# Archean Geology of the Northern Block of the Ishpeming Greenstone Belt, Marquette County, Michigan

U.S. GEOLOGICAL SURVEY BULLETIN 1904–F

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Chapter F

# Archean Geology of the Northern Block of the Ishpeming Greenstone Belt, Marquette County, Michigan

By R.C. JOHNSON and T.J. BORNHORST

U.S. GEOLOGICAL SURVEY BULLETIN 1904

CONTRIBUTIONS TO PRECAMBRIAN GEOLOGY OF LAKE SUPERIOR REGION

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# Archean Geology of the Northern Block of the Ishpeming Greenstone Belt, Marquette County, Michigan

*By* R.C. Johnson[1] *and* T.J. Bornhorst[1]

**Abstract**

The northern block of the Ishpeming greenstone belt occupies 150 square kilometers in north-central Marquette County, Michigan. This block, as well as the entire belt, is composed of Archean volcanic and volcaniclastic rocks and is bounded by Archean gneissic granitoid and Early Proterozoic sedimentary rocks. During Archean time, rocks of the belt were metamorphosed to greenschist and amphibolite facies and were subjected to two deformational events. Recumbent folding ($D_1$) was followed by isoclinal to open folding about east-west axes ($D_2$).

The northern block of the belt is dominated by the Lighthouse Point Basalt, as revised and redefined herein. The Lighthouse Point Basalt is composed of tholeiitic pillowed basalt flows with minor massive flows and subordinate pyroclastic and sedimentary rocks; it has a thickness of approximately 7,100 meters. The formation contains four informal interflow units, from oldest to youngest: Nash Creek glomerophyric basalt unit, Reany Lake pyroclastic unit, Fire Center mine iron-formation unit, and the Hills Lakes pyroclastic unit. The Nash Creek glomerophyric basalt unit is composed of glomerophyric pillowed and massive flows. The Reany Lake pyroclastic unit is an ash to lapilli-ash pyroclastic deposit, stratigraphically in the middle part of the Lighthouse Point Basalt, which is characterized by the occurrence of disseminated base metal sulfides. The Fire Center mine iron-formation unit lies directly above the Reany Lake pyroclastic unit; it is a chert-magnetite iron-formation that contains minor pyrite and chlorite-magnetite or epidote-magnetite beds. The uppermost Hills Lakes pyroclastic unit grades laterally from a lapilli-tuff breccia to a lapilli-ash tuff, near the top of the formation. The Lighthouse Point Basalt is intruded by sill-like bodies of gabbro that are chemically similar to the basalts and probably were intruded shortly after eruption of the Lighthouse Point Basalt. Gneissic granitoid rocks that bound the greenstone belt to the north and east are granite to tonalite in composition. They intruded the greenstone belt during $D_1$ and metamorphosed the adjacent basalt to amphibolite grade. Quartz and quartz-feldspar porphyritic rhyolite dikes intrude the Lighthouse Point Basalt in and adjacent to shear zones. The granodiorite near Rocking Chair Lakes intrudes the hinge of a major fold within the Lighthouse Point Basalt, and is interpreted as being comagmatic with the rhyolite intrusive rocks. The rhyolite and granodiorite were probably emplaced during $D_2$ deformation.

Gold mineralization occurred in sheared, carbonate-altered, and quartz-veined rocks. Anomalous gold commonly is present along the brecciated margins of rhyolite dikes. The gold mineralization is interpreted as being associated with the second ($D_2$) Archean deformational event. Base metal and silver mineralization occurred in quartz-carbonate veins hosted by brecciated fault zones. This mineralization is paragenetically later than that of the gold: it may not be Archean in age.

## INTRODUCTION

The northern block of the Ishpeming greenstone belt is in north-central Marquette County, Mich., and is approximately 150 km$^2$ in area (figs. 1 and 2). It occupies parts of the Marquette, Negaunee, Negaunee SW, Buckroe, Negaunee NW, and Silver Lake Basin 7½-minute quadrangles, and includes the southeastern part of T. 50 N., R. 28 W., the southern part of T. 50 N., R. 27 W., the eastern part of T. 49 N., R. 28 W., most of T. 49 N., R. 27 W., the southwestern part of T. 49 N., R. 26 W., the northeastern part of T. 48 N., R. 27 W., and the northwestern part of

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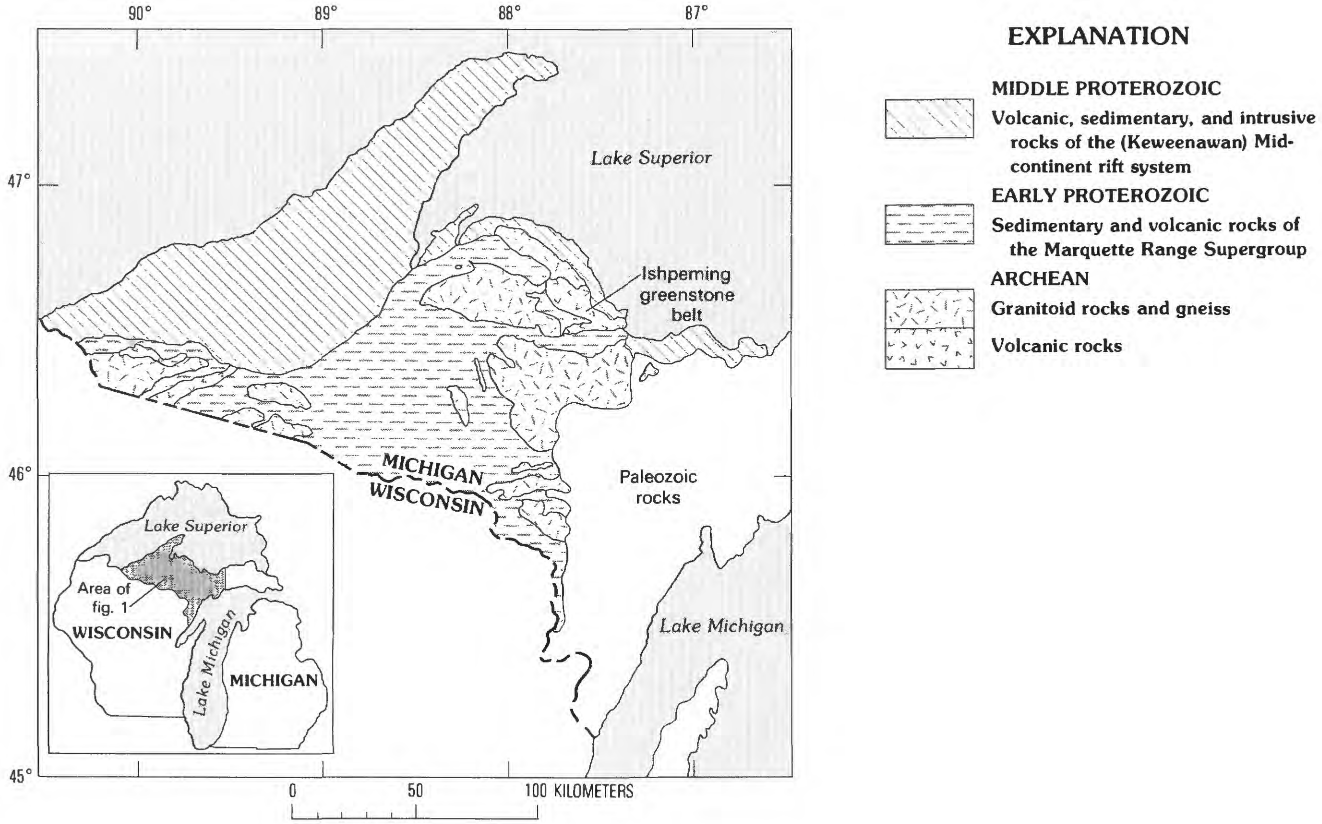



**Figure 1.** Geologic sketch map showing location of the Archean Ishpeming greenstone belt.

T. 48 N., R. 26 W. A shear zone (Dead River shear zone; Bornhorst, 1988, and references therein) that defines the southern boundary of the northern block is parallel to the Dead River Storage Basin on the southwest and at the east end of the basin strikes east-southeast through secs. 8–12 of T. 48 N., R. 26 W. and secs. 7, 15–18, 22, and 23 of T. 48 N., R. 25 W.

## Present Investigation

This investigation is a continuation of mapping of the Ishpeming greenstone belt by Michigan Technological University personnel begun during the summer of 1984 under the direction of Bornhorst and continued during successive summers; mapping has been at scales ranging from 1:2,400 (Owens and Bornhorst, 1985) to 1:24,000 (Johnson, unpub. data, 1990) and represents approximately 24 person-months of field work (table 1). Geologic mapping has utilized a combination of compass-and-pace along traverse lines and direct plotting on topographic sheets where topographic features are distinctive.

One hundred fifty-two whole-rock geochemical analyses have been made by X-ray fluorescence on an automated Phillips wave-length dispersive spectrometer at Michigan Technological University using a modification of the technique described by Rose and others (1986). One hundred seventy-three samples were analyzed for gold using fire assay and neutron activation (1 ppb detection limit), and 22 samples were analyzed for silver using inductively coupled plasma (0.5 ppm detection limit). One hundred eighty-six thin sections have been studied. Plagioclase compositions were determined by the Michel Levy technique when albite twinning was present and otherwise by the relief relative to the mounting epoxy ($n$=1.54). Actinolite and hornblende have been distinguished on the basis of color and Z^C (Winchell and Winchell, 1951).

## Previous Work

Geologic interest in the greenstone belt was instigated by Douglas Houghton, who reported panning gold from a stream between Marquette and L'Anse in 1845. Precious metal exploration began in the northern block during the 1860's with the working of base metal– silver veins (Norby, 1988). In 1880, Julius Ropes discovered gold at the site of the Ropes mine in the southwestern block of the Ishpeming greenstone belt. During the 1930's, Norgan Mining Company explored for gold in the entire greenstone belt and drilled in the Fire Center mine area of the northern block (Kelly, 1936). From the late 1960's to the present,

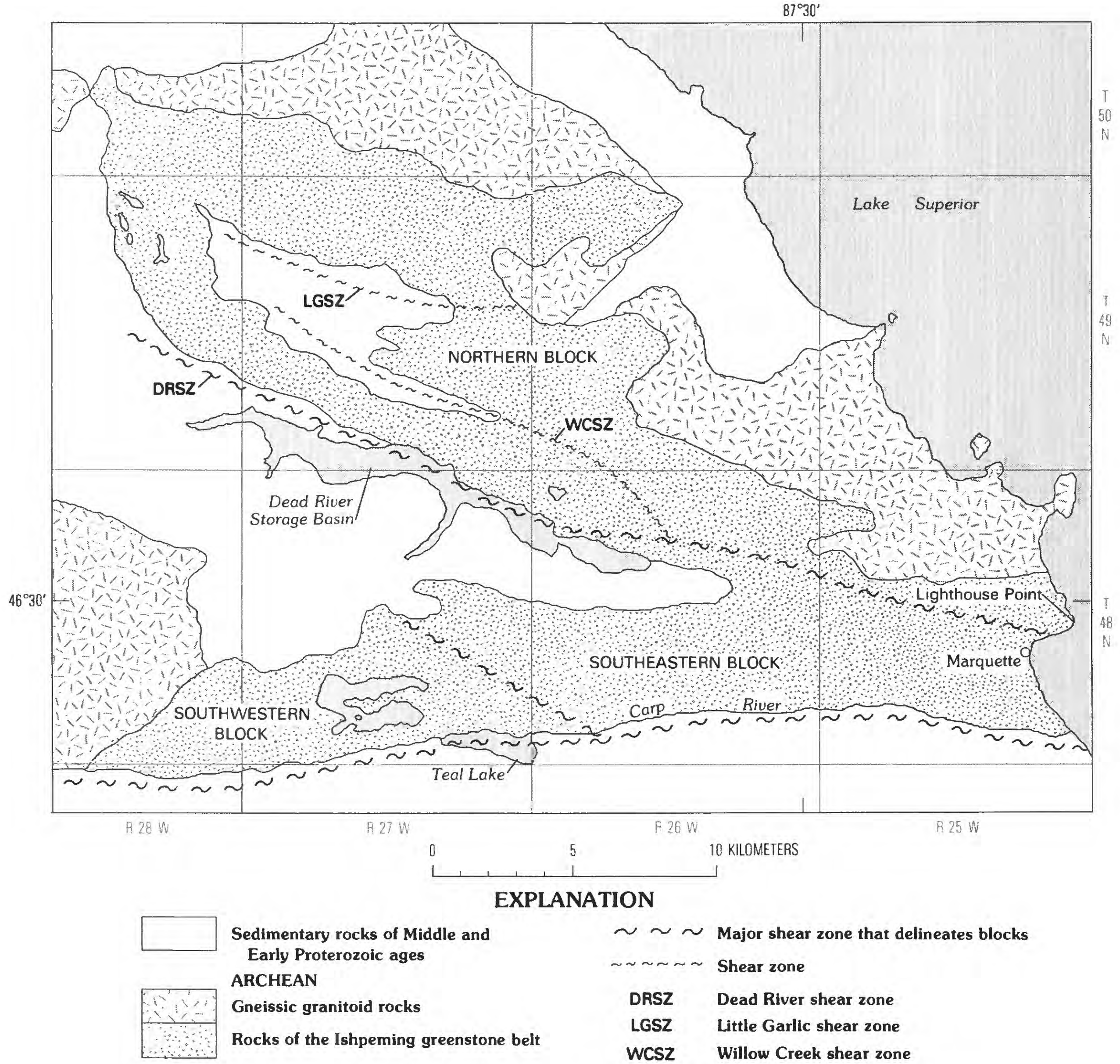



**Figure 2.** Geologic sketch map of the Ishpeming greenstone belt, showing the major lithostratigraphic blocks. Major block-defining shear zones are indicated by the bold shear symbol.

Cleveland-Cliffs Iron Company, Humble Oil, Superior Oil Company, Nicor Mineral Ventures, Chevron, St. Joe American Corporation, Phelps Dodge, Kerr-McGee Corporation, and Callahan Mining Corporation have explored for massive sulfides and (or) precious metals in the Ishpeming greenstone belt. Chevron geologists provided a regional geologic description of the greenstone belt (Morgan and DeCristoforo, 1980). In 1985 Callahan Mining Corporation resumed production at the Ropes gold mine, which continued until late 1989.

Most of the previous geologic work in the greater Marquette area concentrated on the geology and mineral deposits of Early Proterozoic rocks in the Marquette iron range. The work of Van Hise and Bayley (1897) defined the major stratigraphic features of the area. The geologic reports of Gair and Thaden (1968), Puffett (1974), Clark and others (1975), and Cannon and Klasner (1977) provide 1:24,000-scale geologic maps covering the Marquette, Negaunee, Negaunee SW, and southern part of the Diorite and Champion quadrangles, respectively. These maps provide complete geologic coverage of the southern part of the greenstone belt, but they cover only the extreme southern part of the northern block, as defined here. Gair and Thaden's report includes a summary of prior geologic work performed in the southern part of the Ishpeming greenstone belt. Large-scale mapping by the Norgan Mining Company in the 1930's outlined the extent and some internal detail of the geology of the greenstone belt, which was later

Table 1. Michigan Geological Survey reports by Michigan Technological University students that have contributed to this report

| Author | Open-file report | Land description |
|---|---|---|
| Owens, E., and Bornhorst, T.J., 1985. | Geology and precious metal prospects north of the Dead River Storage Basin in sec. 35, T. 49 N., R. 27 W. and north part of sec. 2, T. 48 N., R. 27 W., Marquette County, Michigan: OFR–85–2. | Sec. 35, T. 49 N., R. 27 W.; and sec. 2, T. 48 N., R. 27 W. |
| Johnson, R.C., Bornhorst, T.J., and Van Alstine, J., 1987. | Geologic setting of precious metal mineralization in the Silver Creek to Island Lake area, Marquette County, Michigan: OFR–87–4. | Secs. 3, 10–15, 23– 25, T. 49 N., R. 28 W. |
| Baxter, D.A., and Bornhorst, T.J., 1987. | Geology, structure, and associated precious metal mineralization in vicinity of Clark Creek, Marquette County, Michigan: OFR–87–6. | Secs. 19, 20, 27– 30, 32–34, T. 49 N., R. 27 W. |
| MacLellan, M.L., and Bornhorst, T.J., 1988. | Precambrian bedrock geology and associated mineralization of the Holyoke Trail–Reany Lake area, Marquette County, Michigan: OFR–88–2. | Sec. 36, T. 49 N., R. 27 W.; sec. 31, T. 49 N., R. 26 W.; sec. 1, T. 48 N., R. 27 W.; and secs. 6 and 7, T. 48 N., R. 26 W. |
| Small, J.R., and Bornhorst, T.J., 1990. | Precambrian geology of the Penny Lake area, Marquette County, Michigan: Contributions to Michigan Geology Report 90–1. | Secs. 1 and 2, T. 49 N., R. 28 W.; secs. 25–27, 34–36, T. 50 N., R. 28 W. |
| Wilkin, R., and Bornhorst, T.J., 1990. | Geology of the Boise Creek area, Marquette County, Michigan: Contributions to Michigan Geology Report 90–3. | Secs. 29–32, T. 50 N., R. 27 W.; secs. 4–9, 16, 17, T. 49 N., R. 27 W. |

compiled by Bodwell (1972) at a scale of 1:62,500. The published geologic maps produced by students at Michigan Technological University (table 1), covering approximately 80 km$^2$ of the northern block, and the more regional field studies by Johnson provide the foundation for this report.

## Acknowledgments

Geologic research in the northern block has been supported by the Michigan Geological Survey, the COGEOMAP program of the U.S. Geological Survey, the Mineral Institute Program administered by the U.S. Bureau of Mines, and Michigan Technological University. Several Michigan Geological Survey open-file reports and M.S. theses of Michigan Technological University students contributed to this paper; these reports are listed in table 1.

Robert Reed and Jack Van Alstine of the Michigan Geological Survey are thanked for their support and reviews of open-file reports. Our understanding of the geology of the northern block has been improved through discussions with geologists from Callahan Mining Corporation and Kerr-McGee Corporation. Our understanding of structural aspects has improved through discussions with R. Bauer and S. Nachatilo. S.D. McDowell and J. Kalliokoski provided valuable comments on an early draft of this paper.

## GEOLOGIC SETTING

The Ishpeming greenstone belt occupies an area of 325 km$^2$ west of Marquette in Michigan's Upper Peninsula (figs. 1 and 2). It is a thick accumulation of Archean tholeiitic basalts with subordinate felsic volcanic and minor sedimentary rocks. It is bounded to the north and west by Archean granite and gneissic granitoids (Sims, 1980). To the south the Archean rocks of the belt are unconformably covered by or are in fault contact with sedimentary rocks of the Early Proterozoic Marquette Range Supergroup (Cannon and Gair, 1970).

The greenstone belt is divided into three distinct lithostratigraphic blocks (Bornhorst, 1988)—northern, southeastern, and southwestern blocks (fig. 2)—which are separated by major shear zones. A lithostratigraphic block has an internal stratigraphic continuity that differs from adjacent blocks and is bounded by major deformational zones. The northern and southeastern blocks are dominated by subaqueous tholeiitic basalt flows, with subordinate felsic volcanics and minor sediments. The southwestern block contains both andesite-to-dacite volcaniclastic rocks and subaqueous tholeiitic basalt flows.

The northern block occupies an area of approximately 150 km$^2$, nearly one-half of the entire greenstone belt. The stratigraphy of the northern block is dominated by pillowed tholeiitic basalt flows with minor felsic volcanic and sedimentary rocks. It is bounded to the east and north by gneissic granitoid rocks and to the west by Proterozoic rocks (fig. 2). On the south it is bounded by the Dead River shear zone, which was first recognized by Puffett (1974).

Van Hise and Bayley (1895) named the greenstone near Marquette the Mona Schist. Subsequently, Gair and Thaden (1968) assigned the name Lighthouse Point Member of the Mona Schist to layered amphibole schists

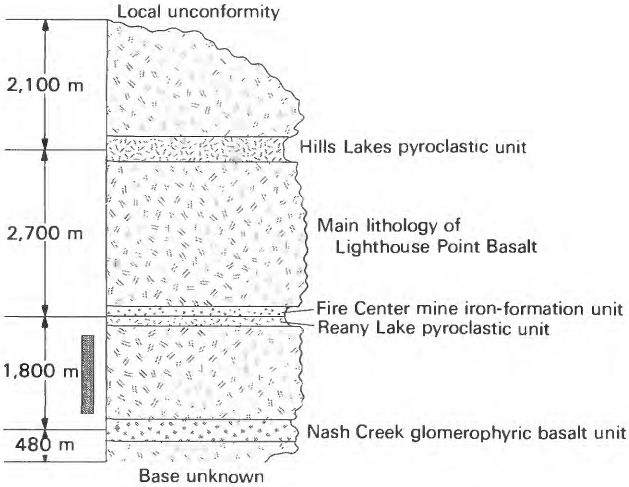



**Figure 3.** Stratigraphic succession of the Lighthouse Point Basalt and its interflow units. Shaded area indicates probable correlation of the Lighthouse Point Member of the Mona Schist of Gair and Thaden (1968) and Puffett (1974) within the revised Lighthouse Point Basalt.

that extend westward from Lighthouse Point, in Marquette, Mich. Puffett (1974) interpreted the pillowed basalts about 8 km west of Lighthouse Point in the Negaunee quadrangle also as part of the Lighthouse Point Member of the Mona Schist. The volcanic rocks of the northern block include large volumes of both pillowed greenschist-facies basalt and layered amphibole-rich basalt and are interpreted as part of the revised and redefined Lighthouse Point Basalt. However, the strata of the northern block are separated from volcanic rocks in the southeastern block by the Dead River shear zone, and hence cannot be correlated with these strata that have been assigned to the Mona Schist. We propose that all the mafic rocks except gabbro in the lithostratigraphic block north of the Dead River shear zone, including the rocks north of the shear zone previously known as Lighthouse Point Member of the Mona Schist, be revised and redefined as the Lighthouse Point Basalt. The rocks south of the Dead River shear zone that were previously interpreted as part of the Lighthouse Point Member are considered here to be part of the Mona Schist restricted.

The volcanic pile is intruded by mafic and felsic bodies of several ages. The granodiorite near Rocking Chair Lakes is a stock-sized intrusion. The remainder of the intrusive rocks are discussed following on the basis of the dominant lithology: gabbro, gneissic granitoids, and rhyolite intrusions.

Unconformably overlying the volcanic and intrusive rocks in the southeastern part of the northern block (fig. 6) is a succession of sedimentary rocks named the Reany Creek Formation by Puffett (1969). Puffett (1969, p. F5) divided the Reany Creek Formation into three units: "(1) a basal conglomerate, (2) a middle sequence of graywacke and slate with disrupted beds of arkose and dispersed pebbles and boulders of granitic rock, and (3) an upper unit of interbedded arkose, quartzite, slaty graywacke, and conglomerate." These sedimentary rocks strike approximately east-west, dip steeply, and young stratigraphically to the south. Puffett (1969) and others have assumed the age of the Reany Creek Formation to be Early Proterozoic, partly because it is apparently not cut by any igneous dikes other than Middle Proterozoic (Keweenawan) dikes. The precise age of these rocks has been uncertain, however (Small and Bornhorst, 1988; Owens and Bornhorst, 1985; Mattson and Cambray, 1983; Ojakangas, 1984; Puffett, 1969). Because of the structural relationships and resemblance to "Timiskaming-type" sequences, Sims (in press) has modified the age of the Reany Creek Formation; it is now interpreted as Archean and is no longer considered as the basal part of the Marquette Range Supergroup.

## ARCHEAN ROCKS

## Lighthouse Point Basalt

The Lighthouse Point Basalt is composed dominantly of pillowed and massive tholeiitic basalt flows, and includes four informal lithologically distinct and mappable interflow units: from bottom to top, Nash Creek glomerophyric basalt unit, Reany Lake pyroclastic unit, Fire Center mine iron-formation unit, and Hills Lakes pyroclastic unit (fig. 3). Stratigraphically, the Nash Creek glomerophyric basalt unit is near the base of the exposed Lighthouse Point Basalt, the Reany Lake pyroclastic unit is near the middle of the formation, and the Fire Center mine iron-formation unit immediately overlies the Reany Lake pyroclastic unit. The Hills Lakes pyroclastic unit is near the top of the formation.

### Distribution

The mafic volcanic rocks of the northern block that are assigned to the Lighthouse Point Basalt cover nearly the entire block, an area of approximately 150 $km^2$. The northwesternmost exposures of the formation are found east of Pinnacle Falls in sec. 27, T. 50 N., R. 28 W., and the northeasternmost exposures lie east of Blemhuber Lake in sec. 4, T. 49 N., R. 26 W. The northern extent is defined by the contact between the basalts and the bounding gneissic granite and the southern limit by the Dead River shear zone. This unit is covered by Early Proterozoic sedimentary rocks in the Clark Creek basin in the central part of the northern block.

### Thickness

Thicknesses are difficult to determine in lithologically monotonous, mafic volcanic piles that have undergone polyphase deformation. However, as noted, the Lighthouse Point Basalt contains four distinct mappable units. Consequently, it has been possible to decipher some of the structural complexity. (See section, "Structure.") If the $F_1$ folds are recumbent and isoclinal and the $S_1$ foliation is axial-planar, the minimum stratigraphic thickness is estimated to be 7,100 m (fig. 3).

## Description

The Lighthouse Point Basalt is a monotonous pile of pillowed tholeiitic basalt lava flows. Pillows are typically bun shaped and 30–60 cm in cross section, although mattress-shaped pillows as much as 2 m in cross section are present. Pillows in greenschist-facies rocks are typically ellipsoidal and have classic pillow shapes. Amphibolite-facies basalts are typically well banded or layered, and in many places "layers" can be seen as the result of extreme flattening of pillows. Flattening tends to obliterate pillow cusps that are used to determine stratigraphic top directions, and shearing produces pillows with amoeboid shapes and feathered margins. Except for a few flows above and below the Fire Center mine iron-formation unit, vesicles are absent within the pillows throughout the sequence. Where present, vesicles are less than 5 mm in diameter.

Massive flows are common but subordinate in volume to pillowed flows. The massive flows as well as intrusive gabbro bodies have characteristic ophitic textures, and accordingly it is difficult to distinguish one from the other. For example, the Fire Center mine iron-formation unit near Reany Lake was mapped by Puffett (1974) as being within a metadiabase intrusion and by MacLellan and Bornhorst (1989) as being within Archean gabbro. In general, bodies of gabbro-like rock are mapped as intrusions barring evidence to the contrary; and in this instance the continuity of the gabbro-iron-formation "sandwich" along a strike length of approximately 3 km suggests that these particular gabbro-like rocks are massive flows rather than intrusions. The unit also contains rare pillow breccias, hyaloclastites, and hyalotuffs as discontinuous lenses that are typically less than 1 m thick and rarely more than 30 m long.

The basalts range from light gray to black in color. The lighter colored basalts are generally foliated and contain carbonate as disseminations and as fine crosscutting veinlets; these basalts commonly effervesce with HCl. At greenschist facies, most basalts are light grayish green, whereas at amphibolite facies they are black. Mineralogy of the basalts correlates with metamorphic grade. (See section, "Metamorphism.")

Foliated basalts occur along faults, sheared contacts, high strain zones, and shear zones throughout the area. This variety of basalt has two macroscopically distinct end members: (1) dull-black to dull-brown, aphanitic, friable, and generally limonite rich schists; and (2) medium-green phyllonite. The black end-member is composed dominantly of chlorite and albite, but commonly contains abundant disseminated pyrite (estimated as much as 15 percent). The phyllonite is composed dominantly of chlorite and albite with minor quartz, and commonly contains lenses of porphyroblastic carbonate with quartz. In the phyllonite, pyrite occurs as fine disseminations in the chloritic groundmass that surrounds the carbonate-quartz lenses.

The Lighthouse Point Basalt is composed of magnesian to low-iron tholeiitic basalt (table 2; fig. 4). The chemical composition of greenschist- and amphibolite-facies basalts is comparable (Small, 1989), suggesting that metamorphic mobilization of elements and magmatic chemical variability are small. The chemical composition is similar to that of other Archean basalts of the Superior province (Jensen and Langford, 1985).

## Nash Creek Glomerophyric Basalt Unit

Within the eastern exposures of the Lighthouse Point Basalt, Puffett (1974) mapped a "felsic augen zone." Our recent field and petrographic studies, however, indicate that the "felsic augens" within this zone are relict glomerophyric plagioclase phenocrysts. Based on lateral continuity, this zone is interpreted as representing one or more glomerophyric basalt flows and is informally called Nash Creek glomerophyric basalt unit.

The Nash Creek glomerophyric basalt unit crops out in the eastern part of the northern block, in secs. 1 and 2, T. 48 N., R. 26 W., and secs. 4, 5, 20, 29, 32, 33, and 34, T. 49 N., R. 26 W., and is traversed by Nash Creek in sec. 29, T. 49 N., R. 26 W. The outcrop pattern has a sinuous form which traces out $F_1$ folds and mimics the shape of the contact with the gneissic granitoid rocks (fig. 5).

In the Negaunee quadrangle, the Nash Creek glomerophyric basalt unit has a map width of 200–300 m (Puffett, 1974). If the $S_1$ foliation is assumed to be axial-planar with an average dip of 25° and $F_1$ folds are assumed to be isoclinal, the unit is approximately 90– 120 m thick.

The glomerophyric basalt unit contains both massive and pillowed rocks. The basalt ground-color is dark greenish gray to black. In hand samples, the glomerophyric phenocrysts are grayish white and have an elongate amoeboid shape. However, relict phenocrysts retaining albite twinning have been found in oriented thin sections. The phenocrysts are typically replaced by saussurite assemblages of sericite, carbonate, clinozoisite-epidote, and calcic plagioclase. The groundmass is composed of dark-green hornblende, calcic plagioclase, and clinozoisite-epidote, typical of the amphibolite facies in the surrounding Lighthouse Point Basalt. The Nash Creek glomerophyric basalt unit is composed of low-iron tholeiitic basalt (table 2; fig. 4).

## Reany Lake Pyroclastic Unit

The Reany Lake pyroclastic unit is an ash to lapilli-ash tuff found in the middle stratigraphic part of the Lighthouse Point Basalt (fig. 3). This unit crops out south of

**Table 2.** Means, in weight percent, and standard deviations of chemical analyses of rock units in the northern block of the Ishpeming greenstone belt

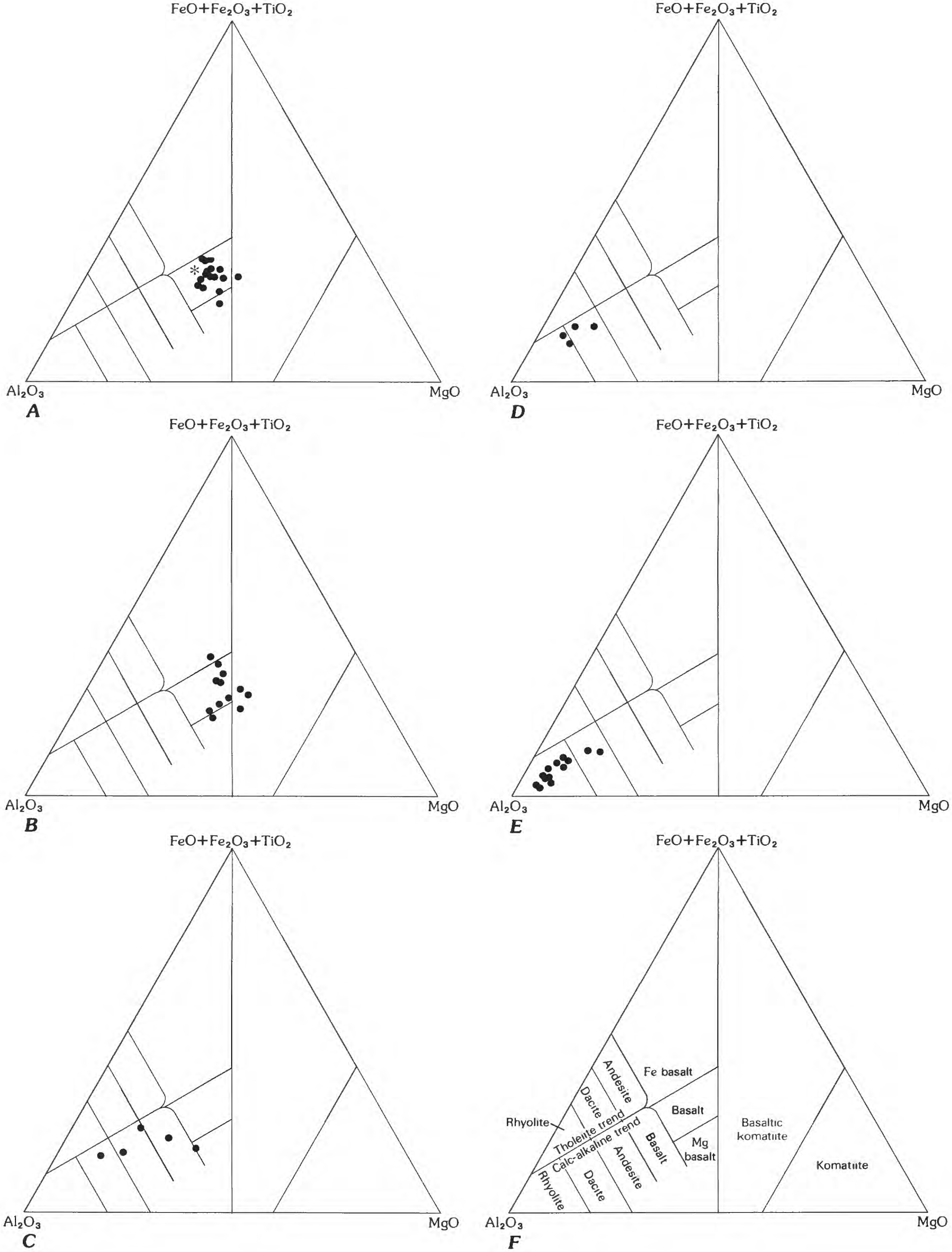
| | Lighthouse Point Basalt | | Archean gabbro | | Nash Creek glomerophyric basalt unit | Reany Lake pyroclastic unit | |
|---|---|---|---|---|---|---|---|
| | $n$=18 | | $n$=12 | | $n$=1 | $n$=5 | |
| | Mean | Standard deviation | Mean | Standard deviation | | Mean | Standard deviation |
| $SiO_2$ | 48.62 | 1.4 | 47.74 | 2.0 | 49.13 | 61.46 | 4.1 |
| $TiO_2$ | 1.07 | 0.3 | 1.08 | 0.3 | 1.08 | 0.61 | 0.1 |
| $Al_2O_3$ | 12.96 | 0.9 | 12.32 | 1.2 | 12.47 | 14.69 | 0.9 |
| $Fe_2O_3$ | 14.43 | 2.3 | 15.49 | 2.7 | 15.19 | 6.82 | 1.8 |
| MnO | 0.18 | 0.1 | 0.19 | 0.1 | 0.22 | 0.06 | 0.0 |
| MgO | 8.19 | 1.1 | 9.18 | 1.7 | 7.38 | 4.04 | 2.2 |
| CaO | 8.56 | 3.4 | 8.14 | 2.3 | 9.81 | 1.80 | 1.1 |
| $Na_2O$ | 1.87 | 0.6 | 1.97 | 0.5 | 2.80 | 3.60 | 1.3 |
| $K_2O$ | 1.06 | 0.8 | 0.93 | 0.7 | 0.99 | 2.14 | 1.3 |
| $P_2O_5$ | 0.12 | 0.0 | 0.14 | 0.1 | 0.17 | 0.20 | 0.0 |
| LOI | 3.05 | 1.4 | 2.79 | 1.3 | 1.54 | 3.72 | 0.8 |
| Total | 100.11 | | 99.97 | | 100.78 | 99.14 | |

| | Hills Lakes pyroclastic unit | | Granodiorite near Rocking Chair Lakes | | Rhyolite intrusions | |
|---|---|---|---|---|---|---|
| | $n$=4 | | $n$=10 | | $n$=16 | |
| | Mean | Standard deviation | Mean | Standard deviation | Mean | Standard deviation |
| $SiO_2$ | 64.46 | 3.3 | 59.90 | 3.6 | 70.87 | 3.6 |
| $TiO_2$ | 0.47 | 0.1 | 0.54 | 0.1 | 0.25 | 0.2 |
| $Al_2O_3$ | 16.96 | 1.2 | 16.01 | 1.5 | 15.31 | 1.7 |
| $Fe_2O_3$ | 4.38 | 0.7 | 4.91 | 1.7 | 2.09 | 1.3 |
| MnO | 0.07 | 0.0 | 0.08 | 0.0 | 0.03 | 0.0 |
| MgO | 1.32 | 0.5 | 4.55 | 2.1 | 1.25 | 1.1 |
| CaO | 4.20 | 0.5 | 2.77 | 1.5 | 0.91 | 0.7 |
| $Na_2O$ | 4.55 | 0.9 | 4.19 | 0.8 | 4.38 | 1.7 |
| $K_2O$ | 1.37 | 0.2 | 3.46 | 1.0 | 3.02 | 1.4 |
| $P_2O_5$ | 0.23 | 0.0 | 0.26 | 0.1 | 0.09 | 0.1 |
| LOI | 2.05 | 0.4 | 2.85 | 1.2 | 1.95 | 0.8 |
| Total | 100.06 | | 99.52 | | 100.15 | |

Reany Lake in sec. 6, T. 48 N., R. 26 W., and has a probable strike length of 25–27 km. The surface trace of this unit defines a large Z-shaped fold in the northern block (fig. 5). Strict continuity is not certain because of the dearth of outcrop. This unit has a maximum thickness of about 45 m to the west of Reany Lake in the Fire Center mine area.

The Reany Lake pyroclastic unit contains an ash–tuff breccia zone of conspicuous angular chert fragments as much as 5 cm long that grades upward into bedded lapilli-ash tuff and further upward into finely laminated and graded tuffs (terminology of Easton and Johns, 1986). The matrix is typically a fine-grained quartz-chlorite-sericite schist. The bedded lapilli-ash tuff zone consists of lapilli-sized clasts that are composed of mosaic-textured quartz-sericite-carbonate aggregates. The tuffs are fine-grained quartz-sericite-chlorite schist. Rocks are typically light gray to yellowish tan. The Reany Lake pyroclastic unit is composed of calc-alkalic dacite to rhyolite lapilli (table 2; fig. 4). Analyses of the ash show calc-alkalic andesite compositions.

A unique feature of the Reany Lake pyroclastic unit is the association of base metal sulfides, as observed southeast of Reany Lake, SE¼ sec. 6, T. 48 N., R. 27 W. (Puffett, 1974) and to the north in sec. 36, T. 49 N., R. 27 W. Possibly, the massive sulfide body was incorporated into the pyroclastic unit during its turbulent descent from the


FeO+Fe$_2$O$_3$+TiO$_2$
Al$_2$O$_3$
MgO
A
FeO+Fe$_2$O$_3$+TiO$_2$
Al$_2$O$_3$
MgO
B
FeO+Fe$_2$O$_3$+TiO$_2$
Al$_2$O$_3$
MgO
C
FeO+Fe$_2$O$_3$+TiO$_2$
Al$_2$O$_3$
MgO
D
FeO+Fe$_2$O$_3$+TiO$_2$
Al$_2$O$_3$
MgO
E
FeO+Fe$_2$O$_3$+TiO$_2$
Andesite
Fe basalt
Dacite
Basalt
Rhyolite
Tholeiite trend
Calc-alkaline trend
Basalt
Mg basalt
Basaltic komatiite
Andesite
Rhyolite
Dacite
Komatiite
Al$_2$O$_3$
MgO
F

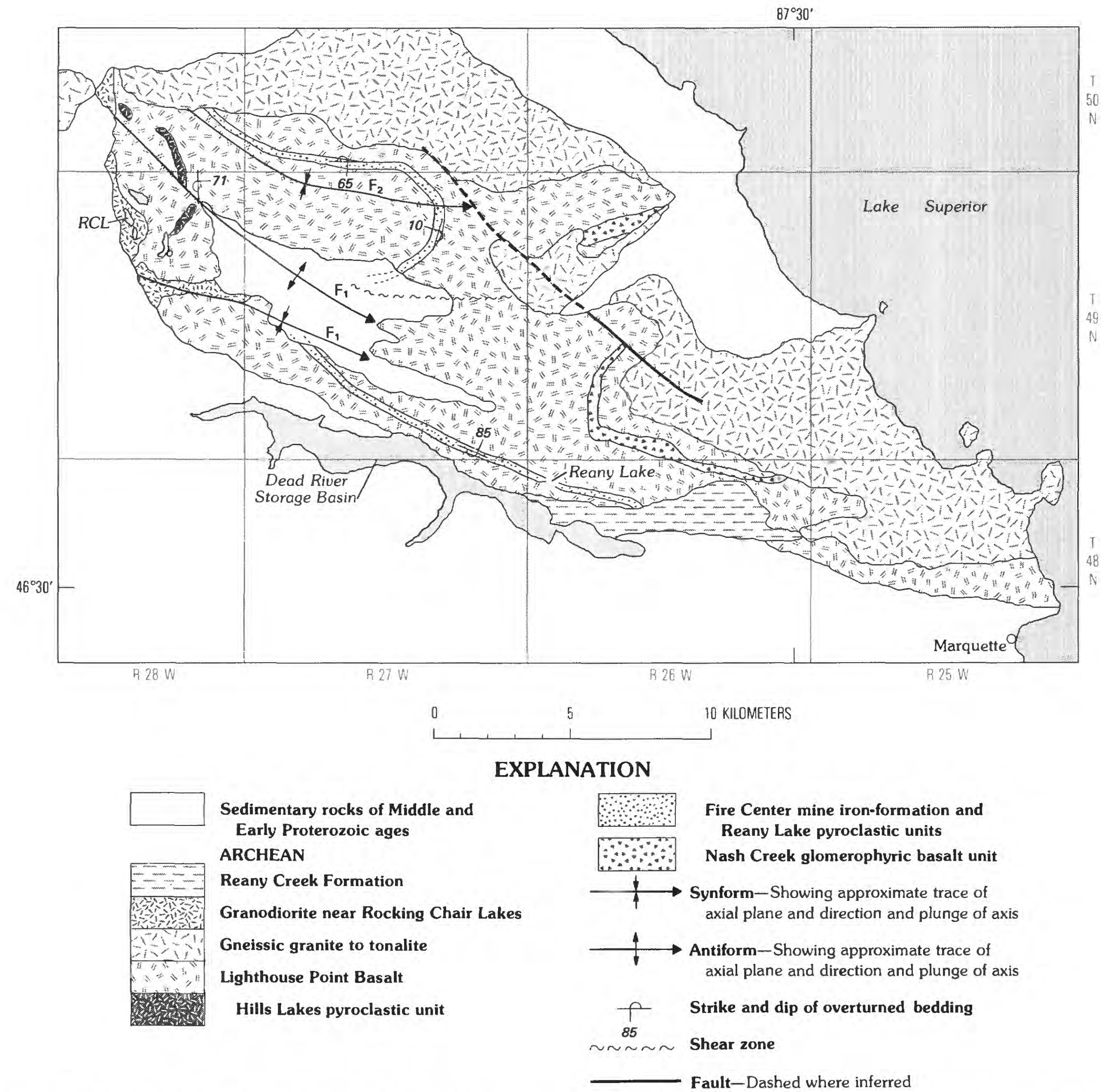



**Figure 5.** Geologic sketch map showing location of major folds in the northern block of the Ishpeming greenstone belt. The width of the interflow units is exaggerated. *RCL*, Rocking Chair Lakes.

volcano. This base metal association and stratigraphic proximity to an iron-formation (described following) provide confidence in stratigraphic correlation of lithologies over a considerable distance.

**Figure 4** (facing page). Jensen cation plots (Jensen, 1976) of *A*, basalt from the Lighthouse Point Basalt and Nash Creek glomerophyric basalt unit (asterisk); *B*, gabbro; *C*, Reany Lake pyroclastic unit (analyses of lapilli and matrix); *D*, Hills Lakes pyroclastic unit (analyses of lapilli); *E*, rhyolite intrusions in southern part of northern block; F, Jensen cation plot classifications.

## Fire Center Mine Iron-Formation Unit

The Fire Center mine iron-formation unit (fig. 3) crops out in the vicinity of the Fire Center mine in sec. 35, T. 49 N., R. 27 W. It is typically less than 9 m thick. Outcrop is generally sparse, and ground magnetic surveys suggest that the unit, although regionally continuous, may pinch and swell and be as much as 23 m thick. This iron-formation unit correlates with the "anomaly north of Dead River" described by Puffett (1974).

The Fire Center mine iron-formation unit can be traced on aeromagnetic maps (Case and Gair, 1965) for approximately 27 km, and it defines the major folds in the

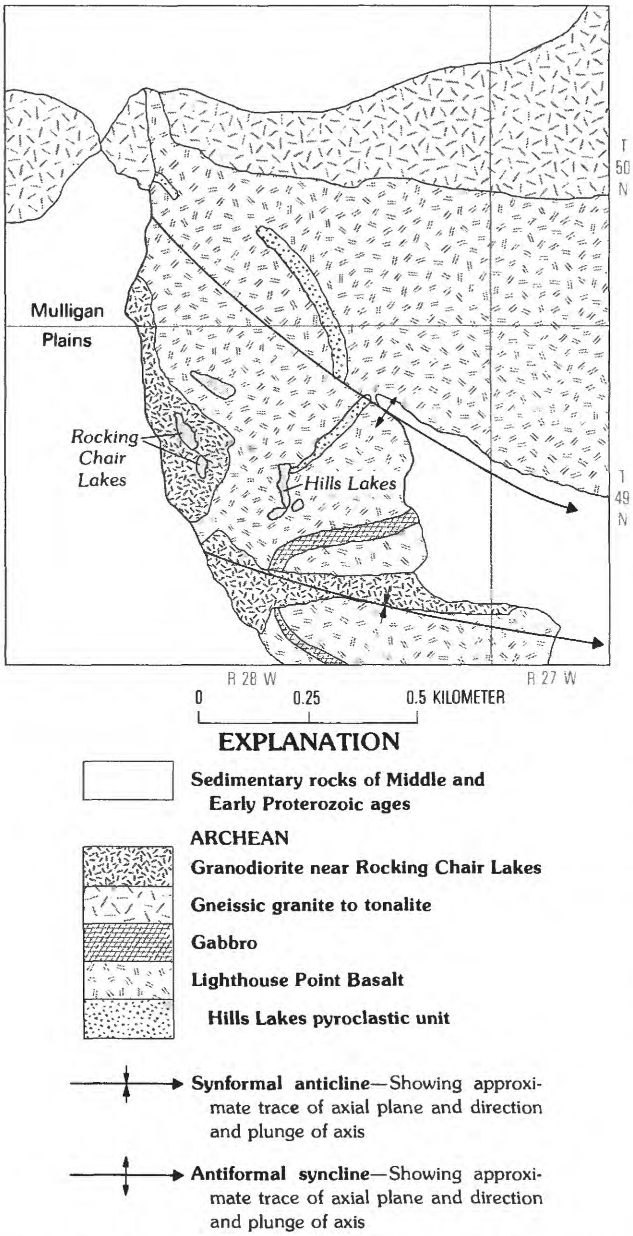



**Figure 6.** Geologic sketch map showing location of the Hills Lakes pyroclastic unit, granodiorite near Rocking Chair Lakes, and axial traces of $F_1$ folds.

northern block (fig. 5). The anomaly can be traced under the Proterozoic sedimentary rocks of the Clark Creek basin; it is segmented, however, by east-west-trending, reversely polarized Keweenawan diabase dikes.

The unit is typically banded chert-magnetite iron-formation with associated chlorite or epidote schist. In the southern part of the northern block, chert layers range from less than 1 to as much as 2 cm thick and alternate with magnetite layers less than 1 cm thick. Pyrite occurs as sparse (<5 percent) thin layers, disseminated euhedral grains, and as sparse grains in crosscutting quartz-carbonate veins. A red disseminated fine-grained acicular mineral, probably an iron amphibole, occurs scattered within the chert layers. In the northern part of the northern block, the iron-formation unit consists of alternating centimeter-wide bands of epidote and magnetite with rare chert bands and minor amounts of pyrite and hornblende.

## Hills Lakes Pyroclastic Unit

The Hills Lakes pyroclastic unit (fig. 3) is a pyroclastic deposit with conspicuous grayish-white pumiceous lapilli in a black schistose matrix. It is well exposed on the eastern shore of the longer, north-south-trending lake of Hills Lakes in sec. 11, T. 49 N., R. 28 W. This unit has a strike length of approximately 5 km and a maximum thickness of 50 m (fig. 6). The lapilli are strongly elongated, giving vertical surfaces a banded appearance.

In the vicinity of Hills Lakes, this unit is a lapilli-tuff breccia, and the lapilli and bombs are monomictic pumice of rhyolite to dacite composition (table 2; fig. 4). The lapilli are composed of calcic plagioclase and quartz with minor hornblende, sericite, and clinozoisite-epidote. The lapilli and bombs are so deformed that they show a banded appearance on vertical faces and an apparent lack of deformation on horizontal surfaces. The ash matrix is composed of hornblende, calcic plagioclase, biotite, and garnet with minor sericite, chlorite, tourmaline, and clinozoisite-epidote. The lapilli show calc-alkalic rhyolite compositions (table 2; fig. 4).

The Hills Lakes pyroclastic unit grades northward along strike into a lapilli-ash tuff where individual lapilli are difficult to distinguish because of intense deformation. It is a plagioclase-quartz-muscovite-chlorite schist containing poikiloblasts of almandine garnet (Small, 1989).

## Metamorphism

Metamorphic grade in the Lighthouse Point Basalt varies from greenschist to amphibolite facies, increasing symmetrically toward the contact with the bounding gneissic granitoid rocks (fig. 7). This relationship suggests that the amphibolite-facies metamorphism is related to higher temperatures associated with the emplacement of the granitoid rocks. The width of this metamorphic aureole indicates a minimum depth of burial of 2–3 km (Jensen and Langford, 1985).

Basalt of lower greenschist facies is characterized by chlorite, pale-green pleochroic actinolite, clinozoisite-epidote, and minor sericite, carbonate, and fine-grained disseminated pyrite. Relict magmatic textures are preserved. Basalt of upper greenschist facies is characterized by pale-green pleochroic actinolite, light-green hornblende, albite, and clinozoisite-epidote; metamorphic textures are present. At lower amphibolite grade, the basalt is characterized by hornblende, calcic plagioclase, clinozoisite-epidote and, in the rare mafic hyalotuffs, by garnet

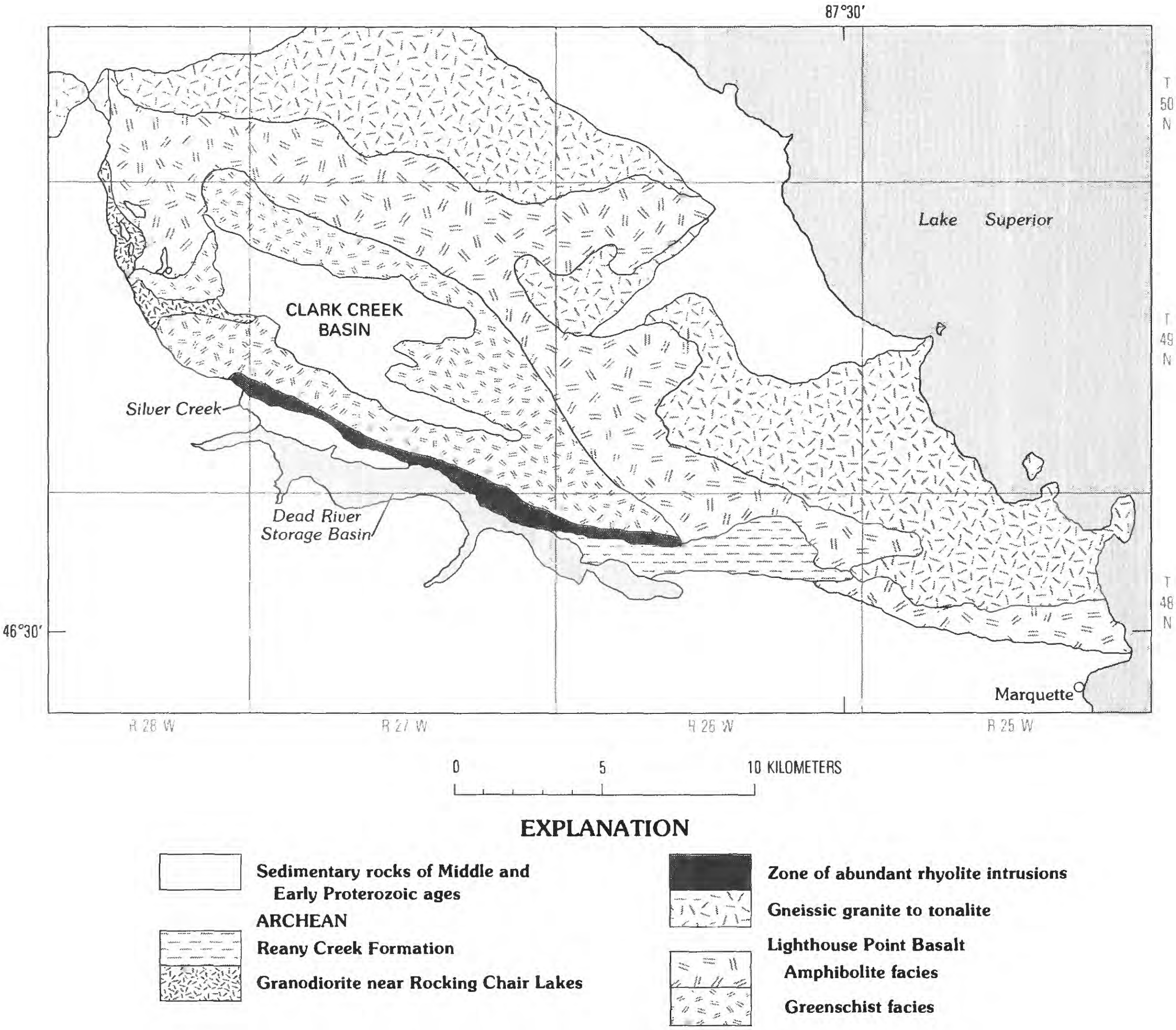



**Figure 7.** Geologic sketch map of the northern block of the Ishpeming greenstone belt, showing distribution of greenschist and amphibolite metamorphic facies in the Lighthouse Point Basalt and the zone of abundant rhyolite intrusions.

and biotite; the rock has well-developed metamorphic textures. At upper amphibolite grade, the basalt contains green to light-brown hornblende, calcic plagioclase, hypersthene, and diopside and has a well-developed schistosity. These differences in mineralogy allow the grade of metamorphism to be approximated by examination of thin sections.

## Alteration

Altered basalt is widely scattered throughout the Lighthouse Point Basalt and is commonly associated with shear zones or faults. Altered basalts can be distinguished from unaltered basalts in being lighter in color (weathered surfaces exhibit various shades of light green and yellow). The altered basalts are typically medium gray to light-gray, aphanitic to very fine grained schists composed of chlorite, albite, sericite, carbonate, and quartz.

Altered basalt is most prevalent along the southern boundary of the northern block. These rocks represent the northwesterly continuation of a unit mapped by Puffett (1974) as "undifferentiated greenstone." Brecciated rhyolite dikes and brecciated margins of rhyolite dikes are commonly associated with intense ankerite alteration in this area. The overall distribution of alteration indicates that a major Archean hydrothermal system may have been focused along the Dead River shear zone.

Thin altered zones are common, and in these zones the basalt contains variable amounts of chlorite, epidote, albite, sericite, and carbonate. The most common sulfide mineral is pyrite, which occurs along thin shears as fine- to medium-grained euhedral masses and as fine-grained euhedral and (or) anhedral disseminations. Less common sulfide minerals include pyrrhotite, arsenopyrite, chalcopyrite, galena, and sphalerite.

The alteration minerals are retrograde products formed after earlier Archean prograde metamorphism. At amphibolite facies, the regional metamorphic assemblage contains hornblende and calcic plagioclase, whereas the altered basalts contain chlorite, albite, and epidote-clinozoisite. Thus, retrograde chlorite-epidote zones are found locally within upper amphibolite-facies assemblage. Retrograde alteration is not readily evident at lower greenschist facies, where chlorite, albite, epidote, and sericite assemblages are typical of the regional metamorphism. However, locally in the greenschist facies where actinolite is the dominant ferromagnesian mineral, the presence of chlorite may indicate retrograde alteration.

## Gabbro

The Lighthouse Point Basalt and its interflow units have been intruded by mafic rocks of several ages. The oldest intrusions are gabbro sills and dikes of probable Archean age. The majority of Archean gabbros are sill-like, but some are dikes. The gabbro is typically medium greenish gray and dark bluish green and medium to coarse grained. It is composed of hornblende or actinolite and plagioclase with minor sericite, clinozoisite-epidote, and sphene. The opaques are magnetite or less commonly pyrite, pyrrhotite, and cubanite. Amphibole is typically bluish green hornblende; it pseudomorphically replaces ophitic pyroxenes. Plagioclase forms aggregates of two types: (1) those retaining their magmatic texture and (2) those having a mosaic texture. The composition of the plagioclase reflects the grade of metamorphism: albite occurs in greenschist-facies rocks and calcic plagioclase occurs in amphibolite-facies rocks. Chemically, the gabbro intrusive bodies are magnesian tholeiites, very similar compositionally to the basalt flows (table 2; fig. 4).

Altered gabbro is associated with faults and shears and may be foliated or massive. Fresh surfaces are light gray to light green and those that are highly epidotized are a distinct pistachio green. Alteration minerals include chlorite, albite, epidote, quartz, sericite, and carbonate with chalcopyrite, pyrrhotite, and pyrite.

## Gneissic Granitoid Rocks

Archean felsic rocks of several ages intrude the mafic pile of basalt and gabbro. The oldest recognizable intrusions are gneissic granitoid dikes that are coeval with the large surrounding bodies of gneissic granitoid rocks. The dikes were intruded parallel to the dominant regional foliation and are located near the contact of the basalt and gabbro with the surrounding gneissic granitoid bodies. The dikes were emplaced during $D_1$ deformation.

The contact between the Lighthouse Point Basalt and the surrounding gneissic granitoid rocks is gradational. As the contact is approached, gneissic tonalite and granite with thin layers of amphibolite grade into banded amphibolite-facies gneiss in near equal amounts, and finally into basalt, where amphibolite is more abundant than felsic gneiss. This aureole of mixed amphibolite and felsic gneiss commonly is as much as 300 m wide. Thus, the exact location of the contact between basalt and gneiss is equivocal. Farther from the contact, the basalt contains thin wisps of felsic material along deformed pillow margins.

The gneissic granitoid rocks are tan to pink, are fine to medium grained, and range in composition from granite to tonalite (fig. 8). They are composed of quartz, plagioclase, and potassium feldspar with minor amounts of biotite and hornblende.

## Rhyolite Intrusive Rocks

Rhyolite dikes that postdate emplacement of the granitoid rocks intrude the mafic pile in areas of high strain. In the northern block, rhyolite dikes are abundant along the Dead River shear zone, particularly from Silver Creek to east of the Fire Center mine area (fig. 7). East of Fire Center mine, this zone of high strain and abundant rhyolite intrusions was mapped as undifferentiated greenstone by Puffett (1974). Most of the rhyolite intrusions are less than 6 m thick. In general, they strike N. 60°–70° W., have nearly vertical dips, and are well foliated. The rhyolite intrusive rocks have a wide range of textures, including porphyritic, aphyric, and granular. Of these, porphyritic rhyolites are most common and granular rhyolites are least common.

Porphyritic rhyolite intrusive rocks are commonly light gray to tan schists, composed of quartz, sericite, and albite. Porphyritic rhyolite intrusive rocks containing only embayed quartz phenocrysts are most common, whereas those containing quartz and albite phenocrysts are less common. The groundmass is typically composed of granoblastic quartz, albite, lepidoblastic sericite, and disseminated pyrite. Aphyric rhyolite intrusions range in color from uniform to mottled pink, orange, red, tan, and white. In hand specimen they resemble chert. The aphyric rhyolites are typically composed of fine-grained sutured quartz and albite with minor disseminated euhedral pyrite. Granular rhyolites are gray to dull pink, fine grained, and allotriomorphic with a granitic texture. They are composed of albite, quartz, microcline, and minor muscovite, epidote, chlorite, apatite, and pyrite. The aphyric and quartz porphyritic varieties are common in the area of Silver Creek, whereas to the east, towards Fire Center mine, quartz-feldspar porphyritic and

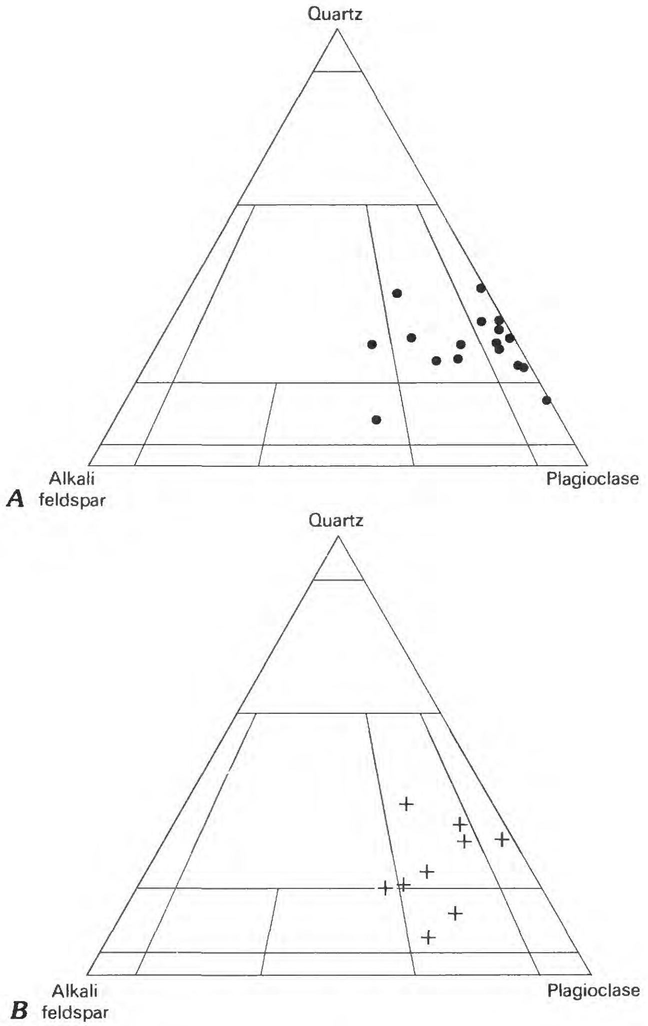



**Figure 8.** Modes of *A*, gneissic granitoid rocks and *B*, granodiorite near Rocking Chair Lakes. Basic diagram from Streckeisen (1975).

granular varieties are more common. Locally the aphyric variety is the oldest and is cut by quartz and quartz-feldspar porphyritic varieties. These intrusions are dominantly calc-alkalic rhyolite in chemical composition (table 2; fig. 4); dacite is subordinate. The chemical variation is small among the textural varieties.

## Granodiorite Near Rocking Chair Lakes

The youngest felsic intrusions in the northern block are granitoid stocks. Representative of these intrusions is a large granodiorite body that intrudes the hinge of the southern $F_1$ synformal anticline (fig. 6). This intrusion is informally called granodiorite near Rocking Chair Lakes.

The granodiorite near Rocking Chair Lakes crops out around Rocking Chair Lakes and along Mulligan Creek in secs. 10 and 15, along the cliff of Mulligan Creek in sec. 3, and as a 300-m-wide body striking subparallel to the basalt foliation across secs. 13, 14, and 24, T. 49 N., R. 28 W. (fig. 6). These stock-sized granodiorite intrusions are commonly in fault contact with the surrounding basalt, but a sharp intrusive contact has been observed in the SE¼ sec. 10. Xenoliths of basalt (as much as 3×2 m) are common within the granodiorite in the NE¼ sec. 10. A large basalt inlier in sec. 3, T. 49 N., R. 28 W. is interpreted as a roof pendant, based on the consistency of its foliation with that in the surrounding basalts.

The granodiorite near Rocking Chair Lakes is medium gray to light pink, medium to coarse grained, and hypidiomorphic to allotriomorphic granular; it has varied compositions, including granodiorite, tonalite, quartz monzonite, quartz monzodiorite, and quartz diorite (fig. 8). It can be subdivided into three types: massive, amphibole-rich, and foliated. The massive granodiorite is composed of plagioclase, potassium feldspar, quartz, amphibole, and minor sericite, epidote, chlorite, apatite, and carbonate. The alteration mineral assemblage is consistent with greenschist-facies metamorphism. The amphibole-rich variety is found near the margins of the intrusive body and probably reflects contamination by the adjoining basalt and gabbro. This variety is most common in the southeast corner of sec. 3 in a wide zone along the basalt-granodiorite contact. It is typically dark gray and fine to medium grained and except for the abundance of amphibole (as much as 55 percent) is similar to the massive type. Foliated granodiorite is found along intrusive contacts and faults that cut across the granodiorite. It is gray to black, fine-grained to aphanitic schist with flaser structures. It is composed of plagioclase, chlorite, potassium feldspar, and quartz with minor apatite, sericite, and epidote. Locally, this variety hosts as much as 20 percent of disseminated euhedral pyrite.

The granodiorite near Rocking Chair Lakes has a calc-alkalic affinity (table 2). It can be classified as an I-type granite according to the criteria of Ferguson and others (1980). The rhyolite dikes, discussed previously, are interpreted as being a phase of the same magmatic event as the granodiorite near Rocking Chair Lakes.

# PROTEROZOIC ROCKS

Early Proterozoic sedimentary rocks assigned to the Michigamme Formation of the Marquette Range Supergroup (Cannon and Gair, 1970), Early Proterozoic diabase dikes, and Middle Proterozoic (Keweenawan) diabase dikes occur within the northern block.

The sedimentary rocks of the Michigamme Formation crop out in the Mulligan Plains and in the Dead River and Clark Creek basins. These rocks include conglomerate, slate, graywacke, and magnetite argillite, which were folded and metamorphosed to greenschist facies during the Penokean orogeny (Clark and others, 1975). Sparse outcrops of basal quartz-pebble conglomerates are found in contact with the Archean Lighthouse Point Basalt around the margins of the Clark Creek basin. The conglomerate in these outcrops is commonly a thin cover over Archean rocks, indicating that the present land surface is at or near the Early Proterozoic land surface.

Early Proterozoic diabase dikes that are well jointed, as much as 18 m wide, and strongly magnetic cut Archean and Early Proterozoic rocks in the area. They are dark gray, fine to medium grained, and hypidiomorphic granular, and are composed of labradorite, hornblende, chlorite, sphene, epidote, and skeletal magnetite. They were metamorphosed to greenschist facies during the Penokean orogeny and have commonly been mapped as metadiabase (for example, Puffett, 1974). They are readily distinguished microscopically from the Archean gabbro on the basis of plagioclase composition and texture, whereas macroscopic distinction can be difficult. Where diabase metamorphosed to greenschist facies cuts the gneissic granodiorite or the amphibolite-facies rocks of the Lighthouse Point Basalt, it is readily mapped as Early Proterozoic diabase. Within the greenschist-facies volcanic rocks, however, all metamorphosed diabase is mapped as Archean gabbro, failing evidence to the contrary.

Keweenawan diabase dikes cut all units in the area and are the youngest rocks within the northern block. These dikes are of two ages: (1) earlier north-south to northeast-trending, weakly metamorphosed or altered and normally polarized diabase and (2) generally east trending nearly fresh, reversely polarized olivine diabase (Baxter and Bornhorst, 1988).

## STRUCTURE

The northern block has had a long and complex structural history that includes at least two major Archean deformational events: first, recumbent folding about east-west axes ($D_1$); second, upright folding about east-west axes ($D_2$). These events resulted in folds with amplitudes and wave lengths measured in kilometers and a Z-shaped pattern, which largely determined the distribution of stratigraphic units.

### Bedding, Foliations, and Lineations

Interpreting bedding attitudes contributes significantly to an understanding of the deformation of the northern block; however, the number of measured attitudes is small because of the scarcity of sedimentary and volcaniclastic rocks. Attitudes recorded from pillows in the Lighthouse Point Basalt and bedding in the Reany Lake pyroclastic, Fire Center mine iron-formation, and the Hills Lakes pyroclastic units are shown in figure 5. The attitudes indicate that bedding in the area is overturned.

The prevalent foliation ($S_1$) in the northern block is a penetrative axial-planar foliation in amphibolite-facies rock defined by nematoblastic hornblende and an anastomosing foliation along pillow margins in greenschist-facies rocks defined by lepidoblastic chlorite and (or) nematoblastic actinolite. Outcrops of amphibolite-facies basalts are banded and layered because of the extreme flattening of pillows. The principal flattening direction in greenschist- and amphibolite-facies rocks is normal to the $S_1$ foliation.

Lineations ($L_1$) identified in the amphibolite-facies rocks are defined by the alignment of hornblende on $S_1$ surfaces. The attitudes of $L_1$ are similar to the attitude of the intersection of bedding and $S_1$, where bedding and lineation data are both available, indicating that $L_1$ defines $F_1$ fold hinges. Thus, $L_1$ is interpreted to be associated with the development of $F_1$ folds.

### Folds

The younger folds ($F_2$) control the overall Z-shaped pattern of stratigraphic units (fig. 5). As sedimentary and volcaniclastic rocks are rare, $F_2$ folds are best defined by the folding of $S_1$ (figs. 9 and 10*A*). At the northwest end of the belt, $L_1$ lineations plunge moderately to the southeast (fig. 10*B*), and $S_1$ is deformed by an upright, tight to isoclinal southeast-plunging $F_2$ synform verging to the southwest (fig. 10*A*). Farther to the east, along the same fold, $L_1$ plunges shallowly to the east (fig. 10*D*) and $S_1$ forms an upright, open, shallow easterly plunging $F_2$ synform (fig. 10*C*), whereas bedding ($S_0$) forms an open synformal anticline plunging shallowly to the west (fig. 9). (Note that the fold plunge direction indicated in fig. 9 is for folded $S_1$ foliation.) This apparent contradictory fold geometry is produced by folding $S_0$ and $S_1$ surfaces that are not parallel. $L_1$ in this area is nearly flat lying; the plunge of folded bedding is less than 10° to the west, and the plunge of folded $S_1$ is less than 10° to the east. The contrary plunge of fold surfaces may be exacerbated by scissors motion along the Little Garlic shear zone, discussed in the section, "Shear zones." If the eastern extreme of the Little Garlic shear zone has a more pronounced north-side-up motion than segments of the shear zone to the west, this would result in an increase in the westerly dip of units north of the shear in relationship to units south of the shear zone.

The older generation of folds ($F_1$) can be observed northeast and southeast of Rocking Chair Lakes (fig. 6), where the outcrop pattern of the Hills Lakes pyroclastic unit and gabbro sills define $F_1$ folds. The southern $F_1$ fold is a synformal anticline and the northern $F_1$ fold is an antiformal syncline. Both folds are tight to isoclinal, are upright, and plunge moderately to the southeast. In the vicinity of the fold hinges, bedding is normal to $S_1$ (figs. 6 and 9), $S_1$ is axial-planar, and $L_1$ plunges moderately to the southeast (fig. 10*B*). Farther to the east, $L_1$ and $F_1$ folds plunge shallowly to the east (fig. 10*D*). In the southeast are two smaller $F_2$ folds that may be controlled by the bounding gneissic granitoids.

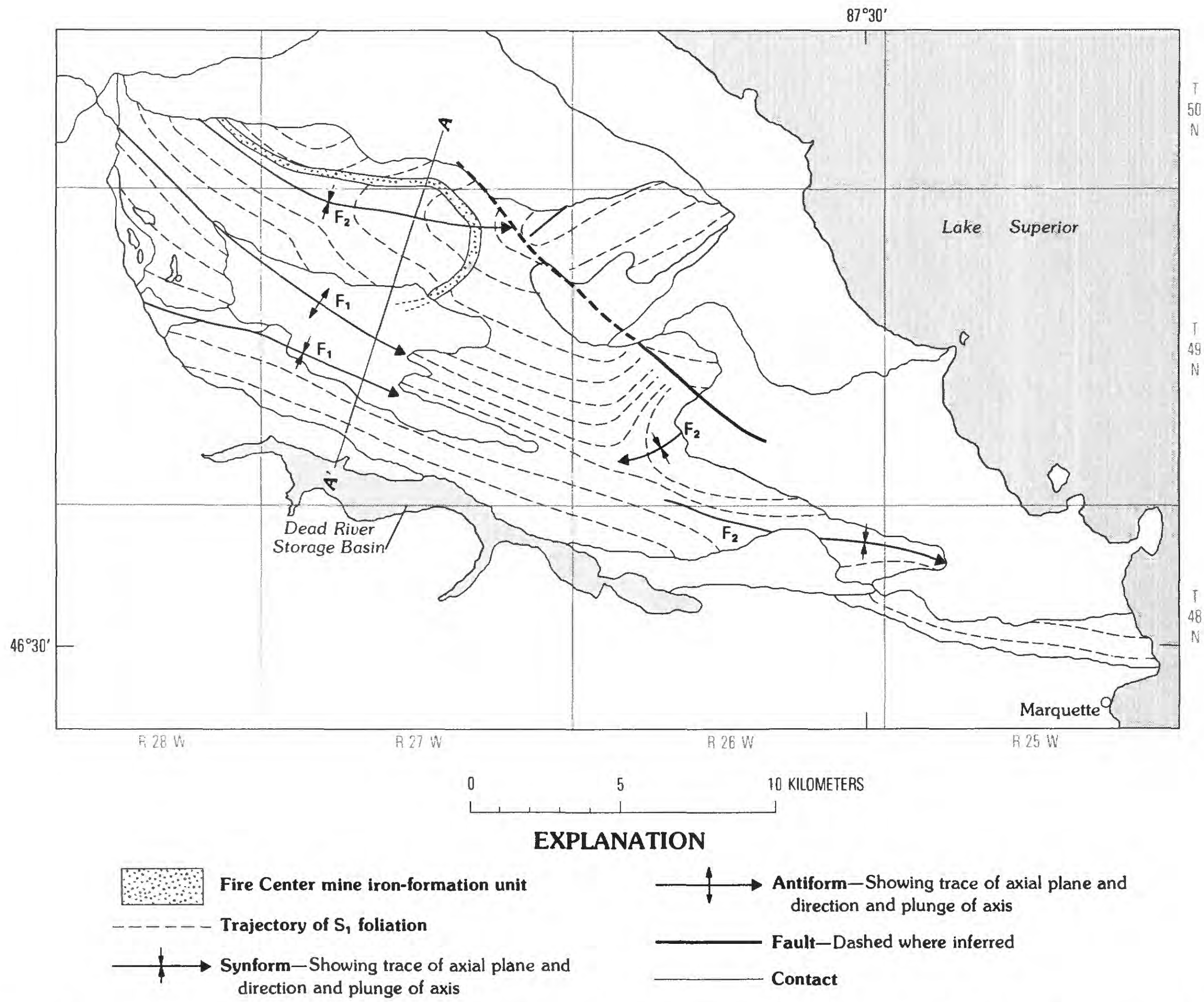



**Figure 9.** Sketch map showing $S_1$ foliation trajectory, $F_1$ and $F_2$ folds, outcrop pattern of the Fire Center mine iron-formation unit, and major fault in east end of the northern block. *A–A'*, line of section shown in figure 11.

The development of folds in the northern block is shown schematically in figure 11. During $D_1$, large-scale recumbent folds developed that are tight to isoclinal $F_1$ folds (fig. 11*A*). Later, during $D_2$, $F_1$ folds were refolded, forming isoclinal to open, upright $F_2$ folds (fig. 11*B*), and shearing occurred along the Little Garlic and Willow Creek shears (fig. 11*C*). This deformational sequence maintained the relative $S_0$–$S_1$ angular relationship observed (that is, $S_1$ typically dips more steeply to the north than $S_0$), which is consistent with the exposed lower limb of the $F_1$ recumbent fold (fig. 11*C*). A similar sequence of deformational events has been observed in northern Minnesota (Bauer, 1985; Hudleston and others, 1988).

## Faults

Several widely spaced subparallel north- to N. 15° E.-trending faults occur along the south margin of the northern block (fig. 2). These faults are commonly zones of breccia cemented with quartz and ankerite; some contain disseminated sphalerite, galena, and chalcopyrite. The age of these faults is uncertain, but because they cut all other fabrics and are cut by Keweenawan diabase they are assumed to be either Late Archean or Early Proterozoic.

A northwest-striking fault mapped by Puffett (1974) within the gneissic granitoid rocks in secs. 21, 27, and 28, T. 49 N., R. 26 W. can be extended into secs. 17 and 20, T. 49 N., R. 26 W., where a northwest-trending valley is associated with truncation and (or) offset of the Nash Creek glomerophyric basalt unit and gabbro sills (fig. 5). Projection pushes this fault farther west of the Third Bass Lake in sec. 2, T. 49 N., R. 27 W. and then into the bounding gneissic granitoids in secs. 34 and 35, T. 50 N., R. 27 W. An apparent left-lateral strike-slip component along the fault is recognized because of the offset of the shallow-dipping Nash Creek glomerophyric basalt unit (fig. 6). This fault is of potential economic interest because along its southwest projection Puffett (1974) mapped zones

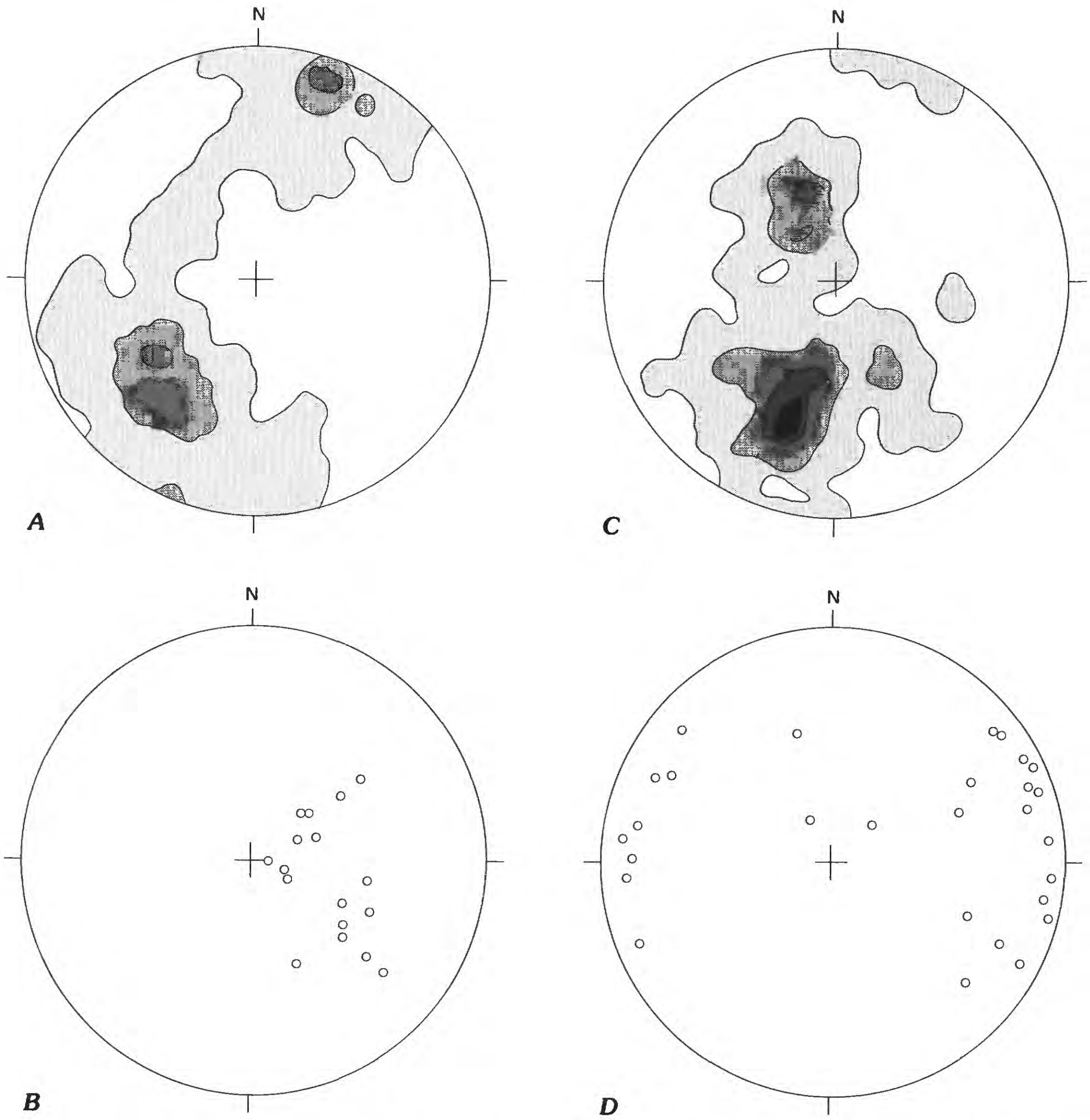



**Figure 10.** Stereographic projections (lower hemisphere) of *A*, $S_1$ poles from west end of the northern block ($n$=363); *B*, $L_1$ from west end ($n$=17); *C*, $S_1$ poles from east end ($n$=184); *D*, $L_1$ from east end ($n$=56). Contours at 0.5, 4.0, 8.0, 12.0, and 16.0 percent points per 1 percent of area.

of intense silicification and abundant pyrite. The fault offsets the Nash Creek glomerophyric basalt unit and $S_1$, suggesting that it postdates $D_2$.

## Shear Zones

Three major shear zones within or bounding the northern block—Dead River, Willow Creek, and Little Garlic shear zones (fig. 2)—are mappable at 7½-minute quadrangle scale. They are ductile to brittle-ductile zones (Ramsay, 1980) and exhibit similar kinematics, with a strong north-side-up and right-lateral (dextral) shear sense. They are interpreted to have developed late during $D_2$ and may have been reactivated during Proterozoic deformation.

Numerous smaller shear zones occur in the belt, for example along the contacts of Archean rhyolite intrusions. The smaller shears are from several centimeters to a meter or two in width. Smaller shears are more abundant in the vicinity of larger shears and may be subparallel to or branch from the major shear zone.

### Dead River Shear Zone

The Dead River shear zone forms the south margin of the northern block (fig. 2). The shear zone controlled the localization of abundant carbonate alteration and rhyolite intrusions from the east end of the Dead River Storage Basin in sec. 10, T. 48 N., R. 26 W. to west of Silver Creek in sec. 23, T. 49 N., R. 28 W. (fig. 7). C bands in mylonite

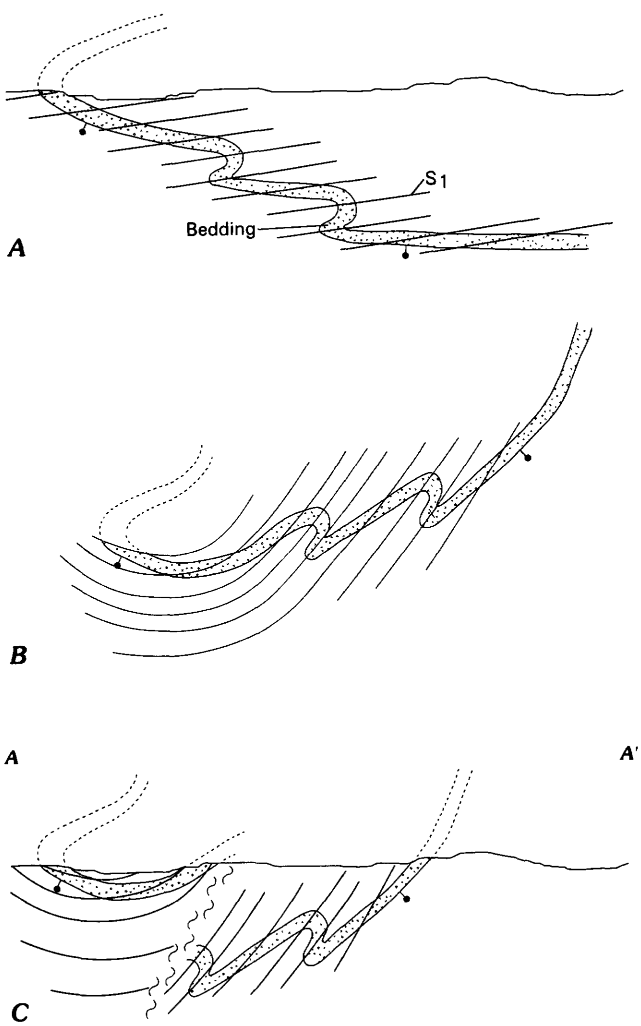



**Figure 11.** Schematic cross sections showing evolution of folding in northern block and relationships of bedding and $S_1$ foliation. Bar and ball symbol indicates stratigraphic top. Line of section for *C* shown in figure 9. *A*, Early recumbent folding during $D_1$; $S_1$ is axial-planar to $F_1$ folds. *B*, Open folding about steep east-west axes during $D_2$; at this stage, $S_1$ dips more steeply than bedding. *C*, Present-day configuration, after late-stage shearing (S symbols) that occurred during $D_2$.

and stretching lineations are typically nearly vertical, indicating dominant vertical displacement during at least the late stage of $D_2$. West of Silver Creek the relationship of flattening and shear foliations (S-C structures) and shallow westerly plunging stretching lineations indicate right-lateral and north-side-up shear sense.

### Willow Creek Shear Zone

The Willow Creek shear zone was named by Puffett (1974, p. 45) for a zone of amphibolite containing "irregular-shaped streaks of felsic rock" in sec. 4, T. 48 N., R. 26 W. and sec. 31, T. 49 N., R. 26 W. (fig. 2 of this report). Puffett interpreted these felsic streaks as fragments of a once-continuous body of felsic rock. MacLellan and Bornhorst (1989) studied a segment of this zone and on the basis of rhyolitic to dacitic and gabbroic "clasts" interpreted the lithology to represent a deformed volcaniclastic breccia. Further study by Johnson indicates the presence of a regionally continuous high strain zone that locally contains dikelets of gabbro and rhyolite.

The Willow Creek shear zone is exposed in secs. 21, 25–28, 35, and 36, T. 49 N., R. 27 W., and forms the north margin of the Clark Creek basin in this area. The east extension is less well defined, but sheared chlorite-carbonate schists in a north-northwest-trending creek in sec. 4, T. 49 N., R. 26 W. support extension of the shear through that area (fig. 2).

### Little Garlic Shear Zone

The Little Garlic shear zone is named for the shear that strikes west from the Little Garlic River in sec. 13, T. 49 N., R. 27 W. and then along the Little Garlic River through secs. 14 and 15, T. 49 N., R. 27 W. The western continuation of this shear is buried beneath Early Proterozoic sedimentary rocks and Quaternary alluvium, but it is likely that the cliff along the north margin of the Clark Creek basin in secs. 17 and 18, T. 49 N., R. 27 W. and a fault in sec. 12, T. 49 N., R. 28 W. form the westerly extension of this shear zone (fig. 2). Carbonate alteration, rhyolite intrusive rocks, and late-stage quartz veins characterize this shear zone.

Kinematic indicators in mylonite within the shear zone (S-C structures) reveal north-side-up and right-lateral shear sense. C bands and stretching lineations in this zone dip and plunge steeply to the north. In contrast, kinematic indicators in the other two notable shear zones indicate near-vertical north-side-up shear sense. This divergence of attitude suggests preexisting stratigraphic and (or) structural control on the orientation of the shears.

## GEOLOGIC HISTORY

The oldest event recorded in rocks of the northern block of the Ishpeming greenstone belt is subaqueous eruption of tholeiitic basalt lava flows, which accumulated to form the Lighthouse Point Basalt. Sporadic deposition of felsic pyroclastic material as turbidity and debris flows of the Reany Lake and the Hills Lakes pyroclastic units, respectively, produced stratigraphically continuous units within the basalt flows. During its turbulent descent from the volcano, the turbidity flow of the Reany Lake pyroclastic unit possibly incorporated parts of a massive sulfide body. The Reany Lake pyroclastic unit is overlain by the Fire Center mine iron-formation unit, which was deposited during a period of volcanic quiescence. Gabbro sills and dikes were emplaced shortly after deposition of the surrounding basalts.

Large-scale, north-directed thrusting ($D_1$) resulted in the development of recumbent nappe folds with an axial-planar foliation in the volcanic pile. Granitoid magmas intruded the belt as large batholiths and dikes. This magmatic event resulted in metamorphism of the volcanic rocks near contacts to amphibolite facies. A second north-directed compression ($D_2$) resulted in folding and shearing of the Lighthouse Point Basalt and associated rocks and deformation of the plutonic granitoid rocks. The right-lateral, north-side-up shear zones suggest that this event may be associated with transpression during the development of the Great Lakes tectonic zone to the south. The granodiorite near Rocking Chair Lakes then was intruded into fold hinges and rhyolite was intruded along zones of high strain. Gold mineralization probably occurred late during this tectonic event.

A period of extension was associated with the deposition of Early Proterozoic sedimentary rocks. Base metal quartz veins may have formed during this time. North-directed compression during the Early Proterozoic Penokean orogeny resulted in thrusting and folding of the Early Proterozoic sedimentary rocks and metamorphism of these rocks to greenschist facies in the northern block. After a considerable hiatus, Middle Proterozoic (Keweenawan) dikes intruded all older rocks in the vicinity of the Midcontinent rift system.

## ECONOMIC GEOLOGY

No mines are active in the northern block. Historic activity includes significant prospecting (trenches and shafts) during the 1860's on base metal–silver veins at Silver Creek in the NE¼ sec. 25, T. 49 N., R. 28 W., the Lead pits in the SE¼ sec. 34, T. 49 N., R. 27 W., and the Holyoke mine in the NE¼ sec. 2, T. 48 N., R. 27 W. The Fire Center Mining Company produced gold from the Fire Center mine from 1892 to 1893. Descriptions of numerous prospects in the northern block are given in Michigan Geological Survey reports listed in table 1.

### Base Metal Occurrence and Iron-Formation

Puffett (1974) described the occurrence of base metal sulfides in the Fire Center mine iron-formation unit; however, our mapping showed that this occurrence is hosted instead by the Reany Lake pyroclastic unit. Pyrite, sphalerite, chalcopyrite, and galena are fine to medium grained, disseminated, and crudely bedded in the lithic-tuff horizon. The sulfide minerals seem to be present along the entire strike length of this unit, but abundances vary greatly from place to place. Because the sulfides compose a thin zone and are disseminated and variable in concentration, this zone has a low potential as a source of base metals. Although detailed studies of the base metals have not been conducted, we presently interpret them as remnants of a massive sulfide deposit that was incorporated into the Reany Lake pyroclastic unit during its deposition.

The Fire Center mine iron-formation unit contains a significant amount of magnetite (up to 30 percent), but its thinness and steep dip (typically over 70°) exclude it as an economical source of iron ore at the present time (1990). The real potential of this iron-formation may be as host for an Archean lode gold deposit, inasmuch as many Canadian gold deposits are hosted in iron-formation (Colvine and others, 1988); however, only minor gold anomalies have been reported in association with this iron-formation.

### Gold Prospects

Several precious metal prospects spatially associated with the Dead River shear zone occur along the south margin of the northern block. Among these prospects, only the Fire Center mine was a producer, yielding about 100 troy oz of gold.

A typical gold prospect may possess any or all of these features: (1) a quartz porphyritic rhyolite dike; (2) brecciated (cemented with ankerite) margins of the dike; (3) sericitization, silicification, carbonatization, tourmalinization, and sulfidization of the dike; (4) sheared country rock immediately adjacent to the dike, with or without intense ankerite alteration; (5) late quartz veins that cut both the rhyolite dike and the sheared mafic country rock; (6) auriferous pyrite in the quartz veins; (7) disseminated auriferous pyrite as a halo about the quartz veins; and (8) calcite alteration as a halo about the gold occurrence. Gold mineralization in the northern block of the Ishpeming greenstone belt is closely associated with carbonatized shear zones, particularly the Dead River shear zone. The intimate spatial relationship between the rhyolite intrusives and the gold mineralization in this shear zone suggests that they may be synchronous. If so, the age of gold mineralization is Archean and syntectonic with $D_2$ deformation.

### Base Metal–Silver Prospects

Numerous historic base metal–silver prospects are located along the south margin of the northern block, again related to the Dead River shear zone. These prospects are quartz-carbonate veins bearing galena, sphalerite, chalcopyrite, pyrite, and arsenopyrite. The sulfides occur as fine- to coarse-grained disseminations and as masses in the vein, and are commonly concentrated along the contact between the vein and the country rock. The quartz is white and vitreous. The carbonate is coarse grained and grayish white, weathering to rusty brown; it is disseminated throughout the quartz vein and forms late crosscutting veinlets. The base metal–silver-bearing quartz-carbonate veins are typically less than 1 m wide and hosted in brecciated fault zones. The dominant trend of the veins is about N. 15° E.

The base metal–silver prospects are too low in grade and too small to be considered as likely sources of either base metals or silver at the present time (1990). Analyses for gold from base metal–silver prospects typically show low values (<30 ppb). At the Silver Creek prospect, the base metal vein is hosted in a fault breccia that cuts across sheared (ductile deformation) carbonate altered basalts that have anomalous gold values. This relationship indicates that the base metal–silver mineralization postdates gold mineralization.

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