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PALEOZOIC STRATIGRAPHIC NOMENCLATURE FOR MINNESOTA

John H. Mossler

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NOTE ON MEASUREMENTS USED IN THIS REPORT

Although the metric system is preferred in scientific writing, certain measurements are still routinely made in English customary units; for example, distances on land are measured in miles and depths in drill holes are measured in feet. Preference was given in this report to retaining the units in which measurements were made. To assist readers, conversion factors for some of the common units of measure are provided below.

English units to metric units:

To convert from	to	multiply by
inch	millimeter	25.40
inch	centimeter	2.450
foot	meter	0.3048
mile	kilometer	1.6093

Metric units to English units:

To convert from	to	multiply by
millimeter	inch	0.03937
centimeter	inch	0.3937
meter	foot	3.2808
kilometer	mile	0.6214

PALEOZOIC STRATIGRAPHIC NOMENCLATURE FOR MINNESOTA

John H. Mossler

ABSTRACT

Several significant revisions are proposed for the stratigraphic nomenclature of the Paleozoic rock formations of Minnesota. These changes reflect new information acquired from sedimentological and biostratigraphic studies conducted since this report was last published in 1987.

Biostratigraphic and sedimentological studies conducted on several Cambrian formations including the Ironton Sandstone, Galesville Sandstone, Franconia Formation, St. Lawrence Formation, and Jordan Sandstone result in the following recommendations:

1. The St. Lawrence Formation and Jordan Sandstone are no longer divided into formal members. The formations instead are informally divided into lithofacies.

2. The interbedded sandstone, sandy dolostone, and shale beds formerly assigned to the Coon Valley Member of the Jordan Sandstone are no longer included in that formation. Instead, the Coon Valley Member is classified as the basal member of the Lower Ordovician Oneota Dolomite. The heterolithic nature of interbedded siliclastics and carbonates better fits with the Prairie du Chien Group than with the siliclastic Jordan Sandstone. Additionally, the formation break now corresponds with a major unconformity, with the Coon Valley Member above it grading transitionally into overlying silty Oneota Dolomite dolostone.

3. The Ironton Sandstone and Galesville Sandstone are classified together as the Wonewoc Sandstone. Lithostratigraphic studies have shown that it is not possible to consistently distinguish the two formations, and it has never been deemed practical to map them separately in Minnesota at any scale. Use of the term Wonewoc also makes Minnesota terminology consistent with neighboring states.

4. The Franconia Formation is renamed the Tunnel City Group. The Mazomanie Member of the Franconia Formation is elevated to formation rank. The Reno, Tomah, and Birkmose Members of the Franconia Formation are grouped together in the Lone Rock Formation. A prominent carbonate unit that intertongues with the Lone Rock Formation in the subsurface of southwestern Minnesota is interpreted to be a tongue of the Davis Formation that extends into Minnesota from Iowa. This revision of nomenclature reflects outcrop and subsurface stratigraphic and sedimentological studies that demonstrate the Mazomanie Member is distinguishable from the rest of the Franconia Formation as a mappable unit. It is as distinct from other parts of the Franconia Formation as other formations historically differentiated in other parts of the Paleozoic section are from one another.

The Carimona Member, formerly included in the Upper Ordovician Platteville Formation as its uppermost member, is moved into the Decorah Shale in order to place the contact between the Platteville Formation and Decorah Shale at a recognizable regional discontinuity surface rather than subjectively placing the formation contact where Carimona Member limestone beds are predominant over interbedded Decorah Shale beds. Additionally, moving the contact to the base of the Carimona Member makes the geologic contact between the Platteville Formation and Decorah Shale consistent with the way it is drawn in neighboring states. For the same reason, the Upper Ordovician Galena Group is redefined to include the Decorah Shale and the Dubuque Formation. In neighboring states, those formations are included in the Galena Group.

The Devonian Wapsipinicon Formation has been raised to group status and expanded to include the Spillville Formation. The Cedar Valley Formation has also been raised to group status and divided into three formations, the Little Cedar, Coralville, and the Lithograph City. This makes Minnesota nomenclature for the Devonian consistent with that used in Iowa. In addition, the revised nomenclature recently was applied in geologic mapping and found to be usable in southern Minnesota.

STRUCTURAL AND SEDIMENTOLOGICAL FRAMEWORK

Mappable Paleozoic sedimentary units of the upper Mississippi River valley are characterized by their sheetlike geometry. Relatively thin layers (a few feet up to several hundred feet in thickness) of sandstone, carbonate, and shale strata extend over thousands of square miles. These strata can be grouped into unconformity-bounded lithologic sequences (Sloss, 1963) that correspond to episodes of flooding of the North American craton by vast epicontinental seas. There have been six episodes of flooding during the Phanerozoic eon. Only the first three episodes occurred during Paleozoic time (Fig. 1). Rocks deposited during the first marine incursion, referred to as the Sauk sequence, are Late Cambrian and Early Ordovician in age (Fig. 1). The rocks deposited during the second marine incursion, the Tippecanoe sequence, include all Middle and Late Ordovician strata (Fig. 1). In Iowa it also contains rocks of Silurian age (Bunker and others, 1985). After deposition of the basal sandstone, carbonate rocks dominated the Tippecanoe sequence. Maximum marine inundation of the North American continent occurred during the deposition of the Tippecanoe sequence, and it is the only Paleozoic sequence represented in northwestern Minnesota. The rocks deposited during the third marine incursion, the Kaskaskia sequence, are Middle Devonian in age in Minnesota (Fig. 1). In Iowa this sequence also includes Late Devonian and Mississippian strata. The rocks of this sequence are predominately carbonate in Minnesota; in Iowa they also include evaporites. The tops of all sequences are characterized by interregional unconformities. The rock sequences are much thinner in Minnesota and represent shorter intervals of time than rocks in regions nearer the margins of the North American continent. Because southeastern Minnesota was near the center of the craton it was one of the last places to be flooded during marine transgressions and the first to be exposed to erosion removing the upper parts of each sequence after seas withdrew.

Most of the Paleozoic sedimentary rock formations in Minnesota were deposited in the Hollandale embayment (Austin, 1969) in southeast Minnesota. Mossler (1983) mapped the geographic distribution for most of these formations. The Hollandale embayment was a shallow depression that extended northward from the Illinois and "Ozark" basins onto the cratonic shelf of northern Iowa, southeastern Minnesota, and southwestern Wisconsin during early Paleozoic time (Fig. 2A). The Transcontinental Arch bordered the embayment on the north and west; on the east the Wisconsin Dome and Wisconsin Arch bordered the embayment. The Wisconsin Arch and Dome were apparently well developed throughout Early Paleozoic time, whereas the Transcontinental Arch may not have developed until the late Cambrian (Runkel and others, 1998).

The Hollandale embayment, a depositional lowland, extends southward from Minnesota through east-central Iowa to the "Ozark" basin of southern Missouri, and the ancestral Illinois basin of southern Illinois (Fig. 2A; Bunker and others, 1985). It follows the trace of predecessor basins formed along the Middle Proterozoic Midcontinent rift system. Minor recurrent movements during the Paleozoic era, such as might be caused by isostatic or thermal adjustment along the large-scale faults bounding grabens, basins, and horsts of the Proterozoic rift system, are responsible for development and configuration of the Hollandale embayment. These movements created numerous, smaller, gently folded synclines and anticlines, and faults within the embayment, such as the Twin Cities basin (Fig. 2B), southern Minnesota syncline, and numerous smaller geologic structures. A variety of Precambrian rocks underlie the Paleozoic rocks of the embayment (Fig. 2C). This is because the region had a complicated history before deposition of the Paleozoic rocks (Sims, 1990). Middle Proterozoic sedimentary, volcanic, and mafic intrusive rocks related to the Midcontinent rift system underlie the axis of the Hollandale embayment. In Minnesota, Cambrian rocks overlie Archean and Early Proterozoic metamorphic and igneous rocks at the northwestern, western, and southeastern margins of the Hollandale embayment. Gneiss and granitic rocks are the most common rock types. In some places on the western side of the embayment in Minnesota, Paleozoic rocks overlie Lower Proterozoic Sioux Quartzite.

The Paleozoic rocks along the western and northwestern margins of the Hollandale embayment are deeply truncated by post-depositional erosion. They show little or no evidence for thinning or pinching out along a western shoreline, except for some thinning of the basal unit, the Mt. Simon Sandstone, around highlands formed by Sioux Quartzite ridges. Therefore the original configuration of the western margin of the embayment is very uncertain.

During Middle to Late Ordovician time, the north–south grain of the Hollandale embayment was disrupted by the rise of the northward-trending Northeast Missouri Arch in southern Iowa and the northeast-trending Sangamon Arch across central

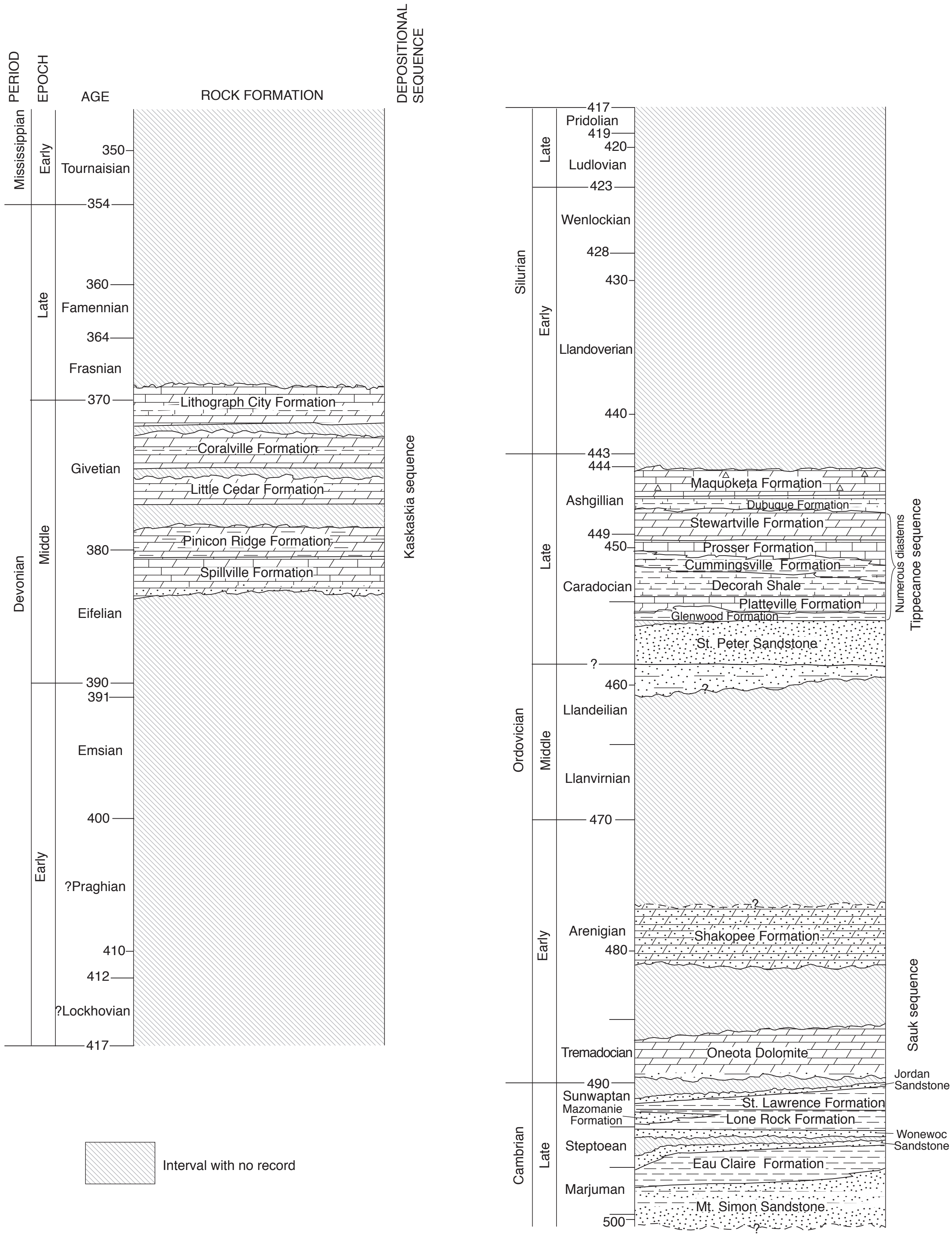
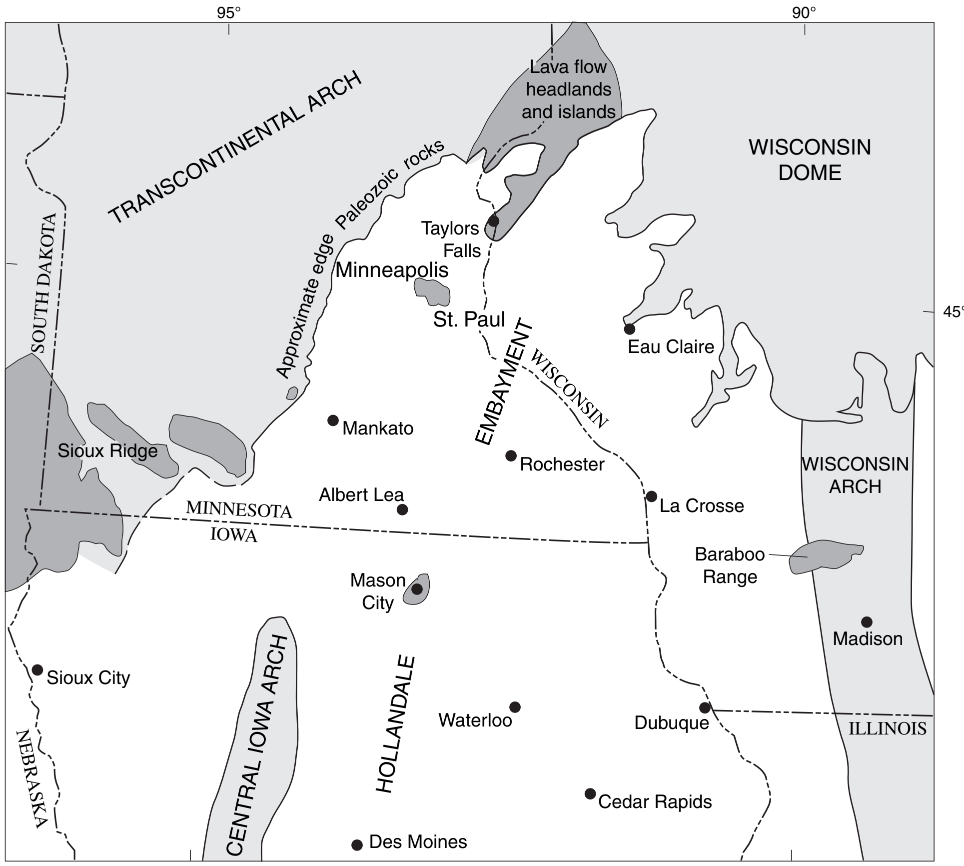
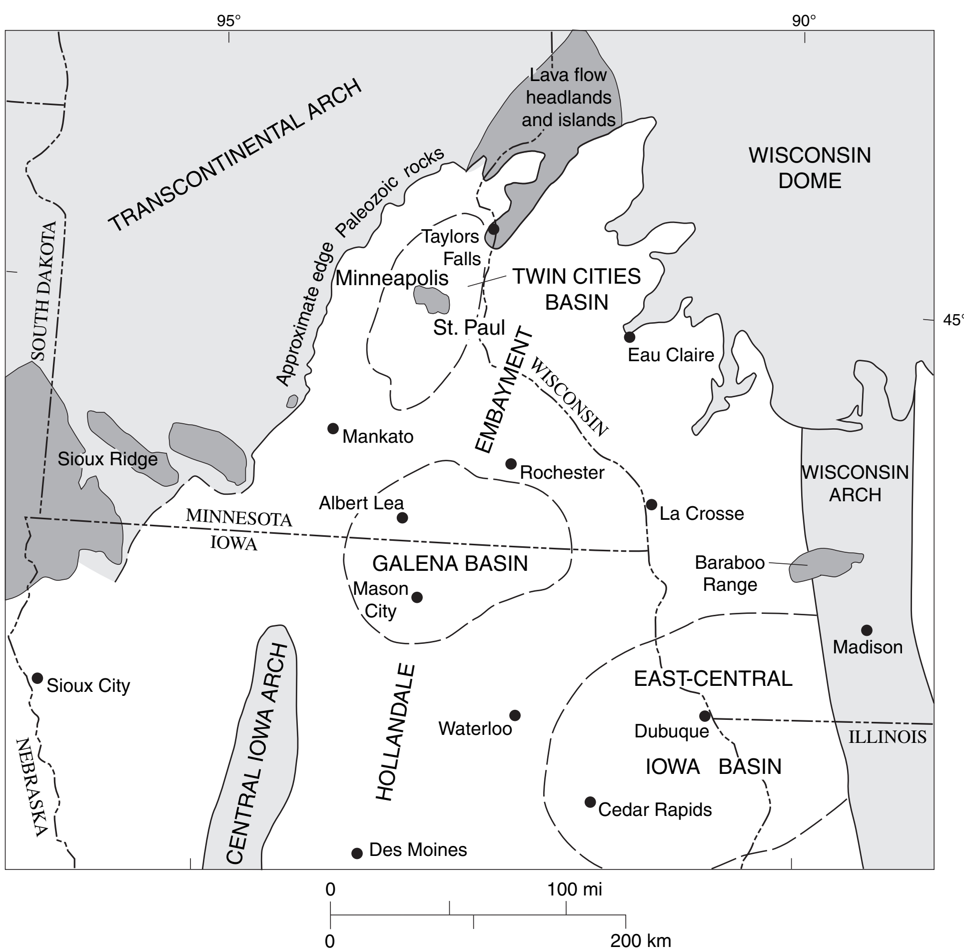


Figure 1. Chronostratigraphic column for Lower to Middle Paleozoic rocks in Minnesota. Note the long intervals of time where there is no preserved geologic record in Minnesota. For lithologic legend, please see Plate 1.

A.


95°
90°
45°
Lava flow
headlands
and islands
TRANSCONTINENTAL ARCH
Approximate edge Paleozoic rocks
WISCONSIN
DOME
Taylors
Falls
Minneapolis
St. Paul
EMBAYMENT
WISCONSIN
Eau Claire
SOUTH DAKOTA
Sioux Ridge
Mankato
Rochester
Albert Lea
La Crosse
WISCONSIN
ARCH
MINNESOTA
IOWA
Baraboo
Range
Mason
City
Madison
CENTRAL IOWA ARCH
HOLLANDALE
Sioux City
Waterloo
Dubuque
ILLINOIS
NEBRASKA
Cedar Rapids
Des Moines

B.


95°
90°
45°
Lava flow
headlands
and islands
TRANSCONTINENTAL ARCH
Approximate edge Paleozoic rocks
WISCONSIN
DOME
Taylors
Falls
Minneapolis
TWIN CITIES
BASIN
St. Paul
EMBAYMENT
WISCONSIN
Eau Claire
SOUTH DAKOTA
Sioux Ridge
Mankato
Rochester
Albert Lea
La Crosse
WISCONSIN
ARCH
MINNESOTA
IOWA
GALENA BASIN
Baraboo
Range
Mason
City
Madison
EAST-CENTRAL
CENTRAL IOWA ARCH
HOLLANDALE
Sioux City
Waterloo
Dubuque
ILLINOIS
IOWA BASIN
NEBRASKA
Cedar Rapids
Des Moines
0
100 mi
0
200 km

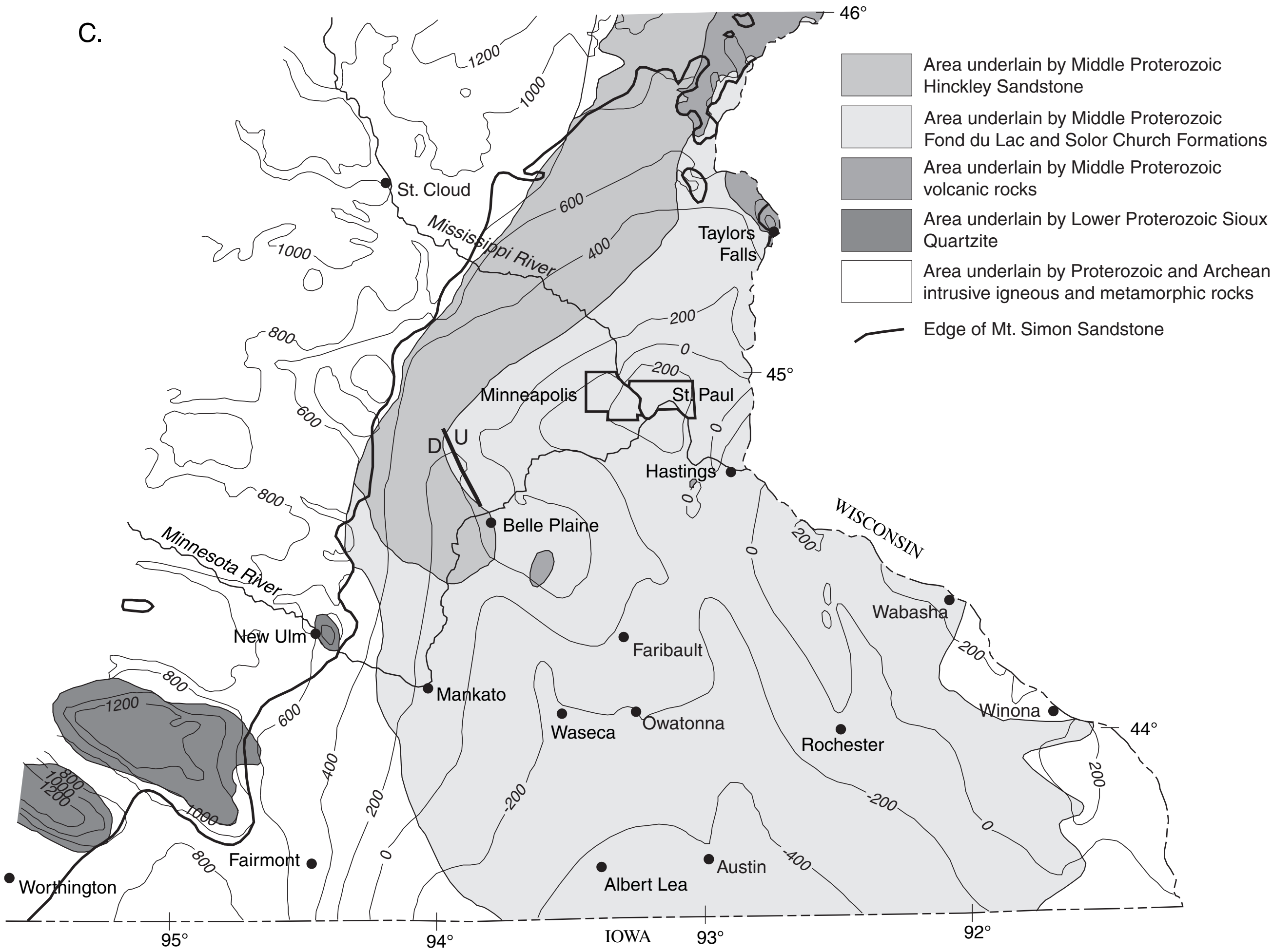


Figure 2. Structural elements of southeastern Minnesota during Early Paleozoic time. Positive areas are shaded on 2A and 2B.

A. Sauk sequence (Upper Cambrian—lower Ordovician).

B. Tippecanoe sequence (Upper Ordovician).

C. Configuration of Precambrian/Cambrian contact and distribution of Precambrian formations at the contact with overlying geologic units. Contour interval is 200 feet (61 meters).

Illinois (Bunker and others, 1985). Smaller basins such as the east-central Iowa basin, the northern Iowa and southern Minnesota "Galena basin" (Witzke, 1983), and the Twin Cities basin formed (Fig. 2B). Structural grain during Devonian time generally resembled that of the Late Ordovician in Minnesota and eastern Iowa.

The Paleozoic rocks of northwestern Minnesota (Plate 1) were deposited on a broad, shallow shelf that bordered the eastern margin of the Williston basin of western North Dakota during Late Ordovician time. They overlie poorly known granitoid intrusions, gneiss, schist, and volcaniclastic and volcanic rocks of Late Archean age (Jirsa and others, 1999). At present, Paleozoic rocks of northwestern Minnesota are separated from those in the Hollandale embayment by deep erosional truncation along their respective margins (Fig. 1). This was not the case when they were deposited. There were seaways across the "Transcontinental Arch" and between the Sioux highlands in southwestern Minnesota during periods when maximum transgression of the epicontinental seas that covered the region occurred.

Marine and continental sedimentary rocks of Late Cretaceous age overlie Paleozoic rocks along the western margin of the Hollandale embayment in south-central Minnesota. Setterholm (1990) described them and mapped their distribution. Rocks of questionable Jurassic age as well as Late Cretaceous rocks overlie the Paleozoic rocks in northwestern Minnesota. They were mapped and described by Jirsa and others (1999). The Jurassic and Cretaceous rocks are not shown on the stratigraphic column on Plate 1. These rocks, considered to be part of a later sedimentary sequence, the Zuni (Sloss, 1963), were deposited during Late Mesozoic time and generally are shale and siltstone with minor sandstone and carbonate. During this time a shallow epicontinental sea covered the western interior of North America. In the extreme southwestern part of the Hollandale embayment of Minnesota, Paleozoic rocks are buried beneath Cretaceous rocks that range up to 350 feet (107 meters) in thickness. Cretaceous rocks elsewhere in the Hollandale embayment, if they are present over Paleozoic strata, are generally very thin and rarely more than 50 to 100 feet (15 to 30 meters) thick. In northwestern Minnesota the Jurassic rocks are up to 100 feet (30 meters) thick locally and Cretaceous rocks typically are less than 115 feet (35 meters) thick.

Continental glaciations during the Quaternary period created thick successions of outwash and till that covered earlier geologic features in Minnesota. As a result, most of the Paleozoic bedrock that crops out in southeastern Minnesota is along major stream valleys or lies within the "driftless" area of extreme southeast Minnesota. These are areas where glacial deposits are thin and discontinuous because of erosion or absent because they were never deposited (see map on Plate 1, page 76). In northwestern Minnesota a thick layer of Quaternary drift covers all Paleozoic and Mesozoic rocks.

ORGANIZATION OF THE REPORT OF INVESTIGATIONS

Description and discussion of the Paleozoic rock units of Minnesota are organized into sections arranged by geologic system, with groups and formation within each system discussed sequentially by relative age. Discussion of each formation is organized in the following manner:

- Origin of the name and locality where first named, accompanied by a brief history of nomenclature.
- Distribution of the formation and geographic occurrence of the unit within Minnesota.
- Thickness of the formation and geographic variation of formation thickness within Minnesota.
- Lithology of the formation, including naming and description of distinctive members and lithofacies. Many of these descriptions are based on rock cores and well cuttings because many of the Paleozoic rock units in Minnesota are known primarily where they are encountered in the subsurface. Most of the area where Paleozoic rocks occur is mantled by thick glacial drift and exposures are scarce and incomplete (see Plate 1).
- General fossil content, including major groups present and citation of some of the sources that describe them.
- Relationship to adjacent rock units including the type of contact between adjacent formations, whether unconformable or conformable, and criteria for identifying it. Terms for discontinuities in interrupted successions of sedimentary strata have been applied inconsistently in the past. In many cases there was honest confusion about the nature of a contact between adjacent rock units because sedimentology had not advanced to include some of the paradigms available today. In other cases the terminology is misapplied.
- Representative sections: locations of outcrops or core (Fig. 3) where readers may examine the units. In addition, articles cited within the body of this report provide more detail about individual rock formations.

This report emphasizes subsurface geology and the application of subsurface geophysical logging methods, specifically natural gamma radiation logging, in correlation of stratigraphic units. This is because more and more stratigraphy is done to support ground-water investigations and the natural gamma radiation log commonly is the tool of choice for correlation. The gamma log is a more empirical tool than most other available logs and yields reproducible results. For example, drillers' or geologists' logs are interpretive logs that are the result of observations by a single person that may be affected by other factors such as incomplete sampling of well cuttings, observational biases, or inattention. Additionally, gamma logging is more widely applicable than other down hole geophysical methods because it can be used to log older wells that have metal casing in them, unlike resistivity and other electrical logging methods, which cannot be used to log cased wells.

CAMBRIAN SYSTEM

Nomenclature for Cambrian rocks in Minnesota and neighboring Wisconsin that began to develop during the late 1800s has been undergoing revision up to the present (Fig. 4). Initially, when the geology of the region was first being mapped, the strata were

Figure 3. General study area for southeastern Minnesota. Outcrop locations mentioned in the text are numbered. Lettered locations are well cores listed in Table 1. Type sections for some of the Paleozoic stratigraphic units mentioned in text are in parentheses (denoted by triangles). The limit of the Twin Cities basin is also shown (thick black line).

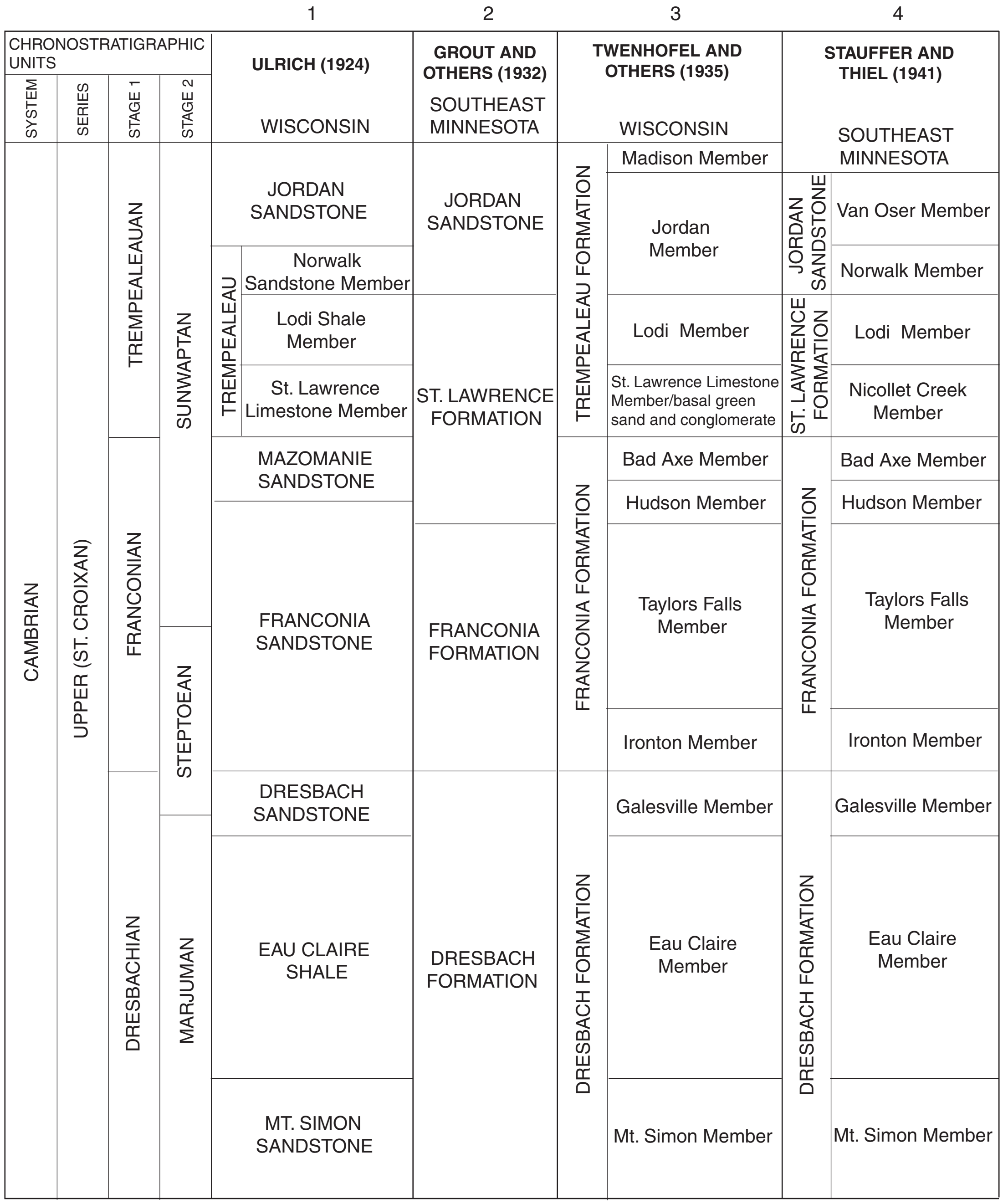


Figure 4. Upper Cambrian stratigraphic nomenclature for Minnesota and Wisconsin. Columns show the development of nomenclature with the older classifications on the left (columns 1 to 6) and the current one (column 8) for Minnesota on the right. Both old (stage 1) and new (stage 2) stage names for the Upper Cambrian series are shown. Thick lines between rock units denote unconformities inferred by the author(s) of the classification. Informal sandstone units in column 8 are approximate equivalents of the Ironton Sandstone and Galesville Sandstone. See text for discussion of the history of Cambrian nomenclature. Early classification schemes are adapted from Austin (1972, Fig. VI-2).

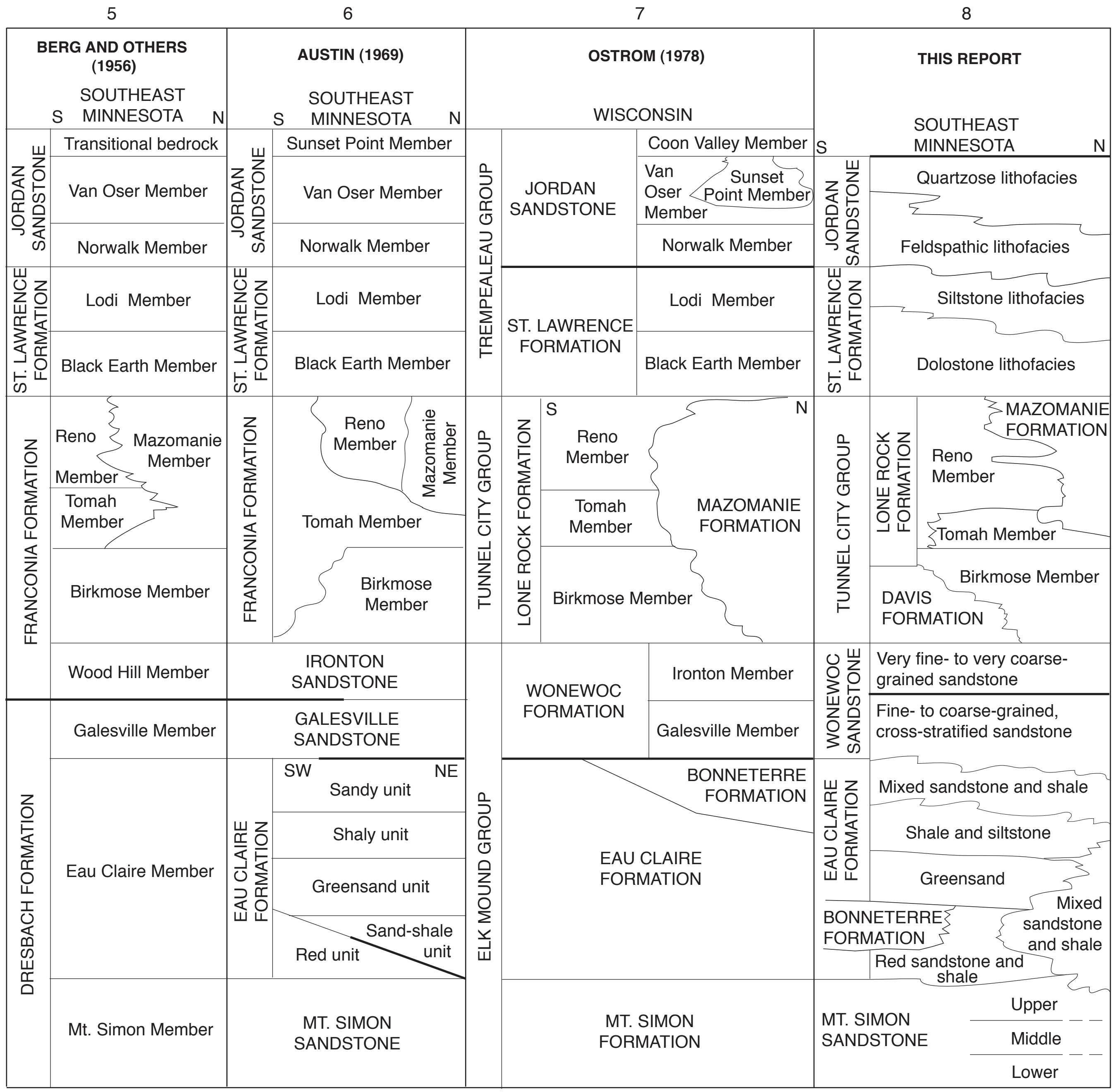

5
6
7
8
BERG AND OTHERS (1956)
SOUTHEAST MINNESOTA
S
N
JORDAN SANDSTONE
Transitional bedrock
Van Oser Member
Norwalk Member
ST. LAWRENCE FORMATION
Lodi Member
Black Earth Member
FRANCONIA FORMATION
Reno Member
Mazomanie Member
Tomah Member
Birkmose Member
Wood Hill Member
DRESBACH FORMATION
Galesville Member
Eau Claire Member
Mt. Simon Member
AUSTIN (1969)
SOUTHEAST MINNESOTA
S
N
JORDAN SANDSTONE
Sunset Point Member
Van Oser Member
Norwalk Member
ST. LAWRENCE FORMATION
Lodi Member
Black Earth Member
FRANCONIA FORMATION
Reno Member
Mazomanie Member
Tomah Member
Birkmose Member
IRONTON SANDSTONE
GALESVILLE SANDSTONE
EAU CLAIRE FORMATION
SW
NE
Sandy unit
Shaly unit
Greensand unit
Sand-shale unit
Red unit
MT. SIMON SANDSTONE
OSTROM (1978)
WISCONSIN
TREMPEALEAU GROUP
JORDAN SANDSTONE
Coon Valley Member
Van Oser Member
Sunset Point Member
Norwalk Member
ST. LAWRENCE FORMATION
Lodi Member
Black Earth Member
TUNNEL CITY GROUP
LONE ROCK FORMATION
S
N
Reno Member
Tomah Member
Birkmose Member
MAZOMANIE FORMATION
ELK MOUND GROUP
WONEWOC FORMATION
Ironton Member
Galesville Member
BONNETERRE FORMATION
EAU CLAIRE FORMATION
MT. SIMON FORMATION
THIS REPORT
SOUTHEAST MINNESOTA
S
N
JORDAN SANDSTONE
Quartzose lithofacies
Feldspathic lithofacies
ST. LAWRENCE FORMATION
Siltstone lithofacies
Dolostone lithofacies
TUNNEL CITY GROUP
LONE ROCK FORMATION
MAZOMANIE FORMATION
Reno Member
Tomah Member
Birkmose Member
DAVIS FORMATION
WONEWOC SANDSTONE
Very fine- to very coarse-grained sandstone
Fine- to coarse-grained, cross-stratified sandstone
EAU CLAIRE FORMATION
Mixed sandstone and shale
Shale and siltstone
Greensand
BONNETERRE FORMATION
Mixed sandstone and shale
Red sandstone and shale
MT. SIMON SANDSTONE
Upper
Middle
Lower

Table 1. Some representative cores in Upper Cambrian formations, southeastern Minnesota (letters refer to location designations on Figure 3). All cores are stored at the Minnesota Department of Natural Resources Repository in Hibbing, Minnesota.

* denotes only part of the geologic formation was cored.

+ denotes core loss, incomplete recovery.

Well name, location	Formations cored (gross interval in feet, measured from the land surface)				
	St. Lawrence	Tunnel City Group	Wonewoc	Eau Claire	Mt. Simon
A. Northern Natural Gas Company Hollandale 1A; Freeborn County T. 103 N., R. 19 W., sec. 7, SE, SE, SW	1,005-1,047*	1,047- 1,200	1,200-1,240	1,240-1,437	1,437-1,619
B. Northern Natural Gas Company Hampton 65-1; Dakota County T. 133 N., R. 18 W., sec. 4, SW, NW, NW	none	41-537*	537-587	587-683	683-916
C. Minnegasco (Centerpoint Energy) L. Williams 4; Waseca County T. 108 N., R. 22 W., sec. 7, NW, SW, NE	none	64-760	760-800+	800-937	937-954*
D. Minnegasco (Centerpoint Energy) Melstrom 1; Rice County T. 109 N., R. 22 W., sec. 28, SW, SE, SW	none	none	none	824-903	903-1,128+*
E. Minnegasco (Centerpoint Energy) J. Kingstrom 1; Faribault County T. 101 N., R. 24 W., sec. 6, NE, NW, NW	650-739	739-867	867-917	917-1,167	1,167-1,363

divided solely on lithologic criteria. However, as these strata came to serve as "type" for the original Upper Cambrian Croixan stages of North America (Howell and others, 1944), investigators placed greater reliance on paleontological studies than on lithologic criteria when subdividing the strata. Therefore the three formations originally mapped in the Upper Cambrian system of the upper Mississippi River valley, the Dresbach, Franconia, and Trempealeau, became synonymous with the three biostratigraphic stages in the Upper Cambrian system (Fig. 4, column 3). Nomenclature before 1956, such as Stauffer and others (1939) and Stauffer and Thiel (1941), relied more on faunal zonation using trilobites than on lithostratigraphic criteria for distinguishing stratigraphic units. Their formations and members (Fig. 4, column 4) were defined on the basis of the faunules that they contained. This limited usefulness of the nomenclature for everyone except paleontologists. Berg and others (1956) proposed a new classification scheme in 1956 that adhered to the then new system of dual nomenclature, in which lithostratigraphic and biostratigraphic units are independent (Fig. 4, column 5). Their lithostratigraphic classification continues to be used in Minnesota with only minor revisions. The chronostratigraphic nomenclature for the Cambrian, however, has been substantially revised so that formal Upper Cambrian stages for North America are now based on zonal sequences from the southwestern United States and western Canada (Ludvigsen and Westrop, 1985) that represent continent-wide extinction events of trilobites and associated faunas. Both the Croixan stage names and new stage names are shown on Figure 4.

Recent restudy of the Cambrian succession in Minnesota and neighboring states has resulted in the following revisions to our nomenclature:

1. Formal members of the St. Lawrence Formation (Ulrich, 1916 *in* Thwaites, 1923) and Jordan Sandstone (Thwaites, 1923; Stauffer and others, 1939; Stauffer and Thiel, 1941) should be abandoned because the member designations apparently do not have

any validity (Hughes and Hesselbo, 1997; Runkel, 1994a, b).

2. A heterolithic facies of mixed carbonate and siliclastic beds referred to as the Coon Valley Member, that lies between the siliclastic Jordan Sandstone and the nearly siliclastic-free Oneota Dolomite, is placed in the Oneota Dolomite as its lowermost member. Formerly it was considered the uppermost member of the Jordan Sandstone. This revision results from investigations that show the base of the Coon Valley Member in the outcrop belt corresponds to a major subsequence boundary (Smith and others, 1993). Paleontological criteria (Runkel and others, 1999) as well as subtle lithologic evidence (Smith and others, 1993; Runkel, 1994a) indicates that a widespread but obscure unconformity occurs beneath the Coon Valley Member. Additionally, this revision places the Coon Valley Member as the lowermost member of a group of strata, the Prairie du Chien Group, that contains lithically similar facies in its upper part.

3. It is proposed that nomenclatural revisions be adopted to make the Minnesota nomenclature more consistent with that applied in neighboring states. These revisions are for the Ironton Sandstone, Galesville Sandstone, and Franconia Formation.

a. The Ironton Sandstone and Galesville Sandstone are difficult to distinguish from one another in outcrop because there is no obvious lithologic break between the units and they do not substantially differ from one another to the degree that other siliclastic formations differ from one another. In subsurface work using drillers' logs, well cuttings, and gamma logs the problem is even more insurmountable and the units are usually referred to as the "Ironton and Galesville Sandstones." It is proposed that Minnesota follow Wisconsin nomenclature (Ostrom, 1966, 1967) and refer to the combined interval as the Wonewoc Sandstone in spite of the fact that there is a sequence bounding unconformity (Runkel and others, 1998) within the interval.

b. It also is proposed that the nomenclature used in Wisconsin (Ostrom, 1966, 1967) for rocks equivalent to the Franconia Formation should be used in Minnesota, chiefly because the Wisconsin nomenclature recognizes that there are two units that are mappable at formation scale in the Franconia Formation. In addition, the Franconia Formation originally was a biostratigraphical name and using the Wisconsin nomenclature avoids confusion with the biostratigraphical stage name. Therefore rocks units formerly placed in the Franconia Formation are assigned to the Tunnel City Group. The Tunnel City Group consists of two formations, the Lone Rock Formation and the Mazomanie Formation. Both are mappable units in Minnesota. The Lone Rock Formation includes all beds that were included in the Birkmose, Reno, and Tomah Members of the Franconia Formation. The Mazomanie Formation includes those beds that were included in the Mazomanie Member of the Franconia Formation.

MOUNT SIMON SANDSTONE

The Mount Simon Sandstone was named for Mt. Simon, an escarpment in the city of Eau Claire, Eau Claire County, Wisconsin (Ulrich, *in* Walcott, 1914, p. 354). The type section (Fig. 3) is 234 feet (71 meters) of mostly medium- to coarse-grained sandstone overlying Precambrian granite and beneath very fine- and fine-grained sandstone and shale of the Eau Claire Formation.

Occurrence—The Mt. Simon Sandstone occurs throughout the Hollandale embayment of southeastern Minnesota (Mossler, 1992b, Fig. 6a), where it is covered by younger Paleozoic and Mesozoic sedimentary strata and by glacial drift. Sandstone that crops out nearby in western Wisconsin, described by Driese and others (1981), is a known correlative with the Mt. Simon Sandstone in Minnesota and is composed of lithofacies similar to those identified in the subsurface of the Hollandale embayment. Outlying occurrences of sandstone north and west of the main body of Paleozoic strata in the Hollandale embayment, such as a few exposures along upper reaches of the St. Croix River in Pine County, have formerly been referred to as the Mt. Simon Sandstone (Nelson, 1949; Morey and others, 1981). However, their age is paleontologically and lithologically poorly constrained. Some exposures could be younger and may be remnants of the Middle Ordovician St. Peter Sandstone (Boerboom, 2001; Boerboom and others, 2002). Similar sandstone outliers in Wisconsin and Iowa are known to be equivalent to younger Cambrian and Ordovician formations.

Thickness—The Mt. Simon Sandstone is thickest in extreme southeastern Minnesota where it measures 360 to 375 feet (110 to 114 meters). It is thin, due to depositional onlap, in the extreme southwestern part of its subcrop near the Sioux Quartzite ridge, where it is less than 25 feet (less than 7.6 meters) thick in places (Fig. 5) and in the northwest part of its subcrop in Sherburne County where it thins to less than 100 feet (30.5 meters). In east-central Minnesota along the Middle Proterozoic St. Croix horst it is absent in places, for example around Taylors Falls, because of nondeposition. In the Twin Cities basin it is about 200 feet (61 meters) thick. Thickness variations are shown on Figure 6a of Mossler (1992b).

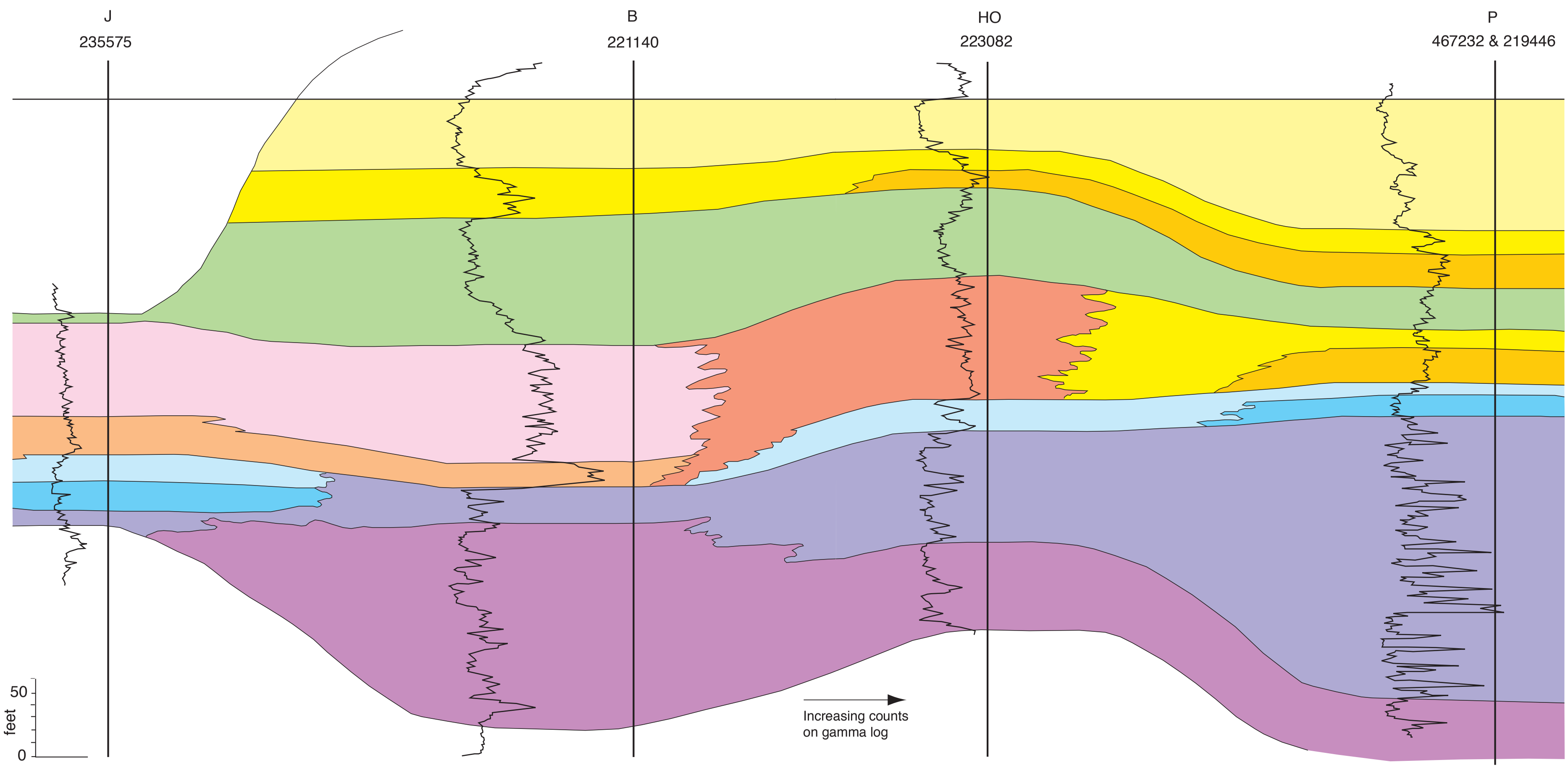
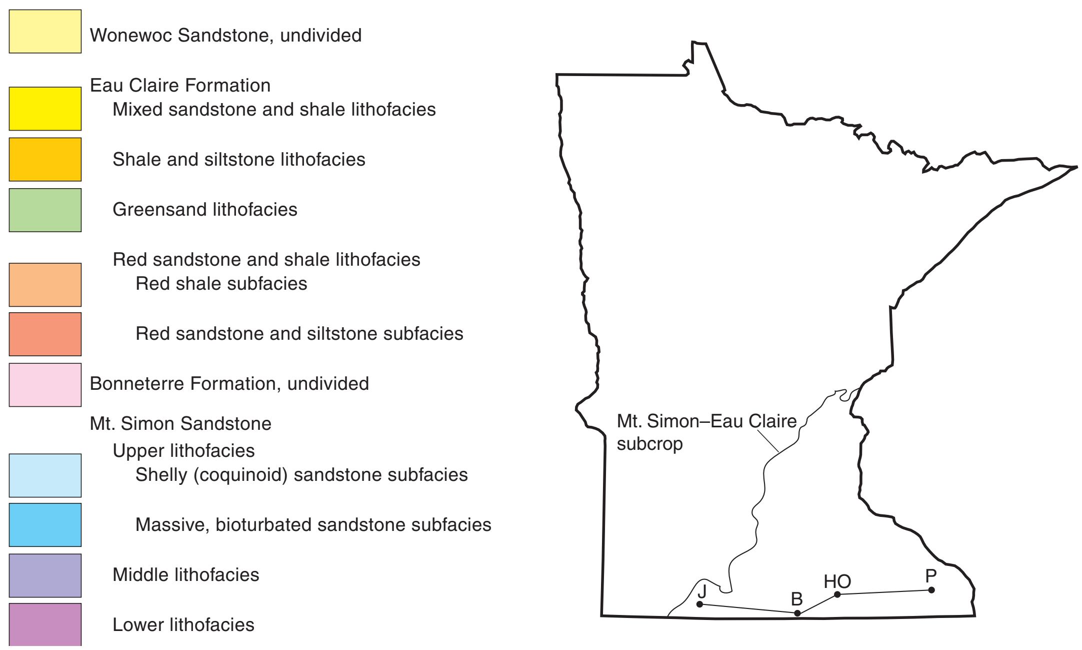


Figure 5. Geologic section showing lithofacies distribution in the Mt. Simon Sandstone, Eau Claire Formation, and Wonewoc Sandstone east to west across the Hollandale embayment. The cross section was constructed on the basis of interpretations of gamma logs (shown), core, and cutting samples (unique well numbers are listed above the logs). Section lines are shown on the inset map (page 21).

EXPLANATION TO FIGURE 5



Lithology—The Mt. Simon Sandstone overall is characterized by medium- to coarse-grained quartzose sandstone with high-angle cross-stratification. Based on study of core and geophysical logs mainly from exploratory test holes for gas storage sites and for mineral exploration, the Mt. Simon Sandstone is divided into three major lithofacies in the subsurface of Minnesota (Mossler, 1992b) that are similar to the lithofacies described in western Wisconsin by Driese and others (1981). These lithofacies are illustrated on the geologic sections on Figures 5 and 6. The distribution and nature of lithofacies is poorly known in much of the southern part of the Hollandale embayment because of the sparseness of data.

Lower lithofacies: Light brown to pale yellowish-brown to grayish-orange-pink, medium- to coarse-grained, moderately to well sorted, quartzose sandstone. Sandstone occurs principally as medium to thick sets of planar cross-stratified sandstone with high-angle foresets, though there are also bedsets of trough cross-stratified sandstone and minor beds with horizontal to sub-horizontal or less commonly very low-angle cross-stratification. Intraclasts of siltstone and shale and granules and pebbles of quartz are present along some scours and cross-bed sets. Shale and siltstone beds are uncommon and are generally very thin. Shale beds are pale reddish-brown, pale red, or greenish-gray. Conglomerate and pebbly sandstone composed of very poorly sorted quartz sandstone and polycrystalline quartz and quartzite clasts generally is present at the base of the lower lithofacies. Its bedding is crudely stratified or structureless and not imbricate. The basal conglomerate ranges from 6 inches (15 centimeters) to 5 or 6 feet (1.5 to 1.8 meters) in thickness.

The lower lithofacies is thickest in the southwestern Hollandale embayment where it reaches 163 feet (49.7 meters). It generally is characterized by a natural gamma pattern that is low and uniform in value compared to overlying parts of the Mt. Simon Sandstone (Figs. 5, 6).

Middle lithofacies: Yellowish-gray to light brownish-gray, fine- to coarse-grained, moderately sorted, quartzose sandstone. Beds commonly are structureless but some have crude, horizontal stratification and rarely planar or trough cross-stratification. Ripple forms are present at the tops of some beds. Thin beds of quartz granules, and more rarely intraclasts, occur at the base of some beds. Some beds contain *Skolithos* traces. Some sandstone is coarsely interlayered with shale partings, thin beds of siltstone, and very fine-grained, feldspathic sandstone. Bedsets are commonly 3 to 5 feet (0.9 to 1.5 meters) thick, but in rare instances are up to 24 feet (7.3 meters) thick. The quartzose sandstone beds are interbedded with beds of very fine- to fine-grained, well sorted, feldspathic to highly feldspathic sandstone that is very thick bedded or structureless, or has crude horizontal stratification. This fine-grained sandstone is coarsely interlayered with pale olive or greenish-gray silty shale. The fine-grained sandstone generally occurs as thin beds

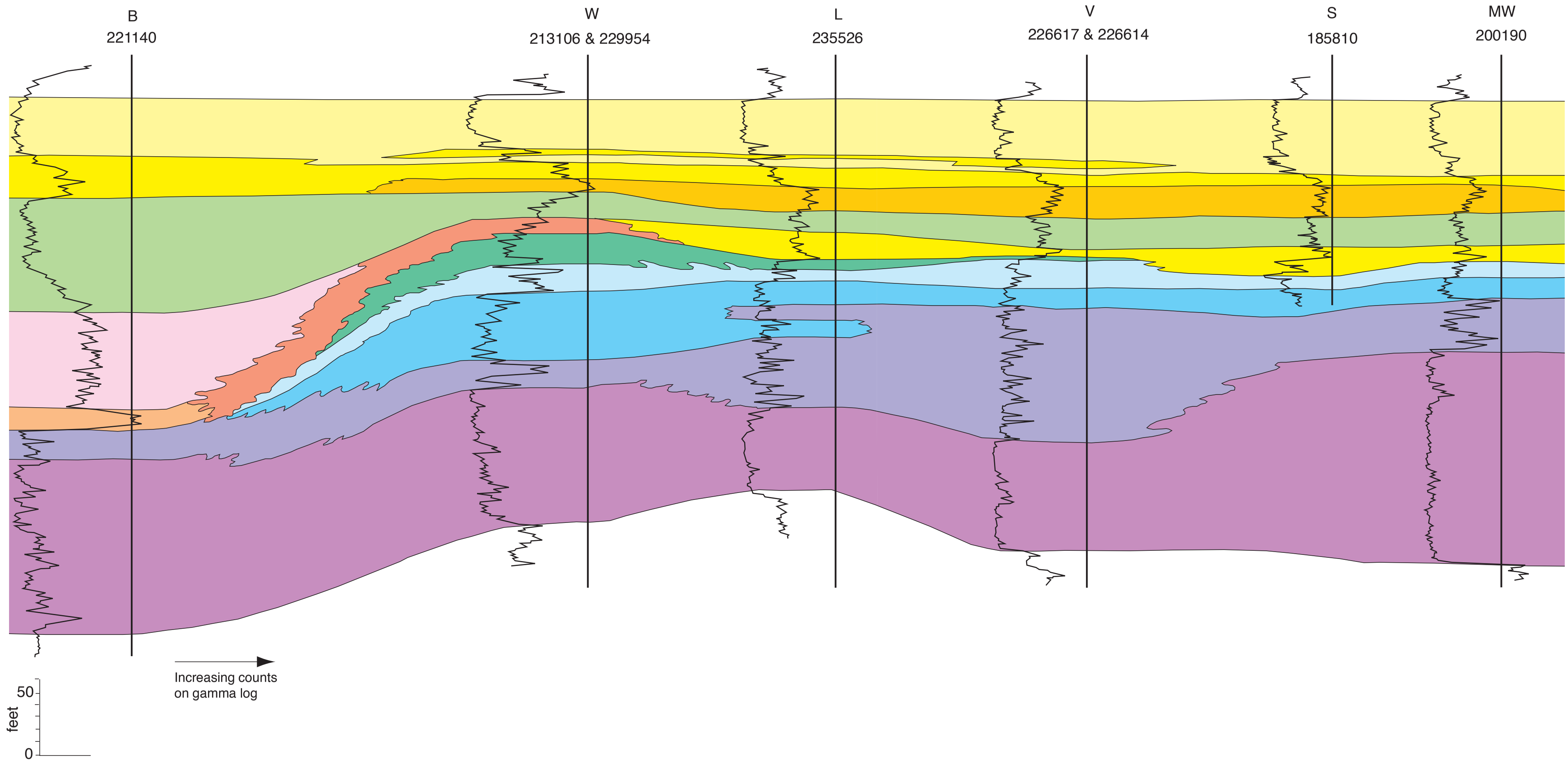
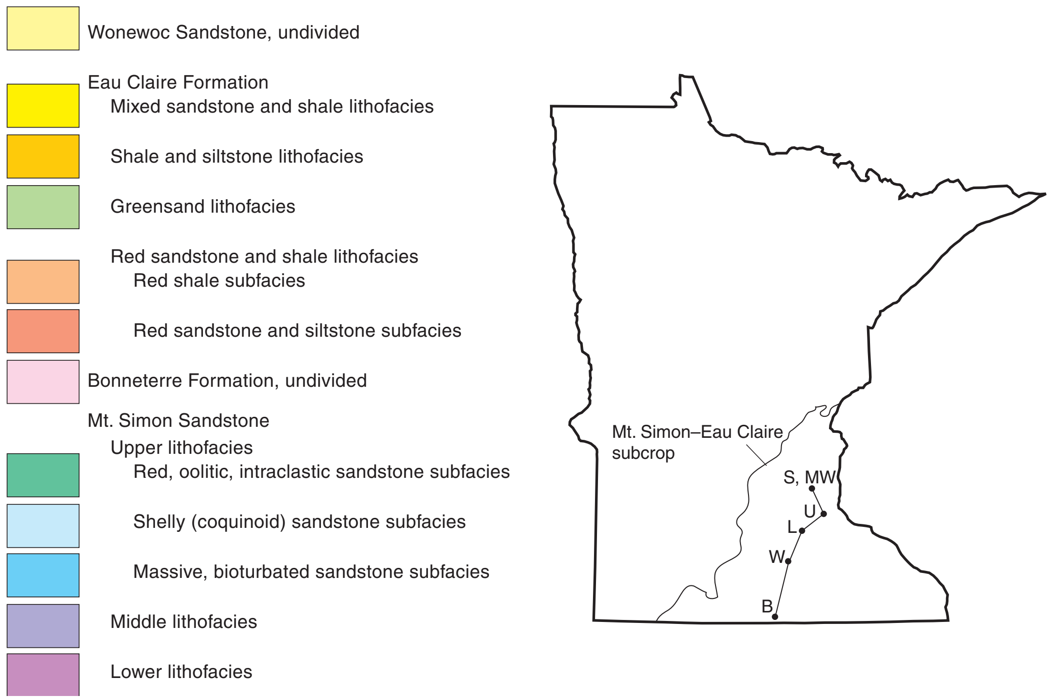


Figure 6. Geologic section showing lithofacies distribution in the Mt. Simon Sandstone, Eau Claire Formation, and Wonewoc Sandstone south to north across the Hollandale embayment. The cross section was constructed on the basis of interpretations of gamma logs (shown), core, and cutting samples (unique well numbers are listed above the logs). Section lines are shown on the inset map (page 23).

EXPLANATION TO FIGURE 6



or bedsets that are 0.5 to 2 feet (0.15 to 0.6 meter) thick though rarely beds reach up to 10 feet (3.0 meters) in thickness. Some of the fine-grained beds in the middle lithofacies resemble lithofacies found in the overlying Eau Claire Formation, including greenish-gray glauconitic and dolomitic siltstone and shale found in the southwestern part of the Hollandale embayment that resembles the shale and siltstone lithofacies of the Eau Claire Formation; and interbedded greenish-gray shale and fine- to very fine-grained, well-sorted, light gray sandstone in the southeastern part of the embayment that resembles the mixed sandstone and shale lithofacies of the Eau Claire Formation.

The intricate interbedding of feldspathic and quartzose sandstone beds that characterize this lithofacies gives rise to ragged natural gamma radiation (Figs. 5, 6) and resistivity readings on geophysical logs. Resistivity is higher in the coarser-grained quartzose sandstone because they are saturated with fresh water. In contrast, gamma readings are lower in the quartzose sandstones compared to the feldspathic, because the feldspathic sandstone contains more elements with naturally occurring radioactive isotopes, particularly potassium. In contrast to the sawtooth pattern of geophysical logs from the middle lithofacies, the lower lithofacies commonly has more uniform patterns, reflecting the uniformity of its lithologies.

The middle lithofacies extends throughout the Hollandale embayment and is thickest in the southeast, where it is more than 200 feet (61 meters) thick (Fig. 5).

Upper lithofacies: This lithofacies consists of three subfacies. These subfacies appear to intertongue with one another as well as with tongues of basal Eau Claire Formation lithofacies. Subfacies are described in ascending order.

Massive, bioturbated sandstone: Yellowish-gray, very fine- to coarse-grained, silty, poorly to moderately sorted, quartzose to feldspathic sandstone. Interbedded shale and siltstone beds are rare. Sandstone beds are intensively burrowed by *Skolithos* and most internal structure such as cross-stratification has been destroyed. The sandstone occurs in thick beds that are 3 feet (0.9 meter) to more than 20 feet (6.1 meters) thick. This subfacies is more common in the west-central part to the western margin of the Hollandale embayment where it occurs in middle to lower parts of the Mt. Simon Sandstone as well as the upper part (see middle lithofacies above). It is the dominant subfacies in much of one core from the western margin of the embayment throughout intervals that aggregate 85 feet (25.9 meters) in thickness. This subfacies has lower gamma patterns (Fig. 6) and higher resistivity patterns on geophysical logs than neighboring units.

Shelly (coquinoid) sandstone: Light brown to light brownish-gray, fine- to medium-grained, moderately to well sorted, quartz sandstone. Beds of the sandstone are generally structureless but may have horizontal stratification or medium-scale cross-stratification. There are abundant disarticulated and fragmental valves from inarticulate brachiopods along bedding planes and on foresets of cross-stratified sandstone. In places they are so abundant that they form coquinas. This subfacies is well developed in west-central and eastern parts of the Hollandale embayment where it is from 15 to 35 feet (4.6 to 10.7 meters) thick (Figs. 5, 6) and is a useful marker for the top of the Mt. Simon Sandstone in well cuttings.

Red, oolitic, intraclastic sandstone: Pale red to grayish-red, fine- to coarse-grained, moderately sorted, quartzose sandstone. Many beds contain intraclasts of light gray siltstone, pale red shale, and red, dense dolostone. Ferroan ooids (oolitic ironstone) and coated grains occur as scattered grains in quartz sandstone and as solid beds that are up to 9 feet (2.7 meters) thick. Oolitic zones are phosphatic with collophane as intergranular cement, within ooids as some of their concentric lamellae, and in brachiopod valves and other fossil remains. Some beds have fine-grained planar or trough cross-stratification, others are structureless or bioturbated. This subfacies is developed at the top of the Mt. Simon Sandstone in west-central parts of the Hollandale embayment (Fig. 6) where it is up to 20 feet (6.1 meters) thick.

Fossil content—Inarticulate brachiopods are common in the top 15 to 60 feet (4.6 to 18 meters). Trilobites of the *Cedaria* zone are found in core from the center of the Hollandale embayment (Runkel and others, 1998). Abundant trace fossils are present in core from the upper half of the formation. The most commonly observed trace fossil is *Skolithos*, which occurs in massive, unbedded, fine- to coarse-grained sandstone beds with bimodal sand grain size distributions, features suggestive of intense bioturbation.

Relationship to adjacent rock units—The Mt. Simon Sandstone overlies Archean and Proterozoic crystalline rocks with profound unconformity along the margins of the Hollandale embayment (Fig. 2C). There generally is a clay-rich zone characterized by kaolinite and mixed-layer mica-montmorillonite clay that traditionally has been referred to as a saprolite on top of the metamorphic and intrusive igneous basement rock. Geochemical analyses of outcrops of this clay-rich zone in Wisconsin indicate alteration there may be the result of post depositional hydrothermal fluid activity (Haupt and Hooper, 1994). The clay-rich zone ranges from 9 to 12 feet (2.7 to 3.7 meters) in thickness in the southeast (Mossler, 1992b) to 60 feet (18 meters) toward the north (Morey, 1972). Along the axis of the Hollandale embayment (Fig. 2C), the Mt. Simon Sandstone unconformably overlies a thick Middle Proterozoic sedimentary sequence that is divided into the Hinckley, Fond du Lac, and Solor Church Formations (Morey, 1977). The Mt. Simon Sandstone overlies the Hinckley Sandstone mainly in the part of the Hollandale embayment that is west and northwest of the Twin Cities basin (Fig. 2C). In the main part of the basin it overlies the Fond du Lac or Solor Church Formations (Fig. 2C). The basal Mt. Simon Sandstone is much coarser-grained and more poorly sorted than the underlying quartz sandstone in the upper part of the Hinckley Sandstone. The upper part of the Hinckley Sandstone is fine- to medium-grained and moderately to well sorted and generally has reddish to pink (salmon) color. The upper part of the Hinckley Sandstone is also generally tightly cemented by quartz overgrowths, whereas basal Mt. Simon Sandstone is friable. As discussed by Boerboom and others (2003), the stratigraphic relationship between the Mt. Simon and Hinckley Sandstones is poorly known and needs further investigation. Some parts of the Hinckley Sandstone may be a landward facies of the better-known Mt. Simon Sandstone to the south. However, until a Paleozoic age can be documented for sandstone classified as Hinckley Sandstone, it will continue to be considered part of the Proterozoic sedimentary sequence.

The Middle Proterozoic Fond du Lac Formation is arkosic (orthoclase, microcline, and granitic rock fragments), and the Solor Church Formation contains abundant aphanitic (basaltic) lithic grains and plagioclase (Morey, 1977). Both the Fond du Lac and the Solor Church Formations contain abundant pale red to red-brown shale beds.

The contact of the Mt. Simon Sandstone and overlying Eau Claire Formation is conformable and uppermost lithofacies of the Eau Claire Formation and Mt. Simon Sandstone appear to be laterally equivalent. For example, the basal red sandstone and shale lithofacies of the Eau Claire Formation is interpreted to be laterally equivalent to the upper lithofacies (the red, oolitic, intraclastic sandstone and the shelly sandstone) of the Mt. Simon Sandstone (Fig. 6).

Representative sections—The Mt. Simon Sandstone is well represented in cores available at the Minnesota Department of Natural Resources Core Library at Hibbing (Table 1). The preceding discussion of lithofacies is based upon study of the listed cores and others at the library. Descriptions for some of the cores in the Minnesota Department of Natural Resources library are available in Austin (1970) and Mossler (1992b).

EAU CLAIRE AND BONNETERRE FORMATIONS

The Eau Claire Formation is named for Eau Claire, Eau Claire County, Wisconsin, (Ulrich, *in* Walcott, 1914, p. 394), where the type section is 100 feet (30 meters) of thin-bedded, partly shaly, fossiliferous sandstone (Fig. 3). The Bonneterre Formation was named for outcrops in St. Francis County, Missouri (Nason, 1901).

Occurrence—The Eau Claire Formation occurs throughout southeastern Minnesota in the subsurface (Mossler, 1983, pl. 6); however, exposures are rare. In Minnesota, exposures representative of typical Eau Claire Formation rock are known only from Wabasha County near the city of Wabasha (Fig. 3, location 1). However, numerous outcrops occur in western Wisconsin, some of them described by Havholm and others (2000). The Bonneterre Formation occurs only in the subsurface of Faribault and Jackson Counties in southwestern Minnesota.

Thickness—The combined thickness of the Eau Claire and Bonneterre Formations is greatest in south-central Minnesota (Faribault County) where their combined thickness is more than 250 feet (76 meters). The Eau Claire Formation thins northward from a maximum thickness in excess of 200 feet (61 meters) near the Iowa border to less than 100 feet (30 meters) in the Twin Cities basin (see Mossler, 1992b, Fig. 6b). The Eau Claire Formation thins to a featheredge by Taylors Falls in northern Chisago County where it onlaps Middle Proterozoic basalt (Fig. 2C).

Lithology—The **Eau Claire Formation** is a relatively fine-grained, thin bedded, siliclastic unit. It is chiefly very fine- to fine-grained sandstone, siltstone, and shale. Its sandstone beds commonly have hummocky cross bedding. The sandstone beds are feldspathic and locally glauconitic. In Minnesota the Eau Claire Formation is divided informally into four lithofacies whose stratigraphic relationships are shown on Figures 5 and 6. The **Bonneterre Formation** is mainly dolostone. It intertongues with the lower part of the Eau Claire Formation in the southwestern part of the Hollandale embayment of Minnesota.

Eau Claire Formation lithofacies follow:

Red sandstone and shale: Two subfacies (Figs. 5, 6): In the southwest, pale red to grayish-red shale, interbedded with abundant thin beds of very sandy (fine- to medium-sand sized quartz grains) inarticulate brachiopod coquina that contains shale rip-up clasts. This subfacies occurs from Faribault County westward into Jackson County in south-central Minnesota. It is more dolomitic west of Faribault County, where it apparently grades into Bonneterre Formation dolostone. East and north of Faribault County, in the center of the Hollandale embayment, the red shale is replaced by pale red and grayish-red siltstone and very fine- to fine-grained sandstone. These contain intraclasts of pale red shale, red dolostone, siltstone, and sandstone and rare ferroan ooids. Although the red sandstone and shale lithofacies extends into the southwestern edge of the Twin Cities metropolitan area, it is absent from counties along the Mississippi River in the eastern Hollandale embayment. Its distribution is shown on Figure 19 of Mossler (1992b). The red shale subfacies is a tabular unit that is 20 to 34 feet (6.1 to 10.4 meters) thick. The red sandstone and siltstone subfacies is wedge shaped and thickest near the axis of the Hollandale embayment in eastern Freeborn County, where it is nearly 90 feet (27.4 meters) thick (Austin, 1970). It is much thinner north and east from Freeborn County, commonly about 15 feet (4.6 meters). It apparently grades into the mixed sandstone and shale lithofacies (see below) and uppermost facies of the Mt. Simon Sandstone toward the east and northeast and into the red shale subfacies and Bonneterre Formation dolostone to the west and southwest. The red sandstone and shale lithofacies is equivalent to the "red unit" described by Austin (1969, 1970). The red shale subfacies is equivalent to facies 7 of Runkel and others (1998), the shale, dolomudstone, and skeletal dolostone lithofacies. The sandstone subfacies is equivalent to part of lithofacies 3 of Runkel and others (1998), the very fine- to fine-grained sandstone.

Mixed sandstone and shale: Very fine- to fine-grained, well sorted, feldspathic siltstone, feldspathic sandstone, and greenish-gray shale. The shale occurs as flasers, clay drapes, or wavy beds in ripple-cross-stratified sandstone, or finely or coarsely interlayered with beds of sandstone.

As discussed in Mossler (1992b), this lithofacies is equivalent to the "sand-shale unit" and the "sandy unit" of Austin (1969). It is equivalent to facies 2 of Runkel and others (1998). It occurs in the basal part of the Eau Claire Formation in the southeastern and northern parts of the Hollandale embayment, and in its uppermost part throughout the embayment (Figs. 5, 6). It is thickest in the basal Eau Claire Formation in the east part of the Hollandale embayment where it is 20 to 30 feet (5.5 to 9.2 meters) thick. It is absent at the base of the Eau Claire Formation toward the west near the center of the Hollandale embayment.

In the upper part of the Eau Claire Formation this lithofacies is generally 18 to 20 feet (5.5 to 6.1 meters) thick but it increases to about 35 to 40 feet (10.7 to 12.2 meters) in thickness in the southwestern part of the embayment (Figs. 5, 6). It intertongues with basal Wonewoc Sandstone along the eastern part of the Hollandale embayment.

Greensand: Well sorted, highly feldspathic to highly glauconitic, very fine-grained sandstone and siltstone. Shale is uncommon, however, there are some flasers and clay drapes. Most sandstone beds have fine-grained planar to slightly inclined laminations, trough cross-stratification, or wavy, hummocky cross-stratification; bioturbated beds are minor. This lithofacies is equivalent to Austin's (1969) "greensand unit" and to facies 3 of Runkel and others (1998). The greensand lithofacies is wedge shaped and thickest in the southwestern part of the Hollandale embayment (Figs. 5, 6). In Faribault County it is 95 feet (29 meters) thick. It thins to about 12 feet (3.7 meters) in thickness near the northern and eastern margins of the Hollandale embayment.

Shale and siltstone: Greenish-gray, grayish-red-purple, and pale brown shale with minor siltstone, grayish-yellow-green and very minor yellowish-gray, feldspathic sandstone. Shale rich layers contain isolated lenses of siltstone and sandstone (lenticular bedding). Intervals with more siltstone and sandstone have finely or coarsely interlayered or wavy beds of siltstone and sandstone. This lithofacies is equivalent to Austin's (1969) "shaly unit" and to facies 1 of Runkel and others (1998). It occurs mainly in the subsurface within the middle part of the Eau Claire Formation, although there is a tongue of this lithofacies also in the subsurface near the base of the Eau Claire Formation in Fillmore County. Its distribution is shown on Figure 23 of Mossler (1992b). Up to 40 feet thick (12 meters) in Dakota and eastern Rice Counties, the shale and siltstone lithofacies thins to a zero isopach to the east and west and is absent along the outcrop belt of the Eau Claire Formation in western Wisconsin and elsewhere along margins of the Hollandale embayment.

***Lithology*—Bonneterre Formation:** Pale olive-gray, sandy, fossiliferous dolostone. The dolostone is finely crystalline, soft, and argillaceous. This lithofacies occurs in Faribault and Jackson Counties, southwestern Minnesota. It is progressively more dolomitic toward the west and more argillaceous toward the east where it appears to merge with the red sandstone and shale lithofacies of the Eau Claire Formation. It is considered to be a tongue of dolostone extending from the Bonneterre Formation, described in northwestern Iowa by Adler (1986). This dolostone unit is wedge-shaped and is thickest (50 to 75 feet [15.2 to 22.9 meters]) in the extreme southwestern part of the Hollandale embayment in Minnesota. It thins to a depositional zero isopach somewhat west of the center of the embayment. Its distribution is shown on Figure 19 of Mossler (1992b). The Bonneterre Formation of Minnesota is equivalent to facies 8 of Runkel and others (1998). Austin (1969) did not identify this lithofacies because the data from Faribault and Jackson Counties on which it is based became available after his study.

Fossil content—The Eau Claire Formation is the most abundantly fossiliferous Cambrian formation in Minnesota. Trilobites of the *Cedaria, Crepicephalus, Aphelaspis*, and *Dunderbergia* zones are common (Runkel and others, 1998). Inarticulate brachiopods are abundant (Nelson, 1949); *Dicellomus* and various acrotretid brachiopods are particularly abundant. Hyolithids also are common. Trace fossils are common, particularly as burrows along bedding planes, for example *Planolites*. In Minnesota, the Bonneterre Formation dolostone contains trilobites, inarticulate brachiopods, hyolithids, and echinoderms (Mossler, 1992b; Runkel and others, 1998).

Relationship to adjacent rock units—The contact of the Eau Claire Formation and underlying Mt. Simon Sandstone is conformable and is generally picked at the highest occurrence of medium- to coarse-grained sandstone beds. In outcrop areas in neighboring Wisconsin the contact is sharp and there is commonly heavy iron (hematite) impregnation and cementation in the sandstone beneath it. The contact is also fairly sharp and well defined in the subsurface in places where the red sandstone and shale lithofacies of the Eau Claire Formation overlies the Mt. Simon Sandstone. However, the mixed sandstone and shale lithofacies of the Eau Claire Formation and the Mt. Simon Sandstone appear to intertongue and have a gradational contact in the subsurface of the Hollandale embayment where they are in juxtaposition.

The contact of the Eau Claire Formation and overlying Galesville Sandstone is conformable (Runkel and others, 1998). Beds of the mixed sandstone and shale lithofacies intertongue with basal Galesville Sandstone. An apparent disconformity observed in neighboring western Wisconsin (Ostrom, 1970) represents localized erosion at the base of lenticular, submarine channel fills within the base of the formation and not a regional unconformity (Havholm and others, 2000).

Representative sections—Outcrops of the Eau Claire Formation in Minnesota or nearby in Wisconsin are very scarce. The few that occur in the upper St. Croix valley (Nelson, 1949) at St. Croix Falls, Wisconsin (Cavaleri and others, 1987), and to the north are on private land or difficult to access. In southeast Minnesota, there was a small outcrop of very fine-grained, glauconitic sandstone in the village of Dresbach (Fig. 3, location 2; T. 105 N., R. 4 W., sec. 18, SE, NE, Winona County), along the Mississippi River south of Winona that was described by Stauffer and Thiel (1941) as a part of the Dresbach Formation. Exposures of intertonguing Galesville Sandstone and Eau Claire Formation, described by Runkel and others (1998) and Havholm and others (2000), crop out along U.S. Highway 61, south of Wabasha (Fig. 3, location 1; T. 110 N, R. 10 W., sec. 9, NW, NW, NE, Wabasha County). A good, accessible outcrop near Minnesota is by the dam at Little Falls State Park in T. 29 N., R. 19 W., sec. 8, NE, St. Croix County, Wisconsin, just east of Hudson (Fig. 3, location 3), where about 70 feet (21 meters) of fossiliferous, very fine-grained sandstone and shale were described by Nelson (1949) beneath sandstone of the Wonewoc Sandstone. The Eau Claire Formation is well represented in the cores available at the Minnesota Department of Natural Resources Core Library at Hibbing (Table 1). Published descriptions for some of these cores are available in Austin (1970) and Mossler (1992b).

WONEWOC SANDSTONE (IRONTON AND GALESVILLE SANDSTONES)

The revisions proposed in this report include recognition of the Wonewoc Sandstone (Ostrom 1966, 1967) as a formation composed of fine- to coarse-grained sandstone that lies between the Eau Claire and the Lone Rock Formations (Fig. 4). The Ironton Sandstone (Berkey, 1897; Thwaites, 1923, p. 550) and the Galesville Sandstone (Trowbridge and Atwater, 1934, p. 45), formerly recognized as discrete formations in Minnesota, are reduced to informal members of the Wonewoc Sandstone.

Ostrom (1966, 1967) first applied the name Wonewoc Sandstone in Wisconsin to the combined Ironton and Galesville Sandstone interval because of the absence of obvious lithologic or temporal breaks between those formations. Today most stratigraphers prefer that name because of the difficulty in distinguishing between the Ironton and Galesville Sandstones. The reference section for the Wonewoc Sandstone is a quarry and bluffs in and around the village of Wonewoc in T. 14 N., R. 2 E., secs. 26 and 35, Juneau County, Wisconsin.

Occurrence—The Wonewoc Sandstone occurs throughout the Hollandale embayment (Mossler, 1983, pl. 5). Outcrops are most abundant along the Mississippi River valley and the lower reaches of its tributaries in southern Wabasha, Winona, and Houston Counties. There are a few outcrops in the St. Croix valley in southern Chisago County south of Taylors Falls.

Thickness—The thickness of the Wonewoc Sandstone ranges from more than 100 feet (30 meters) in eastern Houston and Winona Counties (Fig. 6) to less than 25 feet (7.6 meters) in some places near the center of the Hollandale embayment. It thins to a zero edge where it abuts against Middle Proterozoic volcanic rocks in the upper St. Croix River valley near Taylors Falls in Chisago County.

Lithology—The Wonewoc Sandstone is principally medium- to coarse-grained quartzose sandstone with high-angle cross-stratification. It is divided into two major lithofacies in Minnesota (Runkel and others, 1998), which are described below. A third lithofacies occurs only in a limited area at the northern end of the Paleozoic outcrop belt.

Very fine- to very coarse-grained sandstone: (this facies corresponds generally with the Ironton Sandstone): Laterally extensive sandstone beds from 1.9 inches to 6.6 feet (5 centimeters to 2 meters) thick, each consisting of one of the following: 1. Poorly sorted, shaly, silty sandstone with a pervasive bioturbated texture. Shale and siltstone occur in lenses or as matrix between sand grains; 2. Moderately to well-sorted sandstone that is internally structureless or contains ill-defined trough and tangential cross-strata with rare shale drapes and reactivation surfaces; or 3. Local intercalated shale and sandstone as a set of low-angle, inclined heterolithic strata composed of thin, inclined beds of shale and sandy shale alternating with coarse- to very coarse-grained sandstone beds. These strata are up to 4.9 feet (1.5 meters) thick.

Fine- to coarse-grained cross-stratified sandstone (this facies corresponds generally with the Galesville Sandstone): Sandstone, fine- to coarse-grained, moderately to well sorted, quartzose. Quartzose (greater than 98 percent) except near paleotopographic highs where lithic fragments and feldspar increase. Bedding is dominated by wedge sets of trough cross-strata from 3.9 to 11.8 inches (10 to 30 centimeters) thick. Cross-strata are generally deeply truncated by overlying sets or by laterally extensive scour surfaces marked by thin lag deposits. Broken, abraded, inarticulate brachiopod shells are locally abundant. *Skolithos* burrows are common both as individual burrows and as burrows along thin, laterally extensive horizons.

Shale as drapes on foresets and as intercalated layers is uncommon. Tongues of shaly sandstone with beds that contain climbing ripple cross-stratification, herringbone cross-strata, and thin wedge sets of tangential cross-strata with clay drapes and reactivation surfaces are present.

Conglomerate (this atypical facies, the Mill Street Conglomerate, is present in Chisago County near Taylors Falls where the Wonewoc Sandstone abuts Middle Proterozoic rocks): Conglomerate, angular to well-rounded basalt boulders up to 2 feet (0.6 meter) in diameter. The interstitial sandstone includes quartzose, fine-grained sandstone, glauconitic, quartzofeldspathic, very fine-grained, dolomitic sandstone, and poorly sorted sandstone that contains grains of quartz, feldspar, and basalt. The outcrop of conglomerate is fossiliferous and contains trilobites of the *Elvinia* zone, inarticulate brachiopods, and monoplacophorans (Berkey, 1898; Berg and others, 1956; Cavaleri and others, 1987; Yochelson and Webers, 2006). "Included among the monoplacophorans are hypseloconids, high coned, septate and probably representative of the group from which cephalopods evolved," Webers (1972, p. 475).

Fossil content—The Wonewoc Sandstone contains trilobites from the *Crepicephalus*, *Aphelaspis,* and *Dunderbergia* zones and lower part of the *Elvinia* zone (Runkel and others, 1998). It also contains inarticulate brachiopods, hyolithids, and monoplacophorans (Berkey, 1897, 1898; Stauffer and Thiel, 1941; Nelson, 1949; Cavaleri and others, 1987).

Relationship to adjacent rock units—The Wonewoc Sandstone conformably overlies the Eau Claire Formation in Minnesota. The contact is gradational with fine- to medium-grained sandstone of the Wonewoc Sandstone overlying interbedded very fine-grained sandstone, siltstone, and shale of the Eau Claire Formation. Lithofacies of the Wonewoc Sandstone and Eau Claire Formation intertongue. This intertonguing can be observed in outcrop at locality 1 (Fig. 3) and on geophysical logs from southeastern Minnesota (Fig. 6). Although Ostrom (1978) interpreted the basal contact with the Eau Claire Formation in Wisconsin to be an erosional contact (Dott and others, 1986), this apparent disconformity may simply consist of laterally extensive scour surfaces on fine-grained Eau Claire Formation strata related to submarine deposition of the initial sets of Wonewoc Sandstone cross-strata. The upper contact of the Wonewoc Sandstone also is conformable (see Tunnel City Group section).

Representative sections—Runkel and others (1998) described outcrops near Wabasha, Dresbach, and La Crescent. The intertonguing relationship between basal beds of the Wonewoc Sandstone and the Eau Claire Formation can be seen at the Wabasha outcrop (Fig. 3, location 1; along U.S. Highway 61 south of Wabasha in T. 110 N., R. 10 W., sec. 4, S, SW, and sec. 9, NE, Wabasha County). A series of outcrops along Interstate 90 by Dresbach show the middle part of the Wonewoc Sandstone (Fig. 3, location 4; T. 105 N., R. 5 W., sec. 18, NE, NE, SE, Winona County). The upper part of the Wonewoc Sandstone and upper contact with the Franconia Formation is visible in the city of La Crescent (Fig. 3, location 5; T. 104 N., R. 4 W., sec. 3, W, SE, Houston County).

TUNNEL CITY GROUP (FRANCONIA FORMATION)

Ostrom (1966, 1967) named rock units equivalent to the Franconia Formation of Minnesota as defined by Berg (1954; Berg and others, 1956) the Tunnel City Group. He named rock strata equivalent to the strata that Berg described as the Birkmose, Tomah, and Reno Members of the Franconia Formation the Lone Rock Formation. He elevated the Mazomanie Member to formational status. He did this because the Franconia Formation contained two lithically distinct units mappable as formations and because he wanted to avoid using similar names for lithostratigraphic and biostratigraphic nomenclature, Franconia being well established as a (biostratigraphic) stage name at that time. Ostrom's revisions have generally been accepted by state geologic surveys neighboring Minnesota and by stratigraphers and paleontologists who specialize in the Cambrian system. For these reasons the Minnesota Geological Survey now proposes to abandon the name Franconia Formation and substitute the name Tunnel City Group for rock units between the Wonewoc Sandstone and the St. Lawrence Formation. The Birkmose, Tomah, and Reno Members, originally members of the Franconia Formation, are now to be referred to as members of the Lone Rock Formation. The Mazomanie Member is elevated to formational rank (Fig. 4, column 8).

The type section of the Tunnel City Group named by Ostrom (1966) is in and near the village of Tunnel City and includes exposures along the railroad east and west of Tunnel City, natural exposures and quarries above and south of the railroad tunnel, road cuts on Wisconsin Highway 21 northwest of the village, and the highway quarry and natural exposures north of the highway commencing with the tunnel in T. 18 N., R. 2 W., sec. 25, SW, SW, NW, Monroe County, Wisconsin (Ostrom, 1966).

The Lone Rock Formation (Ostrom, 1966) was named for exposures in a road cut on Wisconsin Highway 133 south of the village of Lone Rock that occur in the south bluff of the Wisconsin River in Iowa County, Wisconsin, (T. 8 N., R. 2 W., sec. 13, NW, SW, SE).

The Mazomanie Formation was named (Ulrich, 1920) at Ferry Bluff, T. 9 N., R. 6 E., sec. 20, SW, Sauk County, Wisconsin. It is situated across the Wisconsin River from the town of Mazomanie.

Occurrence—The Tunnel City Group occurs throughout the Hollandale embayment. Its distribution is shown in Mossler (1983, pl. 4), where it is mapped as the Franconia Formation, with the St. Lawrence Formation. Outcrops are most common along the Mississippi River valley and lower reaches of its tributaries from Goodhue County south through Houston County. It also crops out extensively along the St. Croix River valley from central Washington County (Stillwater and north) through southern Chisago County (south of Taylors Falls). Outcrops along Lawrence Creek near the village of Franconia in southern Chisago County (Fig. 3), were the type section for the Franconia Formation (Berkey, 1897). They have deteriorated since Berkey studied them.

Thickness—The Tunnel City Group varies from 140 to 180 feet (43 to 55 meters) in thickness in the southern Hollandale embayment. Compared to other Paleozoic geologic formations it is relatively uniform in thickness and does not vary much.

Lithology—The Tunnel City Group consists of three formations, the **Lone Rock Formation**, the **Davis Formation,** and the **Mazomanie Formation**:

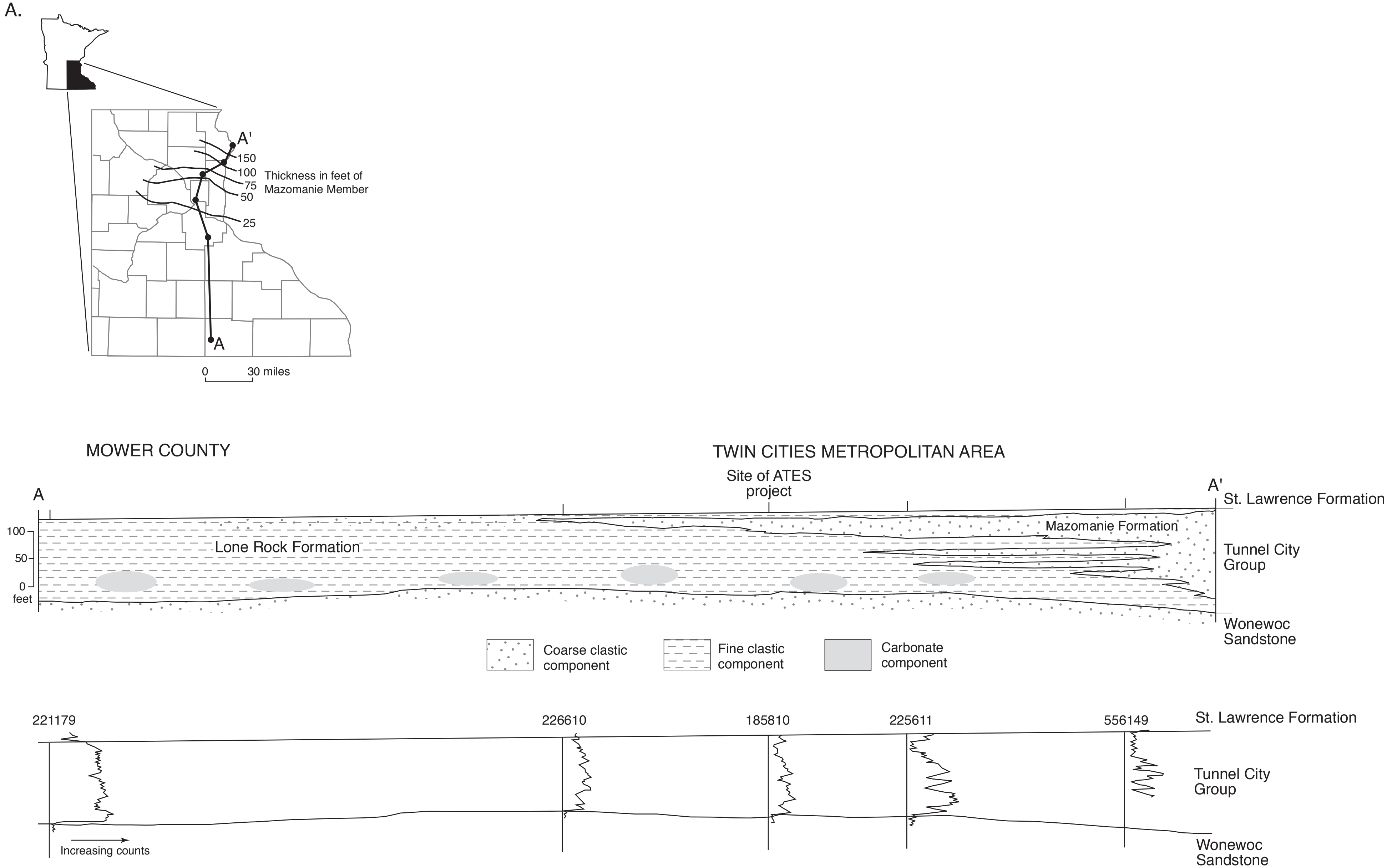
The **Lone Rock Formation** contains three members that originally were named and described by Berg (1954). In ascending order these members are the Birkmose, Tomah, and Reno Members. In southwestern Minnesota, the Lone Rock Formation intertongues with a thin dolostone unit assigned to the Davis Formation and in east-central Minnesota it intertongues with beds of the Mazomanie Formation (Fig. 7).

Birkmose Member: Greenish-gray, very fine- to fine-grained, highly glauconitic and feldspathic sandstone. It is massively bedded with burrow mottling; burrows are commonly lined or filled with light gray silt. There are a few beds that are horizontally laminated or more rarely contain high-angle cross-stratification. Minor, pale red, fine- to coarse-grained dolostone that is glauconitic and intraclastic and commonly cross-bedded is present at the top of the member. The Birkmose Member ranges from about 20 feet (6 meters) in thickness at St. Paul in Ramsey County, to 50 feet (15 meters) in Rice and Waseca Counties. The type section is at Hudson, Wisconsin (Fig. 3). There are outcrops of this member from southern Wabasha County southwards, along the Mississippi River and its major tributaries. These outcrops usually occur in close juxtaposition to outcrops of the underlying Wonewoc Sandstone. However, because of the nonresistant nature of the Birkmose Member and its high content of glauconite, which is a natural fertilizer, the outcrops usually rapidly become grassed over and concealed.

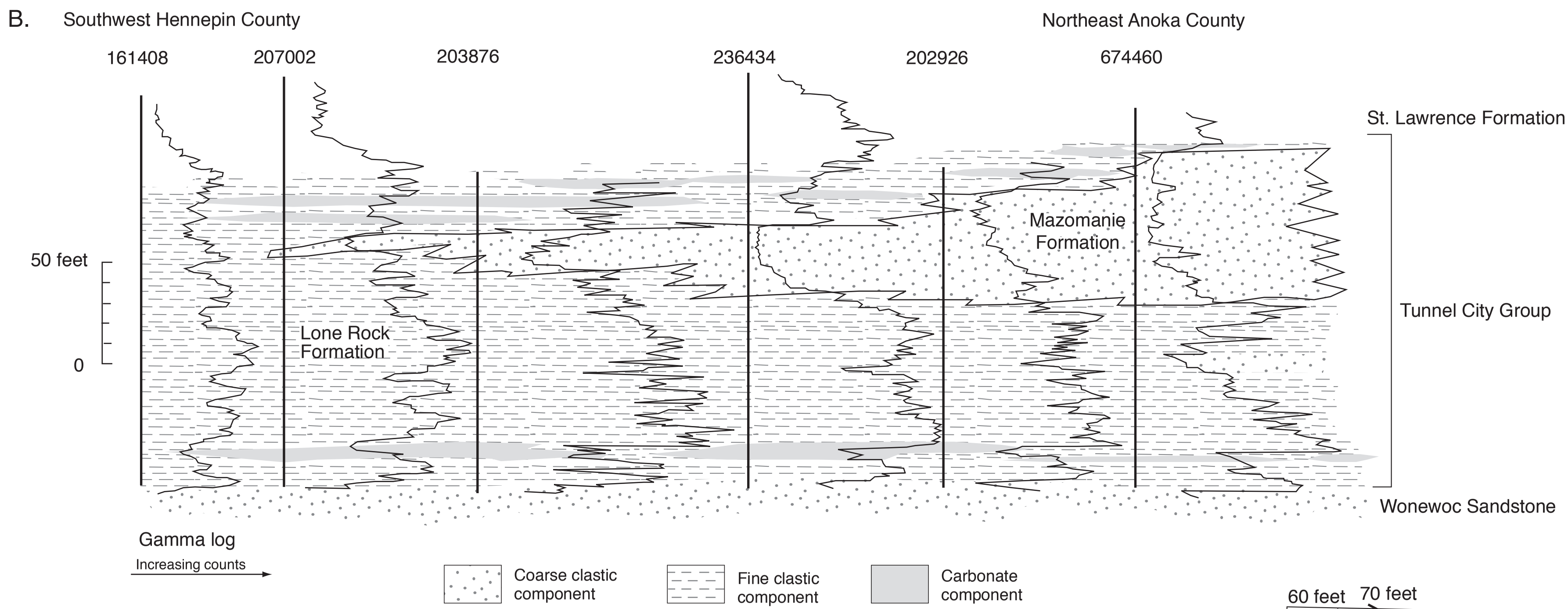
Tomah Member: Light brownish-gray, feldspathic siltstone to very fine-grained, feldspathic sandstone, interbedded with greenish-gray, micaceous shale in very thin beds. Glauconite is very minor where present. Sandstone beds are commonly hummocky cross-laminated and contain shale laminae (James, 1977). Nearly all Tomah Member outcrops contain well-preserved fossils including trilobite molds (Berg, 1954). The contact of the Tomah Member with the underlying Birkmose Member is generally sharp, but conformable. The contact with the overlying Reno Member is gradational and generally indistinct (James, 1977). The distinctive lithology of the Tomah Member is most recognizable where it crops out along the Mississippi and lower St. Croix River valleys and in core from the subsurface of the Twin Cities metropolitan area. Complete cores of Lone Rock Formation strata from the central part of the Hollandale embayment do not resemble it lithically (Mossler, 1987) because that core contains abundant glauconite and lacks the regular interlayering of shale and sandstone beds that Berg described at the type section of the Tomah Member (Berg, 1964). The Tomah Member is 27 feet (8.2 meters) thick at Hudson in St. Croix County, Wisconsin, and 23 feet thick (7 meters) beneath the Twin Cities. Outcrops of this member are not very common, probably because it is a soft, thin unit that is relatively non-resistant to erosion and prone to overgrowth by vegetation.

Reno Member: Light olive-gray to greenish-gray, very fine-grained, glauconitic, feldspathic sandstone. There are minor siltstone and greenish-gray shale beds. Bioturbated beds that contain irregular burrows packed with gray siltstone are interbedded with coarsely interlayered beds of sandstone and siltstone, horizontally laminated and ripple cross-laminated sandstone beds, and largely hummocky cross-stratified beds with minor higher-angle trough cross-stratified beds. Silty or shaly beds commonly contain lenses of fine-grained sandstone that are interpreted to be starved ripples. Oscillation ripple marks and sand-filled cracks in shale are commonly observed in outcrop, as are thin beds of flat-pebble conglomerate (intraclasts). The clasts are generally glauconitic sandstone identical to underlying and adjacent beds of Reno Member rock and are most common in the upper third to half of the member. Typically there is a siltstone

A.



A'
150
100
75
50
25
Thickness in feet of
Mazomanie Member
A
0
30 miles
MOWER COUNTY
TWIN CITIES METROPOLITAN AREA
Site of ATES
project
A
A'
St. Lawrence Formation
Mazomanie Formation
Lone Rock Formation
Tunnel City
Group
100
50
0
feet
Wonewoc
Sandstone
Coarse clastic
component
Fine clastic
component
Carbonate
component
221179
226610
185810
225611
556149
St. Lawrence Formation
Tunnel City
Group
Wonewoc
Sandstone
Increasing counts



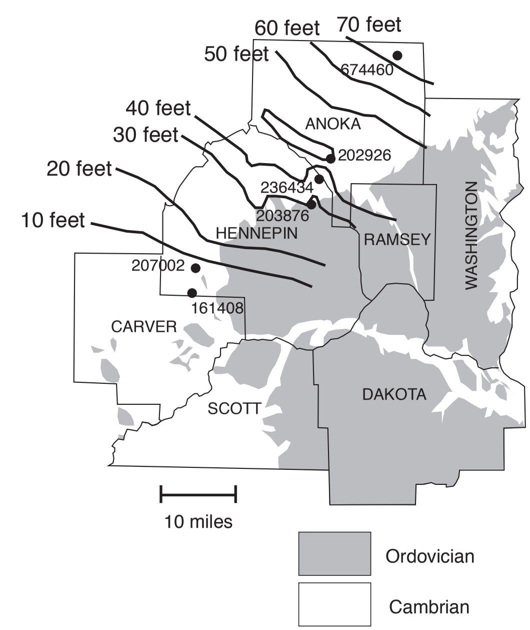


Figure 7. Geologic sections showing lithofacies distribution in the Tunnel City Group. Unique well numbers are listed above the gamma logs.

A. Variations from south to north across the Hollandale embayment (adapted from Runkel and others, 2003, Fig. 22).

B. Detail showing variation in the northern part of the Hollandale embayment (Runkel, unpub. data, 2003).

flat-pebble conglomerate with a matrix of glauconitic sandy dolostone at the top of the Reno Member that ranges from 6 inches to 6 feet (15 centimeters to 1.8 meters) in thickness in outcrop and is thickest in extreme southeast Minnesota in Houston County (Berg, 1954). Core samples indicate that this bed is also widely distributed in the subsurface where it is as much as 10 feet (3 meters) thick. The Reno Member is up to 110 feet (33.5 meters) thick in the Hollandale embayment. There are numerous outcrops of parts this member along the Mississippi River and its major tributaries from Goodhue County southwards through Houston County where its type section is located (Fig. 3), perhaps because it is thicker and slightly more resistant to erosion than the other members of the Lone Rock Formation and also is the uppermost member of the formation so it is less likely to be buried beneath colluvium in bluffs and cliffs.

Davis Formation: In the southwestern part of the Hollandale embayment in Faribault and Freeborn Counties, part of the stratigraphic interval equivalent to the Birkmose Member of the Lone Rock Formation is occupied by yellowish-gray to pale olive, algal-laminated, intraclastic, glauconitic, and thin bedded dolostone. This unit is considered to be a tongue of the Davis Formation that extends from northwestern Iowa (Fig. 4, column 8). It ranges in thickness from 8 feet (2.4 meters) in Freeborn County to 20 feet (6 meters) in Faribault County.

Mazomanie Formation: Light gray to yellowish-gray, very fine- to medium-grained, non-glauconitic to slightly glauconitic (less than 5 percent), and dolomitic sandstone. Generally thin-bedded in outcrop, the beds commonly contain *Skolithos* trace fossils (James, 1977). Most beds of the Mazomanie Formation in Minnesota are cross-stratified with amalgamated beds of hummocky sandstone, trough cross-strata, or ripple cross-strata. Many contain shale drapes and intraclasts. The Mazomanie Formation rarely contains body fossils; most of the trilobites that Berg (1954) found occurred in casehardened sandstone boulders. The Mazomanie Formation occurs mainly in the northern part of the Twin Cities metropolitan area and to the north and east (Fig. 7B). It is the principal lithostratigraphic unit of the Tunnel City Group in central Wisconsin, where it thickens and its constituent sandstone coarsens. The Mazomanie Formation reaches a maximum thickness of 115 feet (35 meters) in east-central Minnesota, south of Taylors Falls in Chisago County, and thins toward the south, in northern Hennepin, Ramsey, and Washington Counties, as it interfingers with beds of Reno Member sandstone (Fig. 7B).

The contact between the Mazomanie Formation and the underlying Lone Rock Formation is placed at the highest occurrence of rock typical of the underlying Long Rock Formation. Because of collapsing boreholes, it is generally best to define such arbitrary boundaries by the highest occurrence of a particular rock type, rather than the lowest. However, intervals of sandstone typical of the Mazomanie Formation interbedded within Lone Rock Formation sandstone recognized in cuttings or geophysical logs may be referred to informally as "tongues of Mazomanie Formation sandstone."

Fossil content—The Tunnel City Group contains trilobites of the upper part of the *Elvinia* zone and the *Conaspis* zone, *Ptychaspis* subzone, *Prosaukia* subzone, and basal part of the *Saukia* zone (Berg, 1951, 1953; Berg and others, 1956). The earliest known articulate brachiopods in Minnesota occur in the Tunnel City Group and are in great abundance ("*Eorthis* beds") at the top of the Birkmose Member (Berg, 1951). Conodonts are rare, but are known from the upper part of the Reno Member in the Tunnel City Group (Runkel, unpub. data). Inarticulate brachiopods and gastropods are present (Stauffer and Thiel, 1941). The abundance of trace fossils has been noted above.

Relationship to adjacent rock units—The Tunnel City Group is conformable with the underlying Wonewoc Sandstone and overlying St. Lawrence Formation. The regionally extensive intraclastic horizon at the top of the Tunnel City Group may represent condensed sedimentation representing a significant hiatus.

Representative sections—The Mazomanie Formation is well exposed along U.S. Highway 8, 1 mile south of Taylors Falls (Fig. 3, location 6; T. 34 N., R. 19 W., sec. 35, SE, and sec. 36, NW, Chisago County). It also can be seen at Boom Hollow near Stillwater (Fig. 3, location 7; T. 30 N., R. 20 W., sec. 15, SE, Washington County), as well as numerous places along the St. Croix River near Copas and Marine-on-St. Croix.

The Birkmose Member of the Lone Rock Formation and basal contact of the Tunnel City Group with the Wonewoc Sandstone are exposed in Hudson, Wisconsin, at the type area (Berg, 1954) along roadcuts on the street from Wisconsin Highway 35 to Birkmose Park (Fig. 3; T. 29 N., R. 20 W., sec. 25, NE, St. Croix County). The Tomah Member was formerly exposed in this series of roadcuts. The Birkmose Member and basal contact with the Wonewoc Sandstone are also visible farther south in Minnesota along the Mississippi River valley (see Wonewoc Sandstone representative sections).

The Reno Member is exposed in numerous places along the Mississippi River valley in and south of Goodhue County. There are numerous roadcuts along U.S. Highway 61 between Lake City and Wabasha (T. 111 N., Rs. 11 and 12 W., Wabasha County) including one at T. 111 N., R. 11 W., sec. 30, SW, SE (Fig. 3, location 8). The long roadcut up to Garvin Park in the city of Winona (Fig. 3, location 9; T. 107 N., R. 7 W., sec. 27, SW, and sec. 34, NW, Winona County) is another of the more accessible localities showing the lithofacies, as well as the St. Lawrence Formation, Jordan Sandstone, and Oneota Dolomite. The type section for the Reno Member in Houston County is not easily accessible.

Members of the Lone Rock Formation (Tunnel City Group) are well represented at the core library at Hibbing (Table 1).

ST. LAWRENCE FORMATION

N.H. Winchell (1874) named the St. Lawrence Formation, a very fine-grained sandstone, siltstone, shale, and dolostone unit for St. Lawrence Township in Scott County where he described the type section (Fig. 3). As mentioned in the section on the Tunnel City (Franconia Formation) Group, the St. Lawrence Formation, as formerly defined in Minnesota, originally included much of the upper part of that group (Fig. 4, column 2). Nelson (1956) defined the present boundaries for the St. Lawrence Formation. He divided the St. Lawrence Formation into two members (Fig. 4, column 5), the Lodi Member, primarily siltstone and very fine-grained sandstone, and the Black Earth Member, primarily dolostone (Nelson, 1956).

McGannon (1960), although he never published his proposals for revising St. Lawrence Formation nomenclature, pointed out several problems with Nelson's interpretation of the formation. Among his proposals was one that would have shifted the dolostone beds of the Black Earth Member into the Franconia Formation. Hughes and Hesselbo (1997) pointed out the Lodi and Black Earth Members do not represent contiguous rock units, or distinct environments of deposition and that they are imprecisely defined, therefore the Minnesota Geological Survey no longer considers these members to be valid. Nelson himself recognized that assignment of beds to one of the members sometimes had to be done arbitrarily (Nelson, 1956).

Occurrence—The St. Lawrence Formation occurs throughout southeastern Minnesota. Its distribution corresponds closely with the distribution of the underlying Tunnel City Group.

Thickness—The St. Lawrence Formation is thickest in south-central Minnesota where it is as much as 130 feet (40 meters) thick in water wells in Fillmore County and reaches 90 feet (27 meters) in cores from test wells in Faribault County. It is thinnest in outcrops along the St. Croix River valley in east-central Minnesota where it ranges from 27 to 37 feet (8.2 to 11.3 meters).

Lithology—The formation is informally divided into two lithofacies, a dolostone lithofacies and a siltstone lithofacies. The dolostone lithofacies is thickest in the central and southwestern parts of the Hollandale embayment where it directly overlies the Lone Rock Formation and underlies a thin sequence of the siltstone lithofacies. Along the eastern and northeastern margins of the Hollandale embayment the dolostone lithofacies intertongues with the siltstone lithofacies and the siltstone occurs beneath as well as above it. In areas that were more shoreward, such as the St. Croix River valley, the St. Lawrence Formation is entirely the siltstone lithofacies (Berg and others, 1956).

Dolostone lithofacies: Light olive-gray to yellowish-gray, generally glauconitic, argillaceous, silty or sandy dolostone, commonly medium bedded or unbedded, though some beds are finely laminated. This lithofacies is vuggy and commonly contains intraclasts and thin, interbedded layers of siltstone and olive-gray shale. Dolomite content generally exceeds 70 percent (Austin, 1969).

Siltstone lithofacies: Light gray to yellowish-gray and pale yellowish-green, dolomitic siltstone. Slightly sandy or slightly glauconitic in places. There are many intraclasts along some horizons, particularly in more dolomitic intervals. Some beds are finely laminated or ripple cross-laminated, and starved ripples of very fine-grained sandstone occur as lenses in some siltstone beds. Other siltstone beds are massive and some are burrow mottled.

Fossil content—The fauna includes trilobites of the *Osceolia* and *Saukia* subzone (Raasch, 1951; Hughes, 1993, 1994). The fauna is locally abundant and diverse. Besides trilobites, Hughes and Hesselbo (1997) list aglaspid arthropods (Raasch, 1939; Hesselbo, 1992), inarticulate and articulate brachiopods, gastropods, dendroid graptolites (Ruedemann, 1933), phyllocarids, rare hyolithids, "serpulids," possible primitive conulariids (Raasch, 1939), and echinoderm columnals. Trace fossils, chiefly burrows along bedding planes, are common.

Relationship to adjacent rock units—The basal contact with the Tunnel City Group is conformable. The contact generally is well defined lithologically;

in much of the Hollandale embayment it occurs at the lithologic change from very fine-grained, glauconitic sandstone of the underlying Reno Member of the Lone Rock Formation to dolostone of the St. Lawrence Formation. A widespread, prominent bed of sandy, glauconitic flat-pebble conglomerate 0.5 to 6 feet thick (0.15 to 1.8 meters), generally present at the top of the Reno Member (Berg, 1954), may mark a hiatus between the formations.

The upper contact with the Jordan Sandstone occurs at the change from predominately siltstone to predominately very fine- to fine-grained sandstone. However, the contact is gradational and hard to discern because the St. Lawrence Formation has substantial very fine-grained and even some fine-grained sandstone beds in addition to siltstone. However, the St. Lawrence Formation is generally well indurated with dolomite cement and the Jordan Sandstone is friable, loose, poorly cemented sandstone. The St. Lawrence Formation generally has conspicuous thin bedding; the basal Jordan Sandstone is poorly bedded to thick bedded. The Jordan Sandstone has less shale between sandstone beds.

Representative sections—Most of the St. Lawrence Formation that crops out in the Mississippi and St. Croix River valleys is the siltstone lithofacies. This facies is well exposed at Barn Bluff at Red Wing, Goodhue County (Fig. 3, location 10; T. 113 N., R. 14 W., sec. 29, NW, NW) and in several road cuts along U.S. Highway 14 between Winona and Lewiston (the best outcrop is a hillside in T. 107 N., R. 8 W., sec. 35, N, SE, Winona County [Fig. 3, location 11]). Other outcrops (in Afton, Washington County and Hokah, Houston County) are described and figured in Hughes and Hesselbo (1997). The more dolomitic facies is not as widely exposed; one of the better exposures is near Judson in the Minnesota River valley along the Swan Lake outlet in T. 109 N., R. 28 W., sec. 33, SW, NE, Nicollet County (Fig. 3, location 12).

JORDAN SANDSTONE

The Jordan Sandstone was named for the city of Jordan in Scott County (Fig. 3), Minnesota, where it was first named and described by N.H. Winchell (1874) from outcrops in streams and quarries. It consists of two distinct, intercalated facies: fine- to coarse-grained, quartzose sandstone and very fine-grained, feldspathic sandstone. In the past, the Jordan Sandstone has been subdivided into members that more or less correspond to these two facies (Stauffer, 1925; Stauffer and others, 1939). However, after restudy, Runkel (1994a, b) stated that the formation cannot subdivided consistently using these criteria, and the members were never adequately defined according to the North American Stratigraphic Code (1983). Therefore, he recommended use of formal members be discontinued.

A mixed siliclastic and carbonate unit above the Jordan Sandstone is considered the lowermost member, the Coon Valley, of the Oneota Dolomite. Geologists (Ostrom, 1967; Austin, 1969; Odom and Ostrom, 1978) previously included these strata in the Jordan Sandstone and considered them its uppermost member. Inclusion of the Coon Valley Member in the basal Oneota Dolomite in this report is based on work by Smith and others (1993) and Runkel (1994a), who described a regional unconformity between the Jordan Sandstone and the Coon Valley Member that includes: 1. A sharp undulatory contact between the Jordan Sandstone and Coon Valley Member in most outcrops; 2. Poorly sorted, intraclastic lag containing Precambrian pebbles (including iron-formation, felsic volcanic rocks, chert, vein quartz, quartzite, and other sandstone clasts) at the base of the Coon Valley Member in many exposures across virtually all of the outcrop belt; 3. Occurrences of silcrete-cemented sandstone clasts at the top of the underlying Jordan Sandstone along the axis of the Wisconsin arch; and 4. Deep truncation of the Jordan Sandstone near the margins of the Hollandale embayment in south-central Wisconsin and along the Minnesota River valley. Conodont biostratigraphy by Runkel and others (1999) demonstrated that the lithically cryptic unconformity is a large-magnitude, regionally extensive unconformity.

Occurrence—The Jordan Sandstone crops out in numerous places in counties bordering the Mississippi River and the lower St. Croix River. It crops out near Jordan in Scott County (Fig. 3), in the Minnesota Valley National Wildlife Refuge north of Jordan, and at an inactive sand pit nearby. It crops out along the Minnesota River valley in LeSueur County between Ottawa and Kasota in natural outcrops and in silica sand pits, in natural exposures and roadcuts in eastern Nicollet County near St. Peter and North Mankato, and in northern Blue Earth County by Mankato. Its distribution in the subsurface of the Hollandale embayment is shown in Mossler (1983, pl. 3).

Thickness—The Jordan Sandstone is from less than 30 to more than 110 feet (9 to 33.5 meters) thick in Minnesota. It is thin along the "anticline" between Red Wing and Rochester and also along the western margin of the Hollandale embayment in the Mankato area where it apparently was deeply eroded and possibly truncated before the overlying Oneota

Dolomite was deposited. It is also thin, possibly because of depositional thinning, in the south-central part of the Hollandale embayment, in southeastern Freeborn and southwestern Mower Counties, where it is less than 50 feet (15.2 meters) thick.

Lithology—Two distinct lithofacies can be recognized (Runkel, 1994b):

Quartzose lithofacies: Fine- to coarse-grained, cross-stratified, quartzose sandstone. This can be subdivided into two subtly different parts: the lower 10 to 20 feet (3 to 6 meters) is composed mostly of fine- to medium-grained sandstone with wedge sets of trough cross-strata that range in thickness from 10 to 30 centimeters. *Skolithos* and *Arenicolites* burrows are common and clay drapes are rare. The upper 20 to 40 (6 to 12 meters) feet of the facies is mostly medium- to coarse-grained sandstone with wedge sets of trough, planar, and tangential cross-strata up to 5 feet (1.5 meters) thick. Scour surfaces with intraclastic lags define sandstone units that range from 1 to 13 feet (0.3 to 4 meters) in thickness. Shale drapes, reactivation surfaces, and herringbone cross-strata are common, burrows are rare. Geophysical logs of this facies generally have very low, uniform gamma readings and high resistivity readings (Fig. 8). This lithofacies is up to 60 feet (18 meters) thick.

Feldspathic lithofacies: Very fine-grained, feldspathic sandstone in extensively burrowed and structureless beds intercalated with hummocky cross-stratified intervals. Extensively burrowed, *Planolites* can be identified at most outcrops. Very thin to thin tabular beds of siltstone and shale are common, as are scour surfaces with poorly sorted, intraclastic lags. This lithofacies occurs at several stratigraphic levels in the Jordan Sandstone. It forms a regionally continuous interval that gradationally overlies the St. Lawrence Formation and passes transitionally upward into the quartzose facies. At higher stratigraphic levels there are similar intervals intercalated in the quartzose facies. These intercalated units overlie erosional surfaces that are overlain by a poorly sorted lag of very fine- to coarse-grained sandstone. This lag is in turn overlain by an interval of very fine-grained, hummocky, cross-stratified sandstone that passes upward into mostly structureless, burrowed, very fine-grained sandstone. Each intercalated interval coarsens upwards into the quartzose lithofacies. These intercalated units are tongues that extend laterally upwards from the regionally extensive fine-grained, feldspathic unit at the base of the Jordan Sandstone. The characteristic upwards coarsening of these beds gives rise to a characteristic pattern on gamma logs. The bases of the units have high readings that tail off toward the tops of the units (Fig. 8). The basal unit is from 5 to 20 feet (1.5 to 6 meters) thick.

Fossil content—Except for trace fossils such as those mentioned above, the Jordan Sandstone is sparingly fossiliferous. It has a meager fauna containing trilobites of the *Saukia* Assemblage Zone (Nelson, 1956; Webers, 1972), some brachiopods, and abundant conodonts (Runkel and others, 1999).

Relationship to adjacent rock units—The Jordan Sandstone conformably overlies the St. Lawrence Formation (see discussion under the St. Lawrence Formation, above). It unconformably underlies the Oneota Dolomite, the upper Jordan Sandstone consists of medium- to coarse-grained, chiefly moderate- to well-sorted quartzose sandstone. In contrast, the Coon Valley Member of the Oneota Dolomite is markedly more heterolithic, containing carbonate rock, sandy carbonate rock, feldspathic sandstone, poorly sorted quartzose sandstone, and only minor moderately well-sorted medium- to coarse-grained sandstone. The contact between them is placed at the poorly sorted, pebbly sandstone that underlies the lowest carbonate (or sandy carbonate) in the Oneota Dolomite. This pebbly sandstone commonly overlies the quartzose sandstone of the Jordan Sandstone with a sharp contact.

Representative sections—The type section of the Jordan Sandstone (in which less than half of the Jordan Sandstone was originally exposed) is now covered. However, nearby type sections for the Van Oser Member (Stauffer and others, 1939) are in good condition (Fig. 3, Van Oser Member locality; numerous stream bank exposures throughout T. 115 N., R. 23 W., sec. 32, and sec. 29, S, in a nature reserve and also exposures in a privately owned quarry in T. 114 N., R. 23 W., sec. 4, NW, Scott County). Accessible outcrops occur north of Stillwater along State Highway 95 in T. 30 N., R. 20 W., sec. 14, NW, Washington County (Fig. 3, location 13). There are also good exposures discussed in Runkel (1994b) and Havholm and others (2000) farther southeast on U.S. Highway 14 in Winona County in T. 106 N., R. 8 W., sec. 8, NE, NW (Fig. 3, location 14) and along Winona County Road 15 about 2 miles south of the town of Homer, Winona County in T. 106 N., R. 6 W., sec. 16, NE, NW, NE, and sec. 9, SE, SW, SE (Fig. 3, location 15). Runkel (1994b) proposed that the Homer locality (Fig. 3, location 15) should be the new principal reference section for the Jordan Sandstone. The locations for many other exposures of Jordan Sandstone in southeastern Minnesota are listed in Runkel (1994b).

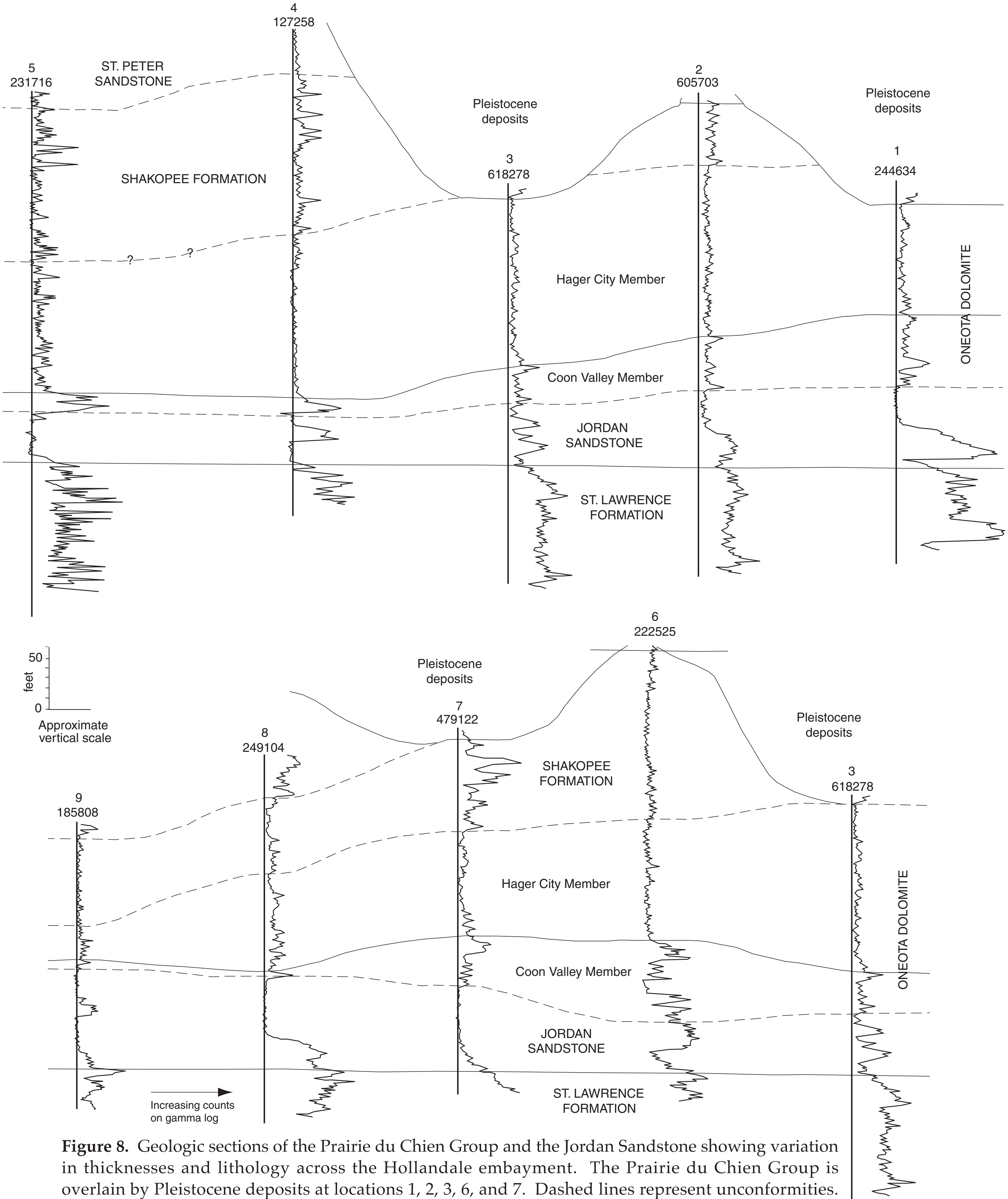


Figure 8. Geologic sections of the Prairie du Chien Group and the Jordan Sandstone showing variation in thicknesses and lithology across the Hollandale embayment. The Prairie du Chien Group is overlain by Pleistocene deposits at locations 1, 2, 3, 6, and 7. Dashed lines represent unconformities. Unique well numbers are listed above logs. Locations of points are shown on page 37.

ORDOVICIAN SYSTEM

LOWER ORDOVICIAN SERIES

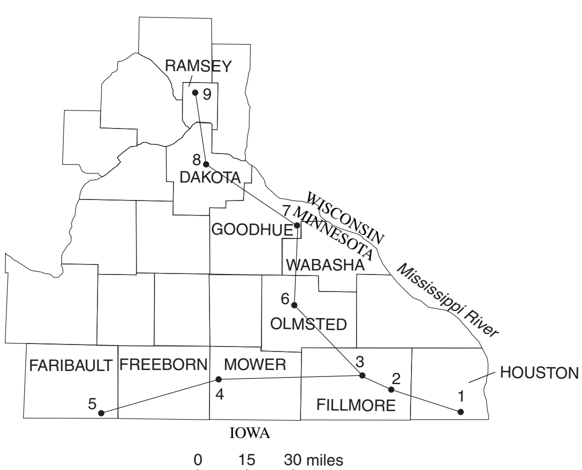
There have been few revisions in stratigraphic nomenclature for the Lower Ordovician series since publication of the last report of investigations on nomenclature (Mossler, 1987). The most significant change has been reassignment of the thin succession of interbedded sandstone, dolostone, and shale beds, named the Coon Valley Member, formerly interpreted to be the upper part of the Cambrian Jordan Sandstone, to the Oneota Dolomite. The purer dolostone of the upper part of the Oneota Dolomite is referred to as the Hager City Member (Davis, 1970) in order to distinguish it from the underlying sandy beds of the Coon Valley Member. Development of the nomenclature is shown in Figure 9.

PRAIRIE DU CHIEN GROUP

The Lower Ordovician Prairie du Chien Group originally was named for exposures near Prairie du Chien, Crawford County, Wisconsin (Bain, 1906, p. 18), where the group consists of 200 to 300 feet (61 to 91 meters) of dolostone and sandstone. The Prairie du Chien Group is separated into two formations, the Oneota Dolomite and the Shakopee Formation, which are considered separately.

Oneota Dolomite

McGee (1891, p. 331-333) named the Oneota Dolomite for exposures along the Oneota (now Upper Iowa) River in Allamakee County, Iowa (Fig. 3). As originally defined, the Oneota Dolomite included all beds of dolomitic quartz sandstone, sandy dolostone, and dolostone above the pure quartz sandstone of the Jordan Sandstone and below the New Richmond Member of the Shakopee Formation (Davis, 1970). Therefore, including beds presently referred to as the Coon Valley Member in the Oneota Dolomite rather than the Jordan Sandstone conforms more closely with the original definition of the formation. Moreover, as discussed under the Jordan Sandstone, recent lithostratigraphic studies (Smith and others, 1993; Runkel, 1994a, b) have revealed a regional unconformity below the Coon Valley Member beds that represents a major hiatus (Runkel and others, 1999).



Locations of points for Figure 8.

The Oneota Dolomite consists of two members, the Coon Valley Member and the Hager City Member (Fig. 8): the lower member, the Coon Valley, is a heterolithic unit containing dolostone, silty or sandy dolostone, feldspathic sandstone, poorly sorted quartzose sandstone, shale, and minor, moderately well-sorted, medium- to coarse-grained sandstone. Two informal beds have been described in the basal part of the Oneota Dolomite in the western part of the Hollandale embayment, the Blue Earth siltstone and the Kasota sandstone. The upper member of the Oneota Dolomite, the Hager City Member, is thick bedded, uniform, dolostone and silty dolostone.

Occurrence—The Oneota Dolomite is present throughout southeastern Minnesota. It crops out extensively in Fillmore, Goodhue, Houston, Wabasha, Washington, and Winona Counties and less extensively in Blue Earth, Dakota, LeSueur, and Scott Counties. The general distribution within the Hollandale embayment of the Oneota Dolomite together with the Shakopee Formation is shown in Mossler (1983, pl. 2B).

Thickness—The Oneota Dolomite is about 50 feet thick (15 meters) in the Twin Cities metropolitan area, but reaches 180 feet (55 meters) in some places along the Iowa border (Fig. 8). The Hager City Member averages 115 to 140 feet (35 to 42 meters) in thickness south of the Twin Cities metropolitan area but ranges from 160 to nearly 180 feet (49 to 55 meters) near the center of the Hollandale embayment. The Coon Valley Member averages 20 to 48 feet (6 to 15 meters) in thickness south of the Twin Cities metropolitan area in counties along the Mississippi River along the eastern side of the Hollandale embayment (Fig. 8); however, it may reach 60 to 85 feet (18 to 26 meters) locally, for example in eastern Goodhue and western Wabasha Counties. The Coon Valley Member is very thin in the Twin Cities metropolitan area and in Rice County, where there is generally only 10 to 15 feet (3 to 4.6 meters) of sandy dolostone at the base of the Oneota Dolomite (Fig. 8). In some places in the Twin Cities metropolitan area, such as in Washington

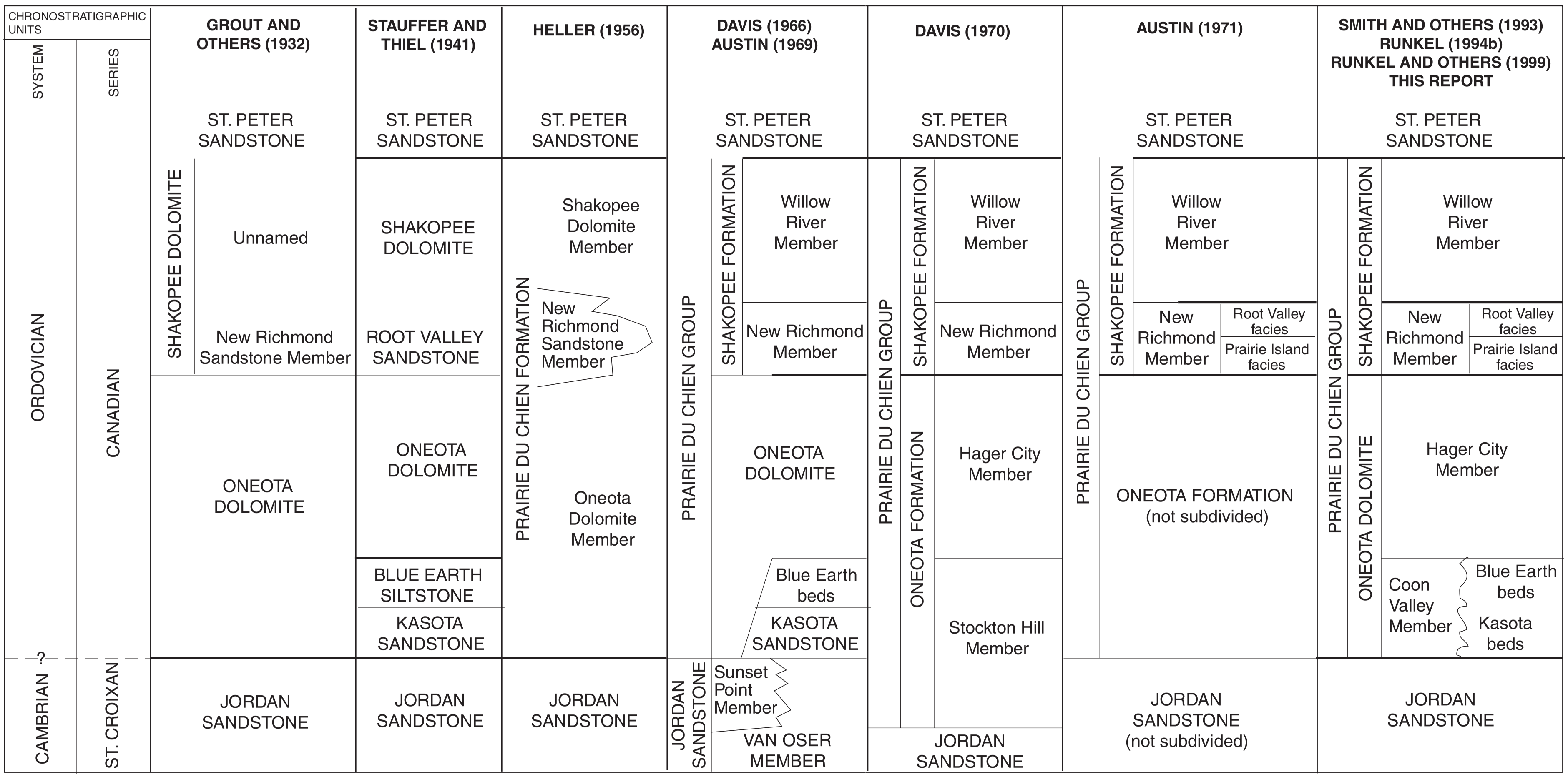


Figure 9. Development of Lower Ordovician stratigraphic nomenclature for southeastern Minnesota. Thick lines between rock units denote unconformities (early classification schemes taken from Austin, 1972, Fig. VI-2).

County near Stillwater (Kraft, 1956), it may be absent. The Blue Earth siltstone beds are up to 16 feet (4.8 meters) thick in Waseca County and around 10 feet (3 meters) thick in Faribault County. Powell (1935) measured 3 feet (1 meter) of Blue Earth siltstone overlying 5 feet (1.5 meters) of Kasota sandstone in the outcrop area of Blue Earth County.

***Lithology*—Coon Valley Member:** Originally named and defined by Odom and Ostrom (1978) for a locality in southwestern Wisconsin (Fig. 3), the Coon Valley Member consists of yellowish-gray to grayish-orange interbedded sandstone and sandy dolostone. The sandstone is fine- to medium- or coarse-grained, generally thin to medium bedded, and well cemented with dolomite or calcite cement. Some sandstone is ripple cross-laminated or contains intraclasts. In the upper part there are minor beds of partially silicified (cherty), oomoldic dolostone, commonly associated with stromatolites, both laterally linked hemispheroids (LLH) and separate vertically stacked hemispheroids (SH). Thin bedded "fucoidal" dolostone and thin partings of greenish-gray shale occur near the top of the member. The lower contact is an unconformity that is directly overlain by a bed of poorly sorted, pebbly sandstone. The abundance of thin, feldspathic sandstone and shale beds gives rise to an irregular natural gamma radiation pattern with many narrow peaks on geophysical logs (Fig. 8). The contrast with the low regular pattern of the underlying quartzose facies Jordan Sandstone is useful in picking the formation contact. The fine-grained feldspathic facies of the Jordan Sandstone has a characteristic pattern on natural gamma logs that differs from the patterns seen in the Coon Valley Member (see preceding section on the Jordan Sandstone).

The Coon Valley Member in the northwestern part of the Hollandale embayment along the Minnesota River consists of light gray, medium- to coarse-grained, poorly bedded, quartz sandstone, informally referred to as "Kasota sandstone," overlain by green to white, thinly laminated, argillaceous, feldspathic siltstone, informally referred to as "Blue Earth siltstone." These beds were originally named and described by Powell (1935). Light gray to light brownish-gray, finely laminated, and intraclastic dolomitic siltstone and silty dolostone, present in rock cores from the western side of the Hollandale embayment south of the outcrop area, are considered to be equivalent to the Blue Earth beds.

Hager City Member: Originally named and defined by Davis (1970) for a location in Wisconsin near Red Wing, Minnesota (Fig. 3), this member is yellowish-gray to pale brown dolostone and silty dolostone, generally in medium to thick beds with minor interspersed thin beds. The beds are massive, color mottled, or faintly laminated and have minor vuggy porosity. Many beds contain algal laminae (algal mats); hemispherical stromatolites and thrombolites are less common. In contrast to the underlying Coon Valley Member and overlying Shakopee Formation, fine- to medium-grained sandstone beds are almost entirely absent. Coarse-grained calcite spar-filled vugs and chert nodules are most common in the upper third of the member. In the Winona–Houston County area large vugs filled with calcite and limonite/goethite that is pseudomorphous after iron sulfide are particularly conspicuous in the upper 15 to 20 feet (5 to 6 meters) of the Hager City Member. Dolostone beds in the upper few feet of the Hager City Member commonly are brecciate (Austin, 1971). The matrix between breccia clasts typically is sandy and argillaceous dolostone that probably infiltrated down between clasts during deposition of the overlying Shakopee Formation. Truncated beds can be observed at the top of the Oneota Dolomite at some outcrops. The uniform lithology of the Hager City Member gives a low uniform gamma radiation pattern on geophysical logs (Fig. 8).

Fossil content—Because of its extensive dolomitization, the Oneota Dolomite is generally regarded as sparsely fossiliferous, except for stromatolites, which are abundant. However, conodonts are common and are even extremely abundant in some intervals such as the Blue Earth siltstone beds (Furnish 1938; Smith and Clark, 1996). Thin dolostone beds in the lower Hager City Member contain abundant trilobites, with hundreds of specimens collected (Runkel, unpub. data). A lower cherty zone contains trilobites and articulate brachiopods (Heller, 1956). The cherty zone in the upper part of the Hager City Member contains trilobites, cephalopods, and gastropods (Heller, 1956). The fossils are locally abundant. In addition to the preceding groups, Powell (1935) also listed cystoids, hydrozoans, pelecypods, and inarticulate brachiopods.

Relationship to adjacent rock units—The Oneota Dolomite unconformably overlies the Cambrian Jordan Sandstone. It unconformably underlies the New Richmond Member of the Shakopee Formation and the contact is drawn at the first occurrence of typically thinly interbedded dolostone, sandy dolostone, and quartz sandstone of the New Richmond Member above massive, non-sandy, in places stromatolitic dolostone of the Oneota Dolomite.

Representative sections—There are numerous outcrops of Oneota Dolomite in Minnesota, particularly in counties that border the Mississippi River and lower reaches of its tributaries south of St. Paul. There also are outcrops along the St. Croix River valley south of Arcola and along the Minnesota River valley and its tributaries from St. Peter to Mankato. One of the better places to see the Oneota Dolomite is along U.S. Highway 52 on Stockton Hill near Winona, the site Davis (1970) described when he proposed naming basal beds of the Oneota Dolomite the Stockton Hill Member (T. 107 N., R. 8 W., sec. 25, SE, SE, and sec. 36, NE, NE, as well as outcrops through T. 107 N., R. 7 W., sec. 36, S, and some in T. 107 N., R. 7 W., sec. 31, SW, NW, Winona County; Fig. 3, location 16). Another very good, accessible location where the entire Oneota can be seen is on Goodhue County Road 18 just east of Red Wing in T. 113 N., R. 15 W., sec. 18, NW, Goodhue County (Fig. 3, location 17). Good exposures of basal Oneota Dolomite occur along a county road north of La Crescent in T. 105 N., R. 4 W., sec. 33, SE, SW, Winona County (Fig. 3, location 18). The upper part of the formation may be seen in a quarry and additional roadcuts further up the bluff.

Shakopee Formation

The Shakopee Formation is a heterolithic unit composed of dolostone, sandy dolostone, and sandstone. It originally was named for isolated outcrops near Shakopee (Fig. 3) in Scott County by Winchell (1874, p. 138-139). Smith and Clark (1996) proposed a composite replacement stratotype for the Shakopee Formation (location described under Representative sections) because the outcrops of Prairie du Chien Group rocks in the Shakopee Formation type area are poorly exposed and documented. The type section may actually be equivalent in age to Oneota Dolomite elsewhere.

The Shakopee Formation contains two members—a lower unit composed chiefly of quartzose sandstone named the New Richmond Member and an upper unit composed chiefly of dolostone named the Willow River Member (Fig. 9). The New Richmond Member was named for outcrops near New Richmond, in St. Croix County, Wisconsin (Fig. 3; Wooster, 1882, p. 106). It was synonymous with the Root Valley Sandstone, a name applied to the same sandstone unit by Stauffer and Thiel (1941); therefore, Heller (1956) recommended suppressing the later name in favor of the earlier one. Austin (1970) resurrected the name Root Valley and applied it to the sandstone facies in the New Richmond Member. He named the sandy carbonate facies in the New Richmond Member the Prairie Island facies. The Willow River Member was named by Davis (1966) who resurrected a name originally applied by Wooster (1882, p. 106) to exposures on the Willow River near Burkhardt, St. Croix County, Wisconsin (Fig. 3). This member was earlier called the Shakopee Dolomite (Stauffer and Thiel, 1941) or the Shakopee Dolomite Member (Heller, 1956) before that name was expanded to include the New Richmond Member (Fig. 9).

Occurrence—The Shakopee Formation is present throughout southeast Minnesota. It crops out extensively in Dakota, Fillmore, Goodhue, Houston, Olmsted, Wabasha, and Winona Counties, and less commonly in Blue Earth, Rice, Scott, and Washington Counties. Many of the better outcrops are in quarries or are roadcuts.

Thickness—The Shakopee Formation is 90 to 180 feet (27 to 55 meters) thick along its outcrop belt near the Mississippi River. Austin (1970) reported 240 feet of Shakopee Formation rock in a well near the center of the Hollandale embayment. The Willow River Member is 80 to 150 feet (24 to 46 meters) thick near areas where it crops out and may reach 240 feet (73 meters) in thickness in the central part of the Hollandale embayment (Austin, 1970). The New Richmond Member has a maximum thickness in Fillmore County, where it is best developed, of about 55 to 60 feet (17 or 18 meters). The Root Valley sandstone facies has a maximum thickness of over 30 feet (9 meters) there. The Prairie Island facies reaches a maximum thickness of about 30 feet (9 meters). In the Twin Cities metropolitan area the Shakopee was deeply eroded prior to deposition of the St. Peter Sandstone and may be missing beneath the St. Peter Sandstone in northwestern parts of Hennepin County (Olsen and Bloomgren, 1989). Generally the Shakopee is up to 80 to 100 feet (24 to 30 meters) thick in the metropolitan area. It is thickest in Dakota County.

***Lithology*—New Richmond Member:** Two major facies were informally named by Austin (1971).

Root Valley (upper) facies: White to light gray, fine-grained, and friable sandstone, with well-developed, large cross-beds. Locally the New Richmond Member may be cemented by quartz to orthoquartzite or stained reddish-brown by hematite (Squillace, 1979).

Prairie Island (lower) facies: Grayish-orange to yellowish-gray to pale yellowish-brown, fine-grained sandstone and sandy dolostone, thinly bedded. Some dolostone beds are oolitic (oomoldic), and some contain intraclasts. Light gray oolitic chert nodules are common in the oolitic beds. Locally, the sandstone beds contain ripple marks and small cross-beds (Squillace, 1979). Dolomitic beds commonly contain stromatolites (LLH and SH). Thin grayish-green shale partings and beds are present.

Willow River Member: Light gray to yellowish-gray to orange, very thin to medium bedded dolostone. It commonly contains beds of oomoldic dolostone and stromatolites (LLH and SH, Austin, 1971). There are minor, thin, light gray, generally medium-grained, and friable sandstone beds that may be ripple marked and/or cross-stratified. Very minor, thin, greenish-gray and maroon shale partings are present. Some light gray chert nodules occur in the dolostone beds.

Fossil content—Except for stromatolites, trace fossils, and to a lesser degree conodonts, the Shakopee Formation is sparingly fossiliferous and its fauna is low diversity. Apparently conditions during deposition were not optimum for marine life (Webers, 1972). The fauna is dominated by mollusks; gastropods are most abundant and cephalopods rank second (Stauffer and Thiel, 1941). The best-preserved fossils are in chert nodules found near Stillwater and Cannon Falls (Stauffer, 1937a, b); preservation of fossils in the dolostone is generally poor (Webers, 1972).

Relationship to adjacent rock units—The Shakopee Formation disconformably overlies the Oneota Dolostone. The Shakopee Formation unconformably underlies the St. Peter Sandstone, but this contact is rarely exposed in Minnesota. Subsurface studies (Olsen, 1976) indicate that there may be appreciable relief on the contact (as much as 100 feet [30 meters]) in parts of the Twin Cities, similar to that in Wisconsin (Thwaites, 1961; Mai and Dott, 1985), Illinois (Buschbach, 1961), and Iowa (Bunker and others, 1985). Biostratigraphic studies based on conodonts indicate that the Shakopee Formation is early Ordovician (Furnish, 1938); those of the basal St. Peter Sandstone indicate a middle Ordovician age (Witzke, 1992; Witzke and Metzger, 2005), indicating a long interval of non-deposition and erosion. However, the exact position of the contact between the Shakopee Formation and St. Peter Sandstone is poorly constrained in the subsurface in Minnesota. Although the contact has generally been placed where sandstone or shale overlies dolostone in well cuttings and on wire-line logs, there is evidence from micropaleontological studies by Runkel and Ethington (Runkel, unpub. data) that the contact may be beneath the sandstone within the dolostone at the Hollandale H-1 corehole in Freeborn County.

Representative sections—The Shakopee Formation is well exposed along Minnesota Highway 19 near Vasa in T. 112 N., R. 16 W., sec. 16, W, and T. 112 N., R. 16 W., sec. 17, E, in Goodhue County (Fig. 3, location 19) and along State Highway 16 south of Lanesboro in T. 103 N., R. 10 W., sec. 23, S, SE (Fig. 3, location 20), and sec. 26, NW, NE, in Fillmore County. The location 20 (Fig. 3) roadcut, illustrated by Smith and Clark (1996), is their proposed composite replacement stratotype for the Shakopee Formation. Another outcrop nearby at Lanesboro on Fillmore County Road 8 in T. 103 N., R. 10 W., sec. 13, W, in Fillmore County also contains most of the Shakopee Formation including the basal contact. Austin (1971) described many other outcrops of the Shakopee Formation.

UPPER ORDOVICIAN SERIES

The term "Middle Ordovician" as long used in the United States is now considered mostly Upper Ordovician in internationally proposed series definitions (Webby, 1998). Therefore the geologic units above the Prairie du Chien Group, with the exception of the lower part of the St. Peter Sandstone, which may be latest Middle Ordovician (Witzke and Metzger, 2005), are now classified as Upper Ordovician.

Several modifications have been made on classification of Upper Ordovician rocks: the Carimona Member, formerly in the Platteville Formation, is transferred into the Decorah Formation to make the basal contact of the Decorah Formation consistent with the manner in which it is drawn elsewhere. The Decorah and Dubuque Formations are included in the Galena Group as they are elsewhere in the Midwest. A new member name is proposed for the basal St. Peter Sandstone in the Twin Cities area. These changes are shown on column 8 of Figure 10, where they can be compared with earlier classifications for Minnesota (columns 3 and 4) as well as with classifications for neighboring states.

ST. PETER SANDSTONE

Owen (1847, p. 169-170) named the St. Peter Sandstone after the St. Peter's River (now called the Minnesota River) of southern Minnesota. The outcrops for the type section by Fort Snelling in Minneapolis, Hennepin County, are still comparatively well exposed and a good place to see the upper part of the formation (Fig. 3). The exposures are the well-sorted, friable quartz sandstone of the Tonti Member, named by Templeton and Willman (1963).

The basal part of the St. Peter Sandstone is not exposed in the Twin Cities area, and it rarely is exposed farther south, where the formation is one-half to two-thirds as thick as it is in the Twin Cities basin. Because of this, the lower part of the formation in the Twin Cities is known mostly from well cutting

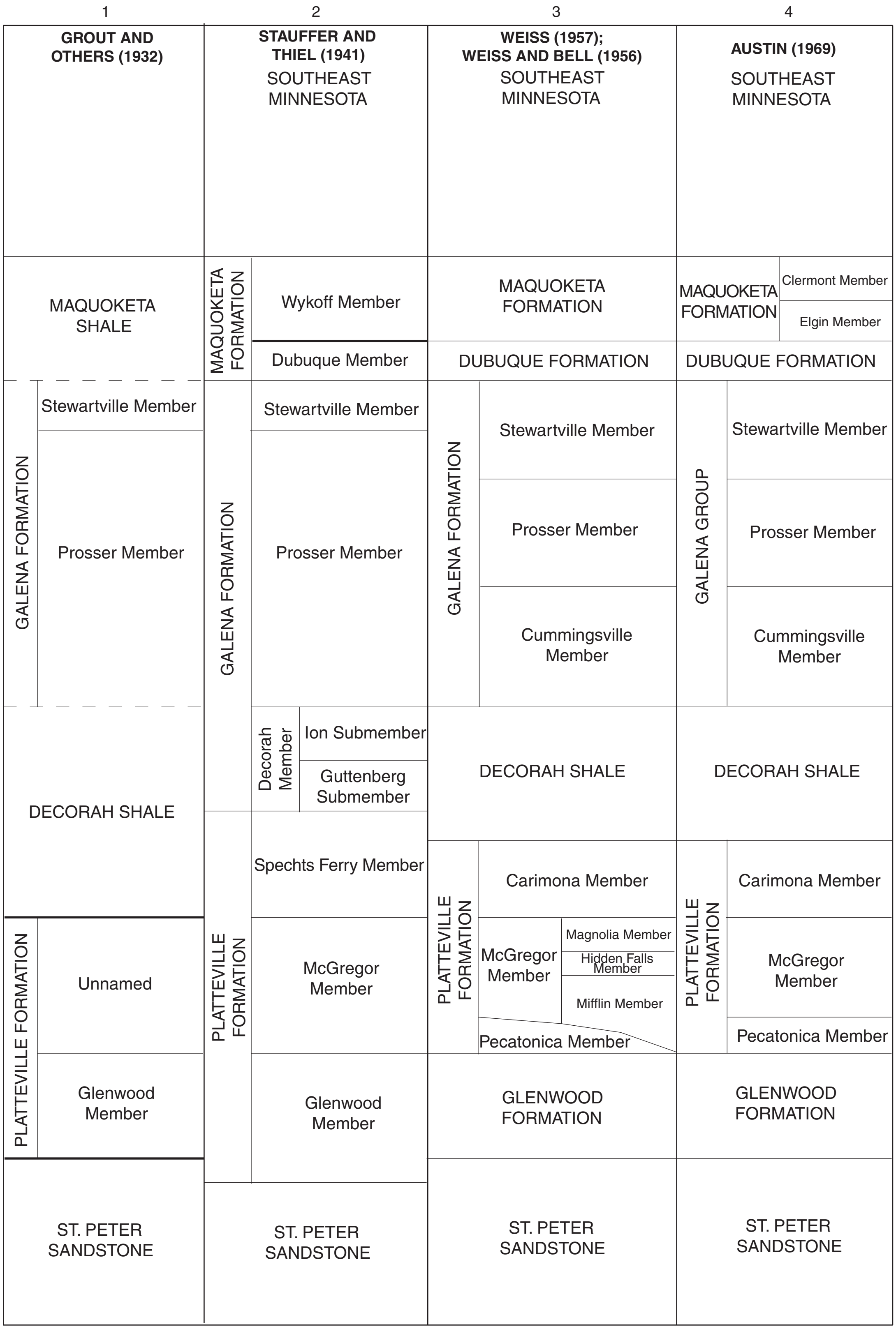
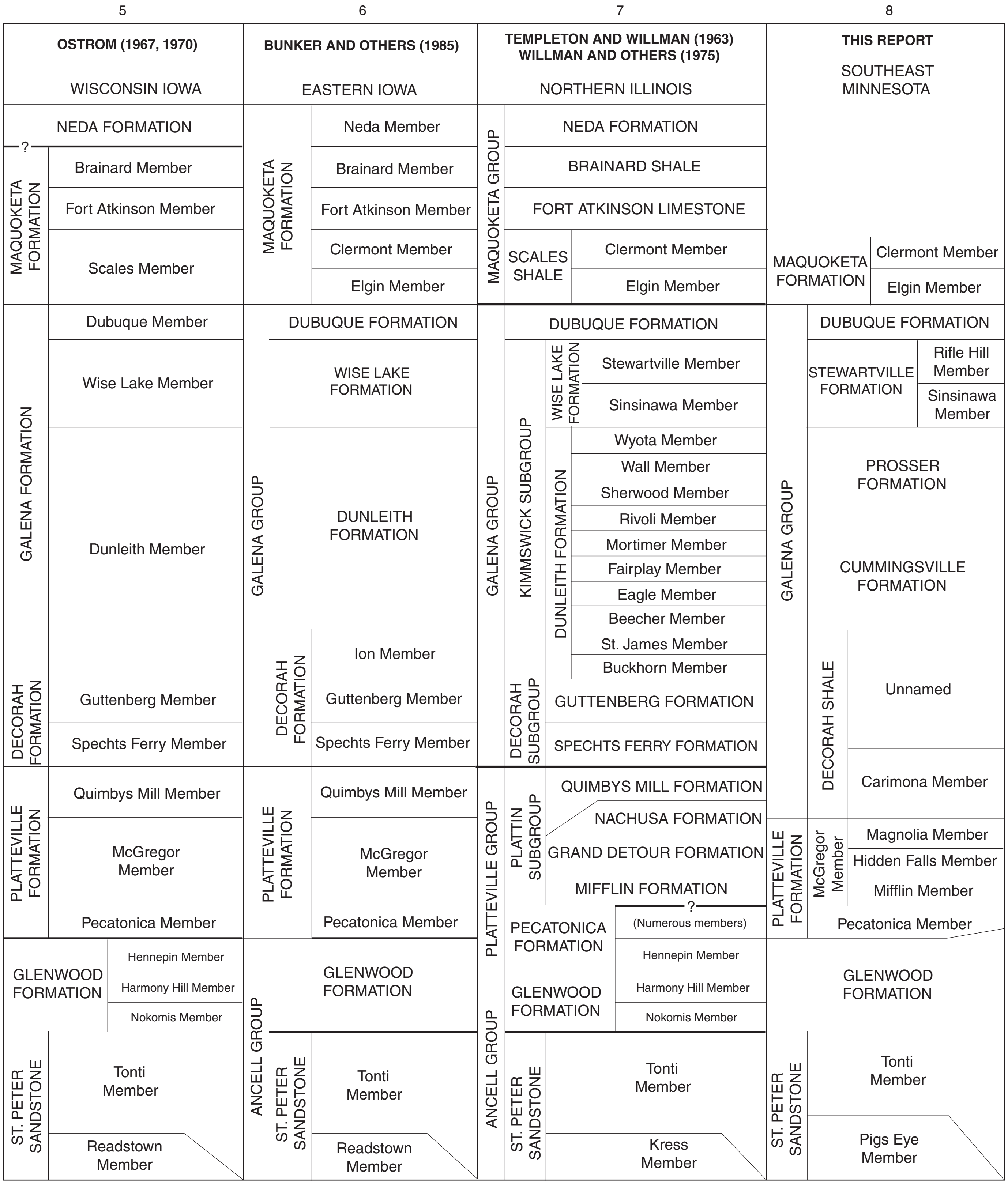


Figure 10. Development of Upper Ordovician stratigraphic nomenclature for southeastern Minnesota and neighboring states. The Dunleith and Wise Lake Formations of Bunker and others (1985), column 6, and the Wise Lake Member of Ostrom (1967, 1970), column 5, are subdivided as shown in column 7. Member nomenclature is not given for the Platteville Group in column 7 because of space limitations (the group is much thicker in Illinois than in Minnesota). Thick lines between rock units denote unconformities (early classification schemes adapted from Austin, 1972, Fig. VI-2).


5
OSTROM (1967, 1970)
WISCONSIN IOWA
NEDA FORMATION
MAQUOKETA FORMATION
Brainard Member
Fort Atkinson Member
Scales Member
GALENA FORMATION
Dubuque Member
Wise Lake Member
Dunleith Member
DECORAH FORMATION
Guttenberg Member
Spechts Ferry Member
PLATTEVILLE FORMATION
Quimbys Mill Member
McGregor Member
Pecatonica Member
GLENWOOD FORMATION
Hennepin Member
Harmony Hill Member
Nokomis Member
ST. PETER SANDSTONE
Tonti Member
Readstown Member
6
BUNKER AND OTHERS (1985)
EASTERN IOWA
MAQUOKETA FORMATION
Neda Member
Brainard Member
Fort Atkinson Member
Clermont Member
Elgin Member
GALENA GROUP
DUBUQUE FORMATION
WISE LAKE FORMATION
DUNLEITH FORMATION
DECORAH FORMATION
Ion Member
Guttenberg Member
Spechts Ferry Member
PLATTEVILLE FORMATION
Quimbys Mill Member
McGregor Member
Pecatonica Member
ANCELL GROUP
GLENWOOD FORMATION
ST. PETER SANDSTONE
Tonti Member
Readstown Member
7
TEMPLETON AND WILLMAN (1963)
WILLMAN AND OTHERS (1975)
NORTHERN ILLINOIS
MAQUOKETA GROUP
NEDA FORMATION
BRAINARD SHALE
FORT ATKINSON LIMESTONE
SCALES SHALE
Clermont Member
Elgin Member
GALENA GROUP
DUBUQUE FORMATION
KIMMSWICK SUBGROUP
WISE LAKE FORMATION
Stewartville Member
Sinsinawa Member
DUNLEITH FORMATION
Wyota Member
Wall Member
Sherwood Member
Rivoli Member
Mortimer Member
Fairplay Member
Eagle Member
Beecher Member
St. James Member
Buckhorn Member
DECORAH SUBGROUP
GUTTENBERG FORMATION
SPECHTS FERRY FORMATION
PLATTEVILLE GROUP
PLATTIN SUBGROUP
QUIMBYS MILL FORMATION
NACHUSA FORMATION
GRAND DETOUR FORMATION
MIFFLIN FORMATION
PECATONICA FORMATION
(Numerous members)
ANCELL GROUP
GLENWOOD FORMATION
Hennepin Member
Harmony Hill Member
Nokomis Member
ST. PETER SANDSTONE
Tonti Member
Kress Member
8
THIS REPORT
SOUTHEAST MINNESOTA
MAQUOKETA FORMATION
Clermont Member
Elgin Member
GALENA GROUP
DUBUQUE FORMATION
STEWARTVILLE FORMATION
Rifle Hill Member
Sinsinawa Member
PROSSER FORMATION
CUMMINGSVILLE FORMATION
DECORAH SHALE
Unnamed
Carimona Member
PLATTEVILLE FORMATION
McGregor Member
Magnolia Member
Hidden Falls Member
Mifflin Member
Pecatonica Member
GLENWOOD FORMATION
ST. PETER SANDSTONE
Tonti Member
Pigs Eye Member

samples, less commonly from cores, and recently from numerous wire-line logs. In an early study of the St. Peter Sandstone in the Twin Cities basin, Sardeson (1935) noted the presence of a "marl-rock zone" about 100 feet (30 meters) beneath the top of the St. Peter Sandstone, described by Thiel (1935) as a single bed of siltstone that varied in thickness from 3 to 50 feet (1 to 15 meters). Later, Olsen (1976) described several beds of shale, siltstone, and claystone interbedded in lower St. Peter Sandstone from numerous well cutting sets and a core from the Twin Cities basin. However, Olson was not confident the individual beds could be traced from well to well using well cuttings. Later, Mossler (1992a) demonstrated that wire-line geophysical logs could be used to trace individual fine-grained (siltstone and shale) beds in the lower St. Peter Sandstone throughout the basin. The distinctive lithology of this unit warrants making it a named member in the St. Peter Sandstone, particularly because its finer-grained lithology makes it behave as a confining layer for ground water (Woodward, 1986), in contrast to the overlying Tonti Member, which is an aquifer.

In Wisconsin (Ostrom, 1964, 1967) and Iowa (Bunker and others, 1985), the basal member of the St. Peter Sandstone, the Readstown, consists of conglomerate composed of fragments of red, green, and gray shale, chert, sandstone, and dolostone in a matrix of sand or clay (Ostrom, 1967), and apparently is mainly residuum. In Illinois, the basal member, named the Kress by Buschbach (1964), consists of red and green shale beds and argillaceous sandstone that represent reworking of the residuum from the Shakopee Formation by the advancing marine waters during deposition of the St. Peter Sandstone (Willman and others, 1975). The basal member of the St. Peter Sandstone in the Twin Cities area is a marine sedimentary rock, not a residuum, and has no obvious connection with the basal St. Peter Sandstone units in Illinois, Iowa, and Wisconsin. Therefore it is appropriate to accord it member rank as the Pigs Eye Member.

Occurrence—The St. Peter Sandstone crops out extensively in southeastern Minnesota, particularly in Fillmore, Olmsted, and Goodhue, and the western parts of Houston, Wabasha, and Winona Counties. In the Twin Cities metropolitan area it crops out along the Mississippi River bluffs in Hennepin and Ramsey Counties and in the sides of small mesas in southern Washington and eastern Dakota Counties. It is widely distributed in the subsurface of the Hollandale embayment (Mossler, 1983, pl. 2A).

Thickness—The entire St. Peter Sandstone averages about 155 feet (47 meters) in thickness in the Twin Cities metropolitan area and reaches a maximum thickness of 190 feet (58 meters) in a few wells in the northern part of the area. South of the Twin Cities metropolitan area it is generally from 100 to 115 feet (30 to 35 meters) thick and thins to 75 to 80 feet (23 to 24 meters) near the Iowa border.

Lithology—The St. Peter Sandstone is divided into two members in Minnesota: the basal member, the Pigs Eye Member, is named for the first time in this report. It consists of interbedded, poorly sorted, quartzose sandstone, shale, and siltstone (see Appendix A). Well-sorted quartzose sandstone of the Tonti Member (Templeton and Willman, 1963) overlies the Pigs Eye Member.

Pigs Eye Member: Interbedded sandstone, siltstone, and shale in the basal part of the St. Peter Sandstone of the Twin Cities metropolitan area that is 40 to 65 feet (12 to 20 meters) thick. The sandstone is light to medium gray, fine- to coarse-grained, and poorly sorted quartzose sandstone. It is interbedded with thin layers of light greenish-gray to pale greenish-yellow to pale red sandy shale and light gray to pale red feldspathic siltstone. Southeast of the Twin Cities metropolitan area, an interval of greenish-gray and silty shale, generally 2 to 5 feet (0.6 to 1.5 meters) thick that is an extension of this unit occurs at the base of the St. Peter Sandstone. Southwest of the metropolitan area, the Pigs Eye Member is thicker and more similar to its occurrence in the metropolitan area (see Woodward, 1986). Unlike the Kress (or Readstown) Member of nearby states (Ostrom, 1967; Willman and others, 1975; Bunker and others, 1985; shown in columns 5 to 8 on Fig. 10), this member is composed of well-bedded marine sedimentary rocks and does not contain residuum or chert conglomerate. Individual beds can be traced laterally from well to well in cutting sample sets and in geophysical (gamma) logs (Fig. 11) across the Twin Cities metropolitan area (see Mossler, 1992a).

Tonti Member: White to light gray, medium- to fine-grained, well sorted, quartzose sandstone. Sand grains are moderately to well rounded and very poorly cemented. The sandstone is commonly characterized by thick beds that are internally structureless, although it has some cross-stratification, mostly trough cross-stratification, near the top of the formation (Mazzullo and Ehrlich, 1987). Most of the St. Peter Sandstone is classified as the Tonti Member (Fig. 11). Natural gamma logs through this member have consistently low values.

Fossil content—The St. Peter Sandstone is generally unfossiliferous though trace fossils, particularly *Skolithos*, are not uncommon; tops of

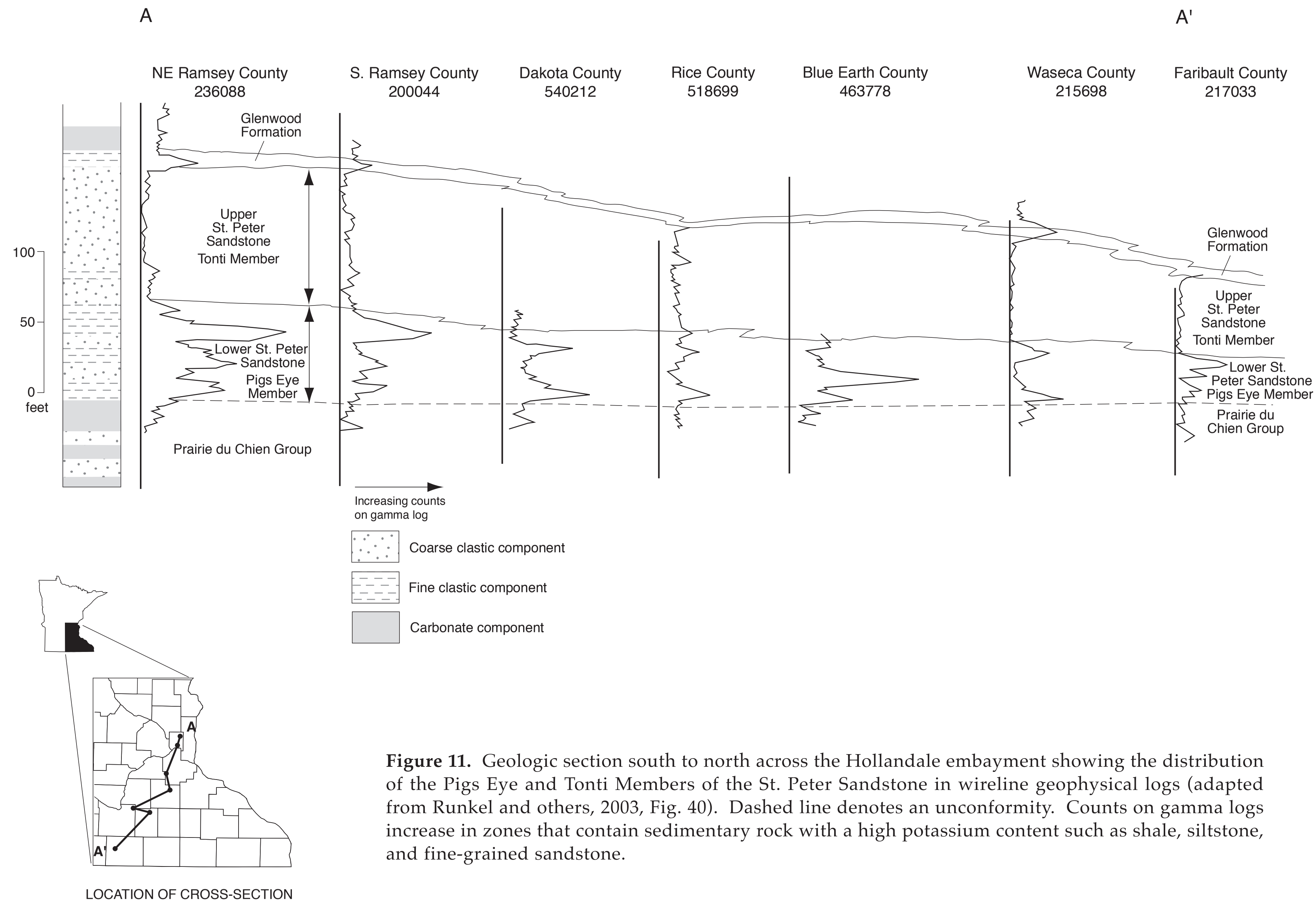


Figure 11. Geologic section south to north across the Hollandale embayment showing the distribution of the Pigs Eye and Tonti Members of the St. Peter Sandstone in wireline geophysical logs (adapted from Runkel and others, 2003, Fig. 40). Dashed line denotes an unconformity. Counts on gamma logs increase in zones that contain sedimentary rock with a high potassium content such as shale, siltstone, and fine-grained sandstone.

some massive beds in St. Paul are zones of complete amalgamation though in many cases *Skolithos* trace fossils can be discerned (Dott and others, 1986). Sardeson (1896) found several hundred body fossils representing a marine molluscan fauna in the middle third of the formation in St. Paul. The fauna includes a variety of bivalves and gastropods as well as nautiloids, monoplacophorans, bryozoans, inarticulate brachiopods, and orthid brachiopods (also see listing by Sloan, 1987b). Olsen (1976) recovered conodonts from shale beds near the top of the lower member in a core from St. Paul and other occurrences are reported in Witzke and Metzger (2005).

Relationship to adjacent rock units—The St. Peter Sandstone's basal contact with the Shakopee Formation and older Paleozoic formations is generally regarded as unconformable and representing a significant hiatus. The contact is historically regarded as corresponding to the boundary between the Sauk and Tippecanoe sequences of Sloss (1963). However, lithic and paleontological evidence for the unconformity is sparse in Minnesota, and therefore the magnitude of the unconformity and its precise position in the uppermost Shakopee Formation and lower St. Peter Sandstone strata is uncertain.

The contact between the St. Peter Sandstone and overlying Glenwood Formation is treated by some as conformable and considered by others to contain one or more disconformities. Geologists who have studied the two formations have placed the contact at different stratigraphic positions. A more thorough treatment of this matter is presented in the discussion of the Glenwood Formation in the following section of this report.

Representative section—The type section for the St. Peter Sandstone is exposed near Fort Snelling in Bloomington in T. 28 N., R. 23 W., sec. 21, SE, SW, Hennepin County (Fig. 3, location 21). The St. Peter Sandstone is also exposed at many other places along the bluffs of the Mississippi River in Minneapolis and St. Paul. About 46 feet of the uppermost part of the St. Peter Sandstone is exposed in Battle Creek Park at the mouth of Battle Creek (T. 28 N., R. 22 W., sec. 3, SE, SE, and sec. 2, NW, SW, Ramsey County; Fig. 3, location 22). Mazzullo and Ehrlich (1987) described this site, which is one of the most accessible exposures in the Twin Cities. All of these exposures include the Tonti (upper) Member.

The Pigs Eye Member is not exposed in the Twin Cities metropolitan area. It is present in rock core acquired for construction or ground-water remediation projects (Appendix A) as well as in many well cutting sample sets and wire-line logs (Appendix B). Olsen (1976) described many of the cutting sample sets. He also described one of the cores (T. 28 N., R. 22 W., sec. 6, NW, NW, NE in downtown St. Paul, see Appendix A) in the Minnesota Department of Natural Resources core library. This member is also present in core from the Twin Cities Army Ammunition Plant (T. 30 N., R. 23 W., sec. 32, NE, SW, Ramsey County) and in other core collected by the Minnesota Department of Transportation.

A rare exposure of the lower part of the St. Peter Sandstone and its basal contact with the Shakopee Formation is present in a bluff along the Cannon River in Goodhue County (Fig. 3, location 23; T. 112 N., R. 18 W., sec. 25, SW, SW). The Tonti Member of the St. Peter Sandstone crops out in nearly all the southeastern counties, generally as exposures in the sides of small mesas and along bluffs capped by Platteville Formation limestone.

GLENWOOD FORMATION

Calvin (1906, p. 60-61, 74-76) named the Glenwood Shale for outcrops in a ravine in Glenwood Township, Winneshiek County, Iowa. Originally the name applied only to the shale in the interval; later stratigraphers expanded it to include argillaceous sandstones beneath the shale (Thiel, 1937; Templeton and Willman, 1963).

Occurrence—It has a distribution very similar to the overlying Platteville Formation (Figs. 12, 13), which is discussed in the following section.

Thickness—Thickness of the shale members of the Glenwood Formation ranges from 3 to 4 feet (about 1 meter) to a maximum of nearly 16 feet (4.9 meters). They are thickest by Sogn in Goodhue County (Fig. 3, location 25; T. 111 N., R. 18 W., sec. 24, NE, SE).

Lithology—The Glenwood shale is typically grayish-green to brownish-gray, calcareous, sandy, and phosphatic. It is weakly fissile and commonly has a blocky fracture. Sand grains are rounded quartz and range from fine to coarse. Sand may occur in relatively discrete layers or may be completely homogenized within the shale (Schutter, 1996), and is poorly sorted to bimodal. Phosphatic grains are black, polished grains as large as an inch (2.5 centimeters) in diameter (Parham and Austin, 1967). Phosphate grains include conodonts and other skeletal grains and nonskeletal steinkerns, cements, fecal pellets, and phosphatic mud clasts (Schutter, 1996). Brassy ooids have been observed in the Glenwood Formation at one locality in Minnesota (Parham and Austin, 1967) and are present elsewhere outside of Minnesota (Witzke and Metzger, 2005). Interbedded sandstone beds are generally less than 8 inches (less than 20 centimeters) thick; however, near Fountain in

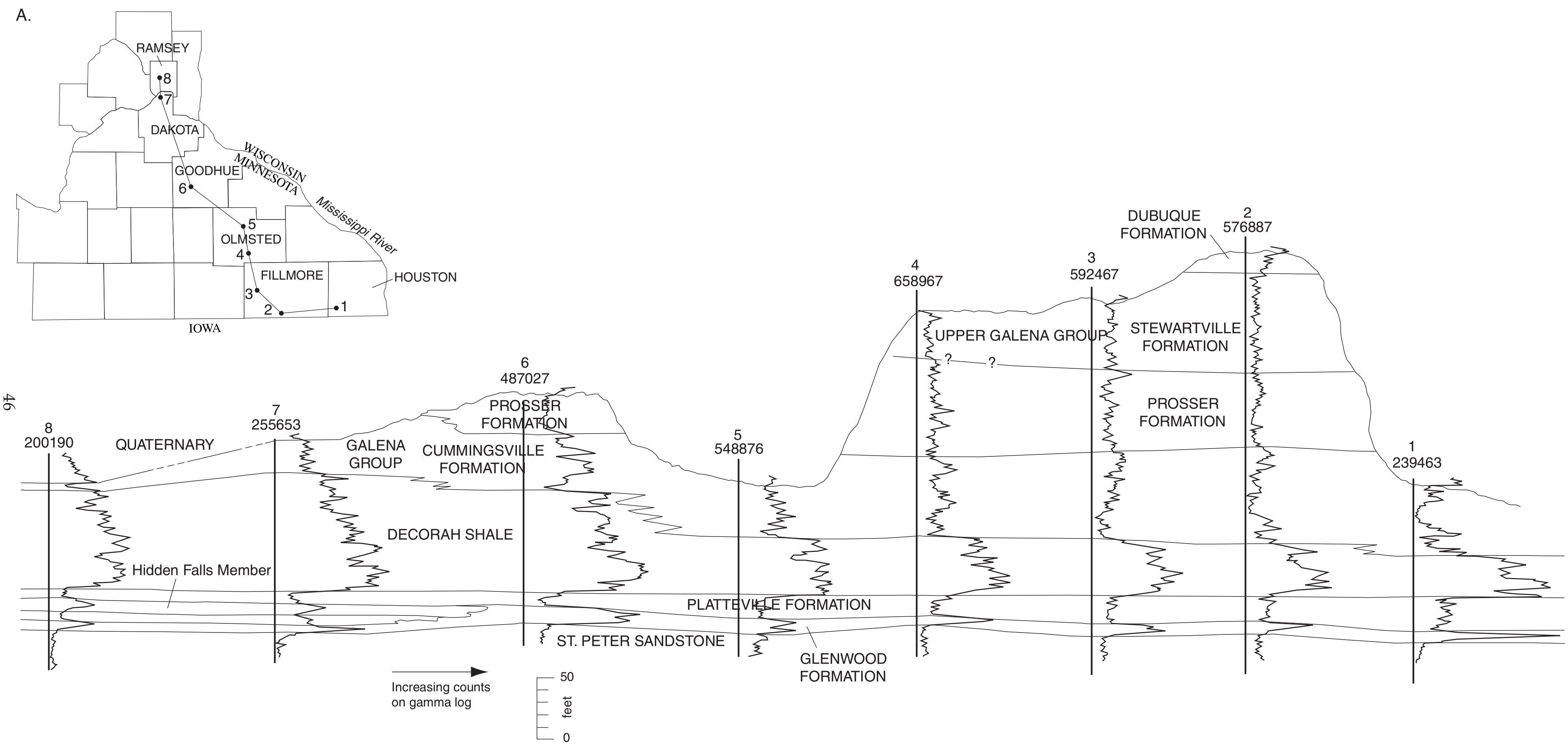


Figure 12A. Explanation appears on page 48.

B.

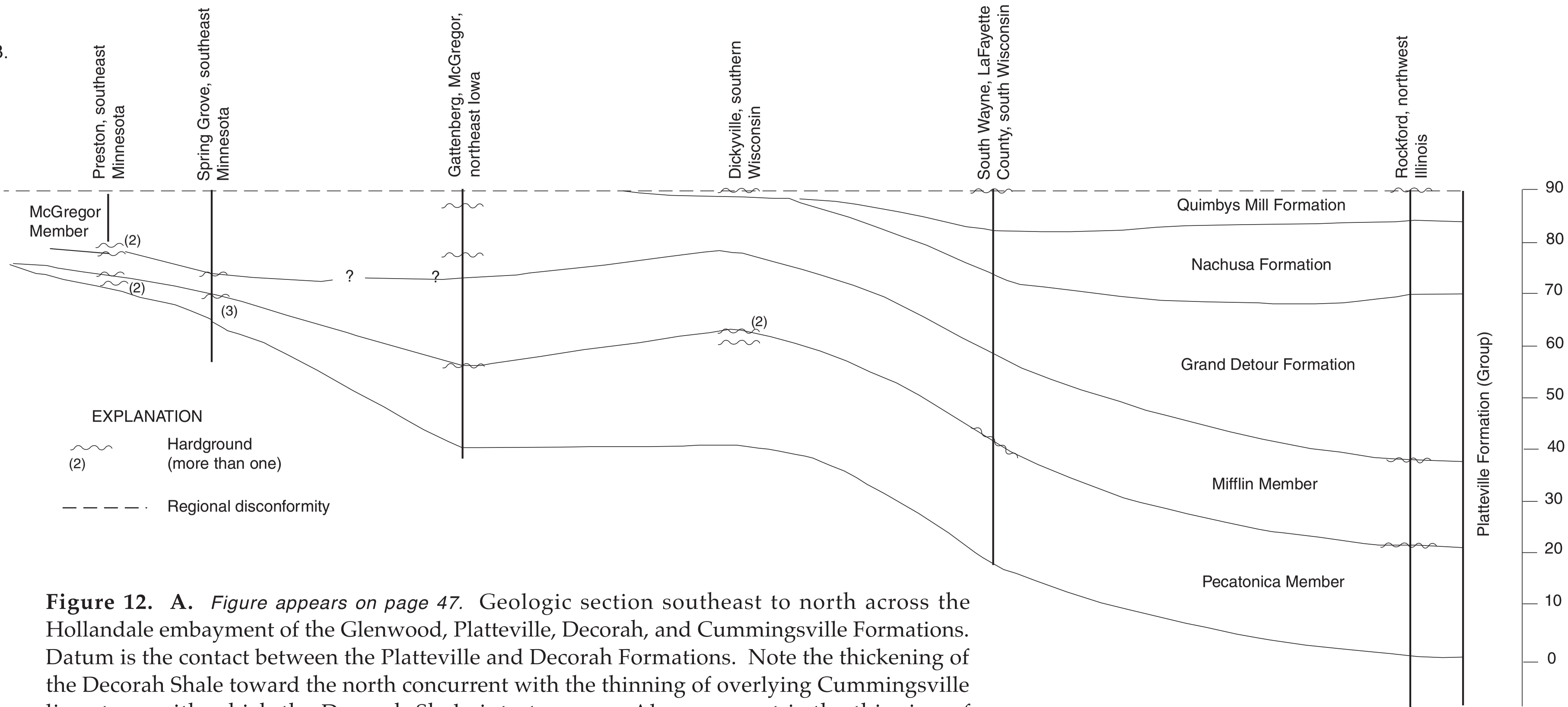


Figure 12. A. *Figure appears on page 47.* Geologic section southeast to north across the Hollandale embayment of the Glenwood, Platteville, Decorah, and Cummingsville Formations. Datum is the contact between the Platteville and Decorah Formations. Note the thickening of the Decorah Shale toward the north concurrent with the thinning of overlying Cummingsville limestone with which the Decorah Shale intertongues. Also apparent is the thinning of the Platteville Formation and concomitant thickening of underlying Glenwood Shale in the Goodhue County area and restriction of the Hidden Falls Member to the northern part of the embayment. The gamma log traces show the variation in shale content within the formations. The traces are deflected toward the right in more shaly intervals.

B. Section from northwestern Illinois through southeastern Minnesota showing regional thinning of units within the Platteville Formation. The Platteville Formation thins from more than 100 feet (30.5 meters) in northwestern Illinois where it is classified as a group to less than 20 feet (6 meters) in parts of Minnesota where it is classified as a formation. The top of the Pecatonica Member contains prominent, regionally extensive hardgrounds. The top of the Platteville Formation is a regional discontinuity surface. Data for the outcrops in Wisconsin, Iowa, and Illinois are from Templeton and Willman (1963) and Willman and Kolata (1978). Data for Minnesota are from Mossler (1985).

C. *Figure appears on page 49.* Section from northeastern Iowa through southeastern Minnesota showing the diachronous nature of the contact between the Decorah Shale and overlying Cummingsville Formation. The positions of the two prominent bentonites at the base of the Decorah Shale (the Deike and Millbrig bentonites) are shown as heavy line. The divergence between them is caused by the more rapid sedimentation in the northwestern part of the outcrop belt. The Carimona Member is shown at the base of the section. Note that the Carimona Member thins southwards and is absent at the south end of the geologic section. Outcrop data are from Kolata and Sloan (1987), Sloan and Kolata (1987), Sloan and others (1987a), and Mossler (unpub. data). The parts of columns with no fill pattern are dominantly shale.

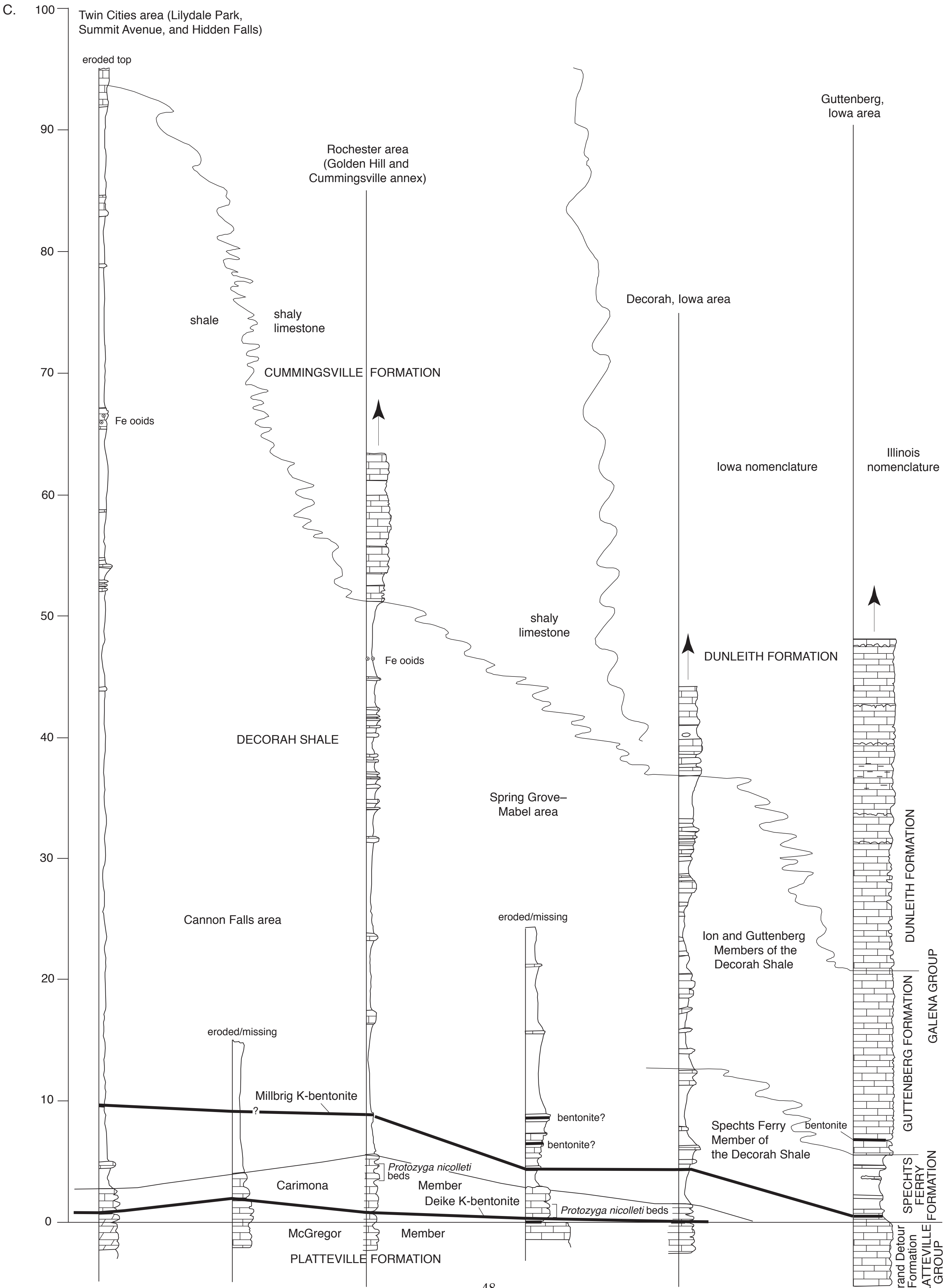


Figure 12C. Explanation appears on page 48.

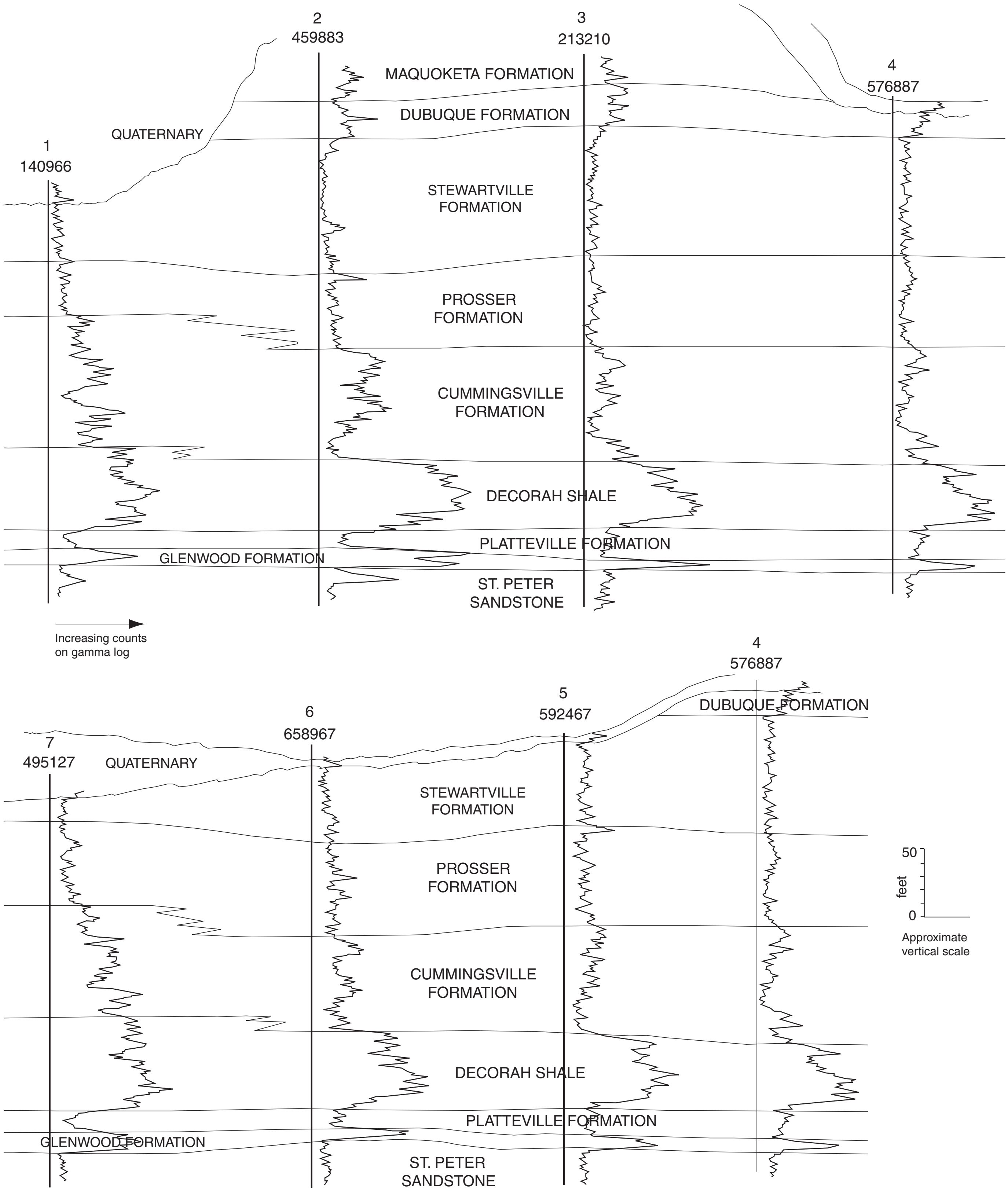
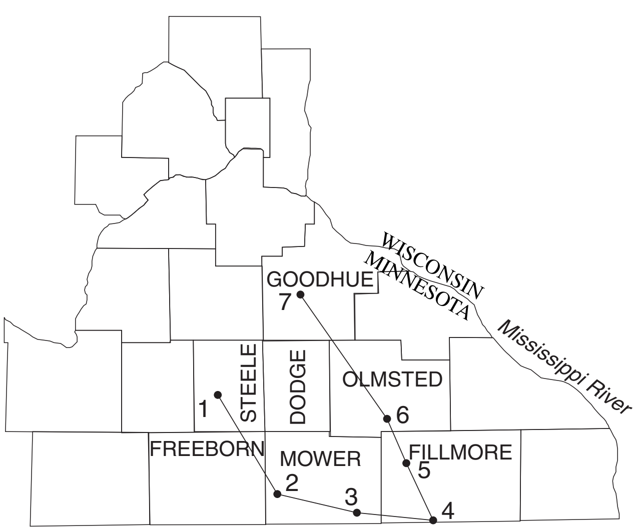


Figure 13. Geologic sections of the upper St. Peter Sandstone through Dubuque Formation sequence. Datum is the contact between the Platteville Formation and Decorah Shale. The gamma log traces show the variation in shale content within the formations. The traces are deflected to the right in more shaly intervals. Note the thickening of the shale units, the Glenwood Formation, and Decorah Shale to the north and west and the concomitant thinning of purer carbonate rocks in the Platteville Formation and the Galena Group. Locations of points are shown on page 51.

Fillmore County there is an interval of cross-bedded sandstone that is 4.6 feet (1.4 meters) thick between Glenwood Formation shale beds.

Although member terminology is generally not applied to the lithofacies of the Glenwood Formation in Minnesota, terminology originally proposed by Templeton and Willman (1963) is used in neighboring states. Brief mention of the members must be made because the uppermost member has been placed in the basal Platteville Formation by some stratigraphers and in the Glenwood Formation by others, and the lowermost member is commonly included with the St. Peter Sandstone. The distinctions between the members are significant to the engineering community involved in mining underground rooms and tunnels. Though the Platteville Formation forms a strong roof rock in mined space, the members of the Glenwood Formation, specifically the Hennepin and Nokomis Members (see below) are weak rocks that cause roof problems in mined underground space (Sterling and Nelson, 1982).

Hennepin Member: The Minnesota Geological Survey considers calcareous, arenaceous shale beds, assigned to the Platteville Formation as the Hennepin Member by Templeton and Willman (1963; Fig. 10), to be the upper part of the Glenwood Formation. This agrees with the Wisconsin Geological and Natural History Survey (Ostrom, 1969) and many of the sedimentary geologists who have studied the formations in Wisconsin (Fraser, 1976; Lien, 1998) and Minnesota (Sloan, 1972; Mossler, 1985). As discussed by Ostrom (1969), the Hennepin beds, though they contain carbonate like the Platteville Formation, are dominantly detrital like the underlying shale beds assigned to the Harmony Hill Member of the Glenwood Formation by Templeton and Willman (1963). The carbonate occurs principally as cement.



Locations of points for Figure 13.

Harmony Hill Member: This member is a laterally extensive, grayish-green shale that is weakly fissile and commonly has a blocky fracture, and lithologic features that correspond most closely with the Glenwood Formation as originally described by Calvin (1906) of the exposures of the type section near Decorah, Iowa. Beds of silt and argillaceous fine-grained sandstone occur at some exposures; in some places most of the member may consist of sandstone (Templeton and Willman, 1963). The top of the unit commonly contains phosphatic pellets.

Nokomis Member: A light greenish-gray, clayey, fine- to medium- and coarse-grained, bimodally sorted, thin bedded to massive sandstone that is up to 8 to 10 feet (2.4 to 3 meters) thick, commonly present beneath the Harmony Hill Member of the Glenwood Formation, though it may be missing at some localities. In other areas, workers have described a one or two foot layer of clayey "greensand" ascribed to ground-water leaching shale from the overlying Glenwood Formation (Payne, 1967), from 5 to 15 feet (1.5 to 4.6 meters) beneath the base of the Harmony Hills Member (Payne, 1967; Olsen, 1976; Sterling and Nelson, 1982). The clayey sandstone is separated from the underlying Tonti Member of the St. Peter Sandstone by a surface described as a disconformity or unconformity by many workers (Thiel, 1937; Templeton and Willman, 1963; Lien, 1998). Although they did not name it, this clayey sandstone has long been considered part of the Glenwood Formation by Minnesota stratigraphers (Thiel, 1937; Stauffer and Thiel, 1941, p. 74; Austin, 1969). In 1963, Templeton and Willman (1963, p. 51-52) named this interval the Nokomis Member of the Glenwood Formation.

Because the Nokomis Member commonly cannot be distinguished from underlying Tonti Member sandstone with certainty when interpreting water well drillers' logs and natural gamma logs, it is impractical to include this shaly sandstone in the Glenwood Formation, even though there are lithological similarities to sandy units in the Glenwood Formation. Small variations in shale content on natural gamma logs commonly are attenuated in large diameter well boreholes, particularly in wells with more than one string of steel casing, and with cement or clayey material filling the annulus between the casing and borehole wall.

Fossil content—The Glenwood Formation is generally considered to be poorly fossiliferous.

The scarcity of macrofossils may be due more to unfavorable conditions for preservation than due to absence of organisms (Schutter, 1996). Macrofossils commonly have been destroyed by dolomitization or through leaching. Schutter observed molds of bivalves, whose shells were lost through leaching. The few calcareous macrofossils preserved in shale observed by the author have been thin, fragile films of bivalves along bedding planes. A few macrofossils including trilobites, echinoderms, bryozoans, and ostracodes survived dolomitization (Schutter, 1996) in more calcareous parts of the formation. Stauffer and Thiel (1941) also reported brachiopods and gastropods. The Glenwood Formation contains an abundant microfauna primarily composed of resistant forms such as conodonts (Stauffer, 1935b; Webers, 1972), scolecodonts (Stauffer, 1933), and chitinozoa. Webers (1966) stated the Glenwood Formation conodont fauna is unique both for its uncommonly large number of species and abundant lamellar and fibrous forms.

Pyrite in the Glenwood Formation generally follows apparent burrow traces, where it forms cylindrical to twig-like masses. Schutter (1996) found some pyritized fossil fragments, including sponge spicules. Phosphatized fecal pellets are present.

Relationship to adjacent rock units—The Glenwood Formation is a condensed sedimentary succession (Schutter, 1978, 1996) and as such contains numerous omission surfaces or hardgrounds. In the past the abundance of phosphatic (collophane) grains in both the Glenwood and the Platteville Formations near their contact were interpreted as evidence for an unconformity (Elder, 1936; Templeton and Willman, 1963, p. 49 and 76). Ostrom (1969) considered the contact between the Glenwood and Platteville Formations to be disconformable in Wisconsin because both the Harmony Hill and the Hennepin Members wedge out between the Nokomis Sandstone and the overlying Platteville Formation. However, sedimentary features attributed to disconformity, such as the presence of hardgrounds and phosphorites and the pinching out of units, are also characteristic of condensed sections, and there is no solid paleontological evidence for a significant time gap between deposition of the Glenwood and Platteville Formations in Minnesota (Sweet, 1987).

The basal contact of the Glenwood Formation with underlying St. Peter Sandstone beneath the Nokomis Member argillaceous sandstone has also been considered to be a disconformity (Thiel, 1937; Templeton and Willman, 1963, p. 51-52; Fraser, 1976; Lien, 1998). Evidence cited is: 1. Relief along the contact, 2. Truncation of faults, folds, joints, and veinlets in the St. Peter Sandstone along the contact, and 3. Occurrence of pebbles and angular sandstone fragments from the St. Peter Sandstone in basal Glenwood Formation sandstone. However, there does not seem to be enough interruption in deposition and erosion along this contact to warrant classifying it as a disconformity (see Bates and Jackson, 1987); rather, it seems more appropriate to call it a discontinuity surface because of the absence of large-scale erosion.

Representative sections—Outcrops of Glenwood Formation shale generally occur in steep slopes of mesas and bluffs beneath carbonate rock of the Platteville Formation. The Glenwood Formation is well exposed at numerous places along the bluffs of the Mississippi River in the Twin Cities area; one of the more accessible places is along the road into Hidden Falls Park (T. 28 N., R. 23 W., sec. 17, SE, SE, Ramsey County; Fig. 3, location 24). South of the Twin Cities, exceptionally thick development of Glenwood Formation shale is observed near Sogn (T. 111 N., R. 18 W., sec. 24, NW, SE, Goodhue County; Fig. 3, location 25). Sloan and others (1987a) described this outcrop. Near Fountain, Minnesota, cross-stratified sandstone is interbedded with typical Glenwood Formation shale (T. 103 N., R. 11 W., sec. 15, NE and T. 104 N., R. 11 W., sec. 27, NE, Fillmore County; Fig. 3, locations 26 and 27).

PLATTEVILLE FORMATION

Bain (1905, p. 18-21) named the Platteville Formation for exposures of limestone and dolomitic limestone with minor shale along the Little Platte River near Platteville, Grant County, Wisconsin.

Occurrence—The Platteville Formation crops out as the cap rock of mesas and bluffs across southeastern Minnesota, particularly in Dakota, Olmsted, and western Fillmore and Goodhue Counties. It also crops out extensively along the bluffs of the Mississippi River in Hennepin and Ramsey Counties. There are fewer outcrops in Houston, Rice, Wabasha, Washington, and Winona Counties. The distribution of combined Glenwood, Platteville, and Decorah Formations shown in Mossler (1983, pl. 1B) essentially is a depiction of the distribution of the Platteville Formation.

Thickness—Total thickness of the Platteville Formation ranges from 13 to 30 feet (4 to 9 meters). The formation is generally about 27 to 28 feet (8.2 to 8.5 meters) feet thick in Houston County next to the Iowa border and in the center of the Twin Cities metropolitan area. It is around 12 feet (3.7 meters) thick near Sogn in Goodhue County and by Nerstrand in Rice County. The cross section in Figure 12 shows the variations in the Platteville Formation's thickness.

Lithology—The Platteville Formation is subdivided into several members that correspond to lithofacies (Fig. 10). The lithology and distribution of these members is described in more detail in Mossler (1985).

Pecatonica Member (basal member): Named for outcrops in Wisconsin (Hershey, 1897). Yellowish-gray, fossiliferous, medium to thick bedded dolostone in tabular beds that are burrowed to internally structureless. The dolostone commonly contains fine- to coarse-grained quartz sand and black sand-sized collophane phosphate nodules. In Minnesota, the Pecatonica Member ranges from less than one to over 7 feet (2.1 meters) in thickness. The Pecatonica Member contains several hardgrounds at the top of the member that are particularly prominent near the Iowa border where the member is thickest. These are surfaces of erosion or nondeposition that represent diastems. They are smooth to slightly irregular surfaces with low relief that are pitted and highly mineralized (pyrite, hematite, and limonite). The surfaces typically are intensively bored, are covered by trails and locally by encrusting bryozoans, echinoderms, and other organisms (Prokopovich, 1955; Byers and Stasko, 1978). Carbonate rock above them may contain abundant quartz sand grains and black phosphate grains.

The Pecatonica Member is thickest in extreme southeast Minnesota where it is over 7 feet (2 meters) thick. In parts of southeastern Minnesota where this member is absent, as in eastern Fillmore County, the McGregor Member lies directly atop the Glenwood Formation (Weiss, 1957).

McGregor Member (upper member, south of the Twin Cities area): Named by Trowbridge (1935) for outcrops in eastern Iowa. It is light olive-gray to yellowish-gray, thin and wavy bedded, dolomitic limestone. It is sparsely fossiliferous biomicrite. Much of its fossil materials are finely comminuted fragments more or less evenly distributed through the rock, though the fragments are somewhat more abundant along the tops of bedding planes (Mossler, 1985). The limestone beds are separated by thin, gray, shale partings. There are a couple of more conspicuously shaly zones near the top of the member (Weiss, 1957). Limestone beds have distinct color and compositional mottling caused by infaunal burrowing (Byers and Stasko, 1978) and have selective dolomitization along the burrows. The McGregor Member is from 5.5 to 18 feet (1.7 to 5.5 meters) thick. The uppermost one or two feet of rock of the McGregor Member in some of the most southeasterly outcrops of southeastern Minnesota are very dense and glassy in appearance and have a conchoidal fracture. These features are characteristic of the Quimbys Mill "glass rock" Member of the upper Mississippi River lead-zinc district of Wisconsin and Illinois, with which the interval is possibly correlative (Witzke, unpub. data, 2004). In the area north of Rochester, the top 0.5 to 1.0 foot (0.15 to 0.3 meter) of the McGregor Member is composed of very thin beds and lenses of limestone interspersed with numerous shale partings (Mossler, 1985) that may represent condensed sedimentation. In the area south of Rochester, there are some hardground surfaces that appear to be mainly in the basal 4 feet (1.2 meters) of the formation (Mossler, 1985).

Mifflin Member (Twin Cities area): This member is named for Mifflin, Iowa County, Wisconsin (Bays, 1938). It is similar lithologically to the McGregor Member; however, bedding on average is half as thick as bedding in the McGregor Member, and insoluble residue content, a reflection of the more abundant shale partings, is twice that of the McGregor Member (Mossler, 1985). Distribution of fossil remains is similar to that in the McGregor Member. The Mifflin Member grades laterally into shale of the Glenwood Formation (Sloan, 1972) along the edges of the Twin Cities basin. It reaches a maximum thickness of about 8.5 feet (2.6 meters) thick at the center of the basin.

Hidden Falls Member (Twin Cities area and neighboring areas to the south): Sloan (1956) named this member for outcrops at Hidden Falls Park in St. Paul (Fig. 3). The Hidden Falls Member overlies the Mifflin Member in the Twin Cities and neighboring areas. It is light olive-gray dolostone with blocky to massive bedding that has a distinctive conchoidal fracture. The dolostone is very argillaceous to silty, phosphatic, generally very sparingly fossiliferous, and has fine microlaminations of pyrite. It is soft, and typically forms a recessive notch in outcrops. Because it is more argillaceous than other members of the Platteville Formation, it is widely traceable on natural gamma logs (Fig. 12). The Hidden Falls Member is 3.5 to 5.5 feet (0.9 to 1.7 meters) thick.

Magnolia Member (Twin Cities area and neighboring areas to the south): This member was named by Bays and Raasch (1935; Bays, 1938) for outcrops near Magnolia, in Rock County, Wisconsin. The Magnolia Member overlies the Hidden Falls Member. It is light olive-gray, medium to thick bedded dolostone that is characterized by coquina layers less than 1 inch (2 or 3 centimeters) thick composed primarily of brachiopods in otherwise sparingly fossiliferous rock. There are minor pyrite-lined borings or burrows and vugs. There is a well-developed hardground at the top of the member. The member is generally around 8 feet (2.4 meters) thick.

The **Carimona Member** is now placed at the base of the Decorah Shale, as discussed in the following section on that formation.

Fossil content—The Platteville Formation is fossiliferous and contains fossils representing several groups. Fossils are particularly conspicuous in the Magnolia Member where they occur as coquina layers.

The Pecatonica Member is sparingly fossiliferous, probably because it has been intensely dolomitized, which possibly obliterated many fossils. Sand-sized and larger fragments of bryozoans, brachiopods, and echinoderms predominate. Most fossils in the Mifflin and McGregor Members are finely comminuted; whole fossils are rare. Echinoderm fragments are numerous; remains of brachiopods, bryozoans, ostracodes, trilobites, and miscellaneous other invertebrates are less common (Mossler, 1985).

Fossil occurrences in the Hidden Falls Member are patchy but accumulations where present are very rich in variety (Brower, 1987; Sloan and others, 1987b) and include starfish, crinoids, cystoids, edrioasteroids, mollusks, and graptolites beside the normal complement of bryozoans and brachiopods. The Magnolia Member has a varied fauna dominated by clams, a horn coral, gastropods, brachiopods, and monoplacophorans (Sloan and others, 1987b). Fossils in the Magnolia Member are preserved as molds.

Weiss (1957) and Rice and Hedblom (1987) listed the trilobites and brachiopods of the Platteville Formation; Kolata and others (1987) listed the echinoderms; Weiss (1957) the bryozoans; Weiss (1957) and Sloan and Webers (1987) the gastropods and monoplacophorans; Catalani (1987) listed the cephalopods; and Weiss (1957) the graptolites. Conodonts are found throughout the formation (Webers, 1966). A variety of trace fossils occur in the Platteville Formation (Dokken, 1987).

Relationship to adjacent rock units—The Platteville Formation is Minnesota is a condensed sedimentary succession. The Platteville Formation is much thicker to the south and east in Wisconsin and Illinois (Fig. 12B). Units found within the Platteville Formation in those states thin and pinch out to the northwest and are absent or much thinner in Minnesota. The Platteville Formation contains numerous hardgrounds indicative of suspended sedimentation in Minnesota. There is a regionally extensive hardground at the top of the Pecatonica Member. The contact between the Platteville Formation and overlying Decorah Shale is a regional discontinuity surface (Templeton and Willman, 1963; Willman and others, 1975; Bunker and others, 1985; Witzke and Bunker, 1996). The contact with the underlying Glenwood Formation is sharp and may be diastemic in some places.

Representative sections—A traditional place to view the Platteville Formation in the Twin Cities region is at Shadow Falls at Summit Avenue and East River Road in St. Paul, Ramsey County (T. 28 N., R. 23 W., sec. 5, SE, NW, Ramsey County; described in Sloan and others, 1987b; Fig. 3, location 28). Hidden Falls Park (Fig. 3, location 24, described under the Glenwood Formation) is the type locality (Sloan, 1956) for the Hidden Falls Member. Farther south an abnormally thin section of the Platteville Formation is exposed near Sogn (T. 111 N., R. 18 W., sec. 24, NE, SE, Goodhue County; Fig. 3, location 25). Another outcrop of the Platteville Formation is the Cummingsville Annex, a roadcut near the type section (Weiss, 1955) of the Cummingsville Formation (T. 105 N., R. 12 W., sec. 28, SW, NW, Olmsted County; Fig. 3, location 33). A nearly complete section of Platteville Formation and the lower part of the overlying Decorah Shale are exposed at the Spring Grove Underpass Quarry (T. 101 N., R. 7 W., sec. 17, SW, SW, SE, Houston County; Fig. 3, location 29). The Sogn, Cummingsville Annex, and Spring Grove exposures were described by Sloan and others (1987a).

GALENA GROUP

The Galena Group consists chiefly of limestone, shaly limestone, and dolostone. It was named for the town of Galena, Jo Daviess County, Illinois (Hall, 1851, p. 146-148). It was formerly assigned formational status in Minnesota (Fig. 10, columns 1-4) but was raised to group rank (Mossler, 1987) because its original members, the Cummingsville, Prosser, and Stewartville, were mappable units over wide areas. It is now proposed that the Decorah Shale and the Dubuque Formation be included in the Galena Group (Fig. 10, column 8). This will make the boundaries of the group correspond with those drawn in other midwestern states. As discussed by Bunker and others (1985), the thick Decorah shale beds are lithostratigraphically equivalent to the lower Galena Group carbonates of Illinois and eastern Iowa, and the Decorah Shale/Galena Group carbonate contact is diachronous (Witzke, 1980). These relationships that suggest that the Decorah Shale and Galena Group carbonates can be included in a single stratigraphic package.

The Galena Group occurs beneath a broad region of southern Minnesota. The general outline of the area containing the original three members is shown in Mossler (1983, pl. 1-A).

Decorah Shale

The Decorah Shale was named for the city of Decorah in Winneshiek County, Iowa (Calvin, 1906, p. 84). Minnesota geologists who have studied the Decorah Shale in the past 50 years (Parham and Austin, 1969; Rice, 1985) did not divide it into members because of its relatively uniform lithology. Earlier Minnesota geologists who did divide it, such as Stauffer and Thiel (1941), relied on faunal zones to distinguish members. Stratigraphers (Kay, 1935; Twenhofel and others, 1954) in neighboring states where the formation contains more carbonate beds and is more lithically variable have long divided the Decorah Shale into members.

The only formally defined member of the Decorah Shale in Minnesota, the Carimona Member, originally was defined as a member of the Platteville Formation by Weiss (1957). There are several problems with this definition. If the top of the Platteville Formation contact is placed at the point in outcrops where Decorah Shale beds are thinner than Carimona Member limestone beds with which they are interspersed as formerly proposed (Sloan and others, 1987b, p. 63-64), then placement of the contact becomes very subjective. In addition, the interbedding of Carimona Member limestone beds with beds of Decorah Shale indicates that the Carimona Member is part of the same continuous depositional sequence as overlying shale of the Decorah Shale.

Another reason for moving the contact between the two formations to the base of the Carimona Member and placing the Carimona Member in the Decorah Shale is to make the basal contact of the Decorah Shale consistent with the way it is drawn elsewhere in the Midwest (see Willman and others, 1975; Bunker and others, 1985). It is also satisfactory from a stratigraphical standpoint: there is a widespread discontinuity (locally an erosional unconformity in northern Illinois) across the region (Willman and Kolata, 1978; Witzke and Bunker, 1996). This discontinuity at the base of the Carimona Member can be observed and traced in Minnesota outcrops.

Occurrence—The Decorah Shale crops out in Dakota, Fillmore, Goodhue, Houston, Olmsted, and Ramsey Counties. The approximate distribution of the formation is shown on Mossler (1983, pl. 1-B).

Thickness—The Decorah Shale ranges in thickness from more than 80 feet (24 meters) in the Twin Cities metropolitan area to about 25 feet (7.6 meters) near the Minnesota–Iowa border (Fig. 12).

Lithology**—Carimona Member (basal member):** Named by Weiss (1955) for outcrops near Carimona in Fillmore County, Minnesota. The limestone is pale yellowish-brown, thin bedded, and interbedded with grayish-green shale. Because the limestone beds bifurcate toward the northwest and west and intervening shale beds thicken, the top of the member is placed lower in the section at the Twin Cities (Fig. 12C) and Faribault and therefore the contact is diachronous (Sloan, 1972).

A widespread 2- to 3-inch (5 to 8 centimeters) K-bentonite, named the Deicke (formerly named the Carimona) K-bentonite (Willman and Kolata, 1978), occurs at or close to the base of the member (Fig. 12C). The limestone and shale beds in the Carimona Member directly above the K-bentonite are very fossiliferous; in some places they are a coquina of gastropods or brachiopods (*Protozyga nicolleti* beds). The limestone bed directly beneath the bentonite also is very fossiliferous (a "packed biomicrite") at some locations. Other beds in the Carimona Member are sparse biomicrite similar to the beds in the McGregor Member.

In Illinois and Iowa, beds lithically similar to the Carimona Member are considered to be basal beds of the Spechts Ferry Formation or Member (Templeton and Willman, 1963, p. 107; Bunker and others, 1985).

The Carimona Member is from 3.5 to 7 feet (1 to 2.1 meters) thick.

Unnamed upper facies or member: The upper facies is primarily grayish-green, fissile to blocky, fossiliferous shale that contains interbedded, thin, grayish-yellow, coquina limestone and calcareous shale beds. A laterally persistent K-bentonite bed 1 to 2 inches (2.5 centimeters) thick named the Millbrig K-bentonite (Fig. 12C) by Willman and Kolata (1978) occurs about 1.5 to 3 feet (0.46 to 0.91 meter) above the base of this member in extreme southern Minnesota and rises to about 7 feet (2.1 meters) above its base in the Twin Cities. Thin beds of ferroan or "brassy" ooids occur just beneath the Galena Group/Decorah Shale contact at some outcrops in Fillmore County (Weiss, 1957). In the Twin Cities, a thin (10 to 12 centimeters) shaly limestone unit with abundant ferroan ooids occurs 62.5 feet (19 meters) above the base of the upper member of the Decorah Shale (Rice, 1985, p. 16) at Lilydale Regional Park (the former brickyard of the Twin City Brick and Tile Company; Fig. 12C). Ferroan ooids in lesser concentrations are present in the park below this zone. Ferroan ooids are present elsewhere at Decorah Shale outcrops in Goodhue and Olmsted Counties (Fig. 12C).

The upper member is about 90 feet thick (27.5 meters) in the Twin Cities but thins southward to about 25 feet (7.6 meters) thickness in Houston County.

Fossil content—The Decorah Shale contains the most diverse and abundant fauna of the Ordovician System in Minnesota (Webers, 1972). Because of the abundance of fossils and the ease with which they can be extracted from the shale, numerous biostratigraphical and paleontological studies have been conducted on the Decorah Shale. The fauna includes conodonts (Stauffer, 1935a; Webers, 1966), bryozoans (Weiss, 1957; Karklins, 1969, 1987), ostracodes (Cornell, 1956; Swain and others, 1961; Swain and Cornell, 1987), brachiopods (Weiss, 1957; Rice, 1985, 1987; Rice and Hedblom, 1987), trilobites (Weiss, 1957; Rice and Hedblom, 1987), horn corals, crinoids (Weiss, 1957; Brower, 1987), pelecypods (Weiss, 1957; Pojeta, 1987), cephalopods (Weiss, 1957; Catalani, 1987), and monoplacophorans and gastropods (Weiss, 1957; Sloan and Webers, 1987).

The Carimona Member contains richly fossiliferous limestone beds: the *Protozyga nicolleti* beds contain brachiopods, trilobites, a gastropod, as well as abundant conodonts (Sloan and Kolata, 1987). Large, straight-shelled nautiloids commonly are preserved in and characterize the Carimona Member.

Relationship to adjacent rock units—The contact between the Decorah Shale and Platteville Formation is a discontinuity surface that represents a minor break in sedimentation. The Decorah Shale conformably underlies the Cummingsville Formation and the boundary between them is diachronous (Figs. 12A, C). In Fillmore County, the contact of the Decorah Shale with the overlying Cummingsville Formation is marked by a significant concentration of brassy ooids (Weiss, 1957); however, at St. Paul this concentration of ferroan ooids is about 27 to 28 feet (8.25 to 8.5 meters) beneath the top of the Decorah Shale (Rice, 1987). At St. Paul, Rice (1987) placed the upper boundary of the Decorah Shale at the top of the uppermost significant greenish-gray shale bed (Rice, 1987).

Representative sections—In the Twin Cities region, the best exposures of the Decorah Shale are at Lilydale Regional Park in T. 28 N., R. 23 W., sec. 12, SW, SE, SE, Ramsey County and T. 28 N., R. 23 W., sec. 13, NE, NE, Dakota County (Fig. 3, location 30). Rice (1987) described the site. Roadcuts in the Decorah Shale along Minnesota Highway 56 from 0.3 to 1 mile north of Wangs in T. 111 N., R. 18 W., sec. 16, SE, and sec. 21, NE, Goodhue County (Fig. 3, location 31) are favorite fossil collecting localities for the Decorah Shale. The Spring Grove Underpass Quarry (Fig. 3, location 29), discussed under representative sections for the Platteville Formation, contains exposures of the basal part of the Decorah Shale.

Cummingsville Formation

The Cummingsville Formation (Weiss, 1955), a unit composed of interbedded shale and limestone, was named for a small community in Olmsted County (Fig. 3, location 33). The Cummingsville Formation and the upper Decorah Shale of Minnesota are equivalent to the lower part of the Dunleith Formation of northern Illinois and adjoining Wisconsin (Willman and Kolata, 1978), where it is primarily dolostone; specifically they are equivalent to the six lowest members (Buckhorn through Mortimer Members) of the Dunleith Formation. In the northern Iowa outcrop, rocks equivalent to the basal two members of the Dunleith Formation of Illinois (Buckhorn and St. James) are included in the Decorah Shale because they are extremely shaly (Fig. 10, column 6), just as they are in Minnesota, and are referred to as the Ion Member (Bunker and others, 1985). Member terminology of the Dunleith Formation has not been applied to the Cummingsville Formation of Minnesota except for some stratigraphic section descriptions done by Levorson and Gerk (unpub. data, 1971-1974) published in Sloan and Kolata (1987) and Sloan and others (1987a). Facies changes along the outcrop in Minnesota from more carbonate-rich rocks in the south to shalier rocks in the north make it difficult to trace these members northward from Iowa and across southeastern Minnesota with any confidence.

Occurrence—The Cummingsville Formation crops out primarily in Fillmore, Goodhue, and Olmsted Counties. There are a few minor outcrops in Dakota, Houston, and Winona Counties. The Cummingsville Formation probably does not extend all the way to the Iowa border. Strata similar to the Dunleith Formation in the neighboring part of northern Iowa likely are present in southernmost Minnesota where shale-limestone couplets typical of the Cummingsville Formation are not seen (Witzke, unpub. data, 2004).

Thickness—The Cummingsville Formation is 63 feet (19 meters) thick at its type section and 74 feet (22.6 meters) thick in the Hollandale H-1 well (Austin, 1970), but is progressively thinner toward the Twin Cities region because of facies change. The lower Cummingsville Formation intertongues northwards with Decorah Shale. Biozonation has shown that the basal Cummingsville Formation of southern Minnesota is laterally equivalent to the upper Decorah Shale of the Twin Cities basin (Rice, 1985, 1987).

Lithology—The formation is composed of interbedded yellowish-gray to pale yellowish-brown, very fine-grained limestone and grayish-green, calcareous shale. The limestone is in thin, crinkly beds with conspicuous shale partings. The thin limestone beds typically are grouped into more massive units separated by smoother, more conspicuous shaly bedding planes (Weiss, 1957). Therefore there are repetitive layers of shaly limestone and limy shale. Exposures commonly weather to a serrated profile because of this alternating shale content, except for the basal few feet, which form a thick limestone ledge, and the top 15 or 16 feet (4.6 meters; Sloan and Kolata, 1987) where the variation is less pronounced. The alternating beds of limestone and shale show up as a distinctive pattern on natural gamma radiation logs (Figs. 12A, 13). Chert nodules occur in the lower part and above the middle part of the member southeast of the type locality in central Olmsted County (Weiss, 1957).

Fossil content—Bryozoans are well represented in the shale and limestone of the lower Cummingsville Formation and articulate brachiopods dominate in the upper Cummingsville Formation (Webers, 1972). Weiss (1957) and Karklins (1987) list bryozoan species and Weiss (1957) lists brachiopod species. Other groups present include trilobites, horn corals, gastropods (Weiss, 1957; Sloan and Kolata, 1987), and ostracodes (Swain, 1987). Conodonts are present but generally rare (Webers, 1966). *Fisherites oweni (*formerly *Receptaculites oweni)*, a fossil of uncertain systematic position that has been classified with the sponges, green algae, and several other groups in the past, occurs in a zone that extends from about 18 feet (5.9 meters) above the base of the formation to 5 feet (1.6 meters) below its top.

Relationship to adjacent rock units—Contacts with the overlying Prosser Formation and underlying Decorah Shale are conformable and diachronous (Figs. 12, 13). The lower Cummingsville Formation probably shares lateral facies relationships with the upper Decorah Shale where the Decorah Shale is thickest at St. Paul. Rice (1987) stated that the prominent bed of ferroan ooids about 19 feet above the base of the upper member of the Decorah Shale at St. Paul is probably coeval with the oolite bed near the top of the Decorah Shale in Fillmore County. The basal contact of the Cummingsville Formation is picked at the level where shale of the Decorah Shale is succeeded by rock that is predominantly limestone, usually beds of lumpy or nodular limestone in a matrix of calcareous shale (Weiss, 1957). In Fillmore County, a thin coquina of *Prasopora* and other bryozoans occurs locally at the top of a 1- to 3-foot (0.3 to 1 meter) interval of limestone and shale at the base of the Cummingsville Formation (Weiss, 1957). *Prasopora* occurs elsewhere in less abundance in these nodular beds.

The upper contact between the Cummingsville Formation and the overlying Prosser Formation is picked where a major detrital component abruptly diminishes (Weiss, 1957). This feature is very evident on natural gamma logs (Fig. 13). In Fillmore and Olmsted Counties the contact is closely approximated by a thin, sandy, silty limestone bed that is poorly fossiliferous, locally rich in pyrite, and contains some phosphatic debris (Weiss, 1957). The large detrital content of the Cummingsville Formation, in comparison to the Prosser Formation, is indicated by the thick, shaly streaks in the Cummingsville Formation, the earthy luster of its limestone, and its sawtooth weathering profile in old quarries and road cuts caused by preferential weathering of more shaly intervals.

Representative sections—Sloan and Kolata (1987) described the roadcut located along the U.S. Highway 52 bypass at Golden Hill, Rochester in T. 106 N., R. 14 W., sec. 14, SW, NW, and sec. 15, SE, NW, Olmsted County (Fig. 3, location 32). The Cummingsville Formation type locality is in a quarry and roadcut 0.5 mile (0.8 kilometer) north of Cummingsville on Olmsted County Road 7 along the west edge of T. 105 N., R. 12 W., sec. 22, SW, Olmsted County (Fig. 3, location 33). Sloan and Kolata (1987) and Sloan and others (1987a) described this outcrop. Weiss (1957) described the Cummingsville Formation at the Mahood's ravine section, type section for the Prosser Formation.

Prosser Formation

Ulrich (1911, p. 369, 524-525) named the Prosser Formation, the limestone unit that overlies the Cummingsville Formation, for Prosser's ravine in Fillmore County (Fig. 3). Weiss (1957) redefined and described the type section, a series of outcrops in the valleys of Spring Valley Creek and Mahood's Creek in Fillmore County.

Beds equivalent to the Prosser Formation in Iowa, Illinois, and Wisconsin are assigned to the upper part of the Dunleith Formation (Fig. 10, columns 5-7). The Dunleith Formation has long been subdivided into several members in Illinois and Iowa (Templeton and Willman, 1963; Levorson and Gerk, 1972). Stone (1980) and Leverson and

Gerk (see their graphic sections in Sloan and others, 1987a) tried to extend these members into Minnesota from northern Iowa; however, they observed many lithic changes within members as they were traced northward toward the Transcontinental Arch. At present the Minnesota Geological Survey does not divide the Prosser Formation into members and does not apply the Illinois nomenclature in Minnesota. It is not deemed practical to extend this nomenclature into Minnesota without a thorough restudy of the Galena Group.

Occurrence—The Prosser Formation is extensively exposed in Fillmore, Goodhue, and Olmsted Counties. It is not present in the Twin Cities metropolitan area.

Thickness—The Prosser Formation is from 38 to 62 feet (12 to 19 meters) thick. Weiss reported it was 51 feet (16 meters) thick at the type section (Weiss, 1957). It is thickest in the southeastern part of its outcrop belt in Fillmore County and thins slightly toward the northwest (Fig. 13).

Lithology—Yellowish-gray to light olive-gray, very fine-grained limestone that is generally very thin bedded with very thin shale partings between the beds (Weiss, 1957). The thin beds are grouped together into massive ledges separated by conspicuous smooth bedding planes. Several hardgrounds occur near the top of the formation. Sandy and silty fossiliferous streaks occur in the formation at different levels, generally becoming more numerous in lower parts of the formation toward the southeast (Weiss, 1957). It is less silty and shaly than the Cummingsville Formation but more silty and shaly than the Stewartville Formation, a characteristic that shows up in patterns of natural gamma radiation on geophysical logs (Fig. 13).

Four widespread K-bentonite layers occur in the Prosser Formation (Willman and Kolata, 1978). The upper beds are dolomitic, especially in the north, and in this respect the Prosser Formation grades into the overlying Stewartville Formation.

Nodular chert layers occur near the top and in the middle of the formation in southern and central Fillmore County, but only near the middle of the formation in northern Fillmore County (Stone, 1980). Chert disappears entirely from the Prosser Formation to the north (see Stone, 1980). The chert nodules are white to light gray; they may either occur along bedding planes or show no preference for bedding planes.

Fossil content—Most fossils in the Prosser Formation are concentrated in coquina lenses. Bottom communities of the Prosser Formation tend to be dominated by articulate brachiopods as in the upper Cummingsville Formation (Webers, 1972). Common brachiopods are listed by Weiss (1957) and Sloan and Kolata (1987). Other fossils found in the Prosser Formation are monoplacophorans and gastropods (Weiss, 1957; Sloan and Webers, 1987), pelecypods (Weiss, 1957; Pojeta, 1987), echinoderms (Weiss, 1957; Kolata and others, 1978), and bryozoans, horn corals, conularids, trilobites, and graptolites (Weiss, 1957). Webers (1966) described conodonts from the Prosser Formation.

*Fisherites oweni (*formerly *Receptaculites oweni),* common in overlying and underlying formations, is rare and almost absent; however, *Ischadites iowensis*, another fossil of uncertain affinity, is locally abundant (Weiss and Bell, 1956).

Relationship to adjacent rock units—The basal contact of the Prosser Formation with the Cummingsville Formation is picked where the detrital component abruptly diminishes. The large detrital component in the Cummingsville Formation, compared to the Prosser Formation, is indicated by its thick shaly streaks, earthy luster of its limestone, and its sawtooth weathering pattern that shows up on natural gamma logs (Fig. 13). Abundant phosphatic grains or pellets were observed at the base of the Prosser Formation just above the contact with the Cummingsville Formation in core from Fillmore County (Niles and Mossler, 1990).

The contact between the Prosser and Stewartville Formations is characterized by a change from argillaceous limestone with chert nodules in upper Prosser Formation rock to non-cherty, less argillaceous dolomitic limestone in the Sinsinawa Member of the Stewartville Formation (Sloan and others, 1987a). This change is most evident on natural gamma logs from extreme southern Minnesota, particularly Fillmore County (Fig. 13). However, the change is gradational because chemical analyses indicate the argillaceous content of uppermost Prosser Formation carbonate can be nearly as low as basal Stewartville Formation (see Niles and Mossler, 1990). Chert content progressively decreases beneath the top of the Prosser Formation northwards in Fillmore County and chert is absent to the north of the county (Stone, 1980).

Austin (1970) observed apparent intertonguing between Stewartville and Prosser Formation lithologies in the Hollandale H-1 core hole. Stone (1980) observed that lithologic changes in the Galena Group from the Iowa border toward Goodhue and Dodge Counties that indicate the contact between the Prosser and Stewartville Formations may be diachronous and intertonguing. Therefore, picking a contact between the Prosser and the Stewartville Formations may be somewhat arbitrary. Templeton and Willman (1963) observed there commonly is an argillaceous to shaly 1- to 6-inch (2.54 to 15.24 centimeters) thick limestone bed below the base of the Sinsinawa Member of the Stewartville Formation (their Wise Lake Formation; Fig. 10, column 7). The author has observed a spike indicating high natural gamma readings on many gamma logs from water wells in Mower and western Fillmore Counties that penetrate this interval of the Galena Group. This spike occupies a stratigraphic position that corresponds to the shaly zone mentioned by Templeton and Willman and is thus useful for picking the contact between those formations in that area.

Representative sections—The Rifle Hill Quarry in T. 102 N., R. 12 W., sec. 35, NE, NW, Fillmore County (Fig. 3, location 34) contains the upper part of the Prosser Formation and its contact with the Stewartville Formation. The basal part of the Prosser Formation and its contact with the Cummingsville Formation is exposed at the Wagner Hill section, a roadcut on U.S. Highway 52, 4 miles south of Cannon Falls, Goodhue County in T. 111 N., R. 17 W., sec. 5, SW, SW (Fig. 3, location 35). Both outcrops are described in Sloan and Kolata (1987). The outcrop descriptions are based upon graphic logs by Levorson and Gerk (unpub. data, 1971-1974). The basal part of the Prosser Formation is also exposed at the Cummingsville Formation type locality described previously (Fig. 3, location 33) as a representative section for the Cummingsville Formation.

Stewartville Formation

The Stewartville Formation, a unit composed almost entirely of limestone and dolostone, was originally named by Ulrich (1911, p. 27) for exposures near the town of Stewartville in southern Olmsted County (Fig. 3). It consists of two members: the upper member is the Rifle Hill Member (Sloan, 1987c) and the lower one is the Sinsinawa Member (Templeton and Willman, 1963).

Stewartville problem—According to Templeton and Willman (1963), the stratigraphic interval named the Stewartville Formation by Ulrich (1911, and Winchell and Ulrich, 1897), the *Maclurites* beds, included only the upper part of the formation as the Minnesota Geological Survey presently defines it. Stauffer and Thiel's (1941) boundary for the base of the Stewartville was somewhat lower than Ulrich's (Fig. 10); they used the Dygerts K-bentonite as the base of the unit. However, Weiss (1957) lowered the base of the formation further to 19 feet, 8 inches below the K-bentonite at Mahood's Creek in Fillmore County, and included underlying beds formerly included in the Prosser Formation by the earlier stratigraphers (Fig. 10), a proposal that Agnew and others (1956) discussed but did not accept. Although Templeton and Willman (1963) retained the name Stewartville (Member) for the uppermost beds of the Galena Group, they renamed the interval formerly assigned to the Stewartville by Weiss (1957) the Wise Lake Formation. They named the lower part of the Wise Lake Formation the Sinsinawa Member. This they said retained the original intent of Ulrich (1911) to apply the Stewartville name only to the *Maclurites* beds. Sloan (1987c, p. 10-11) suggested that the best way to resolve conflicting use of the name Stewartville for different stratigraphic intervals would be to rename the upper member of the Wise Lake Formation of Templeton and Willman the Rifle Hill Member and retain Weiss's boundaries for the Stewartville Formation because of the long usage of Weiss's formation boundaries. And that is how the conflict is resolved in this report.

Occurrence—The Stewartville Formation crops out in western and southern Fillmore, southern Olmsted, and eastern and northern Dodge Counties.

Thickness—The Stewartville Formation is about 75 to 85 feet (23 to 26 meters) thick, where uneroded.

Lithology—The Stewartville Formation consists of dolomitic limestone and dolostone, yellowish-gray where fresh, weathering to yellowish-orange or grayish-orange. Thin beds of thin and crinkly bedding are grouped into more massive units set off by smooth bedding planes as in other Galena Group carbonate formations (Weiss, 1957). The formation is color-mottled and pitted where it has been weathered. It has much lower insoluble residue content than neighboring units, particularly in its upper part: only 2 to 3 percent through most of the unit but up to 7 percent near its base (Weiss, 1957; see also Niles and Mossler, 1990). Because of the low insoluble content it has a low, uniform natural gamma radiation pattern on geophysical logs (Fig. 13). The Stewartville Formation becomes crinoidal at the top where it grades into the Dubuque Formation.

The **Sinsinawa Member** is dolomitic limestone characterized by numerous hardgrounds and an abundant, diverse fauna that decreases upwards in the member (Sloan and others, 1987a). Bedding is more massive than in the Prosser Formation but less than the overlying Rifle Hill Member. There is a thin, discontinuous K-bentonite seam 10 to 20 feet (3 to 6 meters) above the base of the member.

It approaches closer to the base from northwest to southeast (Weiss, 1957).

The **Rifle Hill Member** is pale olive-gray to yellowish-gray, mottled and bioturbated dolostone, that weathers orange, is massive bedded, with prominent stylolitic bedding planes in the upper half. It is a very pure carbonate with low detrital content. The fauna that it contains has very low diversity.

Fossil content—The fauna of the Sinsinawa Member decreases from about 300 invertebrate taxa at the base to about 30 or so typical of the Rifle Hill Member (Sloan and others, 1987a). Common fossils are brachiopods, gastropods, horn corals, and cephalopods (Weiss, 1957; Sloan and others, 1987a). Other fossils include conularids, trilobites and graptolites (Weiss, 1957), echinoderms (Kolata and others, 1987), and conodonts (Webers, 1966).

The very restricted fauna of the Rifle Hill Member includes the gastropods *Hormotoma* and *Maclurites*, *Receptaculites* in the lower half, and a trace fossil *Palaeosynapta flaccida* in the upper half. The upper 20 to 30 feet (6 to 9.1 meters) of the member has abundant crinoids, especially the part immediately below the Dubuque Formation (Weiss, 1957).

Relationship to adjacent rock units—The Stewartville Formation is conformable with the underlying limestone of the Prosser Formation. The nature of the contact was described in the previous discussion of the Prosser Formation.

The contact of the Dubuque Formation with the Stewartville Formation is also conformable and difficult to pick consistently because of its gradational nature. In the past it generally has been placed at the base of the lowest prominent shale parting (Weiss, 1957). During a regional study across the Dubuque Formation outcrop belt of southern Minnesota and northeastern Iowa, Levorson and others (1979) showed that a conspicuous marker bed, about 8 inches (20 centimeters) thick set off from adjacent beds by conspicuous shale partings, was widely traceable in outcrop. They suggested that this "marker bed" should be used as the base of the formation in order to place the base of the formation more consistently rather than relying of the presence of shale interbeds in the basal Dubuque Formation. From a practical standpoint it would not be possible to use this marker bed in the subsurface except where there are cores through the interval. When downhole geophysical logs and well cuttings are used to pick the contact, it generally is placed higher in the section, near where Weiss (1957) and others have placed it based on shale partings (Fig. 13).

The contact between the Stewartville and Dubuque Formations is diachronous. The lithologies intertongue similar to the way that they intertongue along diachronous contacts between and within other formations in the Galena Group, such as between the basal Cummingsville and Decorah Formations and between the upper shale member and the basal Carimona Member of the Decorah Formation.

Representative sections—The entire Stewartville Formation and its basal and upper contacts are exposed at the Rifle Hill Quarry listed above as a representative section for the Prosser Formation (Fig. 3, location 34). Outcrops on the Root River by the town of Stewartville, considered the type section (Fig. 3), no longer exist.

Dubuque Formation

The Dubuque Formation, consisting largely of interbedded limestone and calcareous shale, was named by Sardeson (1907, p. 193) for the city of Dubuque, Dubuque County, Iowa, where the type section is in abandoned quarries on the Loras College campus. In Minnesota, the Dubuque Formation was earlier included in the Maquoketa Formation as the basal member because Stauffer and Thiel (1941) and earlier Sardeson believed a closer affinity existed between the Maquoketa Formation and Dubuque Formation fauna than between the Dubuque Formation and underlying Galena Group faunas. However, Weiss (1957) proposed elevating the Dubuque Formation to formational status and moving it from the Maquoketa Formation because he saw many affinities between the lithology and fauna of the Dubuque Formation and parts of the Galena Group. In the neighboring states of Iowa, Illinois, and Wisconsin (see Fig. 10), the Dubuque Formation is usually classified as part of the Galena Group. The Maquoketa Formation to the south and east of Minnesota is much shalier than it is in Minnesota and has a prominent diastemic surface or condensed surface at its base (Raatz and Ludvigson, 1996); therefore, there was never any question about similarities between the two formations.

Occurrence—The Dubuque Formation has an outcrop distribution similar to that of the Stewartville Formation.

Thickness—The Dubuque Formation is about 34 to 35 feet (10 meters) thick in Minnesota. The beds are roughly subequal in thickness; however, the uppermost Littleport bed is the most variable in thickness.

Lithology—Light olive-gray to light brownish-gray to yellowish-gray, medium bedded limestone that is interbedded with thinner beds of yellowish-gray to light olive-gray shale. The Dubuque Formation is dolomitic near its base and top but is less dolomitic than the underlying Stewartville Formation. Levorson and others (1979) divided the formation into three informal beds of nearly equal thickness based mainly on bed surface morphology. The basal unit (the Frankville beds) has beds with planar surfaces. It lacks the regularly alternating limestone and shale beds of the rest of the Dubuque Formation, though detrital content systematically increases upward in the bed (Levorson and others, 1979) and it has a few weak shale partings. It contains several calcarenite lenses but otherwise is sparingly fossiliferous. The medial Luana bed is characterized by 1- to 2-inch (2.5 to 5 centimeters) shale partings; a parting near the top of the unit contains a K-bentonite. Bedding is planar to only slightly undulose. The uppermost unit, the Littleport bed, is composed of strongly undulose beds of limestone separated by 1- to 5-inch (2.5 to 13 centimeters) shale beds. It is the most fossiliferous unit and contains many brachiopods as well as echinoderm debris and trilobite fragments (Levorson and others, 1979). It contains vugs lined with calcite spar and small pyrite concretions (Levorson and others, 1979). A second prominent K-bentonite occurs 2 to 5 feet (0.6 to 1.5 meters) below the top of this unit.

Fossil content—The Dubuque Formation is moderately fossiliferous; however, the change from the poorly fossiliferous Stewartville Formation is not so pronounced that it is useful in placing the contact. It is a more gradational change, with fossil numbers and variety gradually increasing upward within the formation. Fossils are selectively concentrated in some of the shale beds of the Dubuque Formation. The basal part of the formation is crinoidal, and locally contains lenses composed of crinoid fragments (Weiss, 1957). Higher in the formation brachiopods (Sloan and others, 1987a), dominate and the fauna becomes very similar to the Prosser Formation (Weiss, 1957). In addition to brachiopods and crinoids, the Dubuque Formation contains conularids, bryozoans, pelecypods, trilobites, graptolites (Weiss, 1957), conodonts (Webers, 1966), and ostrocodes (Burr and Swain, 1965).

Relationship to adjacent rock units—The basal contact of the Dubuque Formation with the Stewartville Formation is conformable. In the past it has commonly been placed at the base of the lowest prominent shale (Weiss, 1957). However, the contact has been picked inconsistently by different stratigraphers because of the discontinuous nature of the shale partings in the lower 15 feet (5 meters) of the Dubuque Formation (Levorson and others (1979). During a regional study of the Dubuque Formation, Levorson and others (1979) observed a conspicuous marker bed of limestone about 8 inches (20 centimeters) thick set off from adjacent beds by conspicuous shale partings that was widely traceable in outcrop from Illinois into Minnesota. They suggested that this "marker bed" could be used as the base of the formation in order to place it consistently. Though this marker bed may be useful for outcrop studies, it is impractical for use in the subsurface. In subsurface studies that rely on geophysical logs (Fig. 13) and well cuttings, it is more practical to use shale content and the presence of prominent shale partings to distinguish the Dubuque Formation from the Stewartville Formation. When this is done the contact between the Dubuque and Stewartville Formations is placed higher in the section within Frankville beds, close to the base of the Luana beds, in about the same place where Weiss (1957) had placed it.

Representative sections—The Dubuque Formation is exposed at the Rifle Hill Quarry and adjacent roadcuts (Fig. 3, location 34, discussed under representative sections for the Prosser Formation). It is also exposed in roadcuts east of the Rifle Hill Quarry but in the same section (T. 102 N., R. 12 W., sec. 35, NW, NE).

MAQUOKETA FORMATION

The Maquoketa Formation was named by White (1870, p. 180-182) for exposures of carbonate and shale on the Little Maquoketa River in Dubuque County, Iowa. Bayer (1967) considered most of the Maquoketa Formation in Minnesota to be the basal Elgin Member (1967), but thought that some outcrops of sandy dolostone correlated with the Clermont Member (Bayer, 1965; Fig. 10, columns 4 and 8). However, some of this sandy dolostone may be basal Devonian (Spillville Formation, Lake Meyer Member), which has similar lithologic attributes.

Occurrence—The Maquoketa Formation crops out in western Fillmore County, northeastern Mower County, and southwestern Olmsted County. Most outcrops are small exposures along streams, except in Fillmore County, where some of the exposures are roadcuts. The Maquoketa Formation is present in the subsurface across much of Freeborn and Mower Counties.

Thickness—The Maquoketa Formation reaches thicknesses of 65 to 85 feet (20 to 24 meters) in Minnesota. It is much thicker to the south in Iowa where it was not as deeply truncated by pre-Middle Devonian erosion.

Lithology—The Maquoketa Formation is light gray to yellowish-gray, very fine-grained to sublithographic limestone that is fossiliferous, thin bedded, and interbedded with gray to brownish-gray, unfossiliferous, and shaly dolostone. There is minor interbedded brown shale at its base. Gray to brownish-gray chert nodules are common in the carbonate beds and fossils commonly are replaced by chalcedony and drusy quartz. The shaly limestones are replaced northward by barren shaly dolostone (Bayer, 1967).

Fossil content—In addition to brachiopods (Weiss, 1957; Bayer, 1965, 1967; Sloan and others, 1987a) the Maquoketa Formation contains graptolites (Weiss, 1957; Bayer, 1965, 1967), ostracodes (Burr and Swain, 1965), conodonts (Webers, 1966), rugose corals (Elias, 1987), sponges (Bayer, 1965), echinoderms (Bayer, 1965; Kolata and others, 1987), pelecypods (Pojeta, 1987), gastropods and monoplacophorans (Bayer, 1965; Sloan and Webers, 1987), cephalopods (Bayer, 1965; Catalani, 1987), trilobites (Bayer, 1965, 1967), conularids (Bayer, 1967), and bryozoans (Bayer, 1965).

The basal 10 feet (about 3 meters) of the Maquoketa Formation has a meager fauna consisting mainly of trilobites and graptolites; the medial carbonate section is dominated by articulate brachiopods, and a local, thin interval above the carbonate section is dominated by a single species of rugose coral (Bayer, 1965, 1967).

Relationship to adjacent rock units—In Minnesota, the basal contact of the Maquoketa Formation with the Dubuque Formation is considered to be conformable. Farther south in Iowa and Illinois where the basal Maquoketa Formation is ferruginous, phosphatic carbonate and shale that has a dwarfed fauna, the Maquoketa Formation contains multiple phosphatic hardgrounds (a condensed sequence) at the base that indicate diastems due to slow or condensed sedimentation (Raatz and Ludvigson, 1996).

Weiss (1957) picked the top of the Dubuque Formation at the top of the highest conspicuous shale parting in Fillmore County. Though the carbonate rock of the Maquoketa Formation is shaly, clay is generally more uniformly distributed in it. There is not the regular interlayering of shale and carbonate beds that there is in the Dubuque Formation where shale beds are more conspicuous. Biological markers, particularly graptolites, also serve to identify the Maquoketa Formation (Raatz and Ludvigson, 1996). Levorson and others (1979) observed that basal Maquoketa Formation beds are dolomitic shale and dolostone in Minnesota and beds in the upper part of the Dubuque Formation are calcareous or slightly dolomitic shale and limestone.

Representative sections—The best exposure of the Maquoketa Formation in Minnesota is a stream cut near Granger in Fillmore County in T. 101 N., R. 11 W., sec. 32, SW, SW (Fig. 3, location 36). This exposure was described by Bayer (1967). The lower part of the Maquoketa Formation and its basal contact with the Dubuque Formation is exposed at the Rifle Hill Quarry and nearby roadcuts (Fig. 3, location 34), discussed under representative sections for the Prosser and Dubuque Formations.

DEVONIAN SYSTEM

In recent years, classification of the Devonian System in Minnesota has changed more than classification of either the Cambrian or Ordovician systems because of lithostratigraphic studies in north-central Iowa (Witzke and Bunker, 1984; Bunker and others, 1986; Witzke and others, 1988) and biostratigraphic studies in Iowa and Minnesota (Klapper and Barrick, 1983). We now recognize two groups divided into five formations that are further divided into 15 members in an interval that was formerly considered a single formation (Fig. 14).

WAPSIPINICON GROUP

The Wapsipinicon Group is composed of rocks representing two major marine transgressive-regressive cycles. The rocks are predominantly carbonates in outcrop; however, evaporites are a major constituent in the subsurface of central and southern Iowa (Witzke and others, 1988).

The Wapsipinicon Group was originally named for exposures of carbonate rock along the Wapsipinicon River in Linn County, Iowa (Norton, 1895). At present it contains all Devonian stratigraphic units in Iowa and Minnesota below the Cedar Valley Group (Fig. 14). In Minnesota it includes units formerly assigned to the Solon Member and basal part of the Rapid Member of the Cedar Valley Formation by Austin (1969) and Mossler (1978a; Fig. 14). Paleontological studies (Klapper and Barrick, 1983) showed that the Minnesota rocks were correlative with rocks in the type area of the Wapsipinicon Group in eastern Iowa and older than basal Cedar Valley Group rocks at its type area in southeastern Iowa.

The Wapsipinicon Group was raised to group status by Witzke and others (1988) because it includes rock units, the Spillville Formation and the Pinicon Ridge Formation, earlier given formation status by Klapper and Barrick (1983) and Bunker and others

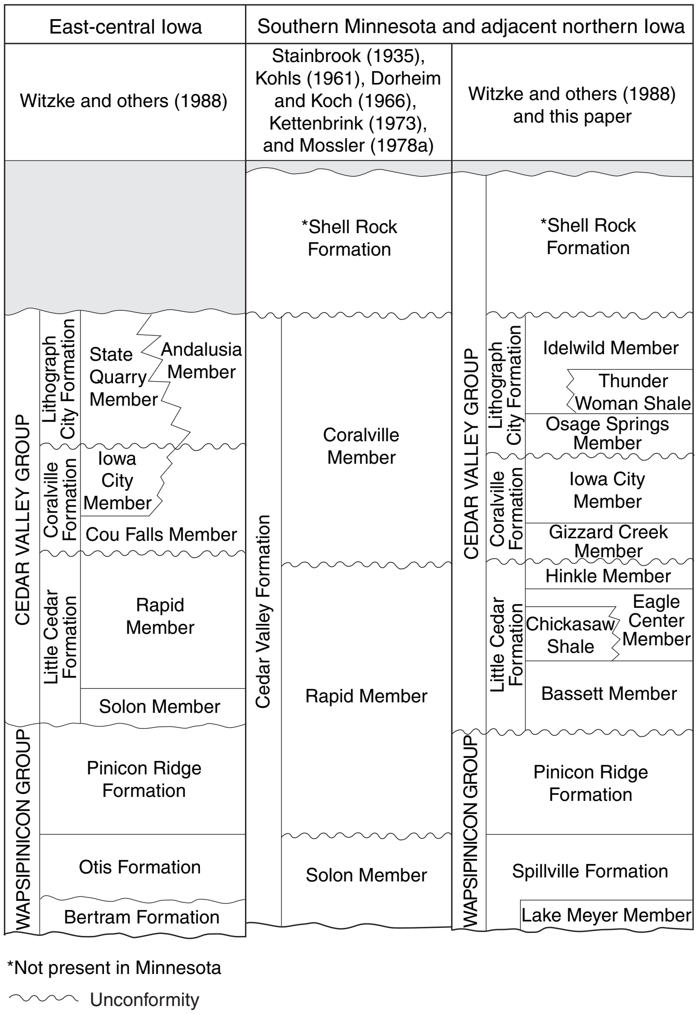


Figure 14. Development of stratigraphic nomenclature for Middle Devonian rocks and lower Upper Devonian rocks of northern Iowa and southern Minnesota. The column on the right shows current nomenclature for Devonian rocks of southern Minnesota and northeastern Iowa. The center column shows earlier nomenclature for the same area, and nomenclature for equivalent rock units in east-central Iowa is on the left. Modified from Witzke and others (1988).

(1985). Including the Spillville Formation in the Wapsipinicon Group returns to the earlier intention of Norton (1920), who included all Devonian units beneath the Cedar Valley Group in the Wapsipinicon Group. In an earlier publication, Bunker and others (1985) restricted the Wapsipinicon Group to the stratigraphic interval now represented by the Pinicon Ridge Formation (Fig. 14) and the earlier version of this Report of Investigations (Mossler, 1987) followed that nomenclature.

Spillville Formation

The Spillville Formation was named by Klapper and Barrick (1983) for exposures in a quarry near Spillville, Winneshiek County, Iowa. Faunal content and stratigraphic position indicate the Spillville Formation is laterally equivalent to the Otis Formation of east-central Iowa (Klapper and Barrick, 1983). It is not laterally contiguous with that formation, however, but is separated from it in Iowa by a prominent Silurian paleo-escarpment, the Hardin-Bremer High, and therefore must have a different name. It is equivalent to the limestone and dolostone formerly included in the Solon Member of the Cedar Valley Group by Kohls (1961), Austin (1969), and Mossler (1978a).

Occurrence—In Minnesota, the Spillville Formation is exposed in western Fillmore and eastern Mower Counties, and in the subsurface it extends from western Fillmore County across Mower County to southeastern Freeborn County.

Thickness—The formation ranges in thickness from 21 to 84 feet (6 to 26 meters). It thins noticeably to the west across Mower County (Fig. 15).

Lithology—Yellowish-gray, massive to very thick bedded, vuggy, and fossiliferous dolostone. Numerous vugs of fossil molds occur in the dolostone, some the result of dissolution of large fossils, including colonial corals. These large vugs commonly are lined with coarse calcite spar. At some

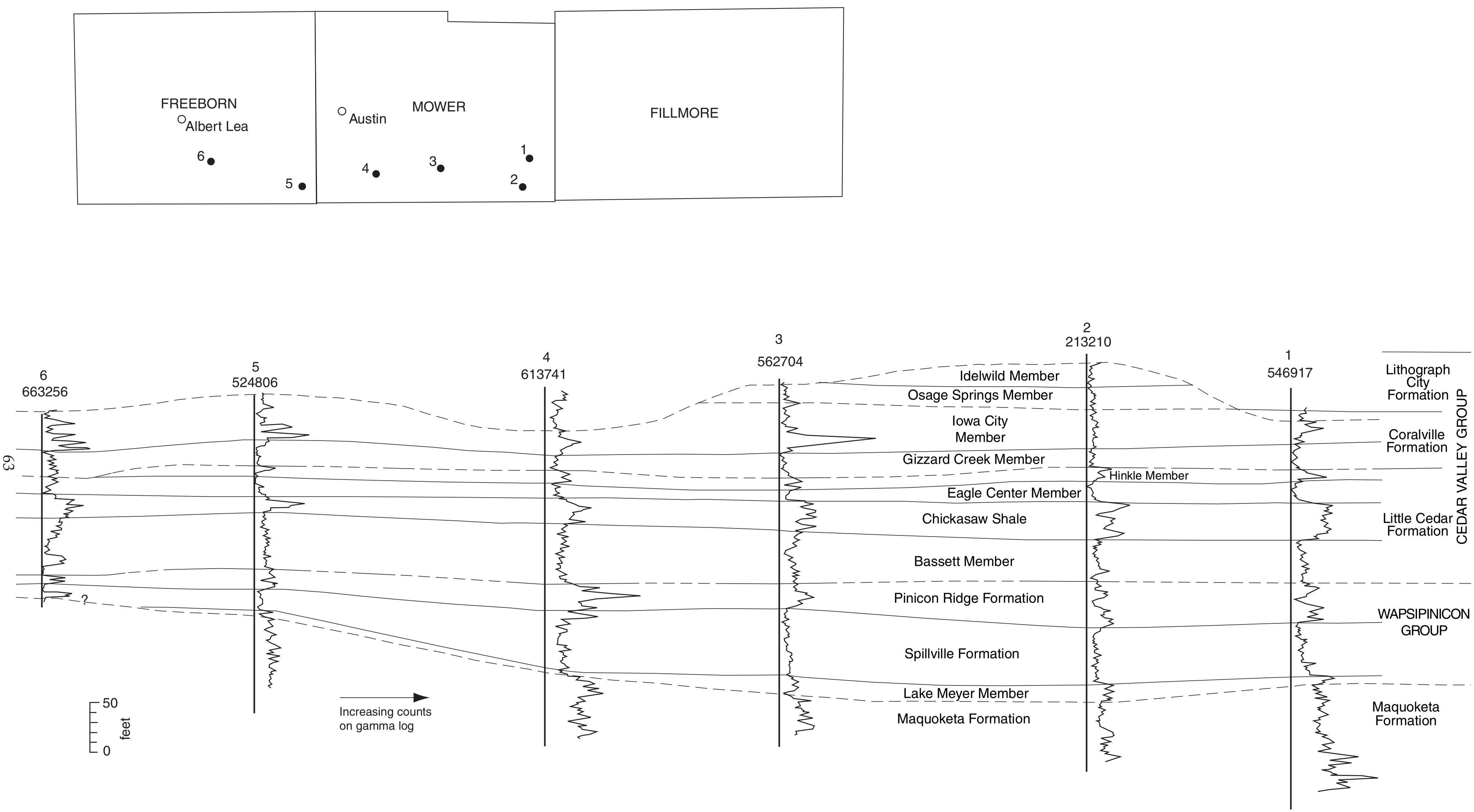


Figure 15. Geologic section of the Devonian formations across the southern part of the Hollandale embayment in Minnesota. Datum is the top of the Chickasaw Shale. Note the thinning in the Spillville and Pinicon Ridge Formations toward the west. Shaly units such as the Chickasaw Shale and Pinicon Ridge Formation are widely traceable and make natural gamma ray logs a useful tool for correlating units in the Devonian system. Dashed lines denote unconformities.

localities, the upper part of the formation consists of yellowish-gray, thin bedded, dense, dolomitic limestone. Sandy dolostone or sandstone that occurs in the basal few feet of the Spillville Formation is called the Lake Meyer Member.

Fossil content—This unit is the most fossiliferous in the Devonian system; however, macrofossils are preserved as molds in the dolostone. Fossils include brachiopods (spiriferids, atrypids, productellids, and others; listed by Day and Koch, 1994), gastropods, nautiloids, rostroconchs, crinoid debris, bryozoans, tentaculitids, stromatoporoids, and trilobites (Witzke and others, 1988). Corals are present and include favositids and solitary and colonial rugosans (Witzke and others, 1988). Conodonts are an important microfossil (Klapper and Barrick, 1983).

Relationship to adjacent rock units—In Minnesota, the Spillville Formation unconformably overlies the Maquoketa Formation. In northern Iowa it also unconformably overlies Silurian rocks. The contact is rarely exposed and is known mainly from the subsurface. The Spillville Formation is yellowish-gray to grayish-orange dolostone with fossil moldic porosity. Commonly the basal few feet are denser dolostone that is silty or sandy (very fine- to medium-grained quartz and chert grains) of the Lake Meyer Member. The underlying Maquoketa Formation dolostone is light olive-gray, finely crystalline rock that is not vuggy and does not have fossil moldic porosity. Fossils of the upper Maquoketa Formation, if present, commonly are resistant calcite echinoderm fragments set in a dolostone matrix, or minute brachiopod shells that have been silicified. The dolostone of the upper Maquoketa Formation commonly contains light gray chert as nodules and associated light gray to gray, dense limestone. The Maquoketa Formation is markedly more argillaceous than the Spillville Formation, which except for its basal Lake Meyer Member, is a very pure carbonate rock. This change in shale content is useful for identifying the Spillville Formation on wire line geophysical logs (Fig. 15).

Representative section—The best exposure of the formation is a large active quarry near Grand Meadow in Mower County in T. 103 N., R. 14 W., sec. 9, N (Fig. 3, location 37). There are other, smaller quarries in northeastern Mower and western Fillmore Counties that also contain exposures (Kohls, 1961; Mossler, 1978a).

Pinicon Ridge Formation

The unfossiliferous rock succession overlying the Spillville or Otis Formations and disconformably underlying the fossiliferous Cedar Valley Group was named the Pinicon Ridge Formation by Witzke and others (1988). The type locality is designated at Pinicon Ridge Park in northwestern Linn County, Iowa. The formation has three named members: in ascending order the Kenwood, Spring Grove, and Davenport (historical summary in Bunker and others, 1985).

Occurrence—The Pinicon Ridge Formation is not exposed in Minnesota but it occurs in the subsurface throughout much of Mower County and eastern Freeborn County.

Thickness—The formation ranges from about 20 to 47 feet (6 to 14 meters) in thickness.

Lithology—**Upper unit (Davenport Member):** the Davenport Member is principally yellowish-gray to light to medium gray, silty or sandy dolostone that may be chalky. In places the dolostone is brecciated. Some dolostone is very argillaceous and contains dark gray shale partings. There is minor fine- to medium-grained, quartzose (with chert grains) sandstone. Minor siltstone and light gray chert also occur.

Medial unit (Spring Grove Member): Yellowish-gray, finely crystalline limestone and dolostone with coarsely-grained crystalline calcite spar in veins and drusy quartz vug fillings. This unit is noticeably less argillaceous than overlying and underlying units, particularly on wire line gamma logs (Fig. 15).

Basal unit (Kenwood Member): Yellowish-gray dolostone. Contains light olive-gray shale partings, drusy quartz nodules of light gray chert, and minor beds of dense yellowish-gray limestone. Some carbonate rock is sandy.

Fossil content—The formation is generally unfossiliferous, although stromatolites and ostracodes have been observed in Iowa (Witzke and others, 1988).

Relationship to adjacent rock units—Where the Pinicon Ridge Formation overlies the Spillville Formation in Minnesota, and equivalent rocks (the Otis Formation) in Iowa (Witzke and others, 1988), there is no evidence for an erosional contact at its base. However, in Iowa the Pinicon Ridge Formation was deposited across a broader region than the Spillville and Otis Formations and unconformably overlies Ordovician and Silurian rocks throughout much of its extent (Witzke and others, 1988).

The upper Spillville Formation generally is yellowish-gray to grayish-orange dolostone that is vuggy and has a low content of sand, silt, and clay. The low content of detrital material is evident in the low natural gamma readings on geophysical logs (Fig. 15). In contrast the overlying Pinicon Ridge Formation is generally sandy, silty, or shaly, and its carbonate rocks are denser than the Spillville Formation with fewer vugs. They also commonly are darker colored (brownish-gray or gray) because of higher shale content, and show higher natural radiation on geophysical logs.

Representative section—The Pinicon Ridge Formation is represented by three cores that are from a quarry near Varco in Mower County in T. 102 N., R. 18 W., sec. 27, SE (Fig. 3, location 38) where the Pinicon Ridge Formation was formerly partially exposed. The cores are stored at the Minnesota Department of Natural Resources Core Library in Hibbing.

CEDAR VALLEY GROUP

The Cedar Valley Group disconformably overlies the Wapsipinicon Group. It contains four formations that are mostly carbonate rock. Each represents a transgressive-regressive sequence separated from preceding and succeeding sequences by disconformities (Witzke and others, 1988).

Owen (1852) referred to the Middle Devonian carbonate succession of eastern Iowa as the "limestones of Cedar Valley," and later McGee (1891) formally designated the interval the "Cedar Valley limestone." Subsequent definition excluded Wapsipinicon Group carbonate rocks from the Cedar Valley Group. The Cedar Valley Group was raised to group status by Witzke and others in 1988. Its four formations are in ascending order, the Little Cedar, Coralville, Lithograph City, and Shell Rock (Fig. 14). The Shell Rock Formation does not extend into Minnesota because of post-depositional erosion. In Minnesota, the Cedar Valley Group is comprised of rock units formerly assigned to middle and upper parts of the Rapid and the Coralville Members of the Cedar Valley Formation by Kohls (1961), Austin (1969), and Mossler (1978a).

Little Cedar Formation

The Little Cedar Formation is a sequence composed of dolostone and shale. Witzke and others (1988) designated the Chickasaw Park Quarry near the Little Cedar River in Chickasaw County, Iowa, as the type locality. The formation is subdivided into three to four members in northern and central Iowa (in ascending order the Bassett, Chickasaw Shale, Eagle Center, and Hinkle) that can be traced into southern Minnesota (Fig. 14). In Minnesota units formerly referred to as the middle and upper parts of the Rapid Member of the Cedar Valley Group (Kohls, 1961; Mossler, 1978a) are now classified as the Little Cedar Formation.

Occurrence—The Little Cedar Formation crops out in southwestern Fillmore County and in southwestern Mower County. It subcrops across much of Freeborn and Mower Counties.

Thickness—The Little Cedar Formation is about 100 to 110 feet (30 to 34 meters) thick. Thicknesses for individual members are given below.

Lithology—**Bassett Member:** Light to medium gray, thick bedded to massive dolostone that commonly contains scattered, small, spherical cavities or vugs 2 or 3 inches (5 to 8 centimeters) in diameter. Most of the vugs are not lined with any mineral. The Bassett Member is 40 to 70 feet (12 to 21 meters) thick.

Chickasaw Shale: Medium gray, dolomitic shale with minor amounts of shaly dolostone. The Chickasaw Shale is 15 to 43 feet (5 to 40 meters) thick. It is a distinctive, easily traceable unit on natural gamma logs (Fig. 15).

Eagle Center and Hinkle Members: These members are yellowish-gray to light gray, thin bedded dolostone. Finely laminated beds, pelletal carbonate beds, intraclasts, and desiccation cracks characterize the Hinkle Member. Minor, thin, pale green, shale beds are present in the Hinkle Member. The combined thickness of the two members is 25 to 35 feet (8 to 11 meters).

Fossil content—Members of the Little Cedar Formation are generally unfossiliferous to very sparsely fossiliferous in Minnesota.

Relationship to adjacent rock units—In Minnesota, the Little Cedar Formation unconformably overlies the Pinicon Ridge Formation and unconformably underlies the Coralville Formation.

Dolostone of the Bassett Member of the Little Cedar Formation is argillaceous, but less argillaceous than underlying Pinicon Ridge Formation dolostone and contains fewer shale partings. Its gamma radiation readings on wire-line logs are lower than the Pinicon Ridge Formation's readings (Fig. 15). The Pinicon Ridge Formation has abundant gray shale partings and contains sandy dolostone, in contrast to the Bassett Member, which though argillaceous does not have discrete shale partings and is not sandy.

Representative sections—The Bassett Member is exposed at the large inactive quarry near Varco, Mower County in the T. 102 N., R. 18 W., sec. 27, SE (Fig. 3, location 38). The Hinkle Member is exposed at an abandoned quarry near Lyle, Mower County in T. 101 N., R. 18 W., sec. 33, NW, SW (Fig. 3, location 39). The Chickasaw Shale and Eagle Center Member are not known to crop out in Minnesota and are known only from well cuttings and wire line geophysical logs.

Coralville Formation

The Coralville Formation is a sequence of limestone and dolostone with minor shale that is named for a suburb of Iowa City. Keyes (1912) originally proposed the Coralville Formation as a stratigraphic unit within the Cedar Valley Limestone. The type section at the Conklin Quarry near the city of Coralville, in Johnson County, Iowa, was designated by Stainbrook (1941). Witzke and others (1988) elevated the Coralville from member to formation rank and divided it into two members, the basal Gizzard Creek Member and the upper Iowa City Member (Fig. 14). The Coralville Formation as presently defined includes rock units formerly included in the lower half of the Coralville Member of Kohls (1961), Austin (1969), and Mossler (1978a).

Occurrence—The Coralville Formation occurs throughout much of the subsurface of southern Mower and southeastern Freeborn Counties.

Thickness—The formation is 57 to 61 feet (17 to 19 meters) thick.

***Lithology*—Gizzard Creek Member**: Light brown to gray-orange to yellowish-gray, very fossiliferous, and thick-bedded dolostone with abundant fossil moldic porosity. The Gizzard Creek Member constitutes the lower 20 feet (6.1 meters) of the Coralville Formation.

Iowa City Member: Light brown to yellowish-gray, thin to medium bedded dolostone and gray and gray-green shale, in beds up to several feet thick. The Iowa City Member constitutes the upper 35 to 40 feet (10.6 to 12.2 meters) of the Coralville Formation.

Fossil content—The basal 20 feet (6 meters) of the formation is very fossiliferous but the fossils are molds. The fauna has low diversity but contains abundant crinoid debris and brachiopods, including *Athyris* and *Independatrypa* (Day, 1989, 1992). The upper part of the formation is sparingly fossiliferous; it contains algal mats, algal biscuits (oncolites), and ostracodes.

Relationship to adjacent rock units—In Minnesota, the Coralville Formation unconformably overlies the Little Cedar Formation and unconformably underlies the Lithograph City Formation.

The basal member of the Coralville Formation, the Gizzard Creek Member, is nonargillaceous, light colored, and vuggy with fossil moldic porosity. The underlying Hinkle Member of the Little Cedar Formation is argillaceous dolostone that is commonly laminated, lacks moldic porosity, and generally is darker colored. On wire-line geophysical logs, the Hinkle Member has a higher gamma reading and forms a sharp peak between the nonargillaceous Gizzard Creek and Eagle Center Members (Fig. 15).

Representative sections—The Coralville Formation crops out near Lyle, southwest Mower County in an inactive quarry by the Cedar River in T. 101 N., R. 18 W., sec. 33, NW, SW (Fig. 3, location 39) and south along the Cedar River in other quarries in neighboring parts of northern Mitchell County, Iowa, such as in Oronto Township, T. 100 N., R. 18 W., sec. 34, NE, SE).

Lithograph City Formation

Witzke and others (1988) named the sequence of limestone, dolostone, and thin shale beds between the Coralville Formation and Shell Rock Formation or Sweetland Creek Shale the Lithograph City Formation (Fig. 14). They divided it into three members, two of which, the lower Osage Springs and the upper Idelwild, extend into Minnesota. A medial shale member, the Thunder Woman, does not occur in Minnesota. Earlier classifications placed the rock sequence assigned to the Lithograph City Formation in the upper part of the Coralville Member of the Cedar Valley Formation (Fig. 14) even though it does not correspond with any part of the Coralville Formation sequence in the Coralville Formation's type area. The type locality for the Lithograph City Formation is the old quarry area near the former town of Lithograph City, Floyd County, Iowa (Witzke and others, 1988).

Occurrence—This formation occurs in extreme southern Mower County and is thickest in the area around Le Roy.

Thickness—The formation is up to 50 feet (15 meters) thick.

***Lithology*—Osage Springs Member:** Yellowish-gray to yellow-brown, thick to medium bedded dolostone that is shaly in places. The Osage Springs Member forms the lower half of the Lithograph City Formation.

Idelwild Member: Interbedded limestone and dolostone with minor grayish-green shale partings. The limestone is yellowish-gray, very dense (sublithographic), and thin bedded. The dolostone is gray-orange to yellowish-gray. The Idelwild Member forms the upper half of the Lithograph City Formation.

Fossil content—Brachiopods (*Allanella, Athyris, Strophodonta*) dominate the lower dolomitic member and echinoderm debris, bryozoans, gastropods, and corals are present locally (Day, 1989, 1992). As in underlying formations, faunas in the lower marine facies are less diverse in the northern rocks than they are farther south in Iowa (Witzke and others, 1988). The upper limestone member is more sparsely fossiliferous and is characterized by ostracodes, stromatolites, and gastropods. Minor, thin, fossiliferous beds in the upper member contain brachiopods, bryozoans, gastropods, and echinoderm debris. Stromatoporoids are present, but are more abundant farther south in northern Iowa.

Relationship to adjacent rock units—The Lithograph City Formation is unconformable with the overlying Shell Rock Formation (in Iowa); the Shell Rock Formation has been stripped back from the Minnesota outcrop so that the Lithograph City Formation is overlain by the Cretaceous Windrow Formation or by Quaternary glacial deposits everywhere. The Lithograph City Formation unconformably overlies the Coralville Formation. The basal Osage Springs Member of the Lithograph City Formation is less argillaceous than the upper Coralville Formation and does not have as many shale partings. It can be distinguished by its relatively low, flat gamma readings on wire-line logs, which contrasts with the relatively jagged pattern exhibited by the upper Coralville Formation (Fig. 15). It is more difficult to distinguish them in water well cuttings because the dolostones are similar. However, cuttings from the upper Coralville Formation commonly contain more shale and the dolostone from the Osage Springs Member generally contains calcite spar fissure fillings.

Representative sections—Most outcrops of Lithograph City Formation are in quarries in and around the town of Le Roy in T. 101 N., R. 14 W., sec. 27, T. 101 N., R. 14 W., sec. 27, SW, SW, through sec. 34, NW, NE, Mower County, in Minnesota (Fig. 3, location 40) and T. 100 N., R. 14 W., sec. 10, NE in Howard County, Iowa.

NORTHWESTERN MINNESOTA

Two Ordovician formations, the Winnipeg and the Red River, extend into northwestern Minnesota from the Williston basin of the western interior of North America. Both are entirely covered by a continuous layer of Quaternary drift in Minnesota. The nearest outcrops are in the Lake Winnipeg area of Manitoba, Canada, where these units were first described. These formations are lateral equivalents of the St. Peter Sandstone through Stewartville Formation of southeastern Minnesota that are Upper Ordovician in age (Blackriveran through Maysvillian stage; Sloan, 1987c). Deposition of the uppermost units may have been continuous across the Transcontinental Arch (Webers, 1972), although that continuity is now breached by erosion.

WINNIPEG FORMATION

The Winnipeg Formation is a siliclastic unit that was first described by Dowling (1895, p. 66) in reference to rocks underlying Ordovician carbonate rocks and overlying Archean crystalline rocks in the Lake Winnipeg area. No specific type section has ever been designated for the Winnipeg Formation because all outcrops are incomplete exposures of the formation. Although the Winnipeg Formation is divided into members in the Williston basin by some authors (Carlson, 1960; Fuller, 1961), this geologist is reluctant to apply this terminology in Minnesota because of questions about lateral continuity of these units across the basin.

Occurrence—The Winnipeg Formation subcrops across western Kittson, Marshall, and northwestern Polk Counties.

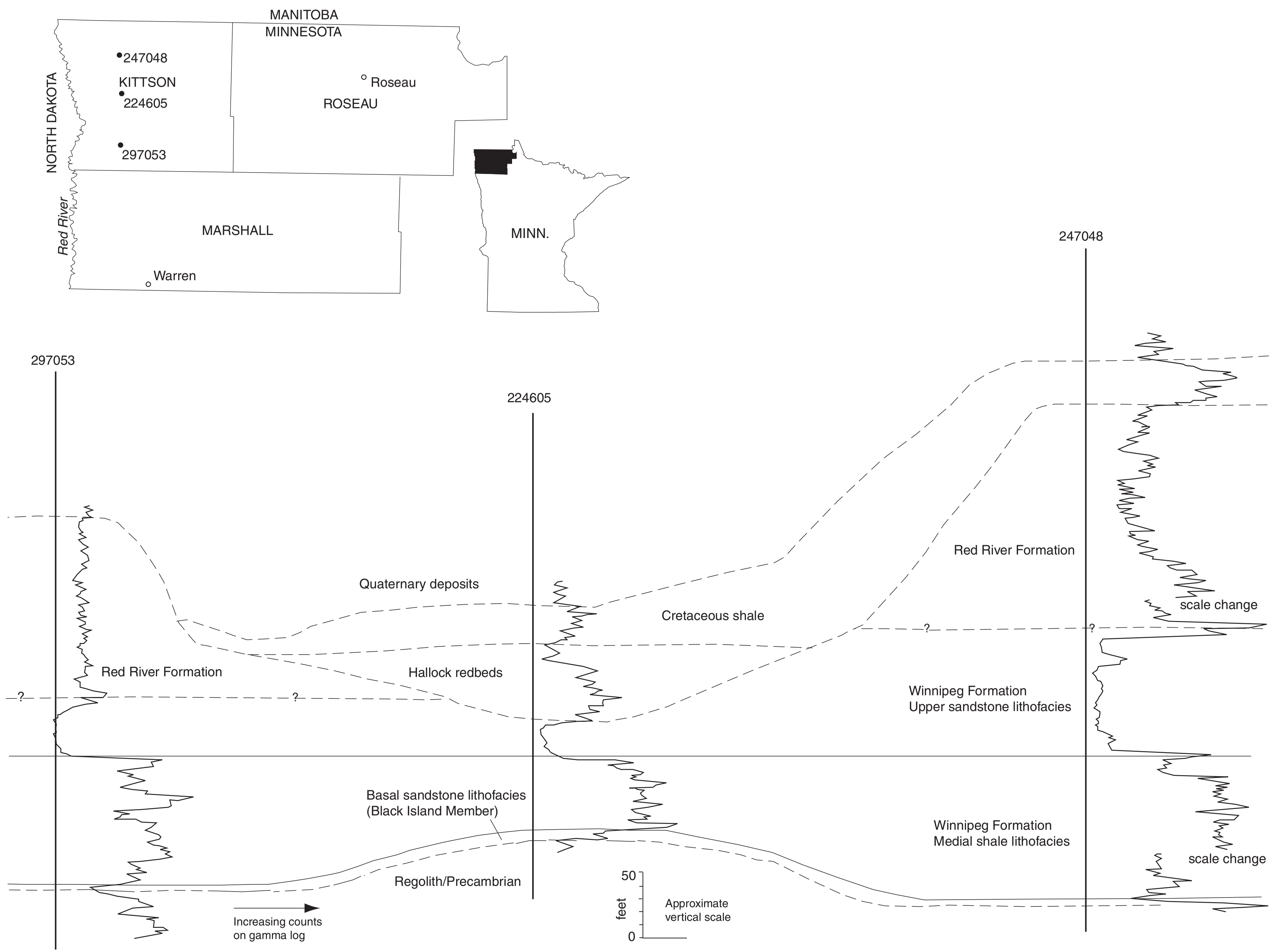
Thickness—The Winnipeg Formation reaches a maximum thickness of around 170 feet (52 meters) in Kittson County (Bayer, 1959, unpub. data). It thins to an erosional featheredge toward the east.

Lithology—The Winnipeg Formation contains three major lithofacies that are illustrated on Figure 16:

Basal sandstone lithofacies: Sandstone, light gray to dark yellowish-brown, medium- to coarse-grained, calcite cemented, and quartzose. There is minor interbedded shale that is purple to grayish-green and soft. This lithofacies ranges from 4 to 14 feet (1.2 to 4.3 meters) in thickness. This unit is considered equivalent to the Black Island Member of Manitoba.

Medial shale lithofacies: Shale, light brownish-gray to greenish-gray, traces are maroon, yellowish-brown or light green. There are a few thin interbedded

Figure 16. Geologic section across Kittson County in northwestern Minnesota. Datum is the base of the sandstone in the upper part of the Winnipeg Formation. The sandstone has low natural gamma readings compared to underlying shale in the Winnipeg Formation and overlying argillaceous carbonate rock in the Red River Formation and therefore is widely traceable. The natural gamma signatures of the Jurassic Hallock redbeds and the Cretaceous shale are also illustrated. Note they have high readings and cannot readily be distinguished from the Winnipeg Formation shale without well cutting samples. Dashed lines denote unconformities.


MANITOBA
MINNESOTA
NORTH DAKOTA
Red River
247048
KITTSON
224605
297053
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Roseau
MARSHALL
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297053
224605
247048
Quaternary deposits
Cretaceous shale
Red River Formation
Hallock redbeds
Red River Formation
scale change
?
Winnipeg Formation
Upper sandstone lithofacies
Basal sandstone lithofacies
(Black Island Member)
Winnipeg Formation
Medial shale lithofacies
scale change
Regolith/Precambrian
Increasing counts
on gamma log
50
feet
0
Approximate
vertical scale

sandstone stringers and thin lentils of yellowish-gray, dense limestone below the middle of the unit. This lithofacies ranges from 80 to 97 feet (24 to 30 meters) in thickness.

Upper sandstone lithofacies: Sandstone, mostly yellowish-gray, fine- to medium-grained, well sorted quartzose. Generally very friable, the upper sandstone lithofacies contains some concretionary zones cemented by calcite. The lithofacies is about 70 feet (21 meters) thick but its thickness is variable: Andrichuk (1959) interpreted sandstone in the Winnipeg Formation of Manitoba in a similar stratigraphic position to be part of a sandstone bar.

Fossil content—Few fossils have been recovered from the subsurface of Minnesota, except for some conodont faunules recovered from shale layers (Bayer, 1959). In the outcrop area of southern Manitoba, the Winnipeg Formation also contains graptolites, conulariids, rugose corals, echinoderms, bryozoans, brachiopods, pelecypods, gastropods, nautiloids, trilobites, and ostracodes (Baillie, 1952). The trace fossil *Skolithos* is also present.

Relationship to adjacent rock units—The basal contact with the Archean crystalline rock is nonconformable. There is generally a clayey regolith developed on the Archean rocks. The contact with overlying Red River carbonates is present in few well cutting sets from northwestern Minnesota and therefore is poorly known. In neighboring Manitoba, where the contact with the Red River Formation has been more thoroughly studied, it is interpreted to be unconformable (Sweet, 1982; Stott, 1991).

In some drill holes the Winnipeg Formation is unconformably overlain by shale-rich Mesozoic rock formations that may be difficult to distinguish from Winnipeg Formation shale or basal Red River Formation shaly carbonate on natural gamma radiation logs if well cuttings are not available (Fig. 16).

Representative section—Well cuttings and core from Hallock test well A (T. 161 N., R. 49 W., sec. 13, SW, NW, Kittson County, and Fig. 17, location 1), described in Mossler (1978b), and for other deep wells are available. The cuttings are stored at the Minnesota Geological Survey. The core is at the Minnesota Department of Natural Resources Core Library in Hibbing.

RED RIVER FORMATION

The Red River Formation was first named and described by Foerste (1929) for limestone and dolostone widespread near Lake Winnipeg. The type sections are quarries near Winnipeg, Manitoba, and outcrops near Winnipeg are the nearest exposures to Minnesota of this formation.

Occurrence—The Red River Formation occurs in extreme western Kittson and Marshall Counties.

Thickness—The Red River Formation reaches a maximum thickness of nearly 300 feet (91 meters) in Kittson County; it thins to the east to an erosional featheredge.

Lithology—Formal member names from the outcrop area of Manitoba have not been extended

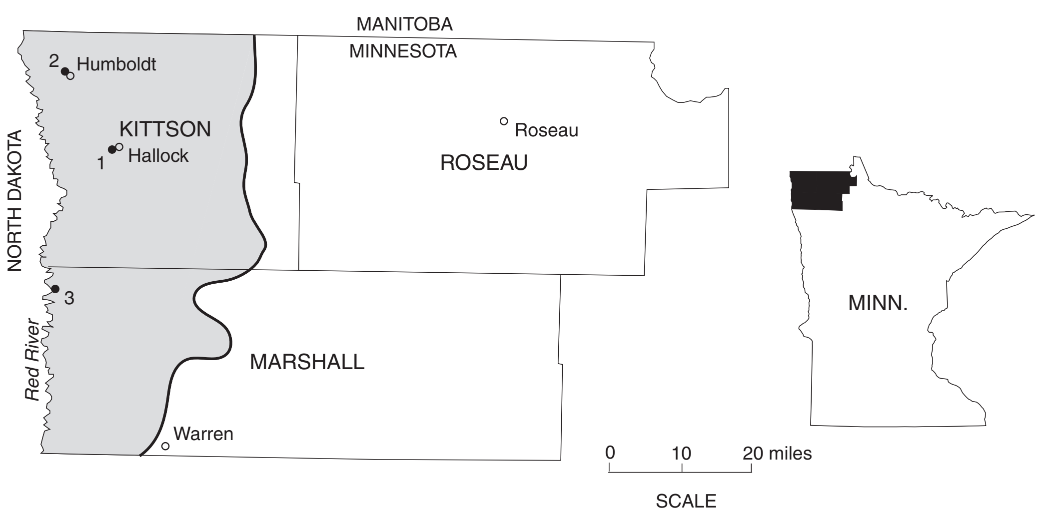

Figure 17. Locations (numbered) of well cores and cuttings from northwest Minnesota mentioned in the text. The approximate extent of Paleozoic rocks in northwest Minnesota is shaded.

into the subsurface of the Williston basin; instead the formation has been divided into informal lithologic units (Andrichuk, 1959; Fuller, 1961). In the main part of the Williston basin the lower 90 percent of the Red River Formation consists of variably dolomitized fossiliferous limestone; the upper 10 percent is interbedded dolostone and anhydrite. Only the lower unit has been identified in Minnesota; it is fossiliferous limestone that becomes progressively more dolomitized upward in the section.

Lower limestone lithofacies: This lithofacies consists of limestone that is light gray, dense and micritic, fossiliferous, with pale red color mottling along the numerous thin shale partings. This lithofacies is more argillaceous than overlying dolostone lithofacies (note gamma log at right side of section on Fig. 16).

Upper dolostone lithofacies: Consists of dolomitic limestone and dolostone that is yellowish-gray to grayish-orange with grayish-brown to grayish-orange color mottling along shale partings, dense and finely crystalline, fossiliferous, vuggy.

Fossil content—A varied marine fauna including echinoderms, brachiopods, bryozoans, trilobites, and ostracodes was found in core from a test well in Marshall County (Mossler, 1978b). Baillie (1952) listed a varied fauna that includes sponges, rugose and tabulate corals, graptolites, conulariids, bryozoans, brachiopods, pelecypods, gastropods, cephalopods (nautiloids), trilobites, ostracodes, *Receptaculites*, and trace fossils.

Relationship to adjacent rock units—The Red River Formation/Winnipeg Formation contact formerly was interpreted to be conformable (Fuller, 1961), but is now considered to be unconformable (Sweet, 1982; Stott, 1991). The upper contact of the Red River Formation in Minnesota is an erosional surface overlain by Mesozoic (Fig. 16) and Quaternary formations. Younger Paleozoic formations of Ordovician, Silurian, and Devonian age that are present in nearby areas of Manitoba and North Dakota may have extended into northwestern Minnesota at one time but were stripped back by erosion, before deposition of the Mesozoic rocks.

Representative section—In Minnesota, well cuttings from the D.H. Valentine well near Humboldt in Kittson County (T. 163 N., R. 50 W., sec. 33, SE, SE, SW, Fig. 17, location 2) afford the most complete section of the Red River Formation. Core from the Thibodo test well B (T. 158 N., R. 50 W., sec. 21, NE, SE, Marshall County, Fig. 17, location 3), described in Mossler (1978b), is available at the Minnesota Department of Natural Resources Core Library at Hibbing.

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APPENDIX A

Type section for the Pigs Eye Member of the St. Peter Sandstone

The Pigs Eye Member is named after a lake that is about 4 miles (6.4 kilometers) southeast of the type locality in T. 28 N. R. 22 W, secs. 10, 11, 14, and 15, Ramsey County, Minnesota (St. Paul East, Minnesota, 7.5' quadrangle).

Test boring for a proposed Investors Diversified Services–Minnesota Mutual Life–American National Bank Building, Sixth Street midway between Minnesota Street and Cedar Street, St. Paul, Minnesota.

T. 28 N., R. 22 W., sec. 6, NE, NW, NE, Ramsey County

Depth	Description	Percent Core Recovery
Recent and Quaternary		
0-6	Pavement and fill	SS
6-10.1	Sand	SS
10.1-11.5	Silty sand	SS
11.5-12.5	Peat	SS
12.5-42.0	Clay	SS
42.0-47.0	Silt	SS
47.0-68.0	Colluvium, limestone boulders	SS
St. Peter Sandstone, Tonti Member (upper part is eroded)		
68.0-85.3	Sandstone, white, tan, light gray	No recovery
85.3-93.3	Sandstone, yellowish-gray, very fine- to fine-grained, well sorted quartz. Unbedded, massive. Somewhat indurated (clay cement).	52
St. Peter Sandstone, Pigs Eye Member		
93.3-98.3	Silty sandstone, light olive-gray, very fine-grained quartz; well sorted. Faint horizontal bedding. Indurated. Contains minor very fine-grained glauconite and mica (muscovite).	85
98.3-103.8	Silty sandstone to sandy siltstone, light olive-gray, very fine-grained quartz. Indurated and glauconitic as above. Faint horizontal bedding. Generally finer-grained than the overlying interval.	100
103.8-108.3	Shale, pale red, slightly sandy with scattered fine- to medium-grained quartz sand, fissile.	100
108.3-113.3	Sandstone, yellowish-gray to grayish-orange, fine- to medium-grained quartz. Rather friable, core is highly fractured. Some iron stain.	36
113.3-118.3	Sandstone as above.	25
118.3-128.3	Sandstone, yellowish-gray, very fine- to medium-grained quartz. Silty. Faint horizontal banding caused by layers of silt. Indurated.	100
128.3-133.3	Sandstone, olive-gray, coarse-grained quartz. Very silty, siltiest at the top of the interval.	80
133.3-138.3	Sandstone, olive-gray, fine- to medium-grained quartz. Silty. Grain size overall is finer-grained than in the overlying unit.	77
138.3-143.3	Sandstone, olive-gray, fine- to medium-grained quartz. Very silty. Bimodal size-grade distribution (poorly sorted). Very fine-grained glauconite. Less sand and siltier in the basal 2.0 to 2.5 feet.	82
143.3-144.3	Sandstone, olive-gray, very fine- to medium-grained quartz. Very silty with faint horizontal siltstone and shale partings that contain pyrite.	80
144.3-147.3	Sandstone, light olive-gray, very fine- to coarse-grained quartz. Silty. Bimodal size-grade distribution. Minor very fine-grained glauconite. Friable, less cementation than above.	80
Shakopee Formation		
147.3-151.0	Dolostone, olive-gray, oolitic, intraclastic. Dense and very finely crystalline, but has some intergranular and vuggy porosity.	*

* Core broke off and only 11 inches of the core interval was recovered.

SS = Split spoon sample

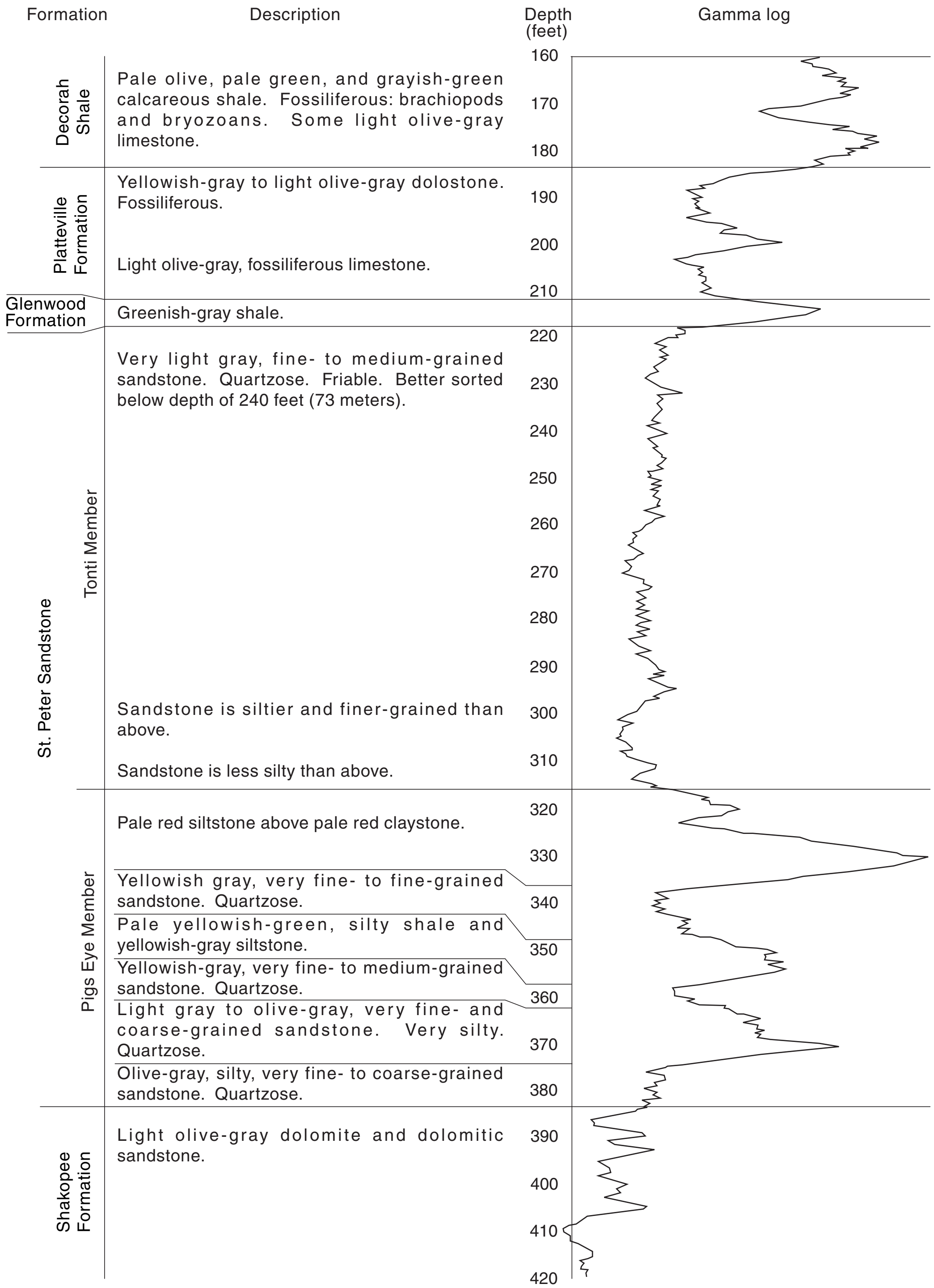
APPENDIX B

Supplemental section for the Pigs Eye Member

Water well for Highland Park Golf Course, St. Paul, Minnesota. Minnesota unique number 462855. (Natural gamma radiation wire-line log and water well cuttings set).

T. 28 N., R. 23 W., sec. 15, NW, NW, NW, Ramsey County

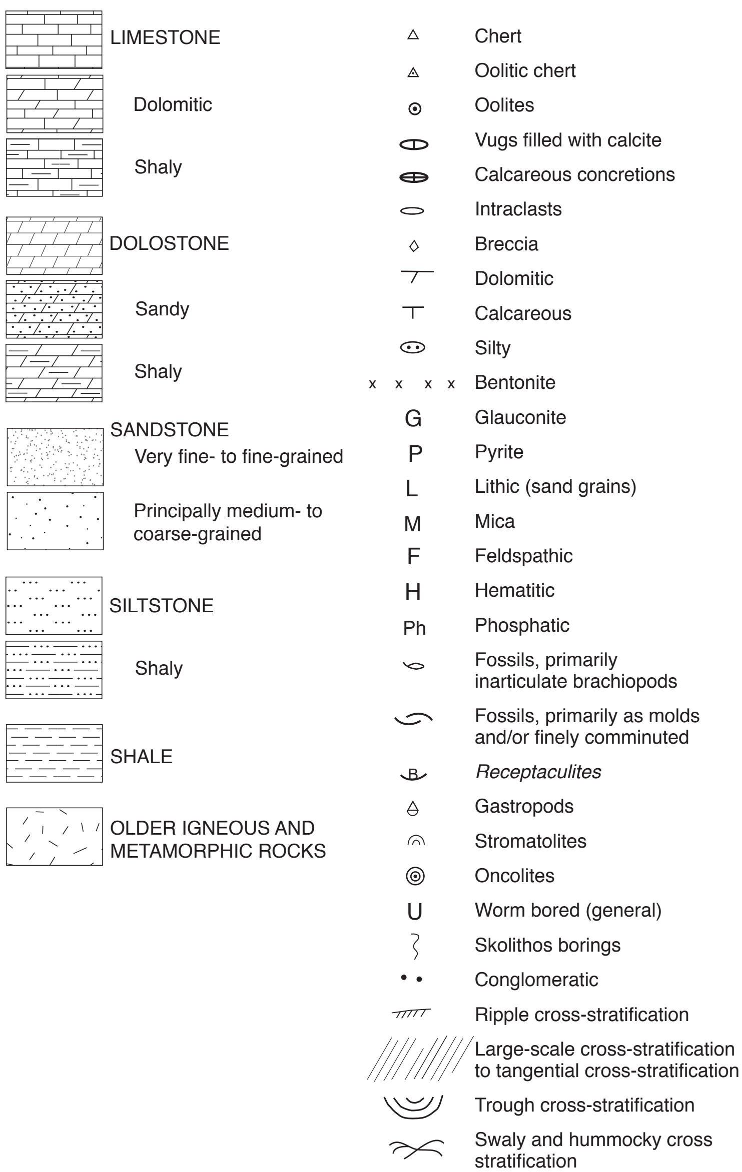
This water well encounters the entire uneroded thickness of St. Peter Sandstone. The water well enters the Jordan Sandstone but the entire length of the wire-line log is not shown. The upper and lower parts are omitted. This log is representative of natural gamma radiation logs of the Pigs Eye Member. There are generally three peaks with high readings in the Pigs Eye Member caused by higher silt and clay content (Appendix Fig. 1). The contact with the underlying Prairie du Chien Group may be obscure if it is sandstone on top of dolostone.



Appendix Figure 1. Well description and gamma log for the St. Peter Sandstone and surrounding units.

PLATE 1

EXPLANATION

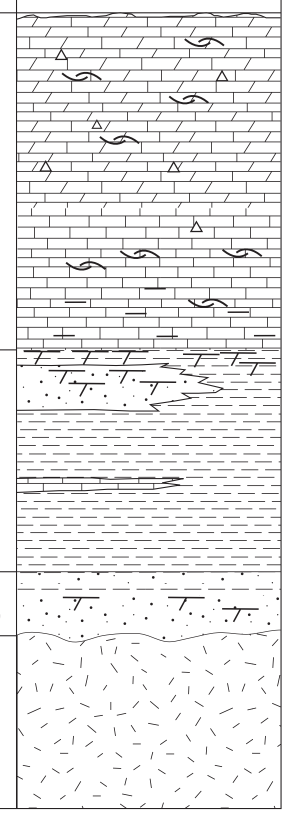


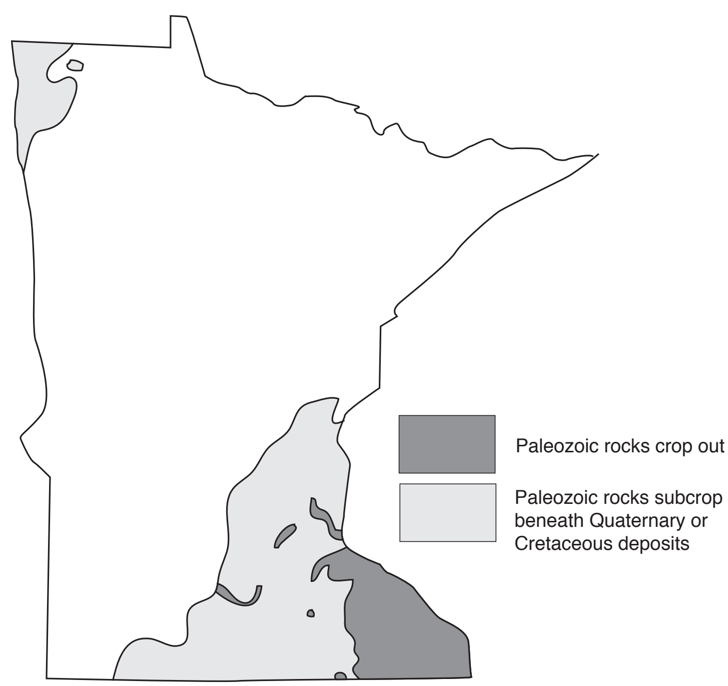
(60, SW) Numbers in parentheses in formation and member columns refer to maximum thickness of unit (in feet).
Letters in parentheses by number refer to part of southeast Minnesota (SW = southwest part, NC = north-central part, etc.) where unit is thickest.

SW-NE Letters in formation column not in parentheses denote direction of facies changes shown on columnar section.

NORTHWEST MINNESOTA

Chronostratigraphic units				Lithostratigraphic units		Columnar section
Eon	Era	System	Series	Formation	Member or bed	
PHANEROZOIC	Paleozoic	Ordovician	Upper	Red River Formation (300)		
				Winnipeg Formation (170)	Roughlock & Icebox Member equivalents (155)	
					Black Island Member (10)	
ARCHEAN	Undifferentiated			Metavolcanic and granitic rocks		





Areal extent of Paleozoic rocks

MINNESOTA GEOLOGICAL SURVEY
REPORT OF INVESTIGATIONS 65
Plate 1

SOUTHEAST MINNESOTA

Eon	Era	System	Series	Group	Formation	Member or bed
PHANEROZOIC	Paleozoic	Devonian	Upper	Cedar Valley Group	Lithograph City Formation (50)	Idelwild Member (25-30)
						Osage Springs Member (25-30)
			Middle		Coralville Formation (60)	Iowa City (35-40)
						Gizzard Creek (15-20)
					Little Cedar Formation (110)	Hinkle & Eagle Center Members (35)
						Chickasaw Shale (43)
						Bassett Member (70)
				Wapsipinicon Group	Pinicon Ridge Formation (47)	Davenport Member (13)
						Spring Grove Member (7)
						Kenwood Member (13)
					Spillville Formation (84)	Lake Meyer (15-20)
		Ordovician	Upper		Maquoketa Formation (85)	Clermont Member (20+)
						Elgin Member (62)
				Galena Group (345)	Dubuque Formation	
					Stewartville Formation (85)	Rifle Hill Member (38)
						Sinsinawa Member (32)
					Prosser Formation (62)	
					Cummingsville Formation (75)	
					Decorah Shale (80)	
						Carimona Member (11)
					Platteville Formation (30)	McGregor Member (22)
						Pecatonica Member (7, SE)
					Glenwood Formation (18)	
			?		St. Peter Sandstone (190, N)	Tonti Member (100-120, NE)
			Middle			Pigs Eye Member (40-65, NE)
			Lower	Prairie du Chien Group (320)	Shakopee Formation (240, SC)	Willow River Member (240, SC)
						New Richmond Member (55-60, SE)
					Oneota Dolomite (180-210, SE)	Hager City Member (180, SE)
						Blue Earth beds (4+)
						Kasota beds
						Coon Valley Member (60-85)
		Cambrian	Upper		Jordan Sandstone (110, NE)	Quartzose sandstone
						Feldspathic sandstone
					St. Lawrence Formation (130, SC)	Siltstone
						Dolostone
				Tunnel City Group (Franconia Formation) (190, NE)	Lone Rock Formation (175, SE)	Mazomanie Formation (115, NE)
						Reno Member (110, S)
						Tomah Member (23)
					Davis Formation (20, SW)	Birkmose Member (50)
					SW Wonewoc Sandstone (Ironton and Galesville Sandstones) (130, SE) NE	Very fine- to very coarse-grained sandstone
						Fine- to coarse-grained, cross-stratified sandstone
						Conglomerate
					SW Eau Claire Formation (250, SW) NE	Mixed sandstone and shale (22)
						Shale & siltstone (25)
						Greensand (96)
						Mixed sandstone and shale (98)
					Bonneterre Formation	Dolostone (80, SW)
						Red shale (75)
					SW Mt. Simon Sandstone (375, SE) NE	Upper (110+, NC)
						Middle (200+, SE)
						Lower (163, SW)
PROTEROZOIC	Middle				Hinckley Sandstone (<50, S to 500, N)	
					Fond du Lac Formation (8,000+)	
					Solor Church Formation (12,000-13,000)	
Undifferentiated					Older igneous and metamorphic rocks