FIELD TRIP GUIDEBOOK FOR THE PRECAMBRIAN GEOLOGY OF EAST-CENTRAL MINNESOTA

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Matt Walton, Director

FIELD TRIP GUIDEBOOK FOR

THE PRECAMBRIAN GEOLOGY

OF EAST-CENTRAL MINNESOTA

By

G. B. Morey

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INTRODUCTION

The bedrock geology of east-central Minnesota -- generally bounded by latitudes 45 °N. to 47° N. and longitudes 92° 15' W. to 95° W. -- is particularly interesting because the area contains a wide variety of igneous, metamorphic, and sedimentary rocks which span the entire range of Precambrian time. Unfortunately much of the bedrock is not well exposed. Those rock units that do crop out tend to occur as clusters 2 or 3 acres large or as strings 1 or 2 kilometers long; and these outcrop areas are widely separated by vast expanses of Pleistocene and Holocene materials as much as 140 thick. Therefore aeromagnetic and gravity data, and to a lesser extent, water-well and exploration records acquired over the years by the Minnesota and U.S. Geological Surveys were used to prepare a preliminary and somewhat generalized bedrock geologic map of east-central Minnesota at a scale of 1:500,000 (Morey, 1978).

Because considerable extrapolation was required to give continuity to the many rock units in the area, the map itself is somewhat subjective. However the stratigraphic interpretations on the map are based on conclusions derived in large part from on-the-ground observations. Therefore this field guide was prepared so that interested individuals can see the rocks in a systematic manner and in so doing gain a better understanding of the geologic complexities and problems that are inherent to the area.

Because the stops on this field trip are scattered over a fairly large area (fig. 1), it would take four or possibly five days to adequately cover the entire route of the road log. Therefore the road log that follows is subdivided into nine segments so that the users of this guide can choose aspects of the geology that interest them. Lastly it should be emphasized that this guidebook is intended to be used in conjunction with Minnesota Geological Survey Report of Investigations 21, entitled Lower and Middle Precambrian Stratigraphic Nomenclature for East-central Minnesota (Morey, 1978) and Minnesota Geological Survey Regional Map R-1, Bedrock Geologic Map of East-central Minnesota (Morey, in prep).

REGIONAL GEOLOGIC RELATIONSHIPS

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.

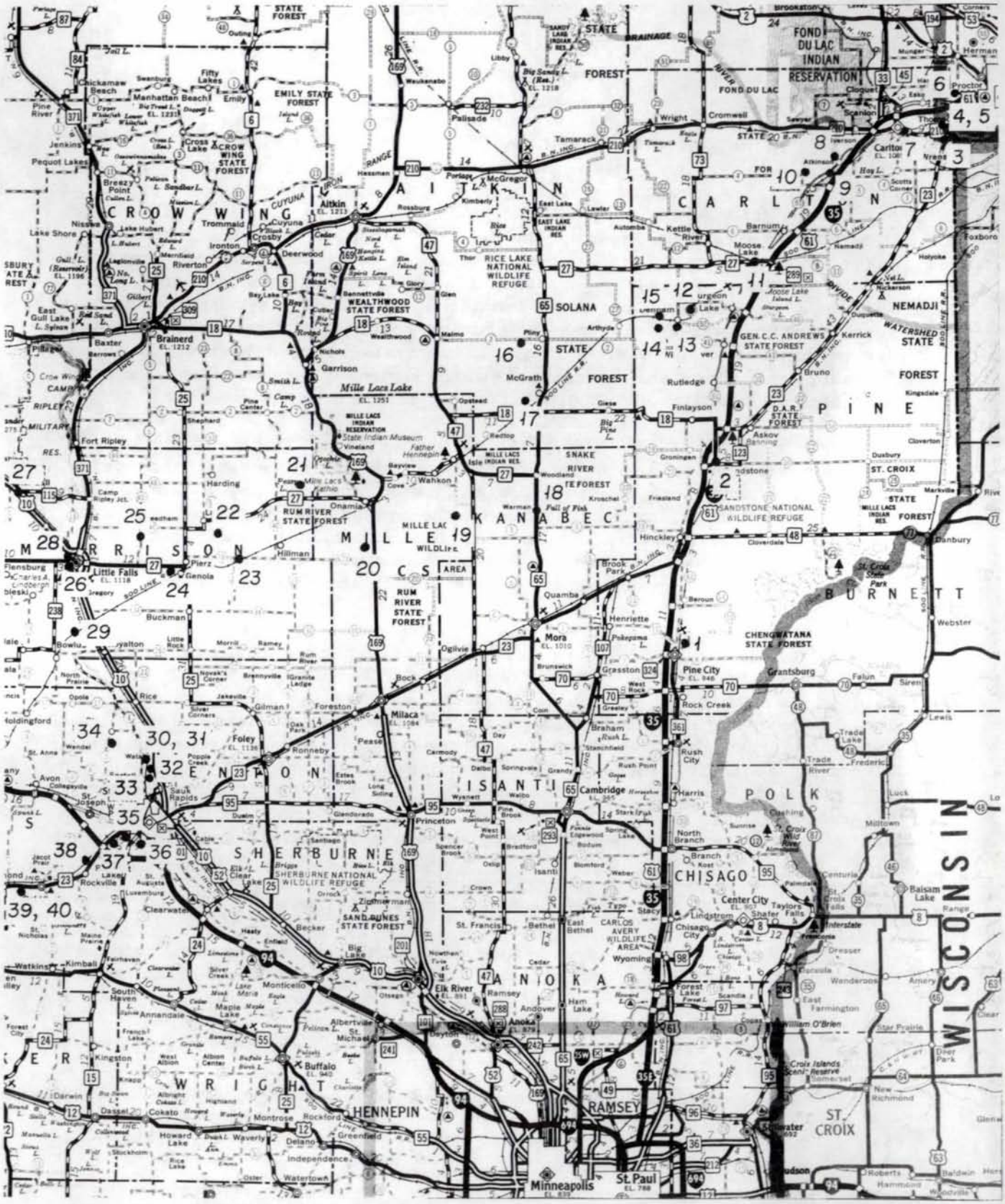

Figure 1--Highway map of east-central Minnesota showing approximate locations of stops described in text

Table 1 -- Generalized stratigraphic succession of Precambrian rocks in east-central Minnesota

LAYERED ROCKS	INTRUSIVE AND METAMORPHIC ROCKS
Hinckley Sandstone (Stop 2)	
Fond du Lac Formation (Stops 3-5)	
-----unconformity-------	
Chengwatana Volcanic Group (Stop 1)	
(in Carlton and Pine Counties)	
-----unconformity (?)------	Duluth Complex*
North Shore Volcanic Group (west of Duluth)	
Ely's Peak basalts (Stop 6)	
Nopeming Sandstone (Stop 6)	
(?) -----major unconformity---	
Unnamed rhyolite †	
(1,800 m.y.) -----major unconformity----	
	Stearns Granitic Complex
	St. Cloud Granite
	(Stops 31, 32, 35, 37)
	Rockville Granite (Stop 38)
	Warman Granite (Stop 18)
	Pierz Granite (Stop 24)
	Isle Granite (Stop 19)
	Reformatory Granite (Stops 35, 36)
	Freedhem Granodiorite (Stop 25)
	Bradbury Creek Granodiorite (Stop 20)
	Unnamed gabbro and diorite (Stop 28)
Animikie Group	
Thomson Formation (Stops 7-12)	
Rabbit Lake and Virginia Formations †	
Trommald and Biwabik Formations †	
Mahnomen and Pokegama Formations †	
-----unconformity-------	
Mille Lacs Group	
Trout Lake Formation †	
Little Falls Formation (Stops 26, 29)	
Randall Formation (Stop 27)	
Glen Township Formation †	
Denham Formation (Stop 13)	
(2,500 m.y.) --major unconformity------	Hillman Migmatite (Stops 21-23)
	Unnamed granites including "granite near Staples" *
Unnamed metabasalt, graywacke and associated volcanogenic rocks †	
(ca 3,000 m.y.)--major unconformity-----	
	McGrath Gneiss (Stops 14-17)
	Sauk Rapids Metamorphic Complex
	St. Wendel Metagabbro (Stop 34)
	Watab Amphibolite (Stops 30-31)
	Sartell Gneiss (Stop 33-34)
	Richmond Gneiss (Stops 39-40)

* Not visited on field trip.
† Not exposed in east-central Minnesota.

Lower Precambrian Rocks

Lower Precambrian (tbl. 1) 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. The southernmost segment consists of highly deformed and metamorphosed gneisses, like those exposed in the Minnesota River Valley of southwestern Minnesota. The northernmost segment consists dominantly of granite and lesser amounts of metasedimentary and metavolcanic rocks that collectively form a greenstone-granite terrane like that exposed in the Vermilion and Rainy Lake districts of northern Minnesota. 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, or they may be reactivated and cataclasized equivalents of less severely deformed rocks of the gneiss terrane. Regardless of their original age and present character, the "schistose" rocks form part of a discrete zone that separates two considerably different Lower Precambrian terranes.

Exposures of the gneiss terrane are confined mostly to the valleys of the Mississippi and Sauk Rivers where two new lithostratigraphic units--the Richmond Gneiss and the Sauk Rapids Metamorphic Complex--have been recognized. Contact relationships between these two units are not exposed. 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 that consists essentially of K-feldspar, plagioclase, quartz, hypersthene, hornblende, and minor amounts of biotite. In contrast the Sartell Gneiss is a light pinkish-gray, medium-grained, equigranular rock that consists dominantly of biotite, quartz, plagioclase and microcline, and contains layers, lenses and pods of fine-grained, equigranular biotite gneiss having minor to locally abundant garnet and cordierite. Both the Watab Amphibolite and St. Wendel Metagabbro are dark-colored, coarse-grained, mafic enclaves; the former contains plagioclase, clinopyroxene, hornblende and biotite, and the latter contains plagioclase and pyroxene.

Biotite-bearing quartzofeldspathic gneiss assignable to the gneiss terrane is also exposed to the east of Mille Lacs Lake 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) 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 porphyroblasts. 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 (tbl. 1) 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 are divided into two groups possibly separated by an unconformity. Each group is estimated to have a maximum thickness of approximately 1 kilometer in the area north and east of Mille Lacs Lake. 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, whereas the younger sequence is correlative with the well known Animikie Group of northern Minnesota and Ontario.

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 occur near the base of the group, and 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 Mille Lacs Group, but are particularly abundant in the upper part where they compose the Trout Lake Formation.

A low-angle unconformity presumably separates rocks of the Mille Lacs Group from those of the overlying Animikie Group. The basal part of the Animikie Group is assigned to the Mahnomen Formation and consists domi-

nantly 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 the Trommald Formation, which in turn is overlain gradationally by various kinds of clastic rocks assigned to the Rabbit Lake Formation. The Rabbit Lake Formation has been divided 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 Member); 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 data are lacking, it is inferred that the Rabbit Lake Formation passes transitionally upward into the Thomson Formation. 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. 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 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. The style of deformation changes from open folds with 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. However, argillaceous rocks overlying schistose basement rocks have a slaty cleavage 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 kilometers 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 kilometers 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 kilometers 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 kilometers 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.

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 indicates 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 for many batholithic terranes. Small dikes, sills, and stocks of gabbroic to dioritic composition are

inferred to be the oldest Middle Precambrian plutonic rocks in east-central Minnesota (tbl. 1). Most of these bodies are too small to map at a scale of 1:250,000 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. 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 was clearly emplaced before the Middle Precambrian stratified rocks were deposited. It may have formed either in the early part of Middle Precambrian time or during Early Precambrian time.

Upper Precambrian Stratified Rocks

Except for several scattered occurrences of rhyolite in the subsurface, all of the Upper Precambrian stratified rocks in east-central Minnesota comprise part of the classical Keweenawan System, Series or Supergroup of the Lake Superior region. In east-central Minnesota, the oldest Keweenawan rocks are assigned to the Nopeming Sandstone (tbl. 1). 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. 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. Although the Ely's Peak basalts crop out only in a small area just west of Duluth, aeromagnetic and seismic data indicate that they extend in the subsurface of east-central Minnesota as far south as lat 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. In Carlton and Pine Counties, these rocks are in contact along the Douglas fault with normally polarized subaerial lava flows assigned to the Chengwatana Volcanic Group. 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. 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. 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. 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.

ROAD LOG

LEG 1 -- PINE CITY TO FOND DU LAC

Leg 1 of the road log starts near Pine City, Minnesota and ends at the Minnesota-Wisconsin border along the St. Louis River near Fond du Lac, the westernmost suburb of Duluth, Minnesota.

Mileage

0.0 [0.0] Junction of U.S. Interstate Highway 35 and Minnesota Highway 70; follow Highway 70 east toward Pine City.

0.7 [0.7] Junction; turn right (south) and go two blocks; turn left (east) 1.5 blocks; cross the Burlington Northern railroad tracks; continue straight ahead 1/2 block.

0.2 [0.9] Junction; turn right (south) and follow Pine County Highway 9 around the south end of Cross Lake. This long, narrow lake trends in a north-northeast direction and is centered on the trace of the Douglas fault. Rocks to the east of the fault are dominantly volcanic in origin and are assigned to the Chengwatana Volcanic Group of Middle Keweenawan age, whereas those to the west are assigned to the Hinckley Sandstone of Late Keweenawan age.

2.5 [3.4] Bridge over Snake River; park on north (far) side of river and walk east to base of dam.

STOP 1. Volcanic rocks exposed here are the type locality of the Chengwatana Volcanic Group of Upper Precambrian (Middle Keweenawan) age. A number of flow units can be seen here and for about 3 miles downstream. Each flow unit is characterized by a regular sequence of textures--a basal aphanitic unit that passes transitionally upward into an ophitic (mottled) diabasic or porphyritic unit, which in turn is overlain by an uppermost vesicular unit that contains variable amounts of secondary minerals.

At several places the vesicular crust is brecciated and it now consists of rubbly or fragmental material in which both vesicles within fragments and interstices between fragments are filled with secondary minerals. Secondary minerals include epidote, chlorite, quartz, and lesser amounts of calcite and laumontite.

Return over same route to U.S. Interstate Highway 35.

3.4 [6.8] Junction; turn right (north) and follow Highway 35 north toward Duluth.

23.0 [29.8] Junction of U.S Interstate Highway 35 and Minnesota Highway 123; follow Highway 123 east to Sandstone.

0.4 [30.2] Junction; turn right (east) and follow Minnesota Highway 123 into Sandstone.

1.0 [31.2] Junction; turn right (east) and follow Minnesota Highways 123 and 30 (toward Duxbury).

0.4 [31.6] Junction; turn left (north) into Sandstone city park.

STOP 2. Exposures in this abandoned quarry are typical of the Hinckley Sandstone (Upper Precambrian; Upper Keweenawan) in east-central Minnesota. The Hinckley is generally buff colored and beds range in thickness from a few centimeters to several meters. Large-scale cross-bedding is common and current ripple marks are present locally. Much of the sandstone is medium to coarse grained. The grains are generally moderately to well rounded; sorting varies from poor to moderate. The rock is weakly to strongly cemented by silica and by iron oxides which were deposited both before and after deposition of the silica cement. The average framwork grain composition is about 96 percent quartz, 2 percent feldspar, and 2 percent felsic volcanic rock fragments, metamorphic rock fragments and chert.

The Hinckley Sandstone was probably deposited in a stable, shallow-water lacustrine environment.

Continue straight ahead (east) on Minnesota Highways 123 and 30.

0.2 [31.8] Bridge over Kettle River; continue straight ahead.

2.5 [34.3] Junction; turn left (north) and follow Highway 123.

4.0 [38.3] Junction; turn right (east) and follow Minnesota Highway 23 to Askov.

1.0 [39.3] Village of Askov; continue on Highway 23.

42.9 [82.2] Narrow gravel road on left (to the north) leads to Stop 3 (Leg 2).

0.1 [82.3] Bridge over St. Louis River; Minnesota-Wisconsin border; end of Leg 1.

LEG 2 -- FOND DU LAC TO THOMSON

Leg 2 of the road log proceeds southwest from the Minnesota-Wisconsin border along the St. Louis River near Fond du Lac, the westernmost suburb of Duluth, Minnesota, and ends near Thomson in Carlton County.

Mileage

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

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

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 3. Exposures at this locality are typical of the Fond du Lac Formation (Upper Precambrian; Upper Keweenawan) 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. Sandstone beds are generally lenticular in shape and 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 to Highway 23.

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 Junction; turn left (north) and follow Minnesota Highway 210

[1.6] toward 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 Little River with a small pond on right (north) side of road; park nearby and follow the river to the north. Stop 4 can can be reached only by walking approximately 0.4 mile along the creek bed; Stop 5 is midway between the road and Stop 4.

STOP 4. 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 18 meters thick and consists dominantly of pebbles and cobbles as much as 15 centimeters 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 the sulfides have been altered to limonite.

The conglomerate grades upward through a stratigraphic interval of approximately 1 meter into arkosic sandstone like that seen at Stop 3. 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 toward the highway.

STOP 5. 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 along Little River to the highway.

Minnesota Highway 210; continue west toward Thomson and Carlton.

4.4 [8.3] Village of Thomson, Minnesota; junction with Carlton County Highway 1; end of Leg 2.

LEG 3 -- THOMSON TO ELDES CORNER AND RETURN

Leg 3 of the field trip starts at the village of Thomson in Carlton County, visits Stop 6 near Eldes Corner in St. Louis County, and returns to Thomson.

0.0 [0.0] Junction; turn right (east) and follow Carlton County Highway 1 through Thomson.

0.6 [0.6] Sharp turn to the left (north); follow Highway 1 toward Esko.

2.7 [3.3] Junction; turn right (east) and follow U.S. Interstate Highway 35 toward Duluth.

3.1 [6.4] Carlton County-St. Louis County border; continue straight ahead on Highway 35.

0.8 [7.2] Follow right-hand exit to Midway Road.

0.2 [7.4] Junction; turn left (north) and follow Midway Road toward Eldes Corner.

0.2 [7.6] Eldes Corner on left (west); continue straight ahead on Midway Road.

0.75 [8.35] Junction; turn right (east) and follow narrow gravel road. Note the outcrops of Thomson Formation (Middle Precambrian) straight ahead at the top of hill on Midway Road and in field along the left (north) side of gravel road.

0.35 [8.7] West-facing slope of a steep hill; park and walk to the left (north) along the slope face for approximately 500 feet.

STOP 6. Approximately 7.5 meters of quartzite and quartz-pebble conglomerate assigned to the so-called Nopeming Sandstone (Upper Precambrian; lowest Keweenawan) are exposed at this locality. These sedimentary rocks dip gently eastward and appear to unconformably overlie near-vertical beds of the Middle Precambrian Thomson Formation, although the basal contact is not exposed anywhere.

Two and one-half meters of conglomerate is interbedded with quartzite near the bottom of the exposed sedimentary rocks. The conglomerate is composed of 10 percent pebbles and 90 percent quartzite matrix. The pebbles are well rounded and rarely exceed 4 centimeters in diameter. The majority of them are composed of white quartz, but a small number of quartzite pebbles also are present. The overlying quartzite beds may be divided into two lithotopes; the upper lithotope is a fine-grained, laminated to thin-bedded metasiltstone, whereas the lower lithotope consists of cross-bedded, medium- to coarse-grained quartzite.

The sedimentary rocks are overlain by flows of gray, fine-grained, augite basalt porphyry and augite porphyritic basalt assigned to the Ely's Peak basalts (Lower Keweenawan) of the North Shore Volanic Group. Small-scale load structures in the upper 15 centimeters of the quartite and pillow structures in the overlying basal lava flows suggest that flows were extruded into the same body of water in which the sediments were deposited.

Return over same route.

0.35 [9.05] Junction; turn right (south) and follow Midway Road to Eldes Corner.

0.95 [10.0] Junction; turn right (west) and follow U.S. Interstate Highway 35 toward Esko.

4.2 [14.2] Follow right-hand exit to Esko.

0.2 [14.4] Junction; turn left (south) and follow Carlton County Highway 1 toward Thomson.

3.4 [17.8] Village of Thomson; junction with Minnesota Highway 210; end of Leg 3.

LEG 4 -- THOMSON TO DENHAM

Leg 4 of the road log starts at Thomson in Carlton County and ends near Denham in northwestern Pine County.

0.0 [0.0] Village of Thomson; junction with Minnesota Highway 210; turn right (north) and follow the highway toward Carlton.

0.3 [0.3] 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 7. This is the type locality of the Thomson Formation of Middle Precambrian age. Approximately 760 meters 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 30 centimeters thick and apparently have consistent thicknesses over

the lengths of the longest exposures--a distance of approximately 30 to 50 meters--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 and sole marks 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 meter or so to 180 meters, and amplitudes from about 45 meters to 50 meters. 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 10 meters 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 [1.3] 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 (toward Cromwell).

2.4 [3.7] Junction with Minnesota Highway 61; turn left (south) toward Atkinson.

4.2 [7.9] Village of Atkinson; turn right (northwest) and follow Carlton County Highway 144.

0.3 [8.2] Junction; follow narrow road to the left (southwest).

0.1 [8.3] STOP 8. 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 millimeters 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 [8.7] Junction with Highway 61; turn right (southwest) and continue toward Mahtowa.

0.5 [9.2] STOP 9. 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 facies. It is particularly interesting for it contains evidence of syndepositional deformation and at least one and perhaps two periods of folding.

3.7 [12.9] Village of Mahtowa; turn right (northwest) and follow Carlton County Highway 4.

0.4 [13.3] Sharp turn to the left (west); continue on Highway 4.

0.5 [13.8] Junction; turn right (north) and continue on Highway 4.

1.0 [14.8] Junction; turn left (west) and continue on Highway 4.

0.1 [14.9] Junction; turn right (north) and follow Carlton County Highway 7.

0.5 [15.4] Crossroads; turn left (west) and follow narrow road.

0.4 [15.8] Park Lake Creek straight ahead; walk northwest along abandoned road.

STOP 10. 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 struc-

ture 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 [17.8] Village of Mahtowa and junction with Highway 61; turn right (southwest) and follow Highway 61 toward Barnum.

6.0 [23.8] Village of Barnum; continue straight ahead on Highway 61.

4.8 [28.6] City of Moose Lake; stop lights; turn right (west) and follow Minnesota Highway 27.

0.4 [29.0] 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 11. 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 [29.4] Stop lights; turn right (southwest) and follow Minnesota Highway 61.

0.8 [30.2] Junction with Carlton County Highway 73 (to U.S. Interstate Highway 35); turn right (west) and follow Highway 61.

5.2 [35.4] 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 [36.4] Sharp bend to the right (north); continue on County Highway 46.

0.5 [36.9] Sharp bend to the left (west); continue on County Highway 46.

1.7 [38.6] Bridge over the Kettle River.

3.3 [41.9] Crossroads; turn left (south) and follow Pine County Highway 40.

1.5 [43.4] Crossroads; turn left (east) and follow Pine County Highway 159.

1.5 [44.9] Crossroads; continue straight ahead.

0.4 [45.3] Soo Line railroad tracks. Park and follow tracks to the northeast for approximately 0.2 mile.

STOP 12. 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 less than a meter and wave lengths of several meters to several tens of meters, display a geometry similar to that seen at the type locality of the Thomson Formation at Stop 7.

Return over same route.

0.4 [45.7] Crossroads; turn left (south).

0.4 [46.1] Soo Line railroad tracks; continue straight ahead (south).

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

[46.8]

0.5 [47.3] 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 13. 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 3 meters 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 5 meters 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 9 meters thick and are characterized by light-gray, angular, and vaguely porphyritic fragments as much as 10 centimeters 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 a meter to more than 9 meters 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 [47.7] Junction; Pine County Highway 52 turns right (north) to Denham; continue straight ahead.

0.5 [48.2] Junction; turn right (north) and follow Pine County Highway 157.

0.5 [48.7] Junction; turn left (west) and follow Pine County Highway 40.

0.5 [49.2] Junction; turn left (south) and continue on County Highway 40.

1.0 [50.2] Junction; turn right (west) and follow Pine County Highway 156.

1.5 [51.7] Junction; County Highway 156 turns left (south); turn right (north) and follow Pine County Highway 169.

0.1 [51.8] STOP 14. The modal mineralogy of this small outcrop of McGrath Gneiss (Lower Precambrian) on the right (east) side of

the road at this stop is similar to that of the McGrath Gneiss at its type locality (see Stop 17). 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 [53.0] 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 15. 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 [53.2] Junction, turn right (east) and follow Pine County Highway 159 toward Denham.

2.0 [55.2] Junction; turn left (north) and follow Pine County Highway 40.

1.5 [56.7] Junction with Pine County Highway 46; end of Leg 4.

LEG 5 -- DENHAM TO WOODLAND

Leg 5 of the field trip starts near Denham, in northern Pine County and ends at the village of Woodland in Kanabec County.

0.0 Junction with Pine County Highway 46; turn left (west) toward Arthyde.

4.0 [4.0] Carlton County-Aitkin County line; turn right (north) and follow Aitkin County Highway 41.

0.5 [4.5] Aitkin County Highway 41 ends; continue straight ahead (north) on Aitkin County Highway 2.

0.5 [5.0] Junction; turn left (west) and follow highway 2 toward Arthyde and Pliny (Dads Corner).

2.75 [7.75] Junction with Aitkin County Highway 27 north to Arthyde; continue straight ahead on highway 2.

8.1 [15.85] Pliny (Dads Corner); junction with Minnesota Highways 27 and 65; continue straight ahead on Aitkin County Highway 2.

2.5 [18.35] STOP 16. The McGrath Gneiss (Lower Precambrian) at this locality is relatively uncataclasized and consists of 35 percent quartz, 38 percent plagioclase (sodic andesine), 13 percent microcline, 9 percent biotite and 3 percent muscovite. A conspicuous foliation is given by biotite, which is wraped around large crystals of microcline. Small discontinuous pegmatite veins and quartz veins cut the foliation, and pale-green epidote and pyrite occur on some joint surfaces.

Inclusions of foliated biotite schist as much as 45 centimeters long and 5 centimeters wide occur at several places at this locality. The inclusions are elongated parallel to a northeast-trending foliation in the McGrath Gneiss, but foliations within the inclusions trend in a more easterly direction. These inclusions probably were derived from Lower Precambrian metasedimentary rocks intruded by the igneous precursor of the McGrath Gneiss.

At this locality the McGrath Gneiss also is cut by a tabular body of fine-grained, equigranular aplite that more or less parallels the regional foliation. This aplite sill consists of approximately 25 percent quartz, 30 percent plagioclase, 42 percent microcline, and trace amounts of muscovite, biotite and opaques. The texture, modal mineralogy and structural occurrence of this aplite is more or less typical of all the aplitic bodies that cut the McGrath Gneiss.

Return over same route.

2.5 [20.85] Junction with Minnesota Highways 27 and 65; turn right (south) toward McGrath.

6.6 [27.45] Village of McGrath; turn right (north).

0.2 [27.65] Soo Line railroad crossing; turn left (west) at junction immediately north of the railroad tracks.

0.15 [27.8] Intersection; turn left (south) and continue straight ahead on gravel road.

1.0 [28.8] Intersection; follow gravel road to the right (west).

1.2 [30.0] STOP 17. The exposures at this locality constitute the type locality of the McGrath Gneiss (Lower Precambrian). The rock is a coarse-grained, pinkish-gray biotite gneiss characterized by large crystals of microcline that have the appearance of porphyroblasts. The McGrath typically contains 39 percent quartz, 33 percent plagioclase (sodic andesine), 20 percent microcline and 7 percent biotite. The biotite occurs in well-developed foliae, and a fine-scale mineralogic layering is present locally.

Continue straight ahead on gravel road.

0.5 [30.5] Intersection, turn left (south)

1.0 [31.5] Junction with Minnesota Highway 18; turn left (east) toward Minnesota Highways 27 and 65.

2.3 [33.8] Junction, turn left (south) and follow Minnesota Highways 27 and 65 to Warman.

4.0 [37.8] Aitkin County-Kanabec County line; continue straight ahead on Highways 27 and 65.

3.0 [40.8] Village of Woodland; junction with Minnesota Highway 27 to Isle; end of Leg 5.

LEG 6 -- WOODLAND TO PIERZ

Leg 6 of the field trip starts at Woodland, Minnesota and ends near the city of Pierz, in Morrison County.

0.0 [0.0] Village of Woodland; junction with Minnesota Highway 27 to Isle; continue straight ahead (south) on Minnesota Highway 65.

4.0 [4.0] Village of Warman; continue straight ahead on Highway 65.

0.2 [4.2] Turn left (east) onto narrow dirt road into abandoned quarry.

STOP 18. This abandoned quarry and one approximately 0.2 miles to the north constitute the type locality of the Warman

Granite (Middle Precambrian). Throughout east-central Minnesota, the Warman typically is a fine- to medium-grained, light-gray rock consisting essentially of 25-35 percent quartz, 25-30 percent sodic plagioclase, 18-35 percent K-feldspar (dominantly microcline) and 7-20 percent biotite. The Warman is generally massive except for numerous small inclusions of biotite-quartz-plagioclase schist that are scattered throughout.

Return to Minnesota Highway 65; turn right (north) and continue to the village of Woodland.

4.2 [8.4] Village of Woodland; turn left (west) and follow Minnesota Highway 27 toward Isle.

7.0 [15.4] Kanabec County-Mille Lacs County line; continue straight ahead.

0.1 [15.5] Junction with Minnesota Highway 47; continue straight ahead on Milles Lacs County Highway 31.

1.9 [17.4] Junction; turn left (south) and follow Mille Lacs County Highway 17.

1.5 [18.9] Junction; continue straight ahead on Mille Lacs County Highway 27.

2.35 [21.25] STOP 19. This small quarry on the right side of the road constitutes the type locality of the Isle Granite (Middle Precambrian). The Isle Granite can be divided into two facies--an older, light pinkish-gray, porphyritic facies characterized by plagioclase phenocrysts as much as 2.5 centimeters long; and a younger light-gray, fine- to medium-grained facies that resembles the Warman Granite (Stop 18). Both facies are well developed at this locality. The younger facies is generally equigranular and structureless except for scattered small, blocky inclusions of biotite schist; like the Warman Granite, it is fairly homogeneous and consists of 25-35 percent sodic plagioclase, 20-30 percent K-feldspar (dominantly microcline), 25-40 percent quartz and 1-10 percent biotite. By contrast, the older porphyritic facies contains 40-45 percent sodic plagioclase, 29-32 percent quartz, 16-20 percent K-feldspar, 8-9 percent biotite and trace amounts of augite.

Because the younger facies of the Isle has textural and mineralogic attributes similar to those of the Warman Granite, it is assumed that they are part of the same magmatic event, and that the older porphyritic facies most likely represents an earlier phase of that event.

Return over same route.

2.35 [23.6] Junction; turn left (west) and follow Mille Lacs County Highway 17 to Wahkon.

3.8 [27.4] Village of Wahkon; turn left (west) and follow Minnesota Highway 27 toward Bayview.

3.8 [31.2] Village of Bayview; follow Highway 27 toward Cove.

1.2 [32.4] Village of Cove; continue straight ahead on Highway 27.

1.2 [33.6] Junction with U.S. Highway 169; turn left (south) and follow Highways 169 and 27 to Onamia.

2.5 [36.1] Junction with Minnesota Highway 27; continue straight ahead on U.S. Highway 169.

3.3 [39.4] Junction; turn right (west) and follow Mille Lacs County Highway 3.

1.1 [40.5] Intersection; turn left (south) and follow Mille Lacs County Highway 7.

1.55 [42.05] STOP 20. The small group of outcrops along this north-south road constitute the type locality of the Bradbury Creek Granodiorite (Middle Precambrian). Geophysical data indicate that the exposures are part of a small, poorly exposed, elliptical pluton about 11 kilometers long and 6 kilometers wide that discordantly cuts the Hillman Migmatite (Stops 21-23). The interior part of the pluton is generally gray to black in color, fine to medium grained, and contains 35-40 percent plagioclase (andesine), 25-35 percent quartz, 10-15 percent K-feldspar and 5-15 percent hornblende. As much as 10 percent biotite occurs near the margins of the pluton, and together with elongate grains of hornblende and plagioclase it defines a steeply dipping foliation that is conformable to the boundaries of the pluton as inferred from the geophysical data.

Return over same route.

1.55 [43.6] Intersection; turn right (east) and follow Mille Lacs County Highway 3.

1.1 [44.7] Junction; turn left (north) and follow U.S. Highway 169 to Onamia.

1.5 [46.2] Junction; follow Alternate U.S. Highway 169 left to Onamia.

0.6 [46.8] Village of Onamia; turn left (west) and follow Minnesota Highway 27 toward Little Falls.

7.0 [53.8] Mille Lacs County-Morrison County line; continue straight ahead.

2.0 [55.8] Junction; turn right (north) and follow gravel road.

0.5 [56.3] STOP 21. The Hillman Migmatite of either Early or Middle Precambrian age is a composite unit consisting of various proportions of igneous and metasedimentary material. At this locality metasedimentary rocks dominate and include hornblende schist, metagraywacke and biotite schist. The mineralogy of the hornblende schist and metagraywacke is rather simple. The former contains variable proportions of hornblende, quartz, plagioclase and biotite, whereas the latter contains quartz, plagioclase and biotite; minor amounts of garnet also are present in both rock types. In contrast, the mineralogy of the biotite schist is much more complex. It consists of quartz, plagioclase, biotite, garnet and cordierite. Many of the garnet grains have been rotated and crushed; the crushed grains now resemble augen drawn out parallel to a foliation defined by elongate grains of plagioclase and biotite. These early-formed garnet grains are mantled by a second generation of garnet that has grown either in the pressure shadows of the rotated grains, or as large, undeformed grains that poikilitically enclose crushed grains of the earlier period.

Return over same route.

0.5 [56.8] Junction; turn right (west) and follow Minnesota Highway 27 toward Little Falls.

2.0 [58.8] Junction with Morrison County Highway 40; continue straight ahead on Minnesota Highway 27.

7.8 [66.6] Junction; turn left (south) and follow Morrison County Highway 267.

1.0 [67.6] Junction; turn left (west) and follow Morrison County Highway 268.

1.0 [68.6] Junction; turn left (south) and follow Morrison County Highway 276.

0.4 [69.0] STOP 22. The metasedimentary rocks of the Hillman Migmatite at this locality resemble those described at Stop 21. Metagraywacke inclusions are very abundant, at places making up about half of the outcrop. They range in size from several centimeters to several meters in diameter and locally contain garnet as much as 5 centimeters in diameter. Additionally the metasedimentary rocks are isoclinally folded about axes striking N. 30° E. to N. 40° E. This structural grain appears to have controlled the emplacement of the tonalitic material.

The tonalitic material at this locality is greatly contaminated and a well-developed foliation is defined by elongate grains and lenticular aggregates of biotite which constitutes more than 10 percent of the modal mineralogy. Pegmatite also forms a significant part of the igneous component at this local-

ity. The pegmatite occurs as tabular bodies that cut the tonalite in places, but more commonly it is injected in the tonalite to form a complex of interlayered tonalite and pegmatite with gradational contacts. The pegmatite is coarse and variable in grain size with K-feldspar crystals as much as 7 centimeters in length. Quartz is abundant, but micas are rare; large euhedral grains of garnet are locally abundant, particularly near mafic inclusions in the tonalite.

Fine-grained aplite dikes, composed largely of microcline, sodic plagioclase, quartz and minor amounts of muscovite and biotite, parallel the regional foliation, but in detail cut across the structure of the tonalite and pegmatite. They are clearly the youngest rock type at this locality.

Continue straight ahead on Highway 276.

2.0 [71.0] Junction; turn left (east) and follow Morrison County Highway 39.

1.2 [72.2] Soo Line railroad crossing; park and proceed to the right (southwest) along railroad tracks for approximately 0.3 miles.

STOP 23. Exposures in this railroad cut are typical of the tonalitic phase of the Hillman Migmatite not contaminated by metasedimentary material. The tonalite is a vaguely foliated, gray, medium- to coarse-grained, equigranular rock composed of 20-50 percent quartz, 20-50 percent plagioclase (dominantly andesine), 7-10 percent biotite, and trace to minor amounts of K-feldspar, hornblende pyroxene, chlorite, muscovite and calcite.

The weak foliation that characterizes this rock may be cataclastic in origin, for features such as bent feldspar crystals, pericline twinning and undulatory extinction of quartz grains, and minerals such as sericite epidote, chlorite and calcite imply incipient cataclasis and low-grade metamorphism.

Return to Highway 39 and return over same route toward Pierz.

6.8 [79.0] City of Pierz; junction with Minnesota Highways 25 and 27; turn left (south) and follow Minnesota Highway 27 through Pierz.

1.0 [80.0] Junction with Highway 25 to Genola; end of Leg 6.

LEG 7 -- PIERZ TO LITTLE FALLS

Leg 7 of the field trip starts near Pierz, Minnesota and ends west of the city of Little Falls in Morrison County.

0.0 [0.0] Junction with Minnesota Highway 25 (to Genola); turn right (west) and follow Minnesota Highway 27 toward Little Falls.

1.4 Junction; turn right (south) and follow Morrison County Highway

[1.4] 253.

0.7 [2.1] Fence line; park and walk west along the fence line for approximately 0.25 miles to a small abandoned quarry.

STOP 24. This abandoned quarry is the type locality of the Pierz Granite (Middle Precambrian). As judged from geophysical data the Pierz Granite forms a small elliptical pluton with a long axis of about 9 kilometers and a short axis of about 3 kilometers. The pluton is oriented subparallel to the structural grain of the Hillman Migmatite which apparently controlled its emplacement.

The Pierz Granite resembles the Warman Granite and the younger facies of the Isle Granite in both texture and mineralogy and most likely formed during the same magmatic episode.

Return over same route.

0.7 [2.8] Junction; turn left (west) and follow Minnesota Highway 27 toward Little Falls.

4.1 [6.9] Junction; turn right (north) and follow Morrison County Highway 44 toward Freedhem.

3.2 [10.1] STOP 25. The several quarries on both sides of the north-south road at this locality constitute the type locality of the Freedhem Granodiorite (Middle Precambrian). Well-defined gravity and magnetic anomalies indicate that the Freedhem Granodiorite forms an ellipitical pluton, about 18 kilometers long and 10 kilometers wide that discordantly cuts the Hillman Migmatite. Where exposed, the Freedhem is a medium dark-gray to grayish-black, fine- to medium-grained, generally massive rock. However the edges of the pluton are characterized by a steep foliation, and a few poorly developed east-northeast-trending cataclastic zones as much as a meter wide may be observed locally in the more massive interior of the pluton.

Essential minerals include 30-40 percent plagioclase (dominantly andesine), 10-20 percent quartz, 19-30 percent K-feldspar (antiperthitic blebs within plagioclase and interstitial microcline), 17-18 percent biotite and minor amounts of hornblende and pyroxene.

The Freedhem Granodiorite at this locality is cut by several meter-wide granitic dikes of sodic composition. The dikes trend in an east-northeasterly direction, and are characterized by a primary flow structure accentuated by elongate inclusions of granodiorite and schlieren of biotite schist. Granodiorite in proximity to the dikes contains small clusters or individual phenocrysts of K-feldspar, suggesting that some potassium metasomatism has occurred.

Return over same route.

3.2 [13.3] Junction; turn left (west) and follow Minnesota Highway 27 toward Little Falls.

6.0 [19.3] Junction with U.S. Highway 10 and Minnesota Highway 371; continue straight ahead on Highway 27.

0.5 [19.8] Little Falls city limits; continue straight ahead on Highway 27 (Broadway Ave.).

0.6 [20.4] Junction with U.S. Highway 10; continue straight ahead for one block, turn left (south) proceed one block, turn right (west) two blocks to the Mississippi River. Park and walk to the exposures at the foot of the dam.

STOP 26. Exposures at this locality and on Mill Island immediately to the west constitute the type locality of the Little Falls Formation (Middle Precambrian). This formation consists dominantly of argillaceous material--slate, phyllite, or finely crystalline schist, depending on metamorphic grade--intercalated with thin beds of quartz-rich metasiltstone and thin to very thick beds of quartz-rich metagraywacke. In general, the framework grains in the metagraywacke and metasiltstone beds consist dominantly of quartz and minor amounts of sodic plagioclase. They are set in a finer grained matrix consisting of quartz and muscovite. The argillaceous units are generally laminated and consist dominantly of very fine silt-size quartz and muscovite, or quartz, muscovite and chlorite.

At this locality the rocks have been metamorphosed to the lower amphibolite facies, as shown by appreciable quantities of biotite and lesser amounts of chloritoid, garnet and staurolite. The latter two minerals have a sievelike texture and contain abundant included quartz. The argillaceous units also are characterized by elongate, lense-shaped concretions consisting of large grains of hornblende or garnet set in a hard, dark-colored, siliceous groundmass.

The Little Falls Formation was intensively folded, presumably during the Penokean orogeny. Wave lengths of observed folds range from a few centimeters to several hundred meters, and amplitudes from about 4 meters to 100 meters. The folds are generally broad and open, have a near-vertical axial-plane cleavage, and plunge gently to the southwest.

Return to parking area and proceed straight ahead for one block to junction with U.S. Highway 10; turn left (west) and cross the Mississippi River.

0.2 [20.6] Junction; Minnesota Highways 27 and 28 straight ahead; turn right (west) and follow U.S. Highway 10 toward Randall and Staples.

10.2 [30.8] Village of Randall; junction with Morrison County Highway 6; park at junction and walk to outcrops straight ahead on right (east)

side of Highway 10.

STOP 27. Exposures at this locality, as well as those along the Soo Line railroad tracks in the village of Randall, constitute the type locality of the Randall Formation (Middle Precambrian). In general the Randall Formation consists of metamorphosed volcanic rocks of mafic to intermediate composition, iron-formation, quartzite and quartz-pebble conglomerate. However only dark greenish-black basalt, much of which is vaguely pillowed, is exposed at this locality. The pillows have length to width ratios of around 3:1 to 7:1 and consist of extensively sericitized plagioclase, actinolite, chlorite, quartz and magnetite. The actinolite and chlorite appear to be pseudomorphic after pyroxene. Plagioclase occurs both as a groundmass mineral and as zoned phenocrysts 1 to 2.5 millimeters long. The latter are in part replaced by calcite and epidote. The pillows are set in a fragmental interpillow matrix characterized by mineral constituents similar to those in the pillows and by pebble-size, angular fragments of chert.

Return over same route to Little Falls.

10.2 [41.0] Junction; turn right (west) and follow Minnesota Highways 27 and 28.

0.8 [41.8] Junction; turn right (north).

0.75 [42.55] STOP 28. The unnamed gabbroic and dioritic rocks (Middle Precambrian) exposed in the farmyard on the left (west) side of the road are more or less typical of dark-gray, fine-grained gabbro and medium-gray, medium-grained diorite that crop out sporadically in and around Little Falls. Most of these occurrences are too small to map, but the rocks exposed here are part of a mappable unit, which to judge from geophysical data is at least 600 meters wide and 1.5 kilometers long. The gabbro and diorite are coeval at this locality, as indicated by a lack of chilled contacts and the fact that both contain 50-70 percent subhedral plagioclase zoned from sodic labradorite to calcic andesine. The two rock types differ mainly in the nature of the mafic minerals. The gabbro contains 23-25 percent augite, 17-20 percent biotite and 1-3 percent hornblende. Much of the augite is mantled by hornblende and some biotite, which in turn is altered to chlorite and opaque minerals. Some of the biotite also occurs as large late-forming grains that poikilitically enclose plagioclase, augite and zircon. The diorite, in contrast, contains 1-2 percent augite, 1-3 percent biotite and 35-40 percent hornblende. A few of the hornblende grains have pyroxene cores, some of which are partly altered to chlorite or serpentine; the hornblende is altered partly to actinolite. Biotite occurs as small interstitial plates and is partly altered to chlorite.

Return over same route.

0.75 [43.3] Junction with Minnesota Highways 27 and 28; end of Leg 7.

LEG 8 -- LITTLE FALLS TO SARTELL

Leg 8 of the field trip starts west of the city of Little Falls and ends in the city of Sartell in Morrison County.

0.0 [0.0] Junction; follow Minnesota Highways 27 and 28 to the west toward Long Prairie.

1.0 [1.0] Junction; turn left (south) and follow Minnesota Highway 238 toward Albany.

8.8 [9.8] Junction turn left (east) and follow Morrison County Highway 26 toward Royalton.

2.2 [12.0] Junction with Morrison County Highway 25 on the right; continue straight ahead on Highway 26.

0.2 [12.2] Junction; turn right (north) and follow Morrison County Highway 224.

0.2 [12.4] Junction; keep to the right.

2.1 [14.5] Soo Line railroad crossing; turn right (northeast) and follow dirt road to parking area near Blanchard Dam. Walk to the Mississippi River at the foot of the dam.

STOP 29. This exposure of the Little Falls Formation is notable for its large metacrysts of staurolite and garnet. Additionally the metamorphism has completely obliterated the original sedimentary fabric and the resulting schist is coarsely crystalline; elongate quartz and biotite together define a schistosity that is generally parallel to bedding, except where it is locally distorted around large grains of staurolite and garnet.

Return over same route.

2.3 [16.8] Junction; turn left (east) and follow Morrison County Highway 26.

3.3 [20.1] Village of Royalton; turn right (south) and follow U.S. Highway 10 toward St. Cloud.

0.6 [20.7] Morrison County-Benton County line; continue straight ahead on U.S. Highway 10.

5.8 [26.5] Village of Rice on the right (west); continue straight ahead on U.S. Highway 10.

6.1 [32.6] Junction; turn right (west) and follow Benton County Highway 55 to Watab.

0.3 [32.9] Junction; turn left (south) and continue on Highway 55.

0.6 [33.5] Junction; turn right (north) and proceed approximately 0.2 miles toward Mississippi River.

STOP 30. The Watab Amphibotite (Lower Precambrian) at this locality is a vaguely foliated hornblende-pyroxene-plagioclase gneiss whose mineralogy and texture are varied. As judged from general field relationships the unit forms an east-trending lenticular mass at least 3 kilometers wide and 5 kilometers long. It is interlayered to the west and north with rocks assigned to the Sartell Gneiss (Stop 33) and is truncated on the south and east by rocks assigned to the St. Cloud Granite (Stop 32).

In general the amphibolite consists of medium- to coarse-grained plagioclase of labradoritic composition, clinopyroxene, hornblende, biotite and ubiquitous iron oxides. The clinopyroxene is replaced by variable amounts of hornblende, which in turn is altered to biotite and chlorite. The original plagioclase grains are rimmed by plagioclase of albitic composition, and most are altered to sericite and zoisite.

Return to County Highway 55; continue to the left (southwest).

0.1 [33.6] STOP 31. A contact between the Watab Amphibolite (Lower Precambrian) and the St. Cloud Granite (Middle Precambrian) is exposed at several places along this road. The Watab Amphibolite here is mineralogically similar to that observed at Stop 30, except that perthitic microcline and quartz occur locally as interstitial anhedral grains near apophyses of the St. Cloud Granite.

The St. Cloud Granite at this locality grades transitionally through a light-gray porphyritic granite into a reddish-gray granite porphyry at the contact with the Watab Amphibolite. The granite porphyry occurs as dikes and apophyses that twist and branch irregularly so as to form a boxwork pattern in the amphibolite. The granite porphyry is characterized by euhedral phenocrysts of plagioclase set in a finer grained groundmass of K-feldspar, plagioclase, augite, hornblende, biotite and minor quartz. The phenocrysts are zoned from andesine to oligoclase and are rimmed by albite which is little altered in contrast to the sericitized cores. Plagioclase in the groundmass, however, is albitic in composition and is little altered. Augite and hornblende occur as small euhedral grains in the groundmass; the augite is strongly zoned and in part is replaced by biotite and chlorite, or less commonly by hornblende and biotite, whereas the hornblende is altered to a very fine grained mosaic of biotite and chlorite. Much of the K-feldspar in the groundmass is

perthitic microcline that has been replaced by quartz.

The porphyritic granite is characterized by subhedral phenocrysts of K-feldspar, sodic plagioclase, biotite, and quartz set in an equigranular, anhedral groundmass of quartz with minor amounts of biotite and hornblende. The relative proportions of all the mineral phases are so varied that the modal compositions of individual samples range from granodiorite to granite.

Continue straight ahead.

0.9 [34.5] Junction; turn left (east) and follow gravel road.

0.6 [35.1] Junction; turn left (southwest) and follow Benton County Highway 33.

0.1 [35.2] STOP 32. St. Cloud Granite (Middle Precambrian). Although somewhat weathered, this small, flat outcrop approximately 100 feet to the right (west) of the highway, is typical of the St. Cloud Granite that crops out north and east of the Mississippi River. This facies is typified by a coarse-grained, equigranular texture, and a pale-pink color; essential minerals include 42-61 percent microcline, 26-44 percent quartz, 3-19 percent albitic plagioclase, trace amounts to 5 percent biotite, and trace amounts to 2 percent hornblende.

Continue straight ahead on County Highway 33.

1.2 [36.4] STOP 33. Although this large block of Sartell Gneiss (Lower Precambrian) approximately 100 feet to the west of the highway, may not be in place, it contains all of the mineralogical and textural attributes associated with the Sartell Gneiss. This formation consists of interlayered light pinkish-gray quartzofeldspathic gneiss and light to dark brownish-gray, garnet- and cordierite-bearing, biotite gneiss. The quartzofeldspathic phase is a medium-grained biotite-quartz-plagioclase-microcline rock that has discontinuous lenses of coarser grained material of the same modal composition. The lenses are parallel to a foliation accentuated by subparallel plates of biotite. The biotite-bearing phase is highly variable in grain size and mineralogy but consists dominantly of two facies: (1) a medium-grained, well-foliated rock having irregular clots and lenses of coarser grained granular material; and (2) a medium-grained moderately massive gneiss. The medium-grained rocks in both facies contain plagioclase, quartz, biotite and lesser amounts of garnet and cordierite, whereas the coarser-grained lenses in the well-foliated facies contain plagioclase, quartz, microcline, garnet, and locally, cordierite. At places, relatively fine-grained, quartz-rich biotite gneiss occurs as boudins in the biotite gneiss.

Continue straight ahead on County Highway 33.

1.3 [37.7] City of Sartell; turn left (west) and follow Benton County Highway 29.

0.2 [37.9] Bridge over the Mississippi River; end of Leg 8.

LEG 9 -- SARTELL TO RICHMOND

LEG 9 of the field trip starts at the city of Sartell and ends near the city of Richmond in Stearns County.

0.0 [0.0] Bridge over the Mississippi River; Benton County-Stearns County line; continue straight ahead.

0.1 [0.1] Junction; turn right (north) and follow Stearns County Highway 1 through Sartell.

1.3 [1.4] Junction; turn left (west).

Junction; turn right (north).

1.8 [3.2] Junction; turn left (west).

0.5 [3.7] Sharp bend to the right (north).

0.2 [3.9] Sharp bend to the left (west).

1.5 [5.4] Junction; turn left (south).

1.35 [6.75] STOP 34. The road to the small abandoned quarry on the right (west) side of the road is built on quartzofeldspathic rocks assigned to the Sartell Gneiss, but the quarry itself is developed in the St. Wendel Metagabbro (Lower Precambrian). At this quarry, which is the type locality, the St. Wendel Metagabbro is a dark greenish-gray to greenish-black, plagioclase-clinopyroxene gneiss characterized by grains as much as 8 millimeters in diameter. Plagioclase occurs as large, relatively fresh to slightly sericitized, euhdral grains of generally labradoritic composition. In contrast the clinopyroxene occurs interstitially to the plagioclase as small subhedral to anhedral grains that are generally altered along cleavage planes to hornblende and opaque oxides. Commonly the clinopyroxene and its alteration products are poikilitically enclosed in somewhat larger grains of strongly pleochroic biotite. Minor amounts of quartz occur as small, irregularly shaped interstitial grains, and trace amounts of chlorite replace both the biotite and the clinopyroxene.

Continue straight ahead.

0.05 [6.8] Junction; turn left (west).

1.2 [8.0] Junction; turn left (south) and follow Stearns County Highway 2.

1.4 [9.4] Junction; turn left (southeast) and follow Stearns County Highway 4.

1.8 [11.2] Junction with Stearns County Highway 133; continue straight ahead on County Highway 4.

3.3 [14.5] Bridge over Sauk River; continue straight ahead to junction; turn left (southwest) and follow Stearns County Highway 138 (10th Ave.) through city of Waite Park.

3.1 [17.6] Junction with U.S. Highway 52; continue straight ahead.

0.6 [18.2] STOP 35. Exposed in the small quarry on the right (west) side of the road are dusky-red, medium- to coarse-grained, vaguely porphyritic rocks typical of the St. Cloud Granite (Middle Precambrian) south and southwest of the cities of St. Cloud and Waite Park. In general this rock type contains 24-38 percent sodic plagioclase, 20-34 percent K-feldspar (dominantly microcline), 24-25 percent quartz, 23-26 percent hornblende, 3-11 percent biotite and 5-12 percent augite. A vaguely porphyritic texture is imparted by 1- to 2-millimeter grains of plagioclase and somewhat larger grains of perthitic microcline.

Numerous blocky inclusions of the Reformatory Granite (Stop 36) are present at this locality. Pegmatitic and aplitic phases of the St. Cloud Granite occur as rims that partially surround the inclusions and as apophyses that cut them. Also present are small inclusions of biotitic material and younger dikes of basalt porphyry.

Continue straight ahead.

0.3 [18.5] Junction; turn left (east) and follow Stearns County Highway 137.

0.9 [19.4] Junction with Minnesota Highway 15; continue straight ahead.

0.5 [19.9] Junction; turn left (south).

2.4 [22.3] STOP 36. The Reformatory Granite (Middle Precambrian) is a generally light- to dark-gray, relatively massive rock characterized almost everywhere by small to large inclusions of hornblende schist, biotite schist or garnet-biotite schist. Dikes of granite porphyry and aplite are common, as are dikes and apophyses of the St. Cloud Granite that twist and branch irregularly so as to form in many places a boxwork pattern. Most of the felsic dikes and apophyses have gradational contacts and the surrounding country rocks have been considerably altered, particularly by the introduction of K-feldspar. Nonetheless,

samples of Reformatory Granite well way from any apparent source of contamination contain on the average 17-30 percent quartz, 20-40 percent sodic plagioclase 25-45 percent K-feldspar, 1-10 percent hornblende, 1-8 percent biotite and 1-4 percent augite.

Continue straight ahead.

0.6 [22.9] Junction; turn right (west) and follow Stearns County Highway 122.

1.25 [24.15] Junction with Minnesota Highway 15; continue straight ahead on Stearns County Highway 6.

1.75 [25.9] Junction; turn right (north) and follow Stearns County Highway 137.

1.75 [27.65] Junction; turn left (west).

1.1 [28.75] Junction; turn right (north) and follow Minnesota Highway 23.

1.4 [30.15] STOP 37. This large area of outcrops and quarries on the right (east) side of the highway contains a variety of rock types assigned to the St. Cloud Granite. The St. Cloud Granite is cut by dikes of rhyodacite porphyry, granite porphyry and several kinds of basalt porphyry. The St. Cloud Granite is Middle Precambrian in age, but the ages of the various dike rocks are unknown. The apparently oldest rock assigned to the St. Cloud Granite is a dusky-red, medium- to coarse-grained, vaguely porphyritic (microcline and plagioclase) facies that on the average contains 24-38 percent sodic plagioclase, 20-34 percent K-feldspar (dominantly microcline), 24-25 percent quartz, 3-11 percent biotite, 5-12 percent hornblende and trace amounts to 5 percent augite. It is intermixed on all scales with a somewhat younger pinkish-gray, medium-grained, porphyritic (microcline) facies having associated bodies of pegmatite. The younger facies contains on the average 42-46 percent microcline, 37-39 percent quartz, 14-15 percent sodic plagioclase, 2-3 percent biotite, and trace amounts of hornblende and augite. The associated pegmatitic bodies differ mainly by containing more microcline, and less quartz and mafic minerals.

Return over same route.

1.4 [31.55] Junction; turn right (west) into quarry area.

STOP 38. The Rockville Granite (Middle Precambrian), at this quarry as well as elsewhere, is characterized by blocky phenocrysts of pink and red microcline and white, sodic plagioclase; both are set in a coarse-grained groundmass of microcline, plagioclase, quartz, and mafic minerals. Typically the microcline phenocrysts are strongly zoned, with zones of relatively pure microcline alternating with zones of microcline having closely

packed laminae of perthitic albite. The plagioclase phenocrysts also are zoned, generally from andesine to oligoclase, and less commonly to albite; many have rims of perthitic albite and contain angular inclusions of biotite and quartz, quartz and microcline, or plagioclase more sodic than the host grains. The porphyritic texture makes it difficult to obtain statistically significant modal analyses, but on the average the Rockville contains 21-35 percent microcline, 27-31 percent sodic plagioclase, 23-41 percent quartz, 5-13 percent biotite and 1-2 percent hornblende.

Return to Highway 23, and turn right (south) toward Rockville.

4.4 [35.95] City of Rockville; continue straight ahead on Minnesota Highway 23.

4.9 [40.85] City of Cold Spring; continue straight ahead on Highway 23.

2.5 [43.35] Lake on left (south) side of highway.

0.5 [43.85] Junction; turn left (south) onto gravel road.

0.5 [44.35] STOP 39. This small outcrop of amphibolite on the right (south) side of the road appears to be a layer, lens or pod within the Richmond Gneiss (Lower Precambrian). It consists principally of hornblende, calcic plagioclase and lesser amounts of quartz, actinolite, chlorite and calcite. Generally hornblende and plagioclase occur as porphyroblasts set in a granoblastic aggregate of quartz and plagioclase. The plagioclase ranges in composition from labradorite to bytownite, contains inclusions of amphibole, and shows some degree of alteration to sericite. The hornblende contains wormy intergrowths of chlorite, quartz and calcite, and is partly replaced by actinolite.

Continue straight ahead on gravel road.

0.4 [44.75] Junction with road on the left (east); park and follow abandoned road to the right (west) approximately 250 feet to abandoned quarry.

STOP 40. The Richmond Gneiss (Lower Precambrian) exposed in this quarry is a vaguely foliated, dark-colored rock characterized by large porphyroblasts of K-feldspar and plagioclase set in a groundmass of plagioclase, quartz, hypersthene, hornblende, and biotite. Much of the unit is typified by dark reddish-gray zones concentrated along irregularly spaced joints or cataclastic zones, where the original rock has been oxidized and hydrated. Additionally the gneiss contains inclusions of biotite-hornblende schist, generally less than 20 centimeters long. The age of the

inclusions is unknown; they may be older than the gneiss or they may be folded remnants of younger rocks.

Return over same route.

0.9 [45.65] Junction with Minnesota Highway 23; end of Leg 9.