (Fig. 1). Exploration and development (drilling, bulk sampling, shaft sinking, resource calculations) continued through 1978. In 1998, State and Federal mineral leasing and exploration drilling began to increase with the: 1) rise in price of PGEs; 2) possible use of new hydrometallurgical techniques to more efficiently recover copper and nickel; and 3) introduction of new PGE exploration models (sulfide saturation; Miller et al., 2002) for intrusions in the Beaver Bay Complex, i.e., at Sonju Lake, and the Duluth Complex, i.e., Greenwood Lake and Layered Series at Duluth). The maps in this poster illustrate the relationship between geology, geophysics, drilling, and mineral leasing and were produced in ArcView (GIS). The maps were also compiled by using information from: 1) the DNR's online (minarchive.dnr.state.mn.us) attribute- and GIS-based database of non-ferrous minerals' information and State mineral rights holdings; 2) U.S. Forest Service leases, permits, and applications database; and 3) NRRI in-house GIS data on the history of Cu-Ni-PGE mineralization. Using the resulting GIS database, the spatial relationships in the changes in drilling, leasing, etc. with time and place were then combined with geological information from Miller et al. (2002) to better understand the past and present exploration areas and to assist in defining new areas in which to explore for non-ferrous minerals.

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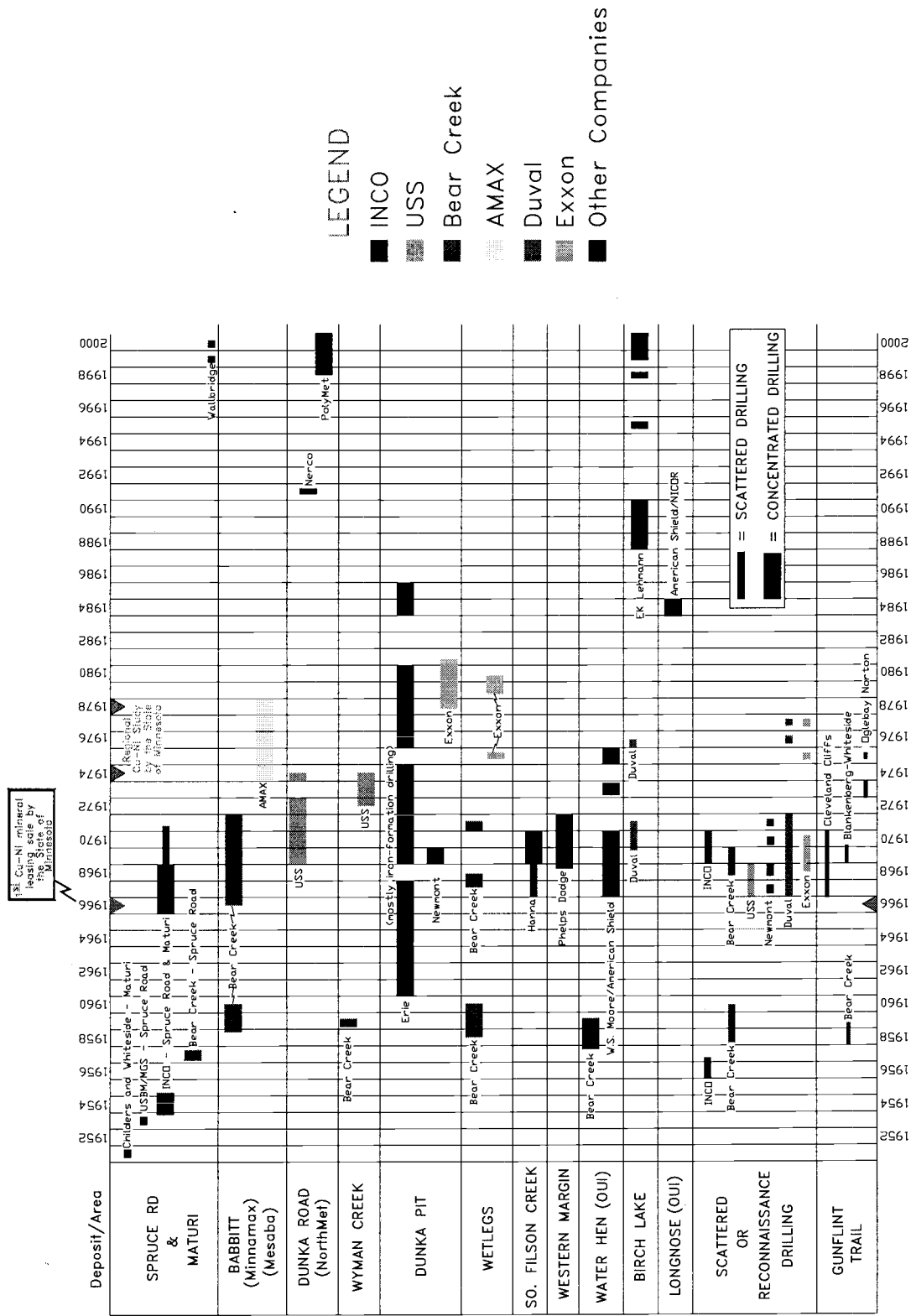


Figure 1. History of Cu-Ni-PGE exploration in the Duluth Complex (after Miller et al., 2002).

Geochemistry and Mineralization of the Seagull Intrusion, Northern Ontario

Heggie, G., and Hollings, P., (*Department of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, On, P7B 5E1, gheggie@mail.lakeheadu.ca*)

Platinum Group Elements (PGE-Platinum, Palladium, Osmium and Iridium) have seen substantial increases in demand over the last 30 years, as industrial and commercial users have increased their consumption. Canadian production of these metals has until recently been limited to by-products from nickel copper mines (e.g., Sudbury). Opening of the Lac des Iles mine in Ontario demonstrated the potential for economic PGE deposits in Canada. Further work on deposit and exploration models is essential to identifying new targets and prospective host rocks.

The Seagull Lake intrusion is found within the Nipigon Embayment, approximately 70km north east of Thunder Bay, Ontario (Fig.1). Relative age dating places the age of the Seagull Lake intrusion to be younger than the Sibley Group sedimentary sequence, (1339 ± 33 Ma) (Franklin et al., 1980),

as part of the intrusion has been seen to cross cut Sibley stratigraphy. A chilled margin has been observed between the Seagull Intrusion and the younger Nipigon Sills defining an upper age of approximately 1.1 Ga (Davis and Sutcliffe, 1985). This falls within the time of mid-continental rifting in the Lake Superior region. Volcanic activity was responsible for production of thick basaltic sequences (Cannon et al., 1989) beneath and around the shores of Lake Superior and the emplacement of numerous mafic to ultramafic complexes (e.g., Duluth complex).

The Seagull Intrusion is currently under exploration by East West Resource Corporation, It is a layered ultramafic intrusion consisting of cumulate olivine, and oxide minerals with pyroxene oikocrysts and interstitial feldspar. Lithological phases include dunites, lherzolites, olivine gabbro-norites, gabbros, and pyroxenites. A distinctive olivine gabbro-norite is found within the intrusion but this exhibits chilled margins and is thought to post date the formation of the rest of the intrusion.

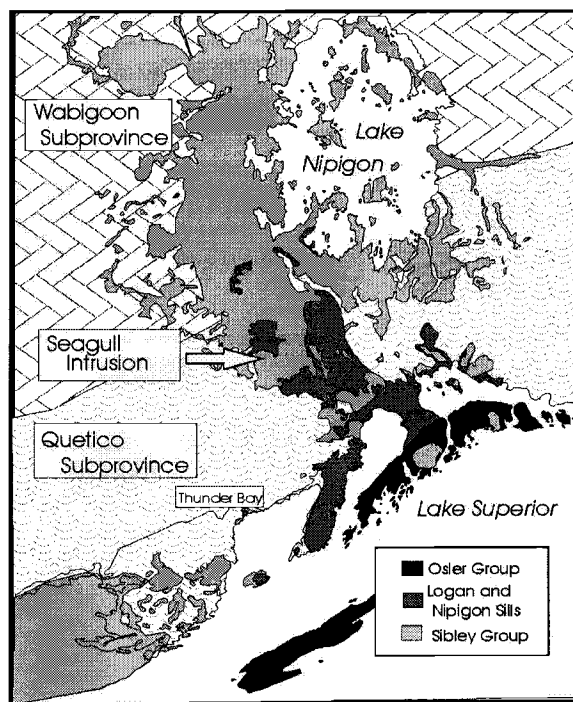


Figure 1. Map showing location of Seagull Intrusion and regional geology.

DDH	Depth (m)	Interval (m)	Cu (ppm)	Ni (ppm)	Pt (ppb)	Pd (ppb)
WM00-01	375.0	4.0	269	1160	307	383
	408.0	4.5	501	1413	336	418
	572.0	12.0	779	1565	363	438
WM98-02	546.0	6.0	1180	987	535	566
WM98-05	379.0	8.0	112	1647	336	393
	569.0	6.0	1843	1841	693	847
	579.0	6.0	1220	1455	458	537

Figure 2. Table of metal contents from assay (Caven, R., 2000)

Mineralization occurs in the form of PGE minerals associated with disseminated FeNi sulfides (pentlandite). Pentlandite is found in higher abundances at discrete intervals throughout the intrusion, with a general increase towards the base of the intrusion.

Work is currently being undertaken to understand the stratigraphy of the intrusion, the nature of the platinum group mineralization, and formational controls on the mineralized zones, which are present in the intrusion in order to aid in the development and refinement of exploration techniques, and deposit models.

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PEPERITES OF THE GAFVERT LAKE VOLCANIC COMPLEX, ST. LOUIS COUNTY, MINNESOTA

Heiling, Carrie D., Department of Geological Sciences, University of Minnesota Duluth, 1114 Kirby Drive, Duluth, MN, 55812; cheiling@d.umn.edu

The Gafvert Lake area, located within the Upper Ely member of the Ely Greenstone of the Vermilion District in Northeastern Minnesota (Figure 1) (Card, 1990), forms part of a large, Archean, felsic volcanic complex. Morton (personal communication) has interpreted the complex to be a composite volcano that underwent late stage caldera collapse. This study has focused on a two square mile area in the central part of the complex. Here the complex, from the oldest to the youngest rocks, is composed of a) coarse, heterolithic breccias (interpreted to represent meso- and mega breccias) (Morton, personal communication), b) more than 3000 feet of massive to bedded pumice-rich lapilli tuff, c) dacitic lavas and domes, and d) lenses and beds of chert and massive to semi-massive pyrite (Figure 2). The breccias and lapilli tuffs have been intruded by a swarm of feldspar porphyry dacite dikes that represent feeders to the domes and/or flows.

Peperites are rocks formed by the in situ disintegration of magma intruding and mixing with wet unconsolidated sediment or ash (Skilling *et al.*, 2002). At Gafvert Lake the peperites formed near the top of the complex where dacite porphyry dikes intruded and mixed with wet, unconsolidated pumice-rich lapilli tuff. This mixing led to quenching and fragmentation of the dacitic magma and disruption and vesiculation of the lapilli tuffs. The peperites occur within 100 feet of dike contacts though they form much more extensive areas where several dikes occur close together. Angular and finger-like blocks of dike material occur within the peperite, locally these are connected to a nearby dike.

Macrotextures in outcrop and microtextures in thin section helped identify and classify the following fragment types and internal structures within the peperites: a) blocky juvenile fragments with chilled rims and occasional jig-saw fit textures, b) platy to ragged juvenile fragments with curvilinear surfaces and broken gas bubbles, c) ameboid to globular juvenile fragments, d) abundant pumice which exhibits variable vesicularity. Most of this pumice is juvenile to the lapilli tuffs but a small percentage contains feldspar crystals identical to those found in the dikes possibly indicating local, rapid vesiculation of dike material. Close to dike margins feldspar crystals are broken and internally fractured with fractures filled by lapilli tuff. Pumice, close to dike contacts, may be broken or disaggregated into several small jigsaw-fit pieces. Locally the ash matrix to the lapilli tuffs is amygdaloidal with amygdules radiating away from dike margins.

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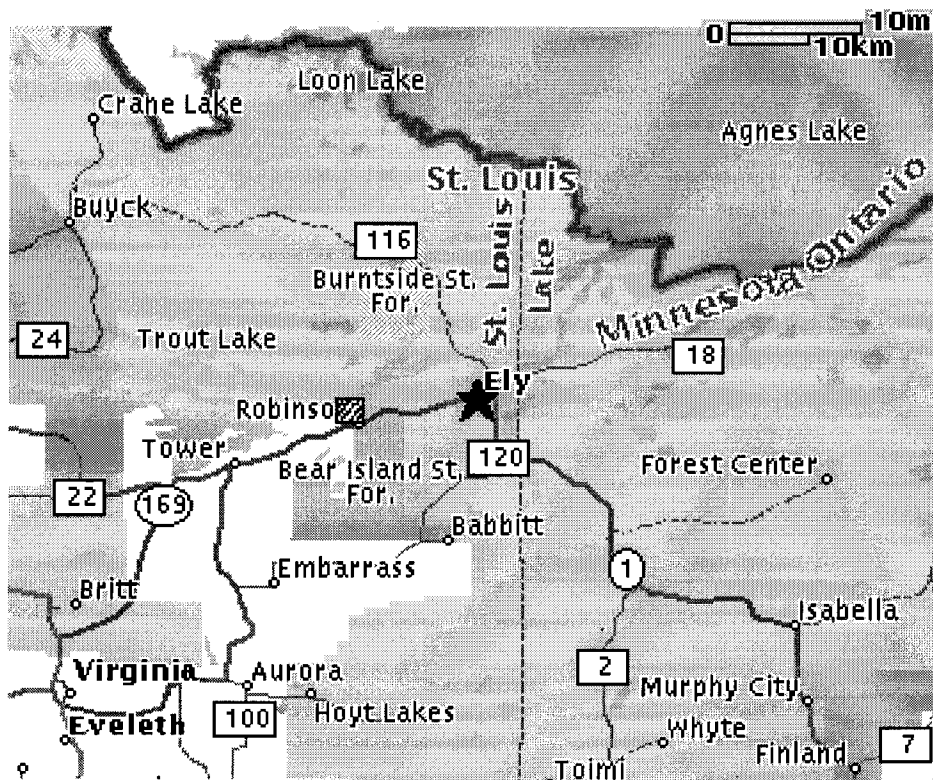
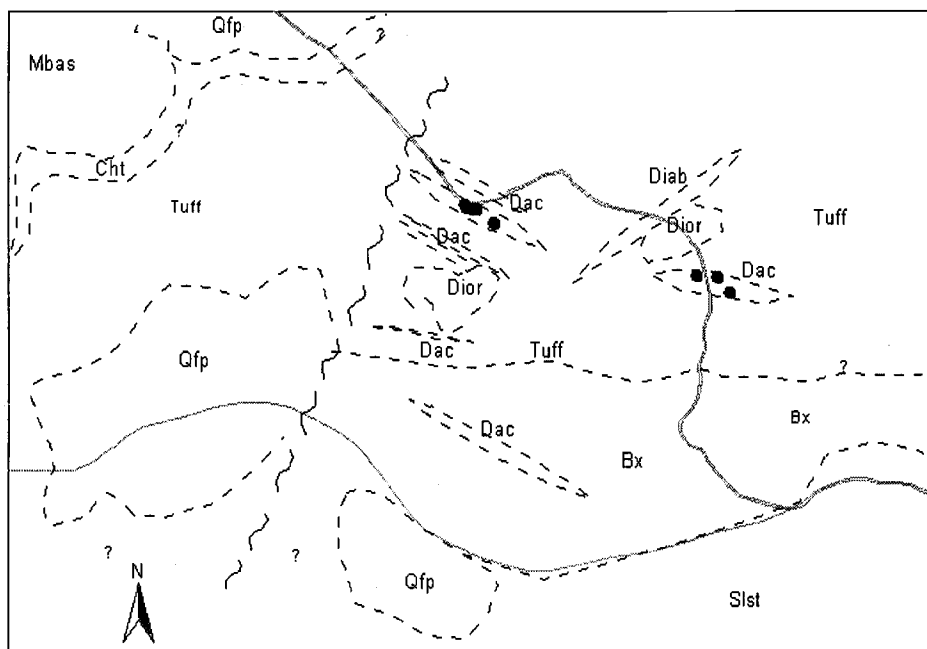


Figure 1: Location of Gafvert Lake complex (Mapquest, 2003).



Explanation

- Peperite samples
- Fault Zone
- ... Contacts
- Railroad grade
- Mud Creek Road

Mbas - Metabasalt
 Qfp - Qtzfeld Porphyry
 Cht - Black Chert
 Diab - Diabase Dikes
 Dior - Diorite
 Dac - Dacite Dikes
 Tuff - Lapilli Tuff
 Bx - Breccia
 Slst - Siltstone & Iron Fm

Figure 2: Generalized map of a portion of Gafvert Lake volcanic complex.

CHEMISTRY OF ALTERATION MINERAL PHASES AT THE FIVE MILE LAKE VOLCANIC-HOSTED MASSIVE SULFIDE PROSPECT, NE MINNESOTA

Hocker, S. M., Hudak, G. J., Odette, J. D., and Newkirk, T. T., Department of Geology, University of Wisconsin Oshkosh, 800 Algoma Blvd., Oshkosh, WI 54901, hudak@uwosh.edu

Alteration mineral assemblage mapping at the Five Mile Lake Prospect in the Vermilion District of northeastern Minnesota has identified two distinct types of alteration zones within 2.7 billion year-old volcanic and volcanoclastic rocks associated with volcanic-hosted massive sulfide (VHMS) mineralization (Hudak et al., in press; Odette et al., 2001a, 2001b; Peterson, 2001). Regional semi-conformable alteration zones are composed of various proportions of quartz + epidote $\pm$ amphibole $\pm$ chlorite $\pm$ plagioclase feldspar. These regional, semiconformable alteration zones are locally cross-cut by several relatively narrow, northeast-trending disconformable alteration zones composed of fine-grained chlorite and/or sericite that are closely associated with synvolcanic fault zones.

Electron microprobe analyses of the various alteration mineral phases (epidote group minerals, chlorite, amphibole, white mica, and feldspar) have been conducted in an effort to better understand hydrothermal processes associated with the development of the semiconformable and disconformable alteration zones at the Five Mile Lake prospect. These analyses indicate that: a) epidote group minerals range in composition from zoisite/clinozoisite to pistacite; b) chlorite is dominantly ripidolite; c) amphibole is primarily actinolite and ferro-actinolite, with magnesio-hornblende and ferro-hornblende also present; d) sericite is fine-grained muscovite; and e) plagioclase feldspar is dominantly albite.

Alteration mineral chemistry at the Five Mile Lake Prospect is remarkably similar to that from the Noranda VHMS mining camp of Canada, as well as other VHMS mining camps around the world. This alteration mineral chemistry suggests the presence of a complex, long-lived hydrothermal system that evolved from seafloor-proximal (hundreds of meters) to deeper subseafloor environments (~1-3 kilometers) as the volcanic rocks were buried by apparently rapid, dominantly effusive mafic to intermediate volcanism and associated sedimentation. This suggests that in addition to the Five Mile Lake Prospect, the uppermost several hundred meters of the Lower Member of the Ely Greenstone also has excellent exploration potential for VHMS mineral deposits.

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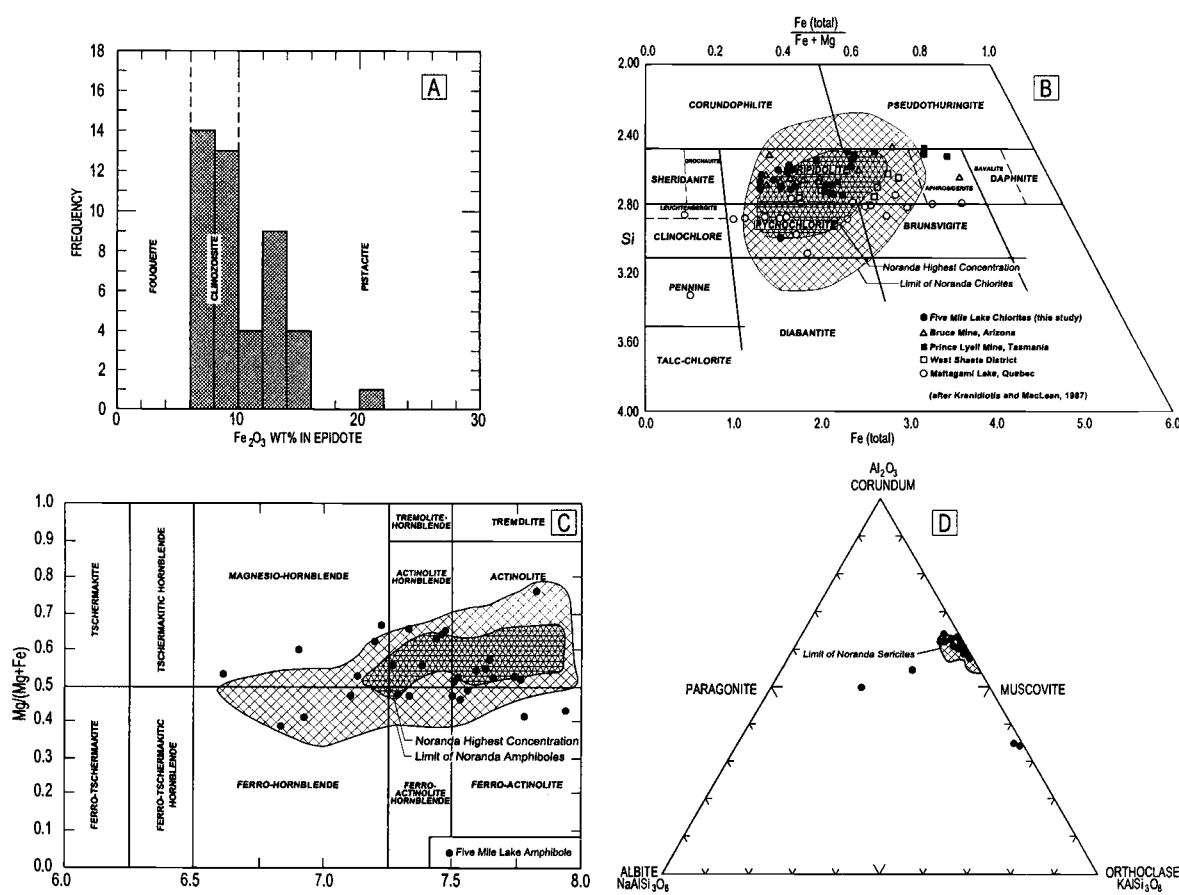


Figure 1. Summary of electron microprobe analyses for epidote-group minerals (A), chlorites (B), amphiboles (C), and white micas (D) from the Five Mile Lake Prospect and selected VHMS mines. Compositional fields for Noranda minerals determined from Galley et al. (2002).

GEOCHEMISTRY AND GEODYNAMIC IMPLICATIONS OF THE 1537 MA REDSTONE POINT ANOROGENIC GRANITE, ONTARIO, CANADA

Hollings, P., Fralick, P. and Kissin, S. (Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada; Peter.Hollings@lakeheadu.ca)

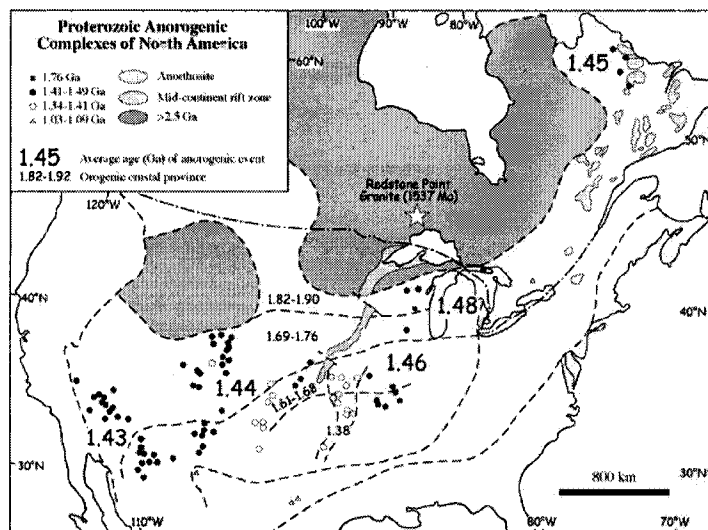


Figure 1. Map showing the location of the Redstone Point granite in relation to Proterozoic anorogenic granite complexes of North America. Modified after Anderson (1983)

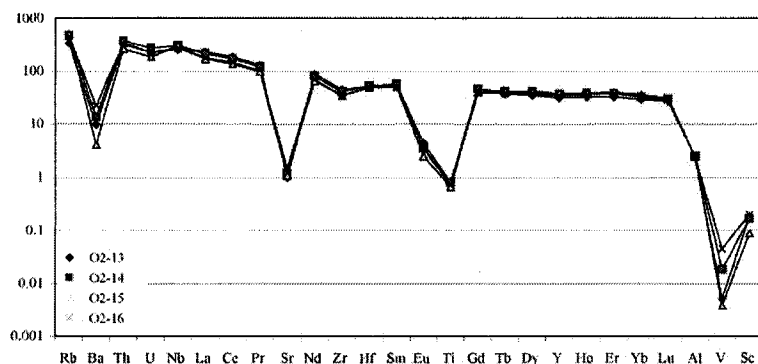
The Redstone Point granite is a Mesoproterozoic felsic igneous complex (1537±10/-2 Ma; Davis and Sutcliffe, 1984) located in the northern portion of the Sibley Basin on the west shore of Lake Nipigon (Fig. 1). It is unconformably overlain by arenites of the Pass Lake Formation of the Sibley Group. These sediments are in turn intruded and overlain by an extensively developed sequence of diabase sills related to an early stage of the Mid-Continent Rifting event. The entire sequence has been gently folded into a shallowly, easterly plunging succession of open synclines and anticlines, with dips not usually exceeding 15°. Outcrop density of igneous units is very good along the shoreline of Lake Nipigon, in contrast to sedimentary sequences, which only provide small, scattered outcrops.

The igneous rocks of Redstone Point have been briefly described by Davis and Sutcliffe (1985), wherein they emphasised that the rocks are anorogenic granites gradational to rhyolites and fragmental rhyolites and dacites. In fact, presently accessible outcrop indicates that extrusive members dominate the magmatic rocks of the area. Porphyritic texture with volcanic features including vesicles, flow structures, agglomeratic units, rubbly flow tops and segregation cylinders differentiate extrusive rocks from more limited exposures of uniformly textured intrusive rocks. As contacts between units are generally unexposed and the base of the section is nowhere exposed, thicknesses of units and of the entire succession are unknown; however, continuous outcrop in cliff-forming units indicates that a minimum thickness of 100m of volcanic rock is present in the area.

The igneous rocks are distinctively brick red, suggesting the dominance of ferric iron in the various mineral hosts but especially in trace amounts in feldspars. The intrusive member displays equigranular phaneritic texture with most mineral grains 1 to 5 mm in diameter. The volcanic rocks are true porphyries with phaneritic phenocrysts of alkali feldspar, quartz and hornblende in an aphanitic matrix of the same minerals. Quartz phenocrysts are euhedral and 1 to 3 mm in diameter associated with alkali feldspar phenocrysts occasionally exhibiting synneusis twinning as well as albite-pericline twins indicative of microcline. Hornblende and magnetite are less

abundant and finer grained than in the intrusive rocks. Near flow tops the porphyries grade into uniformly textured aphanitic rhyolites with sparse phenocrysts.

The samples from the Redstone Point intrusive complex are all characterised by high SiO_2 contents (73-83 wt%) and elevated K_2O and Na_2O abundances (2-7 wt% and 0.2-3.5 wt%



respectively). They are typically LREE enriched with relatively unfractionated HREE ($\text{La}/\text{Sm}_n = 2.8-5.1$; $\text{Gd}/\text{Yb}_n = 1.1-1.6$; Fig. 2) and are characterised by elevated Zr, Y and Nb contents. Samples from the Redstone Point igneous complex fulfil the detailed trace element criteria of Whelan et al. (1987) for anorogenic granites.

Figure 2. Representative primitive mantle normalised diagram for samples from the Redstone Point igneous complex

Similarities between Proterozoic basin sequences (e.g., Athabaska,

Thelon, Hornby Bay and Sibley basin fill sequences) imply that basin genesis and developmental controls were similar. The setting, architecture, depositional systems and deformational histories of all four basins strongly infer that they are intracratonic, forming as a result of heating cratonic lithosphere. The heating event is represented in northern Canada by numerous 1790 to 1730 Ma anorogenic, syenogranite batholiths and comagmatic ash-flow tuffs occurring west of Hudson Bay. In the western Great Lakes region a heating event produced the 1537 Ma Redstone Point assemblage and other 1500 Ma anorogenic batholiths. The southern mid-continent records a lithospheric heating event with anorogenic granite production from approximately 1480 to 1320 Ma (Fig. 1). These events outline a progressive southward displacement of lithospheric heating from a maximum age of approximately 1750 Ma in northern Canada to a minimum age of 1310 Ma in the southwestern United States. As heat transfer from the asthenosphere is the only mechanism for producing extensive lithospheric heating, drift of North America over hotter than average asthenosphere is implied. Using regional ages of heating, drift rates of approximately 1.1 to 1.4 cm/year are necessary, and agree in magnitude with present rates.

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LATE PALEOPROTEROZOIC (1900-1600 Ma) TECTONIC HISTORY OF THE NORTHERN MID-CONTINENT, U.S.A: IMPLICATIONS FOR CRUSTAL STABILIZATION

HOLM, D.K., Dept. of Geology, Kent State University, Kent, OH 44242; VAN SCHMUS, W.R., and MacNEILL, L.C., Dept. of Geology, University of Kansas, Lawrence, KS 66045; BOERBOOM, T.J., Minnesota Geological Survey, 2642 University Avenue, St. Paul, MN 55114; SCHWEITZER, D., Dept. of Geology, Kent State University, Kent, OH 44242; SCHNEIDER, D.A., Dept. of Geological Sciences, Ohio University, Athens, OH 45701

We propose that the late Paleoproterozoic igneous and deformational history preserved in the southern Lake Superior region is the result of northwest-directed convergence during and following geon 18 Penokean accretion. New U-Pb zircon ages indicate that late to post-Penokean magmatism began ca. 1800 Ma and generally migrated southeastward across the newly accreted terrane. Magmatic pulses at ca. 1800, 1775, and 1750 Ma may correlate with northwest-directed subduction associated with southward growth of the North American mid-continent. We suggest that geon 17 Yavapai-age slab rollback caused continental arc magmatism to step southeastward between 1800 and 1750 Ma (Fig. 1A). As the slab steepened, the reduced compressional stresses and increased thermal input allowed for collapse of the overthickened portions of the Penokean crust. In northern Wisconsin, collapse involved the formation of gneiss domes and their exhumation within discrete fault-bounded panels brought up from depth via tectonic extrusion (Schneider et al., ILSG, 2003). Collapse of the Penokean orogen – and possibly temporary cessation of slab subduction – resulted in crustal stabilization and deposition of Baraboo Interval quartzites between 1750 and 1650 Ma. However, in a long-lived orogen model, renewed tectonism to the south resulted in the eventual accretion of a Mazatzal arc (Fig. 1B) with widespread deformation and mild reheating of Penokean crust to the north. The age of this deformation is inferred from conventional Ar/Ar step-heating studies on basement rock beneath deformed and undeformed Baraboo Interval quartzites. The 1900 to 1600 Ma tectonic history of the north-central United States, not surprisingly, records the southward growth and tectonic development of the southern Laurentian margin.

New and published $^{40}\text{Ar}/^{39}\text{Ar}$ mineral ages delineate the northern and western extent of geon 16 crustal deformation. Interestingly, only lower-grade crust intruded by the shallower-level ca. 1750 Ma plutons (and associated rhyolites) were deformed significantly during geon 16. Deeper level collapsed crust and crust pervasively invaded by the older magmatic pulses are largely unaffected by Mazatzal deformation and reheating. We suggest that post-orogenic intrusions and crustal thinning was an important step in strengthening and stabilizing the crust in the southern Lake Superior region.

Schneider, Holm, O'Boyle, Hamilton, and Jercinovic, 2003, Paleoproterozoic development of a gneiss dome corridor in the southern Lake Superior region, USA: Institute on Lake Superior Geology Abstracts (this volume).

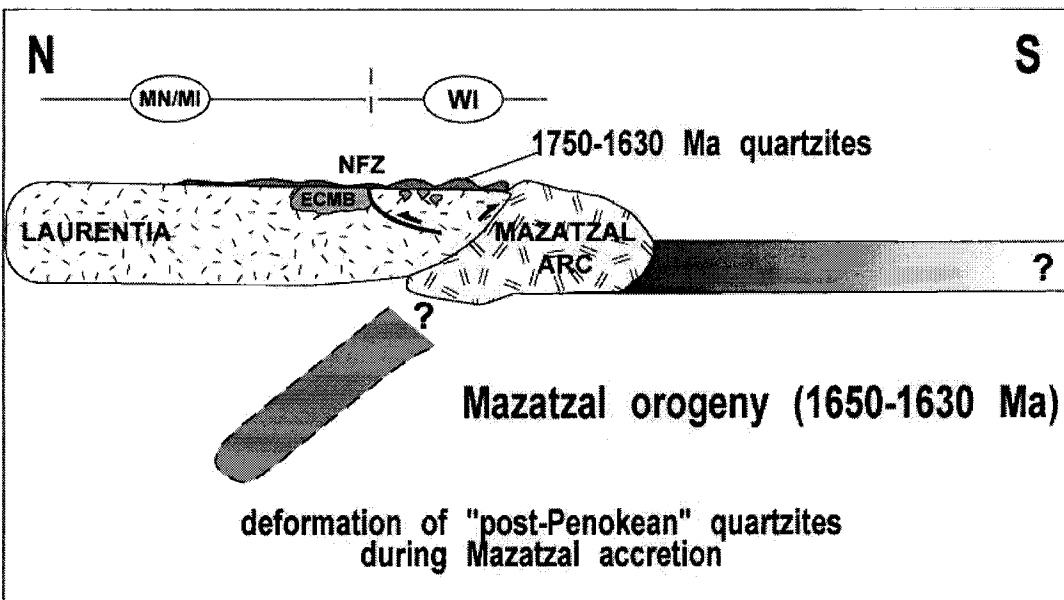
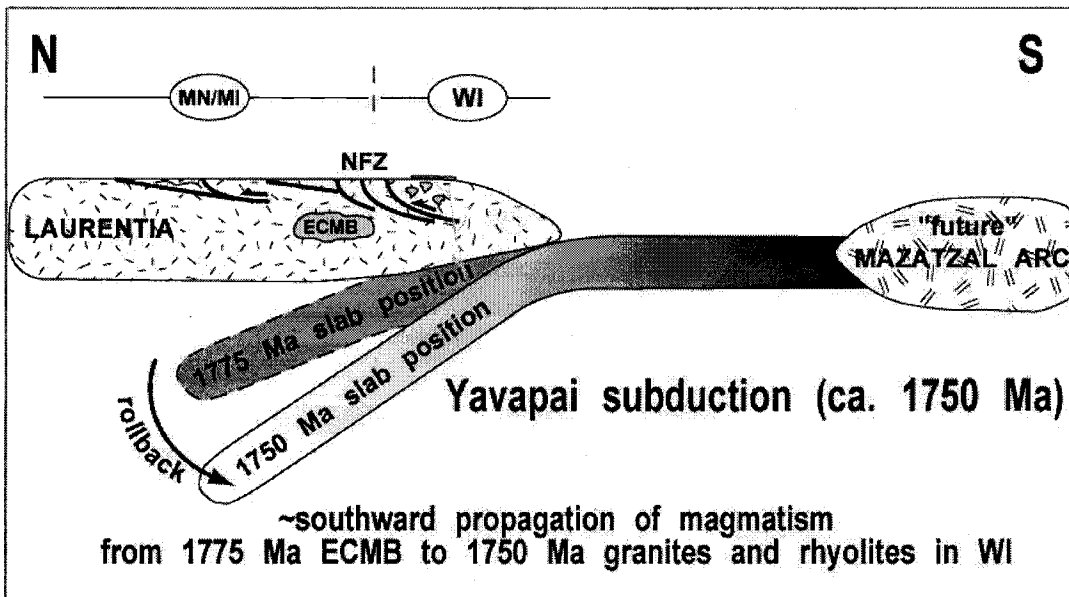


Figure 1: A) Subduction rollback model proposed to explain magmatic age progression across the Penokean orogen, ca. Yavapai convergence, pre-Mazatzal accretion. ECMB = East-central Minnesota batholith. B) Mazatzal accretion model (modified after Romano et al., 2000) to explain deformation of Baraboo Interval quartzites and southward growth of Laurentia.

GABBRO/GRANOPHYRE RELATIONS OF THE CROCODILE LAKE INTRUSION: A POSSIBLE VENT FOR THE HOVLAND LAVAS?

JERDE, Eric A. (e.jerde@morehead-st.edu), Department of Physical Sciences, Morehead State University, Morehead, KY 40351

One of the notable characteristics of the Midcontinent Rift is the presence of large amounts of felsic material. Indeed, the nature and origins of this abundant silicious material has been the source of numerous studies (e.g., Nelson, 1991; Green and Fitz, 1993; Vervoort and Green, 1997; Kennedy et al., 2000; Sandland et al., 2001). To the south of the Early Gabbro Series is a pronounced ridge composed of this felsic material, properly termed a granophyre. The Early Gabbro Series layers are inclined to the south, thus are below the granophyre stratigraphically. This felsic rock was noted and described by Nathan (1969) as a very late-stage material, and has generally been presumed to have formed significantly after the gabbros in the region. However, several observations indicate that the gabbro was emplaced later than the granophyres. These include gradational contacts, with some chilling of the gabbro. Another observation is the abundance of material described as "intermediate rock" by various investigators in the past (e.g., Grout et al., 1959). This material is always found between the gabbro and granophyre, and is presumably the result of assimilation of granophyre by an intruding, hot gabbro.

Investigations into possible origins of the granophyres (Sandland et al., 2001; Karl Wirth, pers. comm.) included radiometric age determinations, and revealed that the granophyres adjacent to the Early Gabbro Series are, like the gabbros, among the earliest rocks of the rift (~1107 Ga), and essentially contemporaneous. Because silicious material generally is a late-stage product of magma evolution, the surprising antiquity of the granophyres adds to questions surrounding their origin.

The early age for the granophyres does, however, suggest an origin for the layered nature of the Early Gabbro Series located below them stratigraphically. Due to their low density, the granophyric material would have created a barrier that retarded the rise of buoyant gabbroic material coming up from below. These rising liquids would have been forced to spread laterally, resulting in the apparent layering that is observed, and providing a cap, blocking any further rise of gabbroic material.

Immediately to the east of the layered Early Gabbro Series of Nathan (1969) is another occurrence of granophyre, also determined to be among those of an early origin (i.e., ~1107 Ga; Karl Wirth, pers. comm.). This rock group has been termed the Crocodile Lake Intrusion by Miller et al. (2001), and the rocks are interpreted to be gabbroic based on geophysical evidence, and a few sample examinations (Babcock, 1959). Work done between 1913 and 1948 included the very edges of this intrusion, and indicates that they are basalt lavas and gabbroic intrusions, along with "red rock" (Grout et al., 1959) that is now known to refer to granophyre. Like the series mapped by Nathan (1969), there is a body of gabbroic material stratigraphically below the granophyre.

During the past year, a reconnaissance was made into the Crocodile Lake Intrusion to examine some of the rock relations (Fig. 1). Traverses were greatly hampered by forest blowdown, but the outcrops are numerous. Several gabbro units are present, as well as a band of "intermediate material" at the very top of the gabbro, below the granophyre. Within the granophyre itself, several bodies of gabbro were found to have actually intruded the granophyre. In the coarse-grained interiors of these bodies, the gabbro is indistinguishable from the gabbros observed further north (i.e., below the granophyre stratigraphically).

Immediately to the south of the granophyre are prominent knobs and ridges that are composed of basalt. These are mapped as part of the Hovland Lavas, which are reversely polarized, and were extruded during the earliest period of the rifting. It is perhaps possible that the discontinuous bodies (and other stringers and local dikes) within the granophyre represent the feeder conduits for the eruptive basalts immediately to the south (shown schematically in Fig. 2). In several other places within the granophyre, there are basaltic stringers and small dikes. Surrounding the larger gabbroic bodies are obvious reaction zones where granophyre has been assimilated into the gabbro. In one of the flows immediately to the south, numerous inclusions are present that are pinkish in color, along with felsic stringers and irregular masses of felsic material.

Further work is planned to assess the relation between the gabbros within the granophyre and the lavas to the south. If this is indeed a feeder system, it might provide insight into the mechanism of magma emplacement and the eventual "breakthrough" to the surface, during the onset of rifting.

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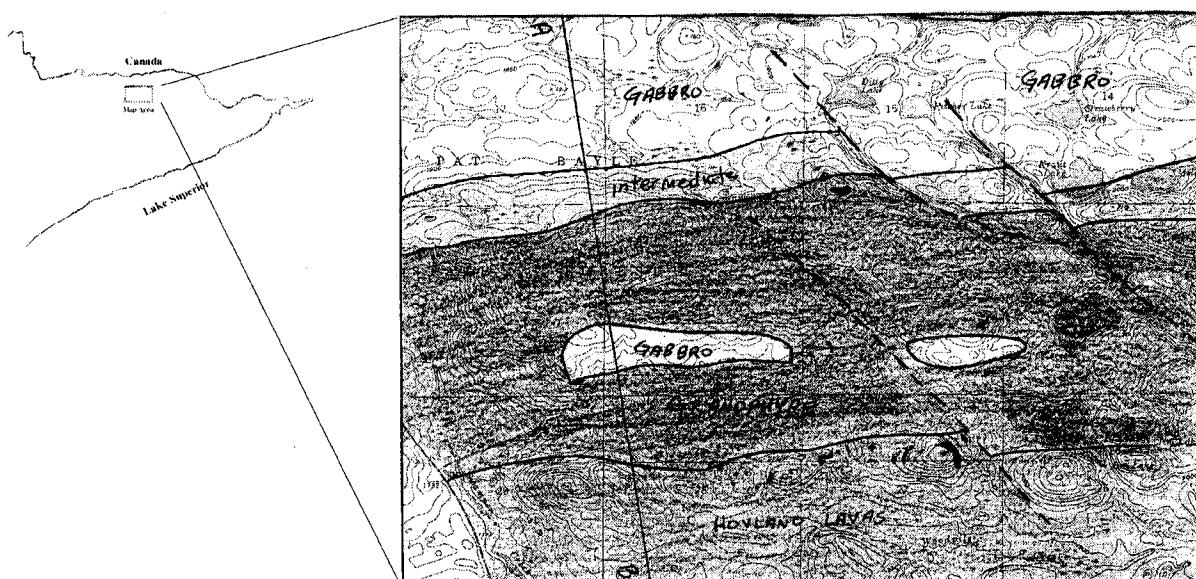


Fig. 1. Reconnaissance geologic map of the region just south of Crocodile Lake, showing location of gabbro bodies in the granophyre that forms the cap above the Crocodile Lake Intrusion gabbros and intermediate rocks.

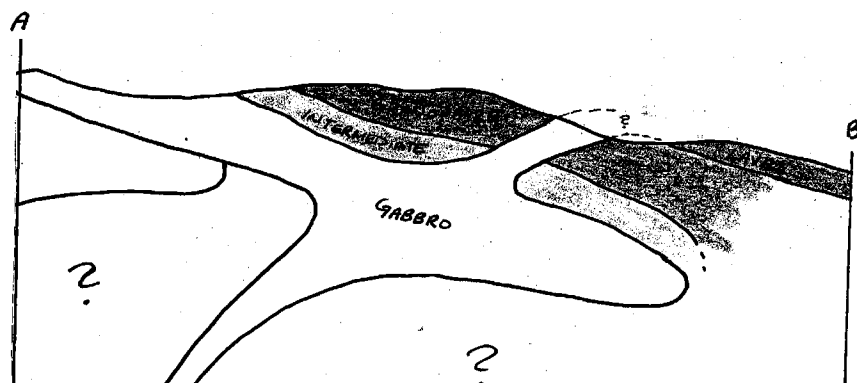


Fig. 2. Schematic N-S cross section of Fig. 1 showing the possible feeder for the Hovland Lavas.

MINERALIZATION OF THE NORTON LAKE Cu-Ni-PGE DEPOSIT

JOHNSON, J.R., HOLLINGS, P. and KISSIN, S.A. Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1, jrjohnsonca@yahoo.ca

The Norton Lake Cu-Ni-PGE deposit is located approximately 50 km northeast of Fort Hope, within the Miminiska-Fort Hope Greenstone belt of the Uchi Subprovince, northwest Ontario (Figure 1). Only limited geological investigations have been undertaken within the belt due to both its remote location and sparse outcrop. As a result of this the belt has been subdivided based on limited structural and regional stratigraphic considerations (Stott and Corfu, 1991). The Norton Lake deposit is located within an unnamed assemblage comprising basaltic flows with magnetite iron formations. It is thought that this assemblage can be correlated, through similar rock types and aeromagnetic trends, with the ~2900 Ma Northern Pickle terrane of the Pickle Lake greenstone belt (Corfu and Stott, 1996).

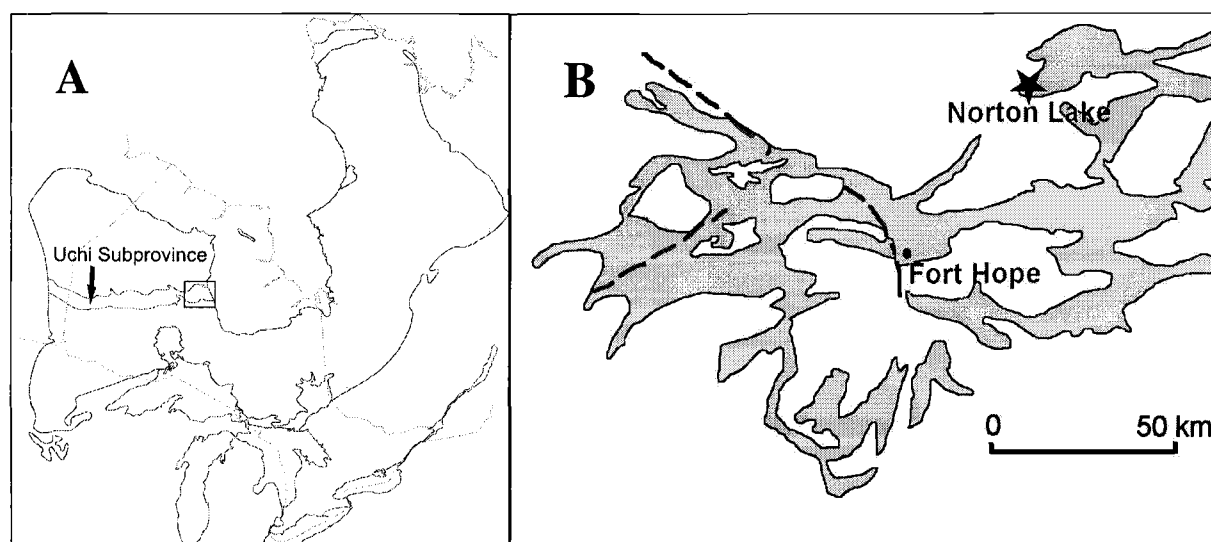


Figure 1: A-Map of Superior Province showing location of Uchi Subprovince.
B Simplified geology map of the Miminiska-Fort Hope Greenstone belt
(after Stott and Corfu, 1991).

The Norton Lake area consists of massive to pillowed basalts with rare ultramafic flows. The deposit itself is hosted within a sheared amphibolite with minor gabbroic units. Previous work determined the deposit to be a 944 500 tonne nickel-copper deposit containing 0.72% Ni and 0.56% Cu with an undefined PGE potential (East West Resource Corporation, 2001). The geological setting, host rock and mineralization of the Norton Lake deposit are comparable to that of the Thierry Deposit, Pickle Lake, Ontario. The Thierry Mine is currently undergoing renewed exploration to determine its viability as a PGE deposit (PGM Ventures).

East West Resource Corporation (EWR) has undertaken a detailed exploration program in the vicinity of Norton Lake, including an extensive drilling program. Detailed examination of drill core has been undertaken with special attention being paid to the mineralized 'main' zone to determine the exact nature of the mineralization. Preliminary results indicate the deposit consists of massive pyrrhotite with pentlandite, magnetite, chalcopyrite and pyrite. The platinum group element's (PGE's) are found forming discrete platinum group minerals and are also believed to form a solid solution with the sulphides. Results show that in addition to primary mineralization a secondary, hydrothermal, enrichment of PGE's has taken place.

Mineral	Formula	Minor Elements	Notes
Pyrrhotite	Fe_{1-x}S	Ni	Main mineral
Pentlandite	$(\text{Fe},\text{Ni})_9\text{S}_8$	Co	Secondary
Pyrite	FeS_2	Co	Trace
Chalcopyrite	CuFeS_2	Ni	Trace, also veins
Manganoan Illmenite	$(\text{Fe},\text{Mn})\text{TiO}_3$		More common than magnetite, easily mistaken for magnetite in polished section
Magnetite	Fe_3O_4		
Michenerite	PdBiTe	Sb, Pt	
Hessite	Ag_2Te		

Table 1: Summary of the mineralogy of Norton Lake deposit.

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East West Resources Corporation, 2001. Annual Report.

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Stott G. M. and Corfu F. 1991, Uchi Subprovince, in *Geology of Ontario*, Ontario Geological Survey Special Volume 4, Part 1.

STRATIFORM Pd-Pt-Au MINERALIZATION IN THE SONJU LAKE INTRUSION, LAKE COUNTY, MINNESOTA

JOSLIN, Gregory D. Department of Geological Sciences, University of Minnesota-Duluth, 1114 Kirby Drive, Duluth, MN 55812, email: josl0013@d.umn.edu; **MILLER**, James D., Jr., Minnesota Geological Survey, c/o NRRI, 5013 Miller Trunk Hwy, Duluth, MN 55811; and **ROWELL**, William, F., Franconia Minerals Corp., 12 S. 6th St., Minneapolis, MN 55402.

The Sonju Lake intrusion (SLI) is a 1200 m thick, closed-system, well-differentiated, tholeiitic, layered intrusion located within the Mesoproterozoic Midcontinent Rift-related Beaver Bay Complex of northeastern Minnesota (Miller and Chandler, 1997). In the late 1990's, outcrop sampling by Miller (1999) indicated the presence of meter-scale stratiform Pd-Pt-Au mineralized interval (or PGE reef) within the oxide gabbro unit of the SLI, located about 2/3 of the way up from the basal contact of the intrusion. In June of 2002 Franconia Minerals Corp. conducted exploratory drilling through the Pd-Pt-Au enriched zone.

In hand sample, the mineralized interval appears as a homogeneous oxide gabbro, with no visible indication of precious metals enrichment. However, geochemically the location of the mineralization is distinct. Three drill cores, spanning a strike length of approximately 800 m, define and are correlated on the basis of a distinctive Cu-Au break datum (Fig. 1). With the exception of localized Pt enrichment associated with an interval enriched in olivine about 110 m below the Cu-Au horizon, all Pd-Pt-Au enrichment occurs over an interval of 0 to 90 m below the defined datum (Fig. 2). In general precious metals peaks are stratigraphically offset from one another, progressing upward in the succession Pd→Pt→Au. Maximum grades in 0.3m long core samples are 410 ppb Pd, 275 ppb Pt, and 1080 ppb Au. Above the Cu-Au break, all precious metals are very strongly depleted. Strong correlation between Fe, Al and modal olivine with precious metals peaks indicates a possible connection between subtle modal layering of plagioclase, oxide, and olivine with mineralization.

The oxide gabbro-hosted PGE reef in the Sonju Lake intrusion shows marked similarities, with some differences, to stratiform PGE mineralization in the Skaergaard intrusion of East Greenland (Andersen et al., 1998), the Rincon del Tigre Complex of Bolivia (Prendergast, 2000), and many other tholeiitic mafic layered intrusions throughout the world. Whole rock geochemistry, clinopyroxene and olivine compositions, and petrographic data are consistent with an orthomagmatic origin for the mineralization related to the fractional segregation of sulfide melt from silicate magma. The homogeneity of the host rock, the thickness of the mineralized interval, and the offset of metal concentrations imply that sulfide saturation was passively triggered by fractional crystallization of the Sonju magma. Mungall (2002) recently argued that stratigraphic offsets of Pd, Pt, Au and Cu peaks common to many PGE reefs can be satisfactorily explained by a kinetic model of sulfide liquation and settling. The model shows that the degree of offset and metal enrichment will be controlled by kinetic factors, such as the diffusivity of chalcophile elements, the degree of sulfide supersaturation, sulfide droplet size, and its settling velocity, which result in variability of the apparent silicate/sulfide melt ratio (R factor). The correlation of multiple peaks of PGE with subtle, broad modal variations may be related to repeated convective overturn caused by the crystallization of magnetite in an environment of sulfide over-saturation, as suggested by Prendergast (2000) to explain a similar correlation in the Rincon del Tigre Complex. Some evidence of late-stage sulfide dissolution and remobilization exists, but it appears to have little to no effect upon the distribution of precious metals.

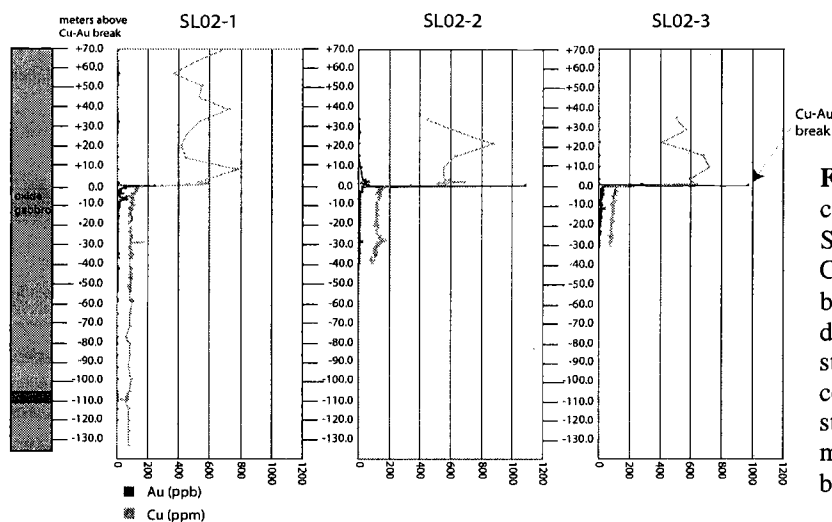


Fig. 1: Correlation of drill cores SL02-1, SL02-2, and SL02-3 showing distinctive Cu-Au break. The Cu-Au break is used to provide a datum to which all stratigraphic plots are correlated, and position in stratigraphy is measured as meters above or below Cu-Au break.

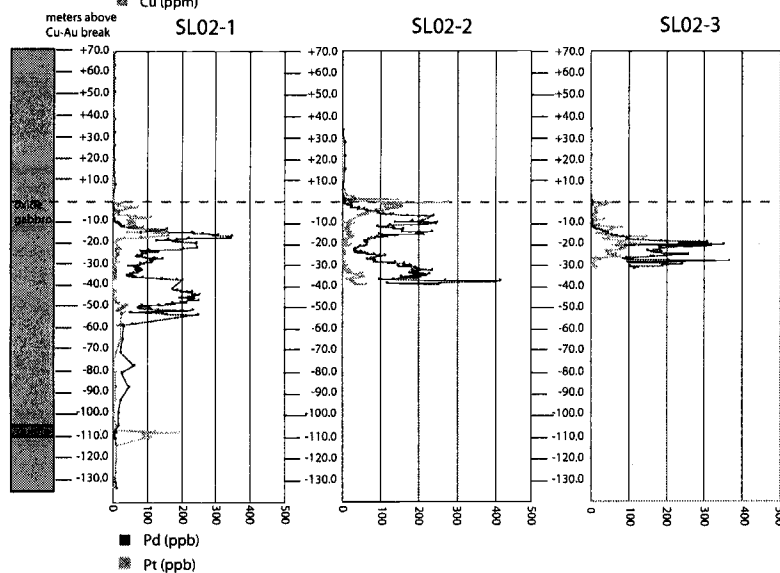


Fig. 2: Correlation of Pd and Pt in drill holes SL02-1, SL02-2, and SL02-3. Notice multiplicity of spikes and offset between Pt and Pd peaks.

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RESULTS OF $^{40}\text{Ar}/^{39}\text{Ar}$ SINGLE-GRAIN ANALYSES OF PRECAMBRIAN MAFIC INTRUSIONS IN NORTHERN AND EAST-CENTRAL MINNESOTA

KEATTS, M.J., Dept. of Geology, Kent State University, Kent, OH 44242; JIRSA, M., Minnesota Geological Survey, 2642 University Avenue West, St. Paul, MN 55114-1057; HOLM, D., Dept. of Geology, Kent State University, Kent, OH 44242

Age information from mafic intrusive suites is critical for proper interpretation of the geologic history and for mineral deposit models in the Lake Superior region. As part of an effort to evaluate PGE potential in mafic intrusions in Minnesota, several plutons have been dated using the CO_2 laser Ar/Ar incremental heating technique at the University of Wisconsin-Madison Rare Gas Geochronology Laboratory. For late-stage shallow plutons containing primary magmatic hornblende, Ar/Ar mineral ages are likely to closely approximate the crystallization age. In regions with a more protracted thermal history (i.e., low-grade metamorphism, slow-cooling, etc.), the Ar/Ar data provide minimum ages for the mafic plutons. Mafic intrusions from Minnesota selected for this study represent a broad range of geologic settings, including 1) small mafic plutons emplaced into Paleoproterozoic supracrustal and intrusive rocks within the Penokean orogen (samples 264, R17); and 2) varied, primarily late- to post-tectonic intrusions in supracrustal rocks of the Archean Wabigoon (samples A1, B21, UBD) and Wawa (samples K15, LP, ANA) subprovinces of Superior Province. We report here the initial results from eight separate intrusions (Fig. 1).

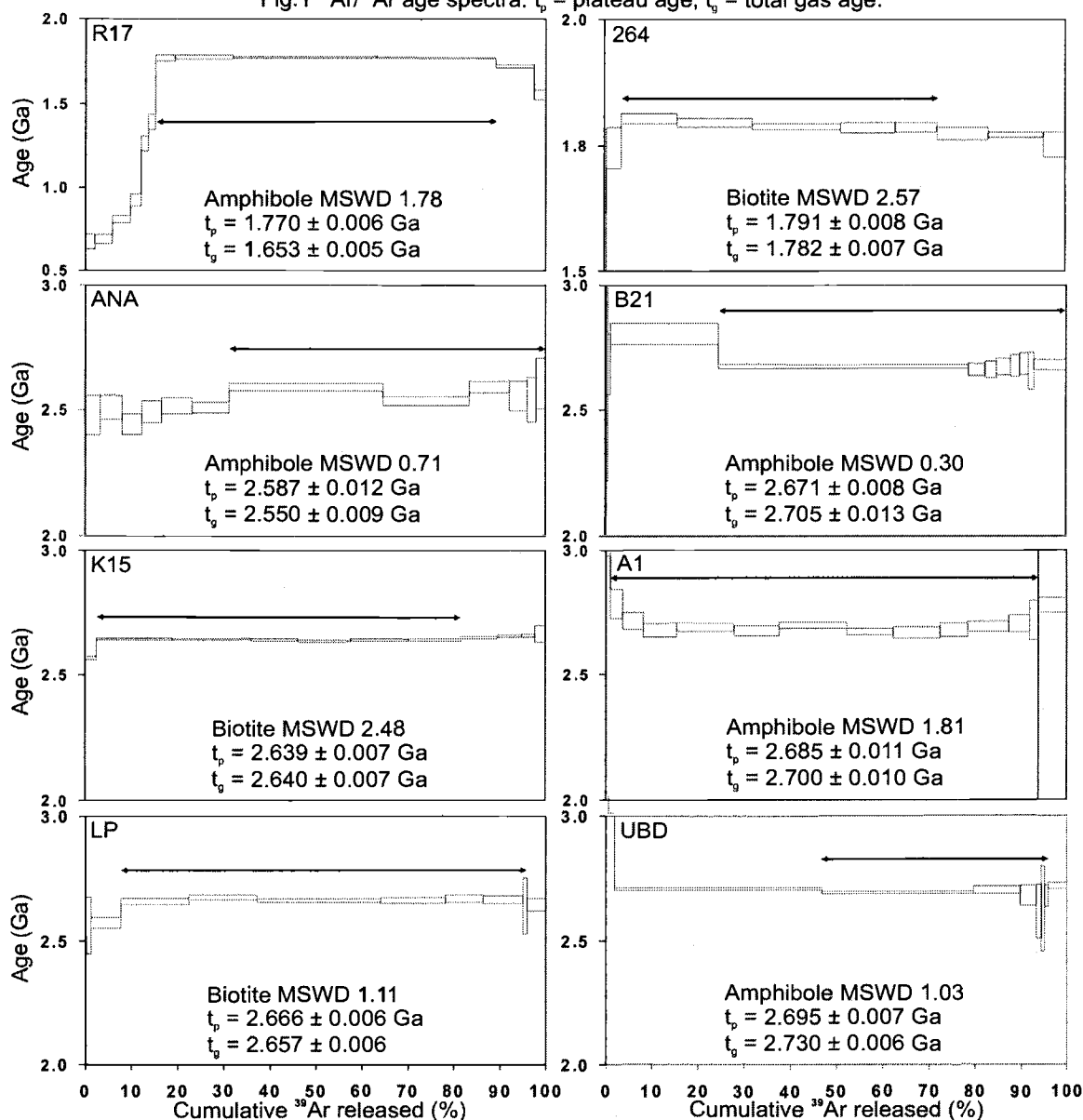
East-central Minnesota. A hornblende grain (R17) from a sample of medium-grained hornblende from the Tibbett's Brook intrusion cutting the East-central Minnesota batholith in Morrison Co. yields a plateau date of 1.770 ± 0.006 Ga from 4 contiguous increments constituting 74% of the gas released. A biotite grain (264) from a sample of coarse-grained biotitic olivine gabbro cutting the Little Falls Formation in Morrison Co. yields a plateau date of 1.791 ± 0.008 Ga from 5 contiguous increments constituting 68% of the gas released.

Wawa Subprovince. A hornblende grain (ANA) from a sample of prismatic hornblende diorite collected near Red Lake in Beltrami Co. yields a near-plateau date of 2.587 ± 0.012 Ga in 5 non-contiguous increments constituting 50% of the gas. A biotite grain (K15) from a sample of biotite granodiorite porphyry collected in Norman Co. yields a plateau date of 2.639 ± 0.007 Ga from 6 contiguous increments constituting 79% of the gas released. A biotite grain (LP) from a sample of porphyritic syenite collected at the Wawa-Quetico subprovince boundary in St. Louis Co., in the Linden Pluton, yields a plateau date of 2.666 ± 0.006 Ga from 7 contiguous increments constituting 88% of the gas released.

Wabigoon Subprovince. A hornblende grain (B21) from the Oaks intrusion leucodiorite sampled near the Vermilion Fault in Roseau Co. yields a plateau date of 2.671 ± 0.008 Ga from 8 contiguous increments constituting 75% of the total gas released. A hornblende grain (A1) from the Black River gabbro, collected in Roseau Co., yields a plateau date of 2.685 ± 0.011 Ga from 11 contiguous increments constituting 90% of the total gas released. A hornblende (UBD) from a sample of hornblende-biotite gabbro collected in Koochiching Co. north of the Rainy Lake-Seine River Fault yields a plateau date of 2.695 ± 0.007 Ga from 6 contiguous increments constituting 49% of the gas released.

The mineral age data from mafic plutons from the Wabigoon subprovince are synchronous with the last deformation event (D2) dated in the range 2.685-2.674 Ga. Mafic plutons from the Wawa subprovince give an 80 m.y. age range from 2.58 to 2.66 Ga. Interestingly, the Linden Pluton gives a biotite date concordant (within error) with the youngest mafic pluton from the Wabigoon subprovince. The younger spread of ages from the Wawa are consistent with southward growth of the Superior Province during the latest Archean. Mafic plugs evident from aeromagnetic maps in east-central Minnesota are comagmatic with the circa 1.775 Ga East-central Minnesota batholith. Further constraining the temporal framework of mafic intrusions may contribute to mineral deposit models for PGE in these intrusions and their analogs in adjacent states and provinces.

Fig.1 $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra: t_p = plateau age, t_g = total gas age.



New zircon ages from the Gunflint and Rove Formations, northwestern Ontario

Kissin, S.A., Department of Geology, Lakehead University, Thunder Bay, ON, P7B 5E1 Canada, stephen.kissin@lakeheadu.ca ; Vallini, D.A., University of Western Australia, 35 Stirling Hwy, Crawley, 6009, W.A., Australia; Addison, W.D., RR 2, Kakabeka Falls, ON, P0T 1W0, Canada; Brumpton, G.R., 211 Henry St, Thunder Bay, ON, P7E 4Y7, Canada.

Previous work based on U-Pb geochronology from presumed volcanogenic zircons obtained from a tuff layer at the lower/upper Gunflint Formation boundary yielded an age of 1878 ± 2 Ma, believed to approximate the age of deposition of the unit (Fralick et al., 2002). This age corresponds closely with the age of the correlative Hemlock Formation of Michigan (1874 ± 9 Ma; Schneider et al., 2002).

We report here preliminary age determinations based on SHRIMP analyses of zircons extracted from three volcanic ash layers; one lying in the Gunflint Formation, and two within the overlying Rove Formation. The Gunflint-Rove contact is an important reference point. Pufahl and Fralick (2000) placed it at the top of a sequence of chert-carbonate grainstones which is overlain by carbonaceous shales of the Rove Formation. The Gunflint exposure outcrops at Little Falls, on the south side of the Kakabeka Falls Gorge, ~10m (topographically) below the Gunflint lapilli tuff dated by Fralick et al. (2002). A Rove volcanic ash exposure at Oliver Creek is estimated to be ~70m (stratigraphically) above the Gunflint-Rove contact. Zircons were also extracted from an ash layer within Falconbridge Pine River (PR98-1) drillcore (688.24m down hole), located ~4m above the Rove-Gunflint contact.

The Oliver Creek zircons recorded a mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1821 ± 16 Ma while a single age of 1840Ma was obtained from the drillcore PR98-1 sample. The errors cited are at the one standard deviation (1σ) and 95% confidence level and the analyses are less than 5% discordant. There are also two younger ages of ~1786Ma recorded from each locality which are assumed to be outliers.

The Little Falls zircons, which are somewhat rounded and fractured, yielded various ages, all older than 2000Ma. Most of the ages are more than 10% discordant, and these samples may have suffered lead loss. As well, there are some indications of admixture of shaley material in the ash layer at this locality. Older zircons from the lapilli tuff layer at the lower/upper Gunflint contact (Fralick et al., 2002) were also found to be admixed with Paleoproterozoic zircons.

Using the stratigraphic column of Pufahl and Fralick (2000), we estimate that the drillhole (PR98-1) samples are ~110m above the Gunflint lapilli tuff layer containing the zircons dated by Fralick et al. (2002), while we estimate the Oliver Creek samples to be ~150m above this same layer. The ages reported here indicate that a slow sedimentation rate must have been required in order to account for the age difference between the lapilli tuff of Pufahl and Fralick and the two sets of Rove dates reported here. This slow Rove sedimentation rate is comparable that reported in banded iron formations of the early Proterozoic Campbell Group, Griqualand, West Sequence, South Africa (Barton et al., 1994).

The Oliver Creek ages reported here are in reasonable agreement with the 1833 ± 6 Ma age reported by Schneider et al. (2002) for the Tobin Lake Pluton, which is undeformed by Penokean deformation and intrudes presumed Hemlock Volcanic equivalents. However, the zircons from the Rove Formation suggest that volcanic activity associated with the Penokean Orogeny continued for at least 40 m.y. Further studies are underway to clarify some of the questions raised by our results.

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MEAN TRANSPORT LENGTH IN TILLS OF THE SOUTHERN PORTION OF THE LAURENTIDE ICE SHEET: IMPLICATIONS FOR DRIFT EXPLORATION IN THE LAKE SUPERIOR REGION

LARSON, Phillip C., Department of Geological Sciences, University of Minnesota, Duluth, MN 55812, plarson2@d.umn.edu

Introduction

Bedrock in the Lake Superior region is typically covered by a mantle of glacial sediments – till, outwash, and lacustrine sediments – that presents a significant challenge to successful application of surficial geochemical techniques widely used to help generate drilling targets. The glacial environment is very complex, with sediments produced by a range of processes. Till represents the ideal sampling media in these environments, since a vector (ice flow direction) is attached to the composition at any location indicating the direction to the source of any defined anomaly. However, recent work has led to recognition that both the magnitude of a till geochemical anomaly and the potential transport distance to its source may have a wide range of values. This is a reflection of the mean transport distance of till-forming material, and is related to the fundamental sediment transport process responsible for forming the till.

Theory

The concentration of an indicator (a distinct lithologic or geochemical component derived from a discrete source) in till is the direct product of the physical processes of glacial erosion, transport, and deposition. Indicator concentration is controlled by a number of variables, including substrate hardness and the efficacy of the glacial erosional regime. Under steady state ice flow conditions and uniform bed erosion rates, indicator mass concentration c_i in till at any transport length T (l) down-ice of an indicator source of finite flow-line length L (l) is:

$$c_i^{T \geq 0} = \frac{L}{(\lambda + L + T)}, \quad (1)$$

where λ is the erosion length scale (l). For tills down-ice of the indicator source, under steady state conditions, the decrease in indicator concentration with increasing transport length $\partial c / \partial T$ assumes a quasi-exponential form. Erosion length scale, λ , is related to the spatial bed erosion rate E ($m \cdot l^{-3}$) and the thickness of the debris layer in transport m_d ($m \cdot l^{-2}$):

$$\lambda = \frac{m_d}{E}. \quad (2)$$

λ is closely related to the mean transport distance of till-forming material; as λ increases, so does the mean transport distance.

Short- vs. Long-Distance Transport: Examples

Tills in the Lake Superior region can be broadly grouped into two categories based on the mean transport length of the till forming material.

Tills characterized by short-distance mean transport length are commonly composed of coarse-grained material containing abundant angular clasts, and display rapid decrease in indicator concentration with transport length. This is exemplified by tills overlying the Vermilion greenstone belt of northern Minnesota, which displays rapid decrease in concentration of numerous indicator lithologies; λ for this till range from 1.0 to $2.0 \cdot 10^3$ m. A dispersal train composed of clasts of Nipigon diabase in till east of Lake Nipigon, Ontario displays similar characteristics. Dispersal is characterized by a similar rapid decrease in indicator concentration; calculated λ for this till range from $5.5 \cdot 10^2$ m over relatively soft greenstone to $2.4 \cdot 10^4$ m over hard diabase. Both tills are interpreted to have formed by erosion of hard bed by quarrying and abrasion, and englacial transport.

Tills characterized by long-distance mean transport length are commonly composed of fine-grained material with a relatively low abundance of rounded clasts, and display little apparent decrease in indicator concentration with transport length. Cretaceous shale grains in Des Moines Lobe tills of the Minnesota River valley show relatively little decrease in concentration along the flow axis extending down the valley (Matsch, 1972); the calculated λ for this till is $5.0 \cdot 10^5$ m. Carbonate-bearing tills overlying the Canadian Shield north of Lake Superior (Thorleifson and Kristjansson, 1993) show similar long-distance transport of Paleozoic carbonate and Proterozoic greywacke clasts with little decrease in concentration; the calculated λ for this till is $6.0 \cdot 10^5$ m. Both tills are interpreted to have deposited from deforming subglacial sediment layers (deformation tills).

Discussion

The data indicate deformation tills are characterized by λ that are 10 to 100 times higher than those of thin, coarse-grained tills. Tills characterized by intermediate values of the erosion length scale λ have not as yet been recognized in the Lake Superior region, and perhaps do not exist. This gap in recognized values suggest there are two main processes by which bed material is eroded and entrained, transported, and deposited – entrainment and transport by a deforming subglacial layer, and erosion by quarrying and abrasion and transport as an englacial debris load with deposition by lodgement or meltout.

Deformation tills form with little accompanying erosion of underlying hard bedrock. Their formation is consistent with redistribution of unconsolidated regolith or sediment derived from a preglacial reservoir. Consequently, till composition reflects that of distant (>100 km) bedrock. Tills characterized by short mean transport length indicate spatially and temporally restricted erosion and entrainment and transport of hard bedrock. Their formation is consistent with erosion by quarrying and abrasion of hard bedrock with subsequent extensive textural modification during transport. Till composition closely reflects that of nearby (~10 km) bedrock. Consequently, these tills have enormous potential value as geochemical sampling media.

Recognition of the process responsible for till formation in a given area is critical for successful application of surficial geochemical and boulder tracing exploration techniques in the Lake Superior region. Limited scope orientation surveys aimed at characterizing the erosion length scale λ provide a means of quickly assessing the potential for successful application of drift exploration techniques on both regional and property scales.

Glacial Lakes Aitkin and Upham: their origin and environmental history

Lisa Marlow, Howard Mooers, & Phillip Larson

Department of Geological Sciences, University of Minnesota, Duluth, Minnesota 55812

Glacial Lakes Aitkin and Upham occupied a basin in north-central Minnesota bounded on the north by the Giants Range and to the east, south, and west by hummocky moraines of the Rainy lobe, Superior lobe, and St. Louis sublobe. The lakes came into existence with the retreat of the Rainy lobe from the St. Croix phase sometime after 15,000 yr BP (Clayton and Moran, 1982; Mooers and Lehr, 1997). The basin was later overridden by the St. Louis sublobe from the northwest. With the wastage of the ice of the St. Louis sublobe, the basin was again occupied by lakes; the earlier phase is referred to as Lake Aitkin/Upham I and the later phase as Lake Aitkin/Upham II. Sediment of the early lake phase is preserved at a few localities. One such locality preserves a sequence that helps redefine the glacial chronology. A sedimentary sequence located in the northeast corner of the Upham basin reveals sub-aqueously deposited Rainy Lobe outwash beneath glaciotectonically deformed fine-grained lake sediments deposited by the St. Louis sublobe. This, along with other geomorphic relationships (P.C. Larson, unpublished data) indicates that the Rainy Lobe ice margin was coincident with the Giants Range when the St. Louis sublobe advanced across the lake basin.

Using a Digital Elevation Model (DEM) the elevation of lake basin was adjusted for isostatic rebound based on the highest lake level, then tilted incrementally through several stages to assess beaches, inlets, and outlets over time. A series of successively lower outlets draining to the St. Louis River served as outlets for Glacial Lakes Aitkin and Upham (Hobbs, 1983; Farnum, 1964; Wright, 1972). Meltwater entered the lakes from Glacial Lake Norwood through the Embarrass gap, and later from Glacial Lake Koochiching along the Prairie River. During this time Aitkin and Upham were confluent, and the outlet was established down the modern St. Louis River. The lakes were separated by a sill ca 11,500-10,100 yr BP, after inflow from Koochiching was diverted to Glacial Lake Agassiz.

Extensive dune fields formed following initiation of drainage of the lakes. Granulometry indicates a 4 ϕ grain size signature characterizes dunes throughout the basin. Maximum dune amplitude is ~3 meters and dune morphologies record prominent northwesterly winds. Dunes overly source areas, which include an underflow fan deposited by the Prairie River inlet and the western margin of Lake Upham.

A sediment core collected from Hay Lake (93°W, 52°N), located within a dunefield at the edge of Glacial Lake Upham, records three prominent peaks in whole-core magnetic susceptibility between 10,100 and 6,600 yr BP. No clastic input is evident after 6,600 yr B.P., suggesting dune stability. The timing of dunes within the basin has important implications for other dunes throughout Minnesota. Eolian events recorded in the core are interpreted as the result of lake drainage and exposure of abundant source material during Late Glacial and Early Holocene rather than landscape destabilization because of mid-Holocene aridity (Keen et al., 1990; Grigal et al., 1976; Dean et al., 1996; Dean, 1997). Additionally, this sediment core places a minimum age on the drainage of Glacial Lakes Aitkin and Upham II. Lake Upham must have drained after

age on the drainage of Glacial Lakes Aitkin and Upham II. Lake Upham must have drained after 11,500 yr BP and before 10,100 yr B.P. and Lake Aitkin may have persisted until ca. 7,000 yr BP.

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Magmatic and Hydrothermal PGE Mineralization of the Birch Lake Cu-Ni-PGE Deposit in the South Kawishiwi Intrusion, Duluth Complex, northeast Minnesota

John Marma, Phil Brown and Steve Hauck*

Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706, USA

*Natural Resources Research Institute, University of Minnesota, Duluth, Minnesota 55811, USA

The Birch Lake Cu-Ni-PGE Deposit is located 12 miles south of Ely, MN in the South Kawishiwi Intrusion (SKI) of the Duluth Complex (DC). The SKI is one of two layered mafic intrusions along the basal contact of the DC to host sub-economic Cu-Ni-PGE deposits. Mineralization is dominantly hosted by the U3 layer, the lower-most of three ultramafic-troctolite packages characterized as a zone of alternating ultramafic (picrite-peridotite) and troctolite horizons with lenses and pods of oxide-bearing (>5%) ultramafic and/or massive oxide. The purpose of this study was to locate, describe, and characterize the textural relationships among platinum group minerals (PGM), sulfides, and silicate phases to help delineate the relative significance of primary and remobilized platinum group element (PGE) concentrations.

Samples from 4 drill holes transecting the Birch Lake Deposit were obtained from the Natural Resource Research Institute (NRRI) located in Duluth, MN. EMPA and detailed petrography were used to locate PGE bearing minerals, averaging <15µm in diameter, and to characterize the host mineral geochemistry. Identifying the PGM textural relationships with other phases is critical to understanding the mechanism by which PGMs were deposited. Data from this study will aid exploration in locating other deposits and guide metallurgists in improving recovery techniques.

PGEs occur most often as various Pd minerals with associated Pt, Os, Ir, Ru, Au, Ag, Te, Bi minerals and were grouped into the following 4 categories of silicate-sulfide-PGM textural relations: 1) PGMs that occur in "halos" residing most commonly in anorthite-enriched zones in primary plagioclase around either interstitial sulfide (dominantly chalcopyrite), interstitial sulfide and silicate (dominantly chalcopyrite, clinopyroxene, and hydrous silicates (amphibole and biotite)), or silicate (dominantly clinopyroxene or hydrous silicate) (Figure 1). This style of mineralization hosted 58% of the total PGMs identified. 2) Remobilized PGMs that occur in chlorite, serpentine, or secondary magnetite. This style of mineralization hosted 21% of the total PGMs identified. 3) Random PGMs that occur in poikilitic anorthite-rich plagioclase (An 75-An 95) and clinopyroxene (Wo 30-Wo 50) with PGEs sometimes residing in disseminated chalcopyrite or hydrous silicate pockets, but no association with "halos". This style of mineralization hosted 11% of the total PGMs identified. 4) In interstitial sulfides or silicates that include hydrous silicates, chalcopyrite, clinopyroxene, sulfides with symplectite (?) textures, or calcite. This style of mineralization hosted 10% of the total PGMs identified.

The following is a summarized model for the formation of high PGM concentrations in the Birch Lake deposit. The SKI begins as a magma body that is replenished with multiple injections of magma, which becomes sulfur saturated. The magma body is relatively PGE poor, due to partial loss of sulfides during emplacement leaving the conduits with a PGE enriched segregation of the total sulfide. The sulfides in the magma body scavenge available PGEs and crystallize as disseminated, interstitial sulfide grains. Primary hydrous phases form at this time

from a fluorine-rich, deuteritic fluid. A Cl-, Cu-, PGE-rich, sulfide-poor fluid enters the magma chamber at its base via the original magma conduit(s) and/or faults. The fluid migrates along grain boundaries, and interacts with the larger interstitial sulfides. A dynamic environment is created in which the fluid, containing a significant concentration of dissolved metals, begins to consume and use sulfur from the larger grains to produce more sulfides. At the same time, the fluid is reacting with neighboring grains, specifically plagioclase, and through a cation exchange reaction, alters the plagioclase rims, enriching them in calcium. This reaction causes a volume loss that is filled with precipitated sulfides and PGMs ($\pm$ chlorite) producing the disseminated "halos" around the larger interstitial grains (Figure 1). Finally, another fluid migrated through the intrusion that remobilized PGMs on a small scale.

Based on evidence solely from the Birch Lake deposit, PGM mineralization appears concentrated or "compartmentalized". This could be the result of two possible mechanisms: 1) Areas of high PGM concentrations are dependent on their proximal distance to "feeder" zones (i.e. conduits or faults) where fluids can be introduced; and/or 2) High PGM concentrations are due to structural controls within these heterogeneous rocks that localize fluid movement.

This study contributes to the current debate on the roles of primary vs. remobilized (deuteritic?) PGE mineralization in layered mafic intrusions. For the Birch Lake deposit, the data suggest both mechanisms played important roles in the origin of the ore minerals.

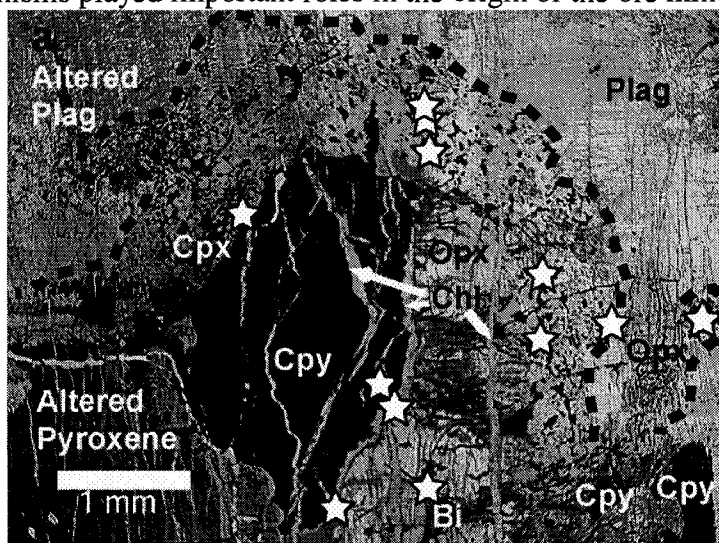


Figure 1

a.) Photomicrograph in plane-polarized light of thin section BL 89-2 2516.4 – locations A-L. Large interstitial chalcopyrite and pyroxene cross-cut by vertical chlorite veins, all of which are surrounded by a disseminated, dominantly chalcopyrite halo that is in An-enriched plagioclase rims. Notice all PGMs, except one, either occur in the halo; in chlorite veins; in interstitial biotite; or in clinopyroxene. The altered plagioclase and altered pyroxene on the left side of the image are devoid of any PGM occurrences –this includes areas within the original halo. This suggests a second alteration fluid event that removed PGMs and altered the minerals, which it passed through. Dashed line represents the extent of halo and An-enrichment in the adjacent plagioclase grains. White stars represent PGM occurrences. Cpx=Clinopyroxene, Opx=Orthopyroxene, Bi=Biotite, Chl=Chlorite, Cpy=Chalcopyrite, Plag=Plagioclase

RESULTS OF EMP MONAZITE GEOCHRONOLOGY IN E-C MINNESOTA: EVIDENCE FOR LARGE-SCALE GEON 17 METAMORPHISM ASSOCIATED WITH POST-TECTONIC PLUTONISM

MCKENZIE, M.A., and HOLM, D.K., both at Dept. of Geology, Kent State University, Kent, OH; SCHNEIDER, D.A., Dept. of Geological Sciences, Ohio University, Athens, OH; JERCINOVIC, M., Dept. of Geosciences, University of Massachusetts, Amherst, MA

Determination of the timing and extent of poly-phase metamorphism is essential in unraveling the tectonic history of a region. The pattern and degree of metamorphism preserved across the Penokean orogenic belt in the southern Lake Superior region is highly variable. Abundant $^{40}\text{Ar}/^{39}\text{Ar}$ dates from east-central Minnesota indicate widespread cooling at ~1760 Ma shortly after the emplacement of the east-central Minnesota batholith (ECMB) at ~1775 Ma (Holm et al., 1998; in review). Yet U-Pb SHRIMP monazite ages from three localities across the region (e-c MN, northern MI, and northern WI) record only a uniform ~1830 Ma metamorphic episode and a secondary younger ~1800 Ma thermal pulse linked to a recently identified ~1800 Ma magmatic event (Schneider et al., in review). This study utilizes the total Pb electron microprobe (EMP) monazite age dating technique to better constrain the extent of thermal overprinting surrounding the batholith.

For this study we obtained *in situ* metamorphic monazite ages from three Paleoproterozoic metasedimentary garnet-staurolite schist samples and one garnet-cordierite gneiss sample from the plutonic zone of east-central Minnesota (Figure 1). Schist sample AM-016 contains predominantly elongate monazite grains displaying a mottled chemical variation in Y and Th content. This sample yielded a mean age of 1746 ± 3 Ma from 79 spots on seven grains. Two age domains were recognized at ~1738 Ma and 1760 Ma. A third less prominent ~1780 Ma age domain was obtained on some high Y regions. Schist sample MN-29 contains sub-euhedral monazite displaying prominent regions of high Th content. This sample yielded a mean age of 1764 ± 10 Ma from 92 spots on five grains. A single prominent age domain was recognized at ~1772 Ma. Schist sample P-16 contains monazite with very irregular grain boundaries, numerous inclusions, and variable Th content. This sample yielded a mean age of 1772 ± 3 Ma from 92 spots on seven grains. Two age domains are identified: a prominent age domain at ~1770 Ma and a smaller population age domain at ~1800 Ma. Lastly, the Sartell gneiss, sample S-2, contains euhedral monazite grains displaying distinctive core/rim textures. This sample yielded a mean age of 1756 ± 3 Ma from 102 spots on seven grains. Three age domains are identified: two prominent domains at ~1750 Ma and 1770 Ma and a third less prominent domain at ~1800 Ma on high U cores.

Our EMP results reveal a profound ~1770 Ma thermal imprint associated with intrusion of the 1775 Ma ECMB. The considerable distance of some of these samples from the western edge of the exposed batholith (30-40 km) and the absence of Penokean metamorphic ages suggests that the thermal pulse must have been dramatic. However, the garnet-schist sample K-R (east of Mille Lacs) that records only geon 18 SHRIMP ages lies north of the region of thermal influence of the batholith. We note that sample K-R is located just north of the Malmo Structural Discontinuity (MSD) and sample AM-016 is located south of it. Our data reveal that the MSD juxtaposes rocks of different metamorphic age (geon 18 metamorphism to the north from geon

17 metamorphism to the south). We propose, therefore, that the MSD is a geon 17 structure that exhumed the plutonic terrane of east-central Minnesota. West of Mille Lacs, a significant portion of the MSD juxtaposes post-Penokean plutons to the south against older metamorphic rocks to the north. This clearly supports our interpretation that this structure was active well after Penokean orogenesis.

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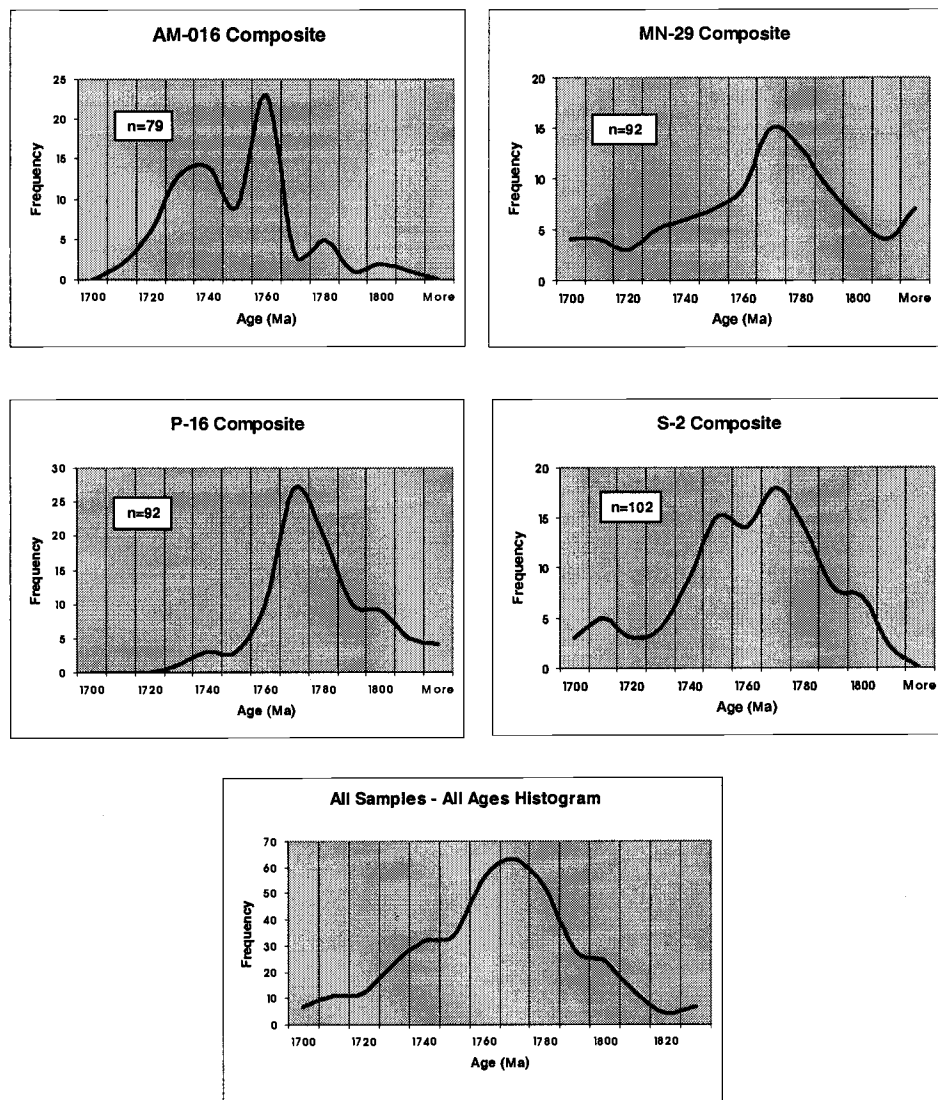


Figure 1: Histograms of EMP Th-U-total Pb *in situ* monazite spot ages.

THE SIOUX QUARTZITE REVISITED: SEDIMENTOLOGY, METAMORPHISM, GEOCHEMISTRY AND THE ORIGIN OF PIPESTONE

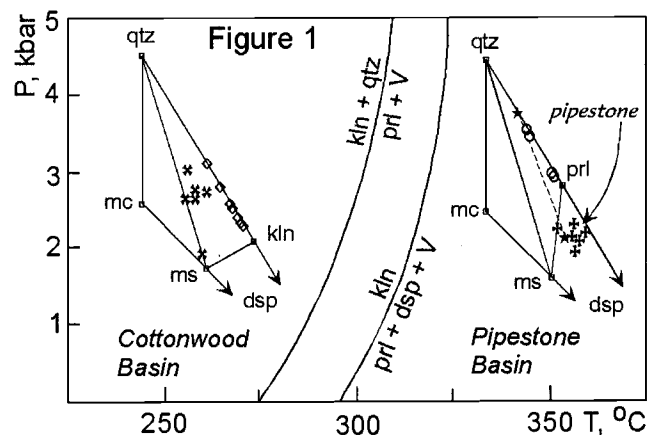
MEDARIS, L.G., Jr., and DOTT, R.H., Jr., Dept. of Geology & Geophysics, University of Wisconsin-Madison, Madison, WI, 53706; medaris@geology.wisc.edu; rdott@geology.wisc.edu

Red, supermature quartzites of the Baraboo Interval were deposited after 1.75 Ga on a stable craton in the presence of free atmospheric oxygen under conditions of intense chemical weathering. Some quartzites (Baraboo and Flambeau) were folded and recrystallized at 1.63 Ga (Holm *et al.*, 1998), and many quartzites were hydrothermally altered at 1.46 Ga (Medaris *et al.*, 2002, in press), presumably in response to brine migration promoted by continental scale A-type magmatism. These discoveries have prompted us to reevaluate the sedimentology, metamorphism, and geochemistry of the Sioux Quartzite.

Sedimentology The Sioux Quartzite, which is several hundred meters thick, is composed mostly of quartz sandstone with interstratified lenses of red mudstone (Southwick *et al.*, 1986). Heterogeneous cobble conglomerate occurs at the base and finer pebbly layers are scattered throughout the lower half or so, whereas mudstones occur chiefly within the upper half. Sedimentary structures in the sandstones include predominant festoon-style, nested trough cross beds averaging 10 – 15 cm in thickness, rare zones of planar-tabular sets, a few examples of herring bone cross bedding, and both asymmetric and symmetric ripple marks. The mudstones are mostly massive, but parallel- laminated and ripple-laminated varieties are also present. In most cases, quartz silt and fine sand grains are disseminated in a finer matrix, but rare graded laminations are also present. Some mudstones show polygonal ‘mud’ cracks, and the overlying sandstones commonly contain intraclasts ripped up from such cracked beds

Interpretations of the Sioux depositional environment include shallow marine and braided fluvial (Dott, 1983; Southwick *et al.*, 1986). In the latter scenario, the cross bedded sandstones represent river channel deposits, and the mudstones, slack water deposits in ponds between active channels. However, this interpretation is inconsistent with the rarity of scoured channel bases and tabular sets of planar cross laminations, which would have formed by laterally migrating bars, and the existence of wave ripples, which are not expected in the sands of a braid plain. Ojakangas and Weber (1984) suggested that the upper one-third of the Sioux formation was deposited in a shoreline marine setting with tidal influences, accounting for the herringbone cross bedding, wave ripples, polygonal desiccation cracks, and thickness and extent of certain mudstone layers (now pipestone). Interpretation of the Sioux as a fluvial-to-marine transgressive succession would conform to the present interpretation of the correlative Baraboo Quartzite, which has wave ripples and reactivation surfaces in its upper half (Medaris *et al.*, in press).

Metamorphism Mineral assemblages in fine-grained Sioux sedimentary rocks can be expressed in the system, KASH, as portrayed in Figure 1, where rock compositions are projected onto the anhydrous plane, K-Al-Si, and two critical dehydration reactions are plotted. Additional phases include abundant hematite and a TiO₂ phase, either anatase in the Cottonwood Basin (CB) (Stelz, 1989), or rutile in the Pipestone Basin (PB). The stable existence of kaolinite in the CB (Stelz, 1989) requires temperatures below ~300°C, whereas pyrophyllite in the PB is stable above ~300°C. The



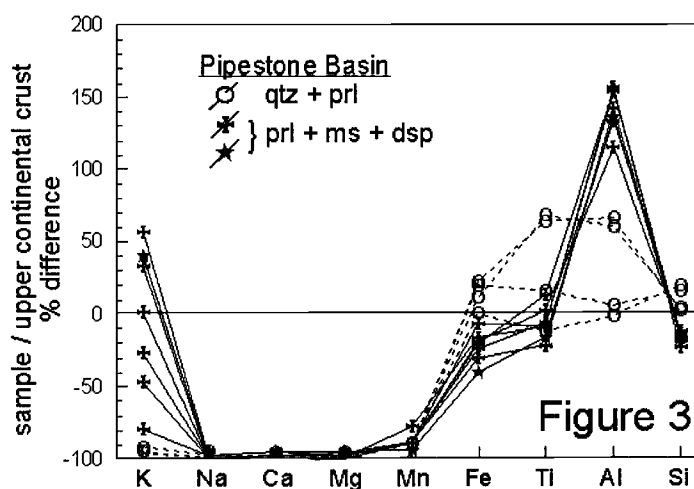
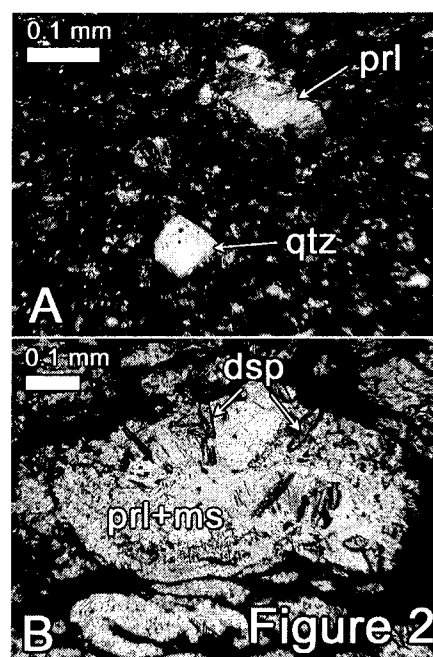
quartz-pyrophyllite assemblage in the PB (O, Fig. 1), in which vermicular kaolinite has been replaced by pyrophyllite (Fig. 2A), most likely represents higher temperature, largely isochemical recrystallization of a quartz-kaolinite protolith, like that in the CB (◇, Fig. 1). The occurrence of muscovite in both basins is attributed to K-metasomatism related to 1.46 Ga hydrothermal activity. Pipestone (★, Fig. 1) is a metasomatic rock composed of pyrophyllite, muscovite, diaspore, hematite, and rutile, in which former quartz grains have been completely replaced by diaspore, pyrophyllite, and muscovite (Fig. 2B). Because the Sioux Quartzite is largely undeformed and lies north of the extrapolated trend of the 1.63 Ga Mazatzal tectonic front (Holm *et al.*, 1998), we suggest that all metamorphic features of the Sioux Quartzite are due to 1.46 Ga hydrothermal activity, rather than a Mazatzal event.

Geochemistry Where unmodified by K-metasomatism, fine-grained sedimentary rocks of the Baraboo Interval are remarkably mature, being practically devoid of K, Na, Ca, Mg, and Mn (Fig. 3), and having Critical Index of Alteration values of 97 to 99. In such rocks the wide range in proportion of Si to Al (Fig. 3) and quartz to kaolinite, or pyrophyllite (Fig. 1), reflects the original proportion of quartz to kaolinite in the protolith sediments.

K-metasomatism has stabilized muscovite in both the CB and PB, but the muscovite-bearing rocks in the CB record a lower temperature and higher ratio of Si/Al compared to pipestone in the PB (Fig. 1). The classic pipestone, in addition to substantial K contents, contains lower Si and higher Al than that in associated quartz + pyrophyllite samples (Figs. 1 & 3). Assuming Zr to be an immobile element, isocon calculations indicate that the mean pipestone composition was produced by removal of 20 to 65% SiO₂, 45 to 55% TiO₂, 35 to 65% Fe₂O₃, and addition of 15 to 45% Al₂O₃ and ~800% K₂O, compared to the average compositions of the two Si-rich and two Al-rich quartz + pyrophyllite samples. The reconstructed composition of one pipestone sample (★, Fig. 1) requires removal of 68% SiO₂ and addition of 50% Al₂O₃ during metasomatism.

Further investigation is underway to provide a more detailed evaluation of brine compositions and metasomatic processes involved in this important, regional scale, 1.46 Ga hydrothermal event.

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A geochemical investigation of Mesoarchean metavolcanic and metasedimentary rocks from the Birch-Uchi greenstone belt

Metsaranta, R., Fralick, P. and Hollings, P. (Department of Geology, Lakehead University, Thunder Bay ON CAN, P7B 5E1)

Most Mesoarchean greenstone belts in the Western Superior Province are comprised primarily of komatiite-tholeiite sequences and associated sedimentary rocks (Thurston and Chivers 1990). These ~2.9-3.0 Ga assemblages have been interpreted to represent plume generated volcanism in oceanic plateau settings (for example, Hollings et al. 1999, Tomlinson et al. 1999). This study is a preliminary investigation of metavolcanic and metasedimentary strata from the Mesoarchean Balmer assemblage of the Birch-Uchi greenstone belt. Rogers et al. (2000) have suggested that, given their geochemical affinities and Nd isotopic evidence for contamination by older crust, volcanic rocks of the Balmer assemblage may represent a continental arc setting. This implies that the Balmer Assemblage may represent a distinct tectonic setting from those proposed for other

Mesoarchean rocks in the Superior Province. Sediment geochemistry and depositional environment studies along with igneous geochemistry will be applied to provide further constraint on the possible tectonic setting of these rocks.

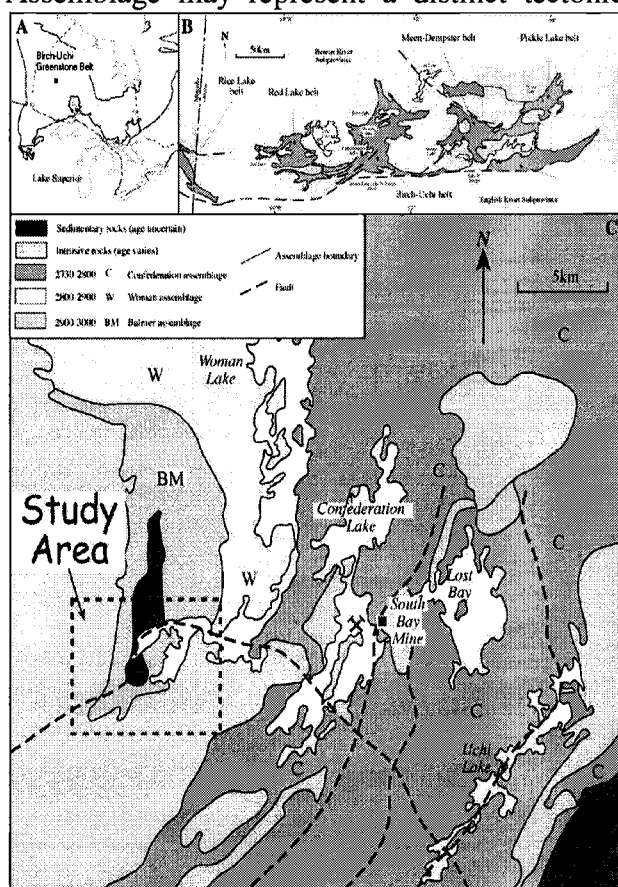


Figure 1- Location and generalized geology of study area and Birch-Uchi Greenstone belt (modified from Stott and Corfu 1991)

16 samples from the lower sedimentary sequence and 34 samples of the mafic volcanic suite of Rogers et al.(2000).

Field observations suggest that the Balmer assemblage sedimentary rocks are turbiditic. Sediment geochemistry will be applied to constrain the source rocks compositions for these sediments. As no contact with underlying older rocks has been identified this might provide valuable information about the preexisting older crust. Alternatively, the sediments may be derived from the Balmer assemblage volcanics and this could support a hypothesis that the Balmer assemblage represents a continental arc setting with the sediments deposited in a fore-arc trench.

Volcanic rock samples appear to fall into two compositional trends. The first is a tholeiitic trend comprised of primarily tholeiitic basalts and andesites. The second is a calc-alkaline trend of andesitic to rhyodacitic composition. The geochemistry of these samples will be applied to suggest a possible tectonic setting for these rocks and implications of this in relation to other Mesoarchean terranes.

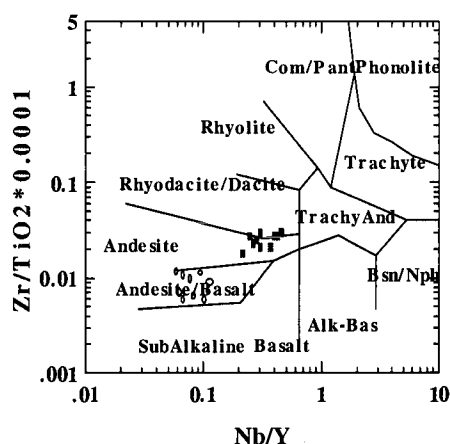


Figure 3- Lithology Discrimination diagram for Balmer Assemblage volcanics. Circles are Tholeiitic trend squares are calc-alkaline trend.

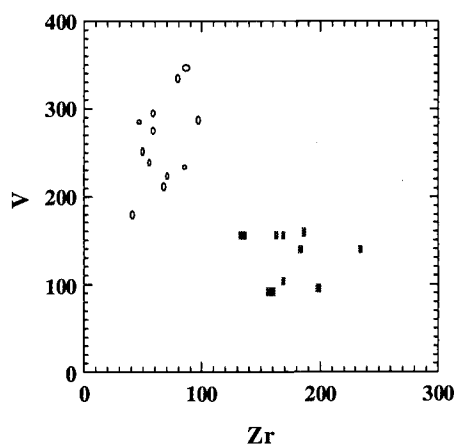


Figure 3-A plot of V vs Zr showing compositional groups in Balmer Assemblage volcanics. Circles are Tholeiitic trend squares are calc-alkaline trend.

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PETROLOGY AND PGE POTENTIAL OF THE GREENWOOD LAKE INTRUSION, CENTRAL DULUTH COMPLEX, LAKE COUNTY, MINNESOTA

MILLER, James, D., Jr., Minnesota Geological Survey, *mille066@tc.umn.edu*

This report summarizes the results of a petrologic and metallogenic study of drill core and outcrop samples that profile the Greenwood Lake intrusion (GLI) of the central Duluth Complex (Fig. 1). The little that was known about this very poorly exposed layered mafic intrusion prior to this study came from interpretation of its aeromagnetic signature, seven drill cores, and sparse, localized outcrop. The purpose of this study was to establish the igneous stratigraphy of the GLI and to evaluate its potential for PGE reef mineralization. The GLI is an approximately two kilometer-thick, sheet-like intrusion that dips gently (approximately 10°) to the east and covers an area of about 300 square kilometers. For this study, 19 bedrock drill cores (20 to 80' in length) were acquired in early 2002 along the west-northwest-trending Erie/LTV railroad and powerline west of Lake County Highway 2 (Fig. 1). Samples from these cores and from intermittent outcrops along the eastern extent of the railroad grade were subjected to petrographic study in transmitted and reflected light, microprobe analyses of olivine and pyroxene composition, and whole rock analyses of their lithogeochemistry, including platinum, palladium, and gold concentrations.

The results of the drilling and petrographic study show that the igneous stratigraphy of the GLI can be grossly subdivided into a lower troctolitic zone (GLtr, 0-650 meters), composed mostly of leucotroctolitic cumulates, a medial gabbroic zone (GLog, 650-1800 meters), composed of olivine oxide gabbro cumulates, and an upper ferrogabbroic zone (GLfg, 1800-2130 meters), composed largely of magnetite gabbro (Fig. 2). The troctolitic zone contains abundant, large anorthositic and oxide gabbroic inclusions, presumably derived from anorthositic series country rock. Although the GLI is a well-differentiated intrusion that formed as an open magma system, microprobe data show that cryptic layering trends (such as Fo in olivine, Fig. 2) are inconsistent with formation by in situ crystallization differentiation. This and other evidence (such as abrupt changes in lithology, leucocratic compositions of troctolitic rocks, and suspect cumulus textures of troctolitic rocks) suggest that the differentiated character of the GLI was probably inherited from a deeper crustal magma chamber, which was itself undergoing open system differentiation.

The chemostratigraphy of chalcophile elements through the GLI are difficult to interpret in such a complex open magma system, but suggest that some potential for PGE reef mineralization may occur in the lower part of the gabbroic zone (Fig. 2). Below this level, recharging magmas appear to have been undersaturated in sulfide, and copper and sulfur concentrations higher in the gabbroic zone (above 800 meters) indicate intermittent saturation. An unexpected result of this study was the discovery of a large, sulfide-bearing oxide gabbro inclusion within the troctolitic zone. Aeromagnetic data suggest that this inclusion is a conformable tabular mass with a strike length of about 8 kilometers. The magnetic data further suggest that similar rock types form part of the footwall to the GLI. The possibility of sulfur contamination in the contact aureole around this inclusion and along the base of the intrusion warrants further exploration of these areas for contact-type Cu-Ni-PGE sulfide mineralization.

Funding for this project was provided to the Minnesota Geological Survey by a grant from the Minnesota State Legislature on the recommendation of the Minerals Coordinating Committee.

Figure 1. Generalized geology of the Greenwood Lake intrusion and the central Duluth Complex. Small dots denote drill hole and diamonds denote outcrop locations along Erie/LTV railroad tracks. Long dashed lines denote faults. Intrusive units are:

GLtr—GLI troctolitic zone
 GLog—GLI gabbroic zone
 GLfg—GLI ferrogabbroic zone
 MW—Mt. Weber granophyre
 CLLS—Cloquet Lake layered series
 BEI—Bald Eagle intrusion
 SKI—South Kawishiwi intrusion
 PRI—Partridge River intrusion
 WMI—Western Margin intrusion

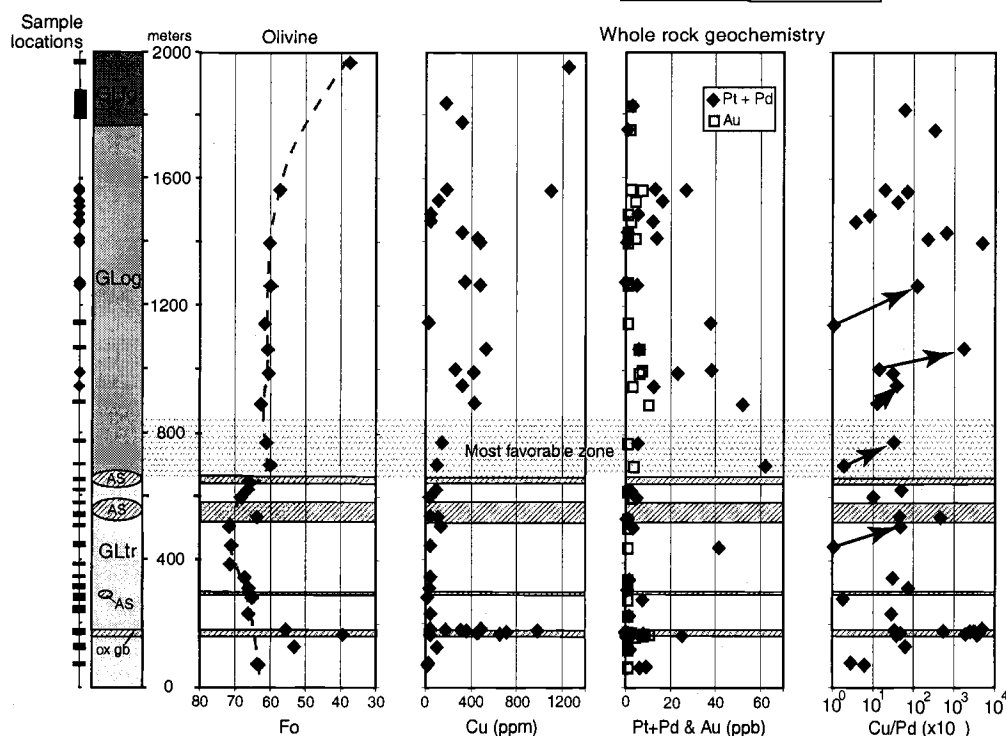
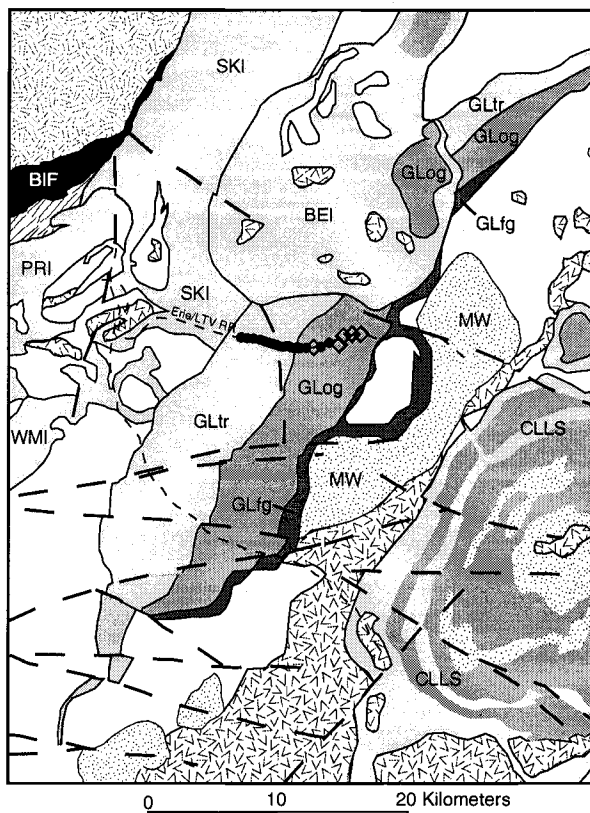
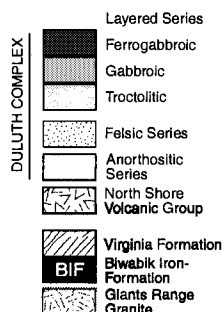


Figure 2. Chemostratigraphy of Fo in olivine and of Cu, Pt + Pd, and Au concentrations through the Greenwood Lake intrusion. Stratigraphic locations of drill core (boxes) and outcrop (diamonds) samples and general lithostratigraphy are shown in the left columns. Large inclusions of anorthositic series rocks (AS) and oxide gabbro (ox gb) are denoted. Abrupt increases in Cu/Pd (arrows) may mark sulfide saturation events. The zone found most favorable to host PGE reef mineralization is identified.

Stratigraphy and structure of Keweenaw rocks of the St. Croix horst, northwestern Wisconsin

S.W. Nicholson, and W.F. Cannon, U.S. Geological Survey, Reston, VA

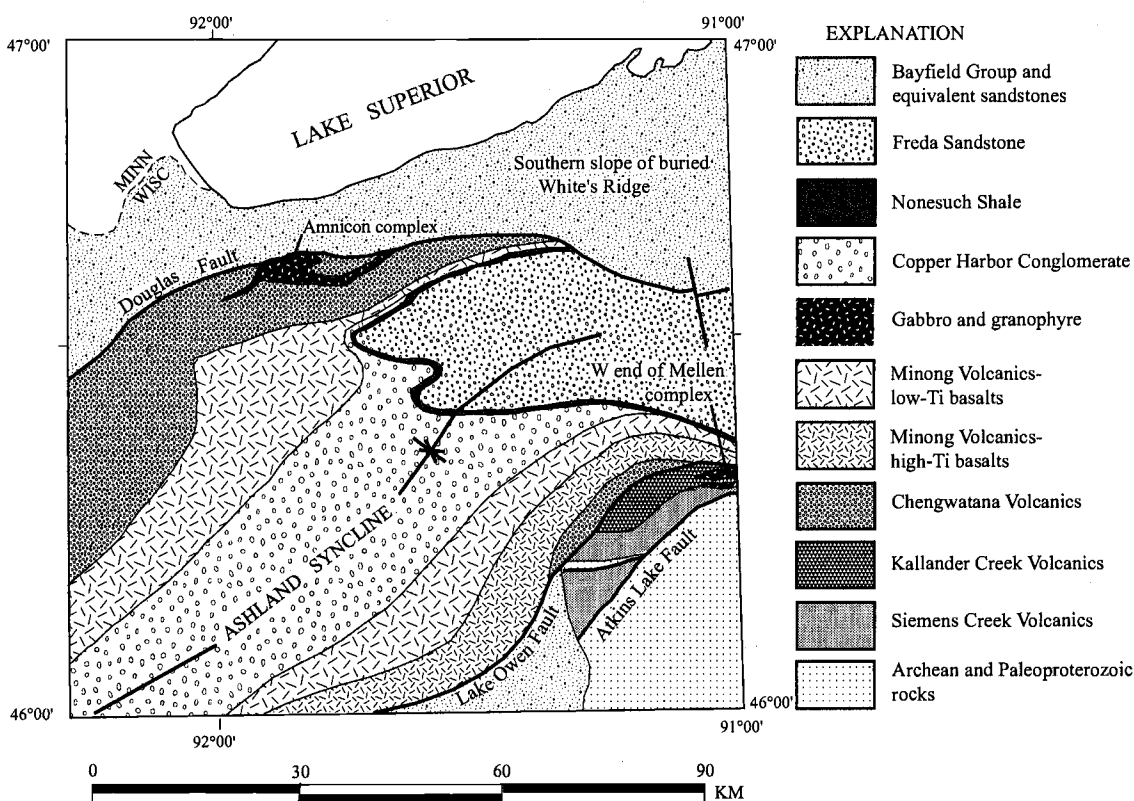
The St. Croix horst is the partially inverted central graben of the Midcontinent Rift System (MRS) that extends southwestward from western Lake Superior. It is bounded by the Douglas fault on the northwest and the Atkins Lake fault on the southeast. Both are now reverse faults, but may have been graben-bounding normal faults during rifting and volcanism. The northern limit of the horst is White's Ridge, a subsurface basement high evident in both seismic and gravity data, which did not subside substantially during rifting and against which rift volcanic and sedimentary rocks pinch out or become much thinner. White's Ridge effectively separates the MRS in western Lake Superior from the St. Croix horst and the volcanic, sedimentary, and structural history of the two rift segments differ in several aspects. High-resolution aeromagnetic, gravity, and seismic data permit the tracing of flow sequences for long distances and to great depth. This geometry combined with the chemistry of the volcanic rocks allows us to decipher a volcanic stratigraphy in spite of widespread cover by glacial deposits and Paleozoic sedimentary rocks (Cannon et al., 2001).

Our interpretation, aided by previous gravity and seismic interpretations (Chandler et al., 1989), is that the original structure of the St. Croix horst was an asymmetric graben, or possibly a half graben, like those of the Lake Superior portion of the MRS. The Lake Owen fault was a major growth fault on the southeast side of the graben and the volcanic fill thickened toward and terminated against the fault. The Douglas fault on the northwest side of the horst is not clearly a growth feature and may be simply a thrust formed during rift inversion. Thrust displacement on the Douglas fault must be 20 km or more because it juxtaposes the base of a thick volcanic sequence over the younger Bayfield Group.

Cannon et al. (2001) and Nicholson et al. (2001) used chemical and aeromagnetic data to define the Minong Volcanics, the underlying Clam Falls Volcanics, and the Chengwatana Volcanics as three formations making up the graben-filling volcanic sequence. The three have similar chemistry, but were defined by structure and geochronology. The three-part division no longer seems justified and the Chengwatana and Clam Falls Volcanics are combined into a single unit. The Chengwatana Volcanics, as earlier defined, were restricted to a fault-bounded belt between the Douglas and Pine faults and their stratigraphic relationships to other volcanics were not known directly. We now believe, based on seismic data, that the Pine fault does not extend into the northern part of the horst, where the previously defined Chengwatana and Clam Falls units appear to be a continuous depositional sequence of compositionally indistinguishable flows that we propose be called entirely Chengwatana. The Minong Volcanics, a sequence of low-TiO₂ basalts about 3 km thick, overlie the Chengwatana, along an apparent low angle unconformity based on aeromagnetic form lines. These form lines also show a unconformity within the Minong volcanics on the southeast limb of the Ashland syncline. A lower unit, not present on the northwest limb, is mostly high-TiO₂ basalt. Based on the presence of abundant high-TiO₂ basalts and more evolved rocks, we infer that a localized magmatic center was active in this area sometime before 1095 Ma, the age of a rhyolite flow in the upper part of this sequence. A second, but apparently older, volcanic center may have existed on the western margin of the graben near

the Amnicon Complex where the Chengwatana Volcanics are mostly high-TiO₂ basalts, andesites and rhyolites.

Clastic sedimentary rocks of the Oronto Group overlie the volcanic rocks. Only the basal unit, the Copper Harbor Conglomerate, is preserved in most of the St. Croix horst where as much as 2 km of sandstone and conglomerate lie along the axis of the Ashland syncline. The Copper Harbor thins to only a few tens of meters toward the northern end of the horst in the same areas where the volcanic section also shows substantial thinning. Apparently the area now comprising the northern part of the St. Croix horst did not subside nearly as deeply as parts farther to the southwest. This relatively positive relief persisted throughout volcanic activity and deposition of the Copper Harbor Conglomerate. The overlying Nonesuch Shale maintains a relatively uniform thickness around the northern part of the Ashland syncline, suggesting that the topographic high was buried by that time.



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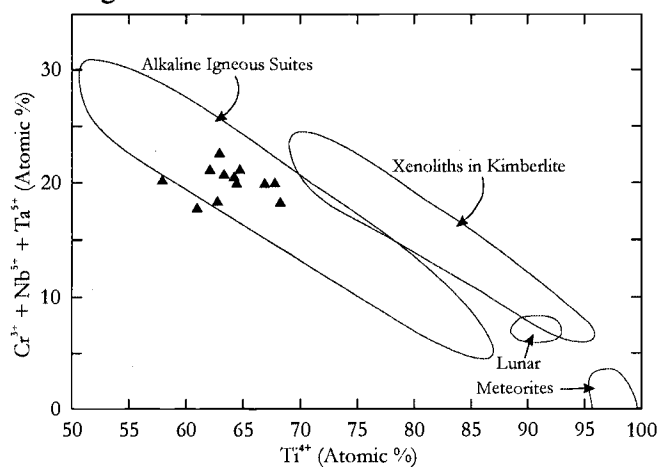
The Rare and Exotic Mineralogy of the Western Subcomplex of the Deadhorse Creek Diatreme, Northwestern Ontario.

Eric G. Potter and Roger H. Mitchell

egpotter@mail.lakeheadu.ca

Dept. of Geology, Lakehead University, 955 Oliver Road, Thunder Bay, ON. P7B 5E1

The main mineralized zone of the western subcomplex of the Deadhorse Creek diatreme exhibits complex mineralization involving: first and second order transition metals (specifically Sc, Ti, V, Cr, Mn, Fe, Zr and Nb); REE; Be; Th; and U. The mineralization is manifested by the presence of the following minerals: thortveitiite, Sc-V-aegirine, Nb-V-rutile, V-crichtonite, Ba-Mn-hollandite, zircon, monazite-Ce, xenotime-Y, uraninite, thorite, thorogummite, barite, barylite, tyuyamunite, phenacite, pyrite, hematite, magnetite and several as of yet unnamed mineral species (Platt and Mitchell, 1996; Smyk *et al.*, 1993; this study). Of interest in this presentation are: Nb-V-rutile, crichtonite and Sc-V-aegirine.



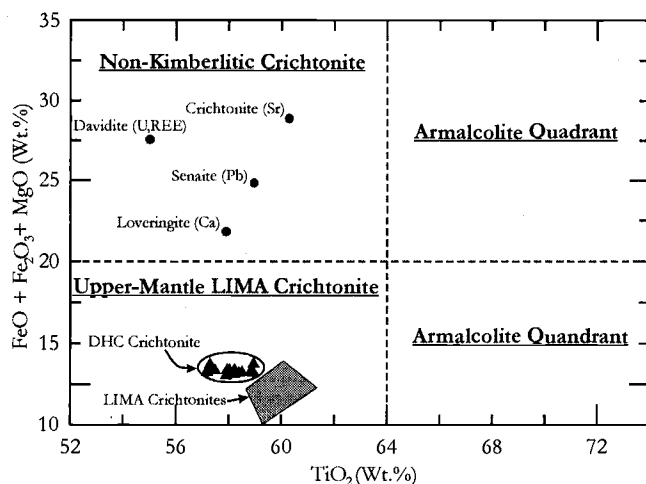
The Nb-V-rutile is enriched in Cr_2O_3 , with concentrations reaching 6.49 wt.%. The enrichment of Cr_2O_3 and Nb_2O_5 is similar to that of rutile reported in alkaline igneous rocks, as illustrated in an atomic percent plot of $\text{Cr}^{3+} + \text{Nb}^{5+} + \text{Ta}^{5+}$ vs. Ti^{4+} (Haggerty, 1991). However, the Nb_2O_5 contents are unusually high compared to alkaline igneous rocks in general, with concentrations reaching 29.32 wt.%. Such Nb_2O_5 contents are

similar to those reported in ilmenorutile, which is historically found in pegmatites. Also unique to the Deadhorse Creek rutile is the distinct enrichment of V_2O_3 (up to 10.52 wt.%) and the lack of tantalum.

The Sc-V-aegirines present at Deadhorse Creek contain the highest reported concentrations of Sc_2O_3 and V_2O_3 (16.46 and 11.99 wt.%, respectively). The only other occurrences of V- and Sc-enriched aegirine have been reported from alkaline metasomatites associated with iron-ore deposits in Ukraine (Valter *et al.*, 1994; Pavlishin *et al.*, 2000). Of note is the presence of both thortveitiite ($\text{Sc}_2\text{Si}_2\text{O}_7$) and Sc-enriched aegirine within the main mineralized zone. Although the source of the Sc in the aegirine remains somewhat conjectural, it appears that the Sc, V and Na was scavenged from alteration of the main mineralized zone by Fe-rich fluids.

The V-rich crichtonites are best termed vanadium-rich analogues of crichtonite-(Sr) and senaite-(Pb). The enrichment in Nb_2O_5 in the crichtonites is peculiar, as the presence of Nb has been a distinguishing feature of the mantle-derived end members lindsleyite-(Ba)

and mathiasite-(K) (LIMA). Interestingly, the crichtonites plot in the upper-mantle LIMA quadrant of $\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}$ vs. TiO_2 (Haggerty, 1991), near the LIMA compositions due to the replacement of iron by vanadium.



The Nb-enriched rutiles and crichtonite are believed to have formed relatively early in a multistage-alteration sequence of the Deadhorse Creek diatreme by reaction of stoichiometric rutile with hydrous alkaline solutions enriched in Nb and V. These hydrous alkaline solutions likely also altered zircon to an unnamed hydrated calcium zirconosilicate, which is found in association with the crichtonite and rutile. Textural and compositional data suggest that

subsequent alteration formed the Sc-V-aegirines and imparted the pervasive hematitization to the main mineralized zone.

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Sibley Basin sediment provenance using zircon and whole rock geochemical methods: Possible source areas of the Pass Lake Formation

Richardson, A., Fralick, P., and Hollings, P. (Department of Geology, Lakehead University, 955 Oliver Rd., Thunder Bay, Ontario, P7B 5E1, Canada; ajrichar@mail.lakeheadu.ca)

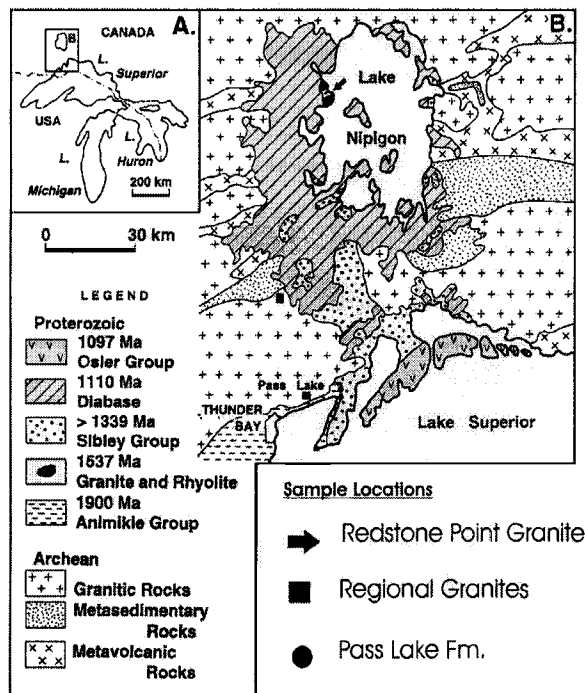


Figure 1. Regional geologic map with sample locations.

were grouped into assemblages consisting of up to 16 beds. Bed thickness became finer and thinner up section. A total of 26 hand samples were obtained from the Pass Lake cliff and consisted of fine to medium grained sandstone. Two additional Pass Lake Formation samples were obtained from road cuts further up-section that consisted of medium grained sandstone.



Figure 2. Backscatter X-Ray SEM-EDS image of a zircon from sample AR-01.

The Sibley Group consists of Proterozoic sediments that outcrop discontinuously over a 15000 sq. km region in the area surrounding central and southern Lake Nipigon. Its age is bracketed by the underlying Redstone Point Complex (1537 $\pm$ 10/-2 Ma; Davis and Sutcliffe, 1985) and a 1339 $\pm$ 33 Ma Rb-Sr age on diagenetically altered Sibley sediments (Franklin, 1978). The Sibley Group was divided into three formations: the Kama Hill Formation (top), the Rosspoint Formation, and the Pass Lake Formation (bottom), by Franklin, et al. (1980). The Kama Hill Formation consists of a laminated shale facies, the Rosspoint of mudstone and stromatolitic facies, and the Pass Lake of a conglomeratic facies and a plane-bedded or cross-bedded sandstone facies (Cheadle, 1986). This study investigates the sources that fed sediment to the Pass Lake Formation in the southern portion of the basin.

Regional granitic sources may include: the Mesoproterozoic Redstone Point anorogenic intrusion, Neoproterozoic peraluminous Quetico granites, and McKenzie granites. Of these, the Redstone Point is more highly evolved than the others and contains abundant zircon and a distinct geochemical signature with very elevated values for the high field strength elements (HFSE).

Samples were collected from surface exposures at several locations (Fig. 1). Representative samples of the Pass Lake Formation of the Sibley Group were taken from a cliff section directly across from Pass Lake on Hwy. 587. Individual beds

Additional granitic samples were obtained from road cuts along Hwy 11/17 and Hwy. 527 (Fig. 1). One sample was taken from each location. Samples of Redstone Point sandstones, and granite samples were previously obtained by P. Fralick from the English Bay region of Lake Nipigon (Fig. 1).

ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectroscopy)

Samples were cut into approximately 4 x 3 x 0.5 cm sections and crushed to a fine powder of <30 microns. Chemical preparation included hydrofluoric acid digestion to remove all silica and allow complete solution of samples. Prepared samples were analysed at the Lakehead University Instrument Laboratory.

SEM-EDS (Scanning Electron Microscope - Energy Dispersive X-Ray Microanalysis)

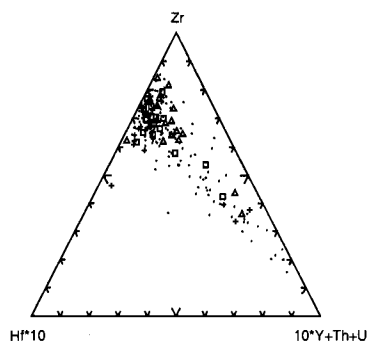


Figure 3. SEM-EDS analyses of zircons from Pass Lake Fm sandstones (points), Redstone Point sandstones (squares), Redstone Point Granites (+), and regional Archean and Neoproterozoic granites (triangles).

Samples were ground to 30 micron thin sections and cut into discs suitable for the SEM stage. Before analysis, samples were carbon coated to prevent charge build-up while being analysed. Samples were analysed for 50 seconds with an accelerating voltage of 20 KeV, and a beam current of 0.475 pA using a JEOL 5900 SEM with a system resolution of 139 eV, at Lakehead University Instrument Laboratory. Images were taken using a backscatter-electron detector. Zircons were analysed for five elements: Zr, Y, Th, U, and Hf.

The use of zircons in sediment provenance studies has been limited to work done by Owen (1987) which involved employing hafnium content of detrital zircons in determining the source of the upper Jackfork Sandstone and the Parkwood Formation. He came to the conclusion that hafnium content of these zircons agreed with optical and cathodoluminescence modal analyses, and is a viable method for provenance determination.

This study is the first to use SEM-EDS methods as well as analyses for Y, Th, and U. Fig. 3 shows zircon analysis results. The majority of zircons plot at Zr/Hf ratio of approximately 40 with relatively low amounts of Y, Th, and U, but a significant population show a Y, Th, U enrichment trend.

The geochemical signature of zircons from both sandstones and granites show similarity, and indicates local sourcing of sediment with a possible influence of regional Archean and Proterozoic felsic igneous intrusives.

Whole rock interpretation of ICP-AES geochemistry (Fig. 4) trends agree with SEM elemental distribution within samples. Immobile element ratios of the Pass Lake sandstones tend to fall on a mixing trend between enriched and non-enriched sources. This study highlights the possible usefulness of using SEM-EDS generated data in concert with more traditional chemical analyses in provenance studies.

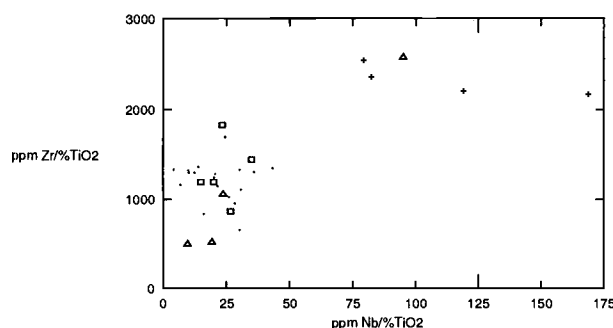


Figure 4. Immobile element plot of ICP-AES analyses. Pass Lake sandstones (points) plot in similar field to sandstones derived from, and overlying Redstone Point granite (squares). Redstone point granite (+), and other granites (triangles) are also shown.

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A Magnetostratigraphic and Secular Variation Study of the Sibley Group

Rogala, B., Fralick, P. and Borradaile, G. (*Department of Geology, Lakehead University, Thunder Bay, Ontario, P7B 5E1, brogala@lakeheadu.ca*)

The Sibley Group is a red bed sequence that was deposited in a subsiding intracratonic basin (Fralick and Kissin, 1995) overlying, in part, a 1537±10-2 Ma (Davis and Sutcliffe, 1984) anorogenic granite-rhyolite complex. The Group was previously divided into three main Formations: Pass Lake, Rossport, and Kama Hill. An unnamed Formation and the Nipigon Bay Formation have recently been added. The Pass Lake Formation consists of the conglomeratic Loon Lake Member and the sheet-like sandstones of the Fork Bay Member, representing a braided fluvial environment (Cheadle, 1986). The Rossport Formation is separated into the Channel Island, Middlebrun Bay, and Fire Hill Members. The Channel Island Member is a cyclic dolomite-shale unit interpreted to be playa lake sediments (Cheadle, 1986). The Middlebrun Bay Member, considered a marker bed for the Sibley Group, is a stromatolitic unit that represents a migrating strandline. The Fire Hill Member consists of mudcracked red silt with mudchip conglomerates and sand sheet incursions. It signifies a time of tectonic tilting of the basin. The Kama Hill Formation is not subdivided, and is composed of purple shales and siltstones interpreted as mud flat deposits (Cheadle, 1986). The unnamed Formation is divided into two unnamed Members. These represent a deltaic and fluvial environment. The Nipigon Bay Formation consists of cross-stratified sandstone beds, and is thought to denote an aeolian environment.

Samples were taken from the Pass Lake, Rossport, Kama Hill, and Nipigon Bay Formations for a paleomagnetic study. The unnamed Formation was not sampled due to the lack of exposure. The Pass Lake, Kama Hill, and Nipigon Bay Formation were used to conduct a preliminary study of the magnetostratigraphy of the Sibley Group. The Rossport Formation was sampled from unoriented drill core, thus could only be used to study secular variation.

The paleopoles calculated from the Pass Lake, Kama Hill, and Nipigon Bay Formations have been plotted along an apparent polar wander path (APWP) defined by Elston *et al.* (2002) (Figure 1). The samples from the Pass Lake Formation have been divided into sample groups corresponding to Quarry Island, Transitional to the Rossport Formation, and an outcrop at Pass Lake. The paleopole of the Quarry Island Group corresponds with a diagenetic event at approximately 1339±33 Ma (Franklin, 1978), and the latter two groups have paleopoles associated with an early Keweenawan overprint. The Kama Hill Formation has an older discordant paleopole and a younger paleopole that is located within the 1500 Ma section of the apparent polar wander path. This suggests that the Sibley Basin formed prior to this, as is supported by the recent discovery of sedimentary xenoliths within the 1537 Ma Redstone Point granite. The Nipigon Bay Formation has paleopoles that lie on the APWP near 1400 Ma and 1100 Ma. The first paleopole may be primary or related to the diagenetic event that affected the Pass Lake samples at 1339 Ma. The latter paleopole correlates with the Osler Volcanics.

The paleomagnetic study on a 90 cm core section from the Rossport Formation revealed a secular variation curve. When this curve was compared to typical secular variation curves (Butler, 1998; Tauxe, 1998), the time-span for Sibley deposition can be estimated. The 90 cm section was estimated to represent 2500 to 3000 years. This can be extrapolated to estimate that the Rossport Formation could potentially represent 75 000 years of deposition.

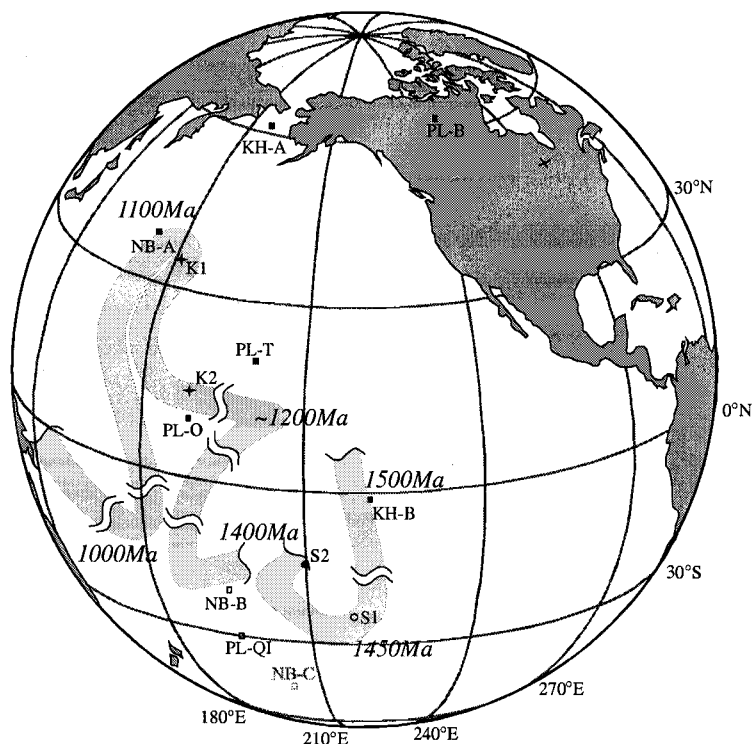


Figure 4.12 A well-defined Proterozoic Apparent Polar Wander Paths (APWP) is plotted (after Elston *et al.*, 2002). The Pass Lake PCA components are designate with QI, T, and O to indicate the Quarry Island, Transitional, and Outcrop Groups. The Kama Hill Formation is designate KH and the Nipigon Bay Formation is NB. The PCA, PCB, and PCC components are denoted respectively by A, B or C after the Formation short form. Note that NB-C is a reversed pole on the back side of the globe. Elston *et al.* (2002) has provided a lower (S1) and upper (S2) Sibley Group pole based on data from Robertson (1973), as well as a pole for the Keweenaw Osler Group (K1) and lower Powder Mill Volcanics (K2).

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Sequence of Precambrian Mafic Dikes in Marquette County, Michigan with emphasis on the Sugarloaf Mountain and Republic Areas

N.A. Sandin and T.J. Bornhorst (Department of Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, MI 49931)

Precambrian mafic dikes are very common throughout Marquette County, Michigan. These dikes have ages from Archean (~2.7 Ga) to middle Proterozoic (~1.1 Ga). Past studies by Kantor (1968), Gair (1969), Cannon (1974), and Baxter and Bornhorst (1988) have suggested up to six different mafic dike events in Marquette County. These events were interpreted to consist of (from old to young): 1) Archean mafic dikes post-Archean volcanism and before Archean granitoid intrusions which cut the Archean volcanic rocks; 2) Archean mafic dikes that cut Archean granitoid intrusions, but are subjected to Archean deformation; 3) Archean mafic dikes that cut Archean basement rocks, but do not cut Early Proterozoic sedimentary rocks of the Marquette Range Supergroup; 4) Early Proterozoic mafic dikes that cut Marquette Range Supergroup sedimentary rocks prior to Penokean metamorphism and deformation; 5-6) N-S and E-W Keweenawan mafic dikes. This study has confirmed much of Baxter and Bornhorst (1988), however, new data indicate significant modifications.

This study focused on the Sugarloaf Mountain area near Marquette, MI because of the excellent exposures on shore and adjacent to Lake Superior, and previous work by Kantor (1968), who identified mafic dikes of multiple ages. In the Sugarloaf Mountain area over 300 mafic dikes intruding Archean tonalitic basement were identified and mapped using a GPS receiver and the compass and pace method. Dikes identified as critically important to understanding the sequence of events were sampled for microscopic and chemical study.

Baxter and Bornhorst (1988) interpreted thin, discontinuous, tabular mafic bodies at Wetmore Landing in the Sugarloaf Mt. area as being Archean post-plutonic/pre-deformation mafic dikes (number 2 above). While this interpretation is still possible, the favored interpretation here is that these mafic bodies are xenoliths that were deformed during the Archean along with the host plutonic rocks.

In Marquette County, Baxter and Bornhorst (1988) as well as previous workers recognized the numerous mafic intrusives that cut Marquette Range Supergroup sedimentary rocks prior to Penokean metamorphism and deformation. These were presumed to be of generally the same age. This study indicates that in the Sugarloaf Mt. area, three age separate mafic intrusive events of this age are present. Based on cross-cutting relationships, the sequence consists of diabase dikes trending N20°E, diabase dikes trending N60°E, and diabase dikes trending east-west. In addition to cross-cutting relationships, these groups can be discriminated from each other by trace elements.

The N20°E diabase dikes are the oldest of the Early Proterozoic dikes. In the Sugarloaf Mt. area, these dikes vary in trend from N05°E to N20°E and range in width from one to 25 feet. Mafic dikes of this age are the most common of the Early Proterozoic dikes in the Sugarloaf Mountain area. These dikes exhibit a varying texture from porphyritic to phaneritic from the dike interiors to the margins. They consist of hornblende, pyroxenes, chlorite, plagioclase, epidote, and sericite. The REE patterns are enriched in light-REE with a moderate slope. Compared to the REE patterns of the sills from the Marquette Range Supergroup, the N20°E series has a higher concentration of light-REE, is less depleted in heavy-REE, and has a shallower slope. Thus, our initial interpretation is that these dikes are not related to the sills.

The N60°E mafic dikes are intermediate Early Proterozoic age. They vary in trend from N45°E to N60°E and range in width from one to 60 feet. These are the least common of the Early Proterozoic dikes in the Sugarloaf Mountain area. They generally have thinly foliated margins with a massive, fine-grained interiors. These dikes have a phaneritic texture and consist of hornblende, pyroxenes, chlorite, plagioclase, epidote, sericite, and minor amounts of carbonate. These dikes cross-cut the N20°E diabase dikes. REE patterns are enriched in light-REE and have a steep slope. Compared to the N20°E series and the sills of the Marquette Range Supergroup, the N60°E dikes are more enriched in light-REE with a steeper slope. The N60°E dikes are more depleted in heavy-REE than the N20°E series. Our initial interpretation is that these dikes are a distinct magmatic event with respect to the earlier N20°E dikes and the mafic sills.

The east-east diabase dikes are the youngest series of the Early Proterozoic dikes. They vary in width from five to 75 feet wide. These dikes generally have thinly foliated margins with a massive, fine-grained interior, although two dikes had porphyritic interiors. They have a phaneritic texture and consist of hornblende, pyroxenes, chlorite, plagioclase, epidote, and sericite. These dikes cross-cut the N20°E diabase dikes and the N60°E diabase dikes. Compared to the REE patterns of the sills from the Marquette Range Supergroup, the east-west dikes have a higher concentration of light-REE and a steeper slope. The east-west dikes are depleted in the heavy-REE compared to the N20°E dikes. They are lower in light-REE and have a shallower slope than the N60°E series. Our initial interpretation is that these dikes are a distinct magmatic event from the earlier dikes and the mafic sills.

There are three distinct mafic dike events in the Sugarloaf Mt. Area. We propose that these dikes are not related to the mafic sills that cut the Marquette Range Supergroup. If true, then there must be at least 4, and likely more, Early Proterozoic mafic magmatic pulses in the Marquette area.

Two groups of unmetamorphosed diabase dikes were identified in the Sugarloaf Mt. area, consistent with Baxter and Bornhorst (1988). These dikes are Keweenawan in age and consist of a north-south trending series and an east-west trending series. Both dikes have a diabasic texture and vary from 10 to 75 feet wide.

In the Republic area, Baxter and Bornhorst (1988) suggested that some metamorphosed mafic dikes with distinct plagioclase phenocrysts are older than the metamorphosed Proterozoic dikes in the Sugarloaf area. They proposed that these dikes might correlate with the Matechewan dike swarm north of Lake Superior in Canada. We tested this hypothesis by doing chemical analysis of these dikes. The REE data for these dikes are similar to Matechewan dikes from elsewhere and support the hypothesis proposed by Baxter and Bornhorst (1988).

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PALEOPROTEROZOIC DEVELOPMENT OF A GNEISS DOME CORRIDOR IN THE SOUTHERN LAKE SUPERIOR REGION, USA

SCHNEIDER, D.A., Dept. of Geological Sciences, Ohio University, Athens, OH 45701; HOLM, D.K., and O'BOYLE, C., Dept. of Geology, Kent State University, Kent, OH 44242; HAMILTON, M., Continental Geoscience Division, Geological Survey of Canada, Ottawa, ON Canada; and JERCINOVIC, M., Dept. of Geosciences, U-Mass, Amherst, MA 01003

Paleo-reconstruction of the Penokean orogen at ca. 1750-1700 Ma reveals the presence of a narrow corridor of Archean cored Paleoproterozoic gneiss domes just north of and parallel to the main suture zone in Minnesota, Wisconsin, and northern Michigan. Penokean (ca. 1850 Ma) metasedimentary rocks infolded within the domes give predominantly 1750-1700 Ma cooling ages and are overlain depositionally by ca. 1700 Ma Baraboo interval quartzites. We conducted U-Pb SHRIMP and total-Pb EMP geochronometry to obtain metamorphic timing constraints on distinct monazite mineral domains from amphibolite grade rocks sampled across the entire length of the gneiss dome corridor. Based on metamorphic monazite crystallization ages, midcrustal amphibolite facies metamorphism (M1) peaked around 1830 Ma and was concurrent with late Penokean plutonism; subsequent thermal pulses are reliably recorded at ca. 1800 Ma (M2) and again at ca. 1765 Ma (M3), both also coeval with magmatic activity.

The youngest monazite ages overlap with abundant Ar-Ar mineral age data, which indicate widespread cooling of the gneiss dome corridor immediately following M3. We propose that the gneiss domes formed at this time during structural modification of the tectonically buried continental margin rocks. In our conceptual model (Fig. 1), northward vertical extrusion of a decoupled midcrustal block containing the gneiss dome corridor accommodated gravitational collapse of overthickened crust. Elevated country rock temperatures accompanied with profuse melting (i.e., intrusion of the East-central Minnesota batholith) promoted doming of the lower density Archean basement into the more dense overlying Paleoproterozoic metasedimentary rocks, ultimately enabling its complete decoupling from the remaining lower crust. This process, primarily driven by buoyancy forces, allows for the redistribution of crustal mass from thick to thin regions without significant horizontal crustal extension. Tectonic extrusion and crustal thinning at this stage may have been facilitated by a decrease in horizontal compressive stresses acting on the region from the south (i.e., Yavapai slab rollback as proposed by Holm et al., ILSG, 2003). In our model (Fig. 1), the faults bounding the gneiss dome corridor are ca. 1765 Ma structures, although some, like the Niagara Fault zone, are reactivated Penokean structures. We note that in east-central Minnesota, a significant portion of the Malmo Structural discontinuity juxtaposes post-Penokean plutons to the south against older metamorphic rocks to the north (west of Mille Lacs). This clearly supports our interpretation that this structure (and the Flambeau Flowage fault equivalent in northern Wisconsin) was active well after Penokean orogenesis.

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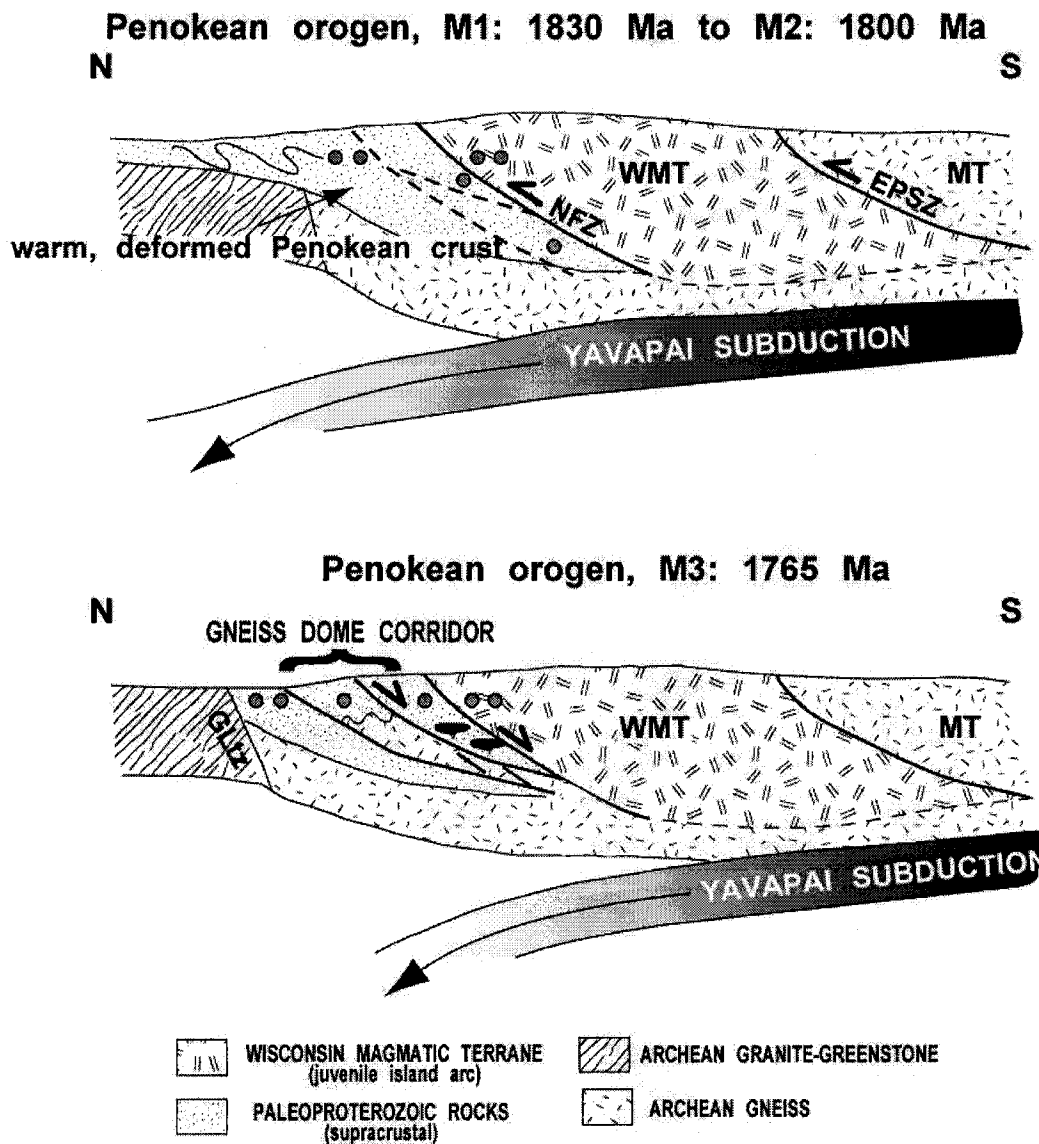


Figure 1. Schematic N-S cross-sections at 1830-1800 Ma (A) and 1765 Ma (B) depicting the proposed evolution of the gneiss dome corridor in northern Wisconsin. Note relative locations of gray circles that represent depth of crustal blocks.

A Paleoproterozoic suprasubduction zone ophiolite-island arc complex in northeastern Wisconsin

Schulz, Klaus J., (*U.S. Geological Survey, Reston, VA 20192, kschulz@usgs.gov*)

The Paleoproterozoic volcanic and associated intrusive rocks exposed in northeastern Wisconsin are the easternmost exposures of the Pembine-Wausau terrane, the northernmost of the two Wisconsin magmatic terranes that were accreted to the southern margin of the Archean Superior Craton during the Penokean Orogeny (Sims and others, 1989). The rocks of the Pembine-Wausau terrane are separated from the epicratonic sedimentary rocks of the Marquette Range Supergroup to the north in Michigan by the Niagara fault zone.

The volcanic rocks of the Pembine-Wausau terrane exposed northeastern Wisconsin, formed at about 1,870 Ma and are cut by a variety of intrusive rocks ranging from syn-volcanic gabbros, diorites, and tonalities to syn-and post-tectonic granitoids (i.e., Dunbar Gneiss and related rocks). The volcanic rocks are divided into four fault-bounded units, the Quinnesec, McAllister, Beecher, and Pemene formations. These units are interpreted to record the evolution of a Paleoproterozoic suprasubduction zone ophiolite-island arc complex, the Pembine ophiolite-arc complex.

The Quinnesec Formation is the oldest volcanic unit and consists predominantly of pillowed basalt flows and massive diabase, but includes andesite and rhyolite lava flows and fragmental rocks locally. Several large gabbro sills are present, particularly near the Niagara fault zone, some with peridotite and pyroxenite layers. In addition, a large serpentinized peridotite-gabbro body that produces a large positive magnetic anomaly is exposed south of Timms Lake (Morgan County Park) east of Pembine, Wisconsin. Serpentinized peridotite is dominant in the western part of this body where it is locally cut by coarse-grained (1-5 cm) dikes of pyroxenite. Layered and massive gabbro and masses of strongly foliated-lineated gabbro are dominant in the eastern part of the body where they are cut by numerous mafic dikes with diabasic to microdioritic textures; some of the dikes appear to be sheeted.

The rocks of the Quinnesec Formation appear to record the birth and youth stages of a suprasubduction zone ophiolite (Shervais, 2001). Rocks formed during the initial phase of ophiolite evolution typically include layered and isotropic plutonic gabbros, sheeted dikes, and a "lower" volcanic section consisting of low-K tholeiitic basalt and basaltic andesite with MORB and primitive arc tholeiite affinities. Gabbros formed during this stage are often ductilely deformed (foliated or boudinaged) in response to syn-magmatic extension. Rocks formed during the second or youth stage of ophiolite formation include intrusive mafic-ultramafic sills and diabase dikes, and an "upper" volcanic unit characterized by basalt and andesite with highly depleted incompatible trace element compositions (i.e., low-Ti basalt, high-Mg andesite and boninite) (Shervais, 2001).

Compositionally, the Quinnesec basalts and gabbros are tholeiitic, with generally low TiO₂ and other high field strength element abundances, and flat to extremely light REE

depleted patterns (Sims and others, 1989). In addition, some of the basalts, gabbros, and andesites have very low TiO_2 and REE abundances, but relatively high Cr and Ni contents. The trace element characteristics of the mafic rocks overlap those of mid-ocean ridge basalts and primitive island-arc tholeiite suites whereas the andesites show compositional affinities with fore-arc-related boninites. The presence in the upper part of the Quinnebec Formation of mafic rocks derived from highly refractory mantle is particularly diagnostic of a relationship to the early stages of intraoceanic subduction and formation in a forearc setting (Shervais, 2001). This also implies that the Quinnebec Formation and associated rocks did not form in a back-arc basin near or on the margin of the Superior Craton, as has recently been proposed (Van Wyck and Johnson, 1997), but rather formed as an intraoceanic ophiolite-arc system above a southward dipping (in present coordinates) subduction zone.

The McAllister, Beecher and Pemene formations consist of volcanic and volcanoclastic rocks ranging from andesite (McAllister) to rhyolite (Pemene), all with calc-alkaline compositions characteristic of mature oceanic arcs. These volcanic rocks and associated intrusives, such as the Newingham Tonalite and Twelve Foot Falls Quartz Diorite, appear compatible with the third or maturity stage of suprasubduction zone ophiolite evolution (Shervais, 2001). Characteristic of this stage are intrusive rocks, such as hornblende diorite, quartz diorite, and tonalite, as well as volcanic rocks ranging from basalt to rhyolite, all with transitional to calc-alkaline compositions. Volcanism typically becomes more silicic with time in these sequences. In many cases, rocks of this stage have not been considered part of the subjacent ophiolite, but rather have been attributed to post-ophiolite arc volcanism (Shervais, 2001).

It appears likely that growth of the Pembine ophiolite-arc complex was terminated by its collision with and obduction onto the passive southern margin of the Superior Craton. Because subduction appears to be largely driven by slab pull, the southward subduction of oceanic lithosphere attached to the Superior continental margin would have pulled the continental lithosphere along with it as it descended into the subduction zone below the ophiolite-arc system. With detachment of the subducting oceanic lithosphere, the buoyancy of the continental lithosphere would have led to its rapid uplift along with the leading edge of the ophiolite-arc complex (Shervais, 2001). This stage is recorded by the deformation of the ophiolite-arc sequence and by the intrusion of the syn- to post-tectonic units of the Dunbar dome.

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THE LAKE NIPIGON GEOSCIENCE INITIATIVE – PLANNED ACTIVITIES AND OBJECTIVES

SMYK, Mark C., Ontario Geological Survey, Ministry of Northern Development and Mines, Suite B002, 435 James St. South, Thunder Bay, ON P7E 6S7, and members of the Scientific and Implementation Committees, Lake Nipigon Geoscience Initiative, c/o Ontario Prospectors Association, 1000 Alloy Drive, Thunder Bay, ON P7B 6A5

The Lake Nipigon Geoscience Initiative (LNGI) was created in 2002 as a \$7.0 M Cdn. project aimed at attracting mineral investment to the area around Lake Nipigon. The Ontario Prospectors Association's (OPA) portion of the project is funded through an agreement with the Northern Ontario Heritage Fund. The OPA is partnering with the Ontario Geological Survey (OGS), the Ministry of Northern Development and Mines (MNDM), the Canadian Mining Industry Research Organization (CAMIRO), Lakehead University, as well as with private sector partners and communities in the Lake Nipigon area. It will focus on four key objectives:

1. Maintain and then increase mineral investment in the Lake Nipigon region through collection of high quality geological data and provision of interpretations that meet the needs and priorities of the mineral industry and that maintain or attract mineral investment to Ontario;
2. Increase the mineral exploration discovery rate by addressing "masking and deep search challenges and skill gap" in the area;
3. Respond to, and evaluate, new and exciting mineral deposit models recently recognized for nickel-copper, palladium-platinum, and gold-copper mineralization in the region;
4. Reinforce and demonstrate an innovative economic development model based on local community, industry, and government partnerships in geoscience that result in mineral resource economic development in the local communities, the region, and Ontario.

The LNGI is focused on the Nipigon Basin / Embayment, which consists predominantly of Mesoproterozoic, Midcontinent Rift-related, ultramafic to mafic intrusions that have intruded Mesoproterozoic Sibley Group sedimentary rocks and Archean basement rocks of the Quetico and Wabigoon subprovinces.

The project will develop a comprehensive geoscience database that will assist in mineral exploration. The LNGI evolved through a series of community and industry consultations that helped define the project parameters. A thorough compilation of previous exploration and geological data provided a baseline for the project and identify potential gaps in the geoscience database. The main components of the initiative include:

- Detailed geological mapping, undertaken by Precambrian Section, OGS
- Airborne magnetic survey
- Gravity survey
- Quaternary (surficial) case studies, undertaken by Sedimentary Geoscience Section, OGS
- Geochronology
- Physical property studies
- Geographic Information Systems (GIS) compilation
- Complementary research at Lakehead University
 - Sibley Group studies (P. Fralick)
 - Nipigon mafic intrusion studies (P. Hollings; G. Borradaile)
 - Sulphide mineralization studies (S. Kissin)

The Ontario Geological Survey will help acquire and publish the results of the geoscience studies as maps, reports, and digital data sets. The information will then be available over the Internet through the MNDM's ERMES and CLAIMap systems. This valuable information will be used to globally market the resource potential and investment appeal of the Lake Nipigon region.

ARCHEAN TECTONOSTRATIGRAPHIC ASSEMBLAGES OF EASTERN WABIGOON SUBPROVINCE, NORTHWESTERN ONTARIO

STOTT Greg M., Ontario Geological Survey, Sudbury, ON, P3E 6B5 (greg.stott@ndm.gov.on.ca), **DAVIS**, Don. W., Department of Geology, University of Toronto, Toronto, ON, **PARKER**, Jack R., Ontario Geological Survey, Sudbury, ON, **STRAUB**, Kristan J., Laurentian University, Sudbury, ON and **TOMLINSON**, Kirsty Y., Geological Survey of Canada, Ottawa, ON

The Archean Wabigoon Subprovince is a complex of volcanic and sedimentary supracrustal assemblages and granitoid suites of Mesoarchean to Neoarchean age. The easternmost part of this subprovince, which includes the Onaman-Tashota greenstone belt east of Lake Nipigon, preserves a history of over 250 million years of volcanism. This area has recently been treated to a regional mapping, geochemical and geochronological synthesis as part of the Western Superior NATMAP project. A 1:250 000 compilation map (Stott et al. 2002) arising from this project illustrates the subdivision of the Onaman-Tashota (O-T) greenstone belt into tectonostratigraphic assemblages (**Figure 1**), based on stratigraphic correlations, geochronological and geochemical similarities and contact relationships. A more interpretive component of this map, summarized in **Figure 2**, is the delineation of the assemblages in terms of the environment of crystallization of volcanic and plutonic rocks and deposition of sedimentary rocks. This is based on lithologic and geophysical characteristics, whole-rock geochemical classification, and where available, Nd isotopic signatures.

The Onaman-Tashota greenstone belt straddles the width of the eastern Wabigoon Subprovince between the English River and Quetico metasedimentary subprovinces. It is mainly composed of Neoarchean (dominantly 2.74 – 2.72 Ga) basaltic and dacitic flows, autobreccia and pyroclastic rocks. Mesoarchean (3.05 – 2.92 Ga) volcanic rocks occur in the northwest and along the western margin of the belt. Widespread Nd isotopic evidence in the northern part of the Onaman-Tashota belt suggests that Neoarchean volcanism erupted through Mesoarchean basement. Basement in the northern half of the belt contains an older component than that south of the Humboldt Bay High Strain Zone. The 2.74 Ga Willet assemblage tholeiitic basalts of ocean floor affinity dominate the northern half of the O-T belt. This assemblage is flanked to the north and south by calc-alkalic assemblages of continental margin arc affinity that border metasedimentary subprovinces composed of flysch-like wacke derived from the erosion of the O-T belt and plutons during orogenesis at circa 2.7 Ga. Most sedimentary units within the O-T belt form the youngest supracrustal assemblages, reflecting erosion of the underlying volcanic and plutonic rocks towards the English River and Quetico basins to the north and south.

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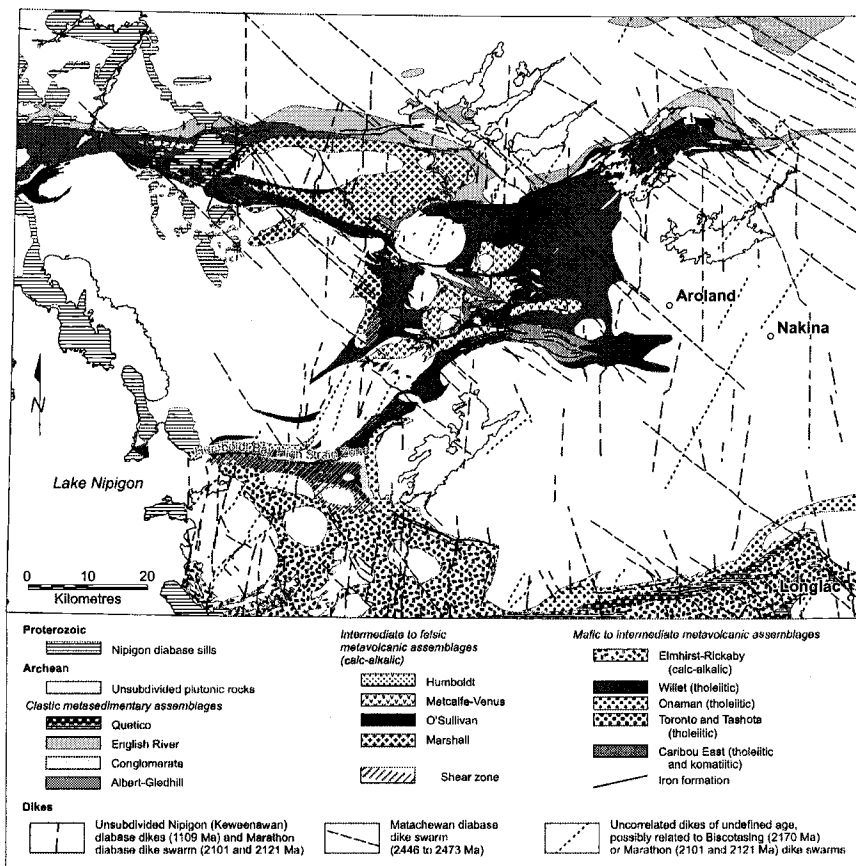


Figure 1. Tectonostratigraphic assemblages of the Onaman-Tashota greenstone belt and Proterozoic diabase dike swarms, Eastern Wabigoon Subprovince.

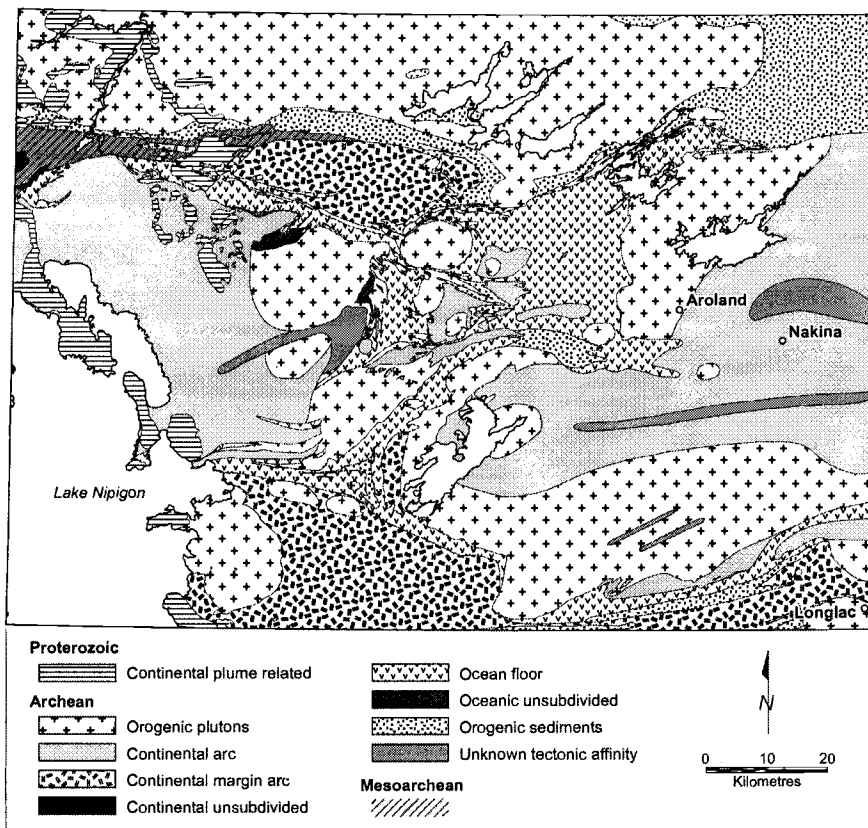


Figure 2. Tectonic affinities assigned to volcanic and sedimentary assemblages and plutonic suites.

FIVE GOLD POSSIBILITIES IN SOME KEWEENAWAN COPPER SULFIDES IN ONTARIO AND MICHIGAN

Trow, Jim, Geological Sciences, Michigan State University,
emeritus, 540 Lake Avenue #2, Hancock, Michigan 49930

Most fire-assayed "invisible" gold, from .12 to 2.50 oz Au/st, occurs in "blue chalcocite" (with minor covellite) but not in black chalcocite (with no covellite) on the adit, 1st, 2nd, and 3rd levels of the Coppercorp mine at Mamainse Point, Ontario. Both occur with specular hematite. Copper mineral zoning extending from carbonates and oxides through native copper, black chalcocite and specularite, "blue chalcocite" and specularite, to bornite and chalcopyrite is related to nearness to the Keweenaw and related faults apparently down which circulated oxidizing solutions during an upward-migrating hydrothermal episode. The former faults display positive SP electrical anomalies, whereas nearly perpendicular cross faults with commercial ores display negative SP anomalies of this convective hydrothermal cell (Trow). Such progressive oxidation of hydrothermal fluids is suggested for the Keweenaw of Michigan by the USGS's Woodruff, Cannon, and Back. For Ontario, Trow deduces thermochemical calculations with standard free energies and typical activities for constituents (except for oxygen, whose activities are the unknowns). These are arrayed on a logarithmic scale which mimics the observed copper mineral zones, and in that sequence AuS^{-1} first oxidized to deposit gold at the same oxygen activity at which chalcopyrite first oxidized to covellite and specularite. At the present it is uncertain if the "blue chalcocite" exsolved into chalcocite and covellite from digenite at low temperatures, or if most of original covellite was replaced by late chalcocite at roughly 2,500 times the oxygen activity at which covellite originally formed.

Essentials for gold at Coppercorp include 1) Keweenaw permeable basaltic vesicular beds and conglomerates, 2) felsite intrusives with permeable border breccias as conduits for rising hydrothermal solutions, 3) nearness to the Keweenaw and related faults with positive SP anomalies, 4) mineralized cross faults with ores yielding negative SP anomalies, and 5) "blue chalcocite".

In Michigan, field examination of ore deposits and structures mapped by the USGS shows that the major lodes (Baltic, Ashbed, Isle Royale, Pewabic, Osceola, Calumet conglomerate, and Kearsarge) and the Cliff, Central, and Delaware fissure deposits all display negative SP anomalies. The Keweenaw, Hancock, Mayflower, and Gratiot-Suffolk faults all display positive SP anomalies, appropriate for downward oxidative contamination of rising hypogene (not supergene) mineralization.

From southwest to northeast the best matches to Canadian gold in Michigan, so far examined, occur 1) from Mass City to the Indiana mine adjacent to felsite intrusives and the Keweenaw fault in Ontonagon County, 2) In Houghton and Keweenaw Counties the Allouez Gap fault between Copper City and New Allouez is near the Copper

City felsite and the Keweenaw fault. According to Bornhorst, page 132, Randy Weege of C & H thought that this fault perhaps was a fluid pathway for 60% of the district's copper production. Further, it replicates and improves upon the best geophysical signature at Coppercorp, the persistent SB zone, with flanking negative SP anomalies in the midst of which is a positive SP anomaly. In Michigan, the positive "core" anomaly splinters westward off the northern end of the negative anomalies in the vicinity of Ahmeek. This part of the district contains arsenic, which accompanies gold in many western mining camps. 3) In 1999 Maki and Bornhorst reported on the 4½ million tonnes of chalcocite in drilled amygduloids of the Gratiot deposit in Keweenaw County, where these beds are intruded by dacite (felsite). This lode appears at the intersection with the southward extension of Trow's negative SP anomaly as observed at the Central mine and 2¼ miles to the SSE. 4) In Keweenaw County, the USGS's Hank Cornwall on pages 166-167 describes minor traces of gold with mainly chalcocite and specularite and some covellite and chalcopyrite in an amygduloid near the top of the Greenstone flow. This is not near the Keweenaw fault, but it is cut by a N.40°E. vertical fault with a negative SP anomaly, which must be intersected at depth by a N.40°E., 35°-45°NW. fault with a positive SP anomaly, where it is exposed to the east of the vertical fault. There exists a possibility for a horizontal ore shoot at these faults' intersection. These four possibilities are plotted on the latest geologic map of the Keweenaw Peninsula, by Cannon and Nicholson. Not yet reconnoitered possibilities may occur to the northeast of these.

Remember, from 1849 to 1961 the old timers all missed the Carlin "invisible" gold. Nevada is now the biggest gold producing state because of the observations, thinking, and perseverance of the USGS's Ralph Roberts and Newmont's John Livermore.

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Using xenotime U-Pb geochronology to unravel the history of Proterozoic sedimentary basins: a study in Western Australia and the Lake Superior Region

Vallini, D.A., dvallini@geol.uwa.edu.au, McNaughton, N.J., Rasmussen, B., Fletcher, I., Griffin, B.J., University of Western Australia, 35 Stirling Hwy, Crawley, 6009, Australia

Diagenetic xenotime (YPO_4) is a trace constituent in a wide variety of siliciclastic sedimentary rocks. It typically forms pyramidal crystals of only a few microns in size, rarely exceeding 10 μm , growing on [isostructural] detrital zircons. A recent study by Vallini et al. (2002) showed convincing petrographic and age relationships that demonstrate this U-bearing phosphate could begin forming in sediments at or just below the sediment-water interface, shortly after burial. A few years ago it was discovered that it is possible to date xenotime crystals $\geq 10 \mu\text{m}$ in size, using the SHRIMP (Sensitive High Resolution Ion Microprobe), providing a robust isotopic age for its formation, hence an age for early diagenesis and a close proxy for sediment deposition. Xenotime is especially useful in that it has very high U contents and remains closed to radiogenic parent-daughter mobility, unlike most other dateable diagenetic mineral. Diagenetic xenotime U-Pb geochronology has the potential to unravel the chrono-stratigraphy of unfossiliferous sedimentary basins, especially those sequences devoid of dateable interlayered volcanic rocks. Its main application is in Precambrian basins where a lack of a reliable temporal framework hinders an understanding of basin evolution and maturation, tectonic affiliations, metallogeny and value as exploration targets.

Xenotime also forms during post-diagenetic fluid flow events, such as alteration, mineralisation and metamorphism, as well as being a magmatic mineral and a detrital heavy mineral. The exceptional range of formation conditions of xenotime, coupled with its excellent properties for *in situ* geochronology, provide many new opportunities in establishing the timeframe of events in many hitherto poorly understood sedimentary basins.

Unusually coarse (up to 200 microns) and abundant diagenetic xenotime crystals in the meta-sandstones of the greenschist facies Mount Barren Group, southwestern Australia, allow the detailed study of xenotime and its host rock. Xenotime occurs within a phosphatic sandstone interval and is present in multiple morphologically different styles - as cement overgrowths on zircons, pyramidal overgrowths on zircons, cement (no zircon) in shale laminations, replacement of shale (?) intraclasts and as xenotime crystals within intraclasts. Multiple fluid events from early diagenetic to low temperature/early hydrothermal, prior to metamorphism, were recorded within single xenotime crystals.

SHRIMP U/Pb geochronology, accompanied by observations of petrographic relationships between the various generations of xenotime and between xenotime and other diagenetic minerals and pyrobitumen, allowed for the construction of a temporal framework for the diagenetic and early hydrothermal events that occurred within these rocks; (1) *ca 1700 Ma*: deposition of partly re-worked phosphatic siliciclastic sediments on the seafloor was followed by in-situ phosphatisation of the sediments and an initial period of xenotime formation (mean age of $1697 \pm 7 \text{ Ma}$), (2) With burial, an early pore-filling carbonate cement was introduced into parts of the interval, as well as early diagenetic cuboid pyrite growth, (3) *ca 1650 Ma*: during burial diagenesis, a fluid- movement event caused the partial dissolution of primary pore space and formation of xenotime (mean age of $1646 \pm 8 \text{ Ma}$), with accompanying phosphate remobilisation, (4) Oil migration event, (5) Several silica cement generations introduced around this time, (6) *ca 1560 Ma*: minor addition of xenotime rims to existing overgrowths, (7) *ca 1480 Ma*: addition of xenotime cement (no zircon) in shale interlaminae, (8) *ca 1200 Ma*: peak of metamorphism.

Wavelength Dispersive Spectrometer (WDS) microprobe analysis of each type of xenotime showed a gradual change from LREE enrichment to MREE enrichment, with time. Due to this gradational nature, discrete boundaries between generations, based on chemistry, could not be established.

This study of diagenetic to hydrothermal xenotime dramatically improved the estimated age range of the Mount Barren Group, which was previously constrained to 1200 Ma (peak metamorphism) and 1790 Ma (youngest detrital zircon population), and discounted some previous tectonic models concerning the timing of collision between major cratons within western Australia and these cratons with East Antarctica.

Using the information gleaned from the study of xenotime in the Mount Barren Group, a similar study is currently underway on another Proterozoic sediment-dominated basin in the Lake Superior Region containing the Marquette Range Supergroup and its equivalents, the North Range, Mille Lacs and Animikie Groups. The early Proterozoic strata consist of three unconformity-bounded lithostratigraphic groups consisting of glaciogenics, quartzites, dolomite, iron formation, greywacke and shale and minor intercalated volcanics. Sedimentation is thought to have begun $\sim 2240 \text{ Ma}$ (correlation of Chocoday

Group with Gowganda Fm, upper Huronian Supergroup, Ontario) (Fairbairn et al., 1969) and ceased by ~1850 Ma (coinciding with orogen-normal arc collision along the Niagara Fault zone and the Malmo Discontinuity, during the Penoken Orogeny) (Sims et al., 1993). Part of the study is to determine if xenotime-rich horizons, such as that in the Mount Barren Group, can be located in this stratigraphy and to document the sedimentological, structural or stratigraphical features that they have in common. Certain rock units from the different sequences over the whole region were targeted for xenotime analysis using proposed sedimentological controls for xenotime formation that were determined from the Mount Barren Group study.

One sedimentary feature favourable to xenotime formation may be the presence of large quantities of sedimentary apatite within the host rock or adjoining rocks. A field sample of low greenschist facies phosphatic chert-conglomerate, at the base of the Baraga Group, from a documented phosphorite locality in the Dead River Basin, northern Michigan, contains large quantities of xenotime ranging from <30 μm pitted overgrowths on detrital zircons, to >100 micron xenotime cements.

Other rock units that contain xenotime overgrowths and cements of appreciable size and quantity, were; (i) quartzite beds in several drillholes through the Mahnomen Formation, Mille Lacs Group, Cuyuna Range, contain up to 50 xenotime crystals per thin section, some of these up to ~60 μm in size, (ii) a sandstone bed within drillcore from the base of the Baraga Group in Dead River Basin- its largest xenotime observed was 60 μm (iii) a grit-pebble conglomerate and very coarse-grained sandstone outcrop at Slate River Hill locality, Baraga Basin, which is assumed to lie at the base of the Baraga Group, averaged ~15 xenotime grains per thin section which are up to ~60 μm in size, and (iv) the basal Baraga Group hematitic conglomerate at Big Eric's Crossing locality, Baraga Basin, contains up to 5 xenotime grains per thin section, some of these are up to ~100 μm in size. Pokegema Quartzite samples, West Mesabi Range, showed minor <30 μm xenotime overgrowths on zircons.

All of the rock samples described above are very coarse-grained sandstone/conglomerate beds which are either located near a stratigraphic boundary and/or are interbedded with shale beds. Xenotime from these localities were analysed on the SHRIMP and revealed several age groups; (i) xenotime in the Mahnomen Formation drillcore revealed ages of ~1870 Ma and ~1770 Ma (1760-1790 Ma), (ii) One large xenotime overgrowth from the Dead River Basin drillcore, gave an age of ~2600 Ma, (iii) xenotime contained within the Slate River Hill outcrop yielded ages of ~2500 Ma, (iv) the samples from Big Eric's Crossing contained xenotime showing ages of ~2550 Ma and ~1750 Ma. The sample from the Pokegema Quartzite in the West Mesabi Range, contained xenotime with an age of ~2300 Ma and ~1770 Ma.

Xenotime yielding ages of ca 2500 Ma or older may be from recycled detrital (magmatic) grains. The younger age of ~1770 Ma (1760-1790 Ma), occurs in xenotime from widespread localities across the Lake Superior Region and may reflect an epigenetic thermal event across the region. The age appears to correlate with an episode at ~1760 Ma of anorogenic magmatism, pluton emplacement and gneissic doming recorded throughout Wisconsin, northern Michigan and central Minnesota. It postdates the Penoken Orogeny and involved partial melting of crustal rocks as a result of continent-continent or continent-arc collision to the south of the region (Sims, 1996). This event is approximately coeval with the development of the Central Plains Orogen (1800-1630 Ma) to the south and may be a consequence of the accretion of this terrane to the North American continent (Sims, 1996).

This study highlights the sensitivity of in-situ xenotime geochronology to identifying cryptic fluid flow events within basins. This study will be ongoing in 2003-2004.

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EVALUATION OF INITIAL MAGMA COMPOSITIONS FOR THE BALD EAGLE INTRUSION AND ASSOCIATED ROCKS

VISLOVA, Tatiana, Department of Geology and Geophysics, University of Minnesota

The funnel-shaped concentrically-zoned Bald Eagle Intrusion in the Duluth Complex is characterized by very restricted mineral compositions, and consists of only two units: an olivine-plagioclase cumulate and an olivine-plagioclase-clinopyroxene cumulate (Weiblen, 1965; Weiblen and Morey, 1980). In terms of differentiated units expected in a typical layered intrusion, the Bald Eagle Intrusion appears to be petrologically incomplete. This has raised the question whether the four-phase (olivine-plagioclase-clinopyroxene-oxide) cumulates, assigned to the Greenwood Lake Intrusion (Miller et al., 2002), and granophyre found to the south of the Bald Eagle Intrusion are genetically related to the Bald Eagle Intrusion (Weiblen and Morey, 1980).

New petrographic studies and microprobe analyses (Vislova, 2003) make it possible to evaluate parent magma compositions for the Bald Eagle Intrusion, and quantitatively assess possible petrogenetic relationships between the Bald Eagle Intrusion and spatially associated rocks. Computer programs (MELTS, Ghiorso and Sack, 1995; and COMAGMAT, Ariskin et al., 1993) were used to investigate these questions. A primitive North Shore Volcanic Group olivine tholeiite (P-melt) was used as an initial magma composition (Miller and Ripley, 1996).

Equilibrium crystallization of P-melt, calculated by MELTS at 1 atm total pressure and oxygen fugacity near or below the quartz-fayalite-magnetite buffer, reproduces the crystallization order and mineral assemblages observed in the Bald Eagle Intrusion. The calculated composition of the first clinopyroxene (**mg** ~ 81) equals the one observed, however calculated compositions of the first plagioclase and olivine are much higher than those observed. This could be ascribed to the dynamics of crystal-melt segregation in a flowing magma system. Until the crystals suspended in magma grow large enough they might be carried away, erupted, and found as phenocrysts in lavas.

At ~7 % melt remaining MELTS reproduces the most evolved mineral compositions in the Bald Eagle Intrusion (Fig. 1). This suggests that the Bald Eagle Intrusion might be a complete crystallization sequence with a few percent remaining melt. It leaves unanswered the question of the origin of four-phase cumulate and granophyre.

Modeling shows that a more evolved high Ti and high Fe melt (D-melt) is required for crystallization of the evolved units in the Greenwood Lake Intrusion (Fig. 1). This melt can be produced by fractional crystallization of P-melt in an intermediate magma chamber at 2-3 kbar total pressure.

Equilibrium crystallization of D-melt at 1 atm reproduces the crystallization order, the appearance of Fe-Ti oxides, and the compositions of most of the units associated with the Bald Eagle Intrusion (Fig. 1). However, the most evolved rocks in the Greenwood Lake Intrusion (ferrogabbro with Fo < 50) and granophyre were not reproduced by equilibrium crystallization. These units might require fractional crystallization or assimilation.

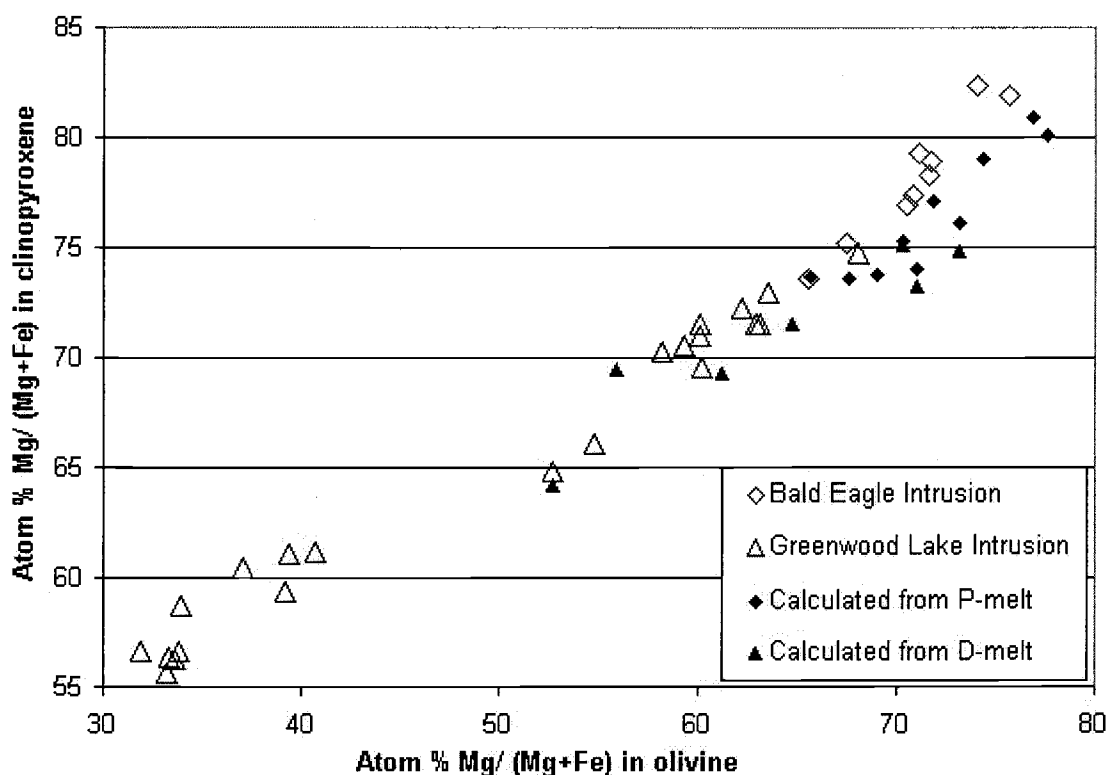


Fig. 1. Mg/(Mg+Fe) variations in coexisting olivine and clinopyroxene.

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A Hydrothermal Component of Iron Formations-A Marquette Range Perspective

Waggoner, T.D., 141 Chippewa, Negaunee, MI 49866

The origin of Lake Superior banded iron formations (BIF) has been a contentious issue for at least a century and a half. Concepts of origin include weathering, volcanic and organic activity whereby ions are carried in and precipitated from solution. Clear definition of the source, mode of transport or depositional mechanisms is generally lacking. This paper will address the strong evidence for a hydrothermal source for "hard ores" found in the upper parts of the Negaunee Iron Formation (NIF) and by extension a possible source for the precursor hematite in the BIF portion. The Range was formed in a tectonically active area believed to be an extensional rifting environment not unlike those found in Fe-Oxide (Cu, U, Au, REE) and some VHMS deposits

The Marquette Range portion of the Lake Superior Iron District displays many features similar to other large Lake Superior BIFs found around the world and, thus, making it an excellent study subject for the source and role played by igneous and sedimentary processes. The Negaunee and basal Goodrich units exhibit BIF, soft supergene enriched concentrations and "hard ores" as massive bodies, banded jaspilites and detrital conglomerates. "Hard ores" are generally dense silver gray to black massive metallic magnetite or schistose metallic hematite associated with jaspilite and contain in excess of 60% iron. Discussion of the origin of the "hard Ores" on the Marquette Range has revolved around supergene enrichment prior to metamorphism or hydrothermal enrichment associated with the Penokian Orogeny.

Many features of the field geology do not support with either of these positions. First, the cobble and pebbles of jasper hematite in the basal Goodrich conglomerate show random orientation of the 'schistose' hematite indicating the schistose nature of the hematite existed prior to emplacement and not a result of metamorphism. In addition many of the rocks associated with the "hard ores" exhibit hydrothermal minerals including sericite, chlorite, chloritoid, high aluminous silicates, garnet, hematite, magnetite and tourmaline.

The lower Proterozoic Chocoley and Menominee sediments below the NIF exhibit multiple examples of high-grade hematite that can be interpreted as vents. Specular, microplaty and bytroidal hematite are fairly common in many outcrop areas. Some of these have been described previously in literature while others have not. All the sites were subject to exploration for iron ore during the late 19th century and most exhibit shallow shafts. The major components are chert, jasper and vein quartz along with coarse specular, microplaty and bytroidal hematite contained in breccia zones that exhibit episodic reworking. There are alterations to the host rock as some occurrences exhibit chlorite, silica, k-spar and aluminous silicates.

A large area in sections 21, 22, and 23, 47-26 contain multiple enriched hematite sites that form two northwest trending breccia zones adjacent to northwesterly trending faults. In addition to the silica flooding, brecciation and hematite concentration there is a significant area of andalusite cordierite and chloritoid adjacent to the eastern linear

breccia zone in section 23. These minerals are present in a much broader lower regional chlorite zone of metamorphism and most likely are a result of the hydrothermal event that impacted the three square miles referenced above.

A conglomerate in Sec. 22 and 23, 47-26 has been previously described as "unusual" and is sandwiched between lower Chocoy argillite units. Clasts causing dimpling in the underlying argillite were described as rafted clasts from a glacial interlude. It is unlikely that a glacial event coincided with significant algal reef growth during the same period of time. The "unusual" conglomerate is extremely coarse, tightly packed and shows no sedimentary features. In addition significant rinds of k-spar have formed on the granite gneiss cobbles. The cobbles and matrix contain euhedral magnetite, martite and specular hematite suggesting this area was tectonically active and may well have been an active vent area over a period starting at the earliest extensional period and continued to be active beyond the Ajibik time. The conglomerate resembles some of the breccias at Olympic Dam and could well be a hydrothermal breccia.

REE chondrite normalized analysis of the hematite vents match quite closely with both the hematite, magnetite and combination hematite/magnetite "hard ores" found throughout the Range. Recent work on the Brockman microplaty hematite confirms a hydrothermal origin due to the recognition of surrounding alteration to the host.

Initially the vent areas were studied in relation to the "hard Ores" but the fact that the vents are all hematite suggests they could be the source for the precursor hematite seed cores that Han identified in low metamorphic grade BIF units. These seed cores have been identified in the Negaunee, Biwabik, Brockman, Sokoman, Temiscamie and Kuruman Iron Formations.

It is quite plausible that the extensional phase of rifting ceased near the end of NIF time and a reverse compressional event started causing faulting that produced erosional material for the basal Goodrich conglomerate.

Reference:

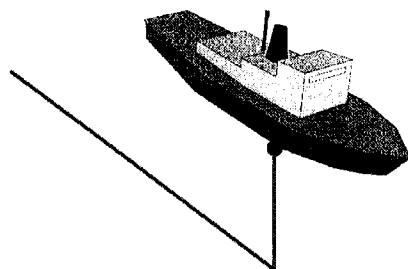
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High-Resolution Multibeam Bathymetry in Lake Superior.

N. J. Wattus

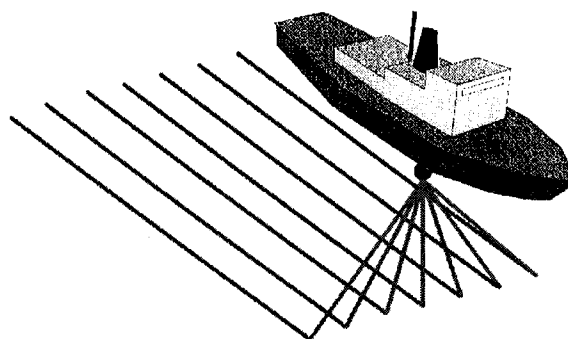
Large Lakes Observatory, University of Minnesota, Duluth, MN 55812

Like all large lakes, the composition and shape of the lake floor of Lake Superior reflects the processes that shape its formation today as well as in the past. Maps of the lake floor made with traditional echosounders lack the resolution to permit scientists to read the subtle "fingerprint" of these processes preserved in the lake-floor. The advent of modern, high-resolution multibeam sonar has revolutionized the mapping of the sea-floor.



In a traditional echosounder, the depth to the lake-floor below the ship is measured by timing how long it takes for an acoustic ping to travel to the lake-floor and back to the ship. The longer the delay, the deeper the lake floor is. This type of surveying provides high-resolution bathymetric information along the trackline followed by the survey boat. Nothing is known about the lake floor either side.

High-resolution multibeam systems use a fan of acoustic beams (over 100) to measure the shape of the lake floor along a "swath". By sailing a series of overlapping swaths, it is possible to achieve complete coverage of the lake floor at high resolution.



Backscatter information collected with the bathymetric data can be used to create psuedo-sidescan images of the lakefloor. These can be used to map spatial variations in the composition of the lake floor.

Examples, drawn from the catalog of multibeam surveys conducted by the Large Lakes Observatory, are presented. These illustrate the potential of this technology for mapping the subtle signal of past geologic processes superimposed on the lake floor.