MINNESOTA GEOLOGICAL SURVEY

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PALEOZOIC LITHOSTRATIGRAPHIC NOMENCLATURE FOR MINNESOTA

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PALEOZOIC LITHOSTRATIGRAPHIC NOMENCLATURE FOR MINNESOTA

by

John H. Mossler

ABSTRACT

Significant changes are made in stratigraphic nomenclature for the Paleozoic formations of Minnesota that reflect subsurface data acquired since 1969 and accord with changes in nomenclature in adjoining states.

For the Cambrian section, dolostone that intertongues with the lower part of the Eau Claire Formation in the subsurface of south-central and southwestern Minnesota is interpreted to be a tongue of the Bonneterre Formation of northwestern Iowa. The Reno Member of the Franconia Formation, together with the Birkmose Member, is now interpreted to compose most of the formation, whereas the Tomah Member is now interpreted to have very restricted subsurface distribution; an additional dolostone member, here informally named the Davis, is recognized in the subsurface in south-central Minnesota. The uppermost member of the overlying Jordan Sandstone is here renamed the Coon Valley Member.

For the Ordovician section, the Galena is now elevated to group status. The Cummingsville Formation, Prosser Limestone, and Stewartville Formation--formerly members of the Galena--now correspond in rank with their equivalents in adjoining states.

In the Devonian sequence, formerly classified as entirely Cedar Valley Formation in Minnesota, the recently named Spillville Formation is recognized in the base of the sequence, and the Wapsipinicon Formation is now known to extend into Minnesota from Iowa. The name Cedar Valley is retained for the overlying Devonian rock unit.

STRUCTURAL AND SEDIMENTOLOGICAL FRAMEWORK

The Paleozoic rocks of southeastern Minnesota were deposited in the shallow marine Hollandale embayment (Austin, 1969) that lay between the Transcontinental Arch and Wisconsin Dome and Arch (Fig. 1). These rocks record three of the major shallow marine incursions that crossed the North American continent during Phanerozoic time (Sloss, 1963). The Sauk sequence includes rocks deposited during the first incursion in Late Cambrian and Early Ordovician time (Plate 1). The second major marine incursion, the Tippecanoe, includes all Middle and Late Ordovician strata; in Iowa (Bunker and others, 1985) it also contains Silurian rocks. Overlying Devonian formations are part of the Kaskaskia sequence. The tops of all sequences are characterized by interregional unconformities. These rock sequences are much thinner in Minnesota and represent shorter intervals of time than nearer the margins of the North American continent. Southeastern Minnesota lies near the center of the craton and was one of the last parts of the continent to be flooded during marine transgressions, and significant erosion occurred at the end of each sequence. In Minnesota only lower parts of the Tippecanoe and Kaskaskia sequences are present, and upper parts of the sequences, if ever present, have been stripped away.

Maximum marine inundation of the North American continent occurred during deposition of the Tippecanoe sequence, and it is the only sequence represented in northwestern Minnesota (Plate 1).

Marine and continental sedimentary rocks of Late Cretaceous age overlie Paleozoic rocks along the western margin of the Hollandale embayment in southeastern Minnesota, and questionable Jurassic rocks as well as Late Cretaceous rocks overlie the Paleozoic rocks in northwestern Minnesota. These rocks, which are not shown on Plate 1, are generally shale, siltstone, and minor units of sandstone and carbonate. They are considered to be part of a later sedimentary sequence, the Zuni (Sloss, 1963), that was deposited during Late Mesozoic time by marine incursion from a seaway across the western continental interior. Paleozoic rocks are buried by as much as 350 feet (107 m) of Cretaceous rocks in extreme southwestern parts of the Hollandale embayment in Minnesota; however, Cretaceous rocks, where they are present over Paleozoic rocks, are generally about 50 to 100 feet (15 to 30 m) thick.

Continental glaciation during the Quaternary created thick sequences of outwash and till that covered most earlier geologic features in Minnesota. As a result, most Paleozoic exposures in southeastern Minnesota are along major stream valleys or in the "driftless" area of extreme southeastern Minnesota where glacial deposits are thin and discontinuous or absent (see insert map, Plate 1). In northwestern Minnesota all Paleozoic rocks are covered by a thick layer of Quaternary drift.

The Hollandale embayment extended southward through east-central and southeastern Minnesota and western Wisconsin, across eastern Iowa into the Ozark basin of southern Missouri, and into the ancestral Illinois basin (Bunker and others, 1985) (Fig. 1). The Hollandale embayment followed the trace of predecessor basins formed along the Middle Proterozoic Midcontinent rift system. Minor recurrent movements, such as might be caused by isostatic adjustment along the large-scale faults bounding grabens, basins, and horsts of the Proterozoic rift system, are responsible for development and configuration of the early Paleozoic Hollandale embayment, as well as for the many smaller structures that later developed within it, such as the Twin Cities basin (Fig. 2), numerous small, gently folded synclines and anticlines, and small faults. Differential uplift during Late Proterozoic time is responsible for the irregular distribution of Middle Proterozoic sedimentary rocks beneath the Paleozoic rocks. At the northern end of the Hollandale embayment, Cambrian rocks overlap Middle Proterozoic lava flows, and along the northwestern and northeastern margins of the embayment, Paleozoic rocks directly overlie Archean and Early Proterozoic metamorphic and igneous rocks; gneiss and rocks of the granite group are the rock types most commonly encountered.

During Late Ordovician time, the north-south grain of the Hollandale embayment was disrupted by rising of the northward-trending Northeast Missouri Arch in southern Iowa and the northeast-trending Sangamon Arch across central Illinois (Bunker and others, 1985). Smaller basins such as the east-central Iowa basin, the northern Iowa/southern Minnesota "Galena basin" (Witzke, 1983) and the Twin Cities basin began to form (Fig. 1b). 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), which were deposited on a broad, shallow shelf that bordered the eastern margin of the Williston basin of western North Dakota, overlie poorly known felsic and intermediate intrusions, volcanogenic metasedimentary rocks, and volcanic rocks of Archean age (Ojakangas and others, 1979). Paleozoic rocks of northwestern Minnesota are separated from the Hollandale embayment by the Transcontinental Arch and the Sioux ridge (Fig. 1), which formed passive highlands throughout much of Paleozoic time.

CAMBRIAN SYSTEM

Classification of Cambrian rocks in Minnesota began to develop during the late 1800s in outcrop areas of Minnesota and Wisconsin, and has been undergoing modifications until the present. All Cambrian rocks in the Upper Mississippi region are considered to be Late Cambrian in age, although paleontological evidence for assigning a Late Cambrian age to the lowermost sandstone units generally is lacking. Because classifications of Late Cambrian chronostratigraphic units for North America (Plate 1) are based upon paleontological studies that were carried out from outcrops along the St. Croix and Upper Mississippi River valleys of Minnesota and Wisconsin, local place names are applied to the stage names and series names for Late Cambrian strata (Howell and others, 1944; Berg and others, 1956). Prior to 1956, as exemplified by Stauffer and Thiel's classification (1941) (see Fig. 3, col. 2), the Cambrian stratigraphic column was subdivided mainly on the basis of faunal zones (trilobites), a system of limited usefulness to everyone but paleontologists. In 1956 a new classification was proposed that adhered to the then new system of dual nomenclature, in which lithostratigraphic and biostratigraphic units are independent (Berg and others, 1956) (see Fig. 3, col. 3). It is this classification that has been used with minor modifications up to present (Fig. 3, col. 4).

Most lithostratigraphic descriptions of Cambrian formations in this report, with the exception of the Jordan Sandstone, are based upon core descriptions. Exposures of most of the units, especially the lowest ones, are small and commonly incomplete. Therefore most reference sections for the Cambrian in this report are cores stored at public repositories.

Mt. Simon Sandstone

The Mt. Simon Sandstone was named for Mt. Simon, an escarpment in the city of Eau Claire, Wisconsin (Ulrich, in Walcott, 1914, p. 354). The type section consists of 234 feet (71 m) of coarse-grained sandstone over Precambrian granite and under fine-grained sandstone of the Eau Claire Formation. The Mt. Simon is the most extensive formation in the Hollandale embayment (Mossler, 1983, pl. 7), but in eastern and southeastern Minnesota it is the most poorly exposed. There are a few exposures in the upper reaches of the St. Croix River in Pine County (Nelson, 1949; Morey and others, 1981), but they are not very representative of the formation. Cores (Table 1 and Fig. 2) provide more represen-

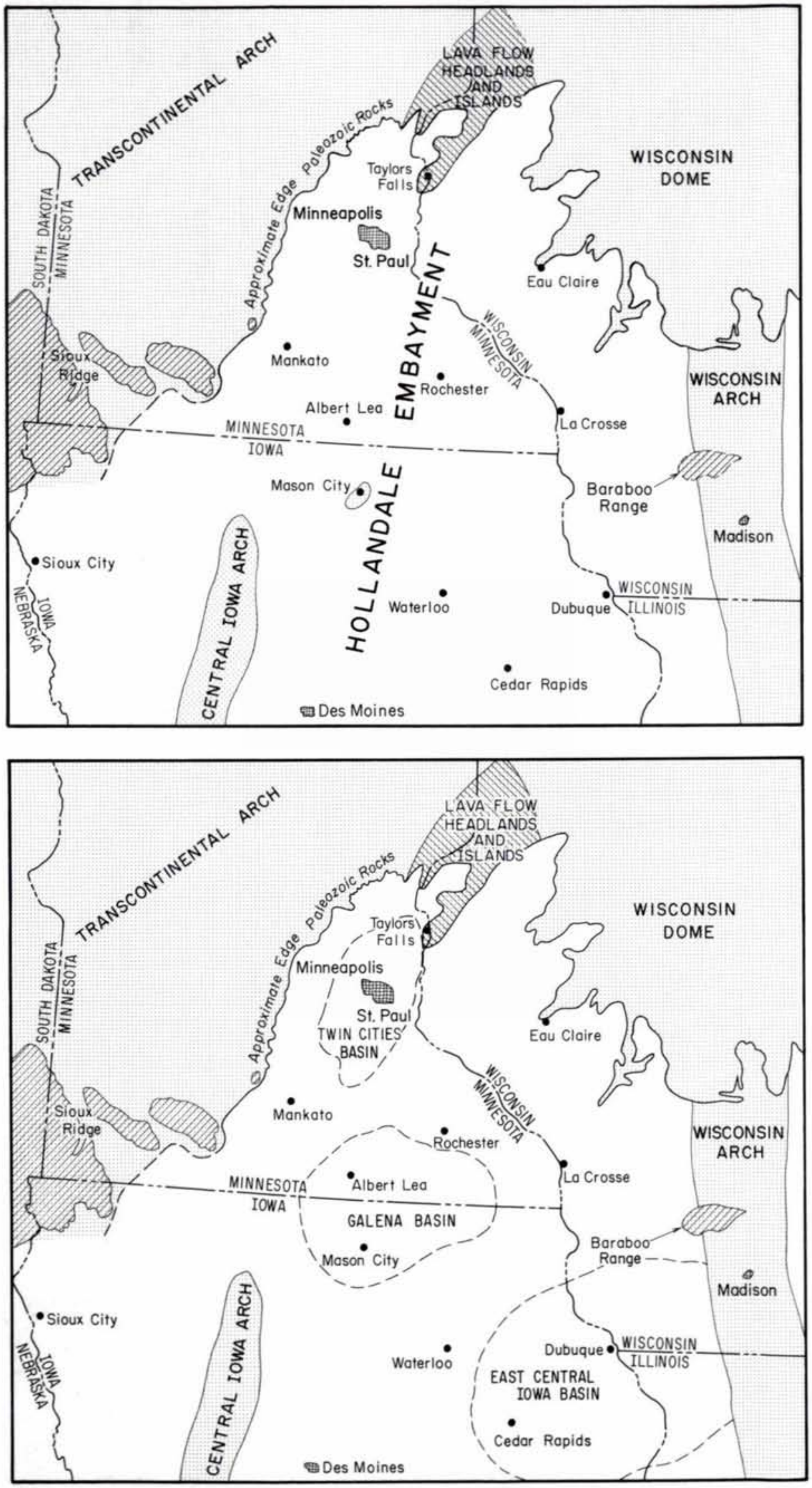

Figure 1. Paleogeography of southeastern Minnesota during Early Paleozoic time. Positive areas are stippled.
(A) Sauk sequence (Upper Cambrian - Lower Ordovician)
(B) Tippecanoe sequence (Upper Ordovician)

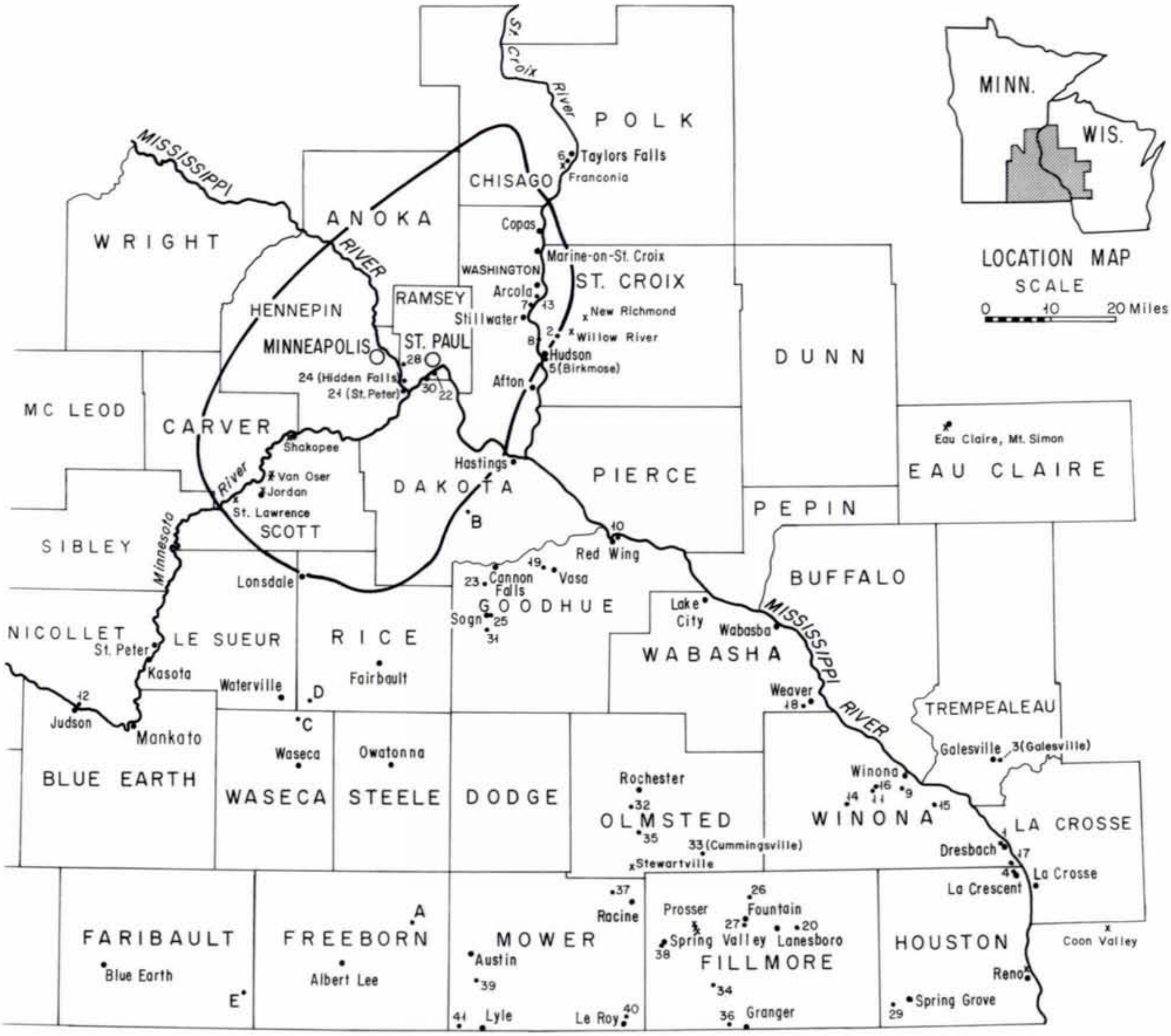

Figure 2. General study area map for southeastern Minnesota. Outcrop localities mentioned in text are numbered. Lettered localities are well cores listed in Table 1. Type sections for certain Paleozoic stratigraphic units mentioned in text are shown; names of units are written out. Limit of Twin Cities basin also is shown.

tative examples of Mt. Simon Sandstone, and the following lithologic descriptions are based upon them. The formation is thickest in extreme southeastern Minnesota where it attains 360 to 375 feet (110 to 114 m). It is thinnest in the extreme southwestern part of the subcrop belt near the Sioux Quartzite ridge (less than 25 feet (<7.6 m) and in east-central Minnesota along the upper St. Croix River over the Middle Proterozoic St. Croix horst where it is absent in places because of nondeposition. In the Twin Cities area it is about 200 feet (61 m) thick. The formation lies with profound unconformity over Archean and Lower and Middle Proterozoic rocks, and some thickness variations in the Mt. Simon are due to relief on the contact. A thin regolith has been observed beneath the Mt. Simon where it overlies Lower Proterozoic granitic rocks (Morey, 1972b).

The Mt. Simon is composed of light-brown to pale-yellowish-brown to grayish-orange-pink, silty, fine- to coarse-grained sandstone with some thin beds of very fine to fine sandstone and minor pale-reddish-brown and greenish-gray shale. The sandstone generally is poorly to moderately sorted, although the very fine to fine-grained beds are well sorted.

The lower third to half of the formation contains thin layers with granules and pebbles of quartz. Rip-up clasts of shale also are present. Thin, very fine to fine-grained sandstone beds are most common in the upper part of the Mt. Simon.

Detrital feldspar is relatively common in the medium- to coarse-grained basal Mt. Simon and is one of the attributes that can be used to distinguish Mt. Simon Sandstone from the underlying Middle Proterozoic Hinckley Sandstone, which is typically nearly pure orthoquartzite. Other distinguishing attributes listed by Morey (1977) are:
(1) There are abundant quartz overgrowths in the Hinckley; the Mt. Simon is friable or only loosely cemented.
(2) Some red or green laminated shale beds occur in basal Mt. Simon.
(3) Clay minerals in the Mt. Simon are illite and montmorillonite; the Hinckley's clay fraction is dominated by kaolinite.

Table 1. Representative cores in Upper Cambrian formations, southeastern Minnesota [Letters refer to location designation on Figure 2; *, only part of geologic formation was cored; +, core loss, incomplete recovery.]

Well name, location, repository	Formations cored (gross interval in feet, measured from land surface)				
(DNR)=Dept. Natural Resources, Hibbing (MGS)=Minnesota Geological Survey	St. Lawrence	Franconia	Ironton & Galesville	Eau Claire	Mt. Simon
(A) Northern Natural Gas Co. Hollandale 1A SE1/4SE1/4SW1/4 sec. 7, T. 103 N., R. 19 W., Freeborn Co. (DNR)	1005-1047 *	1047-1200	1200-1240	1240-1437	1437-1619
(B) Northern Natural Gas Co. Hampton 65-1 SW1/4NW1/4NW1/4 sec. 4, T. 113 N. R. 18 W., Dakota Co. (DNR)	NONE	41-537 *	537-587	587-683	683-916
(C) Minnegasco L. Williams 4 NW1/4SW1/4NE1/4 sec. 7, T. 108 N. R. 22 W., Waseca Co. (MGS)	NONE	64-760	760-800 +	800-937	937-954 *
(D) Minnegasco Melstrom 1 SW1/4SE1/4SW1/4 sec. 28, T. 109 N. R. 22 W., Rice Co. (DNR)	NONE	NONE	NONE	824-903	903-1128 *+
(E) Minnegasco J. Kingstrom 1 NE1/4NW1/4NW1/4 sec. 6, T. 101 N. R. 24 W., Faribault Co. (MGS)	650-739	739-867	867-917	917-1167	1167-1363

The contact with the overlying Eau Claire Formation is clear and is marked by a change from the predominantly medium- to coarse-grained sandstone of the Mt. Simon to very fine grained sandstone and siltstone or shale. Ferroan ooids (and very rare ferroan oncolites in the southwestern part of the area) are locally present near the top of the Mt. Simon. The top few feet of the Mt. Simon are the most fossiliferous; the top 15 to 60 feet (4.6 to 18 m) commonly contains abundant phosphatic brachiopod valves. Abundant trace fossils are observed throughout the upper half of the formation in cores. The most commonly observed trace fossil is Skolithos, which occurs in massive, structureless, fine- to coarse-grained sandstone that commonly has bimodal size grade distributions. Associated very fine to fine-grained sandstone units are coarsely interlayered with shale or have fine horizontal stratification or ripple cross-stratification.

Medium- to coarse-grained sandstone in the lower part of the formation is commonly cross-bedded. These sandstone beds generally are part of fining-upward sequences that have basal conglomerate or granular sandstone overlying scoured surfaces, and are capped by thin, finely laminated, very fine grained sandstone and shale.

The gamma curve of the basal Mt. Simon typically is fairly low. No significant change is observed between the Mt. Simon and Hinckley (Plate 1). If the Mt. Simon directly overlies beds of the Middle Proterozoic Solor Church or Fond du Lac Formations, there is a sharp increase in the gamma reading below the contact, because of an increase in shale content. Gamma readings in the upper part of the Mt. Simon are slightly higher than in the lower, and the presence of many thin beds of very fine grained feldspathic sandstone and shale gives rise to many sharp inflections on the gamma chart toward higher readings (to the right on Plate 1). The contact with shale and feldspathic sandstone of the Eau Claire is marked by a sharp increase in gamma readings, and this contact is one of the easier to pick on gamma curves.

Eau Claire Formation

The Eau Claire Formation is named for Eau Claire, Wisconsin (Ulrich, in Walcott, 1914, p. 354), where the type section consists of 100 feet (30 m) of thin-bedded, partly shaly, fossiliferous, fine-grained sandstone.

Although it is laterally the second most extensive Paleozoic formation in southeastern Minnesota (Mossler, 1983, pl. 6), outcrops are very scarce. A few occur in the upper St. Croix valley north of Taylors Falls (Nelson, 1949), but these are generally on private land or difficult of access. In southeastern Minnesota, a small outcrop of very fine grained, glauconitic sandstone occurs in the village of Dresbach (SE1/4 NE1/4 sec. 18, T. 105 N., R. 4 W., Winona County) in the Mississippi valley south of Winona (Fig. 2, loc. 1). The best outcrop near Minnesota is by the Little Falls State Park dam in the NE1/4 sec. 8, T. 29 N., R. 19 W., St. Croix County, Wisconsin, just east of Hudson, where about 70 feet (21 m) of very fine sandstone and siltstone are exposed (Nelson, 1949) (Fig. 2, loc. 2). Several cores which penetrate Eau Claire are available at repositories (Table 1).

The formation is thickest in south-central Minnesota (Faribault County) where it is more than 250 feet (76 m) thick; throughout most of southeastern Minnesota it is generally about 80 to 90 feet (24 to 27 m) thick. It thins to a feather edge by Taylors Falls in northern Chisago County where it onlaps Middle Proterozoic basalt.

In Minnesota the Eau Claire is divided informally into six beds that form lithofacies within the formation (Plate 1). In south-central Minnesota (Faribault County) and to the west, the basal bed is composed of pale-red to grayish-red shale with abundant thin brachiopod coquinas. Toward the east and north, this unit coarsens into red siltstone and very fine to fine-grained sandstone that in places contains ferruginous ooids. This "red unit" is absent throughout most of the Twin Cities basin (except the extreme southwestern edge) and also is missing along the Mississippi River.

In Faribault and Jackson Counties, in southwestern Minnesota, the "red unit" is overlain by fossiliferous, sandy, pale-olive-gray dolostone with pale-red shale partings. This unit, the "dolostone unit," becomes progressively more dolomitic toward the west, and toward the east appears to merge with the "red unit." In northwestern Iowa, carbonate rocks in this interval are referred to the Bonneterre Formation (Adler, 1986), and this unit is considered to be a tongue of the Bonneterre, particularly in its Jackson County occurrence, where it is nonargillaceous dolostone.

Nonglauconitic very fine to fine-grained sandstone, siltstone, and greenish-gray shale of the "sand-shale unit" overlie the "dolostone unit" and the "red unit" where they are present and form the base of the Eau Claire where they are absent. This unit is characterized by alternating very thin layers of shale and finely laminated sandstone.

Very fine to fine-grained, light-olive-gray, glauconitic sandstone and siltstone and minor grayish-green shale of the "greensand unit" occupy the middle part of the formation. This unit is thickest in south-central Minnesota (Faribault County) where it is 95 feet (29 m) thick versus 20 to 35 feet (6 to 10.7 m) in extreme southeastern Minnesota (Fillmore and Winona Counties). This unit is cross-bedded and ripple cross-laminated in the southwest; to the north and east

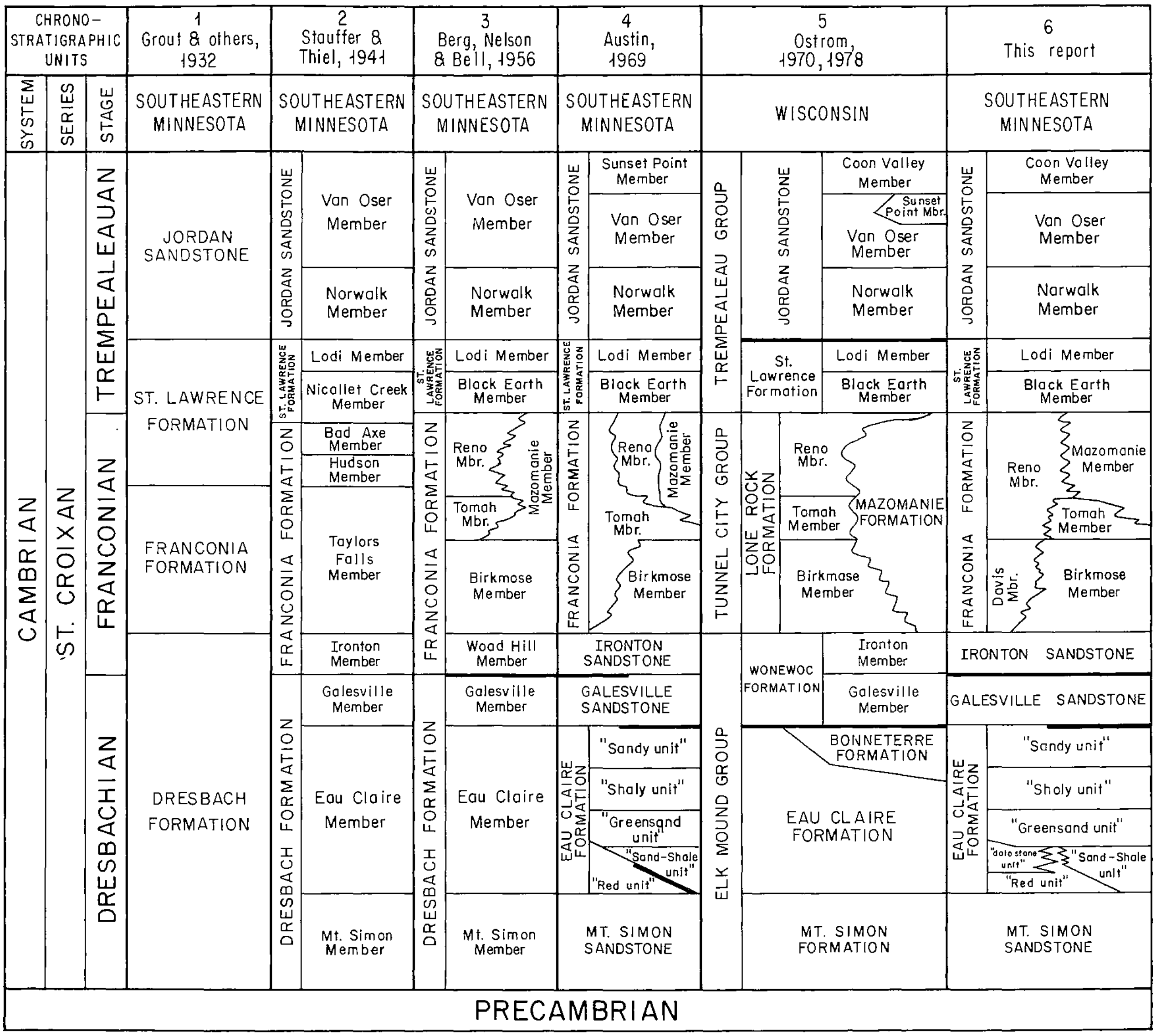

Figure 3. Upper Cambrian stratigraphic nomenclature. Column 5: Nomenclature currently used by the Wisconsin Geological and Natural History Survey. Heavier lines denote interpreted unconformities.

it generally is finely laminated to massively bedded.

The fifth unit is the "shaly unit." It is composed of siltstone and very fine grained, slightly glauconitic sandstone and grayish-green shale. Shale and sandstone beds generally alternate in wavy to lenticular beds or are coarsely interlayered. The thickest shale bed observed in cores is more than 8 feet (2.4 m) thick. This unit is best developed in Rice and Waseca Counties and in the Twin Cities basin.

The uppermost "sandy unit" is composed of very fine to fine-grained, light-gray to yellowish-gray sandstone and minor grayish-green shale. It is generally finely laminated, ripple cross-laminated, or wavy bedded.

The Eau Claire is the most fossiliferous unit of the Dresbachian Stage and contains abundant inarticulate brachiopods and worm burrows in addition to trilobites. It is characterized by the Crepicephalus zone which continues into the basal Galesville Sandstone at Dresbach and La Crescent (Berg and others, 1956). However, the basal Eau Claire at a few localities in western Wisconsin reportedly contains Cedaria zone trilobites, and Aphelaspis zone trilobites were found in rocks at Hudson, Wisconsin (Berg and others, 1956), and in well cuttings at Waconia (Stauffer and others, 1939).

The upper contact of the Eau Claire with the Galesville is at the change from very fine to fine-grained sandstone of the Eau Claire to fine- to medium-grained sandstone of the Galesville. There also is a decrease in shaly partings and siltstone at the top of the Eau Claire. The contact of the Eau Claire and Galesville in Minnesota generally appears to be conformable, although in western Wisconsin (Ostrom, 1970) the contact is an erosional unconformity with significant relief. However in Minnesota the contact is not exposed; it is known only from cores, and therefore exact relationships are obscure.

The gamma curve for the Eau Claire is one of the more distinctive in the Cambrian section. There generally are strong deflections in the curve at the top and base (Plate 1), and the medial "shaly unit" has high gamma readings.

Galesville Sandstone

The Galesville Sandstone (Trowbridge and Atwater, 1934, p. 45) is named for Galesville, Wisconsin (NE1/4NW1/4 sec. 33, T. 19 N., R. 8 W., Trempealeau County), where 88 feet (27 m) of fine- to coarse-grained sandstone of the formation overlies siltstone and very fine grained sandstone of the Eau Claire and underlies poorly sorted, silty, medium- and coarse-grained sandstone of the overlying Ironton Sandstone (Emrich, 1966). The type section, in a city park, is one of the better places to see the formation in outcrop (Fig. 2, loc. 3). The formation is also exposed at a few places in the lower St. Croix valley near Hudson, Wisconsin (Nelson, 1949). There are numerous exposures in highway roadcuts between Winona and La Crescent in the Mississippi valley, although none includes the lower part of the formation or basal contact. The Galesville is also represented in several cores (Table 1; Fig. 2).

The Galesville Sandstone is an extensive formation in the subsurface (Mossler, 1983, pl. 5). It ranges from less than 20 to nearly 70 feet (<6 to 21 m) in thickness in cores from southeastern Minnesota and is thickest in extreme southeastern Minnesota. The Galesville is fine to medium grained, quartzose, well sorted, light gray, and friable. It generally is cross-bedded, but may be massive or have fine horizontal lamination. Commonly it contains very thin layers of black, phosphatic brachiopod shell fragments parallel to bedding.

It generally is easy to distinguish the Galesville from the underlying Eau Claire because of the change from fine- to medium-grained sandstone in the Galesville to very fine grained sandstone and siltstone with interbedded shale in the upper Eau Claire.

The upper contact is more difficult to identify because it is a sandstone-on-sandstone contact. In most cores and outcrops this contact can be identified by the better sorting and finer grain size of the Galesville. However, during drilling, especially rotary drilling, the two sandstones become mixed in samples; because they are very friable and tend to disaggregate, lithologic distinctions are obscured and the contact is hard to identify. Observation of this contact in some of the cores that contain it provides some evidence--intraclasts in basal Ironton, and iron encrustation and slight erosional relief on the Galesville--for at least a slight break or discontinuity in sedimentation at the base of the Ironton. In a study of these formations in the subsurface of Illinois, Emrich (1966) observed what he thought was considerable relief on the Ironton/Galesville contact, although he conceded that some of the apparent relief may be due to facies changes. In Wisconsin the Ironton and Galesville Sandstones are combined into a single formation named the Wonewoc (Ostrom, 1970) (see Fig. 3, col. 5) because of the difficulty of distinguishing the two units in the subsurface, and because the contact between them in Wisconsin is indistinct and probably conformable, in contrast to the demonstrably disconformable contact with the Eau Claire (Ostrom, 1978).

Ostrom (1966 and pers. comm.) thinks that possibly the entire Galesville may lie within the Franconian Stage, there being an absence of definitive fossil evidence to the contrary. Although zone fossils for the Dresbachian Aphelaspis zone are found in the uppermost Eau Claire (Nelson, 1951), and fossils representative of the Franconian Elvinia zone are found in the uppermost Ironton (Berg, 1954; Emrich, 1966), no zone fossils have been found in the Galesville. The late Dresbachian Dunderbergia zone is missing in the Upper Mississippi valley (Lochman-Balk, 1970), and that indicates marine regression and possibly subaerial exposure. Subaerial exposure along the Wisconsin Arch is supported by evidence that the Galesville of central Wisconsin is eolian (Dott and others, 1986). In the absence of definite paleontological evidence for the age of the Galesville, the Minnesota Geological Survey prefers to continue to classify the Ironton and Galesville as separate formations.

On gamma logs the Ironton and Galesville form a broad interval of low gamma readings between intervals of much higher natural gamma radiation from the Eau Claire and Franconia Formations. The deflections or shoulders at the contacts (Franconia/Ironton and Galesville/Eau Claire) are sharp and well defined (Plate 1). The basal deflection between the Galesville and Eau Claire is somewhat gentler than the upper one between the Franconia and Ironton, because the Galesville becomes progressively finer grained and more feldspathic (K-feldspar) toward its basal contact (Woodward, 1984).

Ironton Sandstone

As originally defined (Berkey, 1897), the Franconia Formation in Minnesota included a "compact and thick bedded" sandstone at the base, probably because this basal sandstone had a fauna similar to that in lithically different overlying material. Thwaites (1923, p. 550) proposed that the few feet of hard, calcareous, coarse-grained sandstone at the base of the Franconia Formation be named the Ironton Member, and he designated a type section at Ironton in Sauk County, south-central Wisconsin. The name "Woodhill" was proposed for this unit by Berg (1954) (Fig. 3), because he thought that the name "Ironton" had become a synonym for the biostratigraphic Elvinia zone; however "Ironton" is well entrenched and most stratigraphers have returned to that name (Fig. 3) for the rock unit.

The Ironton Sandstone is widely distributed in the subsurface in southeastern Minnesota (Mossler, 1983, pl. 5), although outcrops generally are limited to the Mississippi valley and lower reaches of tributaries from south of the city of Wabasha to central Houston County. There are a few partial exposures in the St. Croix valley near Hudson, Wisconsin, and near Taylors Falls (Nelson, 1949; Berg, 1954). The formation can be seen in outcrop on U.S. Highway 61 just north of La Crescent in Houston County (SE1/4 sec. 3, T. 104 N., R. 4 W.) (Fig. 2, loc. 4). It is also exposed farther north along that highway in numerous outcrops. In the Twin Cities area the best Ironton exposures are along the southeast-trending street leading into Birkmose Park in Hudson, Wisconsin (SW1/4SE1/4NW1/4 sec. 25, T. 29 N., R. 20 W., St. Croix County) (Fig. 2, loc. 5). Both the upper and basal contacts are exposed; see Berg (1954) for additional details. The formation is also accessible in cores (Table 1; Fig 2).

The Ironton Sandstone is thickest in the extreme southeastern corner of Minnesota, reaching a maximum thickness of about 40 feet (12 m) at La Crescent in Houston County. In the subsurface of the Hollandale embayment, it generally is less than 15 feet (4.6 m) thick; however, in Rice County in test cores near Lonsdale it reaches a thickness of 29 to 30 feet (8.5 to 9 m). The Ironton abuts against Middle Proterozoic rocks in the upper St. Croix valley near Taylors Falls, where it is composed of conglomerate that contains basaltic boulders and a unique molluscan fauna, including monoplacophoran species (Webers, 1972). Generally, the Ironton is medium- to coarse-grained, poorly sorted, partly silty, light-gray to yellowish-gray, quartzose sandstone. In places it is slightly glauconitic. Outcrops contain conspicuous fossil fragments including Elvinia zone trilobites and inarticulate brachiopods (Berg, 1954). The formation commonly is burrow mottled and poorly bedded, although some beds are cross-bedded.

As discussed in the previous section, the underlying Galesville Sandstone is more uniformly sorted and generally finer grained than the Ironton (Emrich, 1966); however, because these distinctions usually cannot be carried into the subsurface in well cuttings, the two units are often combined as the "Ironton and Galesville" Sandstones in well-sample descriptions.

Franconia Formation

The Franconia Formation was named by Berkey (1897) for exposures in Franconia Township, Chisago County, where there is 100 feet (30 m) of sandstone and shale. He defined the formation on the basis of biostratigraphy--it originally comprised the Conaspis zone, and included only the lower half of the beds now generally included within the Franconia (see Stauffer and Thiel, 1941, p. 36) (Fig. 3, col. 2). Ulrich (1924) expanded the definition of the Franconia to include many of the beds now included in the upper part, which were assigned at that time to the overlying St. Lawrence Formation. He also included the Ironton Formation as a member, as did Berg (1954) and Berg and others (1956). Berg was responsible for the lithostratigraphic terminology currently applied to the Franconia (Fig. 3, col. 3). Unlike earlier nomenclature, such as that used in Stauffer and Thiel (1941) (Fig. 3, col. 2), which was essentially biostratigraphic, Berg's nomenclature is lithostratigraphic and independent of biostratigraphic implications.

Although most of Berg's nomenclature is still used by the Minnesota Geological Survey for the Franconia, his basal member, the Woodhill Member, has been elevated to formational status and its name changed back to Ironton (see Ironton section). The Franconia is made up of the four other members named by Berg (1954)--the Birkmose, Tomah, Reno, and Mazomanie Members--and a fifth unit recently found in the subsurface at the base of the formation.

The Mazomanie Member is well exposed along U.S. Highway 8, 1 mile south of Taylors Falls (SE1/4 sec. 35 and NW1/4 sec. 36, T. 34 N., R. 19 W., Chisago County) (Fig. 2, loc. 6). It can also be seen at Boom Hollow near Stillwater (SE1/4 sec. 15, T. 30 N., R. 20 W., Washington County) (Fig. 2, loc. 7), as well as at numerous exposures along the St. Croix River near Copas and Marine-on-St. Croix.

The Birkmose Member and the basal Franconia contact with the Ironton is well exposed in and near Hudson (Berg, 1954) (Fig. 2, loc. 5 and 8). Good exposures occur on roadcuts along the street from Wisconsin Highway 35 to Birkmose Park (NE1/4 sec. 25, T. 29 N., R. 20 W., St. Croix County) and on a private road north of town (NW1/4NE1/4 sec. 12, T. 29 N., R. 20 W., St. Croix County). The Tomah Member is also exposed at the first of these Hudson localities.

In southeastern Minnesota one of the more accessible localities showing the Reno Member is the long roadcut at Garvin Hill in the city of Winona (SW1/4 sec. 27 and NW1/4 sec. 34, T. 107 N., R. 7 W., Winona County) (Fig. 2, loc. 9). The type section of the Reno in Houston County is not easily accessible; however numerous other outcrops with partial exposures of the Reno Member and the Birkmose/Ironton contact are present in recent roadcuts, particularly in eastern Winona County and northern Houston County. Long cores of the Franconia also are available; some are listed in Table 1.

Although its subcrop is not as extensive as that of underlying units, the Franconia extends throughout much of southeastern Minnesota (Mossler, 1983, pl. 4). In the outcrop area along the lower St. Croix valley east of the Twin Cities, the Franconia reaches an estimated thickness of 172 feet (52 m) at Hudson-Afton and 177 feet (54 m) at Arcola (Berg, 1954). The formation appears to be fairly uniform throughout much of southern Minnesota, varying between 140 and 165 feet (42.6 and 50.3 m) in thickness; it is somewhat thinner in south-central Minnesota in Faribault County where it is around 115 to 125 feet (35 to 38 m) thick.

The Birkmose Member, the basal member, is highly glauconitic, very fine to fine-grained, greenish-gray feldspathic sandstone. Near the top it contains pale-red dolostone that is glauconitic, contains intraclasts, and commonly is cross-bedded. Birkmose sandstone typically is massive with burrow mottling; burrows are commonly lined or "stuffed" with silt. However some sandstone units are horizontally laminated and there are minor sandstone beds with high-angle cross-stratification. In south-central Minnesota in Freeborn and Faribault Counties, part of the Birkmose is replaced by algal-laminated, intraclastic, glauconitic, yellowish-gray to pale-olive dolostones that are thin bedded and resemble the Davis Formation of northwestern Iowa and Missouri. The Birkmose ranges from about 20 feet (6 m) in thickness at St. Paul to 50 feet (15 m) in Rice and Waseca Counties. It appears to extend throughout south-central and southeastern Minnesota. The contact with the underlying Ironton Sandstone is sharp; in some places intraclasts occur along the contact, but the contact is not unconformable, merely diastemic. The contact is placed just above the highest essentially nonglauconitic, medium-grained sandstone of the Ironton and just below the fine-grained glauconitic sandstone of the Birkmose. The Birkmose fauna is characterized by trilobites of the Elvinia zone (Berg, 1954).

The Tomah Member is feldspathic, light-brownish-gray siltstone and very fine grained sandstone that is interbedded with very thin beds of greenish-gray, very micaceous shale. Glauconite where present is in very slight amounts. The sandstone beds commonly are cross-laminated and contain flasers (James, 1977). With the exception of the Mazomanie Member, the Tomah appears to be the most areally restricted member in Minnesota and is observed mainly in outcrops along the Mississippi and lower St. Croix Rivers (Berg, 1954) and in the subsurface in the Twin Cities basin. It is 27 feet (8.2 m) thick at Hudson, Wisconsin (Berg, 1954) and 23 feet (7 m) thick in the subsurface beneath the Twin Cities. The contact with the underlying Birkmose Member is sharp; the contact with the overlying Reno is gradational and generally indistinct (James, 1977). The Tomah contains well-preserved fossils in nearly all outcrops (Berg, 1954), and trilobite species of the Conaspis zone occur as molds in most areas.

The Reno Member is glauconitic, commonly bioturbated, very fine to fine-grained, light-olive-gray to greenish-gray, feldspathic sandstone with minor siltstone and shale. Bioturbated beds are massive and contain irregular burrows packed with gray siltstone. Coarsely interlayered units of sandstone and siltstone, finely horizontally laminated and ripple cross-laminated sandstone beds, and high- and low-angle cross-bedded sandstones are present, in addition to the massive bioturbated units. Silty or shaly beds commonly contain lenticles of fine sandstone that apparently are starved ripples. The Reno is subdivided into several fossil zones on the basis of trilobites, which are found only in the laminated beds (Berg, 1954). Oscillation ripple marks and mud cracks 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 and are most common in the upper third to half of the member. The top of the Reno is characterized by a siltstone flat-pebble conglomerate with matrix of glauconitic sandy dolomite that ranges from 6 inches to 6 feet (15 cm to 1.8 m) in thickness in outcrop and is thickest in extreme southeastern Minnesota (Houston County). Core samples indicate that it also is widely distributed in the subsurface where it is as much as 10 feet (3 m) thick. The presence of this unit helps to distinguish the Reno Member from overlying beds of the St. Lawrence Formation.

The Reno and Birkmose appear to be the two principal members of the Franconia in the subsurface of southeastern Minnesota. Austin (1969) considered most of the Franconia in the subsurface of the Hollandale embayment to be the Tomah Member, on the basis of study of core from the Hollandale 1 test well in Freeborn County. However, cores distributed throughout the Hollandale embayment, which have become available since his study, do not support this conclusion. Cored intervals of Franconia overlying Birkmose Member sandstone do not have lithic attributes (high mica content, little or no glauconite, coarsely interlayered shale and sandstone) that are characteristic of the Tomah Member. These intervals have the previously mentioned lithic features typical of Reno greensand, and therefore the Reno is 100 to 110 feet (30 to 33.5 m) thick in the subsurface of southern Minnesota.

An 8-foot (2.4 m) dolostone unit above the Birkmose Member in the Hollandale well (Austin, 1970) resembles the Davis Formation of Missouri, a unit which extends into northwestern Iowa and has been traced into Illinois (Adler, 1986). In Illinois it is described as sandy, argillaceous dolostone with green, gray or red shale partings and flat-pebble conglomerates (Willman and others, 1975). In Faribault County this dolostone unit is the principal rock type in the basal Franconia and is as much as 20 feet (6 m) thick.

In Minnesota the Mazomanie Member interfingers with Reno Member sandstone in outcrops along the St. Croix River as thin-bedded, essentially nonglauconitic (less than 5 percent), dolomitic, very fine to fine-grained, light-gray to yellowish-gray sandstone that resembles the Tomah Member except for absence of shale (Berg, 1954). The Mazomanie occurs mostly in the region north and east of the Twin Cities. In central Wisconsin the Mazomanie sandstone coarsens, is cross-bedded and is the principal lithostratigraphic unit in the Franconian stage. It is given separate, formational status there (Fig. 3, col. 5). The Mazomanie rarely contains body fossils; most of the trilobites that Berg (1954) found in Mazomanie sandstone occurred in case-hardened boulders. However, trace fossils, particularly _Skolithos_, are common in the thin-bedded sandstones of the St. Croix valley. _Skolithos_ are also present in upper Reno sandstones (James, 1977). Some beds in the Mazomanie in Minnesota are cross-bedded or ripple cross-laminated and may contain flasers and intraclasts. The Mazomanie reaches a maximum thickness of 115 feet (35 m) in east-central Minnesota and thins rapidly to a featheredge toward the south.

The Franconia Formation has fairly high gamma log readings (Plate 1) because of its high content of potassium feldspar and glauconite. However, the overlying St. Lawrence Formation also has a high content of potassium-rich minerals, and as a result, the St. Lawrence/Franconia contact generally cannot be distinguished with any confidence on gamma logs. The Ironton/Franconia contact forms a sharp deflection because of the lower potassium feldspar content in the Ironton Sandstone. The Birkmose Member of the Franconia can also commonly be picked up on gamma logs, because the dolostone beds at the top of the Birkmose characteristically have much lower readings than the rest of the Franconia.

St. Lawrence Formation

The St. Lawrence Formation includes the siltstone and dolostone between the underlying glauconitic, feldspathic, and quartzitic sandstone of the Franconia and the overlying quartzitic to feldspathic sandstone of the Jordan. The St. Lawrence was named for St. Lawrence Township in Scott County, Minnesota, by N.H. Winchell (1874). Development of the nomenclature was summarized by Nelson (1956) who is responsible for the present Minnesota nomenclature. The St. Lawrence is currently divided into the basal Black Earth Member, which is primarily dolostone, and the overlying Lodi Member, primarily siltstone, with which the Black Earth Member intertongues. Both members are named for localities in Wisconsin (see Nelson, 1956). Earlier classifications of the Cambrian of Minnesota by the state survey (Fig. 3, cols. 1 and 2) placed sandstone now classified as part of the Franconia in the basal St. Lawrence. Therefore Nicollet Creek (Stauffer and Thiel, 1941) (see Fig. 3, col. 2) is no longer used as a member name in Minnesota (Nelson, 1956), because by definition it included sandstone beds at the top of the Franconia. McGannon (1960), although he never formally published his proposals for revising St. Lawrence nomenclature, pointed out several problems with Nelson's interpretation of the formation. Among McGannon's proposals was one that would have shifted the dolostone beds of the Black Earth Member into the Franconia Formation.

The St. Lawrence is widespread throughout southern Minnesota where it has a distribution that closely coincides with that of the underlying Franconia Formation (Mossler, 1983, pl. 4). It attains 90 feet (27 m) in thickness in cores in Faribault County in south-central Minnesota. It is thinnest in outcrops in the St. Croix valley in east-central Minnesota where it ranges from 27 to 37 feet (8.2 to 11.3 m) in thickness (McGannon, 1960). The lithology also changes toward the northeast. The St. Lawrence is most dolomitic in the southwest and least in the northeast (Berg and others, 1956). Much of the St. Lawrence that crops out in the St. Croix and Mississippi River valleys is the siltstone facies. This facies is best seen in Barn Bluff at Red Wing (NW1/4NW1/4 sec. 29, T. 113 N., R. 14 W., Goodhue County; Fig. 2, loc. 10) and in several exposures between Winona and Lewiston on U.S. Highway 14 (the best outcrop is a hillside in N1/2SE1/4 sec. 35, T. 107 N., R. 8 W., Winona County; Fig. 2, loc. 11). The more dolomitic facies is not as widely exposed; one of the best exposures is near Judson in the Minnesota River valley (along Swan Lake outlet in SW1/4NE1/4 sec. 33, T. 109 N., R. 28 W., Nicollet County; Fig. 2, loc. 12). Reference sections are also available in cores (Table 1).

The lower member of the St. Lawrence, the Black Earth Member, is composed of glauconitic, argillaceous, silty or sandy dolostone; dolomite content generally exceeds 70 percent (Austin, 1969). The dolomite is light olive gray to yellowish gray; it is vuggy and generally contains intraclasts and thin interbedded layers of siltstone and olive-gray shale. It is commonly medium bedded to massive; some beds are finely laminated. The basal contact is generally well defined; it occurs at the lithologic change from dolostone of the Black Earth to very fine grained glauconitic sandstone of the underlying Reno Member of the Franconia. A widespread, prominent bed of flat-pebble conglomerate generally is present at the top of the Reno Member. Intertonguing dolostone and siltstone beds complicate identification of the Black Earth contact with overlying Lodi siltstone (Nelson, 1956), and it is sometimes necessary to be arbitrary in picking the contact.

Where Lodi siltstone directly overlies fine- to medium-grained sandstones of the Mazomanie or Reno Members of the Franconia, as it does in the St. Croix River valley, the basal contact is generally distinguishable on the basis of grain-size differences (Nelson, 1956; McGannon, 1960) because there are only a few very thin beds of fine-grained, silty sandstone in the basal St. Lawrence. The Lodi Member is composed of light-gray to yellowish-gray and pale-yellowish-green, dolomitic siltstone with minor silty shale and dolostone. The siltstone is sandy or slightly glauconitic in places. There are many intraclast layers, particularly in more dolomitic intervals. Some beds are finely laminated or ripple cross-laminated, and starved ripples of very fine grained sandstone occur as lenticles within some siltstones. Other siltstone beds are massive and some are burrow mottled. The Lodi Member generally has a thin-bedded appearance in outcrop. Trilobites of the Saukia zone dominate the St. Lawrence fauna (see Nelson, 1956); inarticulate brachiopods and dendritic graptolites make up the rest of the fauna (Webers, 1972).

Although the Lodi and Black Earth Members can usually be distinguished in well cores and cuttings on the basis of their compositional differences, these members cannot be distinguished on gamma logs, nor can the St. Lawrence/Franconia contact be distinguished solely on the basis of gamma logging. The Jordan/St. Lawrence contact, however, can be distinguished because of a relatively strong positive deflection at the top of the St. Lawrence (Plate 1).

Jordan Sandstone

The Jordan Sandstone was named for the city of Jordan in Scott County, Minnesota, where it first was named and described by N.H. Winchell (1874) from outcrops in streambanks and quarries. The formation is divided into three members--the basal Norwalk, medial Van Oser and upper Coon Valley Members. The Norwalk (Ulrich, 1924) and Coon Valley (Odom and Ostrom, 1978) Members are named for localities in Wisconsin. The Van Oser Member is named for outcrops along Van Oser Creek, a tributary of Sand Creek in Scott County, Minnesota (Winchell, 1874).

The Jordan Sandstone reaches a maximum thickness of 115 feet (35 m) in the Twin Cities basin. It is thinnest in south-central Minnesota along the Iowa border, where it is around 50 feet (15 m) thick. The Jordan is widespread throughout southern Minnesota (Mossler, 1983, pl. 3), and there are outcrops in the region, particularly along the Mississippi, St. Croix, and Minnesota Rivers.

Type sections in the city of Jordan (Fig. 2) are no longer well exposed; however type sections for the Van Oser Member are in good condition (quarry, NW1/4 sec. 4, T. 114 N., R. 23 W., and numerous streambank exposures throughout sec. 32 and S1/2 sec. 29, T. 115 N., R. 23 W., Scott County). Accessible outcrops of Jordan occur along Minnesota Highway 95, north of Stillwater (NW1/4 sec. 14, T. 30 N., R. 20 W., Washington County) (Fig. 2, loc. 13). Good exposures farther southeast are on U.S. Highway 14 in Winona County (NE1/4NW1/4 sec. 8, T. 106 N., R. 8 W.) (Fig. 2, loc. 14) and along a paved county road south of Winona (SW1/4SE1/4 sec. 9, T. 106 N., R. 6 W.) (Fig. 2, loc. 15); there are numerous other outcrops in the tier of counties bordering the Mississippi River.

The basal Norwalk Member is generally silty, very fine to fine-grained, white to light-gray to grayish-orange, feldspathic sandstone that contains some thin grayish-green shale partings. It is commonly massive and burrow mottled, though cross-stratification may be present in the upper part. It has gradational upper and lower contacts in Minnesota. The Norwalk is a nonresistant unit that commonly is covered in natural exposures.

The medial Van Oser Member is fine- to medium- to coarse-grained, supermature (well sorted and well rounded) quartzose sandstone that is generally white to tan but in some places contains grayish-orange to red iron oxide coloration. It commonly is cross-bedded, almost exclusively trough cross-bedded (Dott, 1978); there also is horizontal, planar stratification. Scattered calcite concretions occur in the upper part. Silica cementation, in some places with subhedral to euhedral quartz overgrowths, is common along the Minnesota River valley in the upper Van Oser, particularly where overlying Paleozoic rocks have been stripped off. In Minnesota the upper and lower contacts of the Van Oser are conformable; in contrast, in Wisconsin on the Wisconsin Arch, the Van Oser disconformably overlies the Norwalk Member or the St. Lawrence Formation where the Norwalk is eroded (Odom and Ostrom, 1978). The Van Oser is a resistant unit that forms the lower parts of cliffs in bluffs along the Mississippi River and stands up in roadcuts and other artificial cuts for a long time.

Transitional beds at the top of the Jordan Sandstone formerly were named the Sunset Point Member (Raasch, 1951) for an outcrop near Madison, Wisconsin. Odom and Ostrom (1978) have shown that the Sunset Point type section is a local fine-grained sandstone lens within Van Oser sandstone. They renamed the widespread upper transitional beds of the Jordan Sandstone the Coon Valley Member (Fig. 3, col. 5) for an outcrop near Coon Valley, Vernon County, Wisconsin. The Coon Valley is the most heterogeneous member of the Jordan. It contains buff to tan to brownish-gray, fine- to medium-grained, dolomitic, quartzose sandstone; sandy, cherty, oolitic dolostone; minor stromatolitic (algal mat) dolostone; and minor, very fine grained feldspathic sandstone (Odom and Ostrom, 1978). Some beds contain intraclasts. There are some zones of poikilotopic calcite cement in the sandstone. Thin greenish-gray shale beds occur near the top of the unit in some outcrops along the Mississippi River. The Coon Valley is a thin-bedded resistant unit that has bedding characteristics and color in outcrop resembling the overlying Oneota dolostone. Quartzose sandstone predominates in the basal half to two-thirds of the unit; dolostone is more conspicuous in the upper part (Odom and Ostrom, 1978). The top of the member is drawn at the top of the uppermost conspicuously sandy dolostone; the Coon Valley is gradational with overlying Oneota dolostone. The Jordan has a meager fauna characterized by trilobites of the Saukia zone (Webers, 1972).

Gamma values in the Jordan Sandstone are generally lower than those in underlying St. Lawrence feldspathic siltstone, and the Jordan/St. Lawrence contact typically is marked by a strong deflection on gamma logs (Plate 1). The feldspathic sandstone of the basal Norwalk Member commonly produces slightly higher readings on gamma logs than the overlying Van Oser sandstone (Woodward, 1984). Some broad gamma deflections toward high readings within the Jordan Sandstone interval are probably attributable to fine-grained feldspathic sandstone lenses within the coarser, more quartzitic Van Oser Member that are analogous to the feldspathic Sunset Point Member of Wisconsin (see Odom and Ostrom, 1978).

The upper contact of the Jordan Sandstone with the Oneota Dolomite is commonly difficult to identify on gamma logs in the eastern part of the Hollandale embayment (Woodward, 1984), particularly where the Coon Valley Member occurs, and in the Twin Cities basin. However in the western part of the Hollandale embayment, where the base of the Oneota contains shaly, feldspathic Blue Earth siltstone (Plate 1), there is a strong peak on gamma curves just above the contact.

ORDOVICIAN SYSTEM

Except for minor modifications, Ordovician lithostratigraphic nomenclature for Minnesota remains that of Austin (1969). One modification of Austin's classification is elevation of the Galena to group rank, and its members to formational status (Plate 1). Another is restoration to member status of local members of the Platteville in the Twin Cities basin that Austin had reduced to "submembers." These modifications are discussed in following sections on lithostratigraphic units.

The chronostratigraphic units for the Middle and Upper Ordovician are revised on Plate 1; those for the Lower Ordovician remain unchanged. The revised limits of the Middle and Upper Ordovician chronostratigraphic units are mainly based upon conodont biostratigraphy and several different interpretations that have been put forward in recent years (Sweet and Bergstrom, 1976; Witzke, 1980; Ross and others, 1982). The interpretation used on Plate 1 is based principally upon Sweet's (1984, 1987) graphic correlation of Middle and Upper Ordovician rocks, which in turn was based upon Shaw's (1964) graphic correlation of total stratigraphic ranges of all conodont species for all stratigraphic sections considered. It therefore is much more conceptually absolute and precise and less subjective than earlier attempts at correlation. It must be pointed out that data for graphic correlation were unavailable or insufficient for the upper (Maquoketa Formation) and lower (St. Peter Sandstone) parts of the section in Minnesota (Sweet, 1984, 1987).

Prairie du Chien Group

All Lower Ordovician rocks in Minnesota are included in the Prairie du Chien Group, originally named for exposures near Prairie du Chien, Crawford County, Wisconsin (Bain, 1906, p. 18), where the group consists of 200 to 300 feet (60 to 90 m) of dolomite and sandstone. In Minnesota the Prairie du Chien is separated into two formations which are considered separately.

Oneota Dolomite

The Oneota Dolomite was named by McGee (1891, p. 331-333) for exposures along the Oneota (now Upper Iowa) River in Allamakee County, Iowa. (McGee considered the overlying Shakopee Formation to be part of the St. Peter Sandstone.) In Minnesota, nomenclature for the Oneota and the formation's limits have not changed significantly since its inception. However the position of the basal contact has shifted back and forth because it is gradational with the underlying Jordan Sandstone and therefore subject to reinterpretation. For example, some stratigraphers (Davis, 1970) have proposed placing transitional beds at the top of the Jordan (the Coon Valley Member of present nomenclature) into the Oneota, including them together with the transitional beds in the base of the Oneota as a unit named the Stockton Hill Member (Fig. 4, col. 5).

The Oneota Dolomite has not been subdivided into members in Minnesota as it has in Wisconsin (Raasch, 1952; Davis, 1970); according to Stubblefield (1971), it is difficult if not impossible to trace Raasch's Wisconsin members westward into Minnesota. Two informal units (or beds), the Blue Earth siltstone and Kasota sandstone, which occur at the base of the Oneota along the western margin of the Hollandale embayment, are sedimentologically more akin to the Jordan Sandstone but were originally included in the Oneota because of their Ordovician fossil content (Powell, 1935; Furnish, 1938). In Wisconsin the Jordan Formation crosses the Cambro-Ordovician boundary as that boundary currently is defined in the Midcontinent (Odom and Ostrom, 1978). Recent studies of uppermost Jordan microfossils (conodonts) in Wisconsin by Miller and Melby (1971) indicate conspecific forms in the uppermost Jordan and lower Oneota. Therefore the presence of Ordovician macrofossils in a few feet of coarse-grained quartzose sandstone at the top of the Jordan Sandstone in the Kasota area does

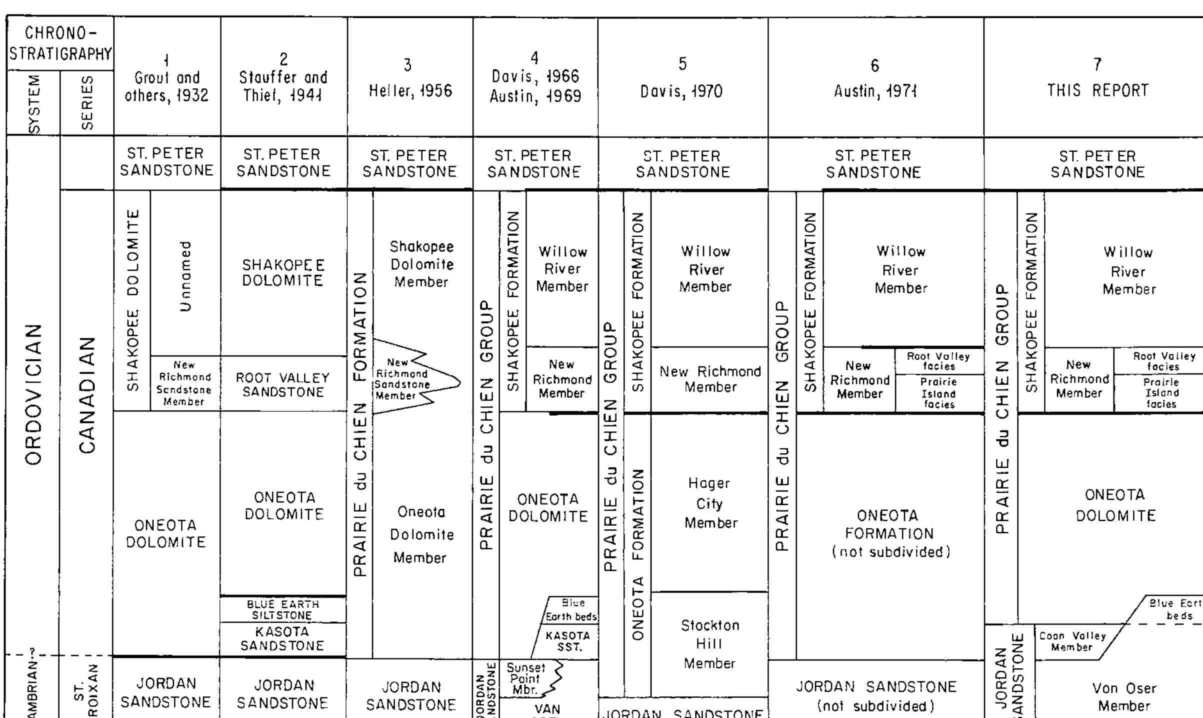

Figure 4. Development of Lower Ordovician stratigraphic nomenclature for southeastern Minnesota. Heavy lines denote interpreted unconformities.

not seem to constitute a valid reason for placing this interval in the Oneota and apparently violates North American Stratigraphic Codes (North American Commission on Stratigraphic Nomenclature, 1983, Articles 24 and 26).

Although continued use of the Kasota sandstone is discouraged, the transitional dolomitic siltstone beds of the Blue Earth seem to correspond with the definition for a key or marker bed. Because the Blue Earth beds can be traced widely in the western Hollandale embayment, particularly on gamma logs, they are useful for lithostratigraphic correlation.

The Oneota Dolomite is present throughout most of southeastern Minnesota south of the northern boundary of the Twin Cities basin, but it is eroded north of the basin (Mossler, 1983, pl. 2B). Maximum thickness of the Oneota is about 170 feet (52 m). It is about 50 feet (15 m) thick around Mankato (Stubblefield, 1971), about 40 feet (12 m) thick near the center of the Twin Cities basin, and about 100 feet (30 m) thick near Winona. Lithologically, the Oneota can be subdivided into three parts: basal transitional beds, the main body, and the upper contact. Most transitional beds between the Oneota and Jordan are currently classified as the Coon Valley Member of the Jordan Sandstone. The greenish-gray, dolomitic, feldspathic Blue Earth siltstone beds are an exception. In southeastern Minnesota (Winona and Houston Counties), the Oneota contains stromatolites--both laterally linked hemispheroids (LLH) and separate vertically stacked hemispheroids (SH)--as well as thin-bedded "fucoidal" dolostone at its base above the conspicuously sandy beds at the top of the Coon Valley.

The main body of the Oneota Dolomite is very fine grained, grayish-orange and pale-orange to pale-yellowish-brown and yellowish-gray dolostone. In outcrop, the formation is commonly composed of very thick to massive beds with very thin beds interspersed among them (Stubblefield, 1971). Dolostone of the overlying Shakopee Formation is commonly uniformly very thin to thinly bedded and the difference in bedding sometimes is useful in distinguishing the two formations in outcrop.

Fossils are scarce in the Oneota and many are dwarfed (Webers, 1972); stromatolites (both LLH and SH, Squillace, 1979) and gastropods are the most common components of the biota. Other components include trilobites, brachiopods, and cephalopods. Though preservational factors caused by intense dolomitization influenced distribution of fossils, the primary factor affecting their distribution may have been an originally inhospitable hypersaline environment (Webers, 1972).

The upper 15 to 20 feet (4 to 6 m) of the Oneota Dolomite in the Winona-Houston County area contains large vugs filled with calcite and with limonite/goethite that is pseudomorphous after iron sulfide. Chert nodules also become more abundant in the upper part of the Oneota both around Winona and near Mankato (Stubblefield, 1971). Some chert nodules are crowded with fossils.

The upper contact of the Oneota is disconformable and is drawn at the first occurrence of typically thin bedded, interbedded dolostone, sandy dolostone, and quartz sandstone of the basal Shakopee above massive, non-sandy, in places stromatolitic dolostone of the Oneota. In the Red Wing/Lake City/St. Paul region the upper few feet of Oneota are brecciated (Austin, 1971). The matrix between clasts typically is sandy and argillaceous dolostone that probably infiltrated down between clasts during deposition of the overlying Shakopee Formation.

There are numerous outcrops of Oneota in Minnesota, particularly along the Mississippi River and lower reaches of its tributaries south of St. Paul. There are also many 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 Oneota is along U.S. Highway 14 on Stockton Hill near Winona (Fig. 2, loc. 16), where Davis (1970) described and named the Stockton Hill Member of the Oneota (SE1/4SE1/4 sec. 25 and NE1/4NE1/4 sec. 36, T. 107 N., R. 8 W., as well as outcrops through the S1/2 sec. 36 and some in the SW1/4NW1/4 sec. 31, T. 107 N., R. 7 W., Winona County). Good exposures of the base of the Oneota occur along a county road north of La Crescent (SE1/4SW1/4 sec. 33, T. 105 N., R. 4 W., Winona County) (Fig. 2, loc. 17). Another good outcrop of Oneota is along County Road 26 near Weaver (S1/2NW1/4 sec. 30, T. 109 N., R. 9 W., Wabasha County) (Fig. 2, loc. 18).

Shakopee Formation

The Shakopee Formation was originally named for isolated outcrops near Shakopee in Scott County (Winchell, 1874, p. 138-139). It contains two members--a lower sandstone member named the New Richmond and an upper dolomitic member named the Willow River (Wooster, 1882, p. 106; Davis, 1966).

The New Richmond Member (Wooster, 1882, p. 106) was named for outcrops near New Richmond in St. Croix County, Wisconsin. This name has long been applied to the medial sandstone of the Prairie du Chien Group, the major exception being Stauffer and Thiel (1941) (Fig. 4, col. 2) who proposed replacing the name with Root Valley Sandstone. They felt the dolomitic sandstone of the New Richmond of the type area simply constituted a sandy phase in the Shakopee Formation, in which sandy beds commonly are observed throughout, whereas the thick quartzose sandstone of the Root Valley was sufficiently well defined and laterally continuous to constitute a separate formation. However, Heller (1956) (Fig. 4, col. 3) concluded that the New Richmond and Root Valley were one and the same, occupying the same stratigraphic position, and recommended supressing the name Root Valley in favor of the earlier name. Significantly, he also expanded the New Richmond to include sandy dolostone he considered to be correlative with the quartzose sandstone that previous authors had named New Richmond. Austin (1971) elaborated upon Heller's work when he studied the Shakopee.

The New Richmond has approximately the same distribution as the underlying Oneota Dolomite and occurs in the Twin Cities basin, and southward in the Hollandale embayment (Mossler, 1983, pl. 2B). One exception is the valley of the St. Croix River where Oneota outcrops are relatively abundant, but New Richmond outcrops are scarce.

The maximum thickness of the New Richmond of slightly more than 56 feet (17 m) is reached near Lanesboro, in Fillmore County; the minimum thickness of slightly less than 13 feet (3.3 m) is found near Shakopee near the northwest edge of the member (Austin, 1971). The member has a lenticular shape with maximum thickness in an area between Red Wing and Lanesboro and subparallel to the Mississippi River (Squillace, 1979). Representative outcrops are the same as those listed for the Willow River Member.

The New Richmond sandstone is composed of two major facies that Austin (1971) informally named the Prairie Island and Root Valley. The Prairie Island facies is thinly bedded, grayish-orange to yellowish-gray and pale-yellowish-brown sandstone and sandy dolostone (Austin, 1971). Some dolostone beds are oolitic, and some contain intraclasts. Locally the sandstone beds contain ripple marks and cross-beds (Squillace, 1979). Carbonate beds commonly contain stromatolites (LLH and SH). There are some thin grayish-green shale beds. Light-gray chert nodules are present, especially in oolitic dolostone beds. The Prairie Island is the more widely distributed of the two major facies of the New Richmond and reaches a maximum thickness of 30 feet (9 m) (Austin, 1971). It disconformably overlies the Oneota.

Typically the Root Valley facies is fine-grained, well-rounded, white to light-gray, quartzose sandstone with well-developed cross-bedding (Austin, 1971). It is locally cemented by quartz to form orthoquartzite. Locally it is stained reddish brown by hematite (Squillace, 1979). There are rare worm burrows, but generally the unit is unfossiliferous. It is restricted in distribution and apparently is entirely absent in the Twin Cities area (Austin, 1971). It attains 40 feet (12 m) in maximum thickness.

The Willow River Member was named by Davis (1966) who resurrected a name originally applied by Wooster (1882, p. 106) for exposures on the Willow River near Burkhardt, St. Croix County, Wisconsin. This member was earlier called the Shakopee Dolomite (Stauffer and Thiel, 1941) or Shakopee Dolomite Member (Heller, 1956) before the name Shakopee was expanded to encompass the New Richmond (Fig. 4).

The Willow River Member is well exposed near Vasa along Minnesota Highway 19 ($W^1/_2$, sec. 16, T. 112 N., R. 16 W. and $E^1/_2$ sec. 17, T. 112 N., R. 16 W., Goodhue County) (Fig. 2, loc. 19) and near Lanesboro on County Highway 8 ($W^1/_2$ sec. 13, T. 103 N., R. 10 W., Fillmore County) (loc. 20). The New Richmond Member also is completely exposed at both localities. Austin (1971) presents complete lithostratigraphic descriptions of these outcrops. The Willow River, like the New Richmond, extends throughout the Twin Cities basin and south from the basin throughout the Hollandale embayment; there are many additional exposures in all southeastern counties, as well as along the Minnesota River Valley near Shakopee and Mankato. In outcrop the Willow River reaches a maximum thickness of about 75 feet (23 m) (Davis, 1966); however in the subsurface it reaches 240 feet (75 m) in thickness (Austin, 1970).

The Willow River Member is lithologically variable, orange to yellowish-gray or gray dolostone that commonly contains oolites or stromatolites (LLH and SH) (Austin, 1971). Mud cracks are common in the upper part of the member, and raindrop craters have been found in exposures 1.5 miles west of Vasa along Minnesota Highway 19 (Fig. 2, loc. 19) in Goodhue County (Sloan, oral comm.). Thin beds of quartzose sandstone are common in the Willow River throughout much of southeastern Minnesota. The sandstone is generally medium grained and may be ripple marked and/or cross-bedded (Davis, 1966). Light-gray chert nodules are present in most Willow River exposures. The Willow River contains greenish-gray and maroon shale partings that range from less than an inch to more than a foot (<2 to >30 cm) in thickness. Like the Oneota Dolomite, it is sparingly fossiliferous, probably because of deposition in hypersaline waters inhospitable to most life forms, though destruction of fossils by dolomitization also played a role (Austin, 1971). A diminutive fauna is found in chert nodules near Stillwater and Cannon Falls (Stauffer, 1937a, 1937b). The Willow River fauna is predominantly molluscan (gastropods and cephalopods) (Webers, 1972).

The upper contact of the Shakopee Formation is unconformable, but because this contact is rarely exposed in Minnesota, it is difficult to demonstrate its nature in outcrops. Subsurface studies in the Twin Cities area indicate there is appreciable relief of as much as 100 feet (30 m) on the contact (Olsen, 1976).

The Shakopee Formation does not have a very distinctive signature on gamma logs; readings are usually fairly low. An exception is the

Shakopee's contact in the Twin Cities basin with the basal argillaceous sandstone of the St. Peter Sandstone, which produces higher readings that provide a marked contrast to the low readings in underlying Shakopee dolostone (Woodward, 1984).

St. Peter Sandstone

The St. Peter Sandstone (Owen, 1847; p. 169-170; also Stauffer and Thiel, 1941, p. 68) was named for the St. Peter's River, now the Minnesota River, of southern Minnesota, where it is mainly white to light-gray, fine- to medium-grained quartzose sandstone. The type section by Fort Snelling in Minneapolis (SE1/4SW1/4 sec. 21, T. 28 N., R. 23 W., Hennepin County) is still comparatively well exposed and is a good place to see the top of the formation (Fig. 2, loc. 21). The St. Peter is also exposed at numerous other places in the Twin Cities, including along Water Street in St. Paul (S1/2SE1/4 sec. 6 and N1/2NW1/4 sec. 7, T. 28 N., R. 22 W., Ramsey County) (Fig. 2, loc. 22). One of the few exposures in Minnesota of the lower part of the formation and its basal contact is on the Cannon River in Goodhue County (SW1/4SW1/4 sec. 25, T. 112 N., R. 18 W.) (Fig. 2, loc. 23). Although the St. Peter crops out in nearly continuous exposures in the center of the Twin Cities basin along the bluffs of the Mississippi River, only small outliers remain in outlying parts of the basin. It occurs throughout most of the Hollandale embayment south of the Twin Cities basin (Mossler, 1983, pl. 2A) and crops out in all the southeastern counties. The St. Peter reaches a maximum thickness of 190 feet (58 m) in a few wells in the northern part of the Twin Cities area. It averages 155 feet (47 m) in thickness in the Twin Cities and thins to the south to about 75 to 80 feet (23 to 24 m) near the border with Iowa.

The St. Peter is white to light-gray, medium- to fine-grained, subrounded to rounded, very quartzose sandstone. The sandstone is very poorly cemented; it is generally massive but has some cross-bedding, mostly trough cross-bedding. Several hundred specimens representing a marine molluscan fauna have been found in the middle third of the formation in St. Paul (Sardeson, 1896), but it generally is unfossiliferous except for trace fossils (*Skolithos*), which are not uncommon; the tops of some massive beds in St. Paul are zones of complete amalgamation (Winfree and others, 1983). Conodonts from the middle third of the St. Peter in St. Paul were identified by Witzke (1980) as Chazyan in age, but later work by Sweet (1984) instead suggests an Ashbyan to lower Blackriveran age for these species.

In the Twin Cities basin, the basal part of the St. Peter Sandstone is a variable interval about 40 to 65 feet (12 to 20 m) thick (Stauffer and Thiel, 1941; Olsen, 1976) of more poorly sorted sandstone interbedded with thin layers of light-greenish-gray and pale-greenish-yellow to pale-red sandy shale and light-gray to pale-red siltstone. Commonly there is a thin siltstone or shale bed at the base of the St. Peter directly over the Shakopee dolostone (Olsen, 1976). The St. Peter Sandstone's basal contact with the Shakopee is unconformable, and a significant hiatus occurs between the two formations (Sloss, 1963; Bergstrom and Morey, 1985). However, residual clay with chert and dolomite fragments, which occurs in the base of the St. Peter Sandstone in Wisconsin and Illinois and is referred to as the Readstown Member (Mai and Dott, 1985), has not been found in Minnesota.

Throughout much of southeastern Minnesota the contact between the overlying shale and sandstone of the Glenwood Formation and the St. Peter is sharp and generally marked by a thin layer of hematite-cemented sandstone (Sloan, 1972). In the Twin Cities basin several feet of clayey sandstone overlying clean well-sorted sandstone at the top of the St. Peter have generally been included in the Glenwood (Stauffer and Thiel, 1941; Austin, 1969). These are discussed in the following section on the Glenwood Formation.

Throughout the Hollandale embayment the top of the St. Peter Sandstone is generally distinguished by a strong deflection in the gamma curve caused by overlying Glenwood shale. Likewise shale and siltstone beds in the basal part of the St. Peter in the Twin Cities basin cause higher gamma readings than recorded in the underlying Shakopee dolostone; however, south of the Twin Cities basin, differences between basal St. Peter and underlying Shakopee are slighter (Woodward, 1984) and the contact is hard to pick from gamma curves.

Glenwood Formation

The Glenwood Formation was named by Calvin (1906, p. 60-61, 74-76) for outcrops in a ravine in Glenwood Township, Winneshiek County, northeastern Iowa. The Glenwood is well exposed at numerous places in the bluffs along the Mississippi River in the Twin Cities area; one of the more accessible places is along the road into Hidden Falls Park (SE1/4SE1/4 sec. 17, T. 28 N., R. 23 W., Ramsey County) (Fig. 2, loc. 24). South of the Twin Cities basin, exceptionally thick development of Glenwood shale is observed near Sogn in Goodhue County (NW1/4SE1/4 sec. 24, T. 111 N., R. 18 W.; described in Sloan and others, 1987) (Fig. 2, loc. 25). Near Fountain cross-bedded sandstone is interbedded with typical Glenwood shale (NE1/4 sec. 15, T. 103 N., R. 11 W. and NE1/4 sec. 27, T. 104 N., R. 11 W., Fillmore County) (Fig. 2, loc. 26 and 27).

Although the Glenwood Formation occurs extensively in the subsurface in southeastern Minnesota south of the Twin Cities basin, it generally does not show up in well cuttings, probably because sampling intervals for cuttings are generally coarser than the thickness of the formation. The Glenwood ranges in thickness from 3 to 4 feet (about 1 m) to a maximum of about 16 feet (4.9 m).

Glenwood shale is characteristically grayish green to brownish gray, calcareous, sandy and phosphatic, and has a blocky fracture. Sand grains range in size from fine to coarse (Stauffer and Thiel, 1941, p. 74). The phosphatic grains are black, polished grains as large as an inch (2.5 cm) in diameter (Parham and Austin, 1967). Brassy oolites have been observed at one locality (Parham and Austin, 1967). Interbedded sandstone beds are generally less than 8 inches (<20 cm) thick; a major exception, noted above, is 3- to 4-foot-thick (0.9 to 1.2 m) cross-bedded sandstone near Fountain (Parham and Austin, 1967; Stauffer and Thiel, 1941, p. 74, p. 144-145).

In the Twin Cities basin, an 8- to 10-foot (2.4 to 3 m) interval of light-grayish-green, clayey, fine- to medium- and coarse-grained, bimodally sorted, thin-bedded to massive sandstone that is at the top of the St. Peter Sandstone has customarily been included in the Glenwood Formation (Thiel, 1937; Stauffer and Thiel, 1941, p. 74; Austin, 1969). Though discontinuous, this interval is found elsewhere; in Iowa, Wisconsin, and Illinois it is referred to as the Nokomis Member of the Glenwood (Templeton and Willman, 1963, p. 51-52).

The Glenwood generally is barren of macrofossils, but it does contain a microfauna that consists primarily of conodonts (Webers, 1972). The few calcareous macrofossils that have been observed occur as very thin, fragile films along bedding planes. Most of the Glenwood is pyritic; some pyrite appears to follow burrow traces, forming cylindrical or twiglike masses.

The upper contact with the Platteville Formation is generally very sharp. There are some hardgrounds in the upper Glenwood and basal Platteville indicative of the presence of diastems during transition from detrital to carbonate sedimentation, but there is no evidence for long interruptions in deposition or for erosion.

The basal contact beneath the "Nokomis" clayey sandstone of the Twin Cities basin was interpreted to be disconformable by early workers (Thiel, 1937; Templeton and Willman, 1963, p. 51-52). More recent work by Fraser (1976) indicates that it is a diastemic contact.

Differences in classifying the Glenwood in neighboring states potentially may create confusion. The Wisconsin Geological and Natural History Survey formerly classified the Glenwood as a member of the St. Peter Formation (Ostrom, 1967). In the Illinois classification, argillaceous, silty dolostone beds and dolomitic siltstone beds placed in the upper part of the Glenwood Formation by the Minnesota Geological Survey are accorded member status (Hennepin Member of Templeton and Willman, 1963, p. 75-76) in the overlying Platteville Formation.

The shale and siltstone of the Glenwood Formation create a strong deflection on gamma logs, and therefore the Glenwood usually is identified without difficulty.

Platteville Formation

The Platteville Formation (Bain, 1905, p. 18-21) is named for Platteville, Wisconsin, which is 4 miles east of the type exposures on the Little Platte River. It crops out in a belt that extends across southeastern Minnesota into the Twin Cities area. Its general distribution is shown in Figure 3 of Mossler (1985). In the Twin Cities accessible outcrops occur along the access road into Hidden Falls Park (SE1/4SE1/4 sec. 17, T. 28 N., R. 23 W., Ramsey County) (Fig. 2, loc. 24) and at Shadow Falls SE1/4NW1/4 sec. 5, T. 28 N., R. 23 W., Ramsey County; described in Sloan and others, 1987) (Fig. 2, loc. 28). South of the metropolitan area an exceptionally thin 16-foot-thick section (<5 m) of Platteville can be observed near Sogn (NW1/4SE1/4 sec. 24, T. 111 N., R. 18 W., Goodhue County; described in Sloan and others, 1987) (loc. 25); this thin Platteville and thick Glenwood occurs in a band of exposures from Ellsworth, Wisconsin, to Cannon Falls, Sogn, and Faribault, Minnesota (Majewske, 1953; Ford, 1958). The Platteville thickens southward from Sogn, and one of the thickest sections in the state, about 30 feet (9 m), occurs in roadcuts and quarries near Spring Grove in Houston County (SE1/4 sec. 17, T. 101 N., R. 7 W.; described by Sloan and others, 1987) (Fig. 2, loc. 29). Numerous other outcrops occur in southeastern Minnesota, particularly in Goodhue, Olmsted and Fillmore Counties; locations of these are listed in Mossler (1985).

In most of Minnesota the Platteville has been divided into three members: the basal Pecatonica Member (Hershey, 1897), medial McGregor Member (Trowbridge, 1935), and uppermost Carimona Member (Weiss, 1955). In the Twin Cities area, the medial McGregor Member is replaced by three members separated on the basis of local lithologic differences in the Twin Cities area (Majewske, 1953; Weiss and Bell, 1956; Sloan, 1956, 1972).

The basal Pecatonica Member (<1 to 7 feet (<2.1 m) thick) is present throughout most of the Hollandale embayment where the Platteville is present, though generally it is quite thin. It is locally absent in eastern Fillmore County (Weiss, 1957), where limestone of the overlying McGregor Member rests directly on Glenwood sandstone and shale. The unit is composed of yellowish-gray, sandy, phosphatic, fossiliferous dolostone that is thick bedded to massive.

The McGregor Member of the main part of the Hollandale embayment (5.5 to 18 feet (1.7 to 5.5 m) thick) and the Mifflin Member (8.5 feet (2.6 m) thick) of the Twin Cities basin are very similar lithologically, even though they are not direct lateral equivalents. Both are light-olive-gray to yellowish-gray, thin- and wavy-bedded, very fossiliferous, dolomitic limestone. The thin limestone beds are generally separated by very thin shale partings. In addition both have distinct color and compositional mottling caused by infaunal burrowing (Byers and Stasko, 1978).

Hardgrounds are common in the Platteville. They are most numerous in the basal part of the McGregor Member and in the underlying Pecatonica Member. These distinctive discontinuity surfaces are typically encrusted with pyrite (that may be oxidized to limonite or hematite) and overlain by thin zones of very sandy, phosphatic carbonate. Most are intensively bored and encrusted with bryozoans and echinoderms (Prokopovich, 1955; Byers and Stasko, 1978).

The Hidden Falls Member (Sloan, 1956) (3.5 to 5.5 feet (1 to 1.7 m) thick) and Magnolia Member (8 feet (2.4 m) thick) extend throughout the Twin Cities basin and outside it into adjacent parts of the Hollandale embayment. Both are light-olive-gray, finely crystalline dolostone. The Hidden Falls is very argillaceous to silty, phosphatic dolostone that is generally very sparingly fossiliferous and typically has fine microlaminations of pyrite. It is blocky to massive, commonly has a conchoidal fracture, and is soft, typically forming a recessive notch in outcrops. The Magnolia is less argillaceous and more resistant than the Hidden Falls. It contains thin coquinoid layers of brachiopods, mollusks, and other fossils and is poorly bedded or massive.

The Carimona Member is composed of interbedded thin beds of pale-yellowish-brown limestone and grayish-green shale. The limestone is typically fossiliferous; some beds are coquinas of gastropods or brachiopods (Protozyga nicolleti beds). The shale beds of the upper part of the Carimona Member have abundant bryozoans. A widespread 2- to 3-inch (5 to 8 cm) K-bentonite, named the Deicke (formerly Carimona) K-bentonite (Willman and Kolata, 1978), occurs near the base of the member. In Illinois, Iowa, and Wisconsin, beds equivalent to the Carimona Member customarily are included in the overlying Decorah Formation.

The basal contact of the Platteville with the Glenwood Formation is well defined and characteristically is carbonate rock over shale or friable, poorly cemented sandstone. However at some places in Fillmore County a calcite-cemented sandstone about 1 foot (30 cm) thick at the top of the Glenwood may be misidentified as basal Platteville dolostone. Thin (1 to 3 feet; 30 to 100 cm) layers of dolomitic or calcareous sandstone, siltstone, and shale considered by the Illinois Survey to be basal Pecatonica (Hennepin Member of Templeton and Willman, 1963, p. 75-76, 226-227) are classified as Glenwood by the Minnesota Survey for the reasons elucidated by Ostrom (1969) for Wisconsin. Therefore the Platteville/Glenwood contact is shown as slightly lower in Illinois than in Minnesota or Wisconsin in Figure 5.

The upper contact with the Decorah Shale is gradational and is customarily placed at the top of the highest prominent limestone ledge (Sloan, 1972).

The Platteville Formation is predominantly carbonate with low average gamma readings, situated between two shaly formations, the Glenwood and Decorah, which produce higher readings. As a result the combination generally creates a distinctive pattern on gamma logs (Plate 1).

Decorah Shale

The Decorah Shale was named for the city of Decorah in Winneshiek County, Iowa (Calvin, 1906, p. 84). In Minnesota the Decorah is grayish-green fossiliferous shale with a few lenses and thin beds of limestone. The formation extends from the center of the Twin Cities basin southward through southeastern Minnesota. It is thickest in the Twin Cities basin, where it is 80 feet (24 m) thick, and thins to 25 feet (<8 m) at the Iowa border.

In Minnesota, most modern workers consider the Decorah too uniform to be subdivided into members (Parham and Austin, 1969; Rice, 1985). Stauffer and Thiel (1941) did attempt to subdivide the Decorah into members in an earlier classification of Minnesota Ordovician rocks (Fig. 5, col. 2). They extended Kay's (1935; Twenhofel and others, 1954) subdivision of the Decorah Formation from Iowa into Minnesota, and following Kay's later work (in Twenhofel and others, 1954) included interbedded shale and limestone at the base of the Decorah Shale (Spechts Ferry Member) in the Platteville Formation. Therefore the Decorah/Platteville contact was drawn higher in their classification than in the more recent Minnesota classifications shown in Figure 5. Modern classifications in adjoining states continue to subdivide the Decorah (Fig. 5) because to the south and east of Minnesota it contains more carbonate beds and is more lithically variable.

In Minnesota the top of the Decorah is drawn where shale of the Decorah is succeeded by regularly alternating limestone and shale of the Cummingsville. Biozonation of Decorah brachiopods by Rice (1985, 1987) has demonstrated that upper beds of the Decorah in the Twin Cities are equivalent to basal beds of the Cummingsville in

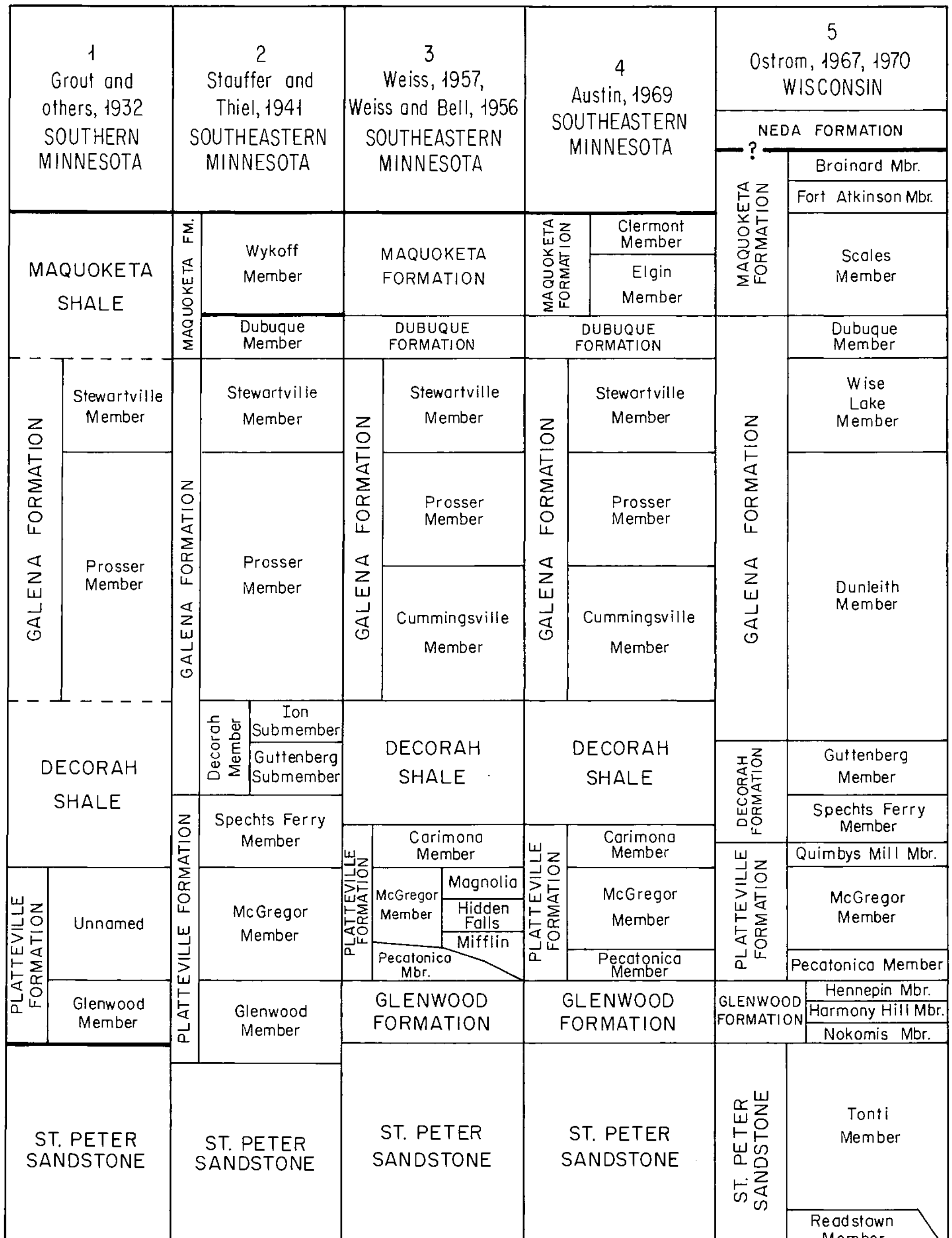

Figure 5. Development of Upper Ordovician stratigraphic nomenclature for southeastern Minnesota and neighboring states. The Dunleith and Wise Lake Formation of Bunker and others (1985) and the Wise Lake Member of Ostrom (1967, 1970) were subdivided as shown in column 7. Heavier lines denote interpreted unconformities; dashed lines are gradational unconformities.

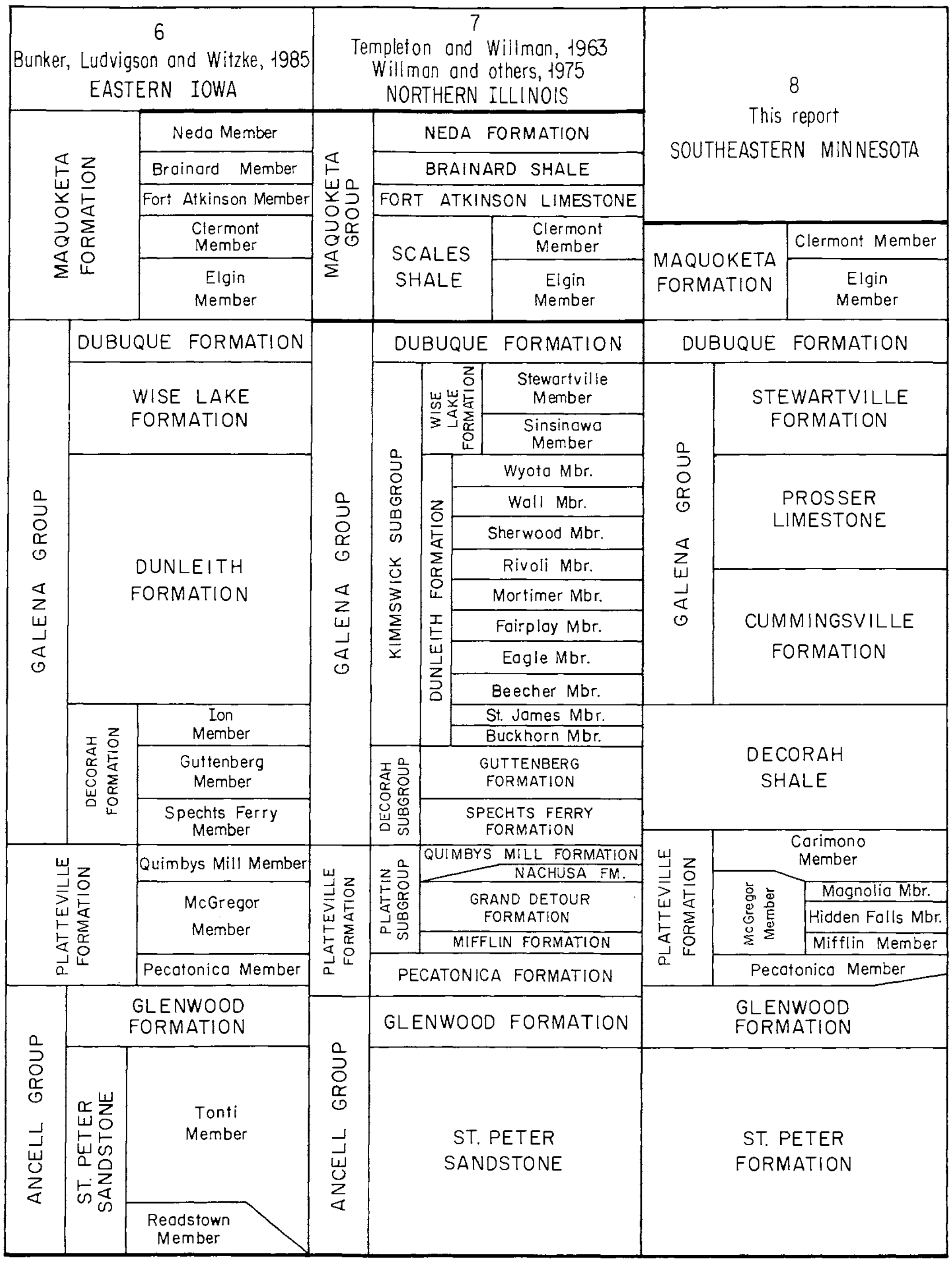

Figure 5 (continued).

southeastern Minnesota, and therefore that the upper contact of the Decorah in Minnesota is slightly diachronous. In Wisconsin and Illinois, beds equivalent to the upper part of the Decorah of Minnesota and Iowa (referred to in Iowa as the Ion Member of the Decorah) are predominantly limestone and are included in the basal part of the overlying Dunleith Formation (Fig. 5, cols. 5 and 7).

In the Twin Cities region the best exposure of Decorah Shale is at the site of the former Twin City Brick Company (SW1/4SE1/4SE1/4 sec. 12, T. 28 N., R. 23 W., Ramsey County; columnar section in Rice, 1987) (Fig. 2, loc. 30). The exposure is the property of the city of St. Paul and written permission from the superintendent of Parks and Recreation is required for access. Shadow Falls Park in western St. Paul contains the basal part of the Decorah (SE1/4NW1/4 sec. 5, T. 28 N., R. 23 W., Ramsey County; described in Sloan and others, 1987) (Fig. 2, loc. 28).

Outcrops along County Highway 14 in Goodhue County south of Sogn (SE1/4NW1/4 sec. 1, T. 110 N., R. 18 W.) (Fig. 2, loc. 31) and along U.S. Highway 52 on Golden Hill in the outskirts of Rochester (SE1/4NE1/4 sec. 15, T. 106 N., R. 14 W., Olmsted County; described in Sloan and others, 1987) (loc. 32) are representative of exposures of Decorah farther south.

The Decorah is fissile to blocky, grayish-green, fossiliferous shale with interbedded thin, grayish-yellow, coquinoid limestone and calcareous shale beds. The laterally persistent, 1 to 2 inches (2.5 cm) thick, Millbrig (formerly Spechts Ferry) K-bentonite of Willman and Kolata (1978) occurs about 1.5 to 3 feet (0.5 to 1 m) above the base of the Decorah in extreme southeastern Minnesota and rises to about 7 feet (2 m) above the base in the Twin Cities. Because it is in a predominantly shaly sequence, it cannot always be easily found.

The Decorah Shale contains thin beds of ferruginous or "brassy" ooids. They occur along the Galena/Decorah contact at some outcrops in Fillmore County (Weiss, 1957). However, in the Twin Cities these ooids occur within the Decorah well below the top of the formation (Rice, 1985, p. 16).

The Decorah is richly fossiliferous and contains a fauna dominated by brachiopods and bryozoans. The abundance of fossils, which attain a maximum of diversity and abundance for the Ordovician in the Decorah (Webers, 1972), and the ease with which the Decorah is disaggregated have resulted in numerous biostratigraphic studies recently: Conodonts (Webers, 1966), bryozoans (Karklins, 1969), ostracods (Cornell, 1956; Swain and others, 1961; Swain and Cornell, 1987); and brachiopods (Rice, 1985, 1987), as well as short studies on other fossils in Sloan (1987a).

The Decorah Shale has a high gamma reading, and gamma curves throughout the formation have a strong and distinctive positive deflection, in contrast to adjacent units (Plate 1).

Galena Group

The Galena Group was named for the town of Galena, Jo Daviess County, Illinois (Hall, 1851, p. 146-148). The Galena was assigned formational status in Minnesota (see Austin, 1969), but is raised to group rank in this report because its members, the Cummingsville, Prosser, and Stewartville, are mappable units over wide areas. Furthermore the elevation of the Cummingsville, Prosser, and Stewartville to formational rank corresponds with the ranks of correlative units in Iowa, Illinois, and Wisconsin (Sloan, pers. comm.). In Minnesota the Galena Group is limited principally to the southeastern part of the state (Mossler, 1983, pl. 1A) from western Goodhue County to the Iowa border.

Cummingsville Formation

The Cummingsville type locality (Fig. 2, loc. 33) is a quarry and roadcut 1/2 mile north of Cummingsville on County Road 7 (east edge SE1/4 sec. 21, T. 105 N., R. 12 W., Olmsted County). The Cummingsville may still be examined there and also may be examined at two localities mentioned in the section on the Decorah Shale: (1) south of Sogn (loc. 31) and (2) Golden Hill, near Rochester (loc. 32; see Sloan and others (1987) for description).

The Cummingsville Formation crops out in Goodhue County and south through Olmsted and Fillmore Counties. A very small outlier crops out near the center of the Twin Cities basin (Rice, 1985, 1987). It is 63 feet (19 m) thick at its type section and 74 feet (22.6 m) thick in the Hollandale 1 well (Austin, 1970), but becomes progressively thinner to the north because of facies change. Biozonation has demonstrated that the basal Cummingsville of southern Minnesota is laterally equivalent to the upper Decorah of the Twin Cities basin (Rice, 1985, 1987).

The Cummingsville 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 that are grouped into more massive units separated by smoother, more conspicuous shaly bedding planes (Weiss, 1957). There are repetitive layers of shaly limestone and limy shale. Exposures commonly weather to a serrated profile, except for the basal few feet which generally forms a thick limestone ledge.

The Cummingsville Formation is not notably fossiliferous, but does contain the lower

Fisherites zone, classically called the lower Receptaculites zone. Bryozoans are well established in shale and limestone of the lower Cummingsville, and articulate brachiopods dominate in the upper Cummingsville (Webers, 1972). The basal contact is commonly marked by a concentration of Prasopora (Weiss, 1957). Chert nodules occur in the member southeastward from the type locality in the lower part of the member and also above the middle (Weiss, 1957).

The upper contact between the Cummingsville Formation and the overlying Prosser Limestone is picked where a major detrital component abruptly diminishes (Weiss, 1957). In Fillmore County 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, in comparison to the Prosser, is indicated by the thick, shaly streaks in the Cummingsville, the earthy luster of its limestone, and its sawtooth weathering profile in old roadcuts and quarries.

The Cummingsville Formation and the upper Decorah Shale of Minnesota are equivalent to the lower part of the Dunleith Formation of Illinois and adjoining Wisconsin (Willman and Kolata, 1978); specifically they are equivalent to the six lowest (Buckhorn through Mortimer) members of the Dunleith and the lower part of the seventh (Rivoli Member) (Stone, 1980). In Iowa, rocks equivalent to the basal two members of the Dunleith of Illinois are in the Decorah Formation because they are extremely shaly (Fig. 5, col. 6), just as they are in Minnesota, and are referred to the Ion Member (Bunker and others, 1985). Member terminology of the Dunleith has not been applied to the Cummingsville of Minnesota except for a few stratigraphic section descriptions done by Levorson and Gerk (pers. comm. and Sloan and others, 1987). 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 with any confidence.

Prosser Limestone

The Prosser Limestone was originally named for Prosser's ravine in Fillmore County by Ulrich (1911, p. 369, 524-525). Weiss (1957) redescribed the type section which is a series of outcrops in the valleys of Spring Valley Creek and Mahoods ravine (SE1/4 sec. 8, south to the head of Mahoods ravine, at the south edge of the SE1/4 sec. 20, T. 103 N., R. 12 W.) (Fig. 2). However, there are other, more accessible places than the type section to examine the Prosser. The basal part and lower contact are exposed at the type section for the Cummingsville Formation. The upper part crops out at the Kapper Company's "Rifle Hill" quarry (NE1/4NW1/4 sec. 35, T. 102 N., R. 12 W., Fillmore County; described in Sloan and others, 1987) (Fig. 2, loc. 34). The Prosser is an important aggregate resource; Stone (1980) describes numerous quarries in the Prosser. Most outcrops are in Goodhue, Olmsted, and Fillmore Counties. It generally ranges from 38 to 62 feet (12 to 19 m) in thickness. The northernmost occurrence is 4 miles south of Cannon Falls (Wagner Hill section of Sloan and DesAutels, 1987).

The Prosser Limestone is yellowish gray to light olive gray, very fine grained, and generally thin and crinkly bedded with very thin shale partings between 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 to the southeast (Weiss, 1957). Four widespread K-bentonites occur in the Prosser (Willman and Kolata, 1978). The upper limestone beds are dolomitic, especially toward the north, and in this respect the Prosser grades into overlying Stewartville.

Nodular chert layers occur near the top of the unit in southern and central Fillmore County; chert also appears in the middle part of the formation in Fillmore and southern Olmsted Counties (Stone, 1980). The white to light-gray nodules may be scattered along bedding planes or may show no preference for bedding planes.

The Prosser Limestone is the most fossiliferous formation in the Galena Group. Most fossils are concentrated in fossiliferous streaks (coquinoid layers). Bottom communities of the Prosser tend to be dominated by articulate brachiopods as in the upper Cummingsville (Webers, 1972). Fisherites (=Receptaculites) is rare and almost absent in the Prosser; Ischadites iowensis is locally abundant (Weiss and Bell, 1956). Infaunal burrowing is commonly observed in this formation.

Beds equivalent to the Prosser in Iowa, Illinois, and Wisconsin are assigned to the upper part of the Dunleith Formation (Fig. 5, cols. 5-7). The Dunleith has long been subdivided into several members in Illinois and Iowa (Templeton and Willman, 1963; Levorson and Gerk, 1972). Stone (1980) and Levorson and Gerk (in Sloan and others, 1987) extended 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 into members.

Stewartville Formation

The Stewartville was originally named by Ulrich (1911, pl. 27) for exposures near the town of Stewartville in Olmsted County. There have been many problems with the nomenclature and especially with varied and imprecise definitions. More recent problems have come about because the name was redefined in two quite different senses by Weiss (1957) and by Templeton and Willman (1963); see Figure 5, columns 3 and 7. The latter substituted the name Wise Lake Formation for Weiss's Stewartville Formation. Sloan (1987b) discusses this nomenclatural problem and resolves it by proposing that the name "Rifle Hill Member" be substituted for "Stewartville Member" as used by Templeton and Willman (1963), and "Stewartville Formation" be used as a lithostratigraphic name as defined by Weiss (1957) and currently used by the Minnesota Geological Survey. As currently defined, the Stewartville Formation of Minnesota is equivalent to the Wise Lake Formation of Illinois and Iowa. Sloan (1987b) also proposes that recognition of the Sinsinawa Member of Templeton and Willman (1963) be extended into Minnesota as the lower member of the Stewartville Formation.

The Stewartville Formation, as defined by Weiss (1957), is about 75 to 85 feet (23 to 26 m) thick. It is exposed in Fillmore, southern Olmsted, and Dodge Counties. The best representative section of Stewartville is the "Rifle Hill" quarry (NE1/4NW1/4 sec. 35, T. 102 N., R. 12 W., Fillmore County) (Fig. 2, loc. 34), described in Sloan and others (1987). Other accessible outcrops are roadcuts near Rochester along Highway 63 about 3 miles north of I-90 in the N1/2N1/2 sec. 2, T. 105 N., R. 14 W., Olmsted County (Fig. 2, loc. 35).

The Stewartville Formation is characteristically fine-grained, dolomitic limestone and dolostone that is yellowish gray when fresh but weathers yellowish orange to grayish orange. It has a "Swiss cheese" weathering pattern caused by differential weathering of dolomitized, bioturbated limestone (Sloan, 1987b). The Stewartville is characterized by thin and crinkly bedding. These thin beds are grouped into more massive units set off by smooth bedding planes as in other Galena Group carbonate formations (Weiss, 1957). A thin, discontinuous K-bentonite occurs about 10 feet (3 m) above the base.

The Stewartville Formation is distinguished from the upper part of the Prosser Limestone by the absence of chert nodules, scarcity of fossils, and pervasive dolomitization, but the contact is gradational and must be placed rather arbitrarily. Unlike the Sinsinawa Member of neighboring states (Fig. 5), which is characterized by multiple hardgrounds, the Rifle Hill member of Sloan (1987b) has numerous stylolitic surfaces. It also has the lowest detrital content of any part of the Galena Group and is the least fossiliferous, though it contains the upper part of the upper Fisherites (=Receptaculites) zone and is characterized by abundant Maclurites and Hormotoma (Sloan and others, 1987).

Dubuque Formation

The Dubuque Formation (Sardeson, 1907, p. 193) is a thin shaly carbonate that overlies the Galena Group in Minnesota. It was named for the city of Dubuque, Dubuque County, Iowa, where the type section is in abandoned quarries on the Loras College campus. In Minnesota, good exposures occur along county roads adjacent to the Rifle Hill quarry in the NE1/4NW1/4 and NW1/4NE1/4 sec. 35, T. 102 N., R. 12 W., Fillmore County (Fig. 2, loc. 34). Several other localities are listed in Levorson and others (1979).

In earlier Minnesota stratigraphic columns such as that done by Stauffer and Thiel (1941) (Fig. 5, col. 2), the Dubuque was included in the Maquoketa Formation as a member, mainly because Stauffer and Thiel, as well as earlier workers such as Sardeson (1907), believed that a closer affinity existed between Maquoketa and Dubuque faunas, than between Dubuque and underlying Galena faunas. Weiss (1957) was the one who proposed elevating the Dubuque to formational status and moving it out of the Maquoketa, because he saw many affinities between its fauna and that in the Prosser Limestone.

The Dubuque Formation is about 34 feet (10 m) thick in southern Minnesota; it is exposed principally in Fillmore and southwestern Olmsted Counties. Its distribution in the subsurface is poorly known, but probably is similar to the overlying Maquoketa Formation.

In Minnesota, the Dubuque Formation is typically light-olive-gray to light-brownish-gray to yellowish-gray, medium-bedded limestone interbedded with thinner beds of yellowish-gray to light-olive-gray shale (Weiss, 1957). It becomes dolomitic near the top and base, but is less dolomitic than the underlying Stewartville. The Dubuque is moderately fossiliferous; the change from the poorly fossiliferous Stewartville is pronounced. Fossils are concentrated in some of the shale beds. Near the base of the rock, crinoids occur as local beds of coquina (criquina). Higher in the formation filter-feeders, particularly brachiopods, dominate, and the fauna becomes very similar to that in the Prosser Limestone (Weiss, 1957).

Levorson and others (1979) divided the Dubuque into three informal beds which illuminate the significant variations in this formation. The basal Frankville, 10 to 16 feet (3 to 5 m) thick in Minnesota, lacks the regularly alternating limestone and shale beds of the rest of the Dubuque, though detrital content systematically increases upward in the bed (Levorson and others, 1979). Overall the unit is sparingly fossiliferous, but it does contain several calcarenite bands. The medial Luana bed, about 19 feet (6 m) thick in Minnesota, is characterized by 1- to 2-inch (2.5 to 5 cm) shale partings; a parting near the top of the unit contains a K-bentonite. The uppermost unit, the Littleport bed, is composed of undulose beds of limestone separated by 1- to 5-inch (2.5 to 13 cm) shale beds. It is the most fossiliferous unit and contains many brachiopods. Another prominent K-bentonite occurs 2 to 5 feet (0.6 to 1.5 m) below the top of this unit. The Littleport bed is the most variable in thickness; in Minnesota, it ranges from 13 to 17.5 feet (4 to 5.3 m).

It is difficult to pick the Dubuque's basal contact with the Stewartville consistently, because of the discontinuous nature of the shale partings in the Dubuque. Levorson and others (1979) place the basal contact at the base of a widely recognized 4- to 6-inch (10 to 15 cm) carbonate "marker bed" that is set off from other beds by persistent 1-inch (2.5 cm) shale beds. This marker bed also is accepted in Iowa as the base of the Dubuque (Bunker and others, 1985). Though sometimes hard to detect in fresher outcrops, this "marker bed" may be a more reliable and consistent base for the Dubuque than the "lowermost shale parting."

The Dubuque Formation is generally interpreted to be conformable with the overlying Maquoketa Formation in Minnesota. Farther south and east, in Iowa and Illinois, the basal Maquoketa is ferruginous, phosphatic carbonate, which has a dwarfed, impoverished fauna and a basal contact that truncates Galena Group beds and is said to represent an important unconformity (Templeton and Willman, 1963).

In Minnesota the top of the Dubuque Formation is placed at the top of the highest conspicuous shale parting (Weiss, 1957). In the Maquoketa, clay is uniformly distributed in the carbonate and does not form discrete beds as it does in the Dubuque where shale beds are conspicuous. In addition, basal Maquoketa beds are more dolomitic than uppermost Dubuque beds (Levorson and others, 1979).

Maquoketa Formation

The Maquoketa Formation (White, 1870, p. 180-182), is named for exposures on the Little Maquoketa River in Dubuque County, Iowa. There are few outcrops of Maquoketa in Minnesota and most are fairly small; the best single exposure is near Granger in the SW1/4SW1/4 sec. 32, T. 101 N., R. 11 W., Fillmore County (Fig. 2, loc. 36). Bayer (1967) provides a description of this section. The Maquoketa crops out in western Fillmore County, extreme northeastern Mower County, and extreme southwestern Olmsted County (Sloan and Austin, 1966). It occurs in the subsurface of southern Dodge, southeastern Steele, Freeborn, and eastern Faribault Counties. It reaches a maximum thickness of 65 to 70 feet (20 to 21 m).

Most of the Maquoketa of Minnesota is classified as Elgin Member (Bayer, 1967). The Elgin Member is composed of thin-bedded, light-gray to yellowish-gray, very fine grained to sublithographic, fossiliferous limestone interbedded with gray to brownish-gray, unfossiliferous, shaly dolostone. There is minor interbedded brown shale at the base. Carbonate beds commonly contain gray to brownish-gray chert nodules and fossils are replaced by chalcedony and drusy quartz. The shaly limestones are replaced northward by barren shaly dolostones (Bayer, 1967).

Questionable Clermont Member sandy dolostone occurs at only a very few outcrops in Minnesota. It is tan, very sandy dolostone that contains some gray shale beds and calcite-filled vugs. It becomes progressively thicker and more sandy northward (Bayer, 1967).

The basal 10 feet (about 3 m) of the Maquoketa has a meager fauna consisting mainly of trilobites and graptolites that Bayer (1965) referred to as the Isotelus-Diplograptus community. The medial carbonates are dominated by articulate brachiopods and referred to as the Thaerodonta-Onniella community (Bayer, 1965, 1967). A local thin interval above the preceding is dominated by a single rugose coral and its fauna is named the Streptelasma-Plaesiomys community (Bayer, 1965).

The basal contact of the Maquoketa, which is interpreted to be conformable in Minnesota, was discussed in the section on the Dubuque Formation. The upper contact with the overlying Spillville Formation is an unconformity and picking it generally is a straightforward matter because the nonargillaceous, porous, massive to thick-bedded dolostone of the Spillville contrasts strongly with underlying sandy, thin-bedded Maquoketa carbonate.

The Maquoketa Formation does not have a very well defined signature on gamma logs, though gamma readings in it may be slightly higher and less regular than those in overlying, less argillaceous Spillville dolostone. Well cuttings are more satisfactory for identifying Maquoketa in the subsurface because of a distinctive lithologic suite that includes: abundant dark-gray to brownish-gray chert, chalcedonic and drusy quartz fossils, sandy dolostone, and sublithographic, light-colored limestone.

DEVONIAN SYSTEM

Classification of the Devonian System in Minnesota has changed more markedly in recent years than classification of either the Cambrian or Ordovician because of recent restudy of

Devonian biostratigraphy and physical stratigraphy in adjacent northern Iowa (Klapper and Barrick, 1983; Witzke and Bunker, 1984; Bunker and others, 1986). Minnesota Devonian rocks have long been classified in the Cedar Valley Formation (Grout and others, 1932; Stauffer and Thiel, 1941); these early investigators did not subdivide the formation into members (Fig. 6, col. 1).

Kohls (1961) extended the member terminology applied in east-central Iowa (basal Solon Member, medial Rapid Member, and uppermost Coralville Member) to lithofacies in Minnesota and adjacent northern Iowa that he thought were the lateral equivalents of those members. He was adapting correlations originally proposed by Calvin (1903) in equating the basal Devonian beds of Minnesota and northern Iowa with the type Solon Member of the Cedar Valley. Kohls's correlations were followed by Austin (1969) (Fig. 6, col. 2) and Mossler (1978a) in Minnesota and also were followed in some Iowa publications (Dorheim and Koch, 1966). Others, however, were more skeptical (Koch and Michael, 1965) and thought basal Devonian rocks of northern Iowa and southern Minnesota were older than Cedar Valley. Presence of pre-Cedar Valley Devonian units subsequently was borne out by Klapper and Barrick's (1983) biostratigraphic study.

Spillville Formation

The Spillville Formation was named by Klapper and Barrick (1983) for exposures in a quarry near Spillville, Winneshiek County, Iowa, where the formation is about 60 feet (18 m) of fossiliferous dolostone. The Spillville 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 by a paleotopographic high, and therefore must have a different name. In Minnesota, the Spillville is exposed in western Fillmore and eastern Mower Counties, and it occurs in the subsurface throughout much of Mower County. It is equivalent to the limestone and dolostone formerly included in the Solon Member of the Cedar Valley by Kohls (1961) and Mossler (1978a). Accessible exposures include a quarry near Racine (NW1/4NW1/4 sec. 20, T. 104 N., R. 14 W., Mower County) (Fig. 2, loc. 37) and a quarry in Spring Valley (NW1/4NW1/4 sec. 33, T. 103 N., R. 13 W., Fillmore County) (Fig. 2, loc. 38). The formation is relatively uniform in thickness and averages around 70 feet (21 m). It is thick- to medium-bedded, yellowish-gray to grayish-orange, finely crystalline, fossiliferous dolostone. There is some light-olive-gray to grayish-orange, dense, thick-bedded, slightly fossiliferous, dolomitic limestone in the upper part of the formation. Much of the fossil material in the Spillville dolostone is comminuted to sand-size fragments and, except for echinoderm fragments, most is leached to moldic porosity. The Spillville commonly contains large vugs which generally are lined with coarse calcite spar. Some of these result from leaching of large fossils, particularly leaching of colonial coral skeletons. Sandy dolostone or sandstone occurs locally at the base of the Spillville. The Spillville unconformably overlies older units; in Minnesota it overlies the Maquoketa Formation.

Wapsipinicon Formation

The Wapsipinicon Formation is named for the Wapsipinicon River in eastern Iowa (Norton, 1895, p. 127, p. 155-156). The type section consists of outcrops along the river in Linn County, Iowa. Until recently it was not known that the Wapsipinicon extended into Minnesota and north-central Iowa, in part because the unit is very thin, unresistant, and rarely crops out. Extension of the Wapsipinicon into northern Iowa and Minnesota largely results from work by Klapper and Barrick (1983) and Witzke and Bunker (1984) who showed that a clastic interval above the Spillville Formation in northern Iowa correlates lithostratigraphically with the middle (Kenwood) member of the Wapsipinicon of the type area.

The best example of Wapsipinicon lithology in Minnesota is a core, stored at the Minnesota Geological Survey repository, from Ulland Bros. Varco quarry south of Austin (NE1/4 sec. 27, T. 102 N., R. 18 W., Mower County) (Fig. 2, loc. 39) that contains 19 feet (5.8 m) of the formation. Distribution of the Wapsipinicon in Minnesota is poorly known because the unit is hard to distinguish from overlying Cedar Valley in well cuttings and it is not known to crop out.

The Wapsipinicon Formation in Minnesota is very light gray to medium-light-gray, dense to very finely crystalline, argillaceous dolostone that is generally poorly bedded or massive or is brecciated. Brecciated zones generally have medium-gray shale between the clasts; sandy zones occur, especially near the base of the formation. The Wapsipinicon is unfossiliferous. Member terminology for the Wapsipinicon of southeastern Iowa is not applied in Minnesota, although it has been used in north-central Iowa by Witzke and Bunker (1984).

Cedar Valley Formation

The Cedar Valley Formation was named by McGee (1891, p. 314) for the valley of the Cedar River in Iowa; he did not designate a type section. Formerly all Devonian rocks in Minnesota were assigned to the Cedar Valley; however this interval has shrunk because of the restudy of biostratigraphy (Klapper and Barrick, 1983) mentioned in preceding sections (Fig. 6). In addition, member nomenclature for southeastern Iowa (Solon, Rapid, and Coralville) is no longer considered to be

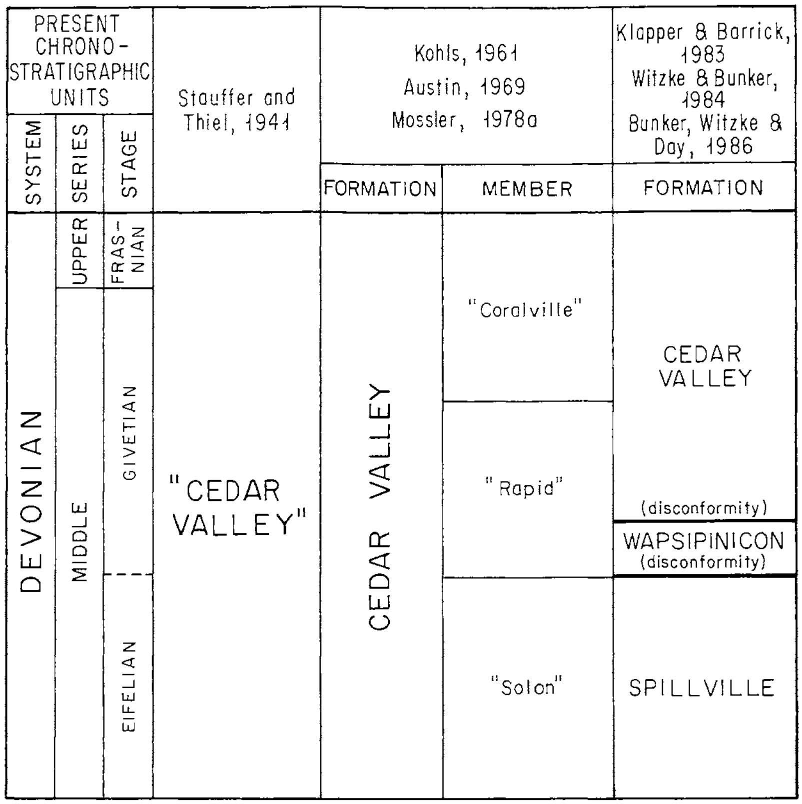

Figure 6. Development of Middle Devonian stratigraphic nomenclature for southern Minnesota and northern Iowa.

valid for Minnesota or northern Iowa (Witzke and Bunker, 1984). In northern Iowa the Cedar Valley has been expanded to include the overlying Shell Rock Formation and has been raised to group status because the entire interval is considered to represent a single large marine transgressive/regressive cycle, within which are several smaller transgressive/regressive cycles (Bunker and others, 1986). The Shell Rock does not extend into Minnesota, however, and therefore it is acceptable to continue to classify the Cedar Valley as a formation in Minnesota (Plate 1). The formation extends through much of Mower and Freeborn Counties, and through the southwestern part of Fillmore County; it attains a maximum thickness of about 150 feet (46 m). The lower part of the Cedar Valley crops out at the Ulland Bros. Varco quarry (NE1/4 sec. 27, T. 102 N., R. 18 W., Mower County) where about 45 feet (14 m) of dolostone is exposed (Fig. 2, loc. 39). The upper part of the Cedar Valley is exposed in quarries near Le Roy; some of the better exposures are in Osmundson's quarry just north of town (NW1/4NW1/4 sec. 27, T. 101 N., R. 14 W., Mower County) (Fig. 2, loc. 40). Beds exposed in a quarry near Lyle (NW1/4SW1/4 sec. 33, T. 101 N., R. 18 W., Mower County) (Fig. 2, loc. 41) lie stratigraphically in between those at Varco and Le Roy. Cedar Valley outcrops are mostly manmade (quarries, roadcuts); natural exposures are rare, and nowhere is more than a partial section exposed. Scarcity of exposures has contributed to the difficulty in unraveling Cedar Valley stratigraphy.

According to Bunker and others (1986), the prominent cyclic character of the lower Cedar Valley Formation can be used in lithostratigraphic correlation. The basal part of the first cycle is light-gray, fossiliferous, argillaceous dolostone that generally is massive to thick bedded and that contains many subspherical vugs, some lined with calcite spar (represented in Ulland Bros. Varco quarry). Sandy dolomite is present at the base. The upper part of this basal cycle is marked by a thin zone of laminated dolomite that contains intraclasts, graded bedding, and thin shale partings (represented in the base of the quarry near Lyle).

The upper part of the Cedar Valley Formation in Minnesota consists of the two succeeding sedimentary cycles which are very similar and are difficult to tell apart. The basal parts of both cycles consist of fossiliferous dolostone like that in the upper part of the Lyle quarry (which is the lower part of the middle or second cycle). It is massive to thick bedded, grayish orange to pale yellowish brown and very finely crystalline. Most fossil material is very finely comminuted and leached and forms moldic porosity. There are also larger calcite-lined vugs that probably are leached colonial corals and stromatoporoids.

The upper regressive part of the uppermost cycle is represented by the limestone beds in the middle and upper parts of a quarry near Le Roy. The beds consist of very thin to medium-bedded, light-gray to medium-gray, dense and sublithographic limestone. Most beds are laminated; some laminations appear to be planar algal mats, and others appear to be current laminations. Ostracods and calcareous algal spores or reproductive bodies are the most abundant components of the biota. A few beds have a more varied biota that includes echinoderms, solitary corals, calcareous algae, and brachiopods. Oncolites locally are present. Thin zones of intraclasts, desiccation cracks, and possible birdseye fabric occur in these beds. Associated dolostone generally consists of dense, yellowish-brown to yellowish-gray, thin-bedded to medium-bedded, unfossiliferous units that locally contain relict primary structures, such as fine current laminations or leached intraclasts. Limestone beds commonly grade laterally into dolostone within the confines of a quarry. Thin greenish-gray shale beds are common.

The basal contact of the Cedar Valley Formation with the Wapsipinicon is apparently conformable; the upper surface of the Cedar Valley in Minnesota is erosional and is generally overlain by either Cretaceous sand and gravel or Quaternary deposits.

The Devonian interval lacks definitive features on gamma logs; however the Spillville Formation appears to have slightly lower average readings than either the overlying Wapsipinicon or the underlying Maquoketa, probably because of its very low shale and insoluble residue content. This characteristic might be useful in picking contacts if used in conjunction with well cuttings studies. The Wapsipinicon and Cedar Valley are very similar in intensity; however gamma curves in the upper part of the Cedar Valley appear slightly more "ragged" or variable in intensity than those in the lower Cedar Valley and Wapsipinicon because of numerous shale partings that are scarce in the lower units.

NORTHWESTERN MINNESOTA

Shelf deposits of two Ordovician formations extend into northwestern Minnesota from the Williston basin of the western interior. These formations are lateral equivalents of the Blackriveran to Maysvillian units of southeastern Minnesota, and the uppermost units may have been continuous across the Transcontinental Arch (Webers, 1972). None of the Paleozoic units crops out in northwestern Minnesota; all are covered by a continuous layer of Quaternary drift and the nearest outcrops are in the Lake Winnipeg area of Manitoba, Canada, where these units were first described and named.

Winnipeg Formation

The Winnipeg Formation was first described by Dowling (1895, p. 66) in reference to rocks underlying Ordovician carbonate and overlying Archean crystalline rocks in the Lake Winnipeg area. No specific type section has ever been described for the Winnipeg because all outcrops are incomplete exposures of the formation. In Minnesota the most complete sections are those described from well cuttings by Bayer (1959) and Mossler (1978b). Well cuttings for Hallock test well A (SW1/4NW1/4 sec. 13, T. 161 N., R. 49 W., Kittson County) (Fig. 7) and other deep wells are available at the Minnesota Geological Survey.

The Winnipeg Formation reaches a maximum thickness of around 170 feet (52 m) (Bayer, 1959) in Kittson County. It thins to an erosional featheredge toward the east. In most of the Williston basin the Winnipeg is divided into three members: the basal Black Island sandstone, medial Icebox shale, and upper Roughlock siltstone and sandstone. In Minnesota we are reluctant to apply this terminology except for the basal sandstone member, the Black Island, which was named for an exposure on Lake Winnipeg in Manitoba, because questions have been raised about lateral continuity of lithic units in the Williston basin (Carlson, 1960; Fuller, 1961). The upper two members were named for exposures in western South Dakota, which also are far from northwestern Minnesota.

The basal unit is light-gray to dark-yellowish-brown, medium- to coarse-grained, calcite-cemented quartzose sandstone that is interbedded with some purple to gray-green soft shale. It ranges from 4 to 10 feet (1.2 to 3 m) in thickness. This unit is considered to be the Black Island Member.

The medial unit is light-brownish-gray to greenish-gray shale with traces of maroon, yellowish-brown and light-green shale. A few thin sandstone stringers are interbedded in the shale, and there are thin lentils of yellowish-gray dense limestone below the middle of the unit. The medial unit ranges from 80 to 97 feet (24 to almost 30 m) in thickness.

The upper unit is predominantly yellowish-gray, fine- to medium-grained, quartzose sandstone. It is generally very friable, but contains some concretionary zones cemented by calcite. This unit is about 70 feet (21 m) thick.

The Winnipeg Formation is generally unfossiliferous except for some conodont faunules recovered from the shale (Bayer, 1959). The basal contact with Archean crystalline rocks is nonconformable.

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 areas are quarries near Winnipeg, Manitoba; outcrops near Winnipeg are the nearest exposures of this formation.

In Minnesota, well cuttings from the D.H. Valentine well near Humboldt in Kittson County (SE1/4SE1/4SW1/4 sec. 23, T. 163 N., R. 50 W.) (Fig. 7) provide the most complete section. It can be observed in core from the Thibodo test well B in Marshall County (NE1/4SE1/4 sec. 21, T. 158 N., R. 50 W.) (Fig. 7, loc. 3) in the DNR repository at Hibbing.

The Red River Formation reaches a maximum thickness of nearly 300 feet (91 m) in Kittson County; it thins to the east to an erosional featheredge. Member nomenclature applied to Red River outcrops has not been extended into the subsurface of the Williston basin (Andrichuk, 1959); instead the formation has been subdivided into informal lithologic units in the subsurface (Andrichuk, 1959; Fuller, 1961). The lower 90 percent of the Red River consists of variably dolomitized fossiliferous limestone; the upper 10 percent is cyclically 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. Fossils consist of a varied marine fauna including echinoderms, brachiopods, bryozoans, trilobites, and ostracods. The lower part of the section is very light gray, fossiliferous limestone with pale-red mottling along shale partings (Mossler, 1978b). This grades upward to dense, color-mottled, yellowish-gray to grayish-orange, fossiliferous, vuggy dolostone and dolomitic limestone.

The Red River/Winnipeg contact is interpreted to be gradational (Fuller, 1961). The upper contact of the Red River in Minnesota is an erosional surface overlain by Mesozoic or Quaternary units; there is no evidence that later Ordovician units extend into northwestern Minnesota.

Gamma logs are useful tools in delineating the Winnipeg and Red River Formations. Shale and clayey till of overlying Mesozoic and Quaternary units ordinarily have much higher readings than much of the Ordovician units, with the major exception of the shale in the lower 70 percent of the Winnipeg (Plate 1).

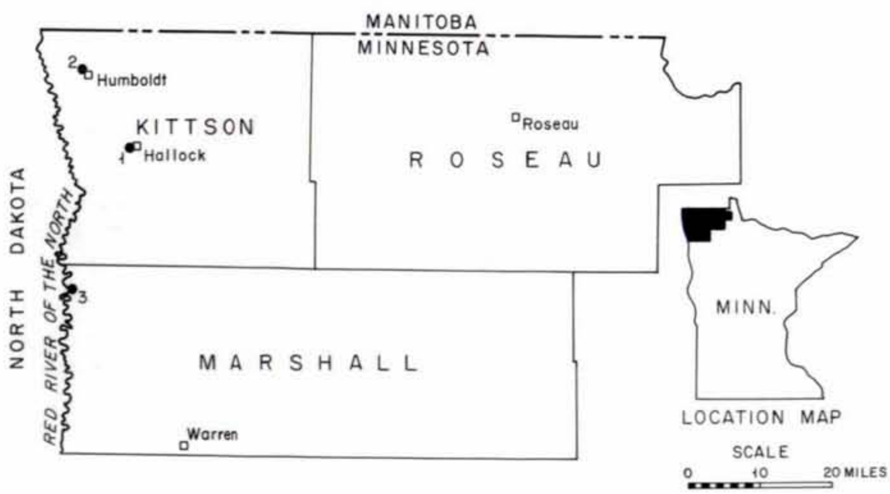

Figure 7. Locations (numbered) of well cores and cuttings from northwestern Minnesota mentioned in text.

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APPENDIX

Principal gamma logs used to construct the composite gamma log illustrated on Plate 1. These logs are on file at the Minnesota Geological Survey.

1.) Lyle Municipal no. 3
SW1/4SE1/4NW1/4 sec. 36, T. 101 N., R. 18 W., Mower County.
Stratigraphic interval: Cedar Valley Formation to Prairie du Chien.

2.) Northern Natural Gas Hollandale 1-A
SE1/4SE1/4SW1/4 sec. 7, T. 103 N., R. 19 W., Freeborn County.
Stratigraphic interval: Spillville Formation to Solor Church Formation.

3.) Northern Natural Gas Lonsdale 65-1
NW1/4SW1/4SW1/4 sec. 14, T. 112 N., R. 21 W., Rice County.
Stratigraphic interval: Prairie du Chien to Solor Church.

4.) Northern Natural Gas Hampton 65-2
SW1/4SW1/4NE1/4 sec. 4, T. 113 N., R. 18 W., Dakota County.
Stratigraphic interval: Prairie du Chien to Solor Church.

5.) Northern Natural Gas Vermillion 66-9
SW1/4NW1/4NW1/4 sec. 11, T. 114 N., R. 18 W., Dakota County.
Stratigraphic interval: Prairie du Chien to Solor Church.

6.) Lund-Gundberg 'oil well'
SW1/4NE1/4SE1/4 sec. 24, T. 115 N., R. 20 W., Dakota County.
Stratigraphic interval: St. Peter to Solor Church.

7.) Minnegasco Melstrom 1
SW1/4SE1/4SW1/4 sec. 28, T. 109 N., R. 22 W., Rice County.
Stratigraphic interval: Prairie du Chien to Hinckley.

8.) Minnegasco Lloyd Williams 4
NW1/4SW1/4NE1/4 sec. 7, T. 108 N., R. 22 W., Waseca County.
Stratigraphic interval: Prairie du Chien to Mt. Simon.