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

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

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

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

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

Cummingsville Formation

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

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

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

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

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

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

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

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

Prosser Formation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Stewartville Formation

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Dubuque Formation

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

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

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

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

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

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

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

MAQUOKETA FORMATION

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

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

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

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

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

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

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

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

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

DEVONIAN SYSTEM

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

WAPSIPINICON GROUP

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

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

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

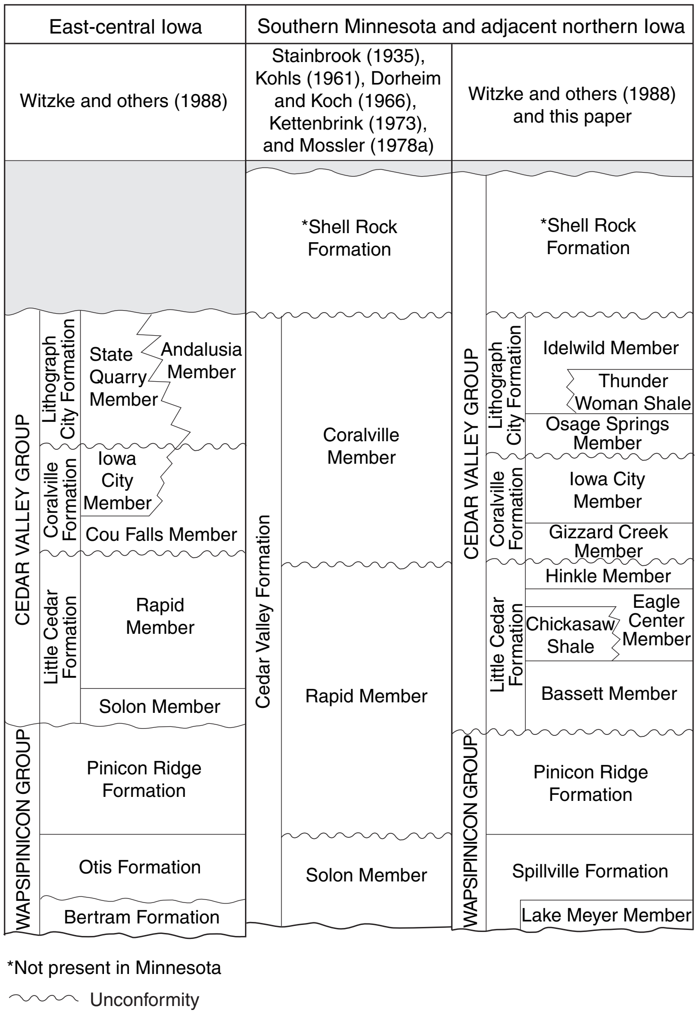


Figure 14. Development of stratigraphic nomenclature for Middle Devonian rocks and lower Upper Devonian rocks of northern Iowa and southern Minnesota. The column on the right shows current nomenclature for Devonian rocks of southern Minnesota and northeastern Iowa. The center column shows earlier nomenclature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

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

Spillville Formation

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

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

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

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

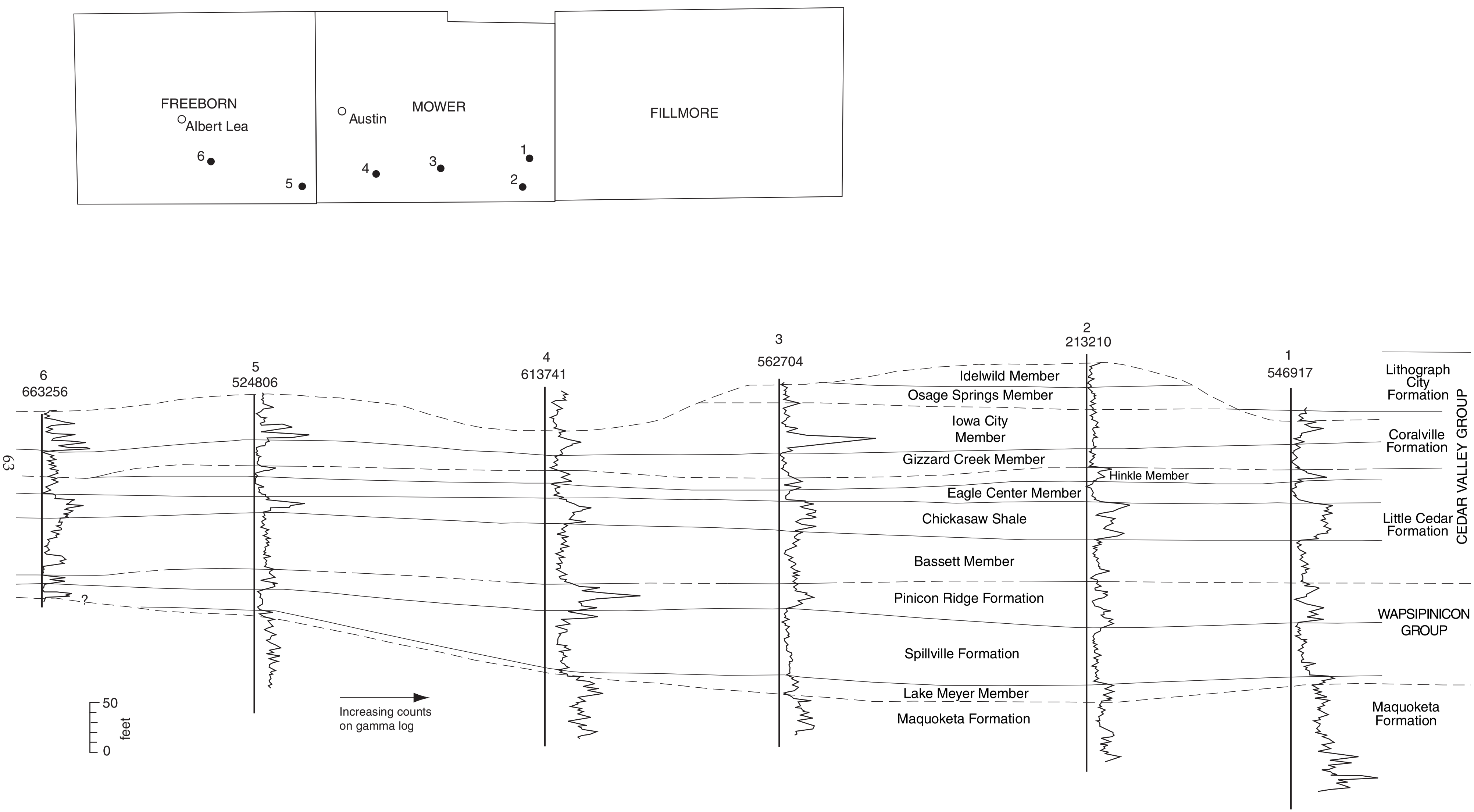


Figure 15. Geologic section of the Devonian formations across the southern part of the Hollandale embayment in Minnesota. Datum is the top of the Chickasaw Shale. Note the thinning in the Spillville and Pinicon Ridge Formations toward the west. Shaly units such as the Chickasaw Shale and Pinicon Ridge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

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

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

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

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

Pinicon Ridge Formation

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

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

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

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

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

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

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

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

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

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

CEDAR VALLEY GROUP

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

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

Little Cedar Formation

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

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

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

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

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

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

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

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

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

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

Coralville Formation

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

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

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

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

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

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

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

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

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

Lithograph City Formation

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

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

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

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

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

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

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

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

NORTHWESTERN MINNESOTA

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

WINNIPEG FORMATION

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

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

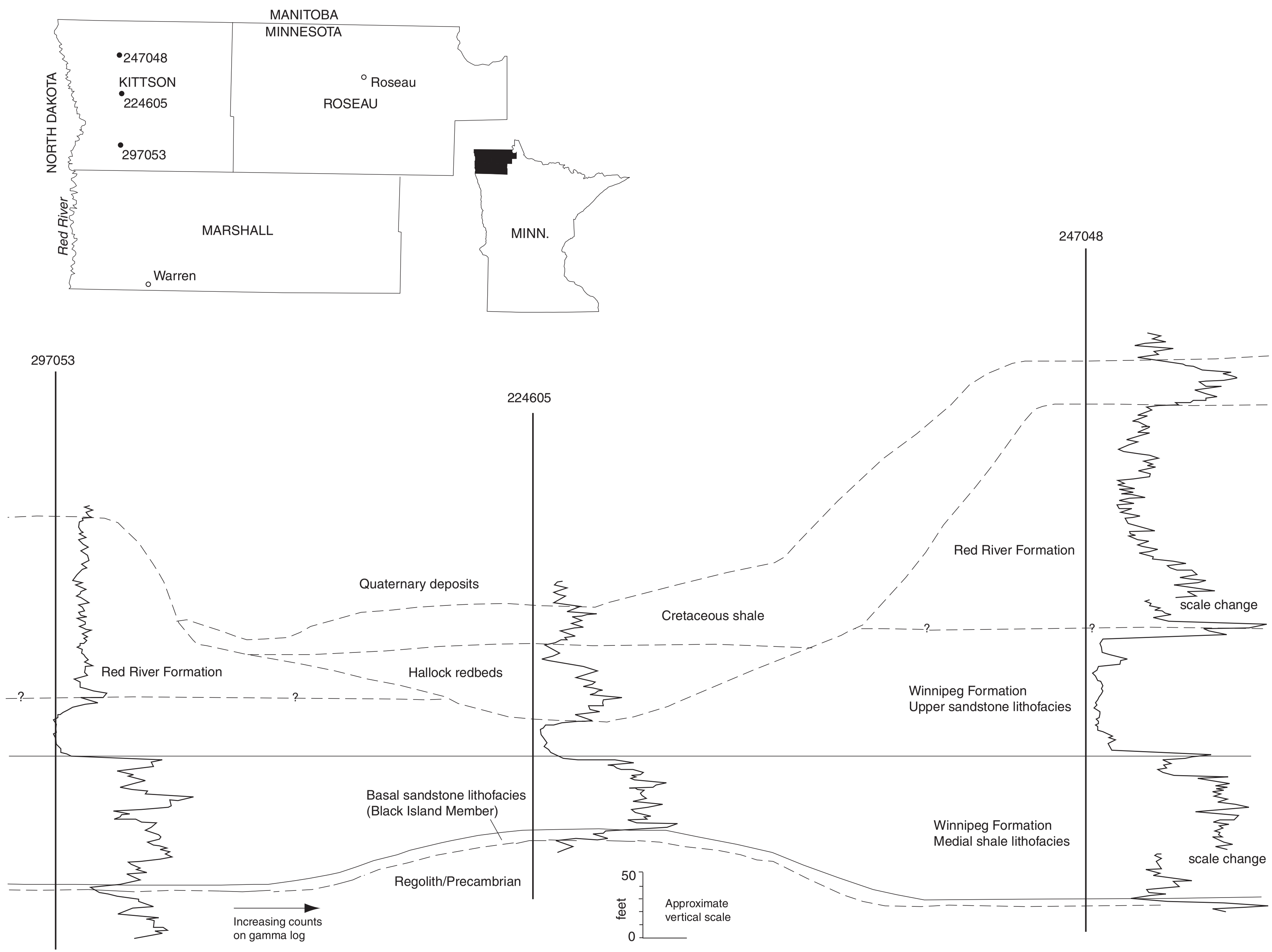
Thickness—The Winnipeg Formation reaches a maximum thickness of around 170 feet (52 meters) in Kittson County (Bayer, 1959, unpub. data). It thins to an erosional featheredge toward the east.

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

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

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

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



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

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

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

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

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

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

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

RED RIVER FORMATION

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

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

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

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

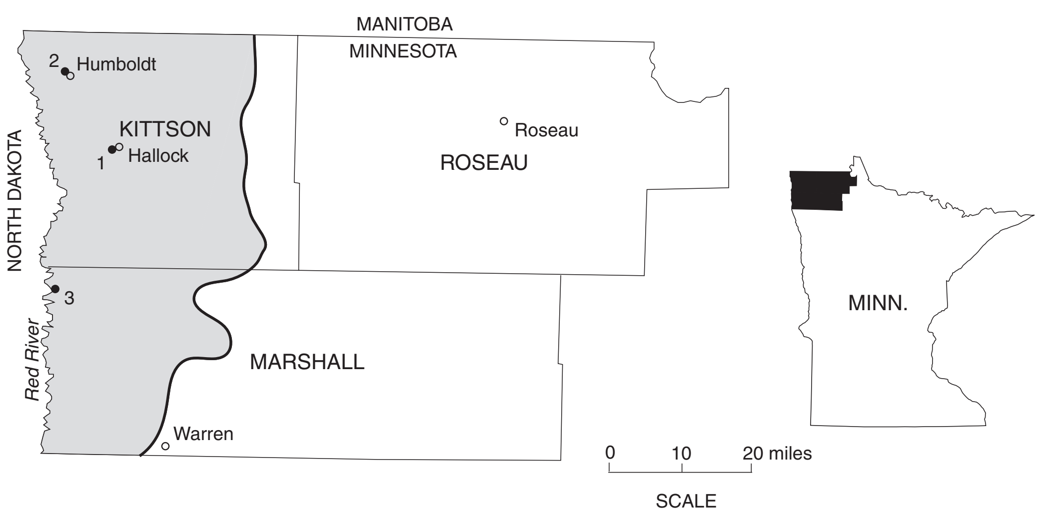


Figure 17. Locations (numbered) of well cores and cuttings from northwest Minnesota mentioned in the text. The approximate extent of Paleozoic rocks in northwest Minnesota is shaded.

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

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

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

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

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

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

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APPENDIX A

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

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

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

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

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

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

SS = Split spoon sample

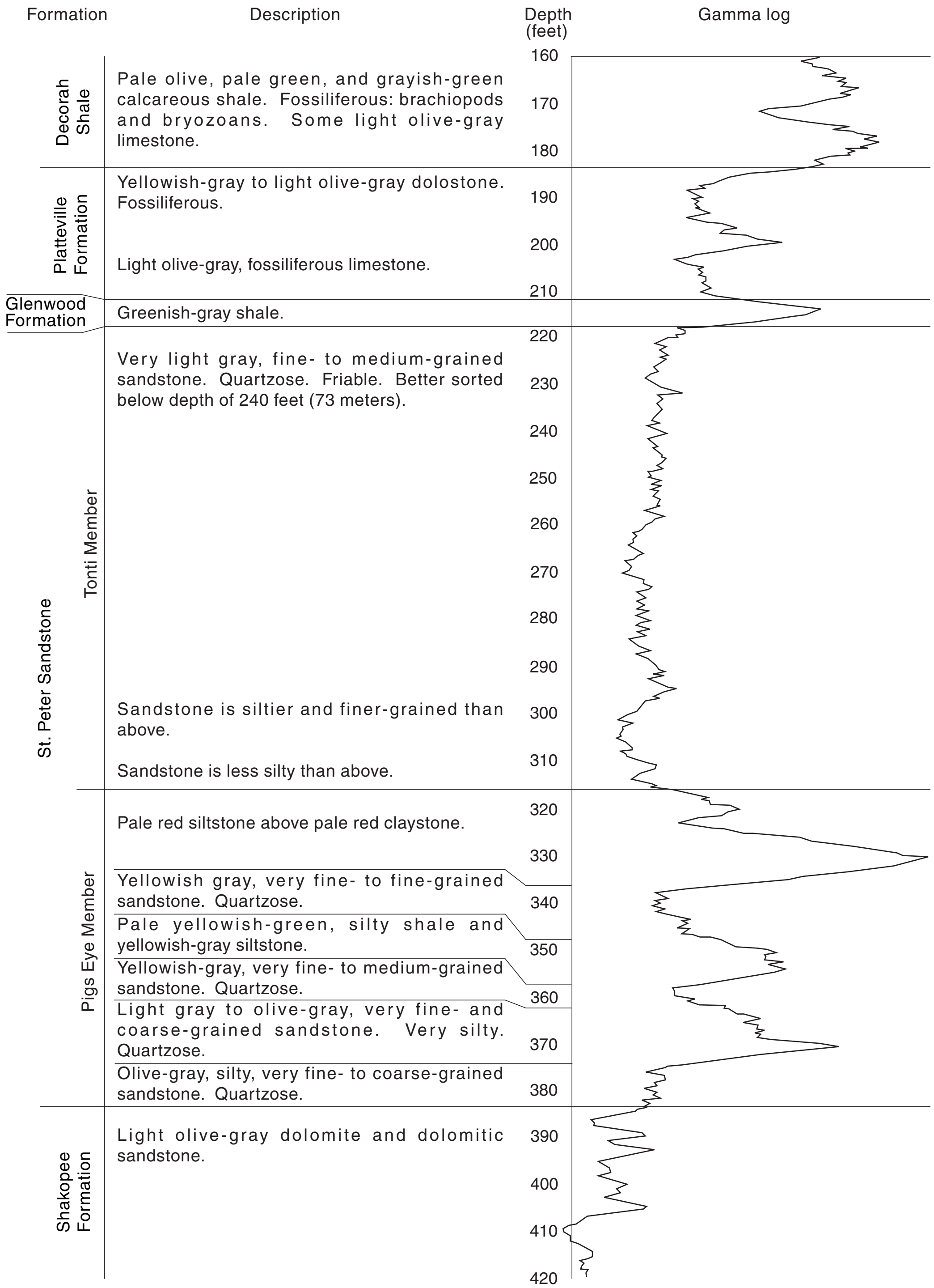
APPENDIX B

Supplemental section for the Pigs Eye Member

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

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

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



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

PLATE 1

EXPLANATION

- LIMESTONE
  - Dolomitic
  - Shaly
- DOLOSTONE
  - Sandy
  - Shaly
- SANDSTONE
  - Very fine- to fine-grained
  - Principally medium- to coarse-grained
- SILTSTONE
  - Shaly
- SHALE
- OLDER IGNEOUS AND METAMORPHIC ROCKS

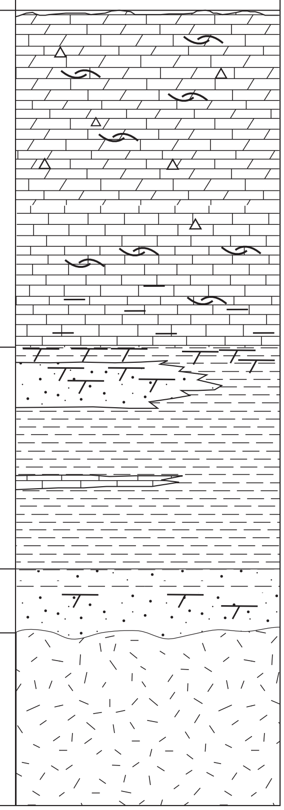
Symbol	Meaning
△	Chert
	Oolitic chert
⊙	Oolites
	Vugs filled with calcite
	Calcareous concretions
	Intraclasts
◊	Breccia
	Dolomitic
⊤	Calcareous
	Silty
x x x x	Bentonite
G	Glauconite
P	Pyrite
L	Lithic (sand grains)
M	Mica
F	Feldspathic
H	Hematitic
Ph	Phosphatic
	Fossils, primarily inarticulate brachiopods
	Fossils, primarily as molds and/or finely comminuted
B	*Receptaculites*
	Gastropods
	Stromatolites
◎	Oncolites
U	Worm bored (general)
	Skolithos borings
• •	Conglomeratic
	Ripple cross-stratification
	Large-scale cross-stratification to tangential cross-stratification
	Trough cross-stratification
	Swaly and hummocky cross stratification

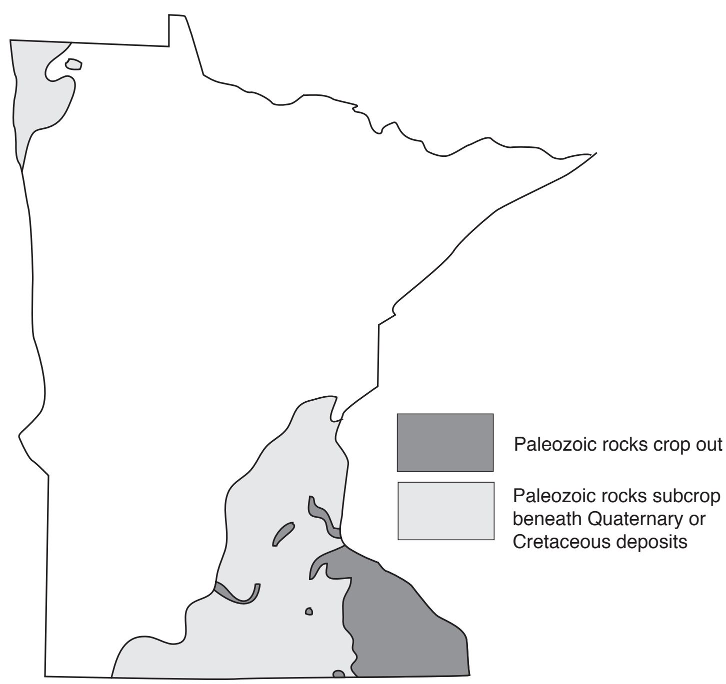
(60, SW) Numbers in parentheses in formation and member columns refer to maximum thickness of unit (in feet).
Letters in parentheses by number refer to part of southeast Minnesota (SW = southwest part, NC = north-central part, etc.) where unit is thickest.

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

NORTHWEST MINNESOTA

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





Areal extent of Paleozoic rocks