D. L. Southwick

FIELD TRIP GUIDEBOOK FOR STRATIGRAPHY, STRUCTURE AND MINERAL RESOURCES OF EAST-CENTRAL MINNESOTA

PREPARED FOR THE 25TH ANNUAL MEETING OF
THE INSTITUTE ON LAKE SUPERIOR GEOLOGY
AND THE GEOLOGICAL SOCIETY OF AMERICA,
NORTH-CENTRAL SECTION
DULUTH, MINNESOTA, 1979

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N.H. Balaban, Editor

G.B. Morey and D.M. Davidson, Jr., Leaders

Special Papers

STRATIGRAPHIC AND TECTONIC HISTORY OF EAST-CENTRAL MINNESOTA

G.B. Morey

SOME STRUCTURAL ATTRIBUTES OF LOWER AND MIDDLE PRECAMBRIAN ROCKS, CARLTON AND PINE COUNTIES, MINNESOTA

D.M. Davidson, Jr.

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FIELD TRIP NUMBER 2

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G.B. Morey and D.M. Davidson, Jr., Leaders

INTRODUCTION

Early in the 20th century, east-central Minnesota became the source of appreciable quantities of iron and ferromanganese, and even earlier, the source of a variety of granite products (Morey, 1977). Because of the obvious economic importance of the commodities to the state, most of the geologic work in east-central Minnesota focused on the Cuyuna iron-mining district or on the St. Cloud area where there are numerous granite quarries. Less attention was given to the geology of other parts of east-central Minnesota and to the possible presence of other mineral resources. This was true mainly because a fairly ubiquitous mantle of Quaternary materials made it difficult, time consuming and expensive for a company to establish the basic geologic information necessary to a sucessful exploration program. However, recent geologic work (Morey, 1978) has led to the recognition of several geologic environments that are similar to mineral-producing districts elsewhere in the world (Morey, 1977). Although these studies have shown that a variety of mineral occurrences may exist, most attention to date has focused on environments that may contain uranium.

The possibly of uranium in east-central Minnesota is not a new idea. Anomalously high radioactivity levels have been known at several localities in the area since the late 1940's (Schwartz, 1949). Six samples from one of these localitites were reported to contain, on the average, 0.005 percent equivalent uranium (Barrett, 1958). Neither of these reports was then thought to be particularly significant and east-central Minnesota was not considered further as a possible source of uranium.

Interest in east-central Minnesota as a potential uranium-bearing area was renewed a few years ago when several mining companies recognized that parts of the area, particularly in Carlton and Pine Counties, have geologic environments similar to parts of Saskatchewan and Northern Territory of Australia where a number of uranium deposits of commercial size have been found. At about the same time, Ojakangas (1976) showed that those areas having anomalously high radioactivity levels in east-central Minnesota were related in one way or another to Middle Precambrian unconformities. In particular, two areas were recognized by Ojakangas as having possible economic potential. One area is associated with a basal unconformity that separates Middle Precambrian rocks of the Mille Lacs Group of Morey (1978) from underlying Lower Precambrian rocks assigned to the McGrath Gneiss, whereas the other area occurs near an exhumed unconformity that separates the Middle Precambrian rocks of the Animikie Group from overlying Upper Precambrian sedimentary rocks of the Fond du Lac Formation (Keweenawan). General geologic relationships suggest that the former may contain detrital uraninite deposits of the Elliott Lake-Rand type, whereas the latter may contain syngenetic pitchblende deposits of the vein-breccia type (Morey, 1977).

The purpose of this one-day field trip is to examine some of the rock types associated with potential uranium occurrences in Carlton and Pine Counties. Typical exposures of the McGrath Gneiss and the Fond du Lac Formation will be examined; additionally various rock types within the Middle Precambrian sequence will be examined, as time and logistics permit. Also included in this guidebook are a brief summary of the stratigraphic and tectonic history of east-central Minnesota, by G.B. Morey, and a discussion of some of the structural attributes of the Lower and Middle Precambrian rocks, by D.M. Davidson, Jr. These are appended to provide a geologic framework for the specific sites that will be visited.

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Ojakangas, R.W., 1976, Uranium potential in Precambrian rocks of Minnesota: U.S. Department of Energy, Grand Junction Colorado, open-file report GJBX-62 (76), 267 p.

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ROAD LOG

This road log starts at the Minnesota-Wisconsin border along the St. Louis River near Fond du Lac, the westernmost suburb of Duluth, Minnesota, and terminates near Sturgeon Lake on U.S. Interstate Highway 35 some 50 miles southwest of Duluth. Note that the mileages in this road log are approximate.

Mileage

0.0 Center of the bridge over the St. Louis River; proceed southwest along Minnesota-Wisconsin Highway 23.

0.1 Junction; turn right (west) and follow narrow gravel road.
[0.1]

0.6 [0.7] Gate; park and walk straight ahead along road for approximately 0.2 miles to the south bank of the St. Louis River.

STOP 1. Fond du Lac Formation (upper Keweenawan; Upper Precambrian). Exposures at this locality are typical of the Fond du Lac Formation throughout much of east-central Minnesota. The formation consists predominantly of red sandstone, siltstone and interbedded shale or mudstone, but conglomerate beds containing clasts of vein quartz, basalt, felsite, chert and quartzite are common locally. Beds of sandstone generally have a lenticular shape and are arkosic or subarkosic in composition. They consist of 36-68 percent quartz, 5-29 percent feldspar (microcline and albite-oligoclase) 1-10 percent rock fragments, 1-15 percent matrix material composed of quartz, illite and rare kaolinite, and 1-20 percent cement of hematite, calcite, quartz and dolomite. The siltstone units also occur as lenticular beds and, although finer grained, are mineralogically equivalent to the sandstone units. Shale units occur both as thin lenses and as thick beds of fairly uniform thickness; they consist predominantly of illite with minor amounts of kaolinite, montmorillonite-illite, quartz and feldspar.

The formation was deposited by fluvial-deltaic processes as indicated by the presence of filled stream channels, intraformational fragments, mud cracks, ripple marks, rain imprints and extensive large- and small-scale cross-bedding.

Return over same route.

0.6 [1.3] Junction; turn left (east) and follow Minnesota Highway 23 to Fond du Lac on the east side of the St. Louis River.

0.3 [1.6] Junction; turn left (north) and follow Minnesota Highway 210 to Jay Cooke State Park. CAUTION -- THIS IS A WINDING AND DANGEROUS ROAD.

1.9 [3.5] Sharp bend in road; St. Louis River straight ahead.

0.4 [3.9] Mouth of Mission Creek with a small pond on right (north) side of road; park nearby and follow the creek to the north. Stop 2 can can be reached only by walking approximately 0.4 mile along the creek bed; Stop 3 is midway between the road and Stop 2.

STOP 2. Basal quartz-pebble conglomerate of the Fond du Lac Formation. The quartz-pebble conglomerate exposed at this locality unconformably overlies folded and metamorphosed rocks of the Thomson Formation (Middle Precambrian) throughout much of Jay Cooke State Park. Although the contact cannot be seen at this locality, exposures of Thomson Formation are present about 0.1 mile to the north and the unconformable contact itself can be seen several miles to the northwest in the valley of the St. Louis River below Oldenburg Point.

The conglomerate is at least 60 feet thick and consists dominantly of pebbles and cobbles as much as 6 inches in diameter. Clasts of vein quartz predominate, but there are minor amounts of chert, quartzite, graywacke and slate. The matrix is mostly a coarse grit of angular quartz and feldspar, with some clay-sized matrix material and dolomite cement. Pyrite and marcasite are common and occur as concretions or individual grains in the matrix; locally they have been altered to limonite.

The conglomerate grades upward through a stratigraphic interval of several feet into arkosic sandstone like that seen at Stop 1. There is no distinct break between the conglomerate and the sandstone--the conglomeratic clasts become progressively smaller and less abundant as the amount of sand-size material increases.

Return towards the highway.

STOP 3. Extraformational basalt-pebble conglomerate in the Fond du Lac Formation. This exposure, consisting of fine-grained reddish-brown sandstone that contains rounded pebbles of highly altered basalt and basalt porphyry, is representative of extraformational conglomeratic units in the Fond du lac Formation, although it is thicker than most and contains more clasts.

Continue south on Mission Creek to the highway.

Minnesota Highway 210; continue west toward Thomson and Carlton.

4.4 [8.3] Sharp turn to the left (west); village of Thomson on the right; continue on Highway 210.

0.3 [8.6] Bridge over the St. Louis River; continue across the bridge (toward Carlton) to the parking area on the left (southwest) side of the river.

STOP 4. This is the type locality of the Thomson Formation of Middle Precambrian age. Approximately 2,500 feet of Thomson Formation are exposed in the Thomson-Carlton area. Data from two measured sections, one between the dam and the railroad bridge and the other south of the railroad bridge, indicate that the exposed section consists of 34 percent graywacke, 35-43 percent siltstone, and 23-31 percent slate. X-ray and thin-section studies reveal that the graywacke consists of 4-35 percent quartz, 2-28 percent feldspar, 1-10 percent rock fragments, 15-85 percent matrix material consisting of muscovite, chlorite and quartz, and 1-17 percent calcite. Mineralogically, the siltstone and shale units are the fine-grained and very fine-grained equivalents of the graywacke.

Most beds, regardless of grain size, are less than a foot thick and apparently have consistent thicknesses over the lengths of the longest exposures--a distance of several hundred feet--and give the impression of having a wide lateral extent. The graywacke and siltstone units are commonly graded and contain other well-defined internal structures common to turbidite sequences. Therefore the graywacke and siltstone beds are interpreted as individual sedimentation units deposited by turbidity currents that flowed from the north.

The Thomson Formation is intensively folded at this locality. Wave lengths of observed folds range from a few feet to 600 feet, and amplitudes from about 15 feet to 300 feet. The folds vary from broad, open, symmetrical folds in graywacke to tight, asymmetric, overturned folds in the less competent slate units. All folds have a near-vertical axial plane cleavage and plunge gently both to the east and to the west. Both normal and reverse faults are present, but they appear to have displacements of only a few tens of feet or less. The normal faults strike N. 30° E., are nearly vertical and have a dominantly dip-slip component. The reverse faults strike approximately east and dip southwest at angles of 20°-40°. Joint sets are well developed. They dip steeply and strike about N. 10° W. and N. 30° E. These sets define a conjugate joint system that probably formed in response to a north-south compressional stress at the time of folding.

Small to large quartz veins with minor amounts of pyrite and chalcopyrite occupy extension fractures near the crests of anticlines, and medium- to fine-grained ophitic microgabbro dikes occupy the northeast-trending joint sets. The age of the quartz veins is unknown, but the dikes are inferred to be of Keweenawan age.

Continue straight ahead (west) on Highway 210 toward Carlton.

1.0 [9.6] City of Carlton; stop sign; junction with Minnesota Highway 45 (to Cloquet) and Carlton County Highway 1 (to Wrenshall); continue straight ahead on Highway 210 (to Cromwell).

2.4 [12.0] Junction with Minnesota Highway 61; turn left (south) toward Atkinson.

2.3 [14.3] STOP 5. This small exposure on the right (northwest) side of the road in this featureless, swampy area is representative of the Thomson Formation metamorphosed to the lower greenschist grade. It is particularly interesting for it contains evidence of syndepositional deformation and at least one and perhaps two periods of folding.

1.9 [16.2] Village of Atkinson; turn right (northwest) and follow Carlton County Highway 144.

0.3 [16.5] Junction; follow narrow road to the left (southwest).

0.1 [16.6] STOP 6. The Thomson Formation at this locality consists of alternating beds of light- to dark-gray graywacke and dark-gray to black, fine-grained, phyllitic slate. The phyllitic rocks are characterized locally by muscovite flakes as much as 10 mm long, whereas the graywacke units are only vaguely recrystallized. Quartz and carbonate veins are common along fold axes and there is a narrow breccia zone where slate fragments are cemented by quartz, carbonate and pyrite. The graywacke consists of approximately 45 percent quartz, 15 percent K-feldspar and oligoclase, and 30 percent muscovite. Some of the phyllitic slate beds contain 5-10 percent carbonaceous material.

Return over the same route.

0.4 [17.0] Junction with Highway 61; turn right (southwest) and continue toward Mahtowa.

4.2 [21.2] Village of Mahtowa; turn right (northwest) and follow Carlton County Highway 4.

0.4 [21.6] Sharp turn to the left (west); continue on Highway 4.

0.5 [22.1] Junction; turn right (north) and continue on Highway 4.

1.0 [23.1] Junction; turn left (west) and continue on Highway 4.

0.1 [23.2] Junction; turn right (north) and follow Carlton County Highway 7.

0.5 [23.7] Crossroads; turn left (west) and follow narrow road.

0.4 [24.1] Park Lake Creek. Walk northwest along abandoned road.

STOP 7. The so-called "Arrowhead Mine" at this locality was dug into the Thomson Formation in about 1910 for carbonaceous slate to be used as coal, and possibly also as a gold prospect. Rocks in the immediate vicinity of the mine include thin, alternating beds of fine-grained graywacke, siltstone, and gray slate. However, the dominant lithology in the mine itself appears to be black carbonaceous slate, much fractured and impregnated with pyrite. Although bedding attributes have an easterly trend, the northerly trend of the pyrite-rich zone implies that it is a vein-filling deposit that follows a fracture.

In general, the graywacke units at this locality contain various proportions of quartz, feldspar (K-feldspar and oligoclase), muscovite and minor amounts of chlorite and calcite. However, biotite in exposures just to the south of the mine indicates an increase in metamorphic grade in that direction. Carbonaceous material having a disordered graphite mineral structure is present throughout all of the rocks at this locality. Together with the muscovite, it defines a strong foliation in most of the coarser grained beds. It is more abundant and has a massive or globular habit in thin section in the fine-grained pelitic beds. Because the carbonaceous concentrations that embay and surround many silicate minerals are cut by small veinlets of quartz and muscovite, the carbonaceous material appears to be a primary component present before metamorphism.

This is one of the two localities in east-central Minnesota known to have anomalously high radioactivity levels. A grab sample from the mine was assayed and found to contain 18 ppm U_3O_8 and 0.2 ppm gold (Ojakangas, 1976, p. 140).

Return over same route.

2.0 [26.1] Village of Mahtowa and junction with Highway 61; turn right (southwest) and follow Highway 61 toward Barnum.

6.0 [32.1] Village of Barnum; continue straight ahead on Highway 61.

4.8 [36.9] City of Moose Lake; stop lights; turn right (west) and follow Minnesota Highway 27.

0.4 [37.3] Soo Line Railroad track crossing; before crossing the tracks, turn left and park in railroad station parking lot. Walk north along railroad tracks for approximately 0.2 mile.

STOP 8. Exposures at this locality illustrate the Thomson Formation metamorphosed to the garnet grade. The pelitic rocks are definitely schistose and both they and the metagraywacke units contain small metacrysts of garnet; other minerals include quartz, calcic oligoclase, biotite and muscovite. The latter two minerals are extensively recrystallized and define a foliation that parallels bedding. Elongate carbonate concretions in nearby exposures parallel the foliation and contain scattered grains of hornblende. Both the sedimentary layering and the pronounced metamorphic fabric define a series of open anticlines and synclines that plunge gently to the east. A second generation of elongate muscovite grains is present on many bedding surfaces and defines a lineation that plunges either to the northeast or the southwest, depending on the geometry of the east-trending folds. Consequently this muscovite appears to define a second metamorphic event in the area.

Return over same route to parking lot and to Highway 61.

0.4 [37.7] Stop lights; turn right (southwest) and follow Minnesota Highway 61.

0.8 [38.5] Junction with Carlton County Highway 73 (to U.S. Interstate Highway 35); turn right (west) and follow Highway 61.

5.2 [43.7] Village of Sturgeon Lake; turn left (west) and cross the Burlington Northern Railroad tracks; turn left (south), go one block, turn right (west) and follow Pine County Highway 46 past school.

1.0 [44.7] Sharp bend to the right (north); continue on County Highway 46.

0.5 [45.2] Sharp bend to the left (west); continue on County Highway 46.

1.7 [46.9] Bridge over the Kettle River.

3.3 [50.2] Crossroads; turn left (south) and follow Pine County Highway 40.

1.5 [51.7] Crossroads; turn left (east) and follow Pine County Highway 159.

1.5 [53.2] Crossroads; continue straight ahead.

0.4 [53.6] Soo Line Railroad tracks. Park and follow tracks to the northeast for approximately 0.2 mile.

STOP 9. This sequence of interbedded metagraywacke and schist metamorphosed to the garnet grade represents the southernmost exposures of the Thomson Formation in east-central Minnesota. Both the metagraywacke and the schist contain calcic andesine, biotite and garnet; some chlorite occurs as a retrograde mineral after biotite. Individual garnet metacrysts are large and are characterized locally by a helicitic texture. Biotite and muscovite wrapped around the garnet indicate that the garnet has been somewhat rotated. Calcareous concretions in nearby outcrops are characterized by rims of hornblende, garnet, plagioclase and quartz, and cores of epidote, quartz, plagioclase and calcite.

Bedding and a well-developed schistosity define a number of small anticlines and synclines that plunge moderately to the east. These folds, which have amplitudes of several feet and wave lengths of several tens to several hundreds of feet, display a geometry similar to that seen at the type locality of the Thomson Formation at Stop 4.

Return over same route.

0.4 [54.0] Crossroads; turn left (south).

0.4 [54.4] Soo Line Railroad tracks; continue straight ahead (south).

0.7 [55.1] Junction; turn right (west) and follow Pine County Highway 52.

0.5 [55.6] Jog in road. Abandoned river valley on left (south) side of road. Park and continue south on foot along the left (east) side of the valley.

STOP 10. Rocks exposed along this abandoned valley have generally been assigned to the Thomson Formation, but Morey (1978) has designated them as the type locality of the Denham Formation of the Mille Lacs Group of Middle Precambrian age. At this locality, the Denham Formation overlies the McGrath Gneiss of Early Precambrian age and forms a heterogeneous sequence consisting dominantly of arenitic quartz-rich rocks that range in grain size from conglomerate to coarse siltstone. Several of the conglomeratic units that occur towards the bottom of the section contain clasts derived from the underlying gneiss. Minor quantities of dolomite, pillowed basalt and agglomerate of mafic to intermediate composition also are present. All of the rocks have been metamorphosed to the amphibolite grade and are strongly deformed. Garnet and staurolite are common in quartzose beds, and hornblende is abundant in the calcareous and volcanic units.

Much of the Denham Formation at this locality consists of thin to thick beds of vitreous quartzite that varies in color from white or very light gray to dark reddish gray. The light-colored varieties consist almost entirely of sand- and silt-size quartz and lesser amounts of microcline and plagioclase, whereas the reddish-gray varieties contain minor amounts of hematite and calcite in addition to quartz. Some of the red-colored rocks may be cherty iron-formation that has been extensively recrystallized. Interbedded pelitic units are light-colored layers rich in quartz that alternate with layers rich in muscovite, biotite, and garnet. The mica flakes and elongate quartz grains have a strong orientation parallel to the lamination, but in places this orientation is obscured by phyllosilicates that define a linear fabric parallel to a well-developed tectonic cleavage.

Structureless layers of dolomite or marble, as much as 10 feet thick, are present locally. Most consist of interlocking inequigranular grains of calcite that enclose metamorphic grains of garnet and detrital grains of quartz, microcline, and plagioclase. Muscovite and biotite commonly occur as small clusters, but in places they occur as thin, irregular laminae.

Layers of metabasalt are generally less than 15 feet thick, and are characterized by dark greenish-gray to greenish-black pillow structures having greenish-gray rinds several centimeters thick. The interior parts of the pillows consist of calcic plagioclase and augite intergrown in a microdiabasic texture. Much of the augite has been replaced by hornblende, which also occurs as large poikilitic grains enclosing plagioclase. Some hornblende is altered to biotite, and trace amounts of quartz and calcite are present in interstitial voids. The agglomeratic rocks occur in layers as much as 30 feet thick and are characterized by light-gray, angular, and vaguely porphyritic fragments as much as 10 cm in diameter, set in a dark greenish-gray, markedly porphyritic groundmass. The light-colored fragments contain a few small phenocrysts of augite set in a very fine-grained, equigranular groundmass of plagioclase and lesser amounts of quartz and hornblende. The hornblende, together with trace amounts of tabular biotite and small rods of intergrown quartz and calcite, forms a pronounced foliation. In contrast, the dark-colored fragments are characterized by abundant phenocrysts of zoned augite and hornblende set in a fine-grained, equigranular groundmass consisting of plagioclase and quartz. Biotite and intergrown sphene occur along cleavage planes in the hornblende, and biotite and calcite form elongate masses which also define a tectonic foliation.

Amphibolitic units less than 3 feet to more than 30 feet thick are intercalated with the quartzitic rocks at several places toward the north end of the Valley. They may be of igneous origin, but extreme recrystalliztion makes it difficult to ascertain their original composition. Although individual amphibolite layers vary considerably in texture and modal mineralogy, most are characterized by large grains of hornblende, plagioclase or biotite set in a finer grained, equigranular matrix of plagioclase and lesser amounts of quartz, biotite, and calcite. A few hornblende porphyroblasts contain remnants of augite, but most poikilitically enclose fine-grained quartz, plagioclase, epidote and calcite. Biotite occurs as small platelets in the groundmass or as psuedomorphs after hornblende; chlorite and actinolite mantle some of the larger biotite grains. Also, a few amphibolitic units contain trace amounts of garnet.

Return over same route and continue straight ahead on Highway 52.

0.4 [56.0] Junction; Pine County Highway 52 turns right (north) to Denham; continue straight ahead.

0.5 [56.5] Junction; turn right (north) and follow Pine County Highway 157.

0.5 [57.0] Junction; turn left (west) and follow Pine County Highway 40.

0.5 [57.5] Junction; turn left (south) and continue on County Highway 40.

1.0 [58.5] Junction; turn right (west) and follow Pine County Highway 156.

1.5 [60.0] Junction; County Highway 156 turns left (south); turn right (north) and follow Pine County Highway 169.

0.1 [60.1] STOP 11. McGrath Gneiss (Lower Precambrian). The McGrath Gneiss, at its type locality some 20 miles to the south, is a coarse-grained, pinkish-gray biotite gneiss characterized by large crystals of microcline that have the appearance of porphyroblasts. A fine-scale mineralogic layering is present locally as are schistose or gneissic inclusions of diverse origin. The McGrath typically contains 35 percent quartz, 35 percent plagioclase, 19 percent microcline, 8 percent biotite and trace to minor amounts of other minerals including muscovite, chlorite and calcite.

The modal mineralogy of the small outcrop on the right (east) side of the road at this stop is similar to that of the McGrath Gneiss at its type locality. However the rock here has been somewhat cataclasized, as indicated by biotite foliae that wrap around microcline metacrysts, which resemble augen. In thin section it can be seen that cataclasis has led to the formation of protomylonitic fabric characterized by the granulation of more brittle minerals such as plagioclase and microcline, and by the shredding of coarse biotite. Concurrent low-temperature metamorphic recrystallization within the protomylonitic zones has led to the formation of appreciable quantities of muscovite and some K-feldspar.

Continue straight ahead (north) on County Highway 169.

1.2 [61.3] Soo Line Railroad crossing; cross the tracks and park on left (west) side. Proceed west along the railroad tracks for approximately 0.2 mile.

STOP 12. Outcrops along the railroad tracks and in the woods immediately to the south of the railroad tracks are representative of extensively cataclasized McGrath Gneiss. Shearing has produced a nearly vertical protomylonitic foliation that strikes to the east. Elongate boudins of fine-grained, quartz-biotite-feldspar gneiss lie in the plane of the foliation, and hornblende rodding within the boudins defines a lineation subparallel to that defined by elongate mineral grains in other parts of the gneiss.

Extreme cataclasis at this locality has led to the formation of thin blastomylonitic zones characterized by finely crushed and recrystallized material, and mineral recrystallization has given rise to a well-developed crystalloblastic structure characterized by fine-grained K-feldspar and somewhat coarser grained hornblende.

The virtual coincidence of cataclastic structures in the McGrath Gneiss with fold axes and linear elements in the folded

Middle Precambrian rocks examined on this field trip implies that cataclasis and folding took place during the same period of deformation.

Continue straight ahead (north) on County Highway 169.

0.2 [61.5] Junction, turn right (east) and follow Pine County Highway 159 toward Denham.

2.0 [63.5] Junction; turn left (north) and follow Pine County Highway 40.

1.5 [65.0] Junction; turn right (east) and follow Pine County Highway 46 to Sturgeon Lake.

6.5 [71.5] Village of Sturgeon Lake; turn left (northeast) and follow Minnesota Highway 61.

0.1 [71.6] Junction; turn right (southeast) and follow Pine County Highway 161.

1.9 [73.5] Interchange with U.S. Interstate Highway 35. Continue north to Duluth.

End of field trip.

STRATIGRAPHIC AND TECTONIC HISTORY OF EAST-CENTRAL MINNESOTA

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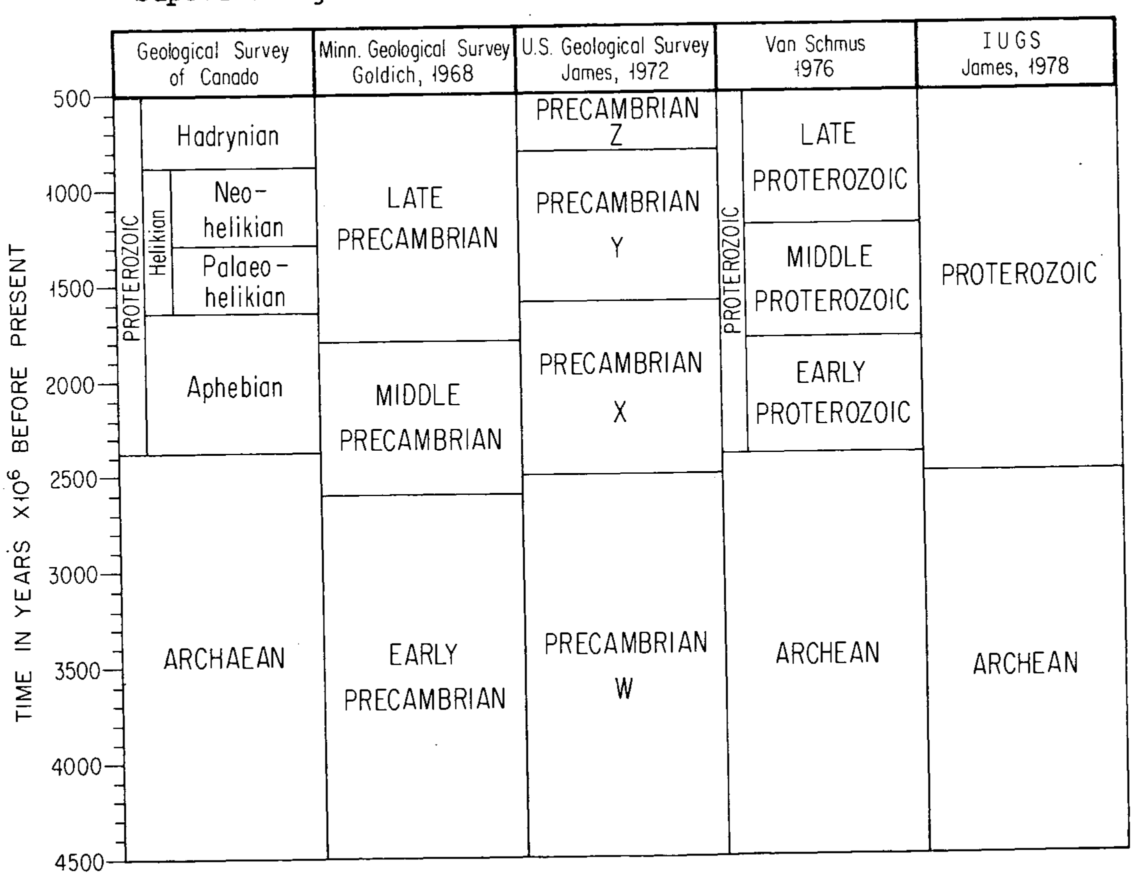
INTRODUCTION

There is still controversy among geologists as to whether the plate tectonic processes visualized for the Phanerozoic were operative since the generation of the first sialic crust in the Proto-Archean or whether global tectonics evolved during Precambrian time, leading gradually, through various stages to present plate tectonic phase. Clearly this problem is of scientific interest, but it also has practical importance because many modern concepts for mineral exploration in the Precambrian are based either directly or indirectly on ideas regarding ore deposits that formed in Phanerozoic time. East-central Minnesota contains a remarkably complete sequence of rocks ranging in age (tbl. 1) from Early Precambrian (ca >2,900 m.y.) through Late Precambrian (ca <1,100 m.y.). The purpose

Table 1--Subdivisions of Precambrian time commonly used for the Lake Superior region.



of this paper is to describe the stratigraphic and tectonic history of these rocks, as a better understanding of their origin may lead to a better understanding of the known and potential mineral deposits of the area (fig. 1).

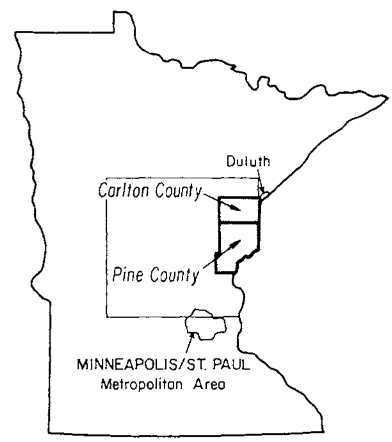


Figure 1--Location map showing Carlton and Pine Counties in relationship to the area of Plate 1 (geologic map of east-central Minnesota.)

Detailed mapping in east-central Minnesota has been hampered by a ubiqituous cover of Pleistocene and Holocene materials that ranges in thickness from less than 6 to more than 140 meters. Therefore, except in the area of the Cuyuna range where a considerable amount of detailed geology has been done in and around the various iron ore mines (Zapffe, 1933; Grout and Wolff, 1955; Schmidt, 1963; Marsden, 1972), and in the vicinity of St. Cloud where there are extensive granite exposures (Woyski, 1949), the cartographic relationships shown on Plate 1 have been interpreted from relatively few data points. Much of the interpretation is based on subsurface data acquired by various mining companies during the course of exploration for iron ores over the past 70 years. Inasmuch as nearly all of this exploration activity centered around rock units having anomalous magnetic characteristics, much extrapolation was required to give continuity to the many nonmagnetic rock units. This extrapolation (Morey, 1978 and in prep.) was based on aeromagnetic and gravity data and the extensive collection of water-well records acquired over the years by the Minnesota and U.S. Geological Surveys. Although more elaborate cartographic interpretations are possible, the temporal relationships shown on Plate 1 represent conclusions derived for the most part from on-the-ground observations.

The Precambrian rocks of east-central Minnesota are divisible into four distinct terranes. The oldest is a diverse Early Precambrian terrane (1), which is overlain unconformably on the north by a thick sequence of folded and metamorphosed Middle Precambrian sedimentary and volcanic rocks (2), and intruded on the south by a variety of Middle Precambrian plutonic rocks (3). The Middle Precambrian rocks are overlain unconformably by eastward-dipping sedimentary and volcanic rocks of Late Precambrian age (4). All of the Precambrian rocks are overlain locally by generally flat-lying sedimentary rocks of Cambrian and Cretaceous age that will not be considered further.

LOWER PRECAMBRIAN ROCKS

Lower Precambrian rocks in east-central Minnesota may be divided into three distinctly different lithotectonic segments by two east-northeast-trending, presumably high-angle fault zones of Early Precambrian age (pl. 1). The southernmost segment consists of highly deformed and metamorphosed gneisses, whereas the northernmost segment consists dominantly of granite and lesser amounts of metasedimentary and metavolcanic rocks that collectively form a greenstone-granite terrane. The lithic and temporal characteristics of Lower Precambrian rocks in the middle structural segment are problematic because of sparse exposures. Cataclasized granitic rocks similiar to those in the greenstone-granite terrane are exposed locally, but definitive data pertaining to the surrounding rocks are sparse. Water-well logs from a few scattered localities describe the host rocks as being "schistose." These "schistose" rocks may be of sedimentary origin as inferred on Plate 1, or they may be reactivated and cataclasized equivalents of less severely deformed gneissic rocks as inferred by Sims (1976a, fig. 2). Regardless of their original age and present character, the "schistose" rocks form part of a discrete zone that separates two considerably different Archean terranes.

Exposures of the gneiss terrane are confined mostly to the western part of Plate 1 where two new lithostratigraphic units--the Richmond Gneiss and the Sauk Rapids Metamorphic Complex--have been recognized (Morey, 1978). Contact relationships between these two units are not exposed, but the latter may be subdivided into three units of formational status--the Sartell Gneiss, Watab Amphibolite, and St. Wendel Metagabbro. The Watab Amphibolite and the St. Wendel Metagabbro occur as lenses or pods of appreciable size in the more widely distributed and somewhat older Sartell Gneiss.

The Richmond Gneiss is a black to dark grayish-black, coarse-grained porphyritic rock consisting essentially of K-feldspar, plagioclase, quartz, hypersthene, hornblende and minor amounts of biotite, garnet and cordierite. In contrast the Sartell Gneiss is a light pinkish-gray, medium-grained, equigranular rock consisting dominantly of biotite, quartz, plagioclase and microcline. However it contains layers, lenses and pods of fine-grained, equigranular biotite gniess having minor to locally abundant garnet and cordierite. Both the Watab Amphibolite and St. Wendel Metagabbro are dark-colored, coarse-grained, mafic enclaves that contain plagioclase, clinopyroxene, hornblende and biotite, and plagioclase and pyroxene, respectively.

Biotite-bearing quartzofeldspathic gneiss assignable to the gneiss terrane also is exposed east of Mille Lacs Lake (pl. 1) where it is named the McGrath Gneiss. This rock unit is a pinkish-gray, medium- or coarse-grained, locally migmatitic gneiss characterized by large crystals of microcline. A fine-scale, probably primary, mineralogic layering characterized by biotite folia is present locally. Primary minerals include quartz, andesine, microcline, and biotite. However, the McGrath has been extensively cataclasized and consequently its mineralogy and texture are quite variable. All gradations from zones of incipient fracturing and minor shearing to zones of intensely crushed and recrystallized rock (blastomylonite of Higgins, 1971) occur, but cataclasis and recrystallization were most intense near inferred contacts with younger sedimentary rocks. In cataclastic zones well away from inferred contacts, the original gneissosity is partly obscured and the rock is a protomylonitic gneiss having large microcline porphyroclasts. In general, cataclasis has caused a decrease in grain size by granulation of more brittle minerals such as plagioclase and microcline and by shredding and bending of coarse biotite. Near inferred contacts the original gneissosity is totally obliterated and the protomylonitic zones contain still smaller zones, 0.5 to 5 mm thick, that are composed of finely crushed and recrystallized material having a preferred blastomylonitic foliation coincident with the orientation of the protomylonitic zones themselves. Low-temperature mineral recrystallization coincident with cataclasis in the blastomylonitic zones has produced a well-developed crystalloblastic fabric involving fine-grained K-feldspar and somewhat coarser grained hornblende.

MIDDLE PRECAMBRIAN STRATIFIED ROCKS

The Middle Precambrian (approximately 2,150-1,850 m.y.) stratified rocks in east-central Minnesota form a broad, eastward-plunging synclinorium bounded on the north, west, and southeast by Lower Precambrian rocks. These sedimentary and volcanic rocks have been divided into two groups (Morey, 1978) separated by an unconformity (fig. 2). Each group is estimated to have a maximum thickness of approximately 1 km in the area north and east of Mille Lacs Lake (pl. 1). However, extensive deformation and lack of exposures make any estimate of thickness debatable.

The distribution and extent of the older sequence, named the Mille Lacs Group, have been recognized only recently (Morey, 1978), whereas the younger sequence is correlative with the well known Animikie Group of northern Minnesota and Ontario (fig. 2).

As defined by Morey (1978), the Mille Lacs Group consists dominantly of quartz-rich sedimentary rocks named the Denham and Little Falls Formations. The former is chiefly quartzose and arkosic sandstone or quartzite interbedded with lesser amounts of siltstone, mudstone and conglomerate, whereas the latter consists mostly of quartz-rich graywacke, siltstone and mudstone. Minor quantities of volcanogenic and hypabyssal rocks of mafic to intermediate composition are interlayered throughout the group. However two mappable bodies of mafic to intermediate volcanic rocks that occur near the base of the group have been formally named the Randall and Glen Township Formations. Both formations interfinger with rocks of the Denham Formation and contain appreciable quantities of oxide- to carbonate-facies iron-formation and pyrite-rich, carbonaceous argillite. Thin to thick beds of impure dolomite or limestone also are present throughout the group, but are particularly abundant in the upper part where they compose the Trout Lake Formation (Marsden, 1972).

A low-angle unconformity presumably separates rocks of the Mille Lacs Group from those of the overlying Animikie Group (Marsden, 1972). The basal part of the Animikie Group is assigned to the Mahnomen Formation (Schmidt, 1963) and consists dominantly of feldspathic siltstone and lesser amounts of quartzite and limestone. The Mahnomen Formation is sharply overlain by oxide- and silicate-facies iron-formation assigned to

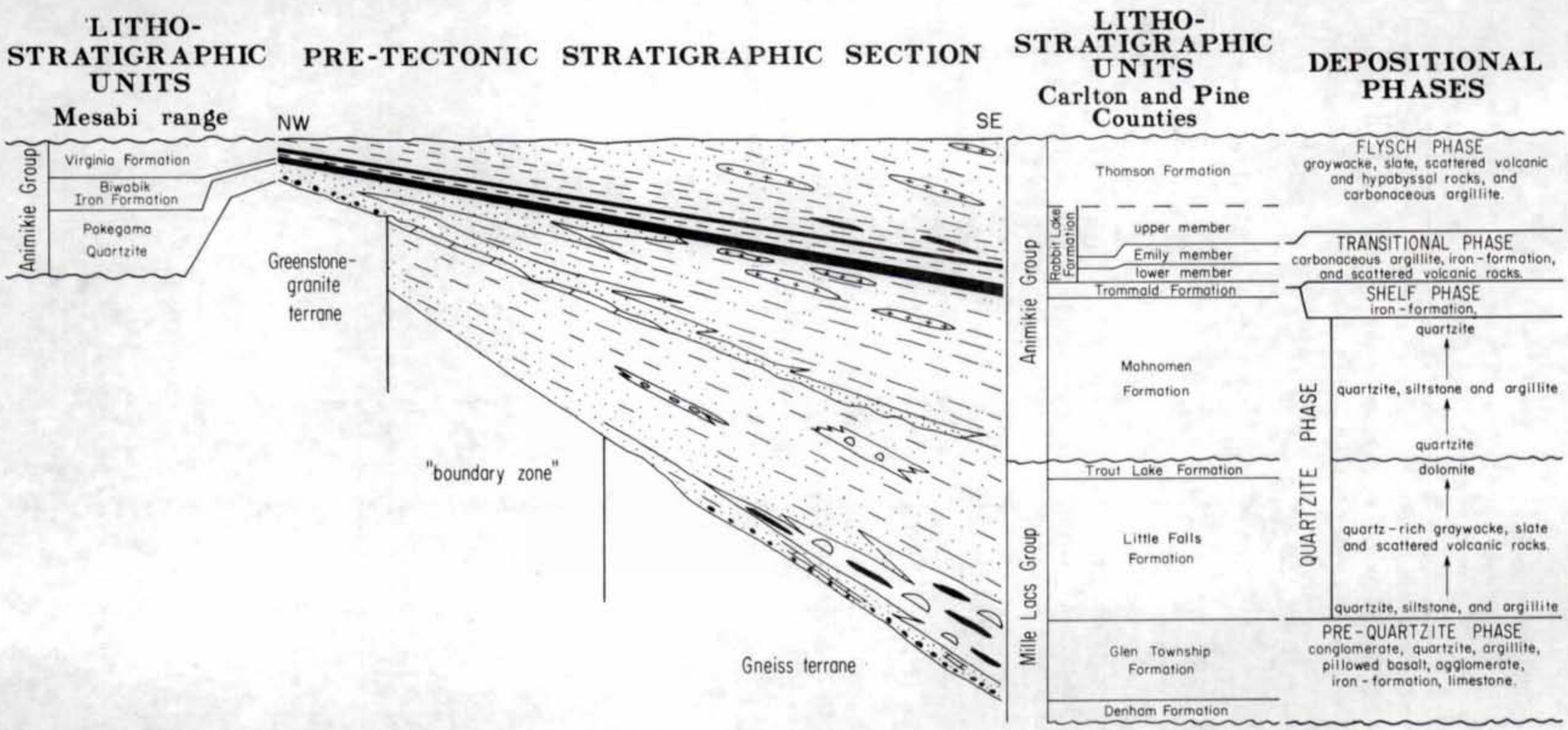


Figure 2--Pretectonic north-south cross section showing lithostratigraphic nomenclature and depositional phases of the Middle Precambrian stratified rocks in east-central Minnesota.

the Trommald Formation (Schmidt, 1963) which in turn is overlain gradationally by various kinds of clastic rocks assigned to the Rabitt Lake Formation (Schmidt, 1963). Marsden (1972) has divided the Rabbit Lake Formation into three members. The so-called "lower member" consists of carbonaceous mudstone, feldspathic siltstone, and mafic tuffs or flows. It is overlain by a persistent layer of iron-formation (Emily iron-formation member of Marsden, 1972); this in turn is overlain by the so-called "upper member" which consists dominantly of carbonaceous mudstone, feldspathic siltstone, and scattered beds of fine- to medium-grained feldspathic graywacke. Lenses of iron-formation as much as several tens of meters thick and at least several kilometers long also are present in the lower part of the "upper member." Although definitive details are lacking, it is inferred that the Rabbit Lake Formation passes transitionally-upward into the Thomson Formation of Schwartz (1942). The latter is chiefly graywacke, siltstone, and slate, but locally it also contains appreciable thicknesses of carbonaceous and pyritic slate and lesser thin to thick beds of mafic tuff, mafic lava and coeval hypabyssal sills and dikes. Abundant carbonate concretions, particularly in the argillaceous units, also characterize the formation.

The Middle Precambrian stratified rocks were extensively deformed and metamorphosed during the Penokean orogeny. However the degree of deformation varies considerably within the synclinorium, and the differences may relate to contrasting kinds of underlying Lower Precambrian rocks (fig. 3). In the northern part of the synclinorium, where the sedimentary strata overlie granitic basement rocks, the beds dip gently southward and the basal unconformity appears to be little deformed. However, where the sedimentary rocks overlie schistose and/or gneissic rocks, the entire section is complexly folded into several large anticlines and synclines that have numerous coaxial second- and third-order folds on their limbs (Schmidt, 1963). The style of deformation changes from open folds with

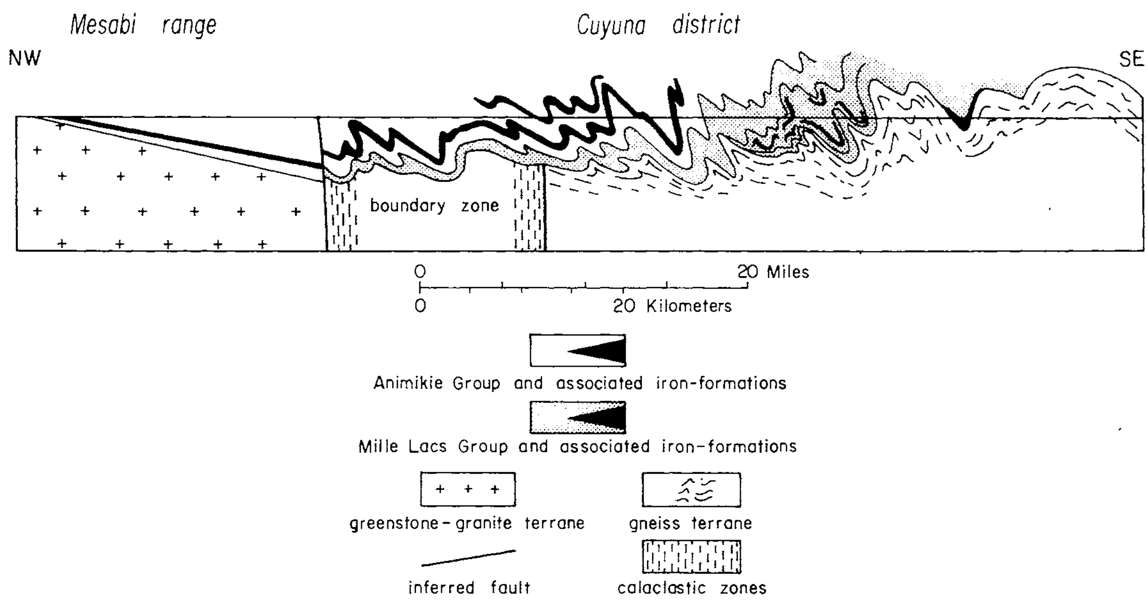


Figure 3--Generalized north-south structural cross section of the Middle Precambrian stratified rocks in east-central Minnesota.

near-vertical axial planes in the central part of the synclinorium to isoclinally overturned folds with axial planes that dip as much as 60° SE. in the southern part. Folds on the north flank of the synclinorium have axial planes that strike east-northeast and axes that plunge gently northeastward. Folds on the south flank have axial surfaces that conform in a general way to the antiformal shape of the McGrath Gneiss, and axes that plunge moderately to the southwest.

The Middle Precambrian stratified rocks also reflect an increase in metamorphic grade from north to south. To the north, iron-formation and associated argillaceous rocks overlying granite-greenstone basement rocks contain minerals indicating metamorphic conditions scarcely above diagenesis (Morey, 1973; Perry and others, 1973). However, argillaceous rocks overlying schistose basement rocks have a slaty cleavage (Marsden, 1972) and mineral assemblages indicative of lower greenschist-facies metamorphism. Metagraywacke and slate of the Thomson Formation have well preserved sedimentary structures and textures near Carlton. These rocks contain greenschist-facies assemblages of quartz, albite or sodic oligoclase, chlorite, sericite, and carbonate. They also contain conspicuous concretions composed of coarse calcite and dolomite grains that enclose detrital grains of quartz, plagioclase, and phyllosilicate. The grade of metamorphism rises slowly to the south and west. Argillaceous beds are phyllitic at Atkinson, about 13 km southwest of Carlton, and metagraywacke beds have developed conspicuous cleavage. Muscovite metacrysts are abundant in phyllitic layers and the detrital plagioclase in sandy layers has lost its twinning. Biotite first appears in argillaceous rocks about 38 km south of Carlton. From there southward, the argillaceous beds have a schistose fabric and the interbedded metagraywacke units are completely recrystallized. At Moose Lake, 46 km south-southwest of Carlton, both the biotite schist and the metagraywacke contain small metacrysts of garnet; other minerals include quartz, calcic oligoclase, biotite and muscovite. The latter two minerals are extensively recrystallized and define a foliation parallel to bedding. Carbonate concretions are flattened parallel to the foliation and contain scattered grains of hornblende. Near Denham, about 64 km southwest of Carlton, both the metagraywacke and the schist contain calcic andesine, biotite and garnet; some chlorite occurs as a retrograde mineral after biotite. Individual garnet metacrysts are large and are characterized by a helicitic texture. Biotite and muscovite are wrapped around the garnet, indicating that the garnet has been somewhat rotated. Calcareous concretions are characterized by rims containing hornblende, garnet, plagioclase, and quartz, whereas the cores contain epidote, quartz, plagioclase and calcite (Weiblen, 1964).

Near Denham, the Thomson Formation is separated from rocks of the Denham Formation by a major northwest-trending fault. Southwest of the fault, the Denham Formation has been metamorphosed to the lower amphibolite facies. Garnet is common in the more quartzose beds, hornblende is abundant in calcareous and volcanic units, and staurolite occurs in proximity to the McGrath Gneiss. Similar metamorphic mineral assemblages occur in the Little Falls Formation at and south of the city of Little Falls, where chloritoid also is present.

On a regional scale, the areas of most intense deformation coincide with the areas of most intense metamorphism. The biotite, garnet, and staurolite isograds conform in a general way to the fold geometry and define a metamorphic high along the northern edge of the McGrath Gneiss. In detail however, the metamorphic isograds transect major fold axes, and it therefore appears that the deformation and metamorphism were discrete events.

MIDDLE PRECAMBRIAN PLUTONIC ROCKS

Middle Precambrian (approximately 1,850-1,800 m.y.) plutonic rocks are confined to that part of east-central Minnesota presumably underlain by Lower Precambrian gneisses. A wide variety of inclusions of metavolcanic and metasedimentary origin in the plutonic rocks indicate that the basement gneisses were overlain by Middle Precambrian stratified rocks when igneous activity occurred.

Igneous activity of calc-alkaline affinity was characterized by the emplacement of several discrete intrusive bodies of variable size. Because these intrusions are in sharp contact with one another or contain inclusions of one rock type in another, it is possible to define a sequence of intrusive events much like that proposed by Woyski (1949). Small dikes, sills, and stocks of gabbroic to dioritic composition are inferred to be the oldest Middle Precambrian plutonic rocks in east-central Minnesota. Most of these bodies are too small to be shown on Plate 1 and are as yet unnamed. It is inferred that this period of igneous activity was followed by the emplacement of several small stocks of granodioritic composition--the Freedhem and Bradbury Creek Granodiorites--and later by the emplacement of several large granitic plutons of generally sodic composition--the Reformatory, Isle, Warman and Pierz Granites of Morey (1978). Plutonic igneous activity culminated with the emplacement of the Stearns Granitic Complex. This composite unit consists of several kinds of potassic granitic rocks assigned to the St. Cloud Granite, and a discrete border facies of sodic composition named the Rockville Granite.

All of the granitic rocks were emplaced after Penokean deformation, as indicated by their relatively homogeneous and undeformed nature and by the fact that they cut structures presumably formed during the Penokean orogeny. However the unnamed gabbroic to dioritic rocks and the Freedhem and Bradbury Creek Granodiorites appear to have been emplaced during the waning stages of the Penokean orogeny, for they contain incipient cataclastic zones that coincide with fold axes and other structural features in the Middle Precambrian stratified rocks. Additionally, an igneous tonalitic phase in the Hillman Migmatite of Morey (1978), was clearly emplaced before the Middle Precambrian stratified rocks were deposited. It may have formed either in the early part of the Middle Precambrian time or during Early Precambrian time.

UPPER PRECAMBRIAN STRATIFIED ROCKS

Upper Precambrian stratified rocks in east-central Minnesota comprise part of the classical Keweenawan System (Goldich and others, 1961), Series (White, 1972) or Supergroup (informal U.S. Geological Survey usage, e.g. King, 1976) of the Lake Superior region.

In east-central Minnesota, the oldest Keweenawan rocks are assigned to the Nopeming Sandstone of Mattis (1972). This thin veneer of normally polarized, quartz-rich sandstone is overlain by a much more extensive accumulation of volcanic rocks named the Ely's Peak basalts of the North Shore Volcanic Group (Kilburg, 1972; Green, 1972). This reversely polarized unit of unknown total thickness consists in part of augite-bearing basalt porphyry or augite porphyritic basalt, rock types typical of the lower Keweenawan in the Lake Superior region (Green, 1977). Although the Ely's Peak basalts crop out only in a small area just west of Duluth (pl. 1), aeromagnetic and seismic data indicate that they extend in the subsurface of east-central Minnesota as far south as latitude 46° N.

Throughout most of east-central Minnesota, the Ely's Peak basalts, as well as Lower and Middle Precambrian rocks, are overlain unconformably by as much as 2,300 meters of sedimentary rocks assigned to the Hinckley and Fond du Lac formations. All of these rocks are in fault contact with normally polarized subaerial lava flows assigned to the Chengwatana Volcanic Group of Morey and Mudrey (1972). The thickness and stratigraphic position of the Chengwatana volcanic rocks are uncertain, but they petrographically and chemically resemble plagioclase-rich olivine tholeiites assigned to the well-known, normally polarized, middle Keweenawan Portage Lake Lava Series of northern Michigan (Morey and Mudrey, 1972). Therefore the Chengwatana Volcanic Group is assigned to the middle part of the Keweenawan.

The Fond du Lac and Hinckley formations are assigned to the upper part of the Keweenawan mainly because they contain detritus derived, at least in part, from the Chengwatana and North Shore Volcanic Groups. The Fond du Lac Formation is a classical fluvial-deltaic sequence consisting of lenticular beds of red, arkosic to subarkosic sandstone, siltstone and interbedded shale derived dominantly from a granitic terrane to the west (Morey, 1967). The Hinckley Sandstone gradationally overlies the Fond du Lac Formation and is a typical orthoquartzitic sandstone with only minor amounts of feldspar and metamorphic and volcanic rock fragments (Tryhorn and Ojakangas, 1972). Its greater textural and mineralogical maturity indicates that the Hinckley formed from Fond du Lac detritus reworked in a shallow lacustrine environment that existed under tectonically stable conditions.

SYNOPTIC TECTONIC HISTORY

The two contrasting Lower Precambrian terranes that have been recognized in east-central Minnesota (Morey, 1978) played a very important role in the tectonic evolution of the area. The two terranes are juxtaposed along a boundary that trends east-northeasterly across Minnesota at approximately its midpoint. Various kinds of gneisses form the basement to younger rocks in the southern part of the area, whereas greenstone-granite complexes--like those in large parts of the Superior province of the Canadian Shield--make up the basement in the northern part. In Minnesota there is no evidence that the Lower Precambrian greenstone was deposited on an older sialic basement. Accordingly the greenstone-granite complexes, on the one hand, and the gneisses, on the other, appear to compose crustal blocks that are geographically separate and geologically distinct from each other (Morey and Sims, 1976).

The gneiss terrane in east-central Minnesota is a grossly interlayed sequence of migmatitic gneiss and amphibolite. Some of the mafic enclaves are older than the surrounding quartzofeldspathic gneisses, whereas others are younger, but all of the rocks have been deformed several times and contain mineral assemblages characteristic of the upper amphibolite to granulite metamorphic facies (Morey, 1978). Therefore they appear to have had a very complex history much like that of the ancient gneisses of the Minnesota River Valley.

The pervasive high-grade metamorphic overprint makes the original nature of the principal gneissic units in the Minnesota River Valley and in east-central Minnesota conjectural. Grant (1972) suggests that the gneisses in the Minnesota River Valley may be older high-grade metamorphic analogs of the greenstone-granite terrane, whereas Goldich and others (1970) prefer a plutonic origin for a substantial part of the gneiss terrane. Either possibility, or some combination of them, may be applicable to the gneissic rocks in east-central Minnesota. Even though it is not yet possible to define original protoliths, the present structural and metamorphic attributes of the gneisses are all consistent with and indicative of a high degree of plasticity during regional deformation and metamorphism. Thus it seems likely that the gneisses formed in an unstable tectonic regime characterized by high heat flow and small, relatively thin plates lacking much internal rigidity.

Very little is known about the greenstone-granite terrane in east-central Minnesota, but in northern Minnesota it is characterized by a number of linearly distributed and mantle-derived greenstone belts which appear to have foundered or been down-faulted between upwelling masses of diapiric granite (Sims, 1976b). The greenstone units in northern Minnesota have eugeoclinal attributes and major- and trace-element abundances similar to modern island-arc volcanic suites (Arth and Hanson, 1975). However, island-arc evolution of these units along a presumed protocontinental margin (Morey and Sims, 1976) has not yet been demonstrated. For one thing the greenstone belts lack most fundamental attributes of Phanerozoic geosynclines, and for another they are surrounded by granitic rocks that suggest a very mobile regime at the time of their formation. Thus even though older blocks of continental material were present in the area in the later part of Early Precambrian time, it appears that the greenstone belts did not form in response to tectonic processes like those that characterize Phanerozoic time.

Toward the end of Early Precambrian time, the two Lower Precambrian terranes were welded together, apparently by voluminous quantities of granite, to form a large craton (Sims and Morey, 1973) that was sufficiently stable to permit the development of large sedimentary basins. Middle Precambrian sedimentation in east-central Minnesota started at about 2,100 to 2,000 m.y. within one such basin centered over and approximately parallel to the boundary between the two contrasting Lower Precambrian terranes. Sedimentation within the basin can be divided into five depositional phases (fig. 2). The first three phases constitute a southward-facing miogeoclinal sequence. The fourth phase forms a transitional sequence as the shelf foundered, whereas the last phase forms a eugeoclinal southward-facing, clastic wedge deposited by southward-flowing turbidity currents (flysch). Rocks of the earliest phase are preserved in the axial part of the basin as a discontinuous veneer of coarse- to fine-grained, generally well sorted clastic rocks and as a thin to thick complex of pillowed basalt, agglomerate, cherty iron-formation and black carbonaceous slate. All of these rocks are overlain by the second or quartzite phase which forms a southward-thickening wedge of compositionally mature quartzite, quartz-rich siltstone, mudstone and shale derived from both the greenstone-granite terrane to the north and the gneiss terrane to the south (Peterman, 1966; Keighin and others, 1972). The ratio of mud to sand increases stratigraphically upward and southward and much of the sequence is characterized by rather monotonous interbeds of quartz-rich graywacke, subgraywacke, siltstone and argillite punctuated by scattered beds of sandy dolomite and quartz-pebble grit or conglomerate.

Rocks of the quartzite phase provided the foundation for a third phase--the formation of a thin, southward-facing shelf characterized by various kinds of iron-formation having shallow-water attributes to the north and west and deeper water attributes to the south and east (Morey, 1973). These shelf deposits are gradationally overlain by the fourth phase--a thin succession of black, laminated argillite intercalated with thin to thick layers of iron-formation and mafic pyroclastic and extrusive rocks; this starved sequence was deposited as the shelf began to founder. As the shelf foundered into deeper water, mud deposition was periodically interrupted by southward-flowing turbidity currents which deposited thin to thick beds of feldspathic graywacke and siltstone (Schmidt, 1963; Morey and Ojakangas, 1970). Sedimentation was also periodically interrupted by the deposition of both felsic and mafic pyroclastic rocks, by the extrusion of microdiabasic flows, and by the injection of diabasic gabbro sills. All of these rocks constitute a southward-thickening wedge of considerable thickness.

Sedimentation was followed by the pronounced tectonism and metamorphism associated with the Penokean orogeny. Emplacement, during the waning stages of this orogeny, of several small stocks of generally mafic to granodioritic composition was followed by the post-tectonic emplacement of several large plutons of generally granitic composition.

The Middle Precambrian geologic record outlined above has a strong family resemblance to the records of Phanerozoic geosynclines (Pettijohn, 1957, p. 640; Hoffman, 1973), and in fact the Middle Precambrian rock record in northern Michigan and Wisconsin has been interpreted in terms of plate tectonic processes of the Phanerozoic type--sedimentation on a continental borderland, and subsequent deformation of that borderland by compressional tectonic processes involving subduction of a fringing island-arc complex (Van Schmus, 1976). However no convincing evidence of a continental plate margin or of an island-arc complex has been recognized in east-central Minnesota. Paired miogeoclinal and eugeoclinal facies belts, typical of an island-arc or continental borderland environment, are absent. Instead, the sedimentary sequence, which was derived at least in part from pre-existing sialic rocks to both the north and the south, implies deposition in an intracontinental rift system.

The fact that the Middle Precambrian rocks in east-central Minnesota were deposited in a rift system does not necessarily mean that Phanerozoic-like tectonic processes were not operative in this area during Middle Precambrian time. Some Phanerozoic rift systems formed well away from plate margins as aulacogens, but the Middle Precambrian rocks in east-central Minnesota lack the longitudinal sediment-dispersal patterns and alkalic igneous rocks characteristic of this kind of rift system. Other Phanerozoic rift systems form during periods of continental extension like that proposed for the present Atlantic Ocean margins. Cambray (1977) has suggested that the Middle Precambrian rocks in northern Michigan were deposited in an intracontinental rift system. However, he went on to infer that continued extension led to the extensive development of new oceanic crust and that the Penokean orogeny reflected the ultimate closing of the basin by subduction of that crust between two colliding continental plates. However, evidence is absent in east-central Minnesota that would indicate a collision-type orogeny--large foreland-directed overthrusts and associated mélanges, and paired high-pressure/low-temperature and low-pressure/high-temperature metamorphic belts. On the contrary, the fact that the depositional basin and the Penokean orogeny are associated with an early fracture system implies that the boundary zone acted as the locus for limited intracontinental plate movement and for rising geothermal gradients with consequent high heat flow, regional metamorphism and abundant igneous activity. The evidence indicates that compression and metamorphism associated with the Penokean orogeny in east-central Minnesota were related to the vertical remobilization of underlying basement rocks, particularly along the boundary between contrasting kinds of Lower Precambrian basement rocks (Morey and Sims, 1976). Therefore I suggest that the Middle Precambrian rocks in east-central Minnesota were deposited along a mobile zone that has all the major components of an arrested rift system that did not reach the continental drift-ocean floor spreading stage.

During the Late Precambrian, plate tectonic processes in the Lake Superior region were clearly like those during Phanerozoic time, for the Keweenawan rocks form an intregal part of a very large rift system (King and Zietz, 1971) with many Phanerozoic attributes. The Keweenawan rocks in east-central Minnesota are part of a rift arm that extends for at least 1,600 km to central Kansas. A second arm of the rift system apparently extends southeastward from the east end of Lake Superior, beneath the Paleozoic strata of the Michigan basin, to at least the buried continuation of the Grenville Front (Hinze, 1963; O'Hara and Hinze, 1971). A possible third arm may extend northward into Canada from north of Isle Royale in Lake Superior to the general vicinity of Lake Nipigon. It is a half-grabenlike structure that may represent the failed arm of a "rrr" triple junction (Burke and Dewey, 1973) centered on Lake Superior (Kustra and others, 1977). The tectonic trends of the greenstone-granite and gneiss terranes, as well as the trend of the overlying Middle Precambrian stratified rocks, were fractured at oblique angles. Therefore the Keweenawan rift system presumably originated in response to tectonic processes unrelated to the fundamental attributes of either of the Lower Precambrian terranes.

CONCLUSIONS

The overall change in the character of the crust through Precambrian time was one of progressive stabilization and cratonization. Blocks or plates of continental material had formed in east-central Minnesota by the middle part of Early Precambrian time, but were probably too thin and too light to be subducted or systematically moved about by the motion of adjacent or underlying oceanic materials. During this period of higher heat production it seems likely that individual plates were jostled about in a more or less chaotic manner, producing internal zones of buckling and faulting. However toward the end of Early Precambrian time these continental plates became sufficiently large and stable to permit extensive rift systems to form in Middle Precambrian and younger times. The Keweenawan rift system is similar to those formed in Phanerozoic time, but many features of the Middle Precambrian rift system differ from those of younger counterparts in several important ways.

The important question remains as to whether the Middle Precambrian rocks were deformed in a mobile belt resulting from intracontinental stresses or in a suture marking two previously separated blocks. Until this question can be answered, concepts of Phanerozoic plate tectonics should be applied with caution in the search for mineral deposits in Middle Precambrian and older terranes.

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SOME STRUCTURAL ATTRIBUTES OF LOWER AND MIDDLE PRECAMBRIAN ROCKS, CARLTON AND PINE COUNTIES, MINNESOTA

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INTRODUCTION

The Precambrian rock record in east-central Minnesota is characterized by a variety of rock types which may be divided into three and possibly four depositional sequences (tbl.1). These depositional sequences were either terminated or shortly followed by distinct periods of tectonism and each lithotectonic assemblage is separated by a long period of erosion or non-deposition. Thus, the general tectonic framework of this area is typical of that of the Canadian Shield.

Tectonic processes leading to the formation of the Lower Precambrian rocks are poorly understood. The Lower Precambrian greenstone belt associations may have formed along the margin of a protocontinent composed of still older gneisses, (e.g. Morey and Sims, 1976) or in an intraplate rift environment formed within a gneissic craton (e.g. Goodwin, 1977).

In contrast, rocks formed during the middle part of Middle Precambrian time seem to record a transition from a cratonic regime characterized by relatively small, thin and internally unstable plates to one characterized by large, relatively thick and internally stable plates. Middle Precambrian assemblages have lithic and tectonic attributes characteristic of Phanerozoic intracontinental rifting, whereas Upper Precambrian rocks have attributes closely akin to those that characterize Phanerozoic plate tectonic processes.

The oldest rocks in Carlton and Pine Counties are assigned to the McGrath Gneiss, a quartzofeldspathic gneiss at least 2.7 b.y. (billion years) old (Stuckless and Goldich 1972). The McGrath locally contains inclusions of metsedimentary rocks metamorphosed to at least the amphibolite grade and is characterized by compositional layering that presumably formed during Archean time. The McGrath Gneiss appears to be part of an extensive gneissic terrane that probably extends as far west as the Minnesota River Valley in southwestern Minnesota and as far east as the Chippewa River valley in Wisconsin where it is locally referred to as the Chippewa Amphibolite Complex (Myers, 1974).

Exposures of the McGrath Gneiss near Denham in northwestern Pine County (fig. 1) lie close to the inferred northern boundary of the gneiss terrane of Morey and Sims (1976). Northward from Denham, the basement

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Table 1. Tectonic events and correlative sedimentary responses for Precambrian rocks of East-central Minnesota.

Age	Tectonic Event	Tectonic Response	Lithic Response
Late Precambrian	intraplate rifting	large rift system with half-graben basins, block faulting, minor metamorphism	mafic igneous rocks; fluvial-alluvial sedimentary rocks
Middle Precambrian	Penokean orogeny	deformation, metamorphism and igneous activity	
	intraplate rifting	moderately large intracontinental basin	miogeoclinal to eugeoclinal sedimentary rocks, minor volcanism
Lower Precambrian	Algoman orogeny	intense deformation, minor metamorphism and extensive igneous activity	
		greenstone belt association, mafic to felsic volcanic piles and flanking eugoclinal sedimentary rocks	
	?	intense deformation, and metamorphism, igneous activity	
	?	?	sedimentary rocks of graywacke affinity (?)

upon which the Middle Precambrian rocks were deposited does not crop out for 150 km where Middle Precambrian strata unconformably overlie greenschist-facies metamorphic rocks characteristic of Lower Precambrian granite-greenstone terrane along the north edge of the Mesabi range. The boundary between the two Lower Precambrian terranes (gneiss to the south, greenstone-granite to the north) is believed to be a fault-bounded zone some 40 km wide, extending northeastward from the northern end of the Minnesota River Valley near Ortonville eastward into Wisconsin passing south of Duluth a few kilometers (fig. 1).

In Minnesota, there is no definite evidence for Lower Precambrian volcanic and sedimentary rocks having been deposited on an older gneissic basement, and accordingly, the gneiss terrane and the greenstone-granite terrane appear to compose geographically separate and distinct crustal blocks.

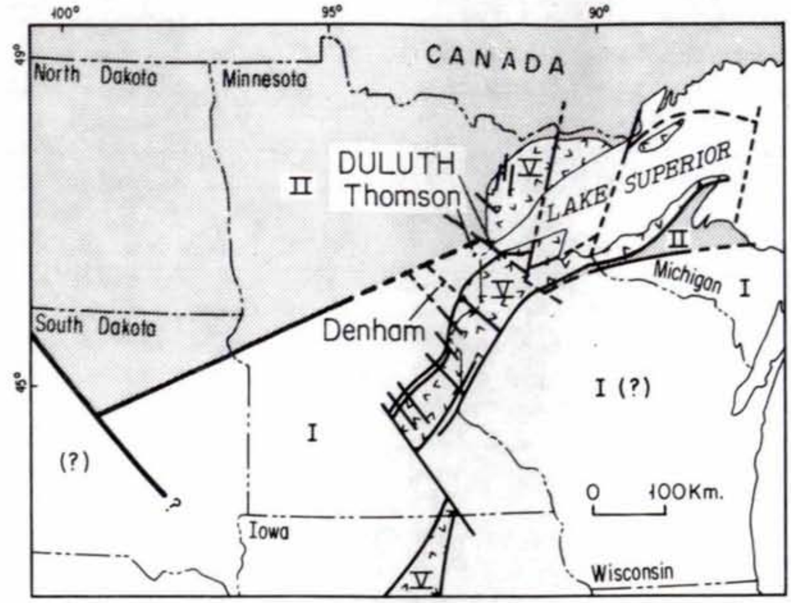


Figure 1. General nature of Lower Precambrian (basement) terranes, Minnesota, Wisconsin, Upper Michigan. After Morey and Sims (1976). Note that the gneiss terrane/greenstone-granite terrane boundary lies just north of Denham.

The Lower Precambrian rocks of east-central Minnesota are overlain unconformably by as much as several kilometers of Middle Precambrian rocks that were deposited at about 2.0 b.y. in an intracratonic basin centered over and approximately parallel to the boundary zone between the two Lower Precambrian terranes. The Middle Precambrian sequence has been divided into two groups, the Mille Lacs Group (see Morey, this guidebook) and the well-known Animikie Group. Although the pre-Animikie Mille Lacs Group generally resembles the Chocolay Group of the Marquette Range Supergroup in Michigan, the possibility exists that it may be Huronian in age, a fact which has potential economic importance, considering the comparable age of the Elliott Lake placer uranium deposits. The contact betwen the McGrath Gneiss and the Mille Lacs Group is not exposed but appears to be unconformable and possibly faulted. Similarly, direct evidence regarding the contact between the Mille Lacs and Animikie strata is lacking. However, an unconformity is assumed mainly because the Animikie Group rests on Lower Precambrian rocks in northern Minnesota, whereas it overlies Mille Lacs Group rocks in east-central Minnesota. However, this unconformity does not appear to represent a major tectonic event, for the strata above and below it are sedimentologically similar.

The general nature of the Middle Precambrian strata suggests that deposition started in a relatively small basin under miogeoclinal conditions, passed through a shelf phase characterized by iron-formation deposition, and ended with turbidite deposition under eugeoclinal conditions in a much enlarged basin (see Morey, this guidebook).

Sedimentation was either terminated or shortly followed by the Penokean orogeny of Goldich and others (1961) at about 1.9 b.y. to 1.8 b.y. ago (Van Schmus and others, 1975). Intrusive granitic rocks in the southern part of east-central Minnesota are a direct manifestation of this orogenic event, as are a wide variety of orogenically related structures (Hall, 1901; Schwartz, 1942b) in the Middle Precambrian strata exposed from Denham northward toward Duluth. Included among these features are distinct changes in metamorphic grade as well as a variety of folds, faults and other minor structures, together with cataclastic textures and structures in the McGrath Gneiss, all of which are described below.

A major hiatus of some 700 million years separates events associated with the Penokean orogeny from deposition of Keweenawan rocks at about 1.1 b.y. ago in Late Precambrian time. Keweenawan history started with the deposition of quartz-rich strata of the Nopeming Sandstone (Mattis, 1972) which was followed shortly by a major period of igneous activity. Clearly, the truncation of near-vertical beds of Thomson Formation by sub-horizontal beds of sandstone and lava of Keweenawan age represents a major unconformity.

Keweenawan igneous activity was confined to an elongate belt that forms one arm of the so-called Midcontinent Rift system, a possible rrr-type rift centered on Western Lake Superior. Igneous activity was characterized by subaerial volcanism leading to the formation of the North Shore and Chengwatana Volcanic Groups (Green, 1972; Morey and Mudrey, 1972) and by mafic plutonism, the principal manifestation of which is the Duluth Complex (Weiblen and Morey, 1975). During the latter part of late Keweenawan time volcanism gave way to the deposition of several red-bed units which occur both in fault-bounded grabens along the axis of the rift and in half-graben basins along the flanks of the rift. The red beds, including the Fond du Lac and Hinckley formations of east-central Minnesota, are spatially separated from the axial part of the rift by high-angle faults such as the Douglas and Pine faults.

East-central Minnesota appears to have been geologically inactive during much of Paleozoic and Mesozoic time except for scattered deposits of Cambrian and Cretaceous strata. The former dip gently to the southeast and form the west edge of the Hollandale embayment (Austin, 1972), an early Paleozoic depo-basin centered over southeastern Minnesota. The Cretaceous strata are thin and patchy, and represent remnants of non-marine and marine strata that were deposited in an epicontinental sea that transgressed Minnesota from the west.

All of the bedrock is covered by accumulations of glacial drift which vary considerably in thickness and which were either deposited from several ice lobes or deposited as lake sediments in Glacial Lake Duluth (Zarth, 1977; Moss, 1977). The extent of glacial scouring is not well known, but it probably involved the removal of only a few tens of meters of rock. Recent drainageways such as the Cloquet, St. Louis, and Kettle Rivers afford most of the bedrock exposures in the area.

METAMORPHIC AND STRUCTURAL FEATURES ASSOCIATED WITH THE PENOKEAN OROGENY

Although a number of orogenic episodes have been recognized in east-central Minnesota, the Penokean orogeny (1.9-1.8 b.y.) was so pervasive that it affected the McGrath Gneiss as well as overlying Middle

Precambrian strata. In particular the Middle Precambrian rocks are complexly folded into several large anticlines and synclines having numerous second- and third-order folds on their limbs. The style of deformation changes from open folds with near-vertical axial planes to the north to isoclinally overturned folds that dip as much as 60° SE. to the south.

There also is a progressive increase in the metamorphic grade in the Middle Precambrian rocks southward from the village of Thomson, where chlorite-grade rocks are common, to south of Denham, where amphibolite-grade rocks prevail (Hall 1901; Schwartz, 1942a,b; Weiblen, 1964; Morey, this guidebook). On a regional scale the areas of most intense metamorphism coincide with the areas of most intense deformation, and various metamorphic isograds involving biotite, garnet and staurolite conform in a general way to the fold geometry and define a metamorphic high along the northern edge of the McGrath Gneiss.

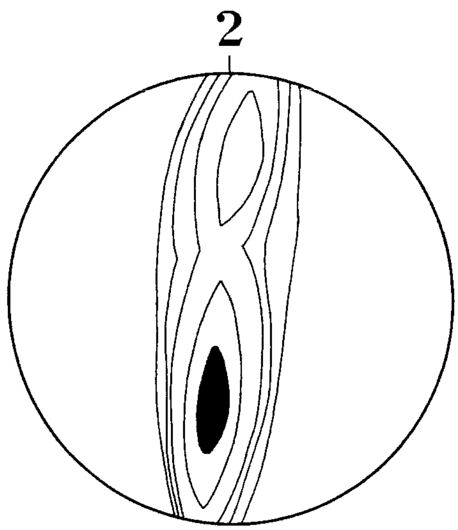
Structural Elements In The McGrath Gneiss

Penetrative planar structures in the McGrath Gneiss include gneissic layering, presumably primary, and a cataclastic foliation. Both of these structures trend in an easterly direction and have variable, although generally steep dips (fig.2).

Compositional layers in the gneiss range in thickness from 0.1 to 5.0 cm and are defined by intercalated units rich in quartz and feldspar and rich in biotite and hornblende. In general, the nature and attitude of the layering define a series of open folds, with upright hinge surfaces, near-vertical axial planes and shallowly plunging axes. All of these data are highly suggestive of similar deformational features observed in the Minnesota River Valley and along the Chippewa River valley in Wisconsin (Meyers, 1974). Cataclastic zones are ubiquitous throughout the McGrath Gneiss, but are particularly abundant near inferred contacts with overlying Middle Precambrian strata such as along the railroad tracks west of Denham where they obscure the gneissic layering. Within the cataclastic zones, mechanical deformation has produced features such as recrystallized quartz aggregates, porphyroblastic feldspar augen and a mortar texture in the groundmass which is typical of cataclastic zones. Low-temperature recrystallization also led to the formation of appreciable quantities of secondary hornblende, biotite and K-feldspar.

Lineations are locally well developed in the McGrath Gneiss and result from the alignment of hornblende grains, elongate biotite flakes, and the long dimension of feldspar crystals and boudins, all of which lie within cataclastic zones. These linear features (fig. 3) plunge consistently to the east (70°-100°) at a shallow angle (5°-13°).

Joints are the only major nonpenetrative structures observed in the McGrath Gneiss. No systematic examination of these brittle structures has been undertaken.



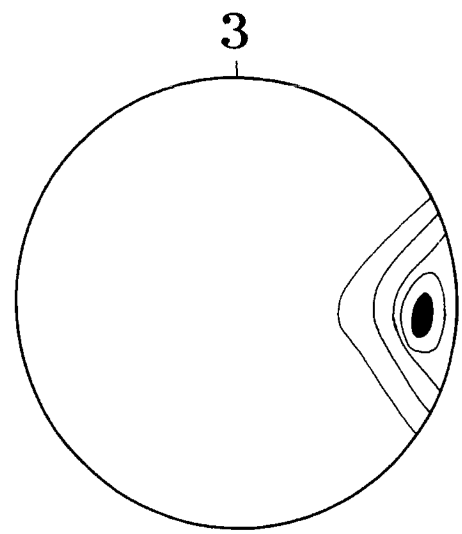


Figure 2. Poles to foliation, McGrath Gneiss, east-central Minnesota. Contours represent 2, 4, 6, 8, 10% of data.

Figure 3. Equal area projection of lineations, McGrath Gneiss, east-central Minnesota. Contours represent 2, 4, 6, 8, 10% of data.

Structural Elements In The Middle Precambrian Rocks

Structures within Mille Lacs Group rocks that immediately overlie the McGrath Gneiss appear to be concordant with structure trends both in the gneiss and in younger rocks of the Thomson Formation exposed a short distance to the north. Thus, all of the Middle Precambrian rocks are considered here as a single structural entity.

Penetrative structures abound within units of Middle Precambrian age in east-central Minnesota. They include folds within all the units, foliation, lineation, schistosity, and mineral alignment, together with gneissic layering and slaty cleavage which are present depending on the lithology and metamorphic grade.

Although beds in the Mille Lacs Group rocks exposed southeast of Denham strike to the east and display variable dips to the north, their fold geometry is not well known (fig. 4). However the presence of numerous linear elements plunging moderately to the east suggests that these beds have east-trending hinge surfaces. By contrast, folding on a variety of scales is seen in the Thomson Formation (fig. 5). Well-developed fold patterns are particularly well exposed in the greenschist-grade rocks near Thomson and Carlton. These folds display upright, rounded hinge surfaces which trend in an easterly direction. The folds have amplitudes on the order of 50-1,000 m and wave lengths of as much as 2,000 m, and are open and asymmetric. Most folds may be classified as a "Type-2 fold" or a "parallel fold" according to the scheme of either Hudleston (1973) or Ramsay (1967). Additionally they appear to be conical (noncylindrical) as their hinge surfaces dissipate over distances of 10-1,000 m. Minor folds have geometries similar to those of the major folds although they tend to be more asymmetric. Fold axes for both major and minor folds plunge both to the east and to the west at angles generally less than 20 degrees (fig. 6).

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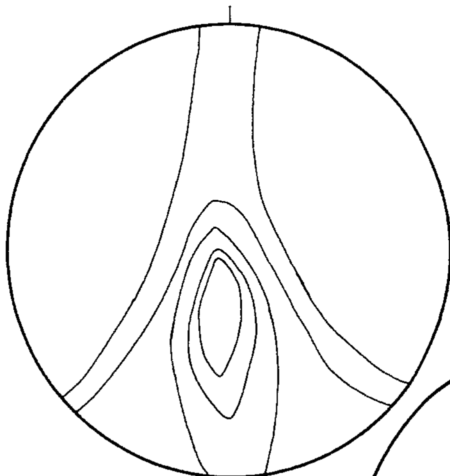

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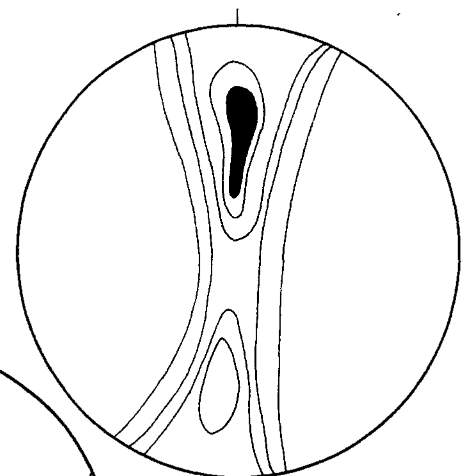

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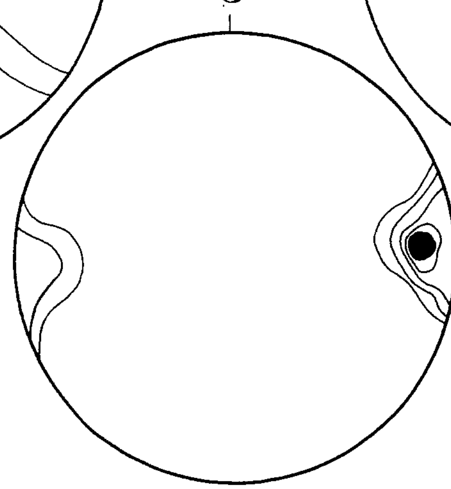

Figure 4. Equal area projection, poles to bedding, Denham Formation, southeast of Denham, Minnesota.

Figure 5. Equal area projection of poles to bedding, Thomson Formation, Minnesota (Thomson to Denham). Contours are at 2, 4, 6, 8, 10% of data.

Figure 6. Equal area projection of cleavage-bedding lineations (fold axes), Thomson Formation, Cloquet-Carlton, Minnesota.

The geometry of the fold structures in the Thomson Formation does not change appreciably to the south despite an increase in metamorphic grade in that direction (Keighin and others, 1972, p. 248).

Several types of foliation are developed within the Middle Precambrian rocks in Carlton and Pine Counties. Slaty cleavage is best developed from near Thomson to Mahtowa where it strikes nearly east, close to the trend of the bedding, and displays a near-vertical dip (fig. 7). Where developed in graywacke units, the cleavage is refracted by as much as 40° from attitudes in adjacent slaty units (fig. 8).

Schistosity is developed extensively within units of the Thomson Formation from Mahtowa southward. At Mahtowa the units are vaguely phyllitic, whereas at Moose Lake they are very definitely schistose with two well-developed cleavage directions (fig. 9). Gneissic layers as much as a meter thick are present northeast of Denham.

Various kinds of linear features are widely developed in the Thomson Formation. In the Carlton-Thomson area, lineations defined by bedding-cleavage intersections persistently plunge to the east at shallow angles (fig. 6). Lineations defined by elongate mineral grains and boudin-like structures increase in abundance southward from Mahtowa. They also plunge to the east, but the angle of plunge is steeper than that farther north.

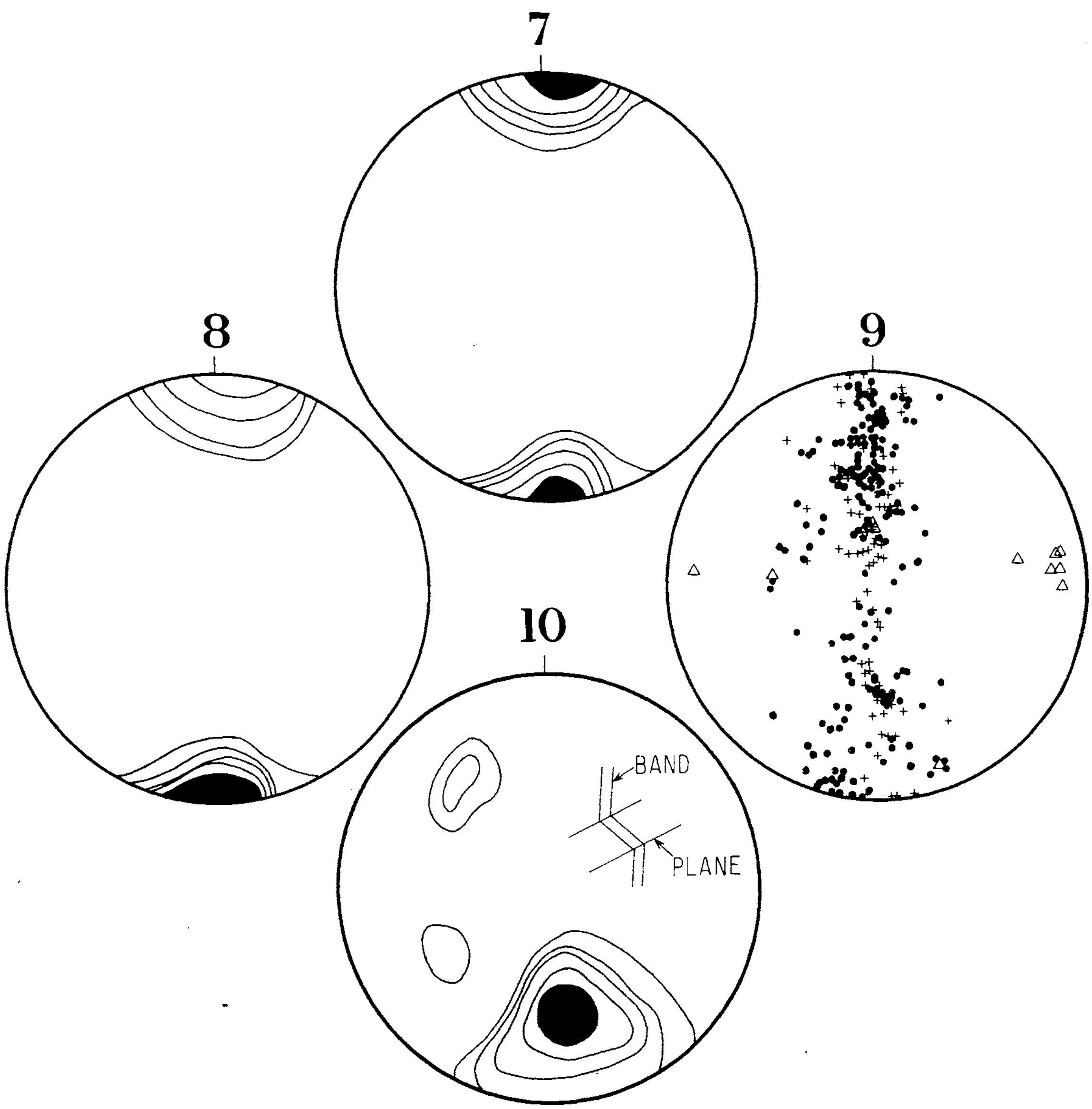

Figure 7. Equal area projection, poles to slaty cleavage in slate units, Thomson Formation, Thomson, Minnesota.

Figure 8. Equal area projection, poles to slaty cleavage in graywacke units, Thomson Formation, Thomson, Minnesota.

Figure 9. Equal area projection, poles to foliation, Thomson Formation, Barnum to Denham, Minnesota.

Figure 10. Equal area projection, poles to kink bands, Thomson Formation, Carlton, Minnesota. Contours at 2, 4, 6, 8, 10% of data.

Nonpenetrative structures developed in the Middle Precambrian strata of east-central Minneosta include faults, spaced cleavage and joints. Although not common, both normal and reverse faults are present in the Thomson Formation and particularly in the Carlton-Thomson area. The normal faults commonly strike N. 30° E., are nearly vertical and have dip-slip displacements. Some of the small faults are simple planar features with displacements of only a few meters, whereas others have extensively developed breccia zones, possibly implying large displacements. Reverse faults strike approximately east and dip southward at angles of 20° to 40°; displacements on these faults generally do not exceed 3 to 6 m. The reverse faults probably formed due to regional stress at the time of folding; the normal faults clearly postdate the time of folding and cleavage, but they formed before the development of kink bands.

Spaced cleavages and joints are common in many parts of the Thomson Formation. Where analyzed in the Carlton-Cloquet area, spaced cleavage is developed in the more competent graywacke beds and is consistent with slaty cleavage trends. In contrast, four distinct joint trends have been noted (Wright and others, 1970); N. 30° W., N. 30° E., N. 20° E., and N. 80° E. The first two trends are interpreted by Wright and others (1970), to be related to regional stresses present at the time of folding.

Kink bands in slaty cleavage have been observed in the Thomson Formation near Carlton. Two trends exist: those where the bands trend N. 85° W. 70° N. with shallow-dipping planes close to cleavage, and a second set where the bands trend N. 60° E. 66° S. with near-vertical planes (fig. 10). The latter set appears to be the younger. The presence of two sets of kink bands implies that some reorientation of the stress field occurred after the time of folding.

MINERAL RESOURCES

Although the Thomson Formation was quarried for roofing slate and explored for gold in the late 1800's or early 1900's, most of the recent exploration activity has focused on the possible presence of uranium deposits and to a lesser extent on the potential for base-metal sulfide deposits.

Exploration for base-metal sulfide deposits of the volcanogenic-exhalative type (Hutchinson and others, 1971) has been carried out within Lower Precambrian greenstone belts in western and northern Minnesota. Additionally the presence of "greenstone units" in the Middle Precambrian sequence of east-central Minnesota is significant in that apparently similar rocks of approximately the same age contain a number of base-metal sulfide deposits of appreciable size (Schmidt and others, 1978). Although extensive quantities of felsic and intermediate volcanogenic rocks (fig. 11) have not been recognized to date, many of the necessary lithic components are present, and therefore this terrane or its extension to the west may be a possible source area for base-metal sulfides.

The past several years have seen a considerable amount of exploration for uranium in east-central Minnesota, and particularly in Carlton and Pine counties. Several areas have been recognized as having anomalously high radioactivity levels (Ojakangas, 1976). One area is associated with a basal unconformity that separates Mille Lacs Group strata from underlying Lower Precambrian gneiss, whereas other favorable areas are associated with an exhumed unconformity that separates the Thomson Formation from overlying Upper Precambrian rocks of the Fond du Lac Formation. Thus two idealized "type" or "model" uranium deposits can be utilized in exploration for uranium in east-central Minnesota. The first type is the lower Proterozoic (i.e. early Middle Precambrian) "detrital-placer" (or Elliott Lake-Rand) model and the second is the "Proterozoic unconformity" or "vein-breccia" model (Kalliokoski and others, 1978).

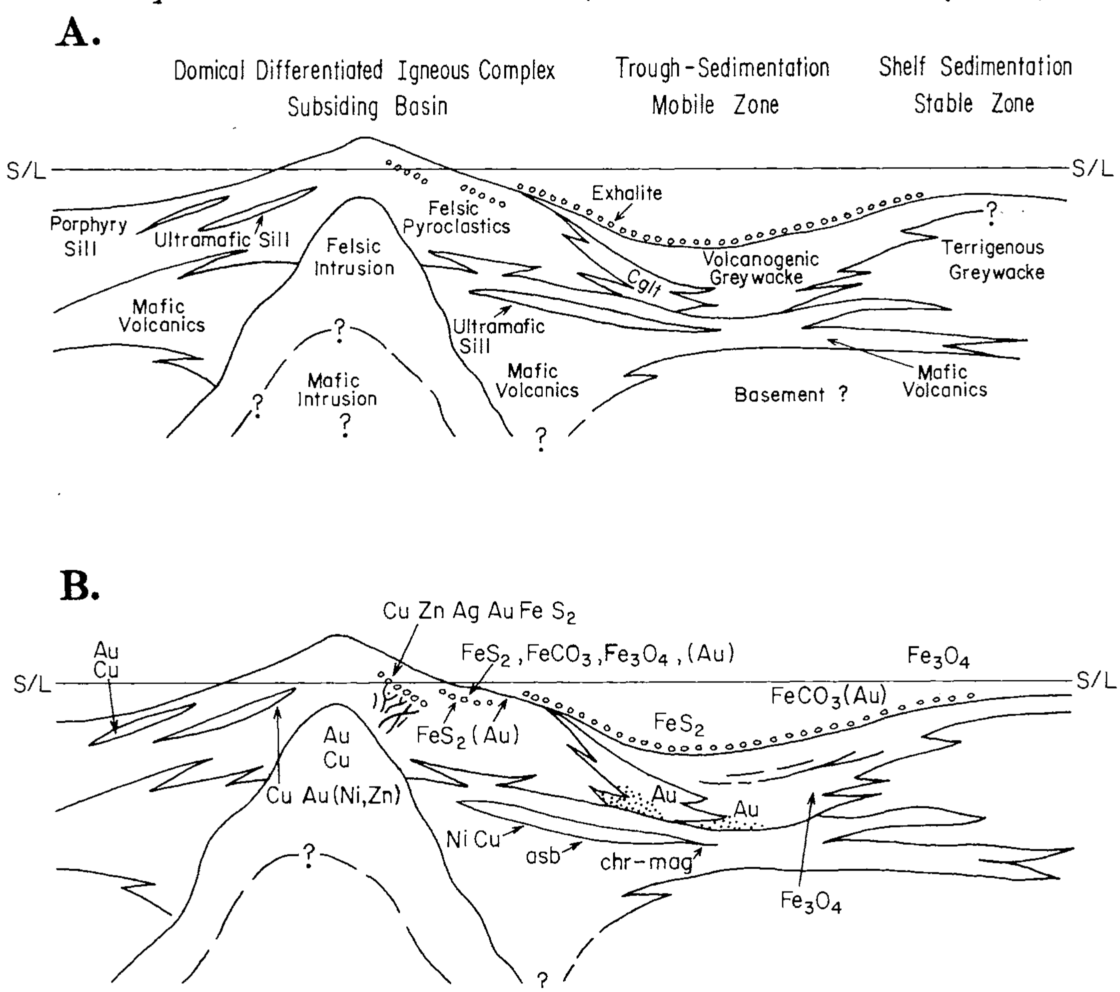

Figure 11. Archean (Lower Precambrian) volcano-plutonic (greenstone) tectonics (A) and metallogeny (B). After Hutchinson and others (1971). Horizontal section 75 km, vertical section 15 km.

In the first model, uranium is assumed to occur as an oxide phase which was concentrated through erosive processes as cobbles or pebbles within early Proterozoic (Huronian) strata. Generally these deposits occur in the basal part of a sequence that may involve several thousand meters of strata such as in the Witwatersrand district of South Africa (Pretorius, 1975). In essence, these placer deposits appear to be the end product of a rather specific sedimentological regime characterized by anoxygenic conditions. Although the importance of an anoxgenic atmosphere to the concentration of detrital uraninite is controversial, the deposits appear to be restricted to the early part of Proterozoic time. Undoubtedly exploration for this type of deposit would be accelerated, should the Mille Lacs Group prove to be equivalent to the Huronian Supergroup in age.

The second type of deposit, the vein-breccia type, occurs in or near breccia zones within fractured, carbon-rich basement rocks near unconformities with overlying unmetamorphosed fluvial strata of Proterozoic age (Deery, 1973). Examples of this class of deposit are world renowned and include those in western Saskatchewan (Rabbit Lake, Key Lake, Cluff Lake and Beaver Lodge) and in the Northern Territory of Australia (Rum Jungle, Pine Creek, Alligator River). These deposits consist dominantly of pitchblende; they exhibit a fair degree of structural control along fault zones and extensive evidence of wallrock alteration (fig. 12).

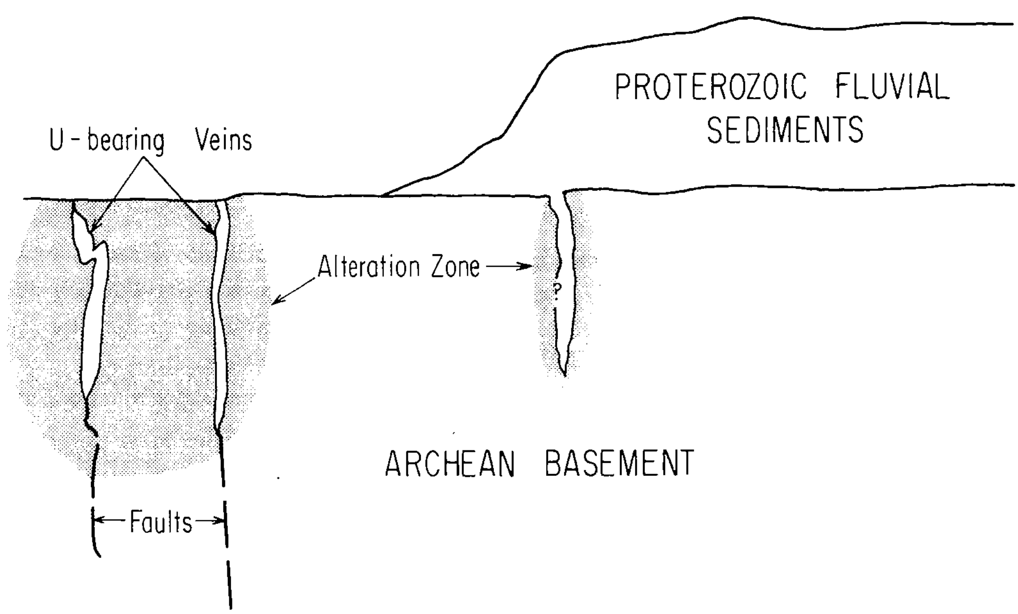

Figure 12. Idealized representation of the occurrences of "Proterozoic-unconformity" type uranium deposits.

The origin of this class of deposit is somewhat controversial. Some have been interpreted as being of primary, epigenetic, "hydrothermal" origin (Deery, 1973) whereas other deposits are interpreted as being syngenetic in origin. The latter deposits are explained by the <u>in situ</u> leaching of uranium by oxidizing solutions in porous, fluvially derived cover rocks (Proterozoic). Uranium is ultimately precipitated along fractures in basement rocks where reducing conditions are prevalent (Kalliokoski and others, 1978).

The possibility that such deposits might occur in Carlton and Pine Counties is intriguing, for here metamorphosed and fractured carbonaceous basement rocks of Middle Precambrian age are overlain unconformably by unmetamorphosed fluvial strata of Late Precambrian age. Although no deposits of commercial size have been discovered as yet, exploration continues in this area at a fairly rapid pace.

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