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SEDIMENTARY ROCKS OF DRESBACHIAN AGE (LATE CAMBRIAN), HOLLANDALE EMBAYMENT, SOUTHEASTERN MINNESOTA

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SEDIMENTARY ROCKS OF DRESBACHIAN AGE (LATE CAMBRIAN), HOLLANDALE EMBAYMENT, SOUTHEASTERN MINNESOTA

by

John H. Mossler

ABSTRACT

The Dresbachian Mt. Simon Sandstone, Eau Claire Formation, and Galesville Sandstone of the Hollandale embayment of southern Minnesota are divisible into eleven major lithofacies and several subfacies. Because the formations are almost exclusively in the subsurface in Minnesota, lithofacies descriptions are based on cores, well cuttings, and geophysical logs.

Along the eastern side of the Hollandale embayment, the lower Mt. Simon Sandstone consists of a thin basal conglomerate lithofacies overlain by medium- and large-scale, cross-stratified and planar-stratified sandstone. Middle Mt. Simon is principally interbedded, coarsely interlayered sandstone, siltstone, and shale; and thin- to medium-bedded, structureless or cross-stratified sandstone. The upper Mt. Simon is structureless sandstone with *Skolithos* and shelly (coquinoid) sandstone. These lithofacies resemble those from outcrops in western Wisconsin described by Driese and others (1981).

Toward the west and south in south-central Minnesota, at the embayment center, medium- and large-scale, cross-stratified sandstone dominates in the Mt. Simon. Along the western side of the embayment, structureless sandstone dominates. There are fewer thin shale and siltstone beds in the Mt. Simon near the embayment center than along the eastern side of the embayment.

Near the embayment center, the uppermost Mt. Simon Sandstone and basal Eau Claire Formation contain ferroan oolites and coated grains that are scattered in some beds and are the principal sand-sized particles in others. Ferroan oolites and coated grains are not observed in outcrop.

Along the eastern side of the Hollandale embayment, the Eau Claire is composed principally of mixed sandstone and shale lithofacies and greensand lithofacies resembling Eau Claire lithofacies that crop out in western Wisconsin (Huber, 1975), especially in cores along structural strike with the Wisconsin outcrops.

Red sandstone and shale lithofacies and dolostone lithofacies are at the base of the Eau Claire in south-central Minnesota. These are overlain by a ripple-cross-stratified or trough-cross-stratified subfacies of the greensand lithofacies that is much thicker than laterally equivalent beds of greensand lithofacies to the north and east.

The Galesville Sandstone, mostly structureless, planar-stratified, or trough-cross-stratified sandstone, appears to be conformable and interbedded with the Eau Claire Formation. The upper part of the Eau Claire and Galesville appear to be part of an upward coarsening sequence. There is evidence of slight disconformity between the Galesville and overlying Ironton Sandstone.

The basal conglomerate of the Mt. Simon is interpreted as a braided fluvial deposit. Medium- to coarse-grained sandstone lithofacies of the lower Mt. Simon are interpreted as braid plain, braid delta, and littoral deposits. Fine- to medium-grained sandstone beds and shale beds in the middle Mt. Simon are interpreted as distal braid delta deposits. Sandstone beds in the upper Mt. Simon are interpreted as sand shoals and tidal flat deposits. Beds of interbedded, fine-grained sandstone and shale in the basal Eau Claire that are tidal flat deposits culminate this initial prograding sequence. Toward the end of the sequence deposition, ferroan oolites formed nearshore, where some were reworked by shifting tidal channels. Red sedimentary rocks were deposited in high tidal flat, channel, and deltaic environments. Carbonate rock was deposited in the southwestern Hollandale embayment as detrital sedimentation ended.

The greensand lithofacies of the medial Eau Claire Formation, which records marine transgression at the base of the next prograding sediment sequence, is succeeded by shaly lagoonal deposits, sandy or shaly tidal flat deposits (upper Eau Claire Formation), and sandy foreshore or shoreface deposits (Galesville Sandstone).

Variation of sandstone composition reflects selective mechanical reduction of contained potassium feldspar grains as observed by Odom (1975). Medium- to coarse-grained sandstone is quartzose, and very fine to fine-grained sandstone is highly feldspathic. This variation, reflected on gamma logs, helps to distinguish lithofacies.

Sandstone in core from southwestern Minnesota contains accessory minerals, including diaspore, that indicate the contribution of sediment from the Proterozoic Sioux Quartzite to the Mt. Simon Sandstone.

INTRODUCTION

This report presents a framework for physical stratigraphy and sedimentology of the lower part of the Upper Cambrian of Minnesota—the Mt. Simon Sandstone, Eau Claire Formation, and Galesville Sandstone. These are among the least studied Paleozoic rock formations in the state, mainly because exposures are rare. There are exposures of Galesville Sandstone along the Mississippi River in southern Wabasha County, and in Winona and Houston Counties, but few away from the river valley (Fig. 1). Exposures of the Eau Claire and Mt. Simon, even scarcer in Minnesota, are limited mainly to a few scattered exposures in the Upper St. Croix Valley (Fig. 1). However, over the past forty years good quality subsurface data have been obtained by several firms who have done continuous coring of the Dresbachian sequence at several locations across the subcrop of Paleozoic rocks in southern Minnesota (Fig. 1). Many of these cores were supplemented by good quality geophysical logs, some by entire suites of logs. Additional geophysical logs are available for areas between cored localities through an ongoing well-logging program at the state geological survey and hydrologic investigations conducted by the U.S. Geological Survey.

Modern sedimentological interpretations of these formations are based on restudy of their lithostratigraphy in the principal outcrop area of western Wisconsin by University of Wisconsin graduate students Driese (1979), Huber (1975), Fielder (1985), Stenzel (1983), and Tanck (1977). Their theses, which emphasize paleoenvironmental interpretation of the formations based on contained physical and biogenic sedimentary structures, provide background for interpretation of similar features in cores.

Mineralogical studies of Cambrian sandstone by Distefano (1973); Kiester (1976); Odom (1975, 1976); Odom, Doe, and Dott (1976); Stablein and Dapples (1978); and Duffin and others (1989) illuminate the relationship between mineralogy and sedimentology, as well as the diagenetic history of the formations.

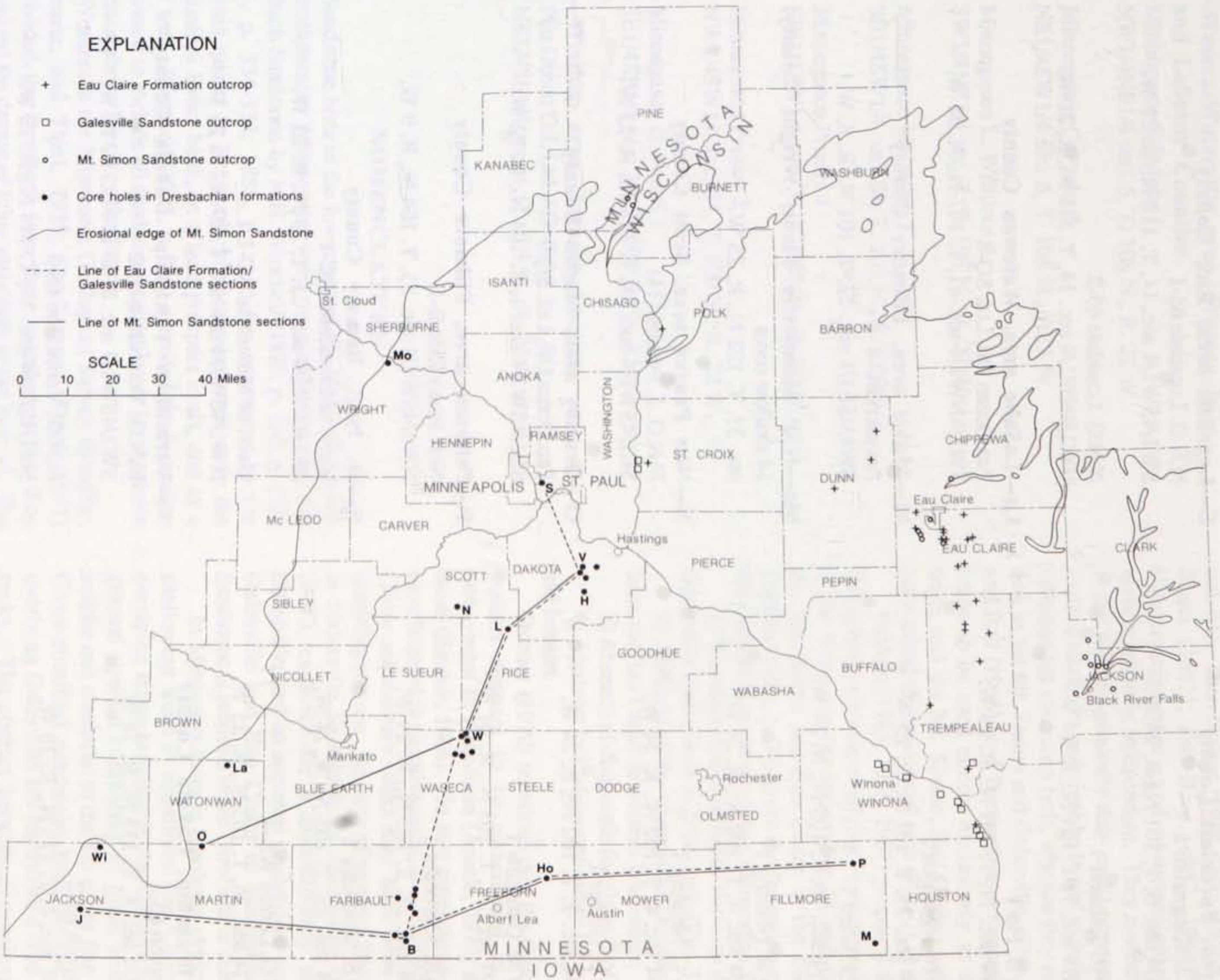


Fig. 1 Location map of cores and important exposures of Dresbach Group. Locations of cores mentioned in report are lettered. Symbols for exposures indicate which formation is cropping out.

B—Bricelyn area, Faribault County
Minnegasco J. Kingstrom 1
NW1/4NW1/4 sec. 6, T. 101 N., R. 24 W.

Minnegasco R. Johnson 1
NW1/4NW1/4 sec. 7, T. 101 N., R. 24 W.

Minnegasco B. Flo 1
SW1/4SW1/4 sec. 11, T. 101 N., R. 25 W.

Minnegasco N. Jergensen 1
NE1/4NE1/4 sec. 13, T. 101 N., R. 25 W.

Minnegasco J. Ward 1
NW1/4SW1/4 sec. 16, T. 103 N., R. 24 W.

Minnegasco R. Nehring 1
NE1/4NW1/4 sec. 4, T. 102 N., R. 24 W.

Minnegasco C. Nehring 1
NE1/4SW1/4 sec. 4, T. 102 N., R. 24 W.

Minnegasco D. Gerber 1
SW1/4NE1/4 sec. 8, T. 102 N., R. 24 W.

Minnegasco M. Ganskow 1
SW1/4SW1/4 sec. 21, T. 103 N., R. 24 W.

Minnegasco R. Schroeder 1
SE1/4SW1/4 sec. 28, T. 103 N., R. 24 W.

Minnegasco B. Schroeder 5
SE1/4SW1/4 sec. 28, T. 103 N., R. 24 W.

Minnegasco G. Lorenz WL-4
NW1/4SW1/4 sec. 36, T. 103 N., R. 25 W.

H—Hampton township, Dakota County
N.N.G. Hampton 65-1
NW1/4NW1/4 sec. 4, T. 113 N., R. 18 W.

N.N.G. Hampton 65-2
SW1/4NE1/4 sec. 4, T. 113 N., R. 18 W.

Ho—Hollandale area, Freeborn County
N.N.G. Hollandale 1-A
SE1/4SW1/4 sec. 7, T. 103 N., R. 19 W.

J—Jackson area, Jackson County
Pan Ocean Oil, Ltd., SQ-5
SE1/4SE1/4 sec. 11, T. 102 N., R. 36 W.

L—Lonsdale area, Rice County
N.N.G. Lonsdale 65-1
SW1/4SW1/4 sec. 14, T. 112 N., R. 21 W.

N.N.G. Lonsdale 65-2
NW1/4NW1/4 sec. 14, T. 112 N., R. 21 W.

La—LaSalle area, Watowan County
Pan Ocean Oil, Ltd. SQ-8
SW1/4NW1/4 sec. 11, T. 107 N., R. 31 W.

M—Mable area, Fillmore County
Amselco BO-1
SW1/4SE1/4 sec. 22, T. 101 N., R. 8, W.

Mo—NSP Monticello Plant, Wright County,
14 shallow cores
sec. 33, T. 122 N., R. 25 W.

N—New Prague area, Scott County
N.N.G. J. Pomije (14)
SE1/4SW1/4 sec. 24, T. 113 N., R. 23 W.

O—Ormsby area, Martin County
Pan Ocean Oil, Ltd. SQ-9
SE1/4SW1/4 sec. 1, T. 104 N., R. 32 W.

P—Peterson area, Fillmore County
New Jersey Zinc B-1
NW1/4SW1/4 sec. 25, T. 104 N., R. 9 W.

S—St. Paul, Ramsey County
Univ. of Minnesota BC-1
SE1/4SW1/4 sec. 21, T. 29 N., R. 23 W.

Univ. of Minnesota AC-1
NW1/4SW1/4 sec. 21, T. 29 N., R. 23 W.

V—Vermillion Township, Dakota County
N.N.G. Vermillion 66-2
SW1/4SW1/4 sec. 8, T. 114 N., R. 18 W.

N.N.G. Vermillion 66-3
NE1/4SE1/4 sec. 19, T. 114 N., R. 18 W.

N.N.G. Vermillion 66-4
SE1/4SW1/4 sec. 21, T. 114 N., R. 18 W.

N.N.G. Vermillion 66-9
NW1/4NW1/4 sec 11, T. 114 N., R. 18 W.

N.N.G. Vermillion 66-11
SW1/4NW1/4 sec. 20, T. 114 N., R. 18 W.

W—Waseca-Waterville area, Waseca Rice and LeSueur Counties
Minnegasco Schulette 1
NW1/4NE1/4 sec. 6, T. 108 N., R. 22 W.

Minnegasco C. Prehn 1
NE1/4SW1/4 sec. 6, T. 108 N., R.22 W.

Minnegasco L. Williams 4
SW1/4NE1/4 sec. 7, T. 108 N., R. 22 W.

Minnegasco Melstrom 1
SE1/4SW1/4 sec. 28, T. 109 N., R. 22 W.

Minnegasco Prusky 1
SW1/4SW1/4 sec. 31, T. 109 N., R. 22 W.

Minnegasco Prusky 2
NW1/4SW1/4 sec. 31, T. 109 N., R. 22 W.

Minnegasco H. Fessel 1
SE1/4SE1/4 sec. 36, T. 109 N., R. 23 W.

Wi—Windom area, Jackson County
Pan Ocean Oil, Ltd. SQ-10
NE1/4SE1/4 sec. 4, T. 104 N., R. 35 W.

NOMENCLATURE

Sandstone beds in the lower part of the Upper Cambrian of southeastern Minnesota were originally named the Dresbach Sandstone by N.H. Winchell (1884, p. 180, p. 258; 1886, p. 334-338; 1888, p. xxii) for exposures in the Tostevin quarry in Dresbach, Minnesota, as well as in the Mississippi River bank, in a lead prospect shaft, and in a local well. Winchell (1905, p. 268) extended the formation downward to include all sandstone beds at lower levels above the Precambrian Hinckley Sandstone.

Workers at the Minnesota Geological Survey (Stauffer, Schwartz, and Thiel, 1939; Stauffer and Thiel, 1941) subdivided the Dresbach into three members when they recognized the degree of lithic variability in the interval. The member names—Mt. Simon, Eau Claire (Walcott, 1914, p. 354), and Galesville (Trowbridge and Atwater, 1934)—came from western Wisconsin, where rocks of this interval were better exposed. Most investigators (Twenhofel, Raasch, and Twaites, 1935; Trowbridge and Atwater, 1934) thought that faunal criteria should prevail over lithic in assignment of names to formations and members. This view was given further weight when the "Conference classification" appeared in the Cambrian correlation chart (Howell and others, 1944, col. 61). Then Nelson (1951, 1953, 1956); Bell, Feniak, and Kurtz (1952); and Berg (1953, 1954) recognized that lithostratigraphic and biostratigraphic units are nomenclaturally independent. They restricted the Eau Claire to the medial, generally thin- and horizontally bedded, fine-grained sandstone and shale beds, and included coarser-grained, crossbedded sandstone beds, whether they contained fossils or not, in the Mt. Simon and Galesville. Though Berg, Nelson, and Bell (1956) used Dresbach as a formational name, it has come to be used almost exclusively as a biostratigraphic term, and the Mt. Simon, Eau Claire, and Galesville have been raised to formational rank (Fig. 2) (Austin, 1969).

Ostrom (1965, 1966, 1967) proposed that the Galesville be included with the overlying Franconian Ironton Sandstone in the Wonewoc Formation (Fig. 2), and the Wonewoc with the Mt. Simon and Eau Claire in the Elk Mound Group. Ostrom (1970, p. 26) gives the following reasons to include the Galesville in the overlying Franconian Stage:

1) Widespread unconformity between the Eau Claire and Galesville Formations in Wisconsin (Fig. 3);
2) Absence of the uppermost Dresbachian faunal zone from the Eau Claire in western Wisconsin;
3) Absence of diagnostic fossils in the Galesville; and
4) Apparent lack of unconformity between the Galesville and Ironton.

Ostrom (1970) mentions that the Galesville/Eau Claire contact appears to be transitional in the Hollandale embayment in Minnesota (Austin, 1970) and in the Illinois basin (Emrich, 1966). He also states that marine waters may have lingered in negative areas, and more recessive upper Eau Claire sedimentary rocks may have been preserved in the subsiding regions. Because of reported Dresbachian trilobites in Galesville Sandstone of Minnesota (Berg and others, 1956), evidence for a disconformity at the top of the Galesville, and an apparent gradational contact between the Galesville and Eau Claire in Minnesota, the Galesville Sandstone is retained in the Dresbach in this report.

In Minnesota there is lithologic evidence of an upward shallowing trend in uppermost Eau Claire strata and basal overlying strata included in the Galesville. For example, a general upward coarsening of grain size begins near the middle and continues to the top of the Eau Claire Formation. Cross-stratified sandstone beds similar to those in the overlying Galesville are interbedded with upper Eau Claire rocks. The contact between formations on gamma and resistivity logs is rounded, rather than abrupt or marked by a sharp deflection (Woodward, 1984); this supports the interpretation of gradational contact.

At two of the cored locations (Locs. B and W, Fig. 1), where the Galesville/Eau Claire contact is disconformable, the base of the Galesville Sandstone is at the base of trough-cross-stratified sandstone beds that rest on scour surfaces. Generally, basal Galesville has fine horizontal stratification, with little or no evidence of disconformity in core. Mossler

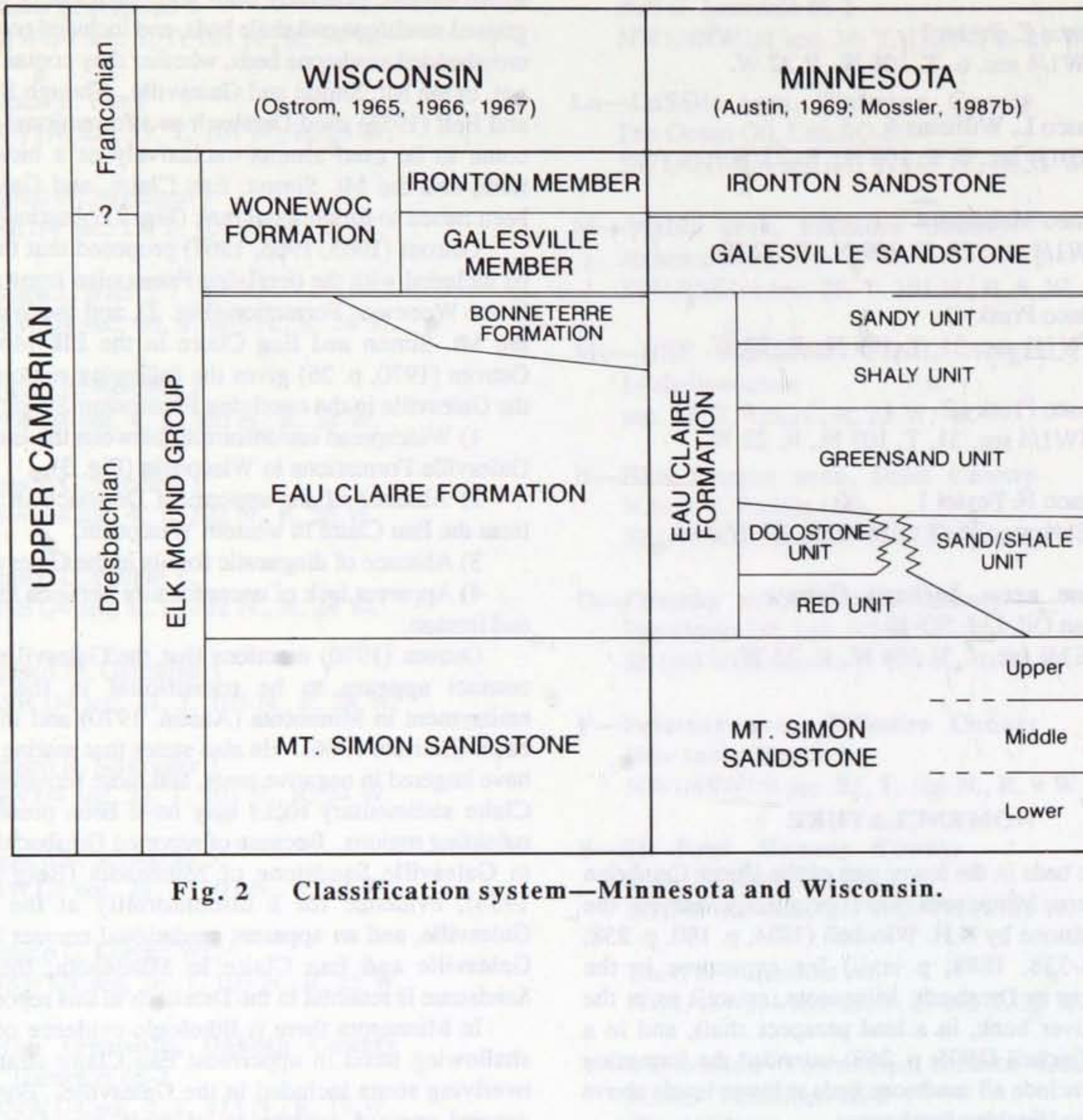


Fig. 2 Classification system—Minnesota and Wisconsin.

(1972) reported this contact as discomfortable in Dakota County; however, reexamination of core from the area showed the contact to be conformable.

Diagnostic fauna are scarce in upper Eau Claire and basal Galesville. Berg, Nelson, and Bell (1956, p. 16) report *Aphelaspis* zone fauna in Galesville Sandstone at Hudson, Wisconsin; and *Crepicephalus iowensis* subzone fauna in Galesville Sandstone at La Crescent and Dresbach, Minnesota. Emrich (1966) and Lochman-Balk (1971, p. 104-105) report *Aphelaspis* zone fauna in Galesville Sandstone. These faunas indicate the Dresbachian.

The contact between the Galesville Sandstone and overlying Ironton Sandstone is disconformable where observed in cores and outcrop in Minnesota. In some cases, the contact is marked by iron oxide incrustation and slight erosional relief at the top of the Galesville (Loc. B, Fig. 1), or by a thin intraclastic zone at the base of the Ironton (Loc. P). It is commonly identified in outcrop and core by subtle lithological differences between the Ironton and the Galesville: The Ironton is poorly sorted, fine- to very coarse grained, silty, slightly glauconite quartz arenite; uppermost Galesville is moderately to well-sorted, very fine to medium-

Fig. 3 Galesville Sandstone/Eau Claire Formation contact in western Wisconsin. Quarry in NE1/4NW1/4 sec. 9, T. 23.W., R. 8 W., Trempealeau County. Hammer lies along disconformity at top of the Eau Claire Formation.

grained, nonglauconitic sandstone that ranges in composition from quartz arenite to highly feldspathic (>25 percent) arenite (see Fig. 28a, p. 48). Ironton beds are fossiliferous. In places they contain brachiopod coquina (Nelson, 1950) and trilobites that indicate the Franconian (Berg and others, 1956). Galesville beds are generally cross stratified, but may be structureless or have fine, planar stratification. Both sandstone formations are generally friable; recovery of the contact in core and preservation of the contact in outcrops are uncommon. Well cuttings for both sandstone units generally consist of loose sand grains that tend to recirculate in drilling fluid and mix, making it difficult to determine exact position of the contact.

Although most investigations in neighboring states consider the Ironton/Galesville contact conformable (Ostrom, 1966; William and others, 1975), Emrich (1966) observed what he thought was considerable relief on the Ironton/Galesville contact in subsurface in Illinois. He conceded that some of the apparent relief could be because of facies changes in the Ironton, the Galesville, or both. He also observed that this contact in the outcrop area of Minnesota and Wisconsin is disconformable.

METHODS

Rock cores, the principal source of information, were described in detail and sampled for thin sections. Outcrops of the Mt. Simon Sandstone and Eau Claire Formation in western Wisconsin described by Huber (1975) and Driese (1979) were examined to compare sedimentary structures in cores with those in outcrops.

Intensity variations in geophysical logs were compared to lithic variations in cores to establish typical geophysical (gamma and resistivity) signatures for different lithofacies.

Well cuttings were redescribed to better characterize lithofacies and establish distributions.

Thin sections were stained for potassium feldspar and plagioclase using cobaltinitrite and amaranth dye (Laniz and others, 1964). They were then described, and selected thin sections were point-counted and classified using the sandstone classification developed by Odom (1975) (see Fig. 25a, p. 42). Three hundred or more points were counted along regular traverses using a mechanical stage. Most sandstone classifications are unsatisfactory for Upper Cambrian sandstone of the Midwest because they do not take into account the abundance of glauconite, a primary constituent in many of the sandstone beds. Several thin sections were examined for relict quartz overgrowths using cathode luminescence.

GEOLOGIC SETTING

The Phanerozoic rocks of the northern Midcontinent overlie Archean and Proterozoic igneous, sedimentary, and metamorphic rocks with profound unconformity. These Precambrian rocks formed during several successive orogenic episodes. The last major orogenic event in the region, creation of the Midcontinent Rift System, is of major importance to early Phanerozoic history in Minnesota. Isostatic or thermal adjustments along the rift that began during the Middle Ordovician created the syncline in which lower Paleozoic rocks are preserved.

During the Upper Cambrian, a broad lowland named the Hollandale embayment (Austin, 1969) extended across southeastern Minnesota and eastern Iowa (Fig. 4). This

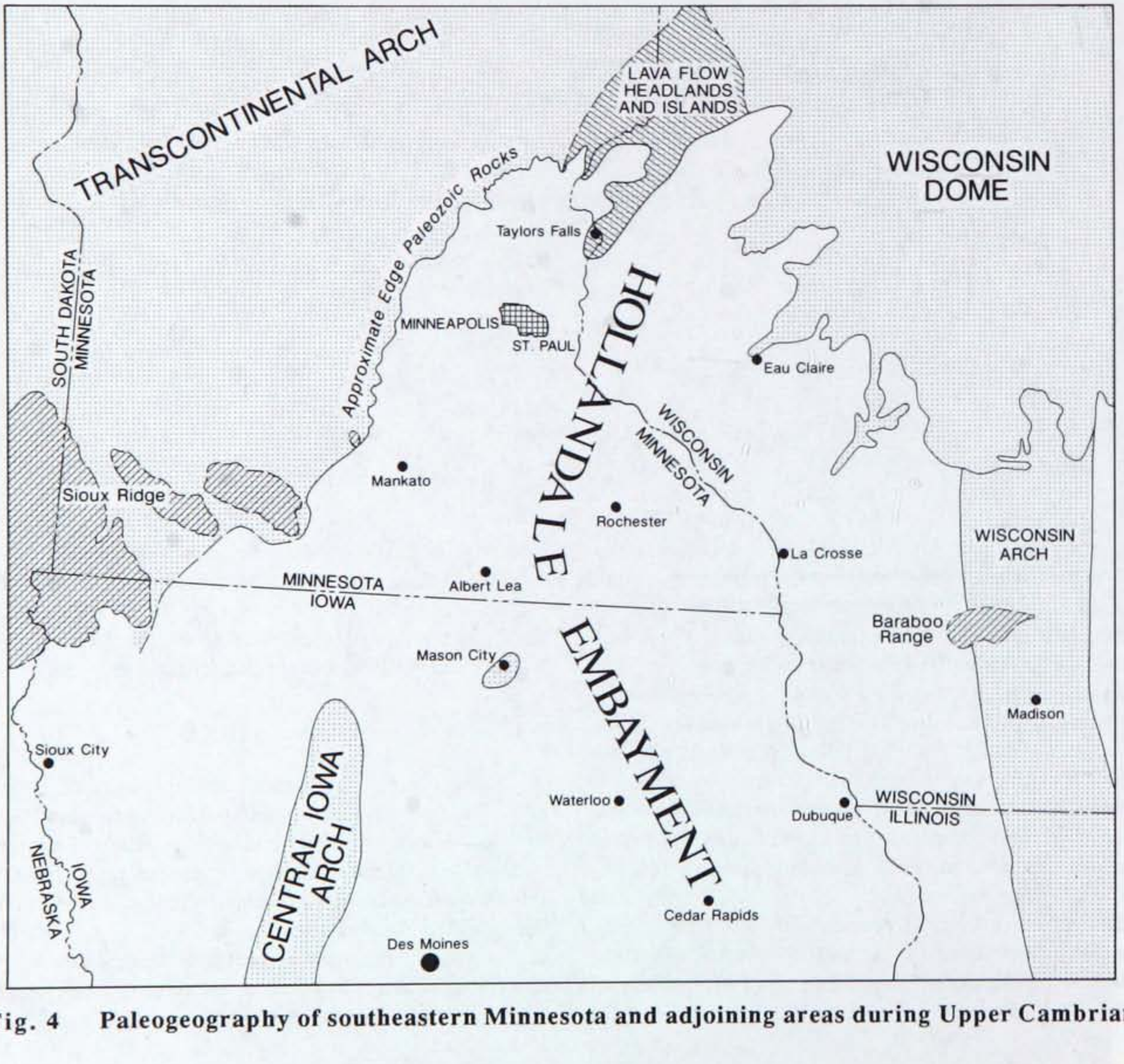


Fig. 4 Paleogeography of southeastern Minnesota and adjoining areas during Upper Cambrian.

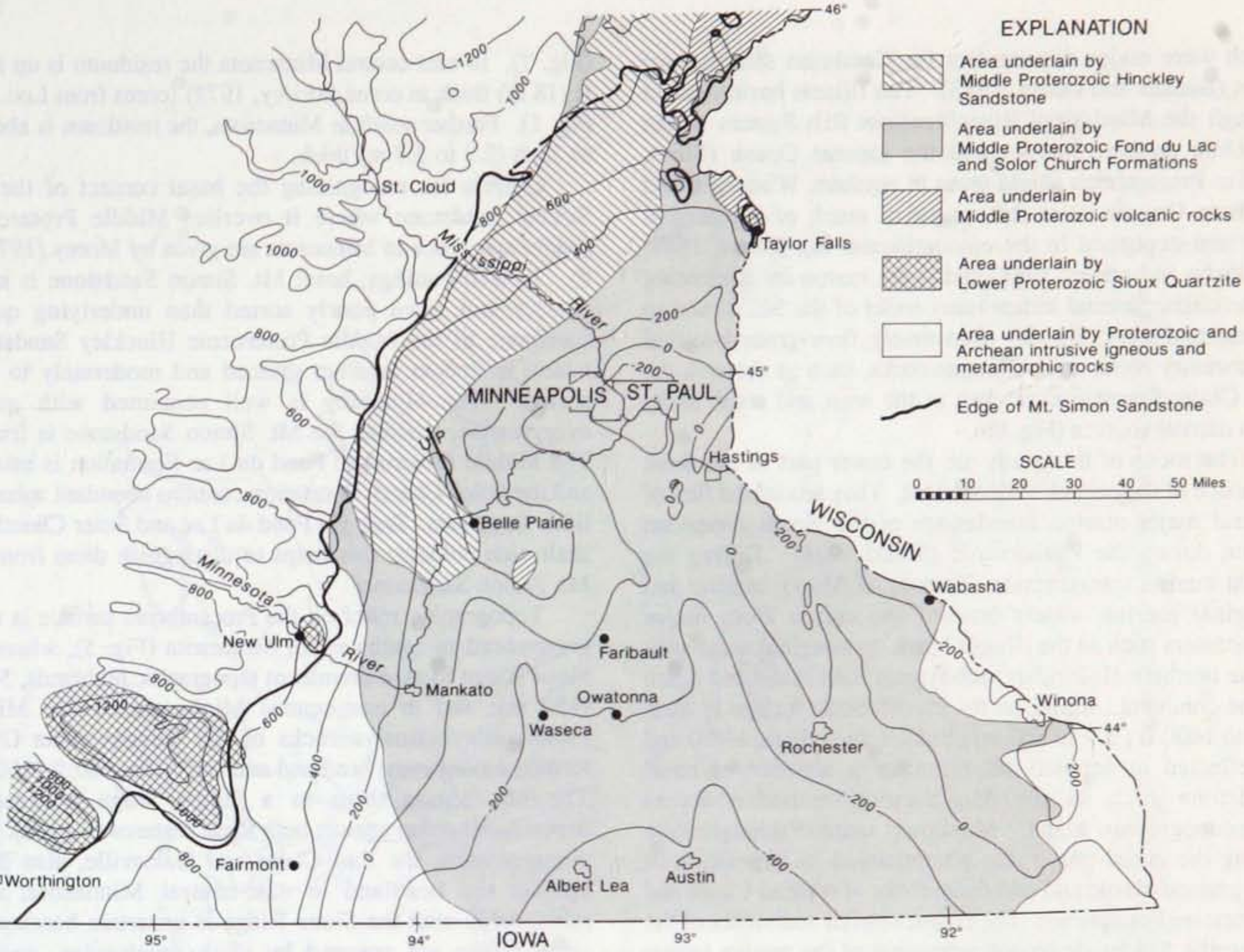


Fig. 5 Configuration of Precambrian/Cambrian contact and distribution of Precambrian formations at contact. Contour interval is 200 ft (61 m).

lowland was flanked by several highlands. To the west in Minnesota it was flanked by four southeast-northwest-trending quartzite ridges of Sioux Quartzite created by differential erosion. The Proterozoic Sioux Quartzite is much more resistant to erosion than flanking, older Precambrian formations. To the north, a prominent headland and islands that were formed from Middle Proterozoic volcanic rock of the Midcontinent Rift System persisted through the Upper Cambrian. Similar highlands of Proterozoic volcanic rock lay along the Midcontinent Rift System in western and north-central Iowa (Bunker and others, 1988).

To the northeast, in northern Wisconsin, the Hollandale embayment was bordered by the Wisconsin dome, a broad positive feature that supplied much detrital sediment during the Upper Cambrian, and by its southerly extension, the Wisconsin arch. Hills caused by differential erosion of Proterozoic quartzite or other resistant rocks also lay east of the Hollandale embayment; for example, the Baraboo Hills, an erosional remnant of Proterozoic quartzite, lay near the crest of the Wisconsin arch.

The paleoslope of the Hollandale embayment (Fig. 5) was south toward the modern Illinois basin and Ozark uplift, which were major depocenters for Cambrian sedimentary rocks (Bunker and others, 1988). The Illinois basin opened through the Mississippi River/Reelfoot Rift System to the Ouachita positive margin and the Iapetus Ocean (Sloss, 1988). Precambrian shield areas in northern Wisconsin and southern Ontario were the source of much of the detrital sediment deposited in the epicontinental sea (Sloss, 1988; Collinson and others, 1988) and is the reason for thickening of the coarse detrital sedimentary rocks of the Mt. Simon to the east and north (Fig. 6a). Conversely, finer-grained detrital sedimentary rocks and carbonate rocks, such as those in the Eau Claire Formation, thicken to the west and south away from detrital sources (Fig. 6b).

The rocks of this study are the lower part of the Sauk sequence of the central Midcontinent. They record the first of several major marine inundations of the North American craton during the Phanerozoic (Sloss, 1988). During the initial marine transgression (Sauk II of Sloss), marine and marginal marine waters crossed the craton from major depocenters such as the Illinois basin, to marginal areas such as the northern Hollandale embayment, and inundated much of the continent. Relief on the Precambrian surface is from 300 to 1600 ft (100 to 500 m) (Bunker and others, 1988) and is reflected in depositional thinning or absence of basal sandstone such as the Mt. Simon Sandstone across paleotopographic highs. Maximum marine transgression during the initial phase was accompanied by deposition of fine-grained clastic and carbonate rocks of the Eau Claire and Bonneterre Formations. The coarse detrital sediments of the Galesville Sandstone record regression of the marine waters prior to their readvance during the Sauk III episode. The Sauk III marine transgression resulted in deposition of younger formations such as the Ironton Sandstone and Franconia Formation.

BASAL UNCONFORMITY

The Mt. Simon unconformably overlies several rock units of Precambrian age in Minnesota, as it does across the Midcontinent. Along the axis of the Hollandale embayment, the units are principally Middle Proterozoic sedimentary rocks associated with the Midcontinent Rift System (Fig. 5). Along some local structural highs within the rift, felsite, basalt, or other extrusive igneous rocks lie directly below the Mt. Simon Sandstone or beneath a thin veneer of the Middle Proterozoic sedimentary rocks. Proterozoic and Archean metamorphic and intrusive igneous rocks flank the rocks of the Midcontinent Rift System (Fig. 5). Generally, these are granitic and gneissic rocks with a thin residuum of kaolinite and mixed layer of mica/montmorillonite (Morey, 1972) at the top along their contact with the Mt. Simon Sandstone (Fig. 7). In east-central Minnesota the residuum is up to 60 ft (18 m) thick in cores (Morey, 1972) (cores from Loc. Mo, Fig. 1). Farther south in Minnesota, the residuum is about 9 to 12 ft (2.7 to 3.7 m) thick.

Criteria for recognizing the basal contact of the Mt. Simon Sandstone where it overlies Middle Proterozoic sedimentary rock in Minnesota are given by Morey (1977, p. 8). In well cuttings, basal Mt. Simon Sandstone is much coarser and more poorly sorted than underlying quartz sandstone of the Middle Proterozoic Hinckley Sandstone, which is fine to medium grained and moderately to well sorted. The Hinckley is well cemented with quartz overgrowths, whereas the Mt. Simon Sandstone is friable. The Middle Proterozoic Fond du Lac Formation is arkosic, and the Solor Church Formation contains abundant aphanitic lithic fragments. Both the Fond du Lac and Solor Church are shale-rich redbeds; this helps to distinguish them from the Mt. Simon Sandstone.

Topographic relief on the Precambrian surface is most pronounced in southwestern Minnesota (Fig. 5), where the Sioux Ridge formed prominent topographic highlands, 500 ft (150 m); and in east-central Minnesota, where Middle Proterozoic extrusive rocks of the Chengwatana Group formed a prominent headland and sea cliffs, 500 ft (150 m). The Mt. Simon thins to a feather edge because of depositional onlap against both these features (Fig. 6a). The younger units, the Eau Claire and Galesville, also onlap against the headland in east-central Minnesota; their relationship with the Sioux Ridge is uncertain because the ridge flanks are covered by thick overburden, and the formations appear to have been stripped back from the Sioux Ridge by postdepositional erosion.

Elsewhere in the Hollandale embayment, relief on the predepositional surface created local thickness variations in the Mt. Simon Sandstone. This relief is generally not apparent because most holes reaching the Precambrian are far apart; where well-control is dense, such as along the Vermillion anticline in Dakota County (Fig. 1, Loc. V), local relief on the surface is documented (Mossler, 1972).

LITHOFACIES

The sedimentary rocks of the Mt. Simon Sandstone, Eau Claire Formation, and Galesville Sandstone are divided into eleven lithofacies, and some further subdivided into subfacies (Table 1). With the exception of the basal conglomerate, these lithofacies are repeated within the stratigraphic sequence, indicating that the environmental conditions under which they formed recurred during the Dresbachian. Relationships between lithofacies and lithostratigraphic units are shown in Figs. 8 and 9 and in Appendix 1.

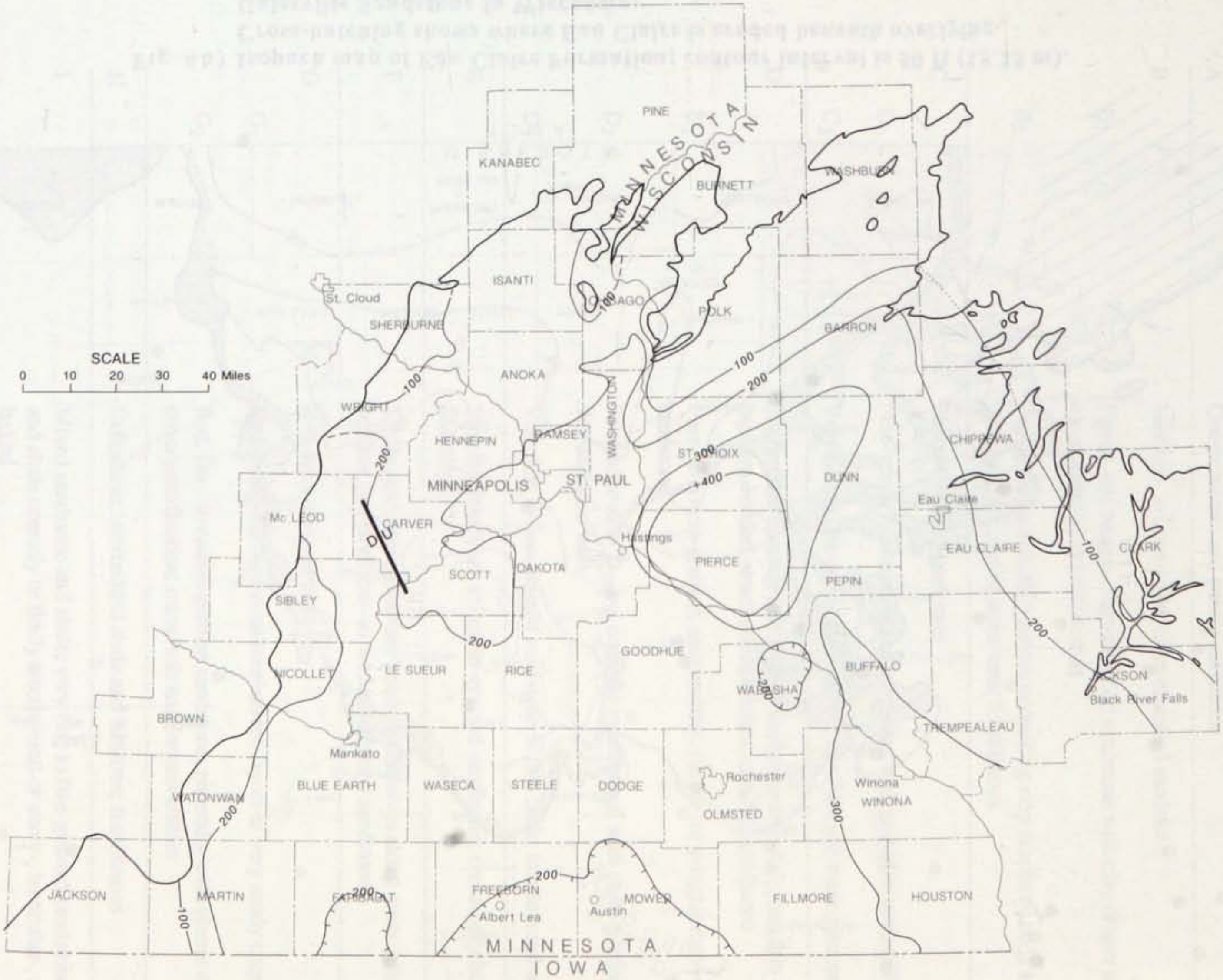


Fig. 6a) Isopach map of Mt. Simon Sandstone; contour interval is 100 ft (30.5 m).

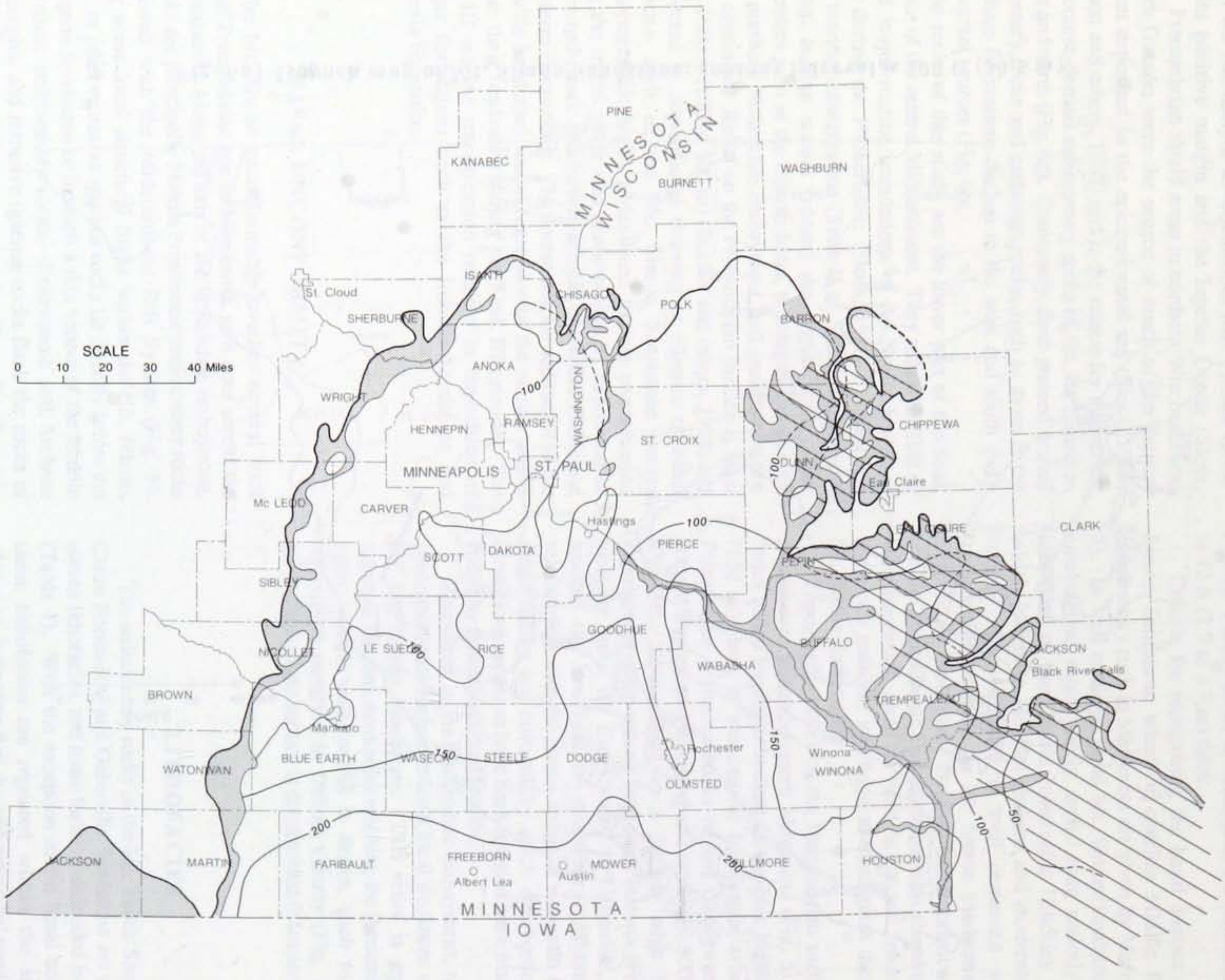


Fig. 6b) Isopach map of Eau Claire Formation; contour interval is 50 ft (15.25 m). Cross-hatching shows where Eau Claire is eroded beneath overlying Galesville Sandstone in Wisconsin.

Table 1 Lithofacies and subfacies of Dresbachian rocks of Minnesota with brief lithologic descriptions

Lithofacies and subfacies	Principal lithology
A	Conglomerate and pebbly sandstone
B	Medium- to large-scale, cross-stratified sandstone
B_1	Planar- and trough-cross-stratified sandstone with clay drapes and conglomerate; unfossiliferous
B_2	Trough-cross-stratified sandstone lacking clay drapes or beds with conglomerate and/or intraclasts; fossilferous
C	Planar-stratified sandstone
C_1	Fine- to very coarse grained sandstone with granules; unfossiliferous
C_2	Very fine to fine-grained sandstone; fossiliferous; trace glauconite
D	Interbedded coarsely interlayered sandstone and shale, and thin- to medium-bedded, structureless or cross-stratified sandstone
D_1	Fine- to coarse-grained, structureless, planar- or trough-cross-stratified sandstone
D_2	Sandstone as in D_1, but coarsely interlayered with shale partings and thin siltstone beds
D_3	Very fine to fine-grained sandstone in thin beds; interlayered with shale
E	Structureless, fine- to coarse-grained sandstone; commonly burrowed by *Skolithos*
F	Shelly sandstone; abundant brachiopod valves along cross sets and bedding planes of fine- to medium-grained sandstone
G	Red sandstone and shale
G_1	Red shale with numerous interbedded layers of very sandy coquina
G_2	Red, fine- to coarse-grained sandstone, generally with planar or trough cross stratification; intraclasts and ferroan oolites
H	Dolostone; interbedded shale and siltstone; fossilferous
I	Mixed sandstone and shale; very fine to fine-grained sandstone, siltstone, and shale coarsely or finely interlayered or wavy-, lenticular-, or flaser-bedded
J	Greensand; siltstone to very fine grained glauconitic sandstone; planar or trough cross stratification
K	Shale and siltstone, lenticular- or wavy-bedded; fossiliferous

Fig. 7 Mt. Simon/Precambrian contact at Irving Park, Chippewa Falls, Wisconsin (Chippewa County). Weathered zone at top of Precambrian is recessive. Hammer on rock slab shows scale.

Lithofacies A—Basal Conglomerate

This lithofacies consists of conglomerate and pebbly sandstone and is from 5 to 6 ft (1.5 to 1.8 m) thick. It is at the base of the Mt. Simon Sandstone in some but not all cores from Locations V and H (Fig. 1) in the northeastern part of the Hollandale embayment. It is also in the outcrop in western Wisconsin (Driese, 1981) (Table 2). Thin remnants of the basal conglomerate up to 6 in (15 cm) thick are in cores from the eastern (Loc. P, Fig. 1) and western (Locs. 0 and J) margins of the Hollandale embayment. The basal conglomerate underlies lithofacies B (medium- and large-scale, cross-stratified sandstone), and lithofacies C (planar-stratified sandstone). Where the basal conglomerate is absent, these lithofacies are at the base of the Mt. Simon. The contacts between the basal conglomerate lithofacies and adjoining lithofacies are sharp and interpreted as erosional.

The conglomerates and pebbly sandstone are poorly sorted quartz arenite and contain very fine to very coarse grained sand. Lenses of siltstone are present. Conglomerates are structureless or crudely stratified and not imbricate. Pebbles are polycrystalline quartz and quartzite-supported in the sandstone matrix; there is no apparent grading.

Lithofacies B—Medium- and Large-Scale, Cross-Stratified Sandstone

This lithofacies consists of medium to thick bedsets of cross-stratified sandstone. The lithofacies is distributed throughout the Hollandale embayment, principally in the lower Mt. Simon Sandstone. It is also in the Galesville Sandstone and overlying Franconian Ironton Sandstone. It is subdivided into two subfacies.

Subfacies B_1, which is developed in lower Mt. Simon Sandstone, is thickest in the southwestern Hollandale embayment (Loc. B, Fig. 1, Fig. 8), where it reaches 163 ft (49.7 m). It is also well developed on the eastern margin of the Hollandale embayment (Locs. H, V, P, and M, Fig. 8) and is equivalent to a major part of the lower lithofacies of the Mt. Simon Sandstone in Wisconsin described by Driese (1981) (Table 2). The subfacies is commonly interbedded with lithofacies C (planar-stratified sandstone) and underlies lithofacies D (interbedded, coarsely interlayered sandstone and shale; and thin- to medium-bedded, structureless or cross-stratified sandstone).

The subfacies is principally medium to thick sets of planar-crossbedded sandstone with high-angle (25 to 30°) foresets (Fig. 10). Sets generally have sharp upper and lower bounding surfaces. There are also bedsets of trough-cross-stratified sandstone that have low-angle (<15 to 20°) foresets with curved laminae and scoured bases. Some cross stratification cannot be positively identified in core because of poor core-recovery or preservation. Rarely, minor complex cross stratification can be identified; for example, small-scale, ripple cross lamination along foresets of larger-scale, cross-stratified beds. Reactivation surfaces are also present (Loc. La, Fig. 1).

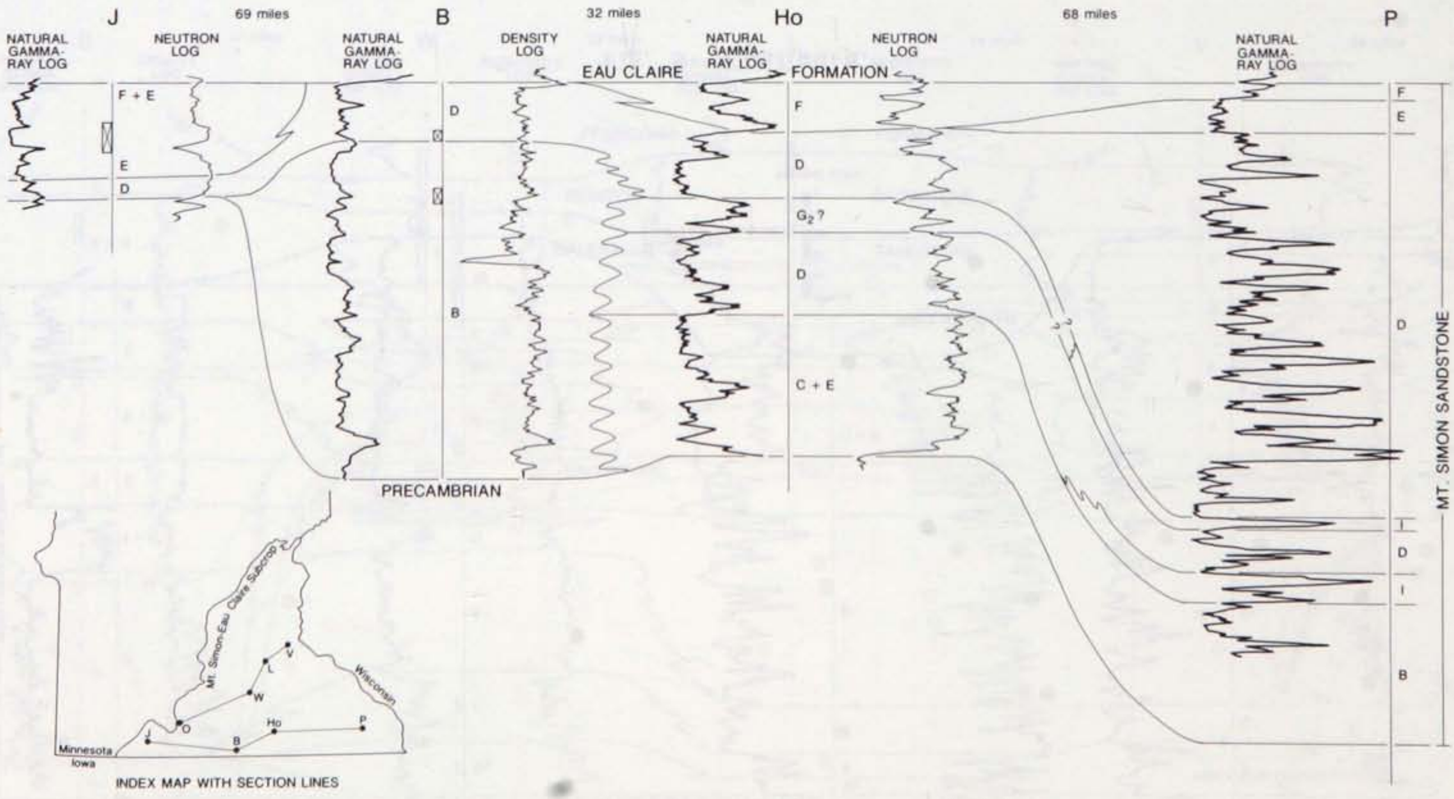


Fig. 8 **Geologic sections showing lithofacies distribution in the Mt. Simon Sandstone across the Hollandale embayment. Letters across the top refer to locations on Fig. 1. Letters within figure refer to lithofacies discussed in text. Section lines shown on inset map.**

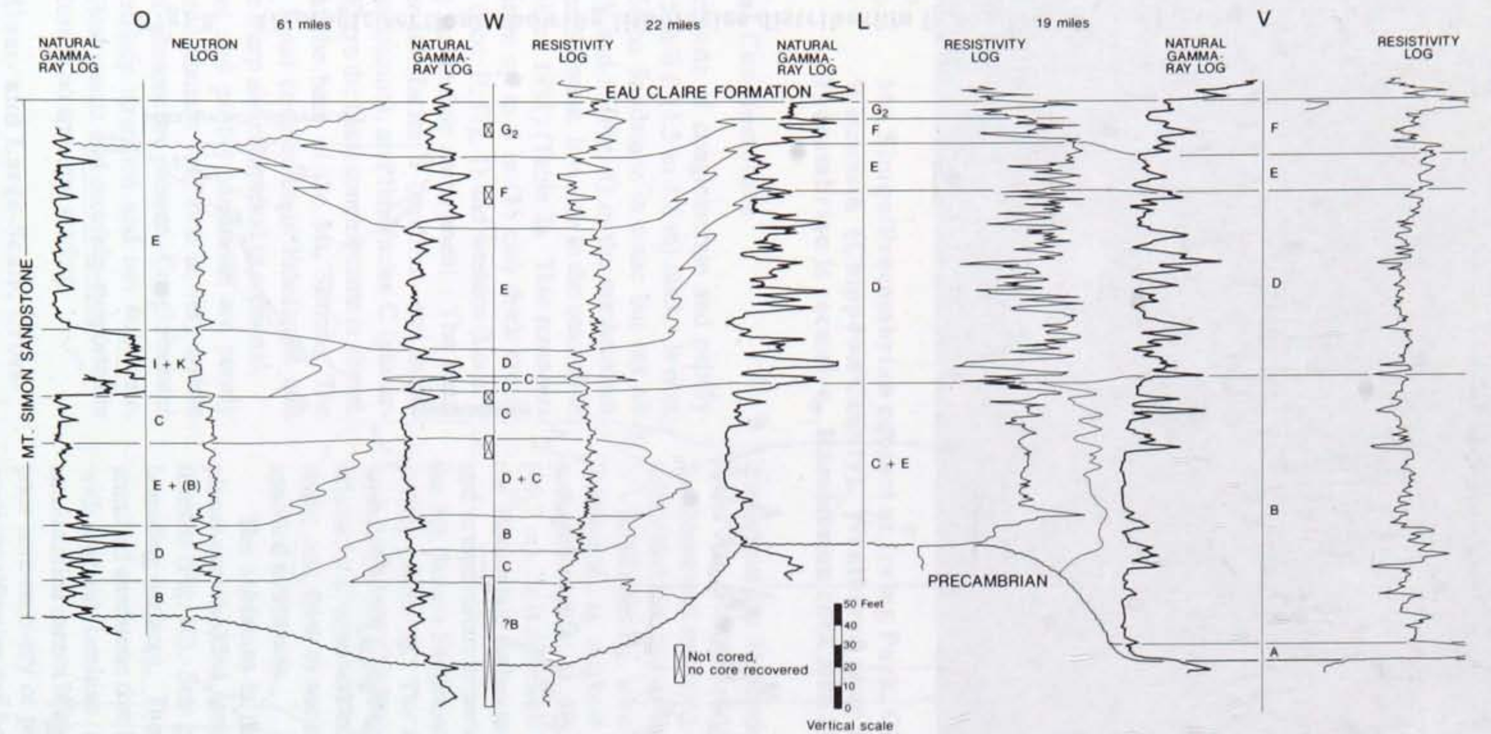


Fig. 8 Continued.

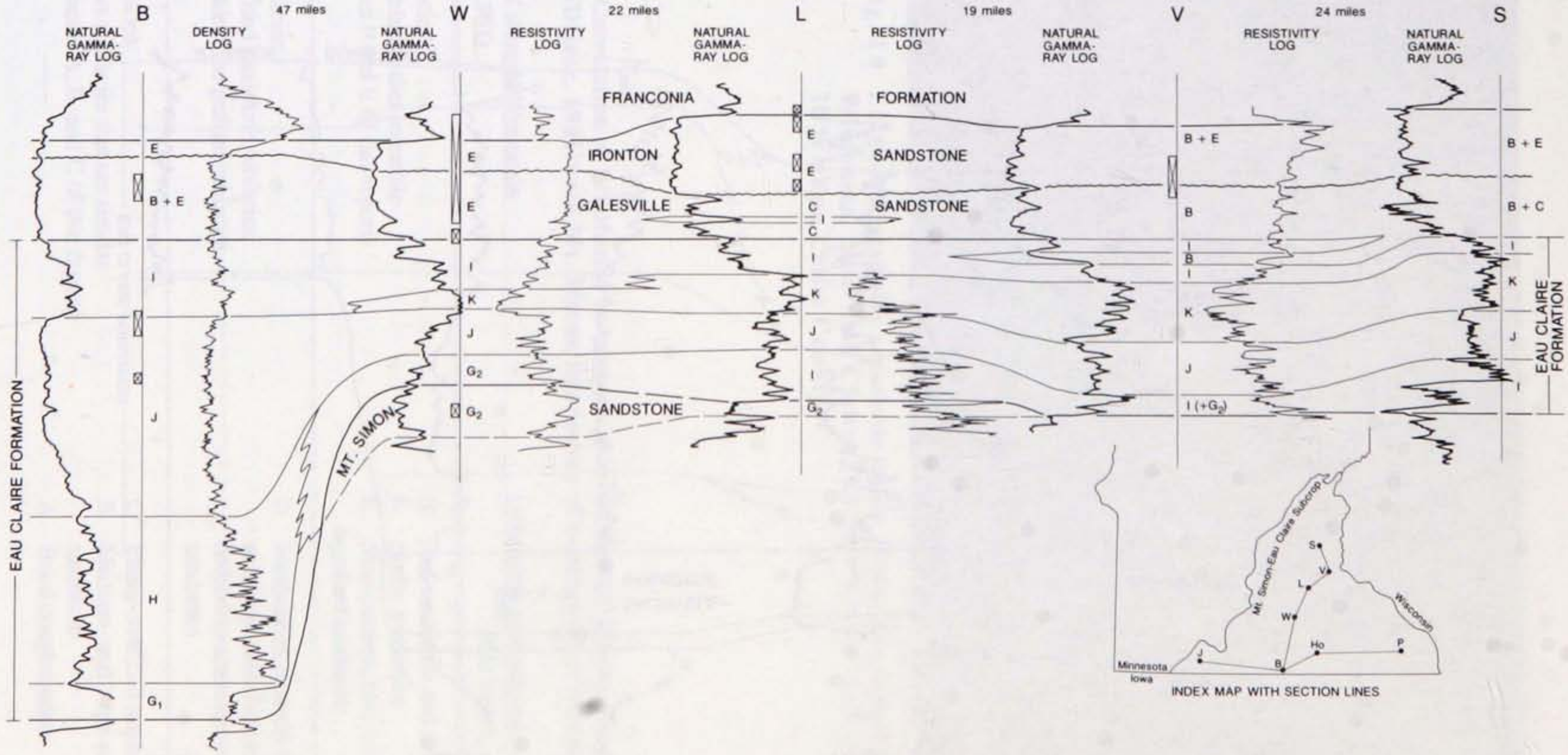


Fig. 9 Geologic sections showing lithofacies distribution in Eau Claire Formation and Galesville Sandstone across the Hollandale embayment. Letters across the top refer to locations on Fig. 1. Letters within figure refer to lithofacies discussed in text. Section lines shown on inset map.

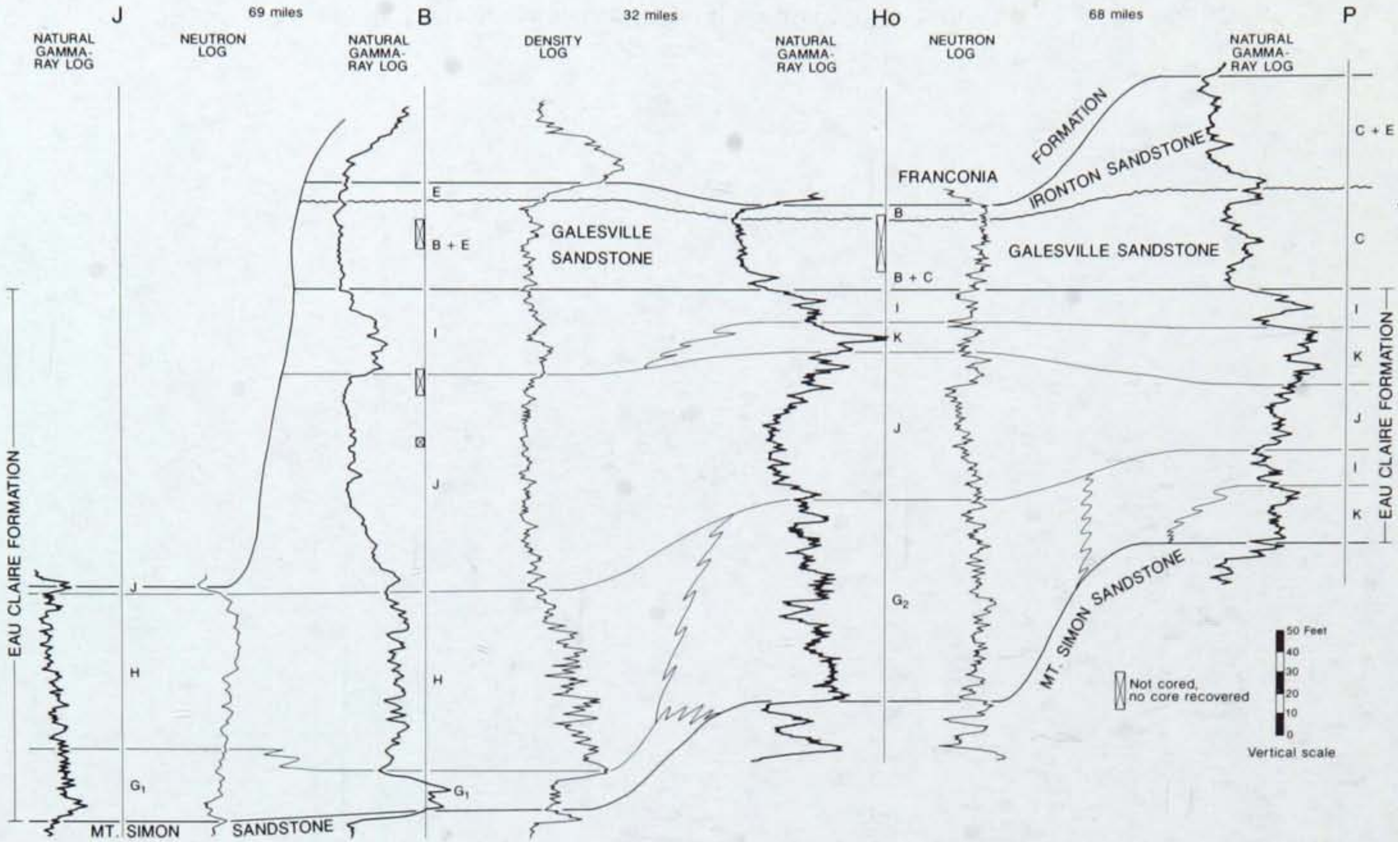


Fig. 9 Continued.

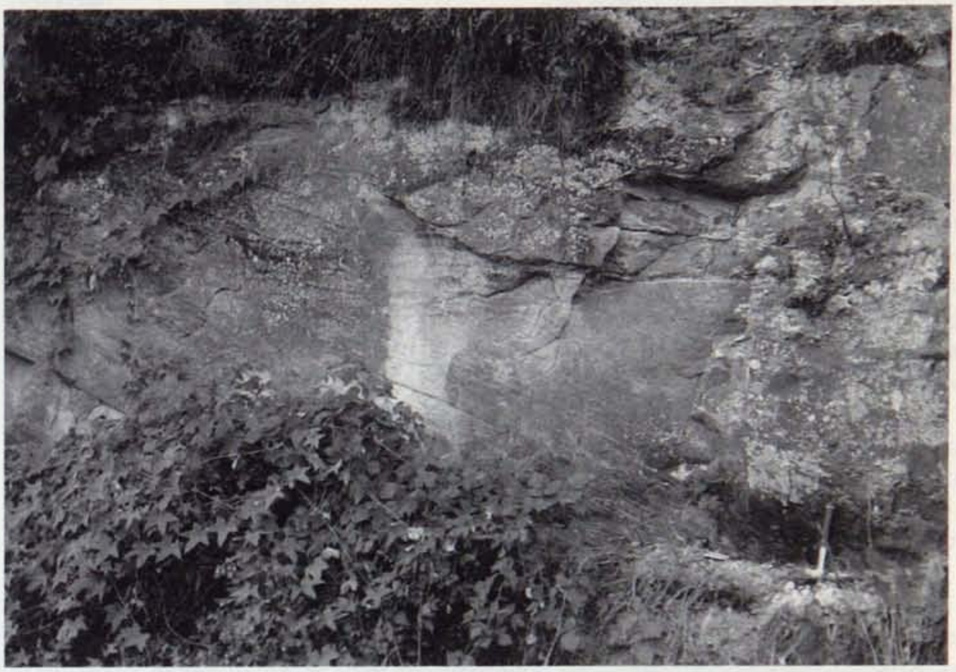


Fig. 10 Large-scale tabular crossbeds in Mt. Simon Sandstone, western Wisconsin. Near Eau Claire, SE1/4NW1/4 sec. 1, T. 26 W., R. 10 W., Eau Claire County.

Table 2 Correlation of lithofacies in western Wisconsin Mt. Simon Sandstone outcrop (Driese, 1981)with Mt. Simon Sandstone of southeastern Minnesota

Lithofacies of western Wisconsin (Driese 1981)		Lithofacies of southeastern Minnesota (this report)
Upper lithofacies	G	Red sandstone and shale, in part
(Two subfacies that resemble	F	Shelly sandstone
lithofacies F and E of this report)	E	Structureless, fine- to coarse-grained sandstone
Middle lithofacies	D	Interbedded, coarsely interlayered sandstone and shale and thin- to medium-bedded structureless or cross-stratified sandstone
Crossbedded sandstone subfacies		
Thin-bedded fine-grained subfacies		
Lower lithofacies	C	Planar-stratified sandstone
(Contains subfacies that are similar	B	Medium- and large-scale, cross-stratified sandstone
to lithofacies A, B, and C of this report)	A	Basal conglomerate

Fig. 11 Granules along bedding plane of lower Mt. Simon Sandstone, western Wisconsin. Irvine Park, Chippewa Falls, Chippewa County. Lens cap shows scale.

Subfacies B_1 is principally moderately to well-sorted, medium- to very coarse grained quartz arenite, although some sets are of fine-grained sandstone. Intraclasts lie along scours at the base of some sets and along foresets. The subfacies is one of the coarser-grained units in the Dresbachian, with granule- to pebble-sized quartz grains along scours and crossbed sets (Fig. 11). Thin conglomerate lenses above some scour surfaces contain pebbles up to 0.6 in (1.5 cm) in diameter.

Although some foresets have inverse graded (avalanche) stratification with coarser zones over finer, grading generally is normal. In some cases, though, it is difficult to determine whether grading is normal or inverse.

Heavy minerals are concentrated in small placers along some laminae (Locs. M and B, Fig. 1). The subfacies contains neither body nor trace fossils. However, trace glauconite grains are in core near the base at Location H.

Shale and siltstone beds are uncommon and generally thin—up to 3 in (7.5 cm), rarely twice that—and sharply bounded. Generally, they are separated from overlying coarse sandstone or conglomerate by an erosional surface, though in rare cases, shale beds grade up into an overlying sandstone bed (Loc. B, Fig. 1). Some shale beds appear to be clay drapes. Shale beds are pale reddish brown, pale red, and greenish gray. Sandstone beds are red-tinted: grayish orange pink, light brown, and pale yellowish brown. The predominance of quartz arenite interspersed with minor thin shale beds gives gamma/resistivity logs of this subfacies a distinctive pattern of rectangular forms with blunt bases and tops (Fig. 12). In some intervals, gamma logs with decreasing upward intensities indicate a gradational upward increase of average grain size. Location B has intraformational deformation (slumping, small-scale faulting). Minor secondary silicification is in this subfacies, but is otherwise rare in the Dresbachian.

Subfacies B_2 is found principally in the Galesville Sandstone in northern and eastern parts of the Hollandale embayment (Locs. M and V), is generally 25 to 50 ft (7.6 to 15.2 m) thick, and is interbedded with lithofacies C, planar-stratified sandstone, with minor beds of structureless sandstone. Where present at the base of the Galesville, subfacies B_2 overlies and is interbedded with lithofacies I, mixed sandstone/shale (see Fig. 20, p. 29). Subfacies B_2 is also in the lower Mt. Simon Sandstone in the eastern part of the Hollandale embayment (Loc. H) at thicknesses up to 37 ft (11.2 m). There it is interstratified with subfacies B_1 and appears to be laterally equivalent to lithofacies C, planar-stratified sandstone (Fig. 13).

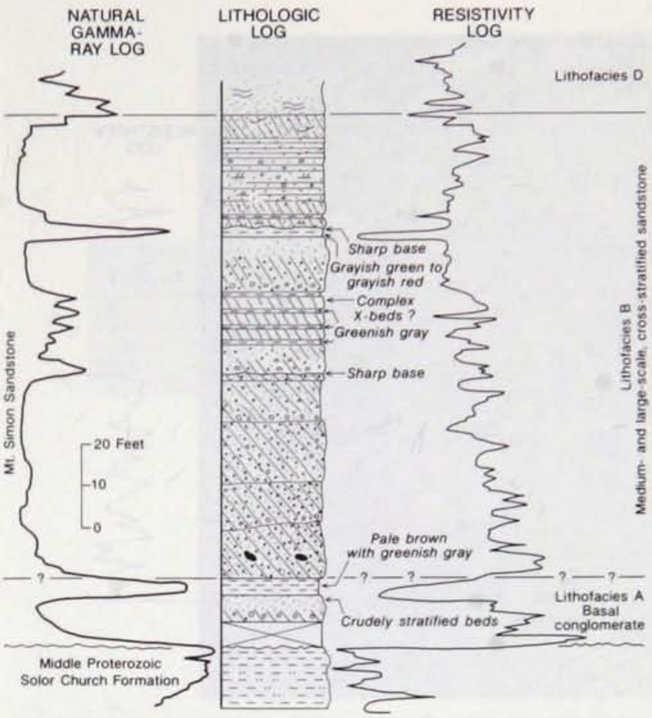


Fig. 12 Columnar section of lower lithofacies of Mt. Simon Sandstone (from core at Loc. V on Fig. 1).

The subfacies is primarily medium sets of trough-cross-stratified sandstone. The sandstone is very fine to medium-grained, well-sorted quartz arenite. Coarse, sand-sized grains and granules are rare. The shale beds are much thinner than those in subfacies B_1 and are generally thin partings or beds less than 1 in (2.54 cm) thick. No prominent scour surfaces are overlain by conglomerate zones and intraclasts, as in subfacies B_1.

Where present in the Galesville Sandstone, this subfacies has abundant dark comminuted fossil fragments, principally from phosphatic brachiopods, distributed along foresets; the sandstone is very slightly glauconitic.

Lithofacies C—Planar-Stratified Sandstone

The sandstone in this lithofacies typically has horizontal or near-horizontal fine, planar stratification; or, less commonly, very low-angle (possibly translatent ripple) cross stratification or ripple cross stratification.

The lithofacies is principally in the lower part of the Mt. Simon Sandstone, where it is most fully developed in northern and eastern parts of the Hollandale embayment

The lithofacies is principally in the lower part of the Mt. Simon Sandstone, where it is most fully developed in northern and eastern parts of the Hollandale embayment (Locs. V, H, and L, Fig. 8). In outcrop in the Mt. Simon Sandstone in Wisconsin, it is included as part of Driese's (1981) lower lithofacies (Table 2). In the Galesville Sandstone, it is best developed in cores from the eastern and northern margins of the embayment (Locs. L, V, H, and P, Fig. 9). The lithofacies is generally overlain, underlain, and/or interbedded with sandstone classified as lithofacies B, medium- to large-scale, cross-stratified sandstone; and lithofacies E, structureless sandstone. It may also grade up into and be interbedded with beds of lithofacies D. It has a maximum thickness of 28 ft (8.5 m) in lower Mt. Simon Sandstone at Location L (Fig. 1). Approximately 45 ft (13.7 m) of this lithofacies is in lower Mt. Simon in two separate intervals at Location H. The thickest sequence of this lithofacies in the Galesville Sandstone, which attains 67 ft (20.4 m), is at Location P .

The planar-stratified sandstone of the Mt. Simon (**subfacies C_1**) consists of fine to very coarse sand grains and granules. It is moderately to well sorted, and laminae are upward fining. Minor thin—1 to 2 in (2.54 to 5.1 cm)—beds of unlaminated, very coarse sand- to granule-sized sandstone are interbedded with the finer planar-stratified sandstone. The planar-stratified sandstone of the Galesville (**subfacies C_2**) is finer grained than that in the Mt. Simon, generally very fine to fine grained with minor medium grains. The Galesville is associated with marine indicators: bands of phosphatic brachiopod fragments aligned parallel to bedding and glauconite traces.

This lithofacies contains little or no shale or siltstone. Though sandstone beds are principally quartz arenite, some of the finest-grained Galesville is feldspathic arenite.

Lithofacies D—Interbedded, Coarsely Interlayered Sandstone and Shale and Thin- to Medium-Bedded, Structureless or Cross-Stratified Sandstone

Most of the middle Mt. Simon Sandstone consists of this lithofacies. It extends throughout the Hollandale embayment and is thickest in the southeast, more than 200 ft (61.0 m) thick. It is equivalent to the middle lithofacies of Driese (1981) (Table 2). It overlies lithofacies C and B, underlies lithofacies E, and interbeds with subfacies G_2 and lithofacies I (Fig. 8). Its three subfacies are interbedded.

Subfacies D_1 consists of fine- to coarse-grained, moderately sorted quartz arenite that is commonly structureless, but may have crude horizontal, planar (Fig. 14), or trough cross stratification. There is minor ripple cross stratification. Thin beds of granules, and more rarely, intraclasts, are at the base of some beds. Bedsets are commonly 3 to 5 ft (.9 to 1.5 m) thick; rarely, they may reach 15 ft (4.6 m). The upper and lower bounding surfacess of the bedsets are sharp. Rarely, sandstone beds have ripple

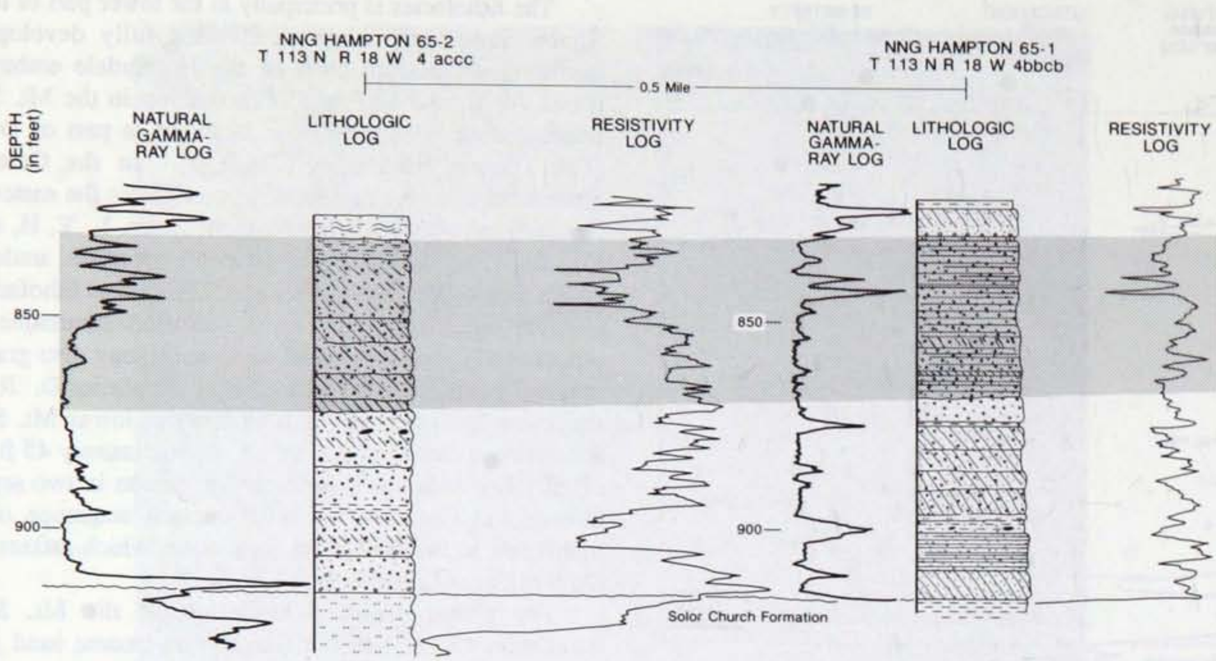


Fig. 13 Local variation of lithofacies in Mt. Simon Sandstone of Dakota County (Loc. H on Fig. 1).

forms at the tops. Some structureless sandstone beds, especially those in the upper part of lithofacies D, contain *Skolithos* traces and are therefore considered to be part of the overlying lithofacies E. Some cross-stratified beds resemble subfacies B_1, but contain *Skolithos* or are interbedded with thin shale beds with body or trace fossils.

Subfacies D_2 consists of fine- to coarse-grained quartz arenite that is structureless or crudely horizontally stratified and, rarely, cross stratified. The sandstone is coarsely interlayered with shale partings, thin beds of siltstone, and very fine grained sandstone (feldspathic arenite). Beds and bedsets, generally thicker than those of the other two subfacies, are up to 24 ft (7.3 m) thick. More than half the thickness of lithofacies D consists of this subfacies.

Subfacies D_3 consists of very fine to fine-grained, well-sorted feldspathic and highly feldspathic arenite, generally in thin beds or bedsets that are 0.5 to 2 ft (0.15 to 0.6 m) thick and occasionally as great as 10 ft (3.0 m) thick. The sandstone is very thick bedded and structureless or has crude horizontal stratification. It is coarsely interlayered with pale olive or greenish gray, finely laminated silty shale. Some shale beds contain lenses of fine-grained sand that are starved ripples; some starved ripples have been deformed to load casts.

The intimate interbedding of the third subfacies with the preceding two gives rise to ragged gamma and resistivity logs (Fig. 15 and Appendix 1). The very fine grained feldspathic arenite and illitic shale of the third subfacies typically have higher gamma readings than do the quartz arenite of the two coarser-grained subfacies. The finer-grained and shalier sandstone also has greater conductivity than does the coarser, more porous sandstone, which is saturated with fresh, nonconductive water.

Lithofacies E—Structureless, Fine- to Coarse-Grained Sandstone

This lithofacies is in the Upper Mt. Simon Sandstone throughout the Hollandale embayment. It is equivalent to the lower part of the upper lithofacies of the Mt. Simon Sandstone of Driese (1981) (see Table 2). It is up to 56 ft (17.0 m) thick in the west-central part of the embayment (Loc. W, Figs. 1 and 8); on the western margin of the embayment it is up to 85 ft (25.9 m) thick in an upper interval and 45 ft (13.7 m) thick in a lower interval at Location O (Figs. 1 and 8). Because of poor recovery, it is uncertain whether core from these intervals consists entirely of this lithofacies.

Lithofacies E generally overlies lithofacies D and underlies lithofacies F and G (Fig. 8). It is also widespread in the Ironton Sandstone (Fig. 9).

Beds of Lithofacies E are 3 ft (.9 m) to more than 20 ft (6.1 m) thick. Interbedded shale and siltstone beds are rare. The sandstone beds are commonly intensively burrowed by

Fig. 14 Tabular cross stratification in middle Mt. Simon Sandstone of western Wisconsin. Along I-94 on northern outskirts of Black River Falls, Jackson County.

Skolithos (Fig. 16) that appear in cores as long vertical tubules. Some structureless beds with no *Skolithos* remnants are probably the result of complete amalgamation. Beds containing *Skolithos* may also contain traces of cross stratification because of incomplete amalgamation. The upper ends of *Skolithos* tubules are generally truncated along a bedding plane or scoured surface.

The sandstone of lithofacies E is very fine to coarse grained, silty, and poorly to moderately sorted. It consists of quartz arenite and feldspathic arenite.

Geophysical logs in thick sequences of this lithofacies, such as those in the Mt. Simon Sandstone at Location W (Fig. 1), are characterized by even curves with constant low gamma readings and constant high resistivity readings (Fig. 17).

Lithofacies F—Shelly Sandstone

The shelly sandstone lithofacies has abundant disarticulated brachiopod valves (*Obolus*) along bedding planes and on foresets of cross-stratified sandstone; in some places shells are so abundant they form coquinas.

Lithofacies F is thickest in the north-central part of the Hollandale embayment, 25 to 35 ft (7.6 to 10.7 m) thick (Locs. W and L, Figs. 1 and 8). In the eastern part of the embayment it is 15 to 25 ft (4.6 to 7.6 m) thick (Locs. V, H, and P). It appears to be absent along the west side of the Hollandale embayment (Fig. 8). It is equivalent to the upper part of the upper lithofacies of the Mt. Simon in Wisconsin described by Driese (1981) (Table 2). The shelly sandstone lithofacies conformably overlies lithofacies E and underlies lithofacies G (red sandstone and shale) and I (mixed sandstone/shale), with which it is apparently interstratified (Fig. 8).

The shelly sandstone lithofacies is composed primarily of fine to medium, moderately to well-sorted quartz arenite; it is generally structureless, but may have horizontal or medium-scale cross stratification. In some cores, very fine to fine-grained sandstone with ripple cross stratification and clay drapes from lithofacies I intertongues with the shelly sandstone.

Thin beds of fossiliferous siltstone and very fine grained sandstone (highly feldspathic arenite) that are structureless or have fine planar stratification also intertongue with the main lithology (shelly sandstone). Some beds contain minor scattered ferroan oolites and coated grains.

Lithofacies F generally has ragged gamma and resistivity patterns that resemble those of lithofacies D (Fig. 17).

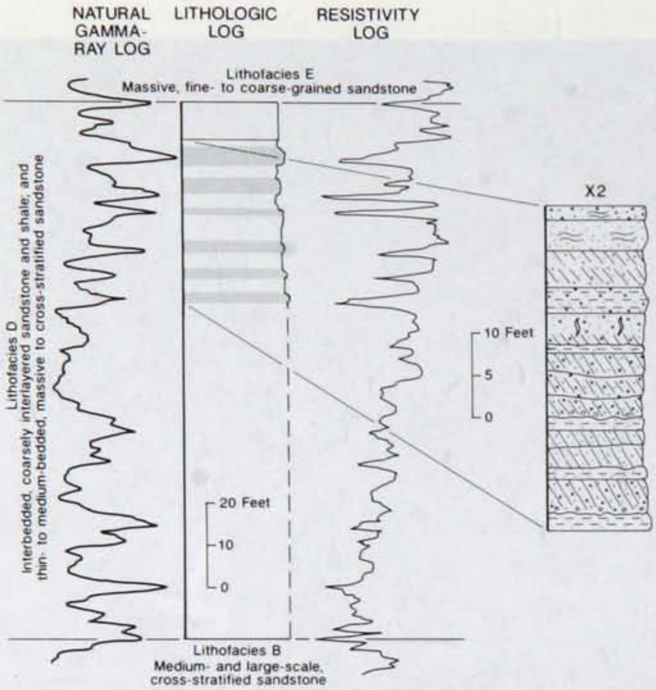


Fig. 15 Columnar section of middle lithofacies of Mt. Simon Sandstone (from core at Loc. V on Fig. 1). Very fine grained sandstone beds are stippled for detailed part of section. Note that fine-grained beds have higher gamma readings and lower resistivity readings than do adjacent beds.

Fig. 16 *Skolithos* tubules in sandstone of Mt. Simon, western Wisconsin. Roadcut on U.S. Highway 12, 5.5 miles south of Merillian Park, Jackson County.

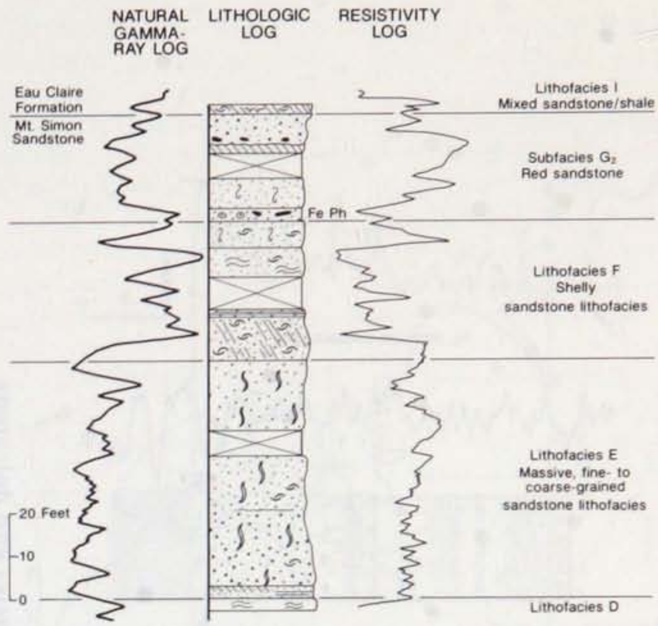


Fig. 17 Columnar section of lithofacies of upper Mt. Simon Sandstone (from core at Loc. W on Fig. 1).

Lithofacies G—Red Sandstone and Shale

This lithofacies extends through the western and central parts of the Hollandale embayment. It consists of two subfacies—one sandstone, the other shale (Fig. 18).

Subfacies G_1, the red shale subfacies, consists of pale red shale with numerous interbedded thin layers of very sandy (fine- to medium-grained) brachiopod (*Obolus*) coquina.

The subfacies is in the extreme southwestern part of the Hollandale embayment (Locs. B and J, Figs. 1, 9, and 19). It is a tabular unit, 20 to 34 ft (6.1 to 10.4 m) thick.

The subfacies overlies coarse sandstone of lithofacies D at Location B (Fig. 1) with a sharp contact that appears to be disconformable with slight relief. Goethite-limonite pisoliths that are possibly vadose underlie the subfacies in one core at Location B. Farther west, at Location J, the subfacies overlies sandstone of lithofacies E and F with a gradational contact. To the east of Location B, it grades laterally into subfacies B_2, the red sandstone subfacies (Fig. 18).

The red shale subfacies contains many thin—1 to 2 in (2.5 to 5.1 cm)—interbedded layers of very sandy coquina composed of brachiopod valves, hyolitha, and other fossil debris that is grainstone or packstone. The coquinas overlie scoured surfaces and contain rip up clasts from underlying shale.

The shale in this subfacies is more dolomitic toward the west at Location J (see Figs. 1 and 9), where much of the upper part of the subfacies consists of silty dolostone and dolomitic siltstone. Concurrent with the lithologic change, the color changes from pale red to pale red mottled with light greenish gray and pale yellowish green; some solid beds are of greenish gray and yellowish green shale. The coquina layers persist, especially in the lower, more shaly part of the subfacies.

Shale in this subfacies is generally finely laminated. There is no evidence of disruption of the bedding in the shale by bioturbation, desiccation, or in-situ formation of evaporitic minerals.

Subfacies G_2 is characterized by pale red and grayish red, fine- to coarse-grained sandstone and ferroan oolites. It is in the central and western parts of the Hollandale embayment (Fig. 19), a wedge-shaped unit 15 to 90 ft (4.6 to 27.4 m) thick. Thickest near the center of the Hollandale embayment (Loc. Ho, Fig. 1) (Fig. 18), it thins toward the north (Locs. W and L). To the west it is laterally equivalent to subfacies G_1 (red shale) and lithofacies H (dolostone). It is very thin or

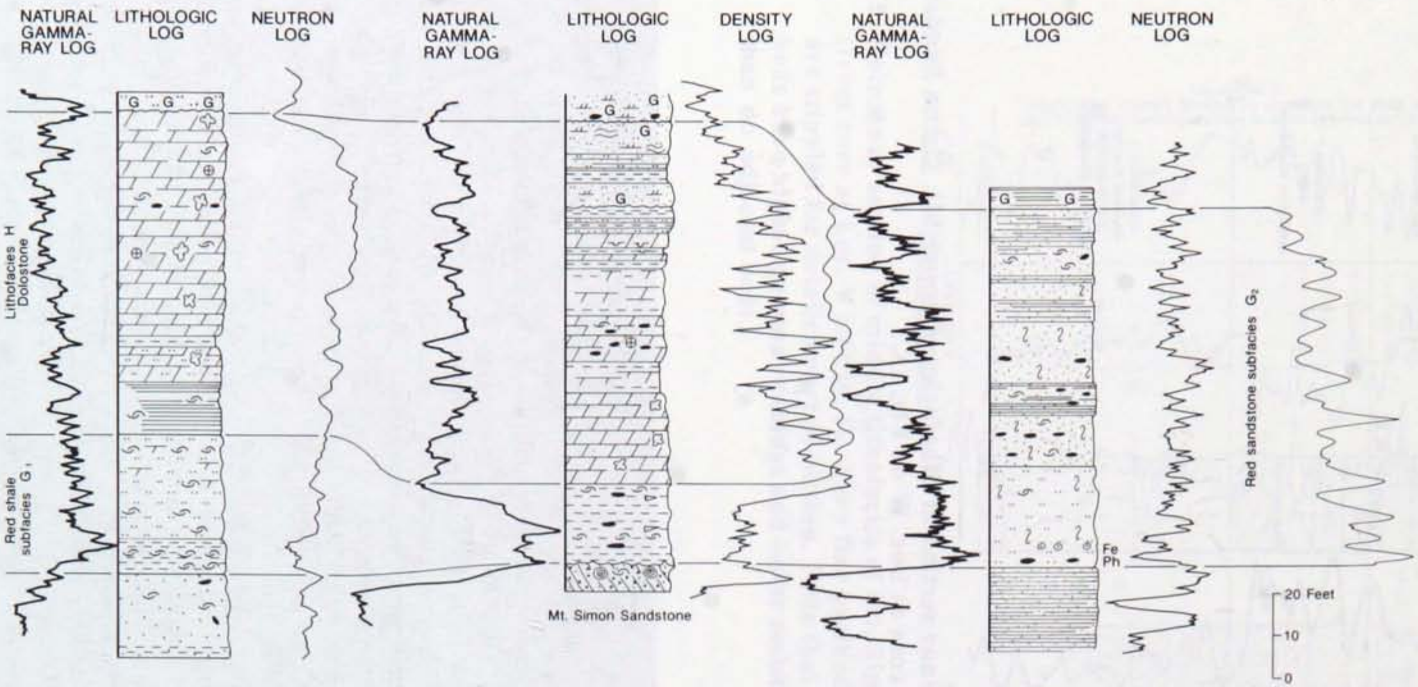


Fig. 18 Representative sections of red sandstone and shale lithofacies and dolostone lithofacies in south-central Minnesota (from cores at Locs. J, B, and Ho on Fig. 1).

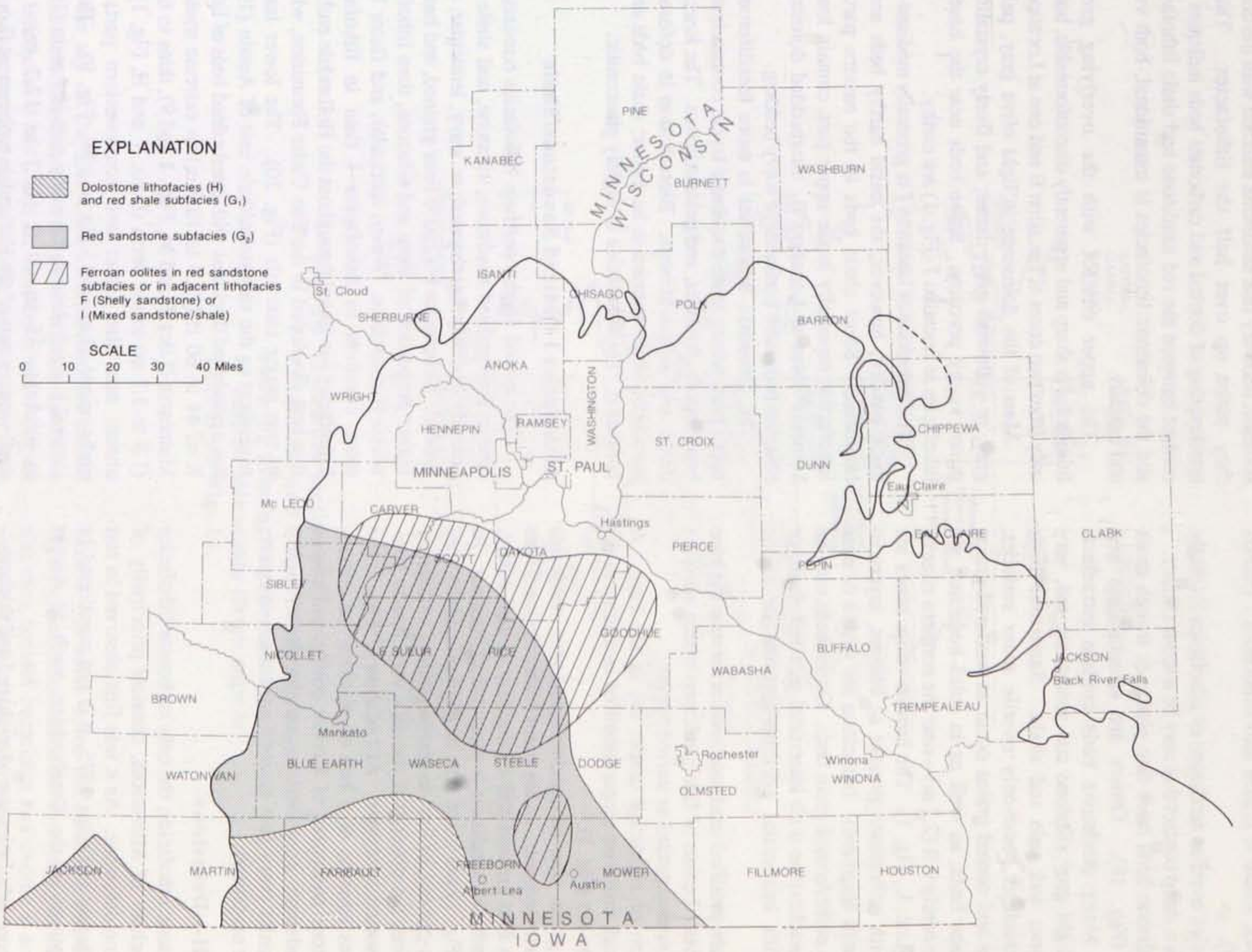


Fig. 19 Distribution of red sandstone and shale lithofacies and dolostone lithofacies.

absent along the eastern margin of the embayment (Locs. S, V, H, P, and M), where it grades into lithofacies I (mixed sandstone/shale).

This subfacies overlies sandstone of lithofacies F (shelly sandstone) with a sharp contact that may be a scour surface.

Some sandstone beds have fine planar or trough cross stratification (Fig. 18). Others are structureless and bioturbated. Many sandstone beds contain intraclasts composed of light gray siltstone and sandstone; red, very dense dolostone; and pale red shale. Sandstone beds containing intraclasts commonly overlie scour surfaces. Ferroan oolites and coated grains occur as scattered grains within sandstone beds, as well as in solid beds that are thickest—up to nearly 9 ft (2.7 m)—near the northern edge of the subfacies (Loc. L, Fig. 1). The ferroan oolite zones are phosphatic, with collophane present as cement, layers in oolites, and fossil fragments. Intraclasts are within or near the tops of the oolite/coated grain beds. Oolite beds may be packstone or wackestone with interstitial pale red shale; or grainstone with interstitial goethite-limonite or minor dolomite.

Ripple-cross-stratified sandstone beds occur near the base of the lithofacies. Lenses of fine sandstone within siltstone and shale beds are interpreted as starved ripples.

Desiccation or shrinkage cracks are in the core. A possible rill mark crosscuts planar-stratified sandstone in the core at Location Ho (Fig. 1).

Average grain size of sandstone in this subfacies increases toward the north. At the basin center the sandstone is very fine to fine grained and moderately to well sorted. Toward the north, the sandstone is progressively coarser. At Location W (Fig. 1) the basal part of the subfacies is very fine to medium-grained, or fine- to coarse-grained, moderately sorted sandstone; the upper part contains very fine to fine-grained, well-sorted sandstone. At Location L (Fig. 1) the entire subfacies consists of a bed of medium- to coarse-grained sandstone composed of ferroan oolites and coated grains. Sandstone composition ranges from highly feldspathic arenite (very fine grained sandstone) to quartz arenite (coarser sandstone).

Lithofacies H—Dolostone

The dolostone lithofacies, the only carbonate lithofacies in the Dresbachian of Minnesota, consists principally of finely crystalline dolostone. As it was first observed in test holes drilled during and after 1975, it is not mentioned in earlier descriptions of the Dresbachian, such as Austin (1969).

The dolostone lithofacies is wedge-shaped and thickest—50 to 75 ft (15.2 to 22.9 m)— at the western edge of the Hollandale embayment (Fig. 18). It thins to a depositional zero isopach somewhat west of the embayment center.

The lithofacies has much more detrital material in its eastern part (Loc. B, Fig. 1) than along the western margin (Loc. J). At Location B, numerous beds of red shale, siltstone, and very fine sandstone interbed with the dolostone; they make up over half the lithofacies. This even interlayering of detrital and carbonate beds indicates that the contact between the red sandstone and shale lithofacies (G) and the dolostone lithofacies is transitional, both vertically and laterally.

The upper contact with the overlying greensand lithofacies is sharp and apparently disconformable, but known only from two cores at Location B and one at Location J.

Most of the dolostone is light olive gray, pale olive gray, or yellowish gray; dense; and finely crystalline with minor vuggy porosity. Some beds near the base of the lithofacies at Location J (Fig. 1) are earthy.

The dolostone at Location J is generally medium- to very thick bedded; however, the basal earthy beds are finely laminated. Some shale beds in the eastern part of the lithofacies, especially in the upper part, contain load casts. In some cores at Location B, interbedded dolostone and siltstone beds have lenticular or wavy bedding.

The dolostone lithofacies is more fossiliferous in its upper part, where some coquinoid layers contain inarticulate brachiopods, hyolitha, and pelmatozoans. The lower part is dense and unfossiliferous. Bioturbation in dolostone and associated shale appears to be minor; shale beds are finely laminated. The lithofacies is slightly glauconitic.

Lithofacies I—Mixed Sandstone/Shale

The mixed sandstone/shale lithofacies consists of very fine to fine-grained sandstone, siltstone, and shale that are coarsely or finely interlayered, or wavy, lenticular, or flaser bedded. Lithofacies I is much finer grained, and has a much higher proportion of shale and siltstone, than lithofacies D, which it resembles. Wavy, lenticular, and flaser beds are more common in lithofacies I than in lithofacies D. Lithofacies I is found throughout the Hollandale embayment; it is best developed in the Eau Claire Formation, where it is in two major intervals (Fig. 20). The lower interval is equivalent to the sandstone/shale unit of Austin (1969). It has a combined thickness with interbedded beds of lithofacies K of 44 to 60 ft (13.4 to 18.3 m) in extreme southeastern Minnesota (Locs. P and M, Figs. 1 and 9), thins to 6 to 12 ft (1.8 to 3.7 m) to the north (Locs. V and H, Fig. 1), and is absent near the center and southwestern parts of the embayment (Locs. B, Ho, and W, Fig. 9). The upper interval is equivalent to the sandy unit of Austin (1969). It is thickest—35 to 40 ft (10.7 to 12.2 m)— in the southwestern part of the Hollandale embayment (Loc. B, Fig. 1); it thins toward the east and south to 18 to 20 ft (5.5 to 6.1 m). Minor thin intervals included in this lithofacies are found in lower and middle parts of the Mt. Simon Sandstone along the western (Loc. O, Fig. 8) and eastern (Locs. M and P, Fig. 8) margins of the Hollandale embayment.

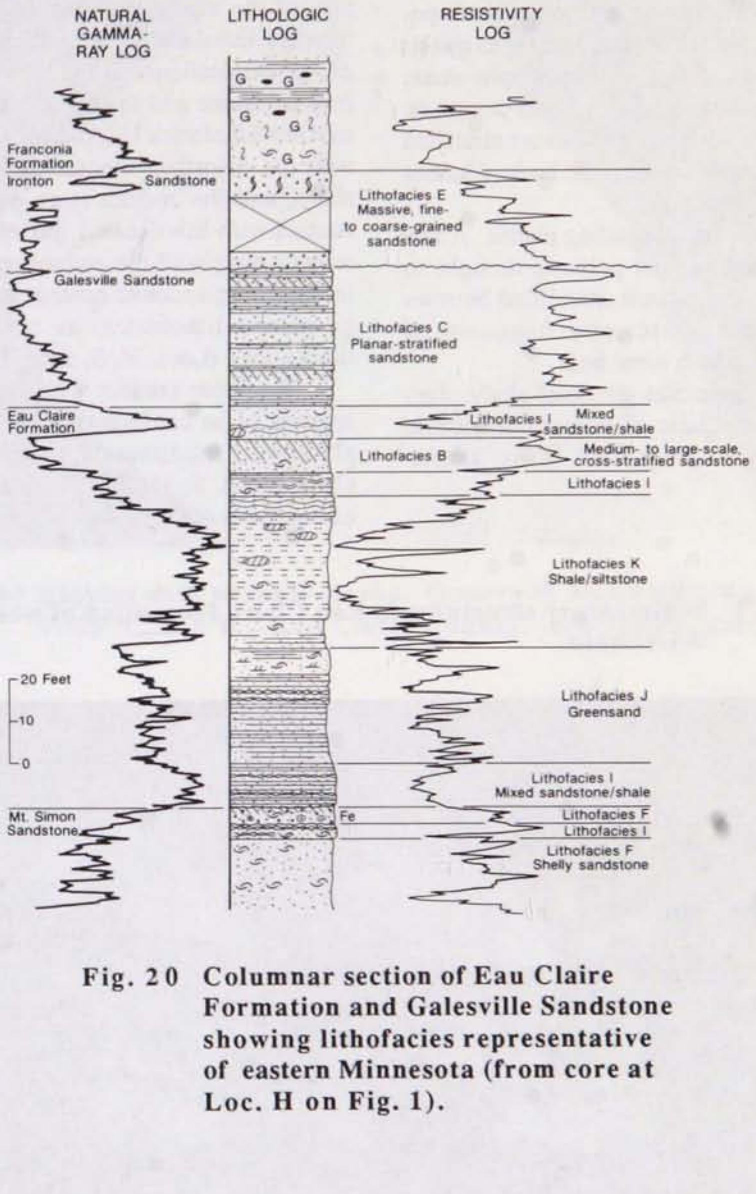


Fig. 20 Columnar section of Eau Claire Formation and Galesville Sandstone showing lithofacies representative of eastern Minnesota (from core at Loc. H on Fig. 1).

At the top of the Eau Claire Formation, the mixed sandstone/shale lithofacies interfingers with thin sandstone beds of lithofacies B and C that are considered to be tongues from the overlying Galesville Sandstone (Fig. 20). The lower contact of the upper interval of lithofacies I with the shale/siltstone lithofacies (J) is gradational.

The lower interval of the mixed sandstone/shale lithofacies in the Eau Claire Formation has a sharp contact with overlying lithofacies J (greensand) and is not interbedded with it. In some cores the contact is marked by a thin, highly glauconitic zone in the overlying greensand lithofacies that may contain intraclasts and overlie a scoured, eroded surface (Locs. B and V, Fig. 1). This relationship is common in the south-central part of Minnesota. The underlying contact with lithofacies F (shelly sandstone) is gradational and the lithofacies intertongue. Where the mixed sandstone/shale lithofacies overlies lithofacies G (red sandstone and shale), the contact is sharp; the size of constituent grains changes markedly from medium sand-sized in lithofacies G, to silt- to very fine sand-sized in lithofacies I. (The Mt. Simon/Eau Claire contact is customarily drawn along this contact in central and eastern parts of the Hollandale embayment).

The sandstone is well sorted and very fine to medium-grained, and ranges from highly feldspathic arenite to quartz arenite (see Fig. 29b on p. 50). It has ripple cross stratification or fine planar stratification. Shale occurs as flasers, clay drapes, or wavy beds in ripple-cross-stratified sandstone, or as finely or coarsely interlayered beds. Shale is greenish gray or pale yellow green.

Grazing traces (*Planolites*) are on bedding planes. A few sandstone beds contain color-mottled patterns thought to result from bioturbation. There are some sand-filled burrows in shale beds. Body fossils, principally fragments of phosphatic brachiopod valves, are in some beds.

This lithofacies closely resembles the basal shaly, thin-bedded lithofacies in the Eau Claire of western Wisconsin described by Huber (1975). They have many similar sedimentary features (Fig. 21).

Lithofacies J—Greensand

The greensand lithofacies is characterized by ubiquity of glauconite. Wedge-shaped, it is thickest—95 ft (29.0 m)—in the southwestern part of the Hollandale embayment and thins toward the north and east—12 ft (3.7 m)—(Fig. 22). It overlies lithofacies I (mixed sandstone/shale) in all cores; except at Locations Ho and W, where it overlies lithofacies G (red sandstone and shale); and at Locations B and J, where it overlies lithofacies H (dolostone) (Fig. 9). The basal contact with the dolostone lithofacies at Locations B and J is very sharp, and the contact is an erosional surface. The basal contact with lithofacies I (mixed sandstone/shale) along the eastern margin of the embayment commonly has an abrupt increase in glauconite content at, or close to, the base of the greensand lithofacies, as mentioned in the section on lithofacies I (Locs. M, S, and V).

The upper contact with lithofacies K (shale/siltstone) appears to be conformable, though a thin layer of highly glauconitic sandstone is just beneath the contact in many cores (Locs. S, H, V, W, M, and P) in the northern and eastern parts of the Hollandale embayment.

Fig. 21 Sedimentary structures in Eau Claire Formation of western Wisconsin.

21a) Thin bedding; wavy- or lenticular-bedded sandstone and shale overlain by very thick bedded sandstone. Quarry by Arcadia is NE1/4NE1/4 sec. 31, T. 21 N., R. 9 W., Trempealeau County.

21b) Ripples with wrinkle marks. Quarry in SE1/4NW1/4 sec. 5, T. 25 N., R.8 W., Eau Claire County. Pen shows scale.

21c) *Cruziana* on ripple-bedded surface containing *Planolites*. Same quarry as Fig. 21b. Lens cap shows scale.

21d) Desiccation cracks. Same quarry as Fig. 21b. Lens cap shows scale.

The greensand is silt-sized to very fine sand-sized and generally well sorted. Composition is highly variable compared to other lithofacies, ranging from highly feldspathic arenite to highly glauconitic arenite (see Fig. 29d on p. 50).

In eastern and north-central parts of the Hollandale embayment, the sandstone has fine planar or slightly inclined stratification. Minor thin to medium beds of trough-cross-stratified sandstone are also present. Flasers and clay drapes are on some ripple cross laminae. Shale beds are scarce in this lithofacies. In extreme southeastern Minnesota, where shale laminae are more abundant, they are finely and coarsely interlayered with sandstone beds; they are generally 0.5 in (1.3 cm), and occasionally, up to 2 in (5.1 cm) thick. Rare thick, structureless beds of bioturbated sandstone are at or near the base of the lithofacies.

Rare intraclasts and desiccation cracks are in this lithofacies along the eastern and northern margins of the Hollandale embayment (Loc. S, P, and L). Body fossils, particularly brachiopod valve fragments, are common; some occur as coquina lenses.

The gamma/resistivity pattern for the greensand lithofacies in much of the embayment is a fining upward (see Locs. Ho and W, Fig. 9). In the western part of the Hollandale embayment (Loc. B, Fig. 1) a well-developed coarsening upward sequence is in both cores and geophysical logs (Fig. 22). The lower sandstone beds contain wave ripple cross stratification, some with very thin clay drapes. Some basal beds are bioturbated. There are minor thin beds of hummocky cross stratification. The upper part of the lithofacies at Location B has trough-cross-stratified beds interbedded with minor fine planar-stratified or wavy hummocky cross-stratified beds. The decreasing intensity from base to top of the gamma log is consistent with increasing size-sorting and decreasing shale content.

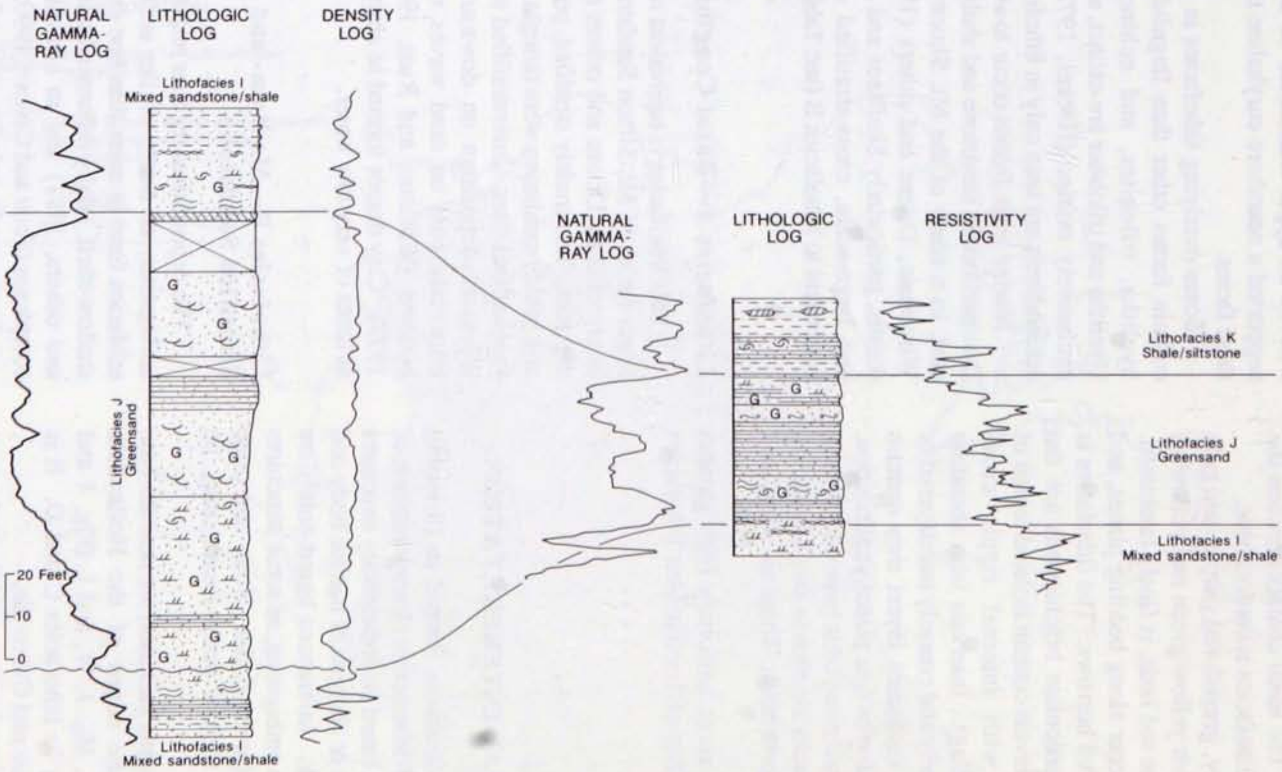


Fig. 22 Comparison of greensand lithofacies from western side of Hollandale embayment (to left) with that from eastern side (to right).

Lithofacies K—Shale/Siltstone

Shale is the principal lithology of this lithofacies, siltstone secondary, and sandstone very minor. The shale/siltstone lithofacies is thickest—slightly greater than 40 ft (12.2 m)—in the eastern Hollandale embayment at Locations V, H, and L (Fig. (9). It thins toward the south and west, and is absent along the eastern and western margins of the embayment (Fig. 23). The basal contact between the shale/siltstone and greensand lithofacies is conformable.

The shale is greenish gray, grayish red purple, and pale brown. The siltstone is grayish yellow green and yellowish gray. The shale, especially the red beds, is finely laminated. However, *Planolites* traces occur along bedding planes, and some shale beds contain stuffed burrows. The lithofacies is moderately fossiliferous; inarticulate brachiopods are the principal form. Shale-rich intervals contain isolated lenses of siltstone and sandstone, with internal ripple cross stratification (lenticular bedding). Intervals with abundant siltstone and sandstone are finely and coarsely interlayered or wavy bedded; siltstone and sandstone layers may contain internal ripple cross stratification or fine planar stratification. Some ripple-cross-stratified sandstone beds have clay drapes. Intraclasts and desiccation cracks are rare in this lithofacies, though more common in adjacent units. There are some load structures.

This lithofacies has the most uniformly high gamma readings and lowest resistivities of Dresbachian lithofacies (Fig. 20).

PALEOENVIRONMENTAL INTERPRETATION

Dresbachian rocks of Minnesota formed in fluvial to nearshore shallow marine environments. Interpretations of depositional environments are based on sedimentary structures formed in the rocks, presence or absence of marine body and trace fossils, and mineralogy. Inferences based solely on sedimentary structures can be ambiguous, as some structures are common to marine and fluvial rocks. Body and trace fossils are less equivocal, though body fossils may be reworked.

Traces of glauconite, a marine indicator, are near the base of the Mt. Simon along the edges of the Hollandale embayment of Locations V, H_O, J, W, and L (Fig. 1 and Appendices 1 and 2), mainly in lithofacies C and D. It is found throughout the Eau Claire and Galesville.

Marine body fossils are found within middle and upper parts of the Mt. Simon Sandstone and throughout the Eau Claire and Galesville. Inarticulate brachiopod shells are found about 40 ft (12.2 m) above the base of an abnormally thin sequence of Mt. Simon at Location J (Figs. 1 and 8) on the southwestern margin of the Hollandale embayment in lithofacies E sandstone.

The only body fossils found in the Mt. Simon Sandstone are lingulid brachiopods. Today lingulids occupy shallow, sandy environments and are adapted to an intertidal life (Paine, 1970). Fossil lingulids probably inhabited environments of variable or reduced salinities similar to environments now occupied by living forms (Rudwick, 1970). Driese concluded that the presence of the lingulid *Obolus* in upper lithofacies of the Mt. Simon Sandstone supported a nearshore euryhaline tidal flat interpretation for these facies.

Some overlying lithofacies in the Eau Claire Formation contain forms other than lingulid brachiopods—primarily hyolitha, trilobites, and echinoderms (pelmatozoans). Hyolitha and trilobites are extinct, and living echinoderms are exclusively marine (Heckel, 1972). In the Dresbachian, echinoderms are seen only in lithofacies H (dolostone).

Marine trace fossils occur lower than body fossils in the Dresbachian, in sandstone and shale of lithofacies D. Farther east, in a study of the Mt. Simon Sandstone in outcrop in Wisconsin, Driese and others (1981) found marine trace fossils, particularly *Skolithos* and *Arenicolites*, in medium- and large-scale, cross-stratified sandstone interpreted as equivalent to lithofacies B (see Table 2).

Lithofacies A—Basal Conglomerate

This lithofacies is equivalent to the basal 1 to 2 m of the lower facies of Mt. Simon Sandstone of western Wisconsin, interpreted by Driese and others (1981) as braided, fluvial deposits. The crudely stratified, poorly sorted conglomerates and pebbly sandstone were thought to represent deposition on longitudinal bars. Interstratified tabular sets of cross strata represent deposition on downstream faces of migrating transverse bars on sand waves migrating across channel bottoms (Williams and Rust, 1969; Smith, 1970; Miall, 1977). Clay drapes formed in abandoned channels and pools at times of very low water.

Lithofacies B—Medium- and Large-Scale, Cross-Stratified Sandstone

The depositional regimes responsible for subfacies B_1 are ambiguous, as many of the sedimentary features of the subfacies form in more than one environment. They form in shallow-shelf, tidally influenced sand wave complexes (Driese and others, 1981) and in alluvial braid plain/braid delta complexes (Fedo and Cooper, 1990; Haddox and Dott, 1990).

Large-scale tabular sets of cross strata indicate a depositional regime with large migrating sand waves. Similar sand waves are seen today in regions with strong tidal currents (Houbolt, 1968; Caston, 1972; Ludwick, 1974). Sand bars containing large-scale tabular sets also form in the braided fluvial environment (Miall, 1977; Cant, 1978), though trough cross stratification is more common.

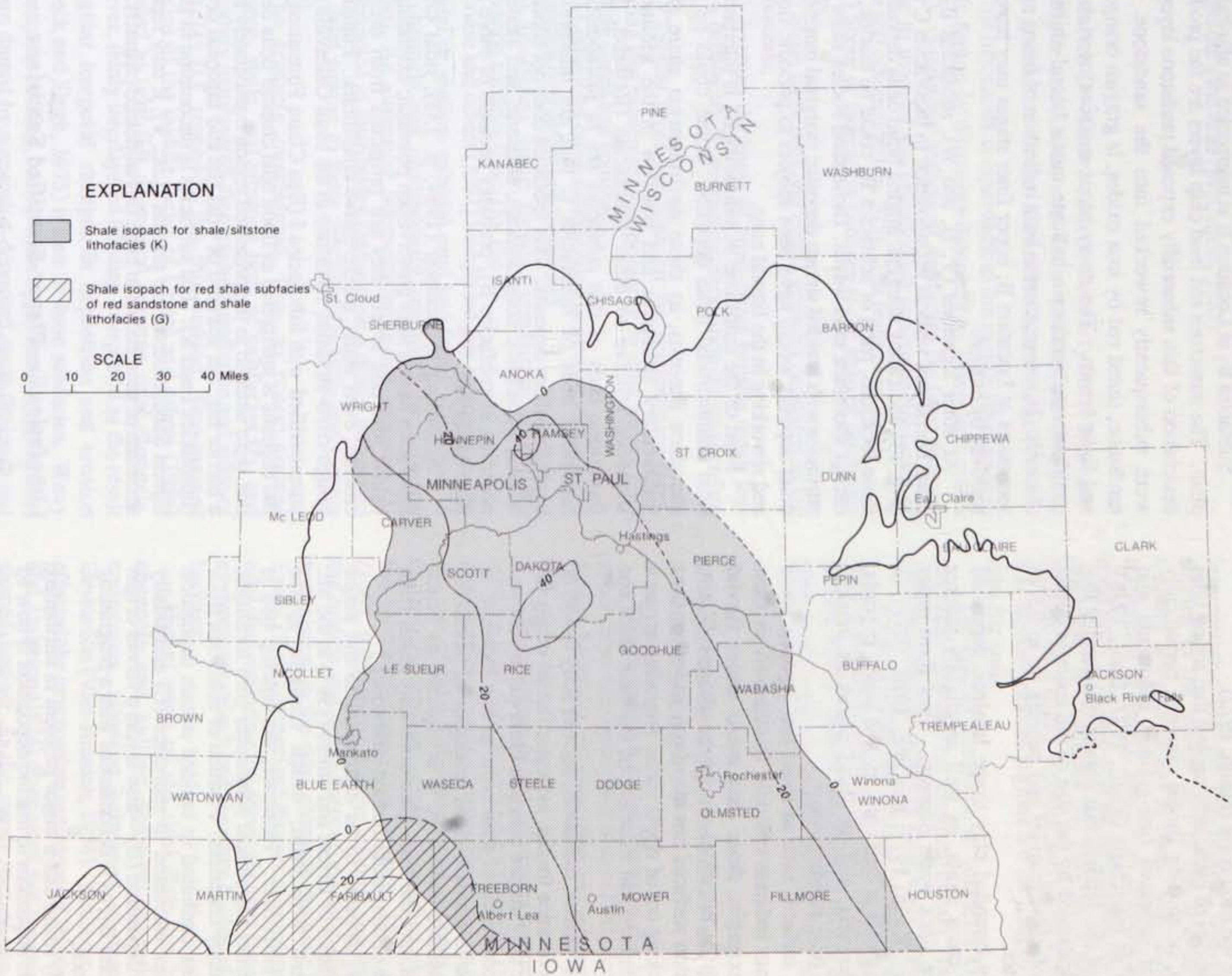


Fig. 23 Eau Claire shale isopach. Contour interval is 20 ft (6.1 m).

Graded foresets in the large-scale tabular sets result from pulsating avalanching at the sand wave margin of sediment previously sorted by small-scale bed forms migrating across the stoss surface of the sand wave (Smith, 1972).

Lag concentrations of intraclasts suggest that strong tidal or storm currents, or shifting fluvial currents, periodically tore up pieces of cohesive fine-grained sediments and redeposited them as intraclasts (Miall, 1977; Cant, 1978). The high energy of the depositional regime that formed this subfacies is also indicated by the size of the coarsest quartz grains in the lithofacies, granules and pebbles up to 0.6 in (1.5 cm) in diameter.

Thin, sharply bounded clay drape laminae deposited between sets of cross strata, as well as slightly thicker siltstone beds, are slack water deposits. They form under marine conditions (Klein, 1977; McCabe, 1970, 1971), in braided stream channels at times of very low water, in pools, in abandoned channels, and on flood plains as vertical accretion deposits from standing water.

Reactivation surfaces such as those that separate some sets of cross strata indicate episodic fluctuations in flow velocities, for example, those that occur under fluvial (Collinson, 1970) or intertidal marine conditions (Klein, 1970). Reactivation surfaces can also form under constant flow stage by working out of ripple forms migrating across a wave crest, with subsequent rounding of the crest (McCabe and Jones, 1977).

The absence of marine indicators, such as body fossils of marine organisms or trace fossils, indicates fluvial origin for subfacies B_1. The only marine indicator observed in core was a questionable occurrence of glauconite at one location, in close juxtaposition to planar-bedded sandstone of lithofacies C. The planar-bedded sandstone is interpreted as beach foreshore deposits, and the trace glauconite may result from reworking of some of this planar-bedded sandstone.

Subfacies B_1 appears to be equivalent to the major part of the lower facies of Driese and others (1981) in the Mt. Simon of western Wisconsin, which contains sparse *Skolithos* and *Arenicolites*. However, the outcrop belt is about 100 miles from the closest Minnesota core localities, making direct analogy uncertain. Position of subfacies B_1—between lithofacies attributed to braided stream deposition (A), and lithofacies attributed to shoreface (C) and tidally influenced deltaic deposition (D)—also favors a fluvial origin for most of subfacies B_1, as it is consistent with a prograding sedimentary sequence.

Walker (1984) states that a major problem in attributing thick quartz arenite sequences to marine deposition is how to explain the accumulation as a succession of sand wave complexes. Unless sand supply and subsidence remained closely matched, either basin-deepening would cause deposition of finer detrital sediments, or supply would outstrip subsidence, causing shallowing and shoreline progradation. Fluvial braid deltas and braid plain form extensive and thick sand bodies (McPherson and others, 1987), compared to modern sand wave complexes, which are thin and form in palimpsest sediments.

Subfacies B_1 at Location B is interpreted as alluvial braid plain. The numerous red mud chip layers are the product of desiccation of thin subaerially exposed mudstone layers that were subsequently reworked into the sandstone. The sandstone, tinted red by iron oxides, is grayish orange pink and light brown. The many scour surfaces overlain with conglomerate sandstone indicate much lateral shifting of channels. However, there is little indication of fining upward sequences at Location B; upper finer stages may have been removed by erosion.

At other locations (V, H, and W), subfacies B_1 is in close lateral and vertical juxtaposition to lithofacies C and D (Fig. 13), indicating marginal marine braid delta deposits. At these locations, parts of subfacies B_1 could be marine, high-energy shoreface sand waves. Those sand bodies share many attributes with braided stream deposits; marginal marine braid delta deposits would have been subject to periodic flooding and reworking in the littoral zone.

Most of the sandstone in **subfacies B_2** is interpreted as tidal channel/tidal delta deposits. Some could be upper shoreface deposits, as these environments share similar sedimentary structures and position in the sedimentary sequence relative to other lithofacies (Reinson, 1984). Sandstone beds of this subfacies are in juxtaposition to sandstone beds of lithofacies C that are interpreted as beach/foreshore deposits. This subfacies does not contain the scours, intraclasts, conglomerate, siltstone, and shale beds observed in subfacies B_1, probably because of more stable flow conditions.

According to Reinson (1984, p. 132), tidal channel lithofacies have a high preservation potential; extending well below low tide level, they are protected from shoreface erosion, even under transgressive conditions. Planar- and trough-cross-stratified sandstone in the basal Galesville that is interstratified with lithofacies I (Eau Claire Formation) tidal flat deposits is interpreted as flood tidal channel delta deposits that were situated in the protected region immediately behind a barrier bar, but seaward of tidal flat and lagoonal deposits (lithofacies I and K). The subfacies is uncommon in the Mt. Simon Sandstone; where present (Loc. V), it may represent accretion of sand bodies in large fluvial/deltaic channels.

Lithofacies C—Planar-Stratified Sandstone

Most sandstone of this lithofacies is interpreted as beach/foreshore deposits similar to those in the Wisconsin outcrop belt described by Driese and others (1981). The lithofacies is characterized by horizontal or slightly inclined, planar-stratified sandstone beds and ripple-cross-stratified sandstone beds similar to those on modern coasts (Clifton, 1969; Clifton and others, 1971) that result from shoaling waves. Associated small- to medium-scale, trough-cross-stratified sandstone beds are interpreted as having formed as megaripples and sand waves in the upper shoreface as a result of longshore sand drift (McCubbin, 1982).

Lithofacies D—Interbedded, Coarsely Interlayered Sandstone and Shale, and Thin- to Medium-Bedded, Structureless or Cross-Stratified Sandstone

This lithofacies is equivalent to the middle lithofacies in the Mt. Simon in Wisconsin described by Driese and others (1981). Sandstone bedsets of **subfacies D_1** have features similar to those of the crossbedded sandstone subfacies of Driese and others (1981, p. 375). The features include:

1) Scour or truncation surfaces at the base of sandstone bedsets;

2) Shale intraclasts and quartz granules deposited as lag conglomerate;

3) Average thickness of cross-strata bedsets much less than in lithofacies B, suggesting deposition by smaller bed forms;

4) Tabular cross stratification the predominant form, indicating that movement was primarily by sand waves, with migrating dunes less common;

5) Compound cross stratification as smaller ripple cross stratification over larger bed forms; and

6) *Skolithos* trace fossils, sometimes related to reactivation surfaces (Loc. Ho, Fig. 1).

Driese and others (1981) interpreted this subfacies as low intertidal or shallow subtidal sand bed forms, deposited in tidal channels and continuously reworked by vigorous currents. An alternative interpretation is that subfacies D_1 was deposited in distributary channels on a tidally influenced braid delta similar to those described by Fedo and Cooper (1990).

The coarsely interlayered, fine- to coarse-grained sandstone, shale, and siltstone beds of **subfacies D_2**; and the coarsely interlayered, fine-grained sandstone and shale of **subfacies D_3** resemble the thin-bedded, fine-grained subfacies of the middle facies of Driese and others (1981) attributed to tidal flat deposition between tidal channels. However, thinly interlayered bedding interpreted as the result of regular temporal changes in deposition and erosion (Reineck and Singh, 1975) is rare in these subfacies. Wavy and lenticular bedding, caused when ripple-cross-stratified sand beds are draped by suspension-deposited muds (Reineck and Singh, 1975), are also rare. The predominance of coarsely interlayered bedding was interpreted by Driese and others (1981) as related to a higher average velocity of sand transport in this lithofacies than in other lithofacies, such as Eau Claire lithofacies, which formed under similar conditions.

Driese and others (1981) noted the absence in outcrop of features such as raindrop impressions, mud cracks, and flat-crested ripples that would suggest emergence in these subfacies. According to Driese, this absence supports the interpretation that the thin-bedded, fine-grained subfacies formed in the lowest part of the intertidal zone. These features are also absent in core. Subfacies D_2 and D_3 are interpreted as having formed on interdistributary parts of a braid delta. The fine-grained, structureless or crudely stratified sandstone in subfacies D_3 may have been deposited in lagoons on a delta. Reineck and Singh (1975, p. 350) state that lagoons of tidal regions are difficult to distinguish from tidal flat areas.

The coarser sandstone in subfacies D_2 may represent overbank deposits on interdistributary flats. Interbedded siltstone and shale represent slack water deposits.

A low-diversity assemblage of trace fossils is consistent with a deltaic environment (see Fedo and Cooper, 1990; Moore, 1979). Marine water could invade the delta between periods of flooding or invade inactive parts of the delta.

Lithofacies E—Structureless, Fine- to Coarse-Grained Sandstone

This lithofacies is equivalent to the lower part of the upper facies that Driese and others (1981) described in the Mt. Simon Sandstone of Wisconsin and interpreted as mid-tidal flat.

The sandstone of this lithofacies resembles sand flats of modern tidal flats described by Reineck (1972), which are populated by abundant organisms of only a few species. The amount of tidal-flat bioturbation depends on a number of factors, the most important of which is physical energy of the subenvironment (Van Straaten, 1954, p. 82). Reineck (1967, 1975) found that the infaunal population is greater on the middle and upper parts of the tidal flat, and smaller or nonexistent in the tidal channels draining lower tidal flats. Evans (1965) recognized distinct subenvironments in British tidal flats, including the *Arenicola* sand flat in the middle part environment, which had abundant U-shaped marine lugworm burrows.

Higher parts of the tidal flats are less dissected by channels and gullies; sediment accretion is slow but continuous, allowing burrowers to destroy all internal lamination (Van Straaten, 1954). Yet some sediment erosion affected the structureless sandstone of lithofacies E. Goodwin and Anderson (1974) determined that *Monocraterion*, a funnel-shaped burrow, is the upper part of the vertical burrow *Skolithos*: Beds with both forms did not have much erosion, whereas beds where *Skolithos* is preserved and *Monocraterion* is missing did. *Monocraterion* was observed neither in outcrop by Driese and others (1981), nor in core in this report.

Lithofacies F—Shelly Sandstone

The shelly sandstone lithofacies is equivalent to the upper part of the upper facies described by Driese and others (1981) in the Mt. Simon Sandstone of Wisconsin.

According to Driese and others (1981), the concentrations of valves of *Obolus*, an inarticulate brachiopod, are lag concentrations that were possibly left in small tidal channels and gullies in middle and upper tidal flat areas. They are analogous to modern lag concentrations of mollusc shell in Wadden Sea middle and high tidal flats, attributed by Van Straaten (1954) to reworking by tidal currents or to infrequent wave activity associated with storms.

As stated earlier, the presence of lingulid brachiopod valves in these beds is consistent with an intertidal environment, as modern forms inhabit environments with variable or reduced salinities (Rudwick, 1970). Facies F and E are interpreted as having formed adjacent to the braid deltas in sand flats and in shoals formed of sand from distributary channels.

Lithofacies G—Red Sandstone and Shale

As this lithofacies consists of two subfacies deposited under different conditions, the subfacies are discussed separately. They have no analog in the outcrop belt of Wisconsin.

Subfacies G_1, the red shale subfacies, could represent the upper or high tidal flat environment, as modern tidal flats pass from sand-dominated near low water level, to mud-dominated near high water (Van Straaten, 1954, 1961). It is a fine-grained analog of lithofacies F, the shelly sandstone lithofacies. Distribution of brachiopod valves and other fossil material is similar to the distribution in lithofacies F; they were probably deposited by the same process—sorting along tidal channels and gullies, and as a result of storm waves.

The red of the shale supports a high tidal flat origin for the subfacies: Red in sediment usually indicates nonmarine conditions, as red sediment deposited in marine waters loses its color through hydration of the iron oxide to limonite, or reduction of the iron to the ferrous state (Heckel, 1972). Under unusual circumstances, modern red sediment has formed in shallow marine environments either because oxidizing conditions are maintained for a distance into the sea (Dorsey, 1926; Raymond, 1972), or because sediment is deposited rapidly before it can be reduced (Dunbar and Rodgers, 1975; Heckel, 1972). In the extreme southwest (Loc. B, Fig. 1), this subfacies contains some green and gray shale, indicating iron-oxide-reduction and normal marine conditions during some of the sedimentation.

This subfacies is very shale-rich, compared to the laterally equivalent shelly sandstone lithofacies. Shale-rich tidal flat lithofacies in south-central Minnesota could result from two factors: 1) it lay near the western edge of the Hollandale embayment, away from regions with the greatest influx of coarse detrital sediment from the Wisconsin dome; and 2) it may have been near good sources of clay-sized sediment. The clay in some modern tidal flat sediments is due to proximity to clay supply (Reineck and Singh, 1975, p. 358; Thompson, 1968) rather than position on the tidal flat, as with many modern tidal flats. Two possible sources for clay-sized sediment along the western Hollandale embayment would have been 1) Mid-Proterozoic redbeds of the Midcontinent Rift Zone and 2) the regolith on top of the Precambrian crystalline rocks of west-central Minnesota. If the clay was derived from Proterozoic redbeds, much of the red from ferric-oxide-staining could have been inherited.

Subfacies G_2, the red sandstone, is interpreted as having formed in several related settings on the emergent tidal flat. The trough-cross-stratified sandstone in the lower part of the subfacies is interpreted as channel deposits; intraclasts of dolostone, siltstone, and red shale result from erosion of penecontemporaneous tidal flat deposits by channel migration. Desiccation cracks and probable rill marks in associated planar-stratified sandstone indicate subaerial exposure. Intraclastic, shaly, or silty sandstone that is very thick bedded and bioturbate, or planar stratified, closely resembles deposits of subfacies D_2—coarsely interlayered sandstone and shale, interpreted as deltaic deposits.

The ferroan oolite and coated sand grain beds of subfacies G_2 resemble beds described by Van Houton and Arthur (1989) and Van Houton and Karasek (1981), attributed to deposition in shallow marine, nearshore clayey environments during periods of waning detrital sediment supply at the end of shoaling upward episodes. According to Pettijohn and others (1987, p. 50-51), the iron in the iron-rich rims on sand grains and in oolites may come down rivers into estuarine or nearshore marine environments as ferric-hydroxide-gel-coating sand grains, as dilute suspension, or absorbed on the surfaces of clay minerals.

Van Houten and Karasek (1981) state that ferroan oolite beds and associated intraclast layers overlying the oolitic ironstones are the uppermost components of upward-shoaling "punctuated aggradational cycles" (Anderson and Goodwin, 1980) and end with renewed encroachment of shallow marine waters.

Lithofacies H—Dolostone

Presence of dolostone indicates detrital sedimentation diminished to a point where it could no longer mask carbonate sedimentation. At Location B (Fig. 1) the carbonate rocks are very argillaceous and have wavy or lenticular beds and minor intraclasts similar to those in detrital tidal flat deposits. The rocks also show compaction and soft sediment deformation, processes common on tidal flats during diagenesis (Klein, 1977, p. 57).

Farther west at Location J (Fig. 1) sedimentation indicates a shallow subtidal origin. Most of the dolostone is structureless, although a thin 12 ft (3.7 m) earthy interval at the base has fine planar stratification, possibly fissility created by clay minerals. The dolostone has none of the features attributed to carbonate-deposition in the intertidal or supratidal zone (Lucia, 1972; Sellwood, 1986, p. 325), such as stromatolites, irregular laminations, bird's-eye texture, mud cracks, or abundant lithoclastic conglomerate. However, glauconite, an exclusively marine mineral, is invariably present. Some bioclastic layers contain pelmatozoans, which are stenohaline marine organisms. Throughout this lithofacies, dolostone mineralization appears to be early diagenetic, rather than primary, as it probably would be if the rock were a supratidal deposit.

Lithofacies I—Mixed Sandstone/Shale

The mixed sandstone/shale lithofacies is mud or mixed sand/mud tidal flat. Most bedding styles in the mixed sandstone/shale lithofacies of the eastern Hollandale embayment are those common on tidal flats (Reineck and Singh, 1975; Klein, 1977). These include thinly interlayered bedding, coarsely interlayered bedding, flasers, wavy bedding, and clay drapes. The mixture of clay and sand is characteristic of mud tidal flat facies (Reineck and Singh, 1975). Huber (1975) considered the basal shaly, thin-bedded lithofacies he described in the Eau Claire Formation of western Wisconsin to be mud flat transitional to sand/mud tidal flat.

The lower interval of mixed sandstone/shale lithofacies, beneath the greensand lithofacies, is discontinuous in the subsurface and absent from cores in the middle of the Hollandale embayment (Locs. Ho and W, Fig. 1) (see Austin, 1970, for description of core at Loc. Ho). This indicates that the lithofacies was either not deposited at the embayment center prior to deposition of the greensand lithofacies or was penecontemporaneously eroded.

The upper interval of mixed sandstone/shale lithofacies in the Eau Claire Formation extends across the embayment, indicating more extensive emergent conditions at that time.

This lithofacies is not common within the middle part of the Mt. Simon Sandstone, although it occurs sparingly in association with lithofacies interpreted as distal braid delta deposits (lithofacies D) and beach/foreshore deposits (lithofacies C). The presence of this lithofacies interbedded with more representative Mt. Simon Sandstone lithofacies led earlier investigators (Berg, Nelson, and Bell, 1956) to conclude that the Mt. Simon and Eau Claire were interbedded or intertongued in southeastern Minnesota.

Lithofacies J—Greensand

Based on the ubiquity of glauconite and on its sedimentary structures, the greensand lithofacies is interpreted as a shallow marine sandstone.

Where the greensand lithofacies is thickest (Loc. B, Fig. 1) it is interpreted as a submarine sand bar or ridge. The succession of sedimentary structures—ripple-cross-stratified sandstone overlain by trough-cross-stratified and minor hummocky cross-stratified sandstone—resembles the succession described for some submarine bars (Young and Reinson, 1975; Berg, 1975; Harms and others, 1975; and Spearing, 1976). There is no fine planar stratification at the top of the sequence to indicate a beach deposit.

Throughout the rest of the Hollandale embayment the greensand lithofacies has fine planar stratification, some of it hummocky stratification. With the planar stratification is minor trough-cross-stratified sandstone (small sand bars) and minor very thick bedded sandstone (zones of complete amalgamation or bioturbation). It resembles shoreface sandstone illustrated by Howard and others (1972) (see Elliott, 1986). Along the northern and eastern margins of the Hollandale embayment some intervals of the greensand lithofacies (Locs. P, M, L, and S) contain intraclasts, desiccation cracks, coarsely interlayered bedding, finely interlayered bedding, and clay drapes; these features indicate tidal flat deposition. The association of these sedimentary structures with glauconite suggests ambiguity about the original depositional environment of the Eau Claire discussed by Byers (1978).

Lithofacies K—Shale/Siltstone

The shale/siltstone lithofacies is interpreted as lagoonal sediment with smaller amounts of tidal flat sediment. Lagoonal sediment consists of quiet water shale deposits. The lithofacies also includes interbedded and interfingering sandstone, and siltstone and shale lithologies; these represent a number of overlapping subenvironments (Reinson, 1984), including tidal flat and washover sheet deposits. The lithofacies is best developed in the northern part of the Hollandale embayment—up to 40 ft (12.2 m) at Locs. L, V, and H. Mapping of this lithofacies using core and well cuttings indicates its absence in most places along embayment margins, where it is replaced by lithofacies I (mixed sandstone/shale).

The shale of this lithofacies lacks the sandy coquinoid layers, attributed to migrating tidal channel and/or storm deposits, found in the red shale subfacies (G_1).

The shale/siltstone lithofacies coarsens upwards; interbedded wavy-bedded or coarsely interlayered sandstone and shale in the upper part is interpreted as tidal flat; interbedded, cross-stratified and planar-stratified sandstone of lithofacies B and C are interpreted as washover deposits. Thus there was an overall shallowing upward trend.

PALEOENVIRONMENTAL SUMMARY

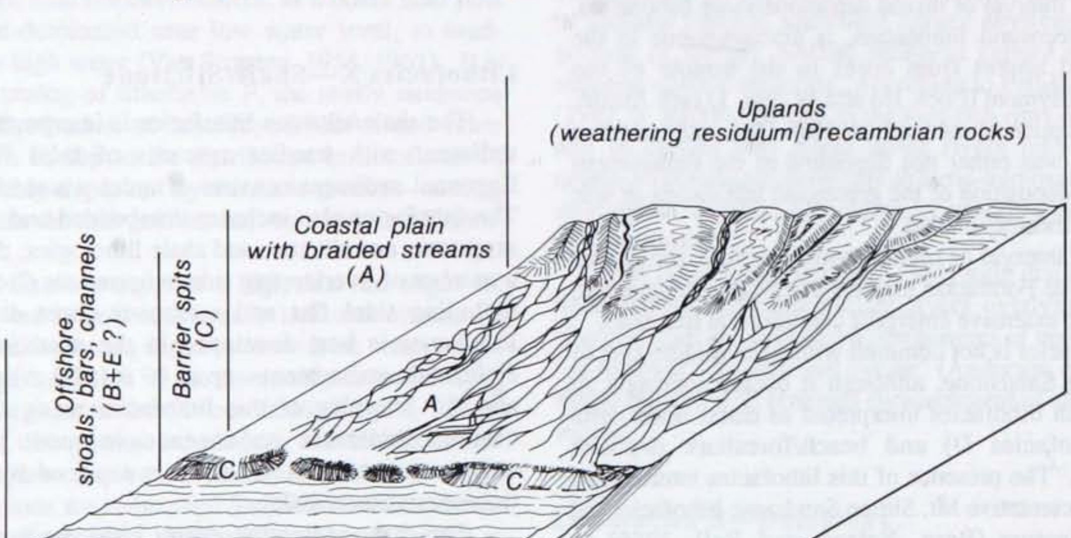
The lower Mt. Simon Sandstone (Fig. 24a) was formed from a prograding sequence of braided stream and marginal marine deposits. The coast is interpreted as similar to modern unvegetated glacial outwash plain coastlines, with major stream systems exiting through narrow distributaries cut through barrier spits accreted to the shoreline (Hine and Boothroyd, 1978). Large bars formed offshore.

During deposition of the middle Mt. Simon Sandstone (Fig. 24b), fluvial sediments accumulated mainly as a thick braid delta. Lagoons formed on interdistributary flats. Some of the deltaic sands were reworked into bars and spits along the coast, while elsewhere along the coast, tidal flats formed contemporaneously with the delta. Offshore, bars and shoals accumulated. The deltaic sediments are thickest to the north and east, toward the Wisconsin dome and northern Michigan highlands that were their source.

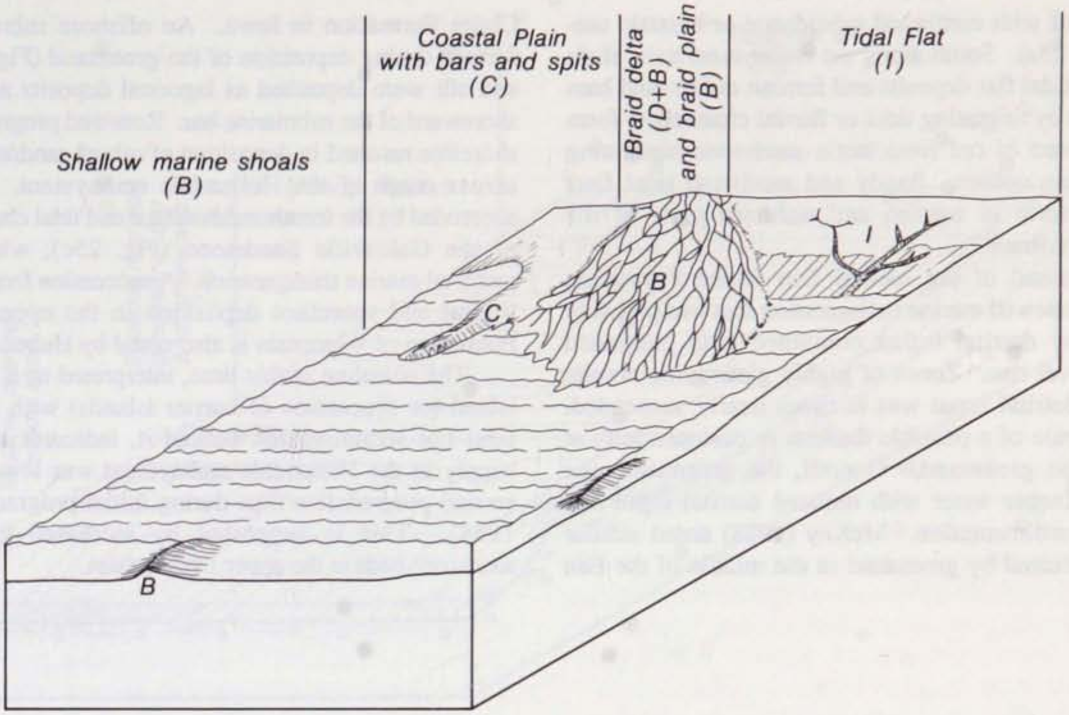
During the prograding episode, the coast configuration must have resembled that of the North Sea coast, inner part of the German Bay, as described by Reineck and Singh (1975), where tidal flats developed without frontal barrier bars. This would imply a relatively high rate of sediment supply under relatively low to moderate levels of coastal energy (Beale, 1968).

Along the western side of the Hollandale embayment lithofacies of the Mt. Simon Sandstone are mainly low and medial tidal flat deposits, and the sequence is thinner than normal. These are interpreted as relatively high-standing areas that were flooded later than the main part of the embayment. Sandy and sand/mud tidal flat deposits of the upper Mt. Simon Sandstone and basal Eau Claire Formation superceded braid delta deposits of the middle Mt. Simon in the eastern part of the Hollandale embayment as deposition continued (Fig. 24c). Clay-rich and mixed clay/carbonate tidal flats of the basal Eau Claire Formation formed along the western side of the Hollandale embayment. Along the north end of the Hollandale embayment, ferroan oolites and coated grains formed near estuarine outlets in response to lowered energy levels and reduced influx of detrital sediment. Sandy shoals were intensively reworked by large infaunal populations. Shallow marine carbonate sedimentation ultimately occurred along the southwestern margin of the Hollandale embayment, probably because of low detrital

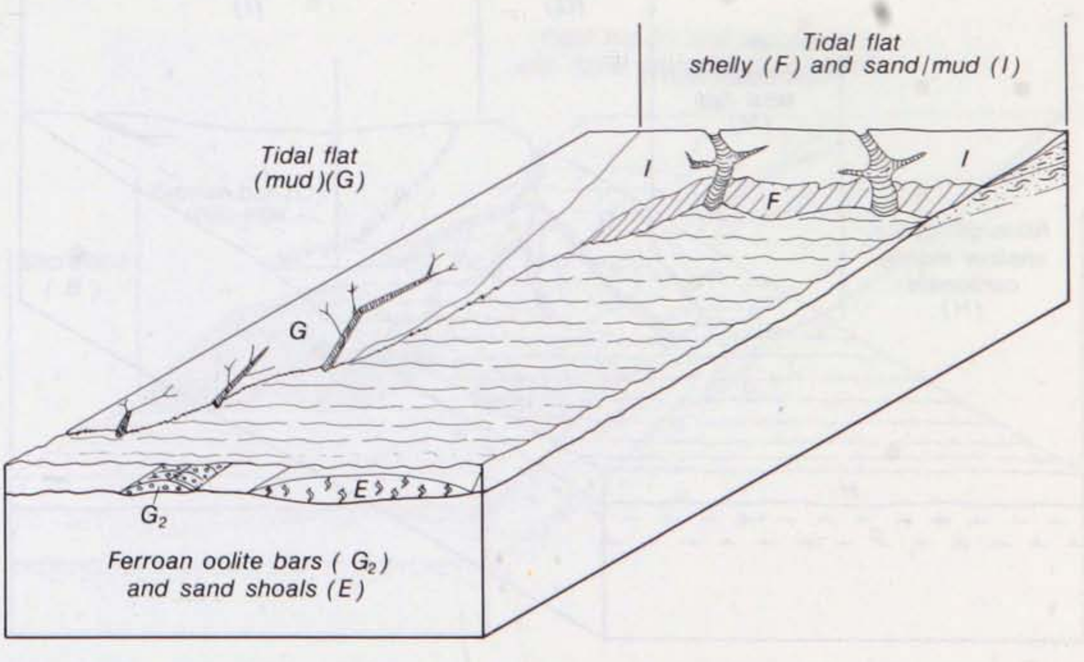
Fig. 24 Succession of lithofacies in Mt. Simon Sandstone.



24a) Lower Mt. Simon lithofacies.



24b) Middle Mt. Simon lithofacies.



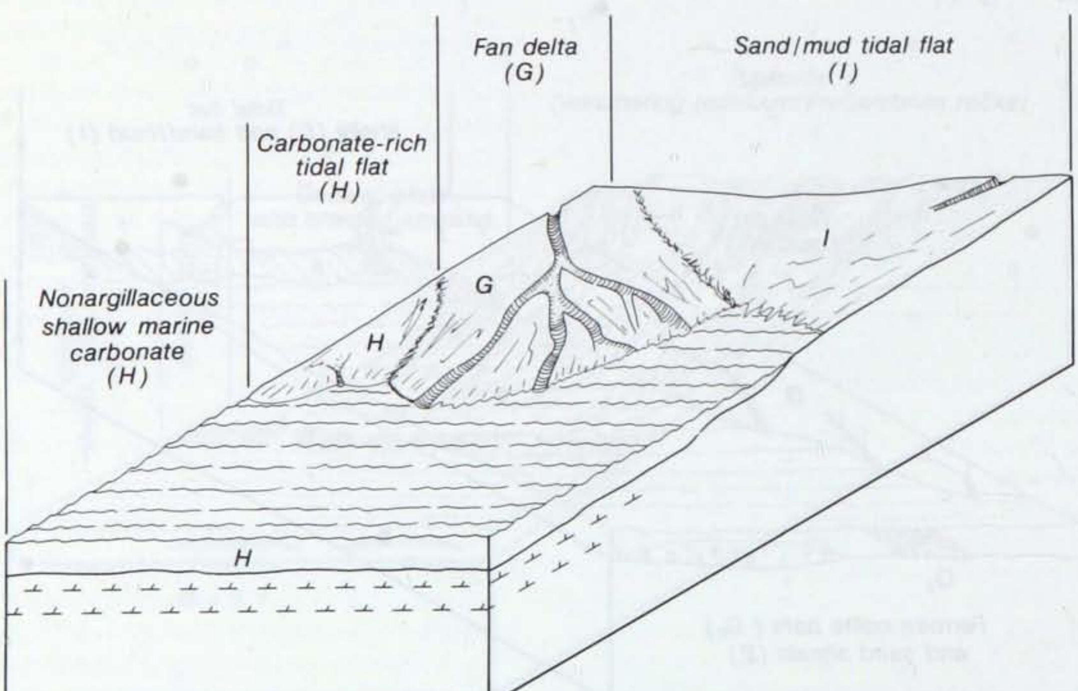
24c) Upper Mt. Simon and basal Eau Claire lithofacies.

influx combined with continued subsidence or eustatic sea-level rise (Fig. 25a). South along the embayment axis, shale and carbonate tidal flat deposits and ferroan oolite sand bars were reworked by migrating tidal or fluvial channels to form a delta composed of red intraclastic sandstone containing scattered ferroan oolites. Sandy and sand/mud tidal flats continued to form in eastern and northern parts of the Hollandale embayment.

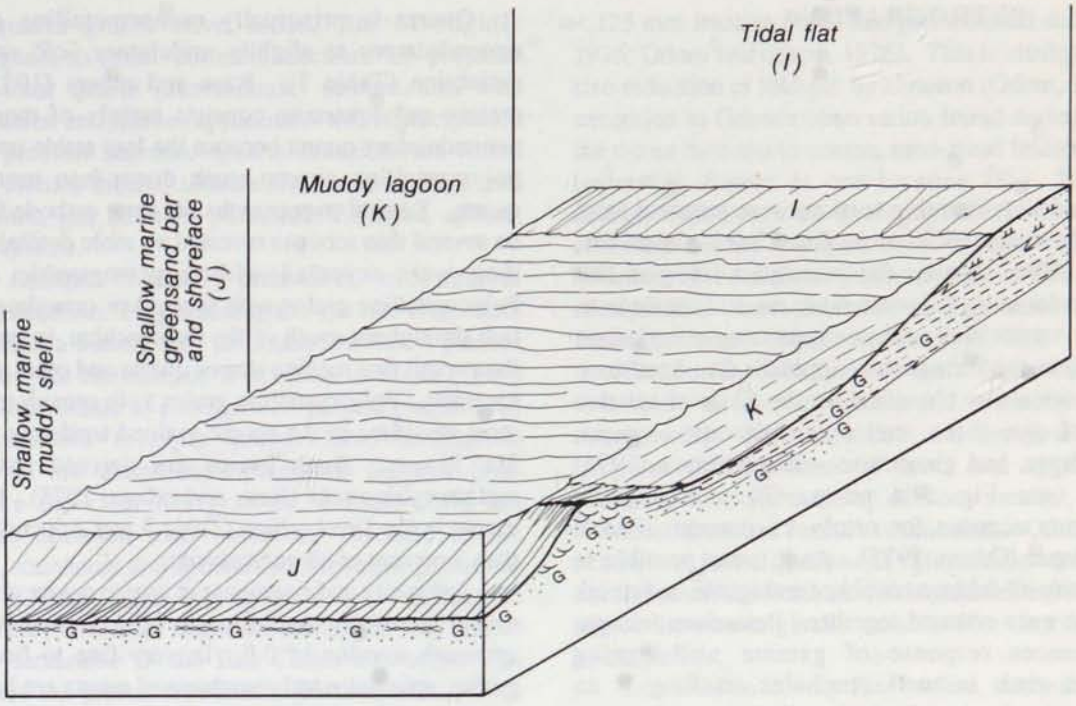
The greensand of the medial Eau Claire Formation resulted from renewed marine transgression that was probably a result of low detrital influx combined with continued eustatic sea-level rise. Zones of highly glauconitic arenite indicate that detrital input was at times nearly suspended. There is evidence of a possible diastem or disconformity at the base of the greensand. Overall, the greensand was deposited in deeper water with reduced detrital input and clearer water sedimentation. McKay (1988) noted similar conditions indicated by greensand in the middle of the Eau Claire Formation in Iowa. An offshore submarine bar(s) formed during deposition of the greensand (Fig. 25b). Clay and silt were deposited as lagoonal deposits and tidal flats shoreward of the submarine bar. Renewed progradation of the shoreline resulted in deposition of mixed sand/mud tidal flats across much of the Hollandale embayment. These were succeeded by the foreshore/shoreface and tidal channel deposits of the Galesville Sandstone (Fig. 25c), which indicate renewed marine transgression. A succession from tidal flat to littoral and shoreface deposition in the upper Eau Claire Formation of Wisconsin is also noted by Huber (1975).

The coastline at this time, interpreted as a broad barrier island (or succession of barrier islands) with lagoonal and tidal flat sedimentation behind it, indicates that sediment supply to the Hollandale embayment was lower during the second progradation than during initial progradation (Beall, 1968). This is supported by increased glauconite in sandstone beds in the upper Dresbachian.

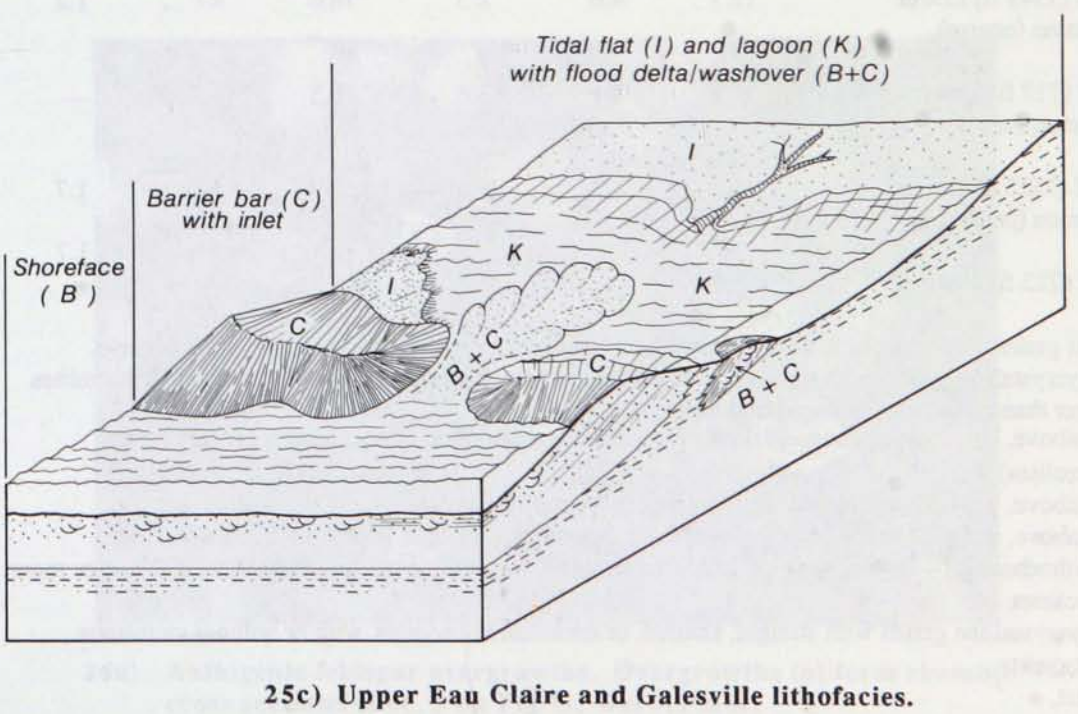
Fig. 25 Succession of lithofacies in Eau Claire Formation and Galesville Sandstone.



25a) Basal Eau Claire lithofacies.



25b) Middle Eau Claire lithofacies.



25c) Upper Eau Claire and Galesville lithofacies.

PETROGRAPHY

General

One hundred sixty-five thin sections were prepared from rock samples from the Mt. Simon, Eau Claire, Galesville, and Ironton. After staining for potassium feldspar and plagioclase, modal analyses were done on 102 sections to determine rock names and delineate mineralogic variations (mineral facies) in the formations (Appendix 2). Sandstone in the thin sections was classified on the basis of relative proportions of the three major constituents—quartz, potassium feldspar, and glauconite—using Odom's (1975) classification (see Fig. 28a on p. 48). Authigenic overgrowths may account for nearly 15 percent of total potassium feldspar (Odom, 1975). As it is not possible to positively identify all feldspar as either authigenic or detrital, both categories were counted together. Potassium feldspar content influences response of gamma well-logging instruments to rock in well boreholes, making it an important parameter in petrophysical studies.

Quartz is principally monocrystalline grains, with nonundulatory to slightly undulatory (<5° on flat stage) extinction (Table 3). Basu and others (1975) state that mature orthoquartzite consists mainly of monocrystalline nonundulatory quartz because the less stable undulatory and polycrystalline quartz break down into monocrystalline quartz. Detrital overgrowths are rare; cathode luminescence on several thin sections revealed no more detrital overgrowths than were revealed with a petrographic microscope. Polycrystalline grains with straight or crenulate margins are rare throughout much of the Dresbachian, in part because of the overall fine median size of quartz and other sand grains in the units. Polycrystalline grains with crenulate margins are most abundant in the coarse-grained sandstone of the lower Mt. Simon. Such grains are derived from low-rank metamorphic rocks (Basu and others, 1975). Chert is very scarce in the Dresbachian (Table 3 and Appendix 2), far less than 1 percent of all quartz types.

Sphericity and roundness of coarse quartz grains are high; using Krumbein and Sloss's (1951) visual chart, both approach a value of 0.9. In very fine to fine sand-sized grades, sphericity and roundness of quartz are low, 0.3 to 0.9 and 0.1 to 0.7, respectively.

Table 3 Modal quartz types of selected samples of Mt. Simon and Ironton Sandstones

	1	2	3	4	5	6	7
Loc. B (1348 ft) Lower Mt. Simon (coarse)	12.7	4.6	2.3	78.6	<1	1.2	—
Loc. P (717 ft) Lower Mt. Simon (coarse)	15.2	1.1	3.6	78.3	1.8	—	—
Loc. H (1525 ft) Lower Mt. Simon (coarse)	20.5	4.3	6.6	61.8	5.0	1.7	—
						1.7	—
Loc. P (222 ft) Ironton	55.0	—	4.8	40.2	—	—	—

1. Unit grains with straight to strongly undulatory extinction, some semicomposite grains coarse. Polycrystalline grains with nonsutured boundaries. All without vacuole trails or with few microlites larger than 10 microns and scattered vacuoles.
2. As above, but with regular inclusions of identifiable tourmaline, biotite, zircon (± bubbles and microlites).
3. As above, but with acicular inclusions, especially rutile.
4. As above, but with irregular inclusions, fluid inclusions, abundant bubble traces, opaques, etc.
5. "Hydrothermal"—brown, very bubbly, sometimes polycrystalline quartz. Bubble trails in two or more directions.
6. Polycrystalline grains with straight, sutured, or crenulate boundaries, with or without inclusions. Metaquartz.
7. Chert.

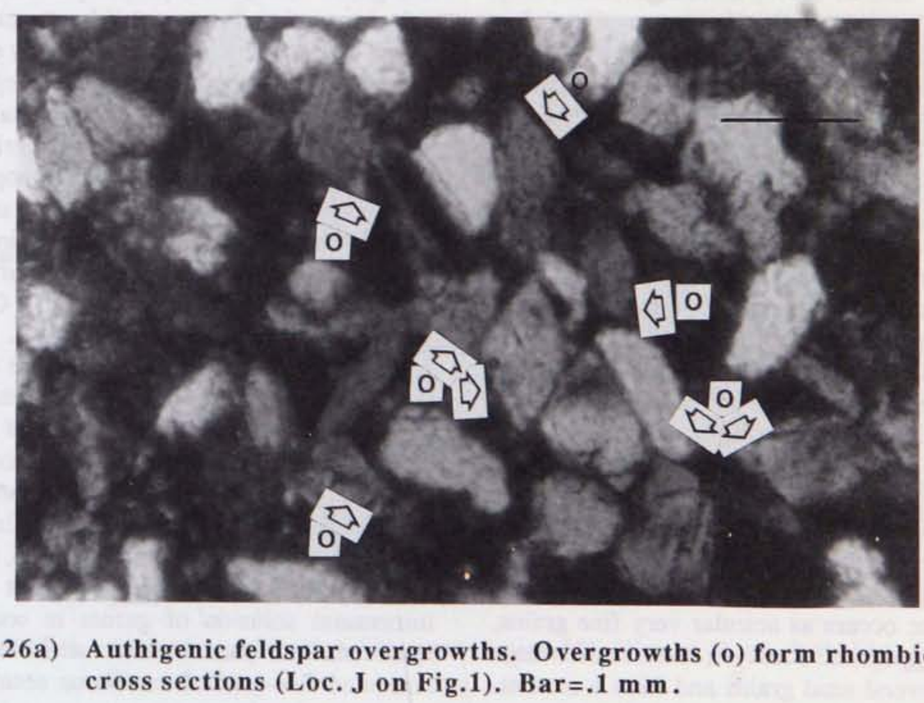
Many quartz grains have broad, flat to slightly undulatory grain-to-grain contacts because of pressure solution. Minor quartz (chalcedonic) cementation with straight extinction and fibrous appearance was reprecipitated near sites of pressure solution. Quartz inclusions are varied and include zircon, biotite, tourmaline, rutile needles and other microlites, gas bubbles, potassium feldspar, apatite, chlorite, and epidote.

Detrital feldspar is mostly orthoclase, with smaller amounts of microcline. Plagioclase grains are rare (Appendix 2); in the basal Mt. Simon, they are much less than 1 percent of all feldspar. In contrast, in Wisconsin, Asthana (1969) observed the Mt. Simon to average 1.84 percent plagioclase. Detrital potassium feldspar grains have authigenic overgrowths of low-temperature potassium feldspar (Fig. 26a). Unlike the clear overgrowths, detrital cores are brownish and crowded with vacuoles. Because of the overgrowths, roundness and sphericity of feldspar grains are low, 0.3 to 0.7 and 0.3 to 0.7, respectively. Authigenic feldspar overgrowths are an important cement in very fine to fine-grained sandstone in the Eau Claire and upper Mt. Simon, and are the principal reason it is much more firmly cemented than adjacent, very friable medium- and coarse-grained quartz sandstone. Feldspar is almost invariably in the <.125 mm fraction (very fine grained sand and finer) (Odom, 1975; Odom and others, 1976). This is attributed to selective size-reduction of feldspar by abrasion (Odom, 1975). The one exception to Odom's observation found during this study are the minor medium to coarse, sand-sized feldspar grains in the lower Mt. Simon at one location (Fig. 26b). Feldspar authigenesis occurred preferentially in zones containing abundant detrital feldspar; there is no evidence of marked zonation of authigenic feldspar and sericite into separate stratigraphic intervals, such as that observed in the Mt. Simon in Illinois (Duffin and others, 1989).

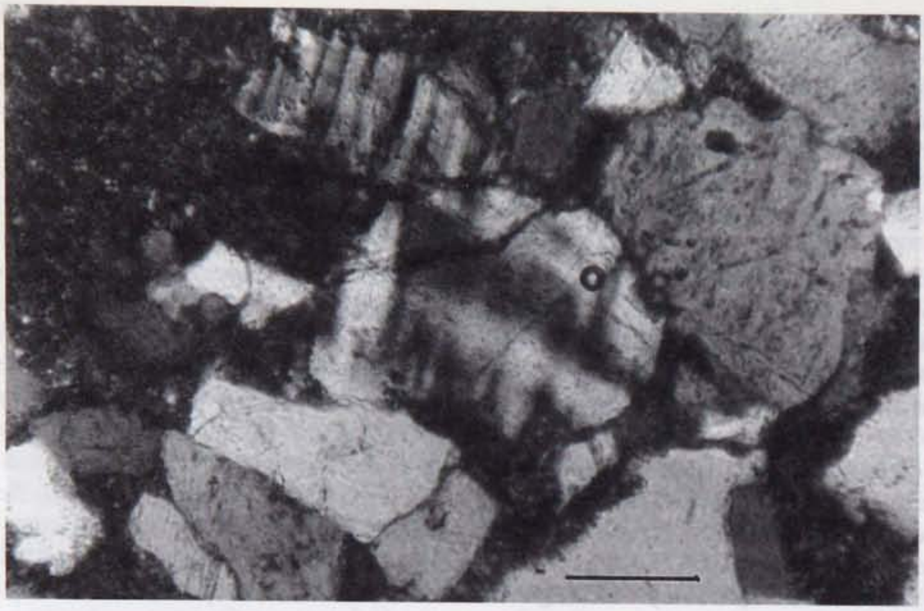
Glauconite is in three forms. Some are small pellets with uniform internal texture and sometimes fibro-radiate overgrowths. More abundant are composite pellets with irregular (lobate) external form and aggregate internal structure; these are made up of many smaller, denser pellets. The least abundant form is vermiculate. Odom (1976), after extensive investigation of glauconite from Cambrian sandstone of the northern Midcontinent, concluded that the glauconite was originally smectite-like clay that was altered by diagenesis.

Dolomite is in very fine to fine, subhedral or euhedral interlocking crystals. Dolomite is authigenic; some replaces the calcite of echinoderm fragments. Some dolostone in

Fig. 26 Feldspar from Mt. Simon Sandstone.



26a) Authigenic feldspar overgrowths. Overgrowths (o) form rhombic cross sections (Loc. J on Fig.1). Bar=.1 mm.



26b) Medium to coarse, sand-sized detrital K-feldspar; grains with twinning (Loc.B on Fig. 1). Bar=.1 mm.

irregular, swirled patterns in detrital units may replace burrow fillings or fill voids along burrows. Calcite is rare; minor amounts of very fine grained calcite may be an alteration product of dolomite. Kiester (1976) concluded from X-ray analyses that most carbonate in the upper Cambrian formations of southeastern Minnesota is dolomite.

Mica is present as megascopic detrital grains, particularly in shalier beds. Muscovite is most abundant; biotite and chlorite are rare. Detrital clay matrix is an important constituent in all facies. However, the abundances reported in the tables are largely an artifact of sampling, as the samples are from less shaly intervals.

Collophane is present as brachiopod valves and other organic detritus in much of the upper Mt. Simon, Eau Claire (greensand lithofacies and shale/siltstone lithofacies), and Galesville (Appendix 2). It is also present as authigenic coatings on detrital grains and as laminae in ferroan ooids; it is an authigenic cement in highly ferruginous sandstone in a hardground at the top of the Mt. Simon (Loc. B., Fig. 1).

Opaque minerals include detrital magnetite and ilmenite (altered in part to limonite and leucoxene); goethite and limonite, as laminae on oolites and cement in the ferruginous hardground at the top of the Mt. Simon; authigenic pyrite; and marcasite. Pyrite occurs as acicular very fine grains, cubes, and granular aggregates. Rarely, it forms masses large enough to enclose several sand grains and form a cement. Marcasite and pyrite form thin skins or outer rims on some oolites (Broberg, 1977). Pyrite commonly encrusts magnetite-ilmenite grains within collophanic fossil fragments and glauconite grains, probably the result of a favorable reducing environment created by organic matter associated with these particles. Ready availability of magnetite-derived iron would favor pyrite-formation in a reducing environment.

Typical for lower Paleozoic strata, the heavy mineral suites are dominated by ultrastable minerals. Zircon and tourmaline are the most abundant nonopaque heavy mineral species. The zircon is in well-rounded or subhedral elongate grains that are invariably abraded. Zircon is sometimes in placers with opaque minerals. Tourmaline crystals are elongate and strongly pleochroic. Garnet is in highly corroded, very irregular hackly grains. In studies of heavy mineral separates from the Wisconsin outcrop by Asthana (1969), garnet was most common in the uppermost part of the Mt. Simon and in overlying beds of the Eau Claire. It is the same in the subsurface of Minnesota, with garnet most abundant in very fine to fine-grained, better cemented sandstone of the upper Mt. Simon and Eau Claire. According to Asthana (1969) and Hamblin (1961), this distribution may be from change of provenance, but the explanation of intrastratal solution of garnet in coarser, more porous sandstone and partial preservation in less porous, well-cemented fine-grained sandstone seems supported by the hackly, corroded appearance of grains observed in this study. Rutile, sphene, pyroxene (diopside), amphibole (tremolite-actinolite), epidote-clinozoisite, and apatite are very minor heavy minerals.

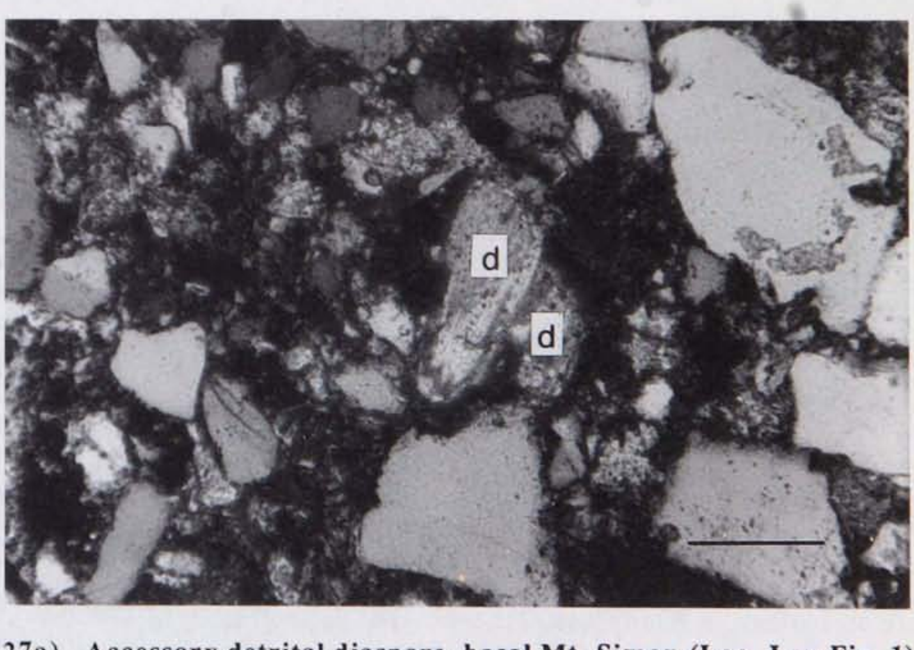
Diaspore is an accessory mineral along the western edge of the Hollandale embayment (Locs. 0 and J, Fig. 1) near outcrops and subcrops of Sioux Quartzite, in which it is an authigenic mineral and from which it was derived (Figs. 27a and 27b) (Mossler, 1987). Books of kaolinite, ragged masses of sericite, and rutile grains occur as detrital grains in association with the diaspore. These minerals are authigenic in the Sioux Quartzite (Southwick and Mossler, 1984); their presence indicates that some sediments along the western edge of the embayment were derived from the Sioux Quartzite.

MINERALOGICAL FACIES

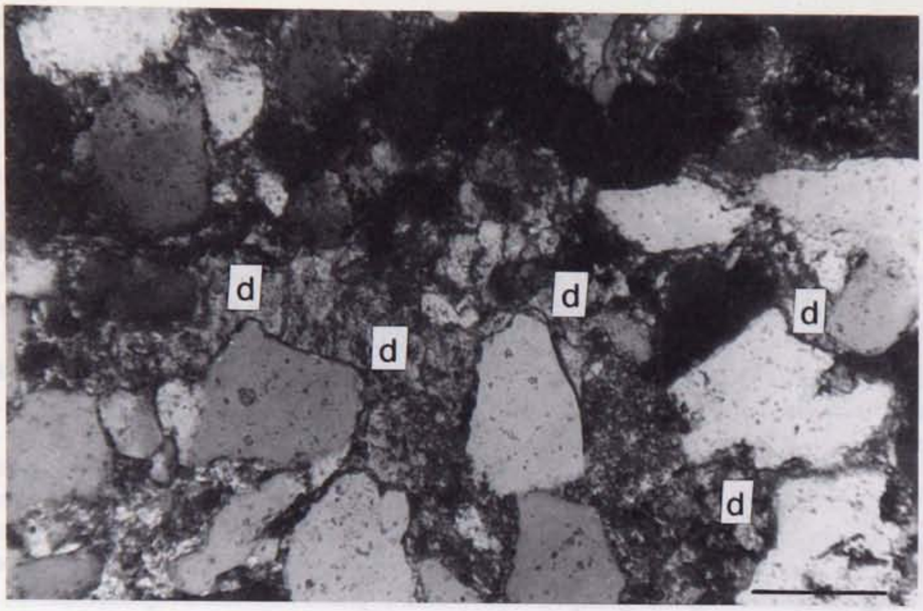
Sandstone of the Dresbachian may be grouped into several categories using Odom's (1975) sandstone classification (Figs. 28 and 29). Orthoquartzite (quartz arenite) is less common than thought in the past (Dapples, Krumbein, and Sloss, 1948). Many sandstone beds are feldspathic arenite (>10 percent feldspar grains) or highly feldspathic arenite (>25 percent feldspar grains). The feldspar grains are almost always concentrated in the very fine grained sand and coarse silt sizes (<0.125 mm dia.), as observed by Odom (1975). Minor medium to coarse sand grains composed of detrital K-feldspar are in lithofacies B (medium- and large-scale, cross-stratified sandstone) at Location B (Fig. 1). These coarse feldspar grains may result from local provenance.

Stratigraphic intervals composed of horizontally stratified or cross-stratified sandstone beds in the lower part of the Mt. Simon (Fig. 28b) and upper part of the Galesville (and Ironton) (Fig. 29a) are the only intervals with a clear predominance of quartz arenite (<10 percent feldspar grains). Though many of the structureless, poorly sorted, fine to coarse, structureless, bioturbated sandstone beds in the middle and upper Mt. Simon are quartz arenite, about half (Fig. 28c) are feldspathic because of a high percentage of fines. Basal Galesville Sandstone is also generally feldspathic because of

Fig. 27 Derivation of detrital diaspore in basal Mt. Simon from the Sioux Quartzite.

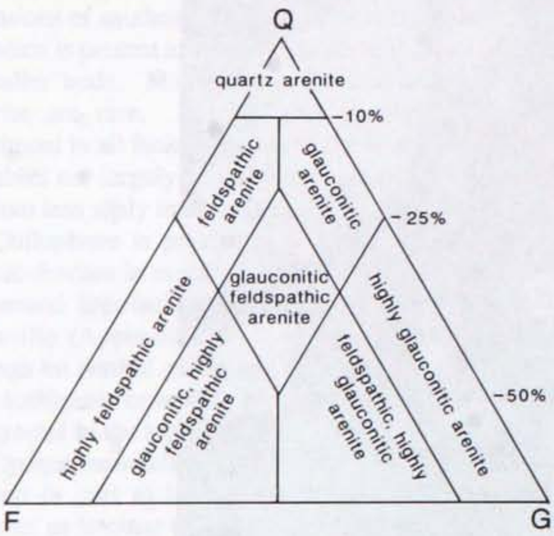


27a) Accessory detrital diaspore, basal Mt. Simon (Loc. J on Fig. 1). Bar=.1 mm.

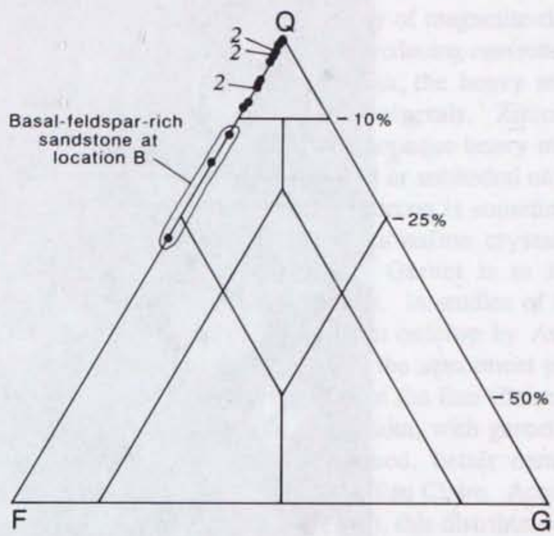


27b) Authigenic diaspore cement, Sioux Quartzite. Outcrop in sec. 18, T. 107 N., R. 35 W. (Cottonwood County).

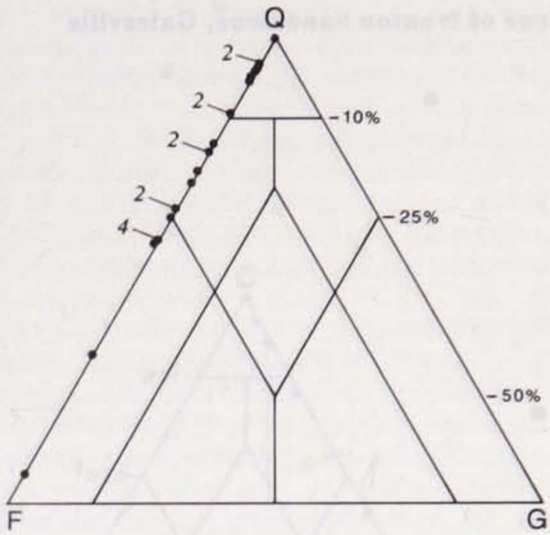
Fig. 28 Compositional classification of Mt. Simon Sandstone.



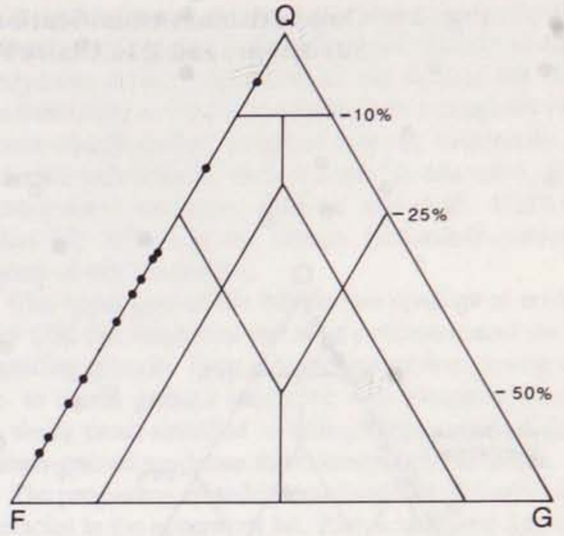
28a) Sandstone classification (Odom, 1975).



28b) Moderately to well-sorted, fine- to coarse-grained, cross-stratified or planar-stratified sandstone.



28c) Poorly sorted, fine- to coarse-grained, very thick bedded sandstone.



28d) Well-sorted, very fine to fine-grained sandstone.

abundant coarse silt and very fine sand grains (Fig. 29a). The thin beds of very fine grained sandstone in abundance in middle and upper Mt. Simon lithofacies are highly feldspathic (Fig. 28d).

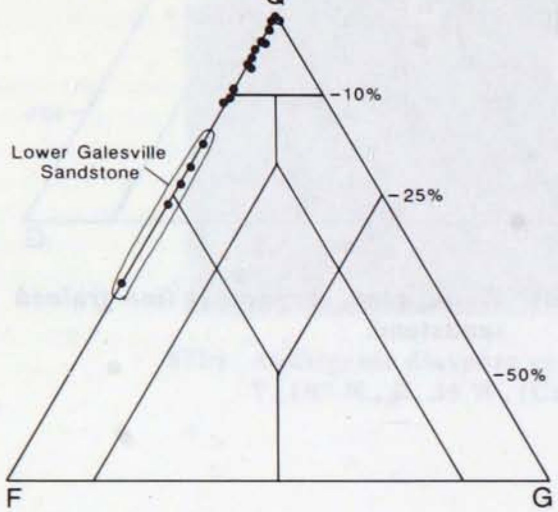
Most sandstone beds in the mixed sandstone/shale lithofacies and the red sandstone subfacies are either feldspathic arenite or highly feldspathic arenite, although coarser-grained beds are quartz arenite (Fig. 29). The only lithofacies with considerable amounts of glauconite are the greensand and shale/siltstone lithofacies (Fig. 29). The red sandstone subfacies and mixed sandstone/shale lithofacies contain minor amounts. Other lithofacies contain only trace amounts, if any. The greensand lithofacies is the most varied in composition. It contains several categories of sandstone, the most common being glauconitic arenite and glauconitic, highly feldspathic arenite.

Generally, a single sandstone type does not represent a given lithofacies in the Dresbachian. In most cases, the significance lies in the relative proportions of different sandstone types. Physical and biogenic sedimentary structures are also important in determining lithofacies. In all lithofacies of the Mt. Simon, particularly the lower and middle parts, the distribution of finer-grained feldspathic sandstone causes distinctive patterns of gamma and resistivity logs that can be used to identify these lithofacies on wire line logs (Fig. 8). Similarly, the higher content of feldspathic silt to very fine sand grains in the basal Galesville, compared to that in the upper Galesville, produces higher gamma readings for that interval.

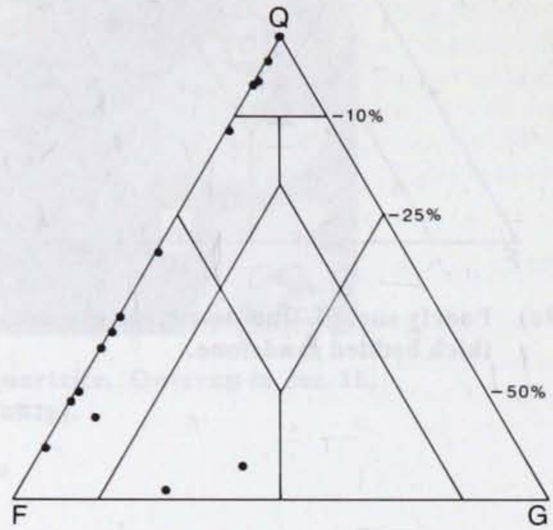
The Eau Claire's abundant potassium-rich illitic shale and glauconite mask the distribution of feldspar on natural gamma logs. Generally, the Eau Claire has higher, more uniform gamma readings than adjacent formations.

Odom's (1975) statement that there is no appreciable stratigraphic or regional change in the composition or size of feldspar in the Cambrian section is supported by this study. The stratigraphic distribution of feldspar within finer-grained sedimentary rocks also favors an explanation of origin by selective abrasion of detrital K-feldspar grains from various Precambrian terranes and deposition of resulting fine-grained sediments in lower-energy environments. The importance attributed to provenance by Hamblin (1961) for compositional and textural variations in Upper Mississippi Valley Cambrian sandstone is not supported by Odom or this study. Swett and others (1971) proposed that quartz arenite in the Cambrian Eriboll Sandstone of Scotland was produced by reduction (abrasion) of unstable grains in sand bodies resembling those in lithofacies B (medium- to large-scale, cross-stratified sandstone) of the Mt. Simon Sandstone. A similar mechanism may have operated during deposition of the Mt. Simon.

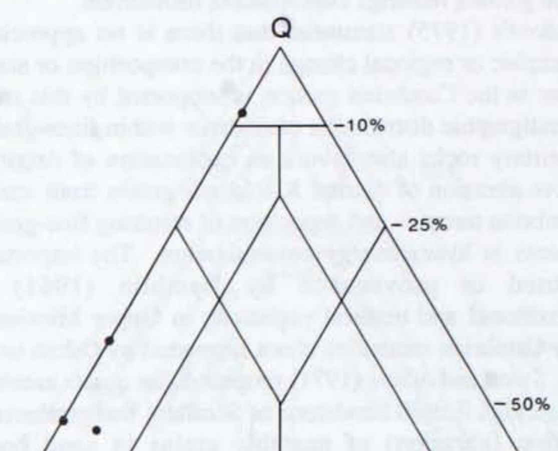
Fig. 29 Compositional classification of sandstone of Ironton Sandstone, Galesville Sandstone, and Eau Claire Formation.



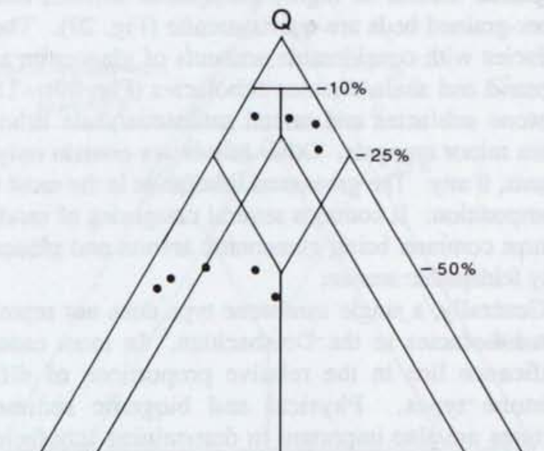
29a) Ironton and Galesville sandstone.



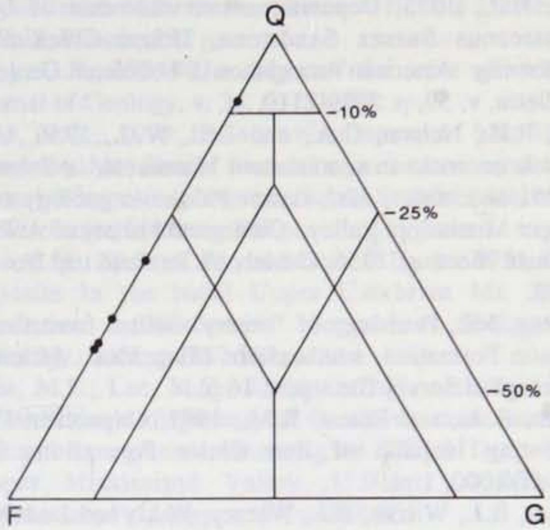
29b) Sandstone of mixed sandstone/shale lithofacies (I).



29c) Sandstone of shale/siltstone lithofacies (K).



29d) Sandstone of greensand lithofacies (J).



29e) Sandstone of red sandstone subfacies (G_2).

SUMMARY

The Mt. Simon Sandstone, Eau Claire Formation, and Galesville Sandstone were deposited in the Hollandale embayment, a broad lowland that extended from the Illinois basin and Ozark highland into the continental interior, between highlands formed from resistant Precambrian rocks.

Rocks of the Mt. Simon, Eau Claire, and Galesville are divided into eleven lithofacies, some of which consist of two or more subfacies. These lithofacies were deposited in environments ranging from braided fluvial to shallow marine shelf. Lithofacies are based on characteristics including composition/mineralogy, grain size and textural maturity, color, physical and biogenic structures, and fossil content.

Rocks of the Mt. Simon, Eau Claire, and Galesville formed during two prograding episodes. At the base of the Mt. Simon is a very thin interval that is primarily crudely stratified pebbly sandstone and conglomerate interpreted as braided fluvial deposits. The lower Mt. Simon is principally medium- and large-scale, cross-stratified sandstone and planar-stratified sandstone interpreted as having formed in alluvial braid plain and braid delta, upper shoreface, and beach/foreshore environments during initial transgression of marine waters into the Hollandale embayment.

A thick wedge of sediments that were deposited primarily on distal parts of braid deltas prograded into the Hollandale embayment during deposition of the medial Mt. Simon. This lithofacies is very heterolithic, but is primarily crudely or cross-stratified, fine- to coarse-grained, moderately sorted sandstone interbedded with coarsely interlayered, fine- to coarse-grained sandstone, siltstone, and shale. Much of the medial Mt. Simon in the eastern Hollandale embayment consists of this lithofacies.

The upper part of the Mt. Simon consists of middle or upper tidal flat lithofacies that are a continuation of the initial prograding episode. They include structureless, poorly sorted, fine- to coarse-grained sandstone with abundant *Skolithos*; and shelly cross-stratified or horizontally stratified, fine- to medium-grained sandstone that contains coquina lenses.

The prograding episode culminated with the deposition of lithofacies in the uppermost Mt. Simon and basal Eau Claire, which are interpreted as having formed in high tidal flat, tidal channel, and deltaic environments. The ferroan oolites and authigenic phosphate (collophane) indicate that influx of detrital sediment was much reduced. Red shale and sandstone with desiccation cracks indicate subaerial exposure on high tidal flats. The presence of dolostone in the southwestern part of the Hollandale embayment indicates that detrital sedimentation had ceased in that area and shallow marine-shelf carbonate sedimentation begun.

Resumption of marine transgression resulted in deposition of a wedge of greensand across the Hollandale embayment. It was deposited primarily in the shoreface and as a submarine sand ridge. This lithofacies forms the middle part of the Eau Claire Formation.

Upper lithofacies of the Eau Claire are lagoonal and tidal flat sediments. They consist of thick shale and siltstone beds (lagoonal), overlain by interbedded, very fine grained sandstone, siltstone, and shale (tidal flat).

The Galesville Sandstone in Minnesota is a thick sequence of cross- or planar-stratified, fine- to medium-grained sandstone formed in foreshore to shoreface and tidal channel environments.

In Minnesota, the contact between the Galesville and underlying Eau Claire appears to be conformable. However, there is evidence of disconformity between the Galesville and overlying Ironton Sandstone.

Most of the detrital sediment came from the Wisconsin dome/upper Michigan highland, as indicated by the thickening of coarser detrital units toward the east and north. However, accessory minerals from the Mt. Simon in southwestern Minnesota, including diaspore, rutile, kaolinite, and sericite, indicate that some detrital material was derived from the Sioux Quartzite.

Although the coarser sandstone beds of the Mt. Simon and Galesville are quartz arenite, very fine to fine-grained sandstone throughout the Dresbach is feldspathic arenite and highly feldspathic arenite. The relationship between size-grade and mineralogy is due to selective mechanical attrition of the feldspar in the depositional environment. Abundance of potassium feldspar in finer-grained lithofacies influences patterns on gamma logs. Recognition of patterns characteristic of different mineralogical facies is useful in identification and correlation of lithofacies, though supporting data on lithologies from well cores and cuttings is usually necessary to substantiate interpretations.

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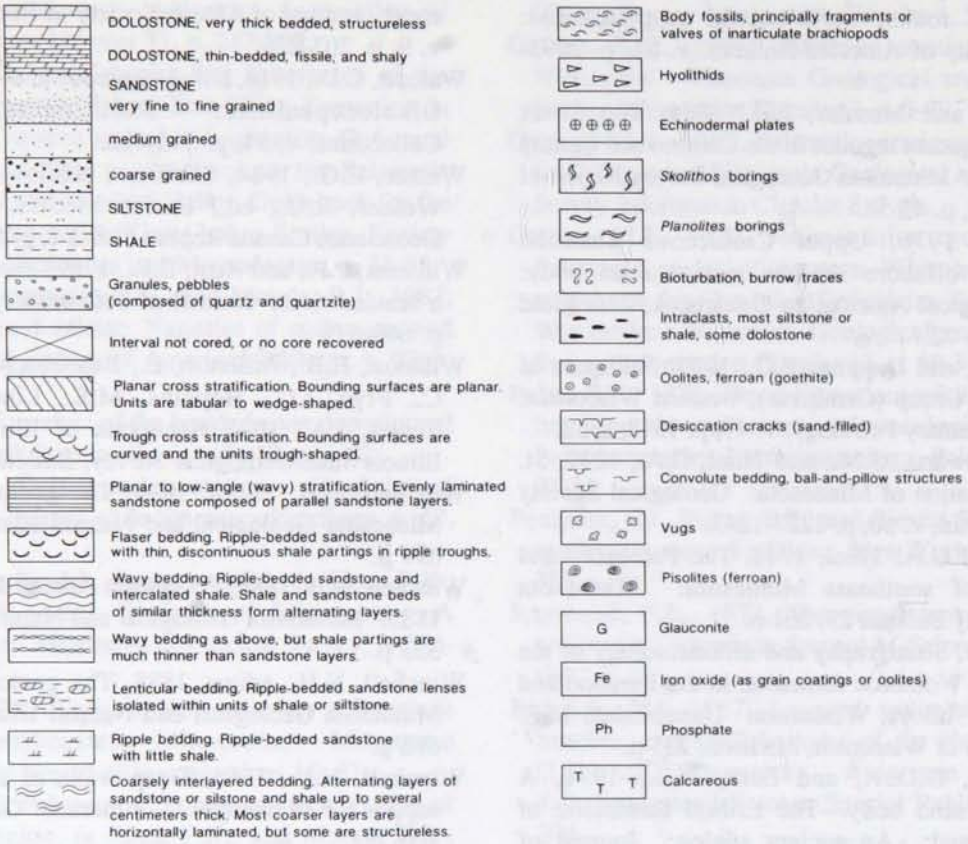
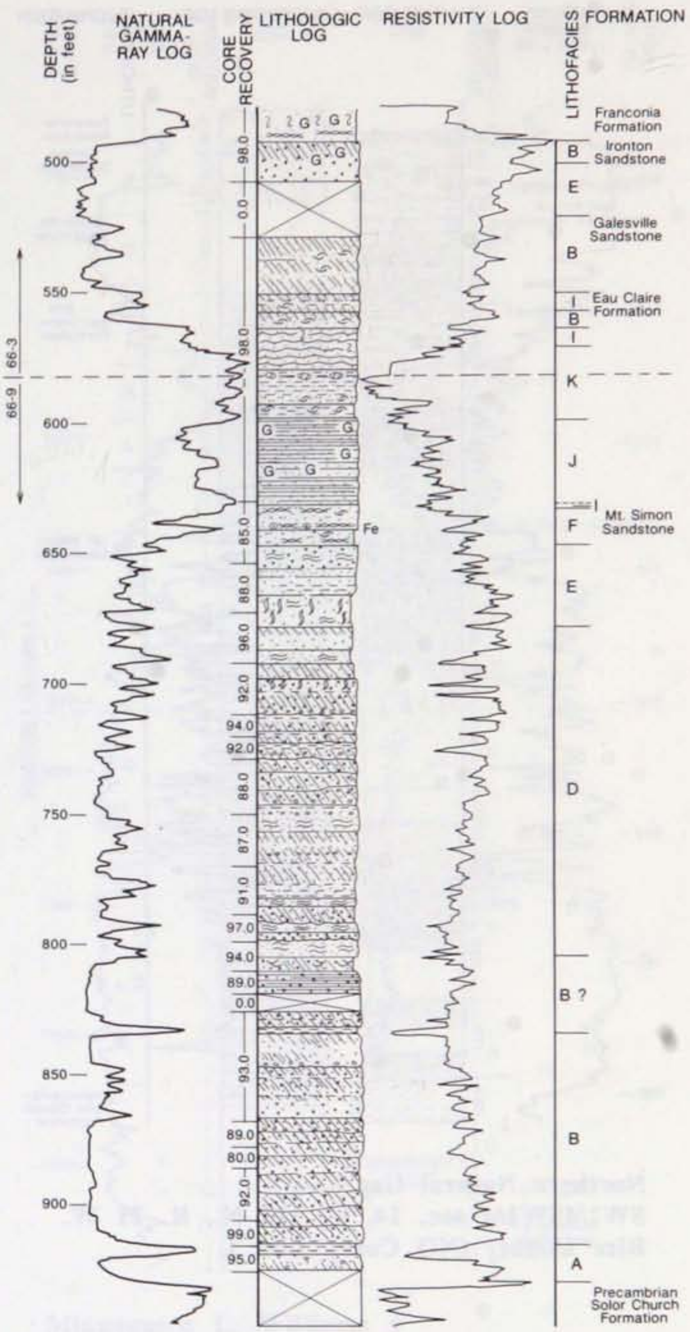
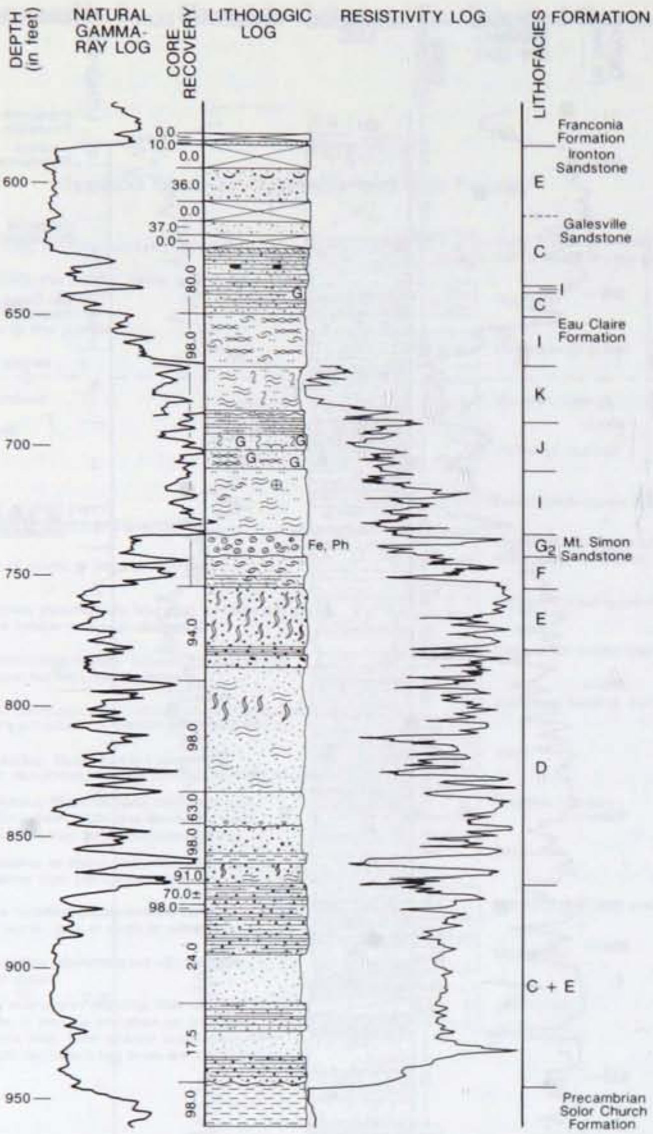
Appendix 1 Graphic Columns for Selected Cores

Symbols Used for Appendix and Text Figures

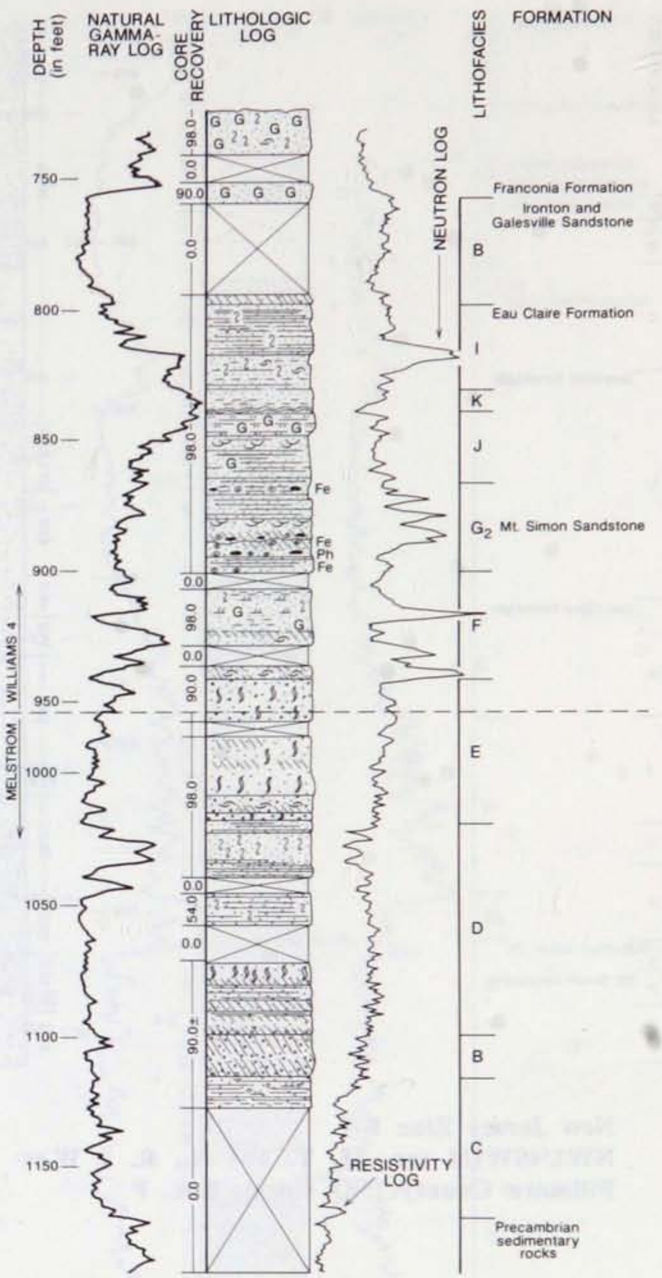




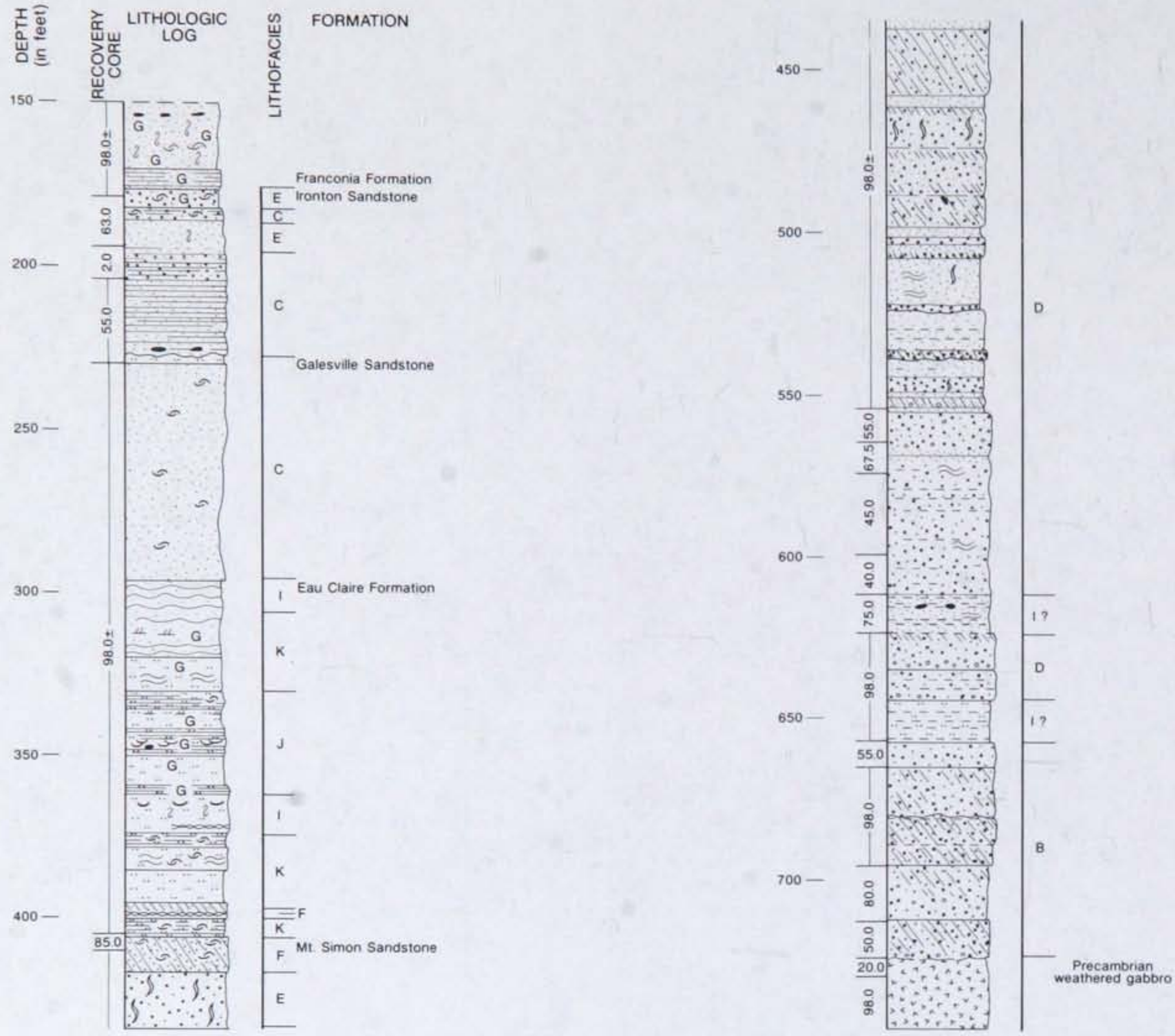
Northern Natural Gas 66-3 and 66-9
NE1/4SE1/4 sec. 19, T. 114 N., R. 18 W.
NW1/4NW1/4 sec. 11, T. 114 N., R. 18 W.
Dakota County (NQ Core), Loc. V



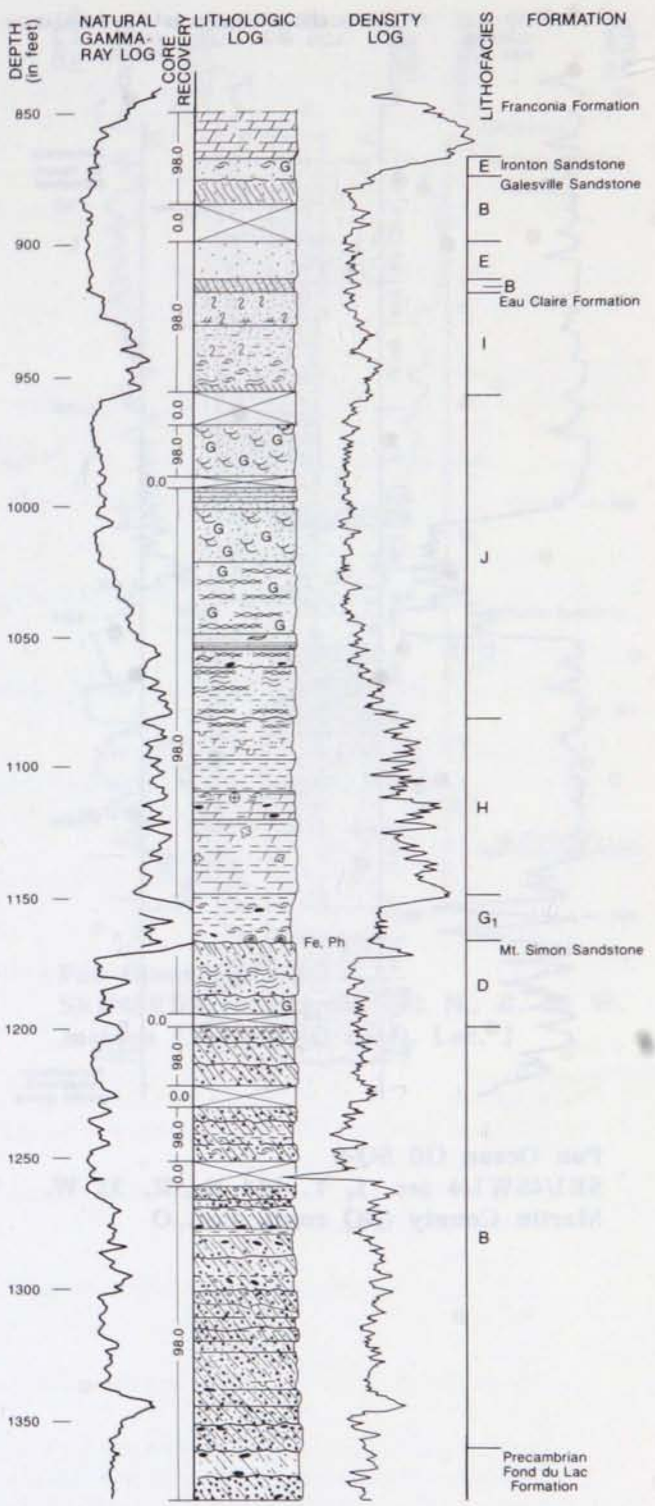
Northern Natural Gas 65-1
SW1/4SW1/4 sec. 14, T. 112 N., R. 21 W.
Rice County (NQ Core), Loc. L



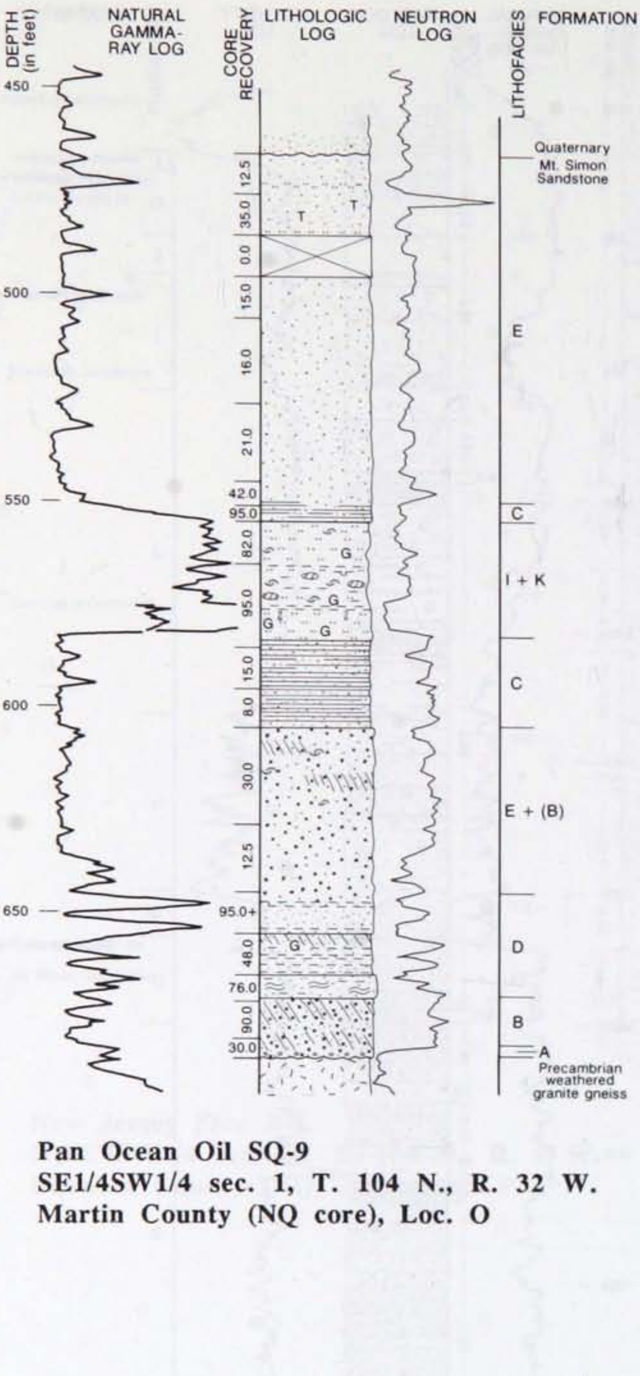
Minnegasco L. Williams 4
SW1/4NE1/4 sec. 7, T. 108 N., R. 22 W.
Waseca County
Minnegasco Melstrom 1
SE1/4SW1/4 sec. 28, T. 109 N., R. 22 W.
Rice County (Composite Log), Loc. W
(3.8-inch diameter core)



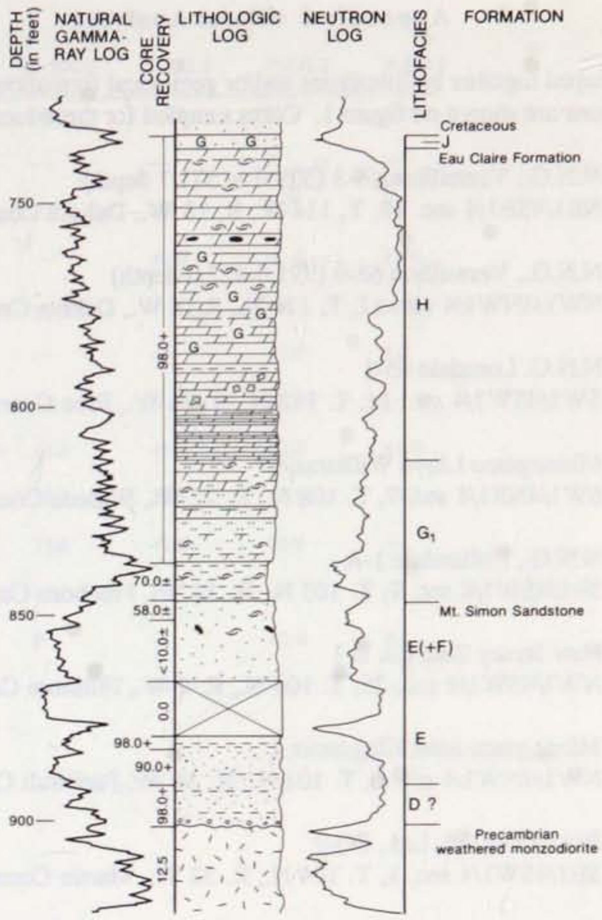
New Jersey Zinc B-1
NW1/4SW1/4 sec. 25, T. 104 N., R. 9 W.
Fillmore County (NQ Core), Loc. P



Minnegasco John Kingstrom 1
NW1/4NW1/4 sec. 6, T. 101 N., R. 24 W.
Faribault County, Loc. B
(3.8-inch diameter core



Pan Ocean Oil SQ-9
SE1/4SW1/4 sec. 1, T. 104 N., R. 32 W.
Martin County (NQ core), Loc. O



Pan Ocean Oil SQ-5
SE1/4SE1/4 sec. 11, T. 102 N., R. 36 W.
Jackson County (NQ core), Loc. J

Appendix 2 Modal Analyses

Modal analyses are grouped together by lithofacies and/or geological formation. All values are given in percentages. Locations are shown on figure 1. Cores sampled for these locations are given below.

Loc. V:	N.N.G., Vermillion 66-3 (529.0 to 571.7 depth) NE1/4SE1/4 sec. 19, T. 114 N., R. 18 W., Dakota County
	N.N.G., Vermillion 66-9 (591.0-922.0 depth) NW1/4NW1/4 sec. 11, T. 114 N., R.18 W., Dakota County
Loc. L:	N.N.G. Lonsdale 65-1 SW1/4SW1/4 sec. 14, T. 112 N., R. 21 W., Rice County
Loc. W:	Minnegasco Lloyd Williams 4 SW1/4NE1/4 sec. 7, T. 108 N., R. 22 W., Waseca County
Loc. Ho:	N.N.G., Hollandale 1-A SE1/4SW1/4 sec. 7, T. 103 N., R. 19 W., Freeborn County
Loc. P:	New Jersey Zinc Co. B-1 NW1/4SW1/4 sec. 25, T. 104 N., R. 9 W., Fillmore County
Loc. B:	Minnegasco John Kingstrom 1 NW1/4NW1/4 sec. 6, T. 101 N., R. 24 W., Faribault County
Loc. O:	Pan Ocean Oil, Ltd., SQ-9 SE1/4SW1/4 sec. 1, T. 104 N., R. 32 W., Martin County
Loc. J:	Pan Ocean Oil, Ltd., SQ-5 SE1/4SE1/4 sec. 11, T. 102 N., R. 36 W., Jackson County

Abbreviations

Qtz.=	Quartz
Meta. Qtz.=	Metamorphic quartz; composite grains with straight or crenulate margins
Lithic Grns.=	Schist and other extrabasinal grains
K-feldspar =	Potassium feldspar: microcline, orthoclase, perthite
Carb.=	Carbonate, principally dolomite
Glauc.=	Glauconite
Colloph.=	Collophane, mainly organic detritus from inarticulate brachiopods, trilobites
Cht.=	Chert
Opaq. Heav. Min.=	Opaque heavy minerals; goethite, limonite, ilmenite/magnetite, pyrite
Poro.=	Porosity
Mica =	Mica, muscovite, biotite, and chlorite coarser than 20 microns
Nonopaq. Heav.=	Nonopaque heavy minerals, primarily tourmaline and zircon
P=	Present in thin section, but not encountered during point count transects

Ironton Sandstone

Loc/Depth (Lithofacies)	L-594.3 (E)	P-183.5 (C)	P-222.0 (C)	B-875.0 (E)
Qtz. except Meta.	68.2	66.6	60.1	60.5
Meta. Qtz.	—	—	P	—
K-feldspar	2.6	4.7	8.9	1.2
Carb.	—	<1.0	<1.0	21.6
Glauc.	—	—	1.0	<1.0
Colloph.	—	—	<1.0	1.2
Cht.	—	—	<1.0	—
Opaq. Heav. Min.	<1.0	<1.0	<1.0	<1.0
Poro.	15.4	26.9	17.1	14.3
Clay Matrix	11.8	<1.0	10.9	—
Mica	<1.0	P	—	—
Nonopaq. Heav.	P	—	<1.0	P
Misc.	—	—	—	—

Galesville Sandstone

Loc/depth (Lithofacies)	V-529.0 (B)	L-615.0 (E)	L-628.2 (C)	Ho-1236.5 (C)	P-292.0 (C)	B-875.4 (B)	B-903.0 (E)
Qtz. except Meta.	75.0	69.3	66.5	49.2	56.8	65.3	71.6
Meta. Qtz.	—	—	—	—	—	—	—
K-feldspar	5.4	7.7	15.2	17.8	17.7	<1.0	<1.0
Carb.	—	—	—	—	2.2	33.3	—
Glauc.	—	P	—	P	P	—	—
Colloph.	P	—	<1.0	P	9.6	P	—
Cht.	<1.0	—	—	—	—	—	—
Opaq. Heav. Min.	<1.0	1.0	1.0	—	<1.0	P	-
Poro.	18.1	19.2	14.0	12.1	12.7	1.0	13.5
Clay Matrix	<1.0	2.9	2.3	20.6	<1.0	—	14.4
Mica	P	—	<1.0	P	P	—	—
Nonopaq. Heav.	P	P	P	P	—	—	P
Misc.	—	—	—	—	—	—	—

Mixed Sandstone /Shale lithofacies (I)
(in Eau Claire Formation)

Loc/depth	V-571.7	L-642.5	L-650.0	L-664.0	L-713.3	L-731.0	W-802.0	W-828.5	Ho-1244.0	Ho-1349.0	B-928.0	B-952
Qtz. except Meta.	59.0	71.3	49.4	37.7	41.1	45.8	73.5	36.8	56.1	22.4	64.6	56.7
Meta. Qtz.	—	<1.0	—	—	—	—	P	—	—	—	—	—
K-feldspar	24.9	10.0	31.6	33.4	42.2	31.8	3.4	51.4	3.3	28.1	1.9	—
Carb.	—	—	—	—	4.4	3.8	—	<1.0	—	21.7	—	—
Glauc.	—	—	—	24.2	P	P	P	P	—	11.1	<1.0	<1.0
Colloph.	<1.0	1.6	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1.3	<1.0	P	27.2
Cht.	—	—	—	—	—	<1.0	—	—	—	—	—	—
Opaq. Heav. Min.	3.0	<1.0	1.0	<1.0	—	<1.0	P	7.5	<1.0	4.8	1.6	2.6
Poro.	7.9	7.4	15.8	3.4	9.5	9.6	21.9	1.9	5.3	7.0	1.9	11.5
Clay Matrix	4.9	8.7	<1.0	<1.0	<1.0	1.5	—	1.2	33.6	4.2	28.8	1.6
Mica	P	—	<1.0	<1.0	1.3	6.1	—	<1.0	—	P	P	—
Nonopaq. Heav.	P	P	P	—	P	P	P	P	P	P	<1.0	P
Misc.	—	—	<1.0	—	—	—	—	—	—	—	—	—

Greensand lithofacies (J)
(in Eau Claire Formation)

Loc/depth	V-606.0	L-690.0	L-704.0	W-851.0	W-866.0	Ho-1280.0	Ho-1303.0	P-346.0	B-996.0	B-1033.0	B-1054
Qtz. except Meta.	2.9	41.6	54.0	37.3	32.8	2.1	59.3	38.1	66.0	59.5	40.5
Meta. Qtz.	—	—	—	—	—	—	—	—	—	—	—
K-feldspar	1.5	31.6	8.1	21.6	21.0	89.3	3.6	36.8	1.9	4.9	42.8
Carb.	39.5	2.1	6.6	3.4	<1.0	—	3.0	6.5	<1.0	1.2	3.3
Glauc.	52.0	8.7	2.1	15.0	20.3	<1.0	14.8	3.9	12.9	7.0	3.6
Colloph.	3.0	1.0	<1.0	2.7	1.6	1.2	2.6	—	4.2	P	P
Cht.	—	—	—	—	<1.0	—	—	—	—	<1.0	—
Opaq. Heav. Min.	<1.0	1.1	<1.0	4.9	3.9	2.8	1.6	<1.0	P	P	<1.0
Poro.	<1.0	12.1	19.1	11.0	6.6	4.0	14.8	6.2	13.9	11.3	7.6
Clay Matrix	—	1.1	8.7	2.9	12.5	—	<1.0	6.2	<1.0	15.6	1.3
Mica	—	<1.0	<1.0	<1.0	<1.0	1.5	—	1.6	—	P	P
Nonopaq. Heav.	—	—	—	P	—	—	P	P	—	P	—
Misc.	—	—	—	—	—	—	—	—	—	—	—

Shale/siltstone lithofacies (K)
(Principally in Eau Claire Formation)

Loc/depth	V-591.0	Ho-1256.5	P-304.5	P-388+
Qtz. except Meta.	32.7	57.4	39.8	49.9
Meta. Qtz.	—	—	—	—
K-feldspar	33.3	4.9	42.8	31.5
Carb.	—	13.4	—	<1.0
Glauc.	2.9	1.0	—	—
Colloph.	<1.0	19.7	6.6	1.7
Cht.	—	P	—	—
Opaq. Heav. Min.	2.0	<1.0	<1.0	<1.0
Poro.	7.3	4.3	8.2	18.1
Clay Matrix	19.8	16.7	2.3	<1.0
Mica	1.3	—	P	P
Nonopaq. Heav.	—	P	P	P
Misc.	<1.0	—	—	—

Red Sandstone subfacies G_2
(in Eau Claire Formation)

Loc/depth	W-869.4	Ho-1353.0	Ho-1376.0	Ho-1408.0	Ho-1420.0
Qtz. except Meta.	65.1	54.6	39.5	35.0	39.4
Meta. Qtz.	—	—	—	—	—
K-feldspar	6.3	24.6	30.0	27.7	30.2
Carb.	1.8	<1.0	17.1	7.0	—
Glauc.	P	P	P	P	P
Colloph.	2.9	P	<1.0	P	—
Cht.	P?	—	—	—	—
Opaq. Heav. Min.	6.0	<1.0	2.4	4.4	5.4
Poro.	16.4	15.1	7.6	7.3	4.1
Clay Matrix	1.5	4.4	2.7	17.2	20.0
Mica.	—	—	—	1.0	1.0
Nonopaq. Heav.	P	P	P	<1.0	P
Misc.	—	—	—	—	—

Mt. Simon
very fine to fine-grained sandstone

Loc/depth (Lithofacies	V-657.0 (E)	V-690.0 (D)	V-777.5 (D)	V-867.0 (B)	L-830.7 (D)	W-886.0 (G_2)	Ho-1499.0 (G_2)	P-458.0 (D)	P-468.0 (E)	P-542.0 (D)	P-654.0 (I)
Qtz. except Meta.	53.0	53.1	46.0	50.6	35.7	70.3	53.8	29.8	60.6	30.1	36.6
Meta. Qtz.	-	-	-	<1.0	-	P	-	-	<1.0	<1.0	-
K-Feldspar	26.1	23.1	29.5	21.6	39.6	3.8	28.9	40.4	12.5	42.1	34.1
Carb.	—	—	—	P	P	<1.0	—	—	—	—	6.6
Glauc.	—	—	—	—	—	P	—	—	—	—	—
Colloph.	P	—	—	—	—	<1.0	P	—	—	—	—
Cht.	—	—	—	—	—	—	—	—	P	—	—
Opaq. Heav. Min.	<1.0	<1.0	<1.0	—	<1.0	P	<1.0	1.2	2.4	1.6	P
Poro.	17.9	17.8	19.6	27.4	16.4	25.3	15.5	18.4	23.5	13.1	20.8
Clay Matrix	1.6	5.6	3.8	—	4.8	—	<1.0	7.9	<1.0	12.6	—
Mica	<1.0	<1.0	P	P	3.1	—	<1.0	2.3	P	<1.0	1.9
Nonopaq. Heav.	<1.0	P	<1.0	P	P	P	P	P	—	P	P
Misc.	—	—	—	—	—	—	—	—	—	—	—

Mt. Simon
structureless, fine- to coarse-grained, poorly sorted sandstone

Loc/depth (lithofacies)	V-638.0 (F)	V-674.0 (E)	V-754.3 (D)	L-748.4 (F)	L-764.0 (E)	L-775.5 (D)	L-794.5 (D)	L-814.3 (D)	L-839.5 (D)	L-849.0 (D)
Qtz. except Meta.	73.2	66.3	63.2	60.0	80.9	59.1	65.5	72.7	70.8	52.4
Meta. Qtz.	<1.0	—	—	—	—	—	P	P	P	—
Lithic grns.	—	—	—	—	—	—	—	—	—	—
K-feldspar	3.1	6.9	6.8	18.8	2.3	18.5	10.8	3.4	12.2	19.9
Carb.	P	—	P	<1.0	—	—	—	<1.0	P	P
Glauc.	P	—	—	—	—	—	—	—	P	P
Colloph.	7.1	—	—	8.2	—	—	—	—	—	—
Cht.	—	—	—	—	—	—	—	—	—	—
Opaq. Heav. Min.	<1.0	<1.0	7.1	<1.0	P	P	P	P	P	P
Poro.	15.3	18.3	22.9	11.5	16.8	15.4	22.2	23.0	16.7	26.8
Clay Matrix	<1.0	7.7	—	<1.0	P	7.1	<1.0	<1.0	<1.0	<1.0
Mica	—	<1.0	—	<1.0	—	P	<1.0	P	P	P
Nonopaq. Heav.	P	P	P	P	P	P	<1.0	P	—	P
Misc.	—	—	—	—	—	—	—	—	—	—

Mt. Simon
structureless, fine- to coarse-grained, poorly sorted sandstone (contd.)

Loc/depth (lithofacies)	L-860.5 (D)	L-862.0 (D)	Ho-1452.0 (D)	Ho-1525.0 (D)	Ho-1582.0 (C)	Ho-1605.0 (C)	Ho-1611.0 (C)	P-433.0 (E)
Qtz. except Meta.	43.6	76.9	59.8	66.6	58.4	60.1	74.4	54.1
Meta. Qtz.	P	P	—	3.0	2.8	3.3	<1.0	—
Lithic grns.	—	—	—	—	—	<1.0	—	—
K-feldspar	34.6	<1.0	22.7	3.6	14.0	10.8	1.9	21.7
Carb.	P	<1.0	—	6.3	—	—	—	—
Glauc.	—	—	—	—	—	—	—	—
Colloph.	—	—	<1.0	—	—	—	—	—
Cht.	—	—	—	—	—	—	—	—
Opaq. Heav. Min.	<1.0	<1.0	1.5	P	P	—	<1.0	<1.0
Poro.	14.9	21.5	15.4	8.3	17.4	16.7	23.1	18.3
Clay Matrix	5.7	—	<1.0	4.6(3)	6.4	—	—	4.3
Mica	P	P	P	P	P	P	P	<1.0
Nonopaq. Heav.	<1.0	—	P	—	—	P	P	P
Misc.	—	—	—	8.3(5)	<1.0(5)	8.8(5)	—	—

Mt. Simon
structureless, fine- to coarse-grained, poorly sorted sandstone (contd.)

Loc/depth (lithofacies)	P-514.0 (D)	P-562.5 (D)	P-694.0 (B)	B-1168.7 (D)	B-1184.0 (D)	J-845.0 (E)	J-899.0 (E)	O-650 (D)
Qtz. except Meta.	28.4	59.3	57.7	27.4	58.1	71.8	67.6	41.2
Meta. Qtz.	—	2.9	<1.0	P	—	P	P	1.3
Lithic grns.	—	—	—	—	—	—	—	<1.0
K-feldspar	47.2	14.9	20.3	P	22.9	1.9(1)	0.0	12.8
Carb.	—	—	1.4	8.8	—	P	<1.0	2.2
Glauc.	—	—	—	—	—	P	P	—
Colloph.	—	—	—	7.5(2)	—	P	P	—
Cht.	—	—	—	—	—	<1.0	2.6	—
Opaq. Heav. Min.	2.5	P	P	—	1.5	<1.0	<1.0	P
Poro.	19.7	20.6	18.9	0.0	13.3	18.6	18.6	3.5
Clay Matrix	<1.0	2.0	—	—	4.3	6.1	7.7	34.2
Mica	P	<1.0	—	—	P	<1.0	1.9(4)	3.5(4)
Nonopaq. Heav.	P	P	P	—	P	P	<1.0	P
Misc.	<1.0(5)	—	—	57.3(5)	—	—	—	—

Mt. Simon planar-stratified or cross-stratified,
moderately to well-sorted, fine- to coarse-grained sandstone

Loc/depth (lithofacies)	V-706.3 (D)	V-734.0 (D)	V-810.0 (B	V-878.0 (B)	V-910.0 (B)	L-883.0 (C)	W-937.5 (F)	Ho-1467.0 (D)	P-410.0 (F)	P-444.0 (D)
Qtz. except Meta.	71.9	74.5	71.8	66.3	73.2	77.4	77.5	73.5	64.0	76.0
Meta. Qtz	1.1	—	1.6	2.2	2.1	P	P	<1.0	<1.0	1.7
Lithic grns.	—	—	—	—	—	—	—	—	—	—
K-feldspar	7.5	2.0	<1.0	4.5	5.2	1.6	P	<1.0	—	2.4
Carb.	—	—	—	P	<1.0	<1.0	—	—	P	—
Glauc.	—	—	P?	—	—	—	P	—	—	—
Colloph.	—	—	—	—	—	—	<1.0	P	3.7	—
Cht.	—	—	—	<1.0	—	—	—	—	—	P?
Opaq. Heav. Min.	<1.0	<1.0	P	<1.0	<1.0	P	—	P	2.3	P
Poro.	15.4	30.3	25.6	26.4	14.9	18.6	22.2	25.2	28.3	19.2
Clay Matrix	2.5	—	—	—	2.1	1.9	—	—	1.4	<1.0
Mica	<1.0	—	—	—	<1.0	—	—	P	—	—
Nonopaq. Heav.	<1.0	P	P	P	P	P	P	P	—	—
Misc.	—	—	—	—	—	<1.0(6)	—	—	—	—

Mt. Simon planar-stratified or cross-stratified,
moderately to well-sorted, fine- to coarse-grained sandstone (contd.)

Loc/depth (lithofacies)	P-682.0 (B)	P-717.0 (B)	B-1204.0 (B)	B-1236.0 (B)	B-1265.0 (B)	B-1303.8 (B)	B-1328 (B)	B-1348.0 (B)	0-674.0 (B)
Qtz. except Meta.	68.9	68.0	68.0	64.8	70.0	69.8	64.8	55.9	78.2
Meta.Qtz.	1.9	3.6	5.7	<1.0	3.1	1.5	P	5.0	2.9
Lithic grns.	—	—	—	—	—	P	1.5	P	P?
K-feldspar	5.1	1.5	14.0	5.9	1.8(1)	13.0	14.2	22.5	P
Carb.	<1.0	9.7	—	—	1.5	—	—	<1.0	1.0
Glauc.	—	—	—	—	P	—	—	P	—
Colloph.	—	—	—	—	—	—	—	P?	—
Cht.	—	P?	—	—	P	<1.0	1.8	P?	—
Opaq. Heav. Min.	<1.0	<1.0	<1.0	<1.0	3.7	1.2	1.0	<1.0	<1.0
Poro.	23.1	16.3	20.4	28.0	19.3	12.3	14.5	17.3	15.9
Clay Matrix	<1.0	<1.0	1.5	—	<1.0	—	1.5	1.6	1.6
Mica	P	P	P	P	—	P	<1.0	P	P
Nonopaq. Heav.	P	P	P	P	<1.0	<1.0	P	P	P
Misc.	—	—	—	—	—	3.1(6)	<1.0(6)	—	—

1. Trace plagioclase 1-3 grains
2. Collophane occurs as cement
3. 1.0% may be authigenic kaolinite
4. Includes sericite, kaolinite, and muscovite
5. Fe oxide cement
6. Silica cement