MINNESOTA GEOLOGICAL SURVEY

MATT S. WALTON, *Director*

# LOWER AND MIDDLE PRECAMBRIAN STRATIGRAPHIC NOMENCLATURE FOR EAST-CENTRAL MINNESOTA

G.B. Morey

*Report of Investigations 21*

UNIVERSITY OF MINNESOTA

Saint Paul · 1978

# LOWER AND MIDDLE PRECAMBRIAN STRATIGRAPHIC NOMENCLATURE FOR EAST-CENTRAL MINNESOTA

CONTENTS

ILLUSTRATIONS

# LOWER AND MIDDLE PRECAMBRIAN STRATIGRAPHIC NOMENCLATURE FOR EAST-CENTRAL MINNESOTA

by

G.B. Morey

## ABSTRACT

This report summarizes stratigraphic nomenclature used by the Minnesota Geological Survey for the Lower and Middle Precambrian rocks that occur in east-central Minnesota. In addition, it provides brief descriptions of dike rocks of possible Middle and Upper Precambrian age.

A sequence of Lower Precambrian rocks consisting of an older gneiss terrane and a younger greenstone-granite terrane has been established on the basis of reconnaissance mapping in the area. The gneiss terrane is divided into three lithostratigraphic units of uncertain relative age. These units are the Richmond Gneiss, the McGrath Gneiss, and the Sauk Rapids Metamorphic Complex. The Sauk Rapids Metamorphic Complex is further subdivided into three units of formational status: the Sartell Gneiss, a broadly distributed quartzofeldspathic unit, and the Watab Amphibolite and St. Wendel Metagabbro, mappable mafic enclaves within the Sartell Gneiss. The younger greenstone-granite terrane is poorly exposed, and these rocks are not described in this report.

The Middle Precambrian consists of both stratified and plutonic rocks. The stratified rocks lie unconformably on the Lower Precambrian rocks and on the Hillman Migmatite, a hybrid rock of uncertain age, and are divided into two groups. From oldest to youngest these are: (1) Mille Lacs Group, comprising the Denham Formation, Glen Township Formation, Randall Formation, Little Falls Formation, and Trout Lake Formation; and (2) the Animikie Group, comprising the Mahnomen Formation, Trommald Formation, Rabbit Lake Formation, and the Thomson Formation. An iron-rich unit named the Emily Member is also formally recognized in the Rabbit Lake Formation.

The stratified rocks were deformed and metamorphosed during the Penokean orogeny, and were subsequently intruded by igneous rocks of gabbroic to granitic composition. The igneous activity was characterized by the emplacement of several plutons of widely varying size. Small dikes or sills of gabbroic to dioritic composition are inferred to be the oldest Middle Precambrian plutonic rocks. Probably this period of mafic activity was followed by the

emplacement of several small stocks of granodioritic composition --the Freedhem and Bradbury Creek Granodiorites of this report-- and later by the emplacement of several large granitic plutons of generally sodic composition--the Reformatory, Isle, Warman and Pierz Granites of this report. Plutonic igneous activity culminated with the emplacement of the Stearns Granitic Complex. This dominantly granitic unit is subdivided into the St. Cloud Granite and a border phase named the Rockville Granite. The former is further subdivided into several unnamed facies. The earlier gabbroic to dioritic and granodioritic rocks were emplaced during the waning stages of the Penokean orogeny, whereas the granitic rocks generally are post-tectonic in age.

The Lower Precambrian rocks and the Middle Precambrian felsic plutonic rocks are cut by both felsic and mafic rocks of unknown age, whereas the Middle Precambrian stratified rocks are cut by several kinds of mafic dikes emplaced during Early and Middle Keweenawan (Upper Precambrian) time.

## INTRODUCTION

East-central Minnesota (fig. 1) is underlain by a wide variety of sedimentary, metamorphic and igneous rocks that range in age from Early to Late Precambrian (Keighin and others, 1972). Inasmuch as the area has been a source of iron ore, ferromanganese ore, and many kinds of granite products, various aspects of the geology, and particularly those that pertain to these commodities, have been studied in considerable detail. Nevertheless, the regional distribution of the rock types and their stratigraphic succession are poorly known. Geologic mapping since 1968 of an area of approximately 4,100 $km^2$--generally bounded by latitudes 45° N. to 47° N. and longitudes 92° 15' W. to 95° W.--has led to a much better understanding of regional geologic relationships, particularly regarding rocks of Early and Middle Precambrian age. This paper discusses the nomenclatural problems in the region and the stratigraphic terms now used by the Minnesota Geological Survey.

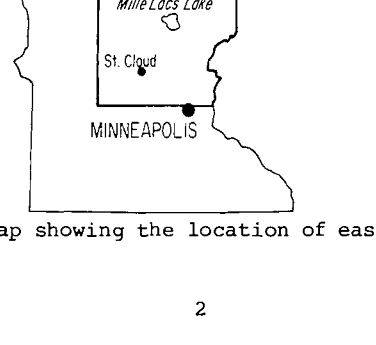


Figure 1--Index map showing the location of east-central Minnesota.

Individual outcrops in the area of Figure 1 are small and tend to occur in clusters of 2 or 3 acres or in strings 1 to 2 km long that are separated by 3 to 24 km of Pleistocene materials. Therefore aeromagnetic (Bath and others, 1964, 1965; Sims and Zietz, 1967) and gravity (McGinnis and others, 1977; Krenz and Ervin, 1977; McGinnis and others, 1978a, b) data were used extensively to prepare a geologic map at a scale of 1:250,000 (Morey, in prep.). A preliminary and somewhat generalized version of this map is shown on Plate 1. Although the area is characterized by a remarkable diversity of rock types and by a paucity of observable contacts, the stratigraphic relationships shown on Plate 1 represent conclusions derived for the most part from on-the-ground geologic observations.

The previous geologic nomenclature for the Lower and Middle Precambrian rocks in the area of Plate 1 needs substantial revision. Although some rock units have well established formal stratigraphic names, many have been described only in terms of lithology without formal designation, or in terms of local or trade names having little geologic significance. Moreover, many of the formal stratigraphic names that are available in the literature were improperly introduced and inadequately defined or were based on faulty interpretations. Other names have become obsolete through disuse or reclassification, but still appear in the literature from time to time. In this report an effort is made to retain or modify the established nomenclature, extending long-established names to similar rock types wherever possible. Nevertheless, it is necessary to abandon or redefine several lithostratigraphic terms and, as in most regional studies of poorly understood areas, to recognize new map units and introduce some new stratigraphic names. These new names are proposed herein in accordance with the requirements of the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1970), and in accord with the recommendations of Sohl (1977) regarding stratigraphic nomenclature in igneous and metamorphic terranes.

Igneous lithostratigraphic units formally identified in this report are named according to the International Union of Geological Sciences (IUGS) classification scheme for plutonic rocks (Streckeisen, 1973). Thus several igneous rock units that were previously classified as "quartz monzonite" are now classified as "granite." However for purposes of discussion, the granite field of the IUGS classification scheme is here informally subdivided into two subfields, one of generally sodic and the other of generally potassic composition. To a first approximation, the sodic granite field corresponds to the quartz monzonite or adamellite fields of other classification schemes commonly used (e.g., Bateman and others, 1963). Although the use of the IUGS classification scheme requires modifying the names of a number of well-established lithostratigraphic units, it will facilitate future uniformity in rock nomenclature throughout Minnesota and the Lake Superior region.

In general, the sedimentary rock nomenclature used in this report is based on the classification scheme proposed by Pettijohn (1957). The migmatitic rocks are described according to the suggestions of Mehnert (1968), and the cataclastic rocks are described according to the scheme outlined by Higgins (1971).

## PREVIOUS STRATIGRAPHIC NOMENCLATURE

The literature on the geology of east-central Minnesota is extensive and contradictory, both with respect to descriptions of local stratigraphic successions and to correlation of these successions with rocks elsewhere. Although several short reports were published earlier, Upham (1882) and Winchell (1884) presented the first comprehensive summaries of the geology of east-central Minnesota, and indicated the locations of the known outcrops. Subsequently several reports describing specific aspects of the various rocks were published (Wadsworth, 1887; Winchell, 1888; Upham, 1888), but these were primarily descriptive in nature, rather than concerned with the development of a stratigraphic succession. The first attempt to construct a stratigraphic succession was made by Hall (1901), who described in detail the so-called "St. Louis Slates"--the Thomson slates of Winchell (1884)--and noted that the igneous rocks described earlier by Upham and other geologists intruded the slates. After discovery of iron ore in the Cuyuna district in 1904, emphasis was placed on developing the stratigraphic succession in that part of east-central Minnesota and on establishing possible correlations of the iron-rich strata there with similar strata on the well-known Mesabi range to the north. For example Zapffe (1907) coined the term "Cuyuna series" and noted that, like the Animikie Group of the Mesabi range, it consisted of a basal quartzite member, an intermediate iron-formation member, and an upper slate member. He suggested that the upper slate member was correlative with the "St. Louis" or "Thomson slates" and with the "Virginia slate" on the Mesabi range. Subsequently Van Hise and Leith (1911, p. 21) retained the term Cuyuna series, but suggested that the iron-rich strata occurred as discontinuous, overlapping lenses and therefore concluded that the iron-bearing beds could not be satisfactorily correlated with the Biwabik Iron Formation of the Mesabi range. Van Hise and Leith therefore applied the name "Deerwood iron-bearing member" of the "Virginia Slate" to these strata, and this name became well entrenched in the literature, particularly after the detailed work of Harder and Johnston (1918).

Although Harder and Johnston (1918) hesitated to formally name and correlate many of the rock units they described, other geologists of the era took markedly different attitudes toward the stratigraphic position of the "Deerwood iron-bearing member." For example, Wolff (1919) correlated parts of the "Deerwood iron-bearing member" with the Biwabik Iron Formation in the Mesabi range and thus applied the Mesabi formational names--Pokegama, Biwabik, and Virginia--to the Cuyuna rocks. Although Zapffe originally believed that the Cuyuna series and the Animikie Group were more or less correlative, he later (1925, 1926) argued that the former was younger than the Animikie Group and was separated from it by an unconformity. Therefore in 1930 Zapffe divided the Cuyuna series into two new lithostratigraphic units which he named the "Aitkin" and "Crow Wing" formations. He divided the younger "Crow Wing formation" into two members--the "Emily member" consisting of dark-colored slaty rocks having many scattered lenses of iron-bearing strata, and the "Cuyuna member" consisting mainly of green partly volcanic slaty rocks and intercalated magnetic iron-bearing strata. Zapffe restricted the use of the term "Deerwood" (e.g. 1933, p. 74-78) to a magnetic "member"--or possibly several "members"--about 30 m thick at several horizons in the "Cuyuna member" of the "Crow Wing formation." Thus Zapffe was the first to recognize the presence of at least two major iron-bearing units, but it is very confusing to read of one member enclosing another member. At about the same time Leith and others (1935) argued for continued use of the term "Deerwood iron-bearing member, but suggested that it rested on "...quartzite much like the Pokegama." Therefore the "Deerwood member" was thought to be correlative with the Biwabik Iron Formation on the Mesabi range. Additionally Leith and others interpreted the igneous rocks that Hall (1901) had recognized as intrusive into the sedimentary rocks of east-central Minnesota as being of "Killarney" or post-Keweenawan age.

Most of the above-mentioned workers followed Zapffe (1907) and correlated the so-called "Thomson slates" with the Virginia Formation of the Mesabi range. However Schwartz (1942) correlated the Thomson strata with the Knife Lake Group of pre-Algoman age in northern Minnesota; thus the igneous rocks in east-central Minnesota were thought to be Algoman or Medial Precambrian in age (Grout and others, 1951).

Grout and Wolff (1955) reiterated Wolff's (1919) stratigraphic classification scheme and again suggested that the Cuyuna rocks were completely correlative with Animikie strata on the Mesabi range. However they continued to correlate the Thomson Formation with the Knife Lake Group, and they also recognized the presence of an unnamed dolomite unit older than the Pokegama Quartzite and younger than strata presumably equivalent to the Knife Lake Group. At about the same time, Woyski (1949) divided the igneous rocks of east-central Minnesota into four groups: (1) intrusion of the McGrath Gneiss into the Thomson Formation (Knife Lake Group) followed by regional dynamic metamorphism during early Algoman time; (2) intrusion of a series of intermediate-composition igneous rocks during late Algoman time; (3) intrusion of granitic rocks; followed by (4) intrusion of felsite and basalt dikes during middle Keweenawan time. Although the local stratigraphic succession that she suggested is still generally valid, Goldich and others (1961) showed that the igneous rocks were neither Algoman (2,600-2,700 m.y. old) nor middle Keweenawan (ca. 1,100 m.y. old) in age, but rather 1,600-1,800 m.y. in age. Therefore they redefined the name "Penokean orogeny"--which was first used by Blackwelder (1914) for what he thought was a period of post-Keweenawan (Killarney) folding and mountain building in the Lake Superior region--and applied it to those metamorphic and igneous events that occurred around 1,600-1,800 m.y. ago.

Schmidt (1963) pointed out that the Cuyuna rocks resembled their Mesabi counterparts in only the most general ways and therefore rejected Mesabi range formational names for the Cuyuna strata. However because he had no real reason to doubt the correlation of Cuyuna strata with those of the Animikie Group, he rejected Zapffe's nomenclature and its stratigraphic implications. Schmidt therefore proposed three new lithostratigraphic units--the Mahnomen, Trommald, and Rabbit Lake Formations--for the Cuyuna district. Shortly thereafter, Morey and Ojakangas (1970) presented geologic evidence indicating that the Thomson Formation was part of the same depositional assemblage that included the Rabbit Lake Formation of the Cuyuna district and the Virginia Formation of the Mesabi range. (See also Morey, 1973.)

Two important papers appeared in 1972. In the first, Marsden presented evidence supporting a one-for-one correlation of the Cuyuna strata with the Animikie Group; he named Grout and Wolff's (1955) "unnamed dolomite unit" the Trout Lake Formation, and suggested that it is underlain by an unknown, but possibly very thick sequence of "slate" and "quartzite." In the second important paper, Keighin and others (1972) suggested that the McGrath Gneiss is Early Precambrian in age and that it is basement to the Middle Precambrian strata. Subsequently Morey and Sims (1976) and Morey (1977) recognized, but did not name, several other gneissic units in east-central Minnesota, and suggested that they and the McGrath Gneiss comprise the northern extension of old (>3,000 m.y.) gneissic rocks exposed in the Minnesota River Valley of southwestern Minnesota. They further suggested that the Animikie strata in the northern part of Plate 1 are underlain by a Lower Precambrian greenstone-granite terrane 2,750-2,700 m.y. old.

## LOWER PRECAMBRIAN ROCKS

Lower Precambrian rocks in east-central Minnesota may be divided into three distinctly different litho-tectonic segments by two east-northeast-trending, presumably high-angle fault zones of Early Precambrian age (pl. 1). The southernmost segment consists dominantly of highly deformed gneisses, whereas the northernmost segment consists dominantly of granite and lesser amounts of metasedimentary and metavolcanic rocks assignable to the greenstone-granite terrane (Morey and Sims, 1976) which compose much of northern Minnesota and adjacent Ontario. The lithic and temporal characteristics of Lower Precambrian rocks in the middle structural segment are problematic because of sparse exposures and a lack of radiometric age data. Cataclasized granitic rocks similiar to those in the Lower Precambrian greenstone-granite terrane are exposed locally near the village of Staples, 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 (1976, fig. 2). 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.

The gneiss terrane in the western part of the area shown on Plate 1 is poorly exposed. However two new lithostratigraphic units--the Richmond Gneiss and the Sauk Rapids Metamorphic Complex --are recognized in this area. The Sauk Rapids Metamorphic Complex is subdivided into three new units of formational status--the Sartell Gneiss, Watab Amphibolite, and St. Wendel Metagabbro. The latter two formations occur as lenses or pods of appreciable size in the more widely distributed Sartell Gneiss. Biotite-bearing quartzofeldspathic gneissic rocks assignable to the southern structural segment also are exposed east of Mille Lacs Lake (pl. 1) where they are named the McGrath Gneiss.

Lower Precambrian rocks assignable to the greenstone-granite terrane are poorly exposed in the area of Plate 1 and their distribution is inferred mostly from geophysical data. Because of the poor exposures, no formal stratigraphic names are used. However geophysical data suggest that the granitic rocks are the western extension of the Giants Range batholith as described by Sims and Viswanathan (1972).

## Richmond Gneiss

The rocks here referred to as the Richmond Gneiss are named for a series of exposures in southwestern Stearns County along the valley of the Sauk River in Wakefield Township (T. 123 N., R. 30 W.) near the town of Richmond and in Rockville Township (T. 123 N., R. 29 W.) north and west of the town of Rockville. The gneiss also is exposed near the village of Cold Spring in the NE¼NE¼ sec. 26, T. 123 N., R. 30 W., where it was quarried under the trade name "Cold Spring Pearl Pink Granite" (Thiel and Dutton, 1935) and is now marketed as the "Opalescent Gray."

Two small abandoned quarries approximately 3 km east of Richmond in the NE¼SE¼ sec. 19, T. 123 N., R. 30 W., are here designated the type locality. Other reference localities include the outcrops and quarries in the SW¼ and NE¼ sec. 22, T. 123 N., R. 30 W., and outcrops along Minnesota Highway 23 near the western edge of the town of Rockville in the NE¼ sec. 17, T. 123 N., R. 29 W.

The Richmond Gneiss is not exposed beyond the limits of the valley of the Sauk River. However geophysical data suggest that the gneiss extends beneath Cretaceous and Pleistocene materials well beyond the southern and western boundaries of Plate 1. The eastern edge of the exposed gneiss is intruded by dikes and apophyses of the Stearns Igneous Complex of Middle Precambrian age (see below).

In general, the Richmond Gneiss is a vaguely foliated rock that is black to dark grayish black in color. Local dark reddish-gray to pale-red zones are concentrated along irregularly spaced joints or cataclastic zones where the original rock has been oxidized and hydrated. Although the texture varies widely, the most common facies is characterized by porphyroblasts of K-feldspar as much as 10 mm long that are somewhat aligned so as to impart a vague, near-vertical foliation that trends in an easterly direction. The unit also is characterized by small inclusions of biotite schist generally less than 20 cm long and by lenticular masses of amphibolite as much as several tens of meters wide and several hundreds of meters long. Both kinds of inclusions are elongate parallel to the regional foliation. The age of the inclusions, particularly that of the amphibolite is unknown. The inclusions may be part of the gneiss terrane or they may be the infolded remnants of the greenstone-granite terrane or of Middle Precambrian strata.

Most of the Richmond Gneiss was originally mapped by Woyski (1949) as part of her Stearns igneous complex. However it is clearly a metamorphic rock consisting essentially of K-feldspar, plagioclase, quartz, hypersthene, hornblende, and minor amounts of biotite, garnet, and cordierite. The porphyroblasts consist dominantly of either zoned plagioclase with cores slightly more calcic than rims, or perthitic microcline with inclusions of strongly altered plagioclase. Less commonly, porphyroblasts of orthoclase with myrmekitic rims also are present. Perthitic microcline with myrmekitic margins and strained and sutured quartz dominate the medium- to coarse-grained groundmass, but symplectic intergrowths of quartz and K-feldspar or quartz and garnet also are present, as are discrete grains of garnet, cordierite, hypersthene and biotite. The garnet and cordierite are generally fresh appearing, whereas the hypersthene is intergrown with or replaced by green hornblende and sphene and the biotite is graphically intergrown with quartz along cleavage planes. Apatite is a major accessory mineral, but zircon, magnetite and secondary alteration products such as chlorite, sericite, and calcite are present in trace amounts.

The dark reddish-gray to pale-red rocks appear to be the oxidized and hydrated equivalents of those described above as indicated by the presence of sericitized K-feldspar porphyroblasts that are reddened by exsolved blebs of hematite, together with appreciable quantities of biotite that appears to replace hornblende and hypersthene. Locally, biotite is replaced by chlorite, hypersthene by serpentine, cordierite by chlorite and muscovite, and garnet by biotite and muscovite. Additionally, some of the more extremely altered samples contain small grains of epidote and calcite that poikilitically enclose many of the above-mentioned minerals.

Generally inclusions of biotite schist are fine to medium grained and consist of various proportions of quartz, plagioclase, K-feldspar and biotite. Elongate grains of plagioclase and biotite define a weak foliation and are corroded, embayed, and in places surrounded by large anhedral grains of quartz. The quartz grains in turn are embayed and surrounded by symplectic intergrowths of K-feldspar and quartz. Additionally, several samples contain highly altered anhedral grains of hornblende that are corroded by quartz and K-feldspar and altered to biotite or chlorite and hematite.

Amphibolite is sparsely distributed as layers, lenses and pods that are concordant with the gneissic foliation. Typical amphibolite is black, fine to medium grained, and consists principally of hornblende, calcic plagioclase and lesser amounts of quartz, chlorite, calcite, opaque oxides, zircon, and apatite. Generally amphibole and plagioclase occur as euhedral to subhedral porphyroblasts set in a granoblastic aggregate of subhedral to anhedral quartz and plagioclase. The amphibole is of two types: pleochroic dark-green to pale yellowish-green hornblende, and radiating aggregates of faintly pleochroic actinolite that surround the hornblende. Alteration products of the hornblende include wormy intergrowths of chlorite, quartz, and calcite. Plagioclase ranges in composition from labradorite to bytownite, contains inclusions of amphibolite, and shows some degree of alteration to sericite.

## Sauk Rapids Metamorphic Complex
(new name)

Following the nomenclatural procedures recommended by Sohl (1977) the name Sauk Rapids Metamorphic Complex is applied in this report to a diverse group of gneissic rocks exposed on both sides of the Mississippi River north of St. Cloud in St. Wendel (T. 125 N., R. 29 W.), and Le Sauk (T. 125 N., R. 28 W.) Townships in Stearns County, and in Sauk Rapids (T. 36 N., R. 31 W.) and Watab (T. 37 N., R. 31 W.) Townships in Benton County. The name is taken from the city of Sauk Rapids in Benton County near the south edge of the outcrop area.

The rocks here assigned to the Sauk Rapids Metamorphic Complex were mapped originally as granite, diorite and gabbro by Bowles (1918, plate I) and as melagranodiorite by Woyski (1949, plate 1). However they have a pronounced gneissic fabric which defines a series of open antiforms and synforms having moderate-dipping limbs and shallow eastward-plunging axes. Small-scale domes and basins indicative of multiple deformation can be seen in many outcrops.

The Sauk Rapids Metamorphic Complex is divided into three lithostratigraphic units of formational status. These are the Sartell Gneiss and the mappable enclaves within it, the Watab Amphibolite and the St. Wendel Metagabbro.

### Sartell Gneiss (new name)

Rocks here named the Sartell Gneiss are exposed principally in T. 36 N., R. 30 W., a short distance north of the village of Sartell on the east side of the Mississippi River in Benton County. Several outcrops in the SW¼ sec. 4 of this township are here designated as the type locality. Other reference exposures occur in the SW¼ and NW¼ sec. 6, T. 125 N., R. 28 W. Although exposures are sparsely distributed, geophysical data suggest that the gneiss extends westward beneath Cretaceous strata and Pleistocene surficial materials to at least the vicinity of long. 95° W. The Sartell Gneiss is truncated on the east by a reddish-gray porphyritic granite presumed to be a border phase of the Stearns Granitic Complex (see below).

The Sartell Gneiss 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 pink, 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 sub-parallel plates of biotite. The biotite-bearing phase is highly variable in grain size and mineralogy, but consists dominantly of two facies: (1) a medium or dark brownish-gray, medium-grained, well-foliated rock having irregular clots and lenses of coarser grained granular material; and (2) a brownish-gray, 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.

Watab Amphibolite (new name)

The term Watab Amphibolite is here applied to a group of black to dark greenish-black gneissic rocks that crop out in Benton County east of the Mississippi River in secs. 26, 27, 34, and 35, T. 37 N., R. 30 W. (Watab Township) and west of the Mississippi River in Stearns County in sec. 10, T. 125 N., R. 28 W. The type locality is here designated as an abandoned quarry near the center of sec. 27, T. 37 N., R. 30 W. (Watab Township) approximately 1 km south of the village of Watab. The formation also is well exposed along U.S. Highway 10, 0.6 km east of the village of Watab. As judged from general field relationships and geophysical data, the unit forms an east-trending lenticular mass at least 3 km wide and 5 km long. It is interlayered to the west and north with rocks assigned to the Sartell Gneiss and is truncated on the south and east by rocks assigned to the Stearns Granitic Complex.

The Watab Amphibolite is a vaguely foliated hornblende-pyroxene-plagioclase gneiss, whose mineralogy and texture are varied; these attributes reflect subsequent alteration by the emplacement of the Stearns Granitic Complex. The least altered phase consists dominantly of medium- to coarse-grained plagioclase, clinopyroxene, biotite, and ubiquitous iron oxides. The biotite is strongly poikilitic. In the more altered phases the clinopyroxene is replaced by variable amounts of hornblende, which in turn is altered to biotite and chlorite, especially at the periphery of grains. Plagioclase of generally labradoritic composition is characterized by moderately broad and indistinct twin bands and is rimmed by more albitic plagioclase. Although some calcic plagioclase is fresh, most grains are altered to sericite and zoisite, and appear almost opaque in thin section. Both perthitic microcline and quartz occur locally as interstitial anhedral grains, particularly near apophyses of the Stearns Granitic Complex.

St. Wendel Metagabbro (new name)

The name St. Wendel Metagabbro is here applied to a series of exposures in the SW¼ sec. 12 and the NE¼ sec. 13, T. 125 N., R. 29 W. (St. Wendel Township) in northeastern Stearns County. The type locality is here designated as an abandoned quarry in the SE¼SE¼ sec. 12, of that township.

This unit forms a series of lenticular bodies ranging in size from about 125 m wide and 300 m long to more than 300 m wide and 2 km long. The several bodies are elongated in an easterly direction parallel to the foliation of the enclosing Sartell Gneiss and in plan view resemble boudins. Contact relationships suggest that the metagabbro bodies were deformed contemporaneously with the enclosing quartzofeldspathic gneiss.

The St. Wendel Metagabbro is a dark greenish-gray to greenish-black, plagioclase-clinopyroxene gneiss characterized by grains as much as 8 mm in diameter. The plagioclase occurs as large, relatively fresh to slightly sericitized, euhedral 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. Apatite and zircon occur as small euhedral inclusions in plagioclase and biotite, respectively.

## McGrath Gneiss
## (modified name)

The name "McGrath kaligranite augen gneiss" was first proposed by Skillman (1946) for a pink quartzofeldspathic gneiss that sporadically crops out in an east-trending belt about 30 km wide that extends from the east side of Mille Lacs Lake to near Denham (sec. 22, T. 45 N., R. 21 W.) in northwestern Pine County, a distance of about 80 km. Woyski (1949) shortened the name to McGrath Gneiss and that terminology is followed here.

The gneiss is typically exposed in sec. 17, T. 43 N., R. 24 W., 3 km southwest of the village of McGrath in Aitkin County and these exposures are designated as the type locality. Other good exposures occur in Pine County: (1) near Denham in secs. 25 and 28, T. 45 N., R. 21 W.; (2) along Breman Creek in the E½, sec. 19 and sec. 20, T. 44 N., R. 21 W.; and (3) along a low ridge in the SW¼, sec. 16, T. 44 N., R. 21 W. The gneiss also is well exposed in Aitkin County in an abandoned quarry 3.5 km west of Dads Corner (Pliney) in the NW¼NW¼ sec. 6, T. 44 N., R. 23 W.

Although known outcrops of the McGrath Gneiss are relatively small and sparsely distributed, geophysical data indicate that the formation underlies a fairly extensive area, where it forms several broad, dome-shaped anticlinoria bounded and locally overlain by stratified rocks of Middle Precambrian age.

The McGrath Gneiss has been described in some detail by Keighin and others (1972). In general, it is a medium- or coarse-grained, locally migmatitic, pinkish-gray, biotite-bearing quartzo-feldspathic gneiss characterized by large crystals of microcline. A fine-scale, probably primary, mineralogic layering characterized by biotite folia is present locally. Modal mineralogical data (Keighin and others, 1972) and a chemical analysis of the gneiss from the quarry west of Dads Corner (Sandell and Goldich, 1943, p. 110) indicate a sodic composition. 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 appear to have been 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 may be characterized as a protomylonitic gneiss having large crystals of microcline that resemble augen. In general the cataclasis has resulted in 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 which is coincident with and parallel to the orientation of the protomylonitic zones themselves. Mineral recrystallization coincident with cataclasis in the blastomylonitic zones has given rise to a well-developed crystalloblastic structure characterized by fine-grained K-feldspar and somewhat coarser grained hornblende.

Relatively uncataclasized rocks in the McGrath Gneiss have yelded a Rb-Sr whole-rock isochron age of at least 2,700 m.y. (Stuckless and Goldich, 1972; Keighin and others, 1972) and thus the unit is Early Precambrian in age. Cataclastic zones and their associated blastomylonitic foliations are subconformable to the bedding in the Middle Precambrian rocks that surround and overlie the gneiss, indicating that cataclasis occurred virtually contemporaneously with folding of the metasedimentary rocks. This interpretation is supported by K-Ar and Rb-Sr ages of biotite from cataclastic zones in the gneiss that are similar to a Rb-Sr whole-rock age of 1,730 to 1,740 m.y. for the Middle Precambrian rocks (Keighin and others, 1972). Thus Morey and Sims (1976) concluded that the McGrath Gneiss is part of the same gneissic terrane that is exposed in the western part of Plate 1 and that it was tectonically reactivated in Middle Precambrian time during the Penokean orogeny.

### Igneous, Metavolcanic and Metasedimentary Rocks of the Greenstone-granite Terrane

Geophysical data and a few sparsely distributed drill holes indicate that Lower Precambrian granitic, metavolcanic, and metasedimentary rocks underlie much of the northern part of east-central Minnesota (pl. 1). However, only the granitic rocks are exposed in the extreme southwestern corner of Cass County in the NW¼ sec. 28 and SE¼ sec. 21, T. 134 N., R. 32 W., approximately 10 km north-northeast of the village of Staples in adjoining Todd County.

The granite exposed north-northeast of Staples is a pinkish-gray to greenish-gray, medium- to coarse-grained rock consisting dominantly of hornblende, sodic plagioclase, and quartz. In some samples quartz and feldspar are almost equally abundant and compose about 80 percent of the rock, but in other samples quartz is rare and the rock grades into a syenite. Accessory minerals include biotite and sphene.

Near-vertical north-northeast-trending cataclastic zones, 1 to 2 m wide, impart a marked protomylonitic fabric to the rock. The edges of these cataclastic zones are characterized by pale-red, somewhat granulated feldspar, and by hornblende that is altered to chlorite and epidote. Within the cataclastic zones, obviously secondary hornblende defines a blastomylonitic lineation that plunges 10°-30° to the northeast. The cataclastic zones also contain ellipsoidal inclusions that consist largely of hornblende with minor epidote, and are oriented parallel to the lineation.

The granite near Staples has not been dated by radiometric methods, but a primary mineralogy similar to that observed in the Giants Range batholith to the north suggests an Early Precambrian age. The presence of cataclastic zones virtually concordant with fold axes in the overlying Middle Precambrian strata (pl. 1) further suggests that the granite is basement to the Middle Precambrian strata and that it was deformed during the Penokean orogeny.

## MIDDLE PRECAMBRIAN STRATIFIED ROCKS

The Middle Precambrian stratified rocks in east-central Minnesota compose a broad, eastward-plunging synclinorium bounded on the north, west, and southeast by Lower Precambrian rocks. However the extent to which the stratified rocks were deformed varies considerably within the synclinorium, and these differences appear to be attributable 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 surface between the basement and overlying rocks appears to be relatively undisturbed. However, where the sedimentary rocks overlie "schistose" and/or gneissic rocks, the entire section is complexly folded into a number of 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 near-vertical axial planes in the central part to isoclinally overturned folds with axial planes that dip as much as 60° SE. in the southern part of the synclinorium. In addition, axial planes of folds to the northwest strike in an east-northeast direction, whereas those to the southeast conform in a general way to the anticlinorial geometry of the McGrath Gneiss. Fold axes on the northeastern side of the anticlinorium--from near Denham northward--plunge gently to the northeast, whereas those on the southwestern side--from Randall to south of Little Falls--plunge moderately to the southwest.

The Middle Precambrian stratified rocks reflect an increase in metamorphic grade from north to south. To the north, iron-formations and associated argillaceous rocks overlying granite-greenstone basement rocks contain minerals indicative of high-grade diagenesis or zeolite-facies metamorphism (Morey, 1973; Perry and others, 1973). However, argillaceous rocks overlying "schistose" basement rocks are characterized by a slaty cleavage (Marsden, 1972) and by mineral assemblages indicative of lower greenschist-facies metamorphism. Farther south the same rocks have been metamorphosed to the upper greenschist-facies as evidenced by mineral assemblages containing biotite, muscovite, plagioclase (oligoclase to andesine), quartz and calcite. Still farther south, the argillaceous rocks have been metamorphosed to the lower amphibolite-facies. Garnet is a common mineral in the more quartzose beds, hornblende is abundant in calcareous units, and staurolite occurs locally in proximity to the McGrath Gneiss.

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, implying that deformation and metamorphism were discrete events.

The sedimentary and volcanic rocks of Middle Precambrian age are divided into two groups presumably separated by an unconformity (Marsden, 1972). 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, here named the Mille Lacs Group, has been recognized only recently, whereas the younger sequence is correlative with the well known Animikie Group of northern Minnesota and Ontario (see Marsden, 1972). Inasmuch as there is no evidence of Middle Precambrian strata younger than the Animikie Group, it is recommended here that member and formational names such as the "Cuyuna series" of Zapffe (1907), the "Deerwood iron-bearing member" of Van Hise and Leith (1911) and the "Crow Wing and Aitkin formations" and their associated members--except the Emily member--of Zapffe (1930, 1933) be abandoned.

## Mille Lacs Group
(new name)

The Mille Lacs Group is named for Mille Lacs Lake. As defined here, the group consists dominantly of quartzose sedimentary rocks of arenitic and wacke affinity named the Denham and Little Falls Formations, respectively. A mappable unit of siliceous dolomite, the Trout Lake Formation of Marsden (1972), is present in the upper part of the group, and lesser beds of impure dolomite or limestone also are present near the base of the Denham Formation. Minor quantities of volcanogenic and hypabyssal rocks of mafic to intermediate composition are interlayered with the quartz-rich rocks throughout the group. Two major bodies of mafic to intermediate volcanic rocks that occur near the base of the group are here named the Randall and Glen Township Formations. Both formations contain some oxide- to carbonate-facies iron-formation and pyrite-rich, carbonaceous argillite, as well as small amounts of quartz-rich rocks of arenitic affinity.

The distribution of the Mille Lacs Group shown on Plate 1 is largely inferred from geophysical data supplemented by a few outcrops and by exploration drilling for iron deposits in a few localities. Much extrapolation is required to give continuity to the many non-magnetic rock units and therefore the distribution of the Mille Lacs Group may be more complex than shown.

### Denham Formation (new name)

The name Denham Formation is here applied to a sequence of quartz-rich sedimentary rocks that extends as a broad belt from near Denham in northwestern Pine County westward to the general vicinity of Mille Lacs Lake in northern Mille Lacs County. The type locality is defined as a series of exposures in an abandoned river valley in the SE¼ sec. 25 and the NE¼ sec. 26, T. 45 N., R. 21 W. These exposures are approximately 1.6 km southeast of the village of Denham.

At the type locality, the Denham Formation overlies the McGrath Gneiss and is a heterogeneous sequence consisting dominantly of arenitic quartz-rich rocks ranging in grain size from conglomerate to coarse siltstone. Several of the conglomeratic units contain clasts derived from the underlying McGrath Gneiss

(Keighin and others, 1972). Minor quantites of dolomite, pillowed basalt, and mafic to intermediate agglomerate also are intercalated with the quartz-rich sedimentary rocks at the type locality. A similar sequence of intercalated sedimentary and volcanic rocks was intersected by drilling approximately 26 km to the southeast of Denham near the village of McGrath in Kanabec County, where several 1- to 3-m-thick layers of laminated hematitic and cherty iron-formation also were encountered (Skillman, 1946). Stratigraphically higher parts of the Denham Formation are characterized by appreciable quantities of quartz-rich argillite (secs. 19, 20, 21, 22 and 29, T. 46 N., R. 21 W.), and lesser amounts of dolomite and intercalated chert (sec. 19, T. 47 N., R. 21 W.), and massive beds of vitreous quartzite (SE¼ sec. 34, T. 47 N., R. 25 W.).

Exposures of vitreous quartzite in T. 47 N., R. 25 W. have been informally referred to in the literature as the "Dam Lake quartzite" (Grout and Wolff, 1955). Drilling to the south in T. 46 N., R. 25 W. indicates that the so-called "Dam Lake quartzite" is interbedded with quartz-rich phyllite and that these rocks pass laterally into the sequence of volcanic rocks and carbonaceous argillite here assigned to the Glen Township Formation.

The epiclastic, quartz-rich rocks of the Denham Formation range in grain size from argillite, through coarse-grained siltstone and medium- to coarse-grained sandstone, to conglomeratic sandstone. Most of the conglomeratic units are restricted to the base of the formation where they occur as single sedimentation units as much as 9 m thick. In general they are massive to very poorly bedded and light greenish gray to brownish gray in color. Conglomeratic clasts as much as 10 mm in diameter include microcline and "granitic" fragments derived from the McGrath Gneiss, recrystallized chert, and clear, gray or blue quartz. The clasts are set in a matrix consisting of medium sand-size grains admixed with various proportions of fine sand-, silt- and clay-size material and carbonate cement. The sand-size grains consist dominantly of granoblastic quartz, strongly sericitized microcline, sodic plagioclase and lesser amounts of "granitic" rock fragments consisting of either quartz and microcline or quartz and plagioclase. The silt- and clay-size matrix is extensively recrystallized, and consists dominantly of quartz, muscovite and lesser amounts of biotite and chloritoid; garnet and staurolite also are present as metamorphic phases, particularly near the McGrath Gneiss.

Much of the exposed Denham Formation consists of thin to thick beds of vitreous quartzite intercalated with thick layers of argillite, argillaceous siltstone, and scattered thin to thick beds of dolomite or marble. The quartzite 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, microcline, and lesser amounts of plagioclase, whereas the reddish-gray varieties contain minor amounts of hematite and calcite in addition to the above-mentioned clastic minerals. Some of the red-colored rocks may be cherty iron-formation that has been extensively recrystallized. The interbedded argillaceous units are light colored and consist dominantly of intercalated laminae or very thin beds of argillite and argillaceous siltstone. Most of the argillaceous siltstone beds are themselves laminated and have layers rich in quartz that alternate with layers rich in muscovite and chlorite, and at higher metamorphic grades, 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 layered silicates that parallel a well developed tectonic cleavage.

Thin to thick layers of dolomite or marble of variable appearance are intercalated widely throughout the Denham Formation. Although pale yellowish-gray, internally structureless layers as much as 3 m thick, occur near the base of the formation, most of the calcareous units occur as yellowish-gray to light greenish-gray laminae and as very thin beds in the more argillaceous parts of the formation. Although it varies widely in composition, the limestone consists generally of interlocking inequigranular grains of calcite that enclose scattered detrital grains of quartz, microcline, and plagioclase. Locally, muscovite and biotite occur as small clusters in the structureless layers and as thin, irregular folia in the laminated layers.

Although water-well logs indicate their presence throughout the Denham Formation, volcanic rocks of generally mafic to intermediate composition are exposed only near Denham. Because of extensive recrystallization, only two types of volcanic rocks have been recognized unequivocally--metabasalt and meta-agglomerate. However, some of the quartz-rich rocks and a number of amphibolite layers may be extremely recrystallized igneous rocks of felsic and mafic composition, respectively.

Layers of metabasalt are generally less than 5 m 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 sphene, and trace amounts of quartz and calcite are present in interstitial voids. The agglomeratic rocks occur in layers as much as 20 m 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 1 m to more than 10 m thick are intercalated with the quartzitic rocks at several levels at the type locality. These rocks may be of igneous origin, but extreme recrystallization makes it difficult to ascertain their original composition. Although individual amphibolite layers differ 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 amphibolites contain trace amounts of garnet.

Little Falls Formation (new name)

Rocks here assigned to the Little Falls Formation crop out sporadically over a large area in southern Morrison and northeastern Stearns Counties (pl. 1). The name is taken from a series of exposures on and near Mill Island in the valley of the Mississippi River near the center of the city of Little Falls (sec. 8, T. 41 N., R. 32 W. and sec. 19, T. 129 N., R. 32 W.). These exposures are here designated as the type locality. Other easily accessible exposures occur at the so-called "Blanchard Dam locality" in the NE¼NW¼ sec. 32, T. 128 N., R. 29 W. and along the Elk River near its junction with the Mississippi River in sec. 5, T. 129 N., R. 29 W.

As judged from sparse outcrop data, the Little Falls Formation consists dominantly of argillaceous material--now slate, phyllite, or finely crystalline schist--intercalated with thin beds of quartz-rich metasiltstone and thin to very thick beds of quartz-rich metagraywacke. Additionally, a few scattered water wells have penetrated what appear to be fine-grained mafic volcanic rocks. Thus the Little Falls Formation differs from the Denham Formation mainly by containing sandstones of wacke, rather than arenitic affinity.

Medium dark-gray to light-gray, very well indurated metagraywacke constitutes about one-third to one-half of the total exposed thickness of the Little Falls Formation. Much of the metagraywacke is coarse-grained siltstone or fine-grained sandstone, but a few beds contain medium-sand-size particles. Individual beds range in thickness from about 3 cm to more than 3 m, and most are single sedimentation units that are massive and fairly uniform in texture; a few of the thicker beds are composite sedimentation units consisting of intercalated laminae of very fine-grained graywacke, siltstone, and argillaceous material.

In general the framework grains in the metagraywacke, regardless of grain size, consist dominantly of quartz and minor amounts of plagioclase. They are set in a finer grained matrix consisting of quartz and muscovite. At higher metamorphic grades, more micaceous beds contain 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. Additionally, some of the larger staurolite grains contain partially resorbed grains of garnet. The argillaceous units are generally laminated and consist dominantly of very fine silt-size quartz and muscovite, or quartz, muscovite and chlorite. However the relative proportions of these minerals vary considerably; some laminae are almost monomineralic, whereas others contain more or less equal proportions of quartz and micaceous minerals. At higher metamorphic grades, other minerals in the argillaceous units include biotite, garnet and chloritoid. At the highest metamorphic grade, metamorphism has completely obliterated the original sedimentary fabric and the resulting schist is coarsely crystalline; elongate quartz and biotite together define a schistosity generally parallel to bedding, but distorted around large grains of garnet and staurolite.

The argillaceous units also are characterized by abundant elongate, lens-shaped concretions, as much as 2 m long and 0.3 m wide. At lower metamorphic grades the concretions are calcareous, but at higher metamorphic grades they consist of large grains of hornblende or garnet set in a hard, dark-colored, siliceous groundmass.

The Little Falls Formation grossly resembles the Thomson Formation (see below), in that both are intercalated graywacke- and shale-bearing sequences having carbonate concretions, similar structural attributes, and megascopically similar metamorphic mineral assemblages. Because of these attributes, Harder and Johnston (1918), Schwartz (1942), Goldich and others (1961), and Keighin and others (1972) correlated the rocks near Little Falls with those of the Thomson Formation. There are two lines of evidence, however, that are not consistent with this correlation. First, regional geologic relationships indicate that the Little Falls strata are infolded with Lower Precambrian gneissic rocks, implying that they occur stratigraphically near the base rather than at the top of the Middle Precambrian sedimentary sequence. Furthermore sparse drill-hole information, supplemented by geophysical data, indicates that the Little Falls strata pass northward transitionally into strata of the Randall Formation (see below), which unequivocally overlies Lower Precambrian basement rocks. Second, the mineralogy of the Little Falls and Thomson Formations is considerably different--the former contains appreciable quartz and much less feldspar and matrix material than does the latter. Furthermore the Little Falls strata contain chloritoid and staurolite, metamorphic minerals characteristic of the Denham Formation, but not observed in the Thomson Formation. For these reasons the strata exposed at Little Falls are assigned here to the Mille Lacs Group.

Glen Township Formation (new name)

The Glen Township Formation as here defined consists predominantly of interbedded pyrite- and pyrrhotite-rich carbonaceous slate, recrystallized cherty iron-formation, metabasalt, highly altered diabase, and lesser amounts of quartzite, quartz-rich siltstone, argillite, and calcareous rocks of limestone affinity. The formation is here named for particularly well developed occurrences in Glen Township (T. 46 N., R. 25 W.) in southwestern Aitkin County. However, except for several outcrops of altered mafic rock in secs. 8, 9, and 10 of Glen Township, the formation is confined entirely to the subsurface.

Drilling logs and core samples from 55 holes intersecting approximately 3,000 m of rock in sec. 28, T. 46 N., R. 25 W. comprise the type material for this formation. The logs and samples are available for study at the offices of the Minnesota Department of Natural Resources, Division of Minerals in Hibbing, Minnesota. These and other drilling records combined with extensive geophysical data indicate that the Glen Township Formation extends northeastward from near Mille Lacs Lake in T. 45 N., R. 26 W., through T. 46 N., Rs. 25 and 26 W. and into T. 47 N., Rs. 23 and 24 W. (pl. 1). Currently available subsurface data suggest that the formation overlies and passes laterally into rocks of the Denham Formation. A few scattered drill holes indicate that it passes upward into argillaceous rocks here assigned to the Mille Lacs Group undivided, and that it is truncated to the southwest by a granitic pluton of presumably Middle Precambrian age. A few scattered drill holes on the southwest side of the pluton indicate the presence of mafic rock and iron-formation similar to those in the Glen Township Formation. However because of a lack of data, the rocks are assigned to the Mille Lacs Group, undivided.

Sulfide-bearing carbonaceous slate, carbonate-facies iron-formation, and basalt are interbedded on all scales throughout the Glen Township Formation (Han, 1968). However slate and basalt are more abundant in the upper part of the sequence. Additionally, sills or dikes of highly altered diabase occur throughout the formation; although they may be younger intrusions, they have been metamorphosed and therefore most likely are the hypabyssal equivalents of the basalt.

Because the Glen Township Formation has been extensively metamorphosed, it is difficult to ascertain the original composition of the sedimentary strata. However, Han (1968) described the pyrite- and pyrrhotite-rich, carbonaceous strata in some detail and concluded that they have attributes similar to those of sulfide-facies iron-formations as described by James (1954). Additionally

Han has described beds of cherty iron-formation that contain appreciable quantities of ferromagnesian carbonate minerals and appear to be similar to James's carbonate-facies iron-formation.

Fine-grained basaltic rocks in the Glen Township Formation resemble those in the Denham Formation in that they are dark greenish gray to greenish black in color and consist of calcic plagioclase and augite intergrown in a microdiabasic texture. As at Denham, some of the augite is altered to hornblende, which in turn is altered to biotite. Trace amounts of quartz and calcite also are present in interstitial voids. In contrast, the presumably coeval, hypabyssal igneous rocks exhibit a distinctly diabasic texture of interlocking calcic plagioclase and augite. Much of the plagioclase is cloudy and partially altered to epidote, and the augite is mantled by a blue-green amphibole. Brown biotite, clinozoisite, sphene, and very fine-grained quartz occur as interstitial void fillings. In places the diabasic rocks have been modified by near-vertical, north-northeast-trending cataclastic zones as much as 1 m wide. These cataclastic zones have a schistose fabric defined by elongate grains of muscovite and actinolite and by crushed feldspar grains strung out as pseudolaminae.

Various kinds of epiclastic sedimentary rocks occur in the Glen Township Formation and these rocks resemble those of the Denham Formation. Thin beds or lenses of gritstone, or very fine-grained conglomerate occur interbedded with beds of vitreous quartzite and basalt near the base, whereas thin to thick beds of quartz-rich siltstone, slate and quartzite are intercalated with carbonaceous slate in the upper part of the formation. A few beds, generally less than 15 cm thick, of impure limestone are intercalated with the finer grained rocks in the upper part of the formation. Generally these beds consist of large interlocking calcite grains that enclose silt- or fine sand-size quartz grains identical to those in the surrounding clastic rocks.

Randall Formation (new name)

The dominantly mafic metavolcanic unit here defined as the Randall Formation is named for exposures in and near the village of Randall in sec. 7, T. 130 N., R. 30 W. in western Morrison County. These exposures also comprise the type locality. Other exposures occur near the center of sec. 3 in the same township, and in the SE¼NW¼ sec. 34, T. 133 N., R. 32 W. near Philbrook in Todd County. The rocks at Randall were mapped originally as chlorite schist by Harder and Johnston (1918). Zapffe (1930) described them as "...green slaty and schistose rocks, partly volcanic...in origin..." and Skillman (1946) suggested that they were probably metamorphosed andesitic lava flows.

Although the Randall Formation consists dominantly of metamorphosed volcanic and hypabyssal rocks of mafic to intermediate composition, a variety of sedimentary rocks including iron-formation, chert, quartzite, quartzose argillite and siltstone, and quartz-pebble conglomerate occur throughout. In general the clastic rocks resemble those in the Denham and Glen Township Formations.

Dark greenish-black basalt, much of which is pillowed, is the most common volcanic rock type at Randall and near Philbrook. 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 mm 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.

Hypabyssal rocks characterized by a fine- to medium-grained diabasic texture are associated with the flows at several localities. They are typified by scattered 1- to 2-mm phenocrysts of andesine set in a somewhat finer grained groundmass of augite and plagioclase. However, some of the plagioclase is altered to calcite and zoisite, and the augite is almost entirely replaced by hornblende which in turn is rimmed by actinolite. K-feldspar, quartz magnetite, and apatite also are present as small interstitial grains.

As judged from drilling data, beds of banded iron-formation and chert are scattered throughout the formation as thin, lenticular bodies that do not appear to persist for any great distance along strike. However, several iron-rich units have been traced for distances of a few kilometers (pl. 1) along strike by drilling. Regardless of thickness or areal extent, these lenses of iron-formation consist of finely laminated layers of black or dark grayish-black chert intercalated with thin to thick chert-rich beds having either finely disseminated hematite or small, euhedral grains of magnetite and ankerite.

Because the Randall Formation crops out at only a few scattered localities, its stratigraphic position relative to other formations in the Mille Lacs Group is somewhat uncertain. However, geophysical data supplemented by extensive exploration drilling for iron ore indicate that the main belt of the formation occurs in proximity to and infolded with Lower Precambrian rocks, as do similar strata that form an outlier several kilometers wide and several tens of kilometers long approximately 25 km northwest of Randall in Tps. 132 and 133 N., Rs. 32 and 33 W. In general the Randall Formation is separated from underlying Lower Precambrian basement rocks by beds of fine-grained conglomerate and quartzite similar to those in the Denham Formation. However, inasmuch as it is not possible to demonstrate lithic continuity, these epiclastic beds are assigned to the Mille Lacs Group undivided. Similarly, a few sparse drill holes indicate that the Randall Formation is overlain by strata similar to those of the Little Falls Formation, but because of a lack of lithic continuity, these rocks also are assigned to the Mille Lacs Group, undivided. Therefore the Randall Formation appears to occupy a stratigraphic position in the Mille Lacs Group similar to that of the Glen Township Formation. Because it differs from the Glen Township Formation by lacking sulfide-rich carbonaceous beds, it is given formal lithostratigraphic status in this report.

Trout Lake Formation

The name Trout Lake Formation was used by Marsden (1972, p. 229) to designate a "...fine-grained, lithographic, locally granular, massive gray to buff, somewhat cherty dolomite..." encountered in drilling in the western part of the Emily district in northwestern Crow Wing County (pl. 1). The unit is confined entirely to the subsurface, but several glacial boulders (Harder and Johnston, 1918; Grout and Wolff, 1955) in the NW¼SE¼ sec. 29, T. 137 N., R. 28 W. are similar to the dolomite intersected in drill holes and thus represent the only known "exposures" of the Trout Lake Formation in the region.

The Trout Lake Formation forms a 24-km-long belt extending from the southwestern part of T. 138 N., R. 26 W. to the southwestern part of T. 137 N., R. 26 W. (pl. 1). A stratigraphic thickness in excess of 27 m is indicated by drilling, but geophysical data suggest a considerably greater thickness.

Marsden (1972) reported that the Trout Lake Formation consists essentially of light-gray to light pinkish-gray dolomite or dolomitic limestone with numerous small masses and thin layers of siliceous material. Many of the siliceous layers have a granular texture and may be recrystallized chert. Other layers are somewhat argillaceous and sericitic and still other layers are definitely epiclastic quartzites.

The stratigraphic position of the Trout Lake strata is somewhat uncertain, for none of the drill holes reported by Marsden (1972, p. 229) intersect the top or the bottom of the formation. However Marsden suggested that it underlies the Mahnomen Formation of the Animikie Group (see below) and overlies slate and quartzite here assigned to the Mille Lacs Group, undivided. Although the available information does not require an unconformable relationship with the Mahnomen Formation, Marsden (1972) inferred that one exists.

Basalt near Mora

Rocks referred to here informally as "basalt near Mora" crop out in a small area about 1.6 km northwest of the city of Mora in central Kanabec County. Most of the exposures occur in sec. 3 and in the NE¼NE¼ sec. 9, T. 39 N., R. 24 W. Geophysical evidence, however, indicates that they form an east-trending body about 3 km wide and 17 km long (pl. 1) that lies between rocks of the Warman Granite to the north and those of the Stearns Granitic Complex to the south (see below). The basalt is overlain to the east by sandstone of Upper Precambrian (Keweenawan) age.

The outcrops near Mora were originally described as a dark greenish-gray "actinolite gabbro" by Woyski (1949). However most of the rock is a very fine-grained microdiabase having rare stubby euhedral plagioclase phenocrysts 1 to 2 cm long. Additionally, a few vesicular zones of sporadic distribution and variable thickness are present locally. Therefore the lithic term basalt is more appropriate.

Although "basalt near Mora" has been extensively altered, primary minerals appear to include plagioclase of labradoritic composition, pyroxene, lesser amounts of interstitial ilmenite and sphene. Plagioclase has been partly replaced by zoisite, pyroxene by actinolite and chlorite, and sphene by hematite and ilmenite. Vesicles are filled with quartz, calcite, plagioclase, and trace amounts of pyrite which together with chlorite and actinolite also fills irregular fracture zones.

The stratigraphic position and age of the "basalt near Mora" are unknown. However the premetamorphic textures and minerals are generally similar to those observed in volcanic rocks included here in the Denham and Randall Formations; therefore the "basalt near Mora" is inferred to be Middle Precambrian in age.

## Animikie Group

The term "Animikie," was first used by Hunt (1873, p. 339) for dark argillite and sandstone in the Thunder Bay district of Ontario on the North Shore of Lake Superior. Similar rocks, exposed 175 km to the southeast around Gunflint Lake in northeastern Minnesota, were thought by Bell (1873, p. 93) to correlate with the Animikie strata around Thunder Bay. Irving (1883, p. 381-390) extended the term Animikie to rocks exposed on the Mesabi range in northern Minnesota. Some 20 years later the U.S. Geological Survey (Van Hise and Clements, 1901) elevated the term Animikie to group status and recognized two new formations--the "Gunflint Iron-formation" and the "Rove slate"--near Gunflint Lake. At the same time, the Animikie (Van Hise and Leith, 1911) strata on the Mesabi range were divided into three formations, from oldest to youngest: (1) Pokegama Quartzite of Winchell (1893), (2) "Biwabik Iron Formation," and (3) "Virginia slate." These and a number of subsequent studies including those of Broderick (1920), Gruner (1922), Gill (1926), Tanton (1931), and White (1954) established in some detail the stratigraphic continuity of the Animikie strata from the Thunder Bay district in Ontario to the westernmost Mesabi range in north-central Minnesota.

As mentioned previously, the correlation of strata in the Cuyuna district with those on the Mesabi range has been the subject of considerable controversy. Much of the controversy resulted from the failure to recognize facies changes, both along the strike of the Mesabi range (Marsden, 1972) and down-dip between the westernmost end of the Mesabi range and the northernmost end of the Cuyuna district (Morey, 1973). Although the main iron-formations of the Mesabi range have never been traced into the main iron-formations of the Cuyuna district, Marsden (1972) had demonstrated that the stratigraphic successions in the two areas are very similar. Furthermore, sparse subsurface information from southeastern Cass County indicates that the argillaceous rocks of the Virginia Formation pass southward into the argillaceous rocks of the Rabbit Lake Formation. Therefore, it is proposed here that the term Animikie Group be extended to include the Mahnomen, Trommald, and Rabbit Lake Formations of east-central Minnesota (Schmidt, 1963).

The extension of the term Animikie into east-central Minnesota accurately portrays the stratigraphic relationships, but it results in six formational names for three lithostratigraphic units. Thus, the boundary between the nomenclatural usage of the Mesabi range and that of the Cuyuna district is here placed along a northeast-trending fault that extends from just north of the Emily area in T. 138 N., R. 27 W. in northern Crow Wing County to the general vicinity of T. 52 N., R. 23 W. in northeastern Aitkin County. North of the fault, argillaceous strata assigned to the Virginia Formation dip gently southward and lack slaty cleavage, whereas south of the fault, similar strata assigned to the Rabbit Lake Formation are folded and have a well developed slaty cleavage. (Marsden, 1972).

Mahnomen Formation

The name Mahnomen Formation was applied by Schmidt (1963) to a sequence of interbedded argillite, siltstone, and lesser amounts of quartzite that overlies rocks of the Mille Lacs Group, undivided, of this report and underlies the main iron-formation--the Trommald Formation of Schmidt (1963)--of the Cuyuna district. The name is taken from the Mahnomen group of mines in sec. 10, T. 46 N., R. 29 W. near the cities of Crosby and Ironton in east-central Crow Wing County.

The Mahnomen Formation is at least 610 m thick (Schmidt, 1963), but it may be much thicker, for the basal contact has never been penetrated by drilling. In contrast the upper contact with the overlying Trommald Formation is fairly well defined on the basis of subsurface data and exposures in several iron ore mines. Generally it is conformable and sharp, but locally as in the Emily district, quartzite near the top of the Mahnomen Formation passes gradationally upward through ferruginous quartzite into sandy iron-formation assigned to the Trommald Formation.

The Mahnomen Formation has never been studied in detail. However, Schmidt (1963) and Marsden (1972) reported that argillite and siltstone are the dominant rock types; quartzite and limestone are present locally, particularly in the upper part of the formation. The argillaceous material--now slate, phyllite, or very fine-grained schist--consists of various proportions of sericite, chlorite, fine-grained quartz and, at appropriate metamorphic grades, muscovite, biotite and garnet. The siltstone is a fine-grained, quartz- and plagioclase-rich massive or laminated rock that contains variable amounts of muscovite, biotite, chlorite, and scattered, minor amounts of pyrite and magnetite or martite. The quartzite is composed of rounded, fine to medium sand-size grains of quartz and trace amounts of plagioclase set in a quartz- or sericite- and chlorite-rich matrix; calcite and iron oxides are present locally as cementing materials. Other beds contain various proportions of admixed sand-size grains of quartz and argillaceous material, and there is a complete gradation between quartzite and argillite. A few beds of brown limestone as much as 40 cm thick have been encountered locally by drilling (Schmidt, 1963), but these rocks have not been described in detail.

Trommald Formation

The main iron-formation of the Cuyuna district, which Schmidt (1963) named the Trommald Formation, forms a distinct lithostratigraphic unit (Marsden, 1972). It is named from drill holes and mines northeast of the village of Trommald (sec. 33, T. 47 N., R. 30 W.) in east-central Crow Wing County. As defined, the formation ranges in thickness from 14 m to more than 150 m on the so-called "North range," from 3 m to 180 m in the Emily district, and averages about 90 m in the so-called "South range" (Marsden, 1972).

Schmidt (1963) and Marsden (1972) described the Trommald Formation in considerable detail and recognized five facies: a thin-bedded facies, a thick-bedded facies, a mixed thin-bedded and thick-bedded facies, an algal chert facies, and an iron-rich quartzite facies. The thin-bedded facies is characterized by quartz-, siderite-, magnetite-, stilpnomelane-, minnesotaite-, and chlorite-rich laminae generally less than 1 cm thick intercalated with chert-rich beds generally less than several centimeters thick; the thin-bedded facies also contains sparsely distributed chert beds as much as 3 m thick. In contrast, the thick-bedded facies is characterized by lenticular layers as much as 1 m thick of granular chert interbedded with thinner layers of thin-bedded strata. Individual chert-rich layers are composed of various proportions of ovoid granules of cherty quartz, carbonates, silicates, or magnetite set in a fine-grained, equigranular groundmass consisting dominantly of chert, chert and carbonates, or chert and silicates. The intercalated thin-bedded layers are mineralogically and texturally similar to strata in the thin-bedded facies.

As the name implies, the mixed thin- and thick-bedded facies is a transitional lithotope characterized by 2- to 15-m-thick layers of interbedded thick-bedded and thin-bedded iron-formation. The algal chert facies is characterized by beds as much as 3 m thick of red algal chert and ubiquitous clastic quartz, whereas the iron-rich quartzitic facies contains abundant grains of clastic quartz set in a matrix of cherty quartz, iron oxides, and manganese oxides. Oolites and pisolites as well as nodules and layers of jaspery chert occur locally in the quartzitic facies.

The distribution of facies in the Trommald Formation is fairly well known on the North range (Schmidt, 1963) and in the Emily area (Marsden, 1972), but is poorly known on the South range. On the North range, parts of the formation consist entirely of either the thin-bedded facies or the thick-bedded facies, but in about a third of the range, the thin-bedded facies underlies the thick-bedded facies and grades upward into it. The stratigraphic succession in the Emily area is similar, in that a mixed facies is gradational into thin-bedded iron-formation below and thick-bedded iron-formation above. However the thin-bedded facies is underlain by the algal chert facies, which in turn is underlain by the iron-rich quartzitic facies.

Although the lithic character of the Trommald Formation on the South range is poorly known, Harder and Johnston (1918) suggested that it consists of rock types similar to those of the thin-bedded facies.

Rabbit Lake Formation

The name Rabbit Lake Formation was proposed by Schmidt (1963) for a thick sequence of gray to black argillite, graywacke, iron-formation, and ferruginous slate that overlies the Trommald Formation near Rabbit Lake in secs. 24 and 25, T. 135 N., R. 26 W. in east-central Crow Wing County. The formation is at least 610 m thick (Schmidt, 1963), but an unknown thickness has been removed by post-Penokean erosion.

The Rabbit Lake Formation has been subdivided into three members (Marsden, 1972), from oldest to youngest: (1) an informal "lower member" composed of carbonaceous slate, graywacke, local mafic flows and coeval hypabyssal, volcaniclastic and volcanogenic rocks; (2) the "Emily Member," a sequence of iron-rich strata; and (3) an informal "upper member" consisting of argillite, slate, graywacke and lesser amounts of carbonaceous slate.

Lower Member: The "lower member" of Marsden (1972) may be as much as 60 m thick and consists predominantly of carbonaceous argillite or slate. On the North range the argillaceous rocks are interbedded with units of chloritized basalt, grayish-green and dark greenish-gray chlorite-bearing tuff, tuffaceous slate, (Schmidt, 1958, 1963), and a few scattered lenses of ferruginous chert less than 3 m thick. Most of the volcanic rocks in this member have not been studied in any detail, but Marsden (1972) reported that the tuffs are composed of flattened and ellipitical or spindle-shaped grains that range in size from fragments a centimeter in diameter to silt- and clay-size particles.

The lower member has not been recognized on the South range, but in the Emily area it consists of quartzose argillite and graywacke, and generally averages 60 to 90 m in thickness; in some places it is as much as 150 m thick, but in other places it is entirely missing. Marsden (1972) reported that some of the lower member in the Emily area is conglomeratic with clasts of quartz, chert and iron-formation.

Emily Member: The Emily Member was informally named and described by Marsden (1972) from subsurface data in T. 138 N., R. 26 W. in northeastern Crow Wing County. He reported that it consists of interbedded iron-rich strata, argillite, slate and carbonaceous slate. Although it is difficult to estimate the thickness of the Emily Member, Marsden (1972) reported drill hole intersections of more than 60 m and in places of more than 300 m. However the latter value may be the result of as yet unrecognized structural complexities. Nonetheless the member constitutes a distinct stratigraphic unit throughout the Emily area that extends, at least locally, into the North range and possibly into the South range (pl. 1). In the Emily area, its thickness and extent justify its being designated a formation. However, because of rather indistinct boundaries, the presence of intercalated argillite, slate, and carbonaceous slate, and the possible lenticularity of the iron-rich strata, Marsden (1972) included the unit as an informal member in the Rabbit Lake Formation. Because the Emily Member is a mappable unit over a wide area on the Cuyuna range, it is designated here as a formal member of the Rabbit Lake Formation. The type locality is the Emily area in T. 138 N., R. 26 W. in northeastern Crow Wing County.

The Emily Member consists predominantly of interbedded green to black, fine-grained, locally carbonaceous argillite, and siderite- and ankerite-rich iron-formation having sparse but characteristic white or light-gray chert in pea-size nodules and centimeter-thick beds. Some of the carbonaceous beds contain about 10 percent pyrite, whereas the layers of iron-formation resemble the thin-bedded facies of the Trommald Formation. However the Emily Member differs from the Trommald Formation in containing interbedded argillite or slate, in having gradational contacts, and in being very siliceous.

Upper Member: A very thick sequence of clastic strata gradationally overlies the Emily Member. Marsden (1972) reported that rocks assigned to this member have been described as being gray, green, or black argillite, gray and green slate, graphitic slate and, rarely, graywacke. Numerous beds of chert, ferruginous chert and iron-formation occur in the lower part of the member, where they are intercalated with beds of graphitic slate and argillite. None of these rocks have been described in detail.

### Thomson Formation

The term "Thomson slates" was introduced by N.H. Winchell (see Spurr, 1894) for a sequence of rocks exposed over a wide area in parts of Carlton, Pine and St. Louis Counties. He named the rocks for exposures along and in the valley of the St. Louis River in secs. 5, 6, 7, and 8, T. 48 N., R. 17 W., just west of the village of Thomson in northeastern Carlton County. Subsequently, these rocks were referred to as the "St. Louis slates" (Hall, 1901), "Cloquet slates" (Spurr, 1894), and "Carlton slates" (Sandberg, 1938). Although the name "Thomson slates" has priority, Schwartz (1942) suggested the name "Thomson Formation" because graywacke and siltstone make up a considerable part of the sequence. The latter usage is retained here.

At the type locality, the Thomson Formation consists of about 46 percent graywacke, 27 percent siltstone and 27 percent slate (Schwartz, 1942; Wright and others, 1970). Two stratigraphic sections described by Morey and Ojakangas (1970) in the same general vicinity have somewhat different proportions averaging 34 percent graywacke, 39 percent siltstone, and 27 percent slate. These data indicate that the relative abundances of graywacke, siltstone, and slate vary considerably and without regard to stratigraphic position. Locally the Thomson Formation 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.

At least 900 m of the Thomson Formation are exposed in and around the type area near the village of Thomson (Wright and others, 1970). Undoubtedly the total thickness of the formation is much greater, but it cannot be measured because of structural complexity, lack of continuous exposures, general absence of recognizable marker beds, and because neither the top nor the bottom of the formation is exposed.

Because neither the top nor the bottom is exposed, the stratigraphic position of the Thomson Formation has been the subject of considerable debate since it was first suggested that it was equivalent to the Animikie strata exposed at Thunder Bay, Ontario (Irving, 1883). Subsequently other workers correlated the Thomson Formation with "Knife Lake strata" of "Earlier Precambrian age" on the basis of presumably similar lithic and structural attributes. (For a summary see Grout and others, 1951, p. 1038). However, Goldich and others (1961) concluded on the basis of radiometric data that the Thomson Formation was metamorphosed during the Penokean orogeny, and Morey and Ojakangas (1970) demonstrated that it is mineralogically and sedimentologically similar to other Middle Precambrian graywacke-argillite successions in Minnesota. Thus the Thomson Formation is believed to represent the down-basin extension of the upper part of the Animikie Group in Minnesota (Morey, 1973).

There is a progressive increase in the metamorphic grade of the Thomson Formation from the type locality near Thomson to exposures in the E½ sec. 19 T. 45 N., R. 20 W., near Denham in northwestern Pine County (Hall, 1901; Schwartz, 1942: Weiblen, 1964). Near Thomson, the metamorphic grade is low; sedimentary textures and structures are well preserved and the formation contains various proportions of quartz, albite or sodic oligoclase, chlorite, sericite, and calcite or dolomite. Interlayered carbonate concretions are characterized by large grains of calcite and dolomite that enclose the above-mentioned detrital minerals. Incipient phyllite first occurs in the argillaceous parts of the formation about 8 km southwest of Thomson, but at Atkinson, about 17 km southwest of Thomson, fine-grained phyllitic rocks characterized by muscovite flakes as much as 10 mm long are well developed. Other minerals include quartz, albite, chlorite, and calcite or dolomite. Detrital textures and minerals are still discernible in the interbedded graywacke units, but twinning in plagioclase is no longer apparent. Biotite first appears in argillaceous rocks about 38 km south of Thomson. From there southward, the argillaceous beds have a schistose fabric and the interbedded graywacke units are completely recrystallized. At the city of Moose Lake, 62 km south-southwest of Thomson, 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 that parallels bedding. Elongate carbonate concretions parallel the foliation and contain scattered grains of hornblende. Near Denham both the metagraywacke and 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 having contorted lines of inclusions that can be traced from one metacryst to another. Biotite and muscovite are wrapped around the garnet, indicating that the latter 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).

## MIDDLE PRECAMBRIAN PLUTONIC ROCKS

Middle Precambrian plutonic rocks are confined to that part of east-central Minnesota presumably underlain by Lower Precambrian gneissic rocks. The wide variety of metavolcanic and metasedimentary inclusions in the plutonic rocks indicates that the basement gneisses were overlain by Middle Precambrian stratified rocks when the plutonic rocks were emplaced.

The igneous activity 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, or 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 of this report-- which in turn was followed by the emplacement of several large plutons of generally sodic composition--the Reformatory, Isle, Warman and Pierz Granites of this report. Plutonic igneous activity culminated with the emplacement of the Stearns Granitic Complex. This granitic pluton consists of the St. Cloud Granite, which in turn is divisible into several facies, and a discrete border facies named the Rockville Granite. Woyski (1949) collectively referred to these rocks as the "Stearns Magma Series," mainly because they compose parts of the same pluton. In accordance with the recommendations of Sohl (1977) the name "Stearns Magma Series" is changed here to Stearns Granitic Complex.

The granitic rocks were emplaced after Penokean deformation, as indicated by their relatively homogeneous and undeformed nature and by the fact that they cut structural features 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 Penokean orogeny, as evidenced by incipient cataclastic zones that coincide with fold axes and other structures of Penokean age in the Middle Precambrian stratified rocks. Additionally, another Middle Precambrian igneous unit, a tonalitic phase in the Hillman Migmatite of this report, was clearly emplaced prior to the Penokean orogeny and perhaps before the Middle Precambrian stratified rocks were deposited.

## Hillman Migmatite
(modified name)

The name "Hillman gneissoid biotite tonalite" was applied by Woyski (1949) to light- or dark-gray, medium- to coarse-grained, strongly foliated rocks that crop out over an area of about 1,700 $km^2$ in eastern Morrison and northern Mille Lacs Counties (pl. 1), and Goldich and others (1961) referred to these rocks simply as the "Hillman tonalite." However, because most exposures contain variable proportions of igneous and metasedimentary material, the name Hillman Migmatite is proposed here to reflect the composite nature of this unit. Woyski (1949) defined the type locality as several exposures along Hillman Creek in the SE¼ sec. 35, T. 41 N., R. 29 W. and it is retained here. Other exposures occur along the West Branch of the Rum River in the SE¼ sec. 9, T. 40 N., R. 29 W., along the Skunk River in the SE¼ sec. 6, T. 41 N., R. 28 W.; near the center of sec. 12, T. 41 N., R. 29 W.; and in the E½ sec. 20 and W½ sec. 21, T. 41 N., R. 29 W.

Metasedimentary material in the Hillman Migmatite consists dominantly of dark-gray to black, fine- to medium-grained biotite schist and lesser amounts of hornblende schist and metagraywacke. These rock types may occur as separate entities or as interlayered masses, but invariably the included material is isoclinally folded about east-northeast-plunging axes; this structural grain appears to have controlled the emplacement of the tonalitic material (Keighin and others, 1972). Where the included material composes one-half to more than two-thirds of the migmatite, it has either an agmatic structure, or more typically, an augen structure (Mehnert, 1968, p. 10) characterized by swarms of closely spaced, subparallel, lenticular inclusions that have relatively straight and sharply defined contacts. However, where inclusions are less abundant, biotite schist occurs as irregular, wisplike schlieren having irregular and transitional contacts with the enclosing tonalite, whereas hornblende schist and metagraywacke are sporadically distributed in linear zones that define a regional foliation. Individual inclusions within these zones have a blocky shape and resemble boudins, but many are rotated as much as 30° to the tectonic grain.

The modal mineralogy of the included 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 fine-grained garnet also are present in both rock types. In contrast, included biotite schist is much more complex mineralogically, consisting of quartz, plagioclase, biotite, garnet and cordierite. Much of the garnet exhibits at least two periods of development; grains of the earlier period, as large as 5 cm in diameter, enclose wormy intergrowths of quartz and commonly have been either rotated, or crushed and drawn out parallel to a foliation defined by elongate grains of plagioclase and biotite. These early-formed garnet grains are mantled by garnet that is inclusion-free and 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.

Where the tonalitic phase of the Hillman Migmatite is not contaminated by metasedimentary material, it is a vaguely foliated, gray, medium- to coarse-grained, equigranular rock composed of 20-50 percent quartz, 20-50 percent feldspar, 7-10 percent biotite, and trace to minor amounts of hornblende, pyroxene, chlorite, muscovite and calcite; most of the feldspar is euhedral plagioclase of andesinic composition, but trace to minor amounts of microcline also are present. Minor amounts of myrmekite, perthite and antiperthite also occur as anhedral, interstitial phases and as inclusions in plagioclase. Principal accessory minerals include apatite, sphene, zircon and magnetite. However, where inclusions are abundant, the tonalite has a well-developed foliation defined by elongate grains and lenticular aggregates of biotite which constitutes more than 10 percent of the modal mineralogy. Additionally, both the contaminated and uncontaminated phases are altered extensively; sericite, epidote, chlorite, and calcite are common secondary minerals. Consequently it is difficult to distinguish uncontaminated from contaminated tonalite on the basis of petrographic criteria.

A number of K-feldspar-, quartz-, and garnet-bearing pegmatites of various sizes and shapes cut both the metasedimentary and igneous phases and exhibit a vaguely developed foliation that transects the regional foliation at a small angle. This foliation is manifested in the included material as small-scale kink bands, in which garnet is replaced by biotite, cordierite by muscovite and chlorite, and plagioclase is fractured and sericitized. This foliation is similarly manifested in the tonalitic rocks by incipient cataclastic zones with broken and sericitized grains of feldspar and undulatory quartz. K-feldspar also occurs as elongate grains in both the included and tonalitic material, and together with the biotite it appears to represent yet another period of mineral growth that was more or less contemporaneous with a late period of deformation.

The Hillman Migmatite is intruded by and therefore is older than the Middle Precambrian igneous rocks of granodioritic and granitic composition. However the stratigraphic position of the Hillman Migmatite relative to that of the Middle Precambrian stratified rocks north and west of it is equivocal inasmuch as contacts are neither exposed nor have they been pentrated by drilling.

Woyski (1949) concluded that the Hillman was older than the Middle Precambrian stratified rocks mainly because she believed that the included metasedimentary rocks were the metamorphosed equivalents of the Thomson Formation which Schwartz (1942) had previously correlated with "Knife Lake" strata of "earlier Precambrian" age. Although Goldich and others (1961) and Morey and Ojakangas (1970) subsequently correlated the Thomson Formation with the uppermost strata of the Animikie Group, Keighin and others (1972) continued to assume that the included metasedimentary rocks were a part of the Thomson Formation that was metamorphosed and intruded by tonalitic rocks during the Penokean orogeny. However, the Penokean orogeny in east-central Minesota was not a migmatite-forming event. Rather, even at the highest metamorphic (staurolite) grade, bedding and other primary structures in the adjacent Middle Precambrian stratified rocks were neither destroyed nor migmatized. Thus the Hillman Migmatite may represent a still older Middle Precambrian sequence, or it may be part of a Lower Precambrian sequence that was reactivated during the early part of Middle Precambrian time. In any event, the Hillman Migmatite appears to form part of the basement upon which the Middle Precambrian stratified rocks were deposited.

## Unnamed Gabbroic and Dioritic Rocks

Several kinds of dark-gray, fine-grained gabbro and medium-gray, medium-grained diorite crop out sporadically in the general vicinity of Little Falls in southern Morrison County. Generally these rocks occur as tabular bodies no more than several tens of meters wide, too small to be shown on Plate 1. However, exposures 1.6 km west of Little Falls in the NE¼NE¼ sec. 13, T. 129 N., R. 30 W. comprise part of a mappable unit, which to judge from geophysical data is at least 600 m wide and 1,500 m long (pl. 1).

Most of the tabular bodies consist of either gabbro or diorite, but the exposure in sec. 13 is a composite body of gabbro intruded by diorite. The two rock types are coeval as indicated by a lack of chilled contacts and the fact that both contain 50-70 percent subhedral plagioclase having a primary flow foliation; additionally the plagioclase in both rock types is zoned from sodic labradorite to calcic andesine and extensively sericitized. The two rock types differ mainly in the nature of the mafic minerals. The gabbroic rocks contain 23-25 percent augite, 17-20 percent biotite, and 1-3 percent hornblende, whereas the dioritic rocks contain 1-2 percent augite, 1-3 percent biotite, and 35-40 percent hornblende. In the gabbroic rocks augite occurs as euhedral to subhedral grains 1-2 mm in diameter. Most are twinned and many are mantled by hornblende and some biotite, which in turn is altered to chlorite and opaque oxides. Some large grains of biotite also occur as a late-forming mineral that poikilitically encloses plagioclase, augite, and zircon. The dioritic rocks, in contrast, contain interstitial grains of hornblende, a few of which have pyroxene cores and wormy surface intergrowths of biotite. Some pyroxene is altered to chlorite or serpentine, and some hornblende is altered to actinolite. Biotite, in part altered to chlorite, occurs as small interstitial plates in the groundmass.

All of the gabbroic and dioritic rocks so far recognized in and around the city of Little Falls are intrusive into the Little Falls Formation. Although contacts are rarely exposed, the igneous rocks appear to trend in a direction that parallels axial plane directions in the Little Falls Formation, implying that they were emplaced after the onset of Penokean deformation. However, argillaceous rocks adjacent to the igneous bodies are somewhat contorted, implying that some additional deformation occurred during or after emplacement. Therefore, these gabbroic and dioritic rocks appear to represent the onset of Middle Precambrian igneous activity during the waning stages of the Penokean orogeny.

## Freedhem Granodiorite
(modified name)

The name "Freedhem hornblende tonalite" was first proposed by Woyski (1949) for exposures in several abandoned quarries about 4.5 km south of the village of Freedhem in northeastern Morrison County. She designated the exposures in secs. 23 and 24, T. 41 N., R. 31 W. as the type locality; additional exposures are in secs. 7 and 18, T. 41 N., R. 30 W. and in sec. 34, T. 42 N., R. 31 W. Goldich and others (1961) referred to these rocks simply as the "Freedhem tonalite," even though they noted that the rocks at the type locality contain 10 to 20 percent K-feldspar. The name Freedhem Granodiorite is proposed here to characterize these rocks more appropriately.

Well-defined gravity and magnetic anomalies indicate that the Freedhem Granodiorite forms an ellipitical pluton, about 18 km long and 10 km wide that discordantly cuts the Hillman Migmatite (pl.

1). Where exposed, the Freedhem Granodiorite is medium dark gray to grayish black, fine to medium grained, and generally massive, but the edges of the pluton are characterized by a steep foliation conformable to the boundaries of the pluton as inferred from geophysical data. Additionally, a few poorly developed, east-northeast-trending, apparently cataclastic zones several centimeters to a meter wide may be observed in the more massive interior of the pluton.

Essential minerals include 30-40 percent plagioclase, 10-20 percent quartz, 19-30 percent K-feldspar, 17-18 percent biotite, trace amounts to 2 percent hornblende, and trace amounts of pyroxene. Large, euhedral grains of plagioclase are strongly zoned with an anorthite content ranging from $An^{50}$ cores to $An^{20}$ rims and averaging around $An^{35}$. Andesinic plagioclase also occurs as small, interstitial grains between larger grains of plagioclase and quartz. Quartz is strained and commonly contains sericite-healed fractures. The K-feldspar occurs as antiperthitic blebs within plagioclase or as fine to medium grains of microcline in interstitial spaces. Hornblende occurs both as a primary mineral and as an alteration product of augite. Large grains of reddish-brown biotite occur as a primary mineral, particularly in the border zone where it defines a primary foliation, and as an alteration product of hornblende. Primary accessory minerals include apatite, zircon, sphene, magnetite, and pyrite. Within the clataclastic zones, quartz is extensively recrystallized, plagioclase is altered to sericite and replaced by zoisite, and hornblende is replaced by fibrous green biotite, which in turn is replaced by chlorite.

The Freedhem Granodiorite is cut by several undeformed, meter-wide granitic dikes of sodic composition. The dikes trend in an east-northeast direction, generally parallel to the trend of the cataclastic zones, 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.

Discordant contact relationships indicate that the Freedhem Granodiorite is younger than the tonalitic phase of the Hillman Migmatite and older than the granitic igneous activity. Additionally, the presence of vaguely developed cataclastic structures virtually coincident in orientation to other Penokean structural elements in the area suggests that the granodiorite was emplaced during the waning stages of the Penokean orogeny.

## Bradbury Creek Granodiorite
(new name)

Rocks here named the Bradbury Creek Granodiorite crop out in a small area along and north of Bradbury Creek in secs. 25 and 26, T. 41 N., R. 27 W., and in secs. 29 and 30, T. 41 N., R. 26 W. in northwestern Mille Lacs County. A small group of outcrops along the north-south line between sec. 25, T. 41 N., R. 27 W. and sec. 30, T. 41 N., R. 26 W. are designated here as the type locality.

The exposures of the Bradbury Creek Granodiorite were originally mapped by Woyski (1949) as a hornblende-bearing phase of the "Hillman gneissoid biotite tonalite." However, geophysical data indicate that the exposures are part of a small elliptical pluton about 11 km long and 6 km wide (pl. 1). The interior of the pluton is generally gray to black in color, fine to medium grained, and contains 35-40 percent andesinic plagioclase, 25-35 percent quartz, 10-15 percent K-feldspar, and 5-15 percent hornblende. Biotite, magnetite, zircon and apatite also are present in minor to trace amounts. Although granodioritic in composition, these rocks differ from the Freedhem Granodiorite in containing abundant hornblende and small amounts of biotite. As much as 10 percent biotite does occur 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.

Discordant contact relationships indicate that the Bradbury Creek Granodiorite is younger than the tonalitic phase of the Hillman Migmatite. Because of generally similar structural and mineralogical attributes, it is correlated here with the Freedhem Granodiorite. It also should be noted that geophysical data indicate the presence of several other elliptical plutons cutting the Hillman Migmatite. Because of similar geophysical signatures, these bodies are correlated with the Freedhem and Bradbury Creek Granodiorites, but inasmuch as they are not exposed, they are shown on Plate 1 as granodioritic rocks, undivided.

### Warman Granite
(modified name)

Exposures in northern Kanabec and adjoining parts of Aitkin and Mille Lacs Counties (pl. 1) were named the Warman Quartz Monzonite by Woyski (1949). She designated the type locality as several abandoned quarries in and near the village of Warman in the SE¼ sec. 5, T. 41 N., R. 23 W. in north-central Kanabec County. At the type locality and generally throughout its outcrop area, the Warman 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, and 7-20 percent biotite. Therefore the name Warman Granite is proposed here to characterize the modal mineralogy more appropriately. Euhedral grains of quartz, which poikilitically enclose smaller rounded grains of plagioclase, have been fractured and partly replaced by myrmekitic intergrowths of quartz and microcline. Plagioclase occurs as euhedral or subhedral grains that are zoned from oligoclase to albite; the calcic cores are extensively altered to sericite, whereas the albitic rims appear relatively fresh. K-feldspar is dominantly microcline and occurs as small, euhedral to subhedral, extensively altered grains in interstitial spaces between large grains of quartz and plagioclase, and as unaltered rims that surround the large plagioclase and the smaller and more altered K-feldspar grains. Biotite occurs as euhedral to subhedral grains more or less uniformly throughout the rock; it contains inclusions of apatite and sphene, and locally is somewhat altered to chlorite. Other accessory minerals include augite, magnetite, sphene and zircon.

The Warman is generally massive except for numerous small inclusions of biotite-quartz-plagioclase schist that are scattered throughout the unit and for large masses of included metasedimentary rocks in secs. 9, 15, and 16, T. 42 N., R. 23 W., where the Warman is in contact with metasedimentary rocks of the Mille Lacs Group (pl. 1). The inner part of this contact zone typically contains sparse and irregularly distributed schlieren of biotite schist which become larger and more abundant toward the contact zone. Additionally, the outer part of the contact zone contains strongly foliated inclusions of fine- to medium-grained quartz-rich biotite schist. Thus the Warman Granite is younger than the Mille Lacs Group and presumably also younger than the basalt at Mora. Additionally, textural and mineralogical modifications--sericitization and replacement of plagioclase by epidote and clinozoisite and replacement of biotite by chorite--in several outcrops in sec. 30, T. 40 N., R. 25 W. in central Kanabec County imply that the Warman is older than the Stearns Granitic Complex. However contact relationships with the Isle Granite have not been observed in outcrop.

### Isle Granite
(modified name)

The name Isle Quartz Monzonite was proposed by Goldich and others (1961) for a light-gray to light pinkish-gray rock quarried approximately 8 km south of the village of Isle in northern Mille Lacs County. Because the Isle characteristically is a granite according to the IUGS classification scheme, the name Isle Granite is proposed here. It can be divided into two facies--an older, light pinkish-gray, porphyritic facies characterized by plagioclase phenocrysts as much as 2.5 cm long; and a younger, light-gray, fine- to medium-grained facies that resembles the Warman Granite. Both facies are well exposed at the type locality, a quarry in the NE¼ sec. 3, T. 41 N., R. 25 W., and are similarly intermixed over a wide area.

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, 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; the plagioclase phenocrysts are randomly oriented and conspicuously zoned from andesine to oligoclase, and the calcic cores are sericitized and replaced locally by zoisite or epidote. Quartz occurs in the groundmass as euhedral grains and in myrmekitic intergrowths which rim the plagioclase phenocrysts. K-feldspar also occurs in the groundmass as perthitic microcline that poikilitically encloses small, rounded grains of plagioclase and quartz. Biotite occurs as small anhedral to subhedral grains in the groundmass and locally as rims around small grains of augite. Although Grout (see Harder and Johnston, 1918, p. 42) has reported that rocks here assigned to the Isle Granite intrude those assigned to the Hillman Migmatite in the NW¼SE¼ sec. 17, T. 42 N., R. 26 W., 7 km southwest of the village of Wahkon in northern Mille Lacs County, I have not been able to find these exposures. Nonetheless, because the younger facies of the Isle has textural and mineralogic attributes similar to those of the Warman Granite, it is assumed here that they are part of the same magmatic event, and that the older, porphyritic facies most likely represents an earlier phase of that event.

## Pierz Granite
(new name)

The name Pierz Granite is applied here to a light-gray, equigranular rock that crops out over a small area a short distance south of Pierz Lake aproximately 3 km west of the city of Pierz in east-central Morrison County. The type locality is here designated as an abandoned quarry in the SE¼ sec. 13, T. 40 N., R. 31 W.

Although this pluton is poorly exposed, geophysical data suggest that it has an elliptical shape with a long axis of about 9 km and a short axis of about 3 km. The pluton is oriented subparallel to the structural grain of the Hillman Migmatite which apparently controlled its emplacement (pl. 1).

The Pierz Granite resembles the Warman Granite and the younger facies of the Isle Granite in both texture and mineralogy, and therefore it was originally mapped by Woyski (1949) as part of her Warman quartz monzonite. Although the Pierz, Warman and Isle Granites most likely formed during the same magmatic episode, the Pierz is separated from the nearest exposures of Warman and Isle by approximately 40 km of rocks assigned to the Hillman Migmatite. Therefore, it seems appropriate that the rocks exposed at Pierz be given a formal lithostratigraphic designation.

## Reformatory Granite
(new name)

The name Reformatory Granite is proposed here for rocks quarried under a variety of trade names, including "Charcoal gray," "Oxford gray," "Reformatory gray," "St. Cloud gray," "Pioneer gray" and "Minnesota dark gray" (Thiel and Dutton, 1935; Bowles, 1918). Woyski (1949) referred to these rocks as the "St. Cloud gray augite-hornblende granodiorite" and that name or the somewhat shorter version "St. Cloud gray granodiorite" (Goldich and others, 1961; Keighin and others, 1972) has been used extensively in the literature to describe these rocks. However because the geographic descriptor "St. Cloud" also has been applied to granitic rocks in and around the city of St. Cloud (see below) and because the unit consists dominantly of sodic granite rather than granodiorite, it is here recommended that the term "St. Cloud gray augite-hornblende granodiorite" and its derivatives be abandoned and replaced by the term Reformatory Granite.

The type locality of the Reformatory Granite is designated here as a group of abandoned quarries immediately north of the St. Cloud State Reformatory in the SE¼SW¼ and SW¼SE¼ sec. 6, T. 35 N., R. 30 W. Other informative exposures occur south of the city of St. Cloud and particularly in the NE¼SW¼ sec. 21, the NW¼SW¼ sec. 27 and the SW¼NW¼ sec. 34, all in T. 124 N., R. 28 W. Although the Reformatory Granite is exposed only in the vicinity of St. Cloud, geophysical and subsurface data indicate that it is a northeast-trending pluton of batholithic dimensions that underlies parts of Stearns, Sherburne, Benton, Mille Lacs, and Kanabec Counties (pl. 1).

The Reformatory Granite is a generally light- to dark-gray, relatively massive rock, but almost every exposure contains inclusions of hornblende schist, biotite schist, or garnetiferous biotite schist. The hornblende schist inclusions have blocky shapes and fairly distinct contacts, whereas the biotite-rich inclusions occur either as small, rounded bodies with distinct contacts or as small "knots" and schlieren with indistinct and gradational borders. Additionally, dikes of granite porphyry and aplite are common, as are dikes and apophyses of the Stearns Granitic Complex, and they 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. Therefore it is difficult to sample unaltered rocks of the pluton with any degree of certainty. Nonetheless samples well away from apparent sources 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. Accessory minerals include zircon, apatite, sphene, magnetite, ilmenite, pyrite, and chalcopyrite.

Much of the Reformatory Granite is vaguely porphyritic with large grains of plagioclase and some orthoclase randomly oriented in a finer grained, more or less equigranular groundmass. The plagioclase phenocrysts are euhedral to subhedral in shape, 2 to 4 mm in length, and commonly zoned from andesine to oligoclase. Many phenocrysts are rimmed by albite or by myrmekitic intergrowths of quartz and oligoclase. Commonly the calcic cores contain small grains of biotite and are altered to epidote and iron oxides, whereas the sodic rims are sericitized and streaked with iron oxides. Although rare, orthoclase phenocrysts as much as 4 mm in diameter always occur as anhedral grains that are dusty and streaked with iron oxides. Perthitic microcline is the dominant K-feldspar; it occurs as a groundmass mineral and commonly contains small, rounded inclusions of oligoclase, quartz and biotite. Additionally some K-feldspar also occurs as antiperthite formed by exsolution from oligoclase, but some possibly formed by subsequent replacement. Quartz occupies interstices between feldspar grains and less commonly occurs as blebs in plagioclase, microcline and mafic minerals. The mafic minerals include biotite, hornblende, and lesser amounts of augite, magnetite and ilmenite. Two varieties of hornblende are present--a brown variety that occurs as euhedral grains which most likely are primary, and a light-green variety that occurs pseudomorphic after augite. Similarly some biotite occurs as brown euhedral grains that most likely are primary, but green biotite dominates as subhedral to anhedral grains that are pseudomorphic after green hornblende. The augite, green hornblende and green biotite all contain inclusions of ilmenite surrounded by magnetite or by sphene. These inclusions occupy cleavage directions in the augite and this distribution is mimicked in both hornblende and biotite. Sphene also occurs as spongelike masses in plagioclase and microcline and as small elongate grains along cleavage directions in the brown biotite. Inasmuch as the green biotite is embayed by quartz, and the brown biotite is included in feldspar, it appears that most of the mafic minerals formed prior to crystallization of the quartz and feldspar.

Only limited data are available regarding the stratigraphic position of the Reformatory Granite. It is younger than the metasedimentary rocks that occur as inclusions in it and older than the Stearns Granitic Complex which intrudes it. The Reformatory Granite is not in contact with the other sodic granites in east-central Minnesota. It generally resembles the porphyritic phase of the Isle Granite in that both contain plagioclase phenocrysts that are zoned from andesine to oligoclase, and relict augite. However, the Reformatory Granite may be somewhat older, mainly because of the more complex paragenetic history exhibited by the mafic minerals.

### Stearns Granitic Complex
(modified name)

The name Stearns Granitic Complex is defined here to include two formal lithostratigraphic units, the St. Cloud Granite and the Rockville Granite. The St. Cloud Granite may be divided into several facies which with additional mapping may prove to be of formational status. Nonetheless, the evidence available now suggests that all the rocks of the complex are part of a northeast-trending pluton about 80 km long and 32 km wide. This pluton crops out over a wide area in western Mille Lacs County, in northwestern, central and western Benton County, eastern and northeastern Stearns County, southeastern Morrison County and northwestern Sherburne County (pl. 1). The Stearns Granitic Complex forms the youngest granitic pluton in east-central Minnesota, for it contains inclusions derived from almost all of the previously described units.

Most inclusions in the southern part of the batholith were derived from the Reformatory Granite, or less commonly from the Richmond Gneiss, whereas inclusions in the northern part were derived from the Warman or Isle Granites, the Hillman Migmatite, and the Watab Amphibolite. Inclusions of metabasalt, iron-formation, quartz-rich metagraywacke, and biotite schist, which have been recognized at various scattered localities throughout the complex, presumably were derived from the Middle Precambrian stratified rocks that once covered the area.

St. Cloud Granite (modified name)

Exposures of the St. Cloud Granite occur in numerous quarries in the vicinity of the cities of St. Cloud and Waite Park in Stearns County. These rocks have been quarried under a variety of trade names including "Indian red," "Rose red," "Melrose red," "North Star red," "Ruby red," "Mahogany red," "Standard red" and "St. Cloud red" (Thiel and Dutton, 1935; Bowles, 1918). Woyski (1949) demonstrated that all these rocks were part of the same intrusive body, which she named the "St. Cloud red augite-hornblende granite." Subsequently Goldich and others (1961) shortened this name to "St. Cloud red granite," but inasmuch as the rock is not everywhere red in color, the name St. Cloud Granite is used here.

Although textural and mineralogical attributes are quite variable, the St. Cloud Granite can be divided into several distinct facies, including: (1) a vaguely porphyritic granite facies of generally sodic composition; (2) a porphyritic granite facies of potassic composition which in places grades into pegmatite; and (3) an equigranular granite facies, also of potassic composition. In addition, a border facies--the so-called "white porphyritic granite" of Woyski (1949)--can be recognized along the northwestern edge of the pluton, particularly in Benton County in the SE¼NE¼ sec. 35, T. 37 N., R. 31 W.

Facies 1 through 3 are well exposed in a group of abandoned quarries in the SE¼ sec. 19 and the SW¼ sec. 20, T. 124 N., R. 28 W. which are designated here as the type locality. Other informative localities in Stearns County include several abandoned quarries in the SE¼ sec. 24, T. 124 N., R. 29 W., in the SE¼SW¼ sec. 17, T. 124 N., R. 28 W., and in the SE¼NE¼ sec. 17, T. 125 N., R. 28 W. Exposures of the St. Cloud Granite occur in Benton County in the SW¼ sec. 13, T. 36 N., R. 31 W. and the SE¼ sec. 17, T. 38 N., R. 28 W.; representative exposures in Sherburne County may be found in the SE¼ sec. 17, T. 35 N., R. 30 W.

Porphyritic Granite Facies of Sodic Composition: This dusky-red, medium- to coarse-grained, vaguely porphyritic facies crops out south and southwest of the cities of St. Cloud and Waite Park. The facies contains 24-38 percent sodic plagioclase, 20-34 percent K-feldspar, 24-25 percent quartz, 3-11 percent biotite, 5-12 percent augite. Accessory and minor minerals include zircon, apatite, sphene, ilmenite, magnetite, tourmaline, and rutile. The porphyritic texture is imparted by 1- to 2-mm grains of plagioclase and somewhat larger grains of perthitic microcline. The plagioclase phenocrysts are zoned from oligoclase to albite and are rimmed by myrmekitic overgrowths of quartz and K-feldspar. The microcline phenocrysts contain exsolved hematite, which imparts the red color to the facies, small rounded grains of plagioclase, and trace amounts of antiperthite. Fine- to medium-size grains of anhedral quartz and microcline fill interstitial voids between the larger feldspar grains, as do sporadically distributed, subhedral grains of hornblende and brown biotite. Additionally, green biotite occurs as feltlike grains in irregularly shaped clusters or as rims surrounding hornblende. Some of the hornblende may be primary as evidenced by exsolution laminae and by corroded contacts with quartz and feldspar, but much of it is pseudomorphic after small anhedral grains of augite. Chlorite has replaced some of the biotite, leucoxene occurs as rims around ilmenite, and calcite, epidote and sericite have replaced some of the hornblende and plagioclase.

Porphyritic Granite Facies of Potassic Composition: This pinkish-gray, medium-grained, porphyritic facies is intermixed on all scales with the sodic porphyritic facies, particularly in and around the type locality southwest of St. Cloud. However, together with various-sized bodies of coarse-grained pegmatite, it forms the dominant facies in and to the north of the cities of St. Cloud and Waite Park. Although widely distributed, the porphyritic granite facies of potassic composition is mineralogically homogeneous, consisting of 42-46 percent microcline, 37-39 percent quartz, 14-15 percent sodic plagioclase, 2-3 percent biotite, and trace amounts of hornblende and pyroxene. The pegmatitic bodies differ mainly in containing more microcline, and smaller amounts of quartz and mafic minerals.

As the name implies, this facies is characterized by medium-size phenocrysts of microcline set in a somewhat finer grained groundmass of quartz, albitic plagioclase, microcline, biotite, hornblende, and augite. The microcline phenocrysts are perthitic and hematite stained, contain inclusions of myrmekitic quartz and albite, and are rimmed by graphic intergrowths of quartz and K-feldspar. Microcline also occurs in the groundmass as rims surrounding grains of vaguely zoned and sericitized plagioclase, as discrete grains, and as graphic intergrowths with quartz. Subhedral plates of brown biotite are more or less uniformly distributed throughout the groundmass, whereas hornblende is localized as small, polycrystalline aggregates. Small, corroded grains of augite occur as inclusions in the hornblende, which in turn is altered almost completely to plagioclase.

Equigranular Granite Facies of Potassic Composition: Rocks of the St. Cloud Granite that crop out north and east of the Mississippi River in Benton, Sherburne, and Mille Lacs Counties differ from those described above in that they have a coarse-grained, equigranular texture and a pale-pink color. This facies consists essentially of 42-61 percent cent microcline, 26-44 percent quartz, 3-19 percent albitic plagioclase, trace amounts to 5 percent biotite, and trace amounts to 2 percent hornblende. Although the modal mineralogy varies considerably, individual minerals have textural and paragenetic attributes similar to those that characterize the porphyritic granite facies of potassic composition.

Border Facies: Near the western margin of the St. Cloud Granite, in sec. 35, T. 37 N., R. 31 W., the equigranular granite facies grades transitionally through a light-gray, porphyritic granite into a reddish-gray granite porphyry at the contact with the Lower Precambrian Watab Amphibolite (pl. 1). The porphyritic granite portion of this facies is characterized by subhedral phenocrysts of K-feldspar, sodic plagioclase, biotite and quartz set in an equigranular, anhedral groundmass of quartz and minor amounts of biotite and hornblende. The relative proportions of all the mineral phases are so varied that the modal composition ranges from granodiorite to granite. The plagioclase phenocrysts are subhedral, zoned from andesine to oligoclase, and extensively sericitized, whereas the K-feldspar phenocrysts consist dominantly of perthitic microcline, which is embayed and replaced by albite. Typically the K-feldspar phenocrysts contain rounded inclusions of andesinic plagioclase and featherlike grains of biotite. Biotite phenocrysts also have a featherlike habit, but more commonly this mineral, together with chlorite, replaces hornblende. Although some quartz is phenocrystic, much of it forms small, discrete grains in the groundmass, or occurs in myrmeketic intergrowths that mantle plagioclase phenocrysts. The quartz phenocrysts formed early, for they are embayed by microcline, but quartz in the groundmass formed late, for it replaces all of the phenocrystic minerals including microcline.

The granite porphyry portion of the border facies occurs as dikes and apophyses that twist and branch irregularly so as to form a boxwork pattern in the Watab Amphibolite. The granite porphyry is characterized by euhedral phenocrysts of plagioclase set in a finer grained groundmass of K-feldspar, plagioclase, augite, hornblende, biotite, chlorite and minor quartz. The plagioclase phenocrysts vary from 1 mm to 8 mm in length, are zoned from andesine to oligoclase, and are rimmed by albite which is little altered in contrast to the sericitized cores. In contrast, plagioclase in the groundmass is albitic in composition and occurs as anhedral grains and in myrmekitic intergrowths. Augite and hornblende occur in the groundmass as small, euhedral grains; the former is strongly zoned and in part is replaced by biotite and chlorite, or less commonly by hornblende and biotite, whereas the latter is altered to a very fine-grained mixture of biotite and chlorite. Much of the K-feldspar in the groundmass is perthitic microcline that has been replaced by quartz.

The border facies is very similar in average mineral composition and general textural attributes to the Rockville Granite, and it could be considered a part of that unit. However, because of its transitional nature and because it has not been possible to trace it for any great distance along the inferred contact of the pluton, it seems better to designate it an informal facies of the St. Cloud Granite.

Rockville Granite (modified name)

The name "Rockville granite" was first used by Tatge (1939) for a group of markedly porphyritic rocks that have been quarried under a variety of trade names including "Pearl Pink" and "Original Minnesota Pink" (Thiel and Dutton, 1935; Tatge, 1939). These rocks crop out along the valley of the Sauk River between the cities of Rockville and St. Cloud in southeastern Stearns County (pl. 1). Woyski (1949) used the name "Rockville Porphyritic Quartz Monzonite" to describe this unit, and this name was subsequently shortened to Rockville Quartz Monzonite by Goldich and others, (1961). However, inasmuch as the rocks at Rockville are granitic in composition according to the IUGS classification scheme, Tatge's (1939) original name, Rockville Granite, is used here. In addition, rocks marketed under the trade name "Crystal Gray" and referred to as the "crystal gray porphyritic quartz monzonite" by Woyski (1949) are included here as a part of the Rockville Granite. The type locality is designated here as a large operating quarry within the city of Rockville in the SW¼ sec. 9, T. 123 N., R. 29 W. Other informative exposures include those in the NE¼ sec. 27, T. 124 N., R. 29 W. and the SW¼ sec. 18, T. 123 N., R. 28 W., all in southeastern Stearns County. Although the Rockville Granite ranges in texture from very coarse grained and porphyritic to medium grained and equigranular, much of it is characterized by blocky phenocrysts of pink and red microcline and white sodic plagioclase set in a coarse-grained groundmass of microcline, plagioclase, quartz, and dark-colored mafic minerals. The phenocrysts, many as long as 6 cm, are vaguely oriented so as to define a flow structure which is further emphasized by the presence of elongate inclusions of Richmond Gneiss and dark-colored, fine-grained sodic granite, and by rare pegmatitic veins of microcline and quartz.

The coarse-grained, 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. Accessory minerals include chlorite, pyroxene, calcite, ilmenite, magnetite, zircon, and sphene. Microcline phenocrysts occur as anhedral grains that are strongly zoned with alternating dark-pink to red zones of relatively pure microcline and light-pink to gray zones containing closely packed laminae of perthitic albite. The outer edges of most microcline phenocrysts are comparatively free of albite except for widely spaced veinlets oriented perpendicular to grain edges. The plagioclase phenocrysts also are zoned, generally from andesine to oligoclase or 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 groundmass consists dominantly of microcline and lesser amounts of quartz, oligoclase, biotite, and hornblende. The microcline formed late in the petrogenetic history of the rock. It has corroded, embayed, and in places almost completely replaced the plagioclase phenocrysts, and it contains inclusions of quartz, biotite, and hornblende. Much of the hornblende, which occurs in randomly distributed clusters of two or three grains about 1 mm in diameter, has rounded corners and a deep bluish-green to greenish-yellow pleochroism suggestive of a sodic composition. In contrast, grains of brown biotite as long as 2 mm are more or less uniformly distributed throughout the groundmass. Both the biotite and the hornblende contain inclusions of zircon and magnetite; the latter in turn contains inclusions of apatite and zircon.

## OTHER MISCELLANEOUS IGNEOUS ROCKS

Dikes and sills of rhyodacite porphyry, granite porphyry, aplite, and various mafic rocks including basalt, basalt porphyry, and microgabbro are widespread in east-central Minnesota. The ages of most of the dikes and sills are uncertain, but with the exception of the rhyodacite porphyry, all appear to be younger than the major period of Middle Precambrian plutonism in that they occupy planar structural features such as faults, joint sets, or other zones of weakness that formed during or after the Penokean orogeny.

### Rhyodacite Porphyry

Several dikes of pinkish-gray rhyodacite porphyry, too small to be shown on Plate 1, crop out south of the city of St. Cloud in the NW¼ sec. 33 and the SW¼ sec. 8, T. 124 N., R. 28 W. These northeast-trending dikes cut the Reformatory Granite and in turn are cut by apophyses of the St. Cloud Granite and by dikes of granite porphyry and basalt. Because of their stratigraphic position, Woyski (1949) considered them to be part of her "Stearns Magma Series," and they are included here as part of the Stearns Granitic Complex.

The dikes have chilled borders characterized by 2-mm hornblende phenocrysts set in a felsitic groundmass consisting of K-feldspar, quartz, and hornblende. Although the hornblende phenocrysts are aligned parallel to the edges of the dikes, the interior portions of the dikes are structureless and characterized by oligoclase phenocrysts as much as 8 mm in diameter set in a groundmass of K-feldspar, quartz, and lesser amounts of hornblende. Woyski (1949) originally referred to these rocks as "quartz latite porphyry," but because they lack sanidine, the rock name rhyodacite porphyry seems more appropriate.

## Granite Porphyry

Dikes of light pinkish-gray to medium reddish-gray granite porphyry cut the Freedhem Granodiorite and the Reformatory, Warman, St. Cloud and Rockville Granites. Most trend in an east-northeast or northeast direction and average about 4 m in width, although they range from less than 30 cm to more than 18 m in width. Generally these dikes have chilled, felsitic borders and coarse-grained porphyritic interiors. Phenocrysts of perthitic microcline dominate most dikes, but phenocrysts of quartz, sodic plagioclase and biotite, or quartz and hornblende are present locally in minor amounts. All are set in a groundmass consisting of the same minerals. Thus their modal mineralogy is similar to that observed in parts of the Stearns Granitic Complex. However, the chilled borders of the granite porphyry dikes that cut the St. Cloud Granite suggest that the dikes are somewhat younger than the granite. Furthermore, some granite porphyry dikes are cut by dikes of basalt, whereas others cut basalt.

## Aplite

Tabular bodies of aplite ranging in width from less than 30 cm to more than 3 m cut the McGrath Gneiss, Sartell Gneiss, and Hillman Migmatite. In the McGrath and Sartell Gneisses these bodies occur as sill-like units composed of fine-grained microcline, sodic plagioclase, quartz, and trace amounts of hornblende, biotite, muscovite, zircon, apatite, and magnetite. Those in the Hillman Migmatite have a similar mineralogy, but are markedly discordant to the regional structure. Although all are generally similar in texture and composition, their relationship to one another and to other dike rocks in the region has not been established.

## Mafic Dikes

Mafic dike rocks in east-central Minnesota may be divided into two broad groups on the basis of structural setting and geographic distribution. One group of mafic dikes cuts all the post-Penokean plutonic rocks except the Freedhem and Bradbury Creek Granodiorites, whereas the other group cuts the McGrath Gneiss and the Denham and Thomson Formations.

Mafic dikes of the first group are particulary abundant in the Reformatory, St. Cloud and Rockville Granites where they occupy northeast-trending joint sets or cataclastic zones. In general they range in width from several centimeters to more than 7 m, although most dikes are less than 2 m wide. Mineralogically this group may be subdivided into two types, one characterized by phenocrysts of quartz and sodic plagioclase, and the other by phenocrysts of calcic plagioclase and amphibole. However the relative ages of these two types are unknown, for no mutual crosscutting relationships have been observed. Additionally, examples of both types cut dikes of granite porphyry, whereas other examples are cut by dikes of granite porphyry.

The second group of mafic dikes cuts the McGrath Gneiss and the Denham and Thomson Formations. These dikes are thought to be Keweenawan in age because of their proximity to the Midcontinent rift system. They also may be subdivided into two types. The first type occupies east-northeast-trending joint sets in the Thomson Formation and is characterized by positive magnetic anomalies. Although some of these dikes are more than 60 m wide, most range in width from 3 to 10 m. They generally are dark grayish black in color and consist dominantly of labradorite and augite; the labradorite has been extensively sericitized and the augite altered to hornblende or chlorite (Wright and others, 1970). A few of the thicker dikes contain inclusions of anorthosite or anorthositic gabbro like those observed in the nearby Duluth Complex of Middle Keweenawan age. For this reason and because these dikes appear to have a positive magnetic polarity, they are assigned to Books's (1972) Middle Keweenawan.

The second Keweenawan dike type occupies northwest-trending fault zones in the McGrath Gneiss and overlying rocks of the Denham Formation. Although exposed only near the village of Denham, these dikes are associated with pronounced negative magnetic anomalies that can be traced along strike for distances of several tens of kilometers (pl. 1). These dikes are typified by phenocrysts of black clinopyroxene set in a dark greenish-gray to greenish-black, fine-grained groundmass. The phenocrysts are 1-5 mm in diameter and commonly are twinned and compositionally zoned. Some of the compositional zones in the larger phenocrysts are partially replaced by chlorite and/or serpentine, whereas many of the smaller phenocrysts are completely replaced. The groundmass consists dominantly of very fine-grained plagioclase with interstitial clinopyroxene and opaque oxides. There is no evidence of metamorphism other than alteration of the clinopyroxene. These dikes are assigned to Books's (1972) Early Keweenawan age, mainly because they appear to have a reverse magnetic polarity.

## ACKNOWLEDGMENTS

Geologic mapping entailed in this project was initiated in 1968 with funds provided by the Minnesota Resources Commission--now the Legislative Commission on Minnesota Resources. Since that time various aspects of the project have been supported, either directly or indirectly, by the Minnesota Department of Natural Resources, Division of Minerals, the Iron Range Resources and Rehabilitation Board, and the United States Department of Interior, Bureau of Mines. Some additional funds were provided by a research grant from the Graduate School of the University of Minnesota.

The invaluable assistance of J.R. Broberg is gratefully acknowledged, as are numerous discussions with many of my colleagues, and particularly with P.K. Sims, Matt Walton and D.L. Southwick.

## REFERENCES CITED

American Commission on Stratigraphic Nomenclature, 1970, Code of stratigraphic nomenclature: Tulsa, Okla., American Association of Petroleum Geologists, 21 p.

Bateman, P.C., Clark, L.D., Huber, N.K., Moore, J.G., and Rinehart, C.D., 1963, The Sierra Nevada batholith - A synthesis of recent work across the central part: U.S. Geological Survey Professional Paper 414-D, 46 p.

Bath, G.D., Schwartz, G.M., and Gilbert, F.P., 1964, Aeromagnetic and geologic map of east-central Minnesota: U.S. Geological Survey Geophysical Investigations Map GP-474.

_____, 1965, Aeromagnetic and geologic map of west-central Minnesota: U.S. Geological Survey Geophysical Investigations Map GP-473.

Bell, R., 1873, Report on the country between Lake Superior and Lake Winnipeg: Geological Survey of Canada, Report of Progress, 1872, 1873, p. 92-94.

Blackwelder, E., 1914, A summary of the orogenic epochs in the geologic history of North America: Journal of Geology, v. 22, p. 633-654.

Books, K.G., 1972, Paleomagnetism of some Lake Superior Keweenawan rocks: U.S. Geological Survey Professional Paper 760, 42 p.

Bowles, O., 1918, The structural and ornamental stones of Minnesota: U.S. Geological Survey Bulletin 663, 225 p.

Broderick, T.M., 1920, Economic geology and stratigraphy of the Gunflint iron district, Minnesota: Economic Geology, v. 15, p. 421-452.

Gill, J.E., 1926, Gunflint iron-bearing formation in Ontario: Geological Survey of Canada, Summary Report 1924, pt. C., p. 28-88.

Goldich, S.S., Nier, A.O., Baadsgaard, H., Hoffman, J.H., and Krueger, H.W., 1961, The Precambrian geology and geochronology of Minnesota: Minnesota Geological Survey Bulletin 41, 193 p.

Grout, F.F., Gruner, J.W., Schwartz, G.M., and Thiel, G.A., 1951, Precambrian stratigraphy of Minnesota: Geological Society of America Bulletin, v. 62, p. 1017-1078.

Grout, F.F., and Wolff, J.F., Sr., 1955, The geology of the Cuyuna district, Minnesota, a progress report: Minnesota Geological Survey Bulletin 36, 144 p.

Gruner, J.W., 1922, Organic matter and the origin of the Biwabik iron-bearing formation of the Mesabi range: Economic Geology, v. 17, p. 407-460.

Hall, C.W., 1901, Keewatin area of eastern and central Minnesota: Geological Society of America Bulletin, v. 12, p. 343-376.

Han, Tsu-ming, 1968, Ore mineral relations in the Cuyuna sulfide deposit, Minnesota: Mineralium Deposita (Berlin), v. 3, p. 109-134.

Harder, E.C., and Johnston, A.W., 1918, Preliminary report on the geology of east-central Minnesota including the Cuyuna iron-ore district: Minnesota Geological Survey Bulletin 15, 178 p.

Higgins, M.W., 1971, Cataclastic rocks: U.S. Geological Survey Professional Paper 687, 97 p.

Hunt, T.S., 1873, The geognostical history of the metals: American Institute of Mining and Metallurgical Engineers Transactions, v. 1, p. 331-395.

Irving, R.D., 1883, The copper-bearing rocks of Lake Superior: U.S. Geological Survey Monograph 5, 464 p.

James, H.L., 1954, Sedimentary facies of iron-formation: Economic Geology, v. 49, p. 253-293.

Keighin, C.W., Morey, G.B., and Goldich, S.S., 1972, East-central Minnesota, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 240-255.

Krenz, K.A., and Ervin, C.P., 1977, Simple Bouguer gravity map of Minnesota, Duluth Sheet: Minnesota Geological Survey Miscellaneous Map M-37.

Leith, C.K., Lund, R.J., and Leith, A., 1935, Precambrian rocks of the Lake Superior region, a review of newly discovered geologic features, with a revised geologic map: U. S. Geological Survey Professional Paper 184, 34 p.

Marsden, R.W., 1972, Cuyuna district, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 227-239.

McGinnis, L.D., Carlson, D.R., Pederson, R., and Schafersman, J.S., 1977, Simple Bouguer gravity map of Minnesota, Stillwater Sheet: Minnesota Geological Survey Miscellaneous Map M-35.

McGinnis, L.D., Jackson, J.K., and Ervin, C.P., 1978a, Simple Bouguer gravity map of Minnesota, Brainerd Sheet: Minnesota Geological Survey, Miscellaneous Map M-40.

McGinnis, L.D., Steffy, D.A., and Ervin, C.P., 1978b, Simple Bouguer Gravity map of Minnesota, Bemidji Sheet: Minnesota Geological Survey, Miscellaneous Map M-41.

Mehnert, K.R., 1968, Migmatites and the origin of granitic rocks: New York, Elsevier Publishing, 393 p.

Morey, G.B., 1973, Stratigraphic framework of Middle Precambrian rocks in Minnesota, in Young, G.M., ed., Huronian stratigraphy and sedimentation: Geological Association of Canada, Special Paper 12, p. 211-249.

_____, 1977, Geology and mineral resources of east-central Minnesota, some new perspectives: Mining Symposium, 38th, Proceedings, University of Minnesota, January 13-14, 1977, p. 23-1--23-24.

_____, in prep., Bedrock geologic map of east-central Minnesota: Minnesota Geological Survey.

Morey, G.B., and Ojakangas, R.W., 1970, Sedimentology of the Middle Precambrian Thomson Formation, east-central Minnesota: Minnesota Geological Survey Report of Investigations 13, 32 p.

Morey, G.B., and Sims, P.K., 1976, Boundary between two Precambrian W terranes and its geologic significance: Geological Society of America Bulletin, v. 87, p. 141-152.

Perry, E.C., Jr., Tan, F.C., and Morey, G.B., 1973, Geology and stable isotope geochemistry of the Biwabik Iron Formation, northern Minnesota: Economic Geology, v. 68, p. 1110-1125.

Pettijohn, F.J., 1957, Sedimentary rocks (2nd ed.): New York, Harper and Brothers, 718 p.

Sandberg, A.E., 1938, Section across Keweenawan lavas at Duluth, Minnesota: Geological Society of America Bulletin, v. 49, p. 795-830.

Sandell, E.B., and Goldich, S.S., 1943, The rarer metallic constituents of some American igneous rocks: Journal of Geology, v. 51, part 1, p. 99-115; part 2, p. 167-189.

Schmidt, R.G., 1958, Titaniferous sedimentary rocks in Cuyuna district, central Minnesota: Economic Geology, v. 53, p.708-721.

_____, 1963, Geology and ore deposits of Cuyuna north range, Minnesota: U.S. Geological Survey, Professional Paper 407, 96 p.

Schwartz, G.M., 1942, Correlation and metamorphism of the Thomson Formation, Minnesota: Geological Society of America Bulletin, v. 53, p. 1001-1020.

Sims, P.K., 1976, Precambrian tectonics and mineral deposits, Lake Superior region: Economic Geology, v. 71, p. 1092-1127.

Sims, P.K., and Viswanathan, S., 1972, Giants Range batholith, in Sims, P.K., and Morey, G.B., eds., Geology of Minnesota: A centennial volume: Minnesota Geological Survey, p. 120-139.

Sims, P.K., and Zietz, I., 1967, Aeromagnetic and inferred Precambrian paleogeologic map of east-central Minnesota and part of Wisconsin: U.S. Geological Survey Geophysical Investigations Map GP-563.

Skillman, M.W., 1946, Intrusives of central Minnesota: unpub. Ph.D. thesis, University of Minnesota, Minneapolis, 211 p.

Sohl, N.F., 1977, Note 45--Application for amendment concerning terminology for igneous and high-grade metamorphic rocks: American Association of Petroleum Geologists Bulletin, v. 61, p. 248-252.

Spurr, J.E., 1894, The iron-bearing rocks of the Mesabi range in Minnesota: Minnesota Geological Survey Bulletin 10, 268 p.

Streckeisen, A.L., chairman, 1973, Plutonic rocks: Classification and nomenclature recommended by the IUGS Subcommission on the Systematics of Igneous Rocks: Geotimes, v. 18, no. 10, p. 26-30.

Stuckless, J.S., and Goldich, S.S., 1972, Ages of some Precambrian rocks in east-central Minnesota (abs.): Institute on Lake Superior Geology, 18th, Houghton, Michigan, Paper 31.

Tanton, T.L., 1931, Fort William and Port Arthur, and Thunder Cape map areas, Thunder Bay district, Ontario: Geological Survey of Canada, Department of Mines, Memoir 167, 222 p.

Tatge, E., 1939, Crystallization of the Rockville granite: American Mineralogist, v. 24, p. 303-316.

Thiel, G.A., and Dutton, C.E., 1935, The architectural, structural, and monumental stones of Minnesota: Minnesota Geological Survey Bulletin 25, 160 p.

Upham, W., 1882, Notes of rock-outcrops in central Minnesota: Minnesota Geological and Natural History Survey, 11th Annual Report, Plate 1 and p. 86-136 and 220.

——, 1888, Geology of Benton and Sherburne, Stearns, Wadena and Todd, Crow Wing and Morrison, Mille Lacs and Kanabec, and Pine Counties: Minnesota Geological and Natural History Survey, Final Report, v. 2, p. 426-470 and 562-645.

Van Hise, C.R., and Clements, J.M., 1901, The Vermilion iron-bearing district: U.S. Geological Survey 21st Annual Report, part 3, p. 401-409.

Van Hise, C.R., and Leith, C.K., 1911, The geology of the Lake Superior region: U.S. Geological Survey Monograph 52, 641 p.

Wadsworth, M.E., 1887, Preliminary description of the peridotytes, gabbros, diabases and andesytes of Minnesota: Minnesota Geological and Natural History Survey Bulletin 2, 159 p.

Weiblen, P.W., 1964, A preliminary study of the metamorphism of the Thomson Formation: unpub. M.S. thesis, University of Minnesota, Minneapolis, 153 p.

White, D.A., 1954, Stratigraphy and structure of the Mesabi range, Minnesota: Minnesota Geological Survey Bulletin 38, 92 p.

Winchell, H.V., 1893, The Mesabi iron range: Minnesota Geological and Natural History Survey, 20th Annual Report, p. 153-165.

Winchell, N.H., 1884, The crystalline rocks of Minnesota: Minnesota Geological and Natural History Survey, 13th Annual Report, p. 36-38.

———, 1888, The crystalline rocks of Minnesota: Minnesota Geological and Natural History Survey, 17th Annual Report, p. 5-74.

Wolff, J.F., Sr., 1919, Correlation of the Mesabi and Cuyuna ranges: Skillings Mining Review, v. 7, no. 45, p. 1 and 4.

Woyski, M.S., 1949, Intrusives of central Minnesota: Geological Society of America Bulletin, v. 62, p. 999-1016.

Wright, H.E., Jr., Mattson, L.A., and Thomas, J.A., 1970, Geology of the Cloquet quadrangle, Carlton County, Minnesota: Minnesota Geological Survey Map GM-3 (with text), 30 p.

Zapffe, C., 1907, The geology of the Cuyuna iron ore district of Minnesota: unpub. B.S. thesis, University of Wisconsin, Madison, 85 p.

———, 1925, Stratigraphy and correlation of the Cuyuna iron ore district, Minnesota: Lake Superior Mining Institute, Proceedings, v. 24, p. 219-227.

———, 1926, Further data on the correlation of the Cuyuna iron-bearing member: Lake Superior Mining Institute, Proceedings, v. 25, p. 219-227.

———, 1930, Cuyuna stratigraphy: Lake Superior Mining Institute, Proceedings, v. 28, p. 99-106.

———, 1933, The Cuyuna iron-ore district: International Geological Congress, 16th, p. 72-88.