THE GEOLOGY OF THE UPPER DUNLEITH FORMATION (PROSSER MEMBER GALENA FORMATION) OF MIDDLE ORDOVICIAN AGE IN SOUTHEASTERN MINNESOTA

A THESIS
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ABSTRACT

The upper Dunleith Formation of the Galena Group was deposited in the Hollandale Embayment of the Ordovician sea. The four members of the upper Dunleith Formation: the Rivoli, Sherwood, Wall and Wyota are composed mostly of fine-grained calcium carbonate (micrite) with lesser amounts of shale and coarse grained calcite (sparite).

The area studied is located in the upper Mississippi River Valley, 30 miles south of Minneapolis-St. Paul southward to northern Iowa. Isopach maps made from outcrop information and data from insoluble residues show that the terrigenous material found in the upper Dunleith strata was likely supplied from the Transcontinental Arch from the west and northwest.

Fossil types found within upper Dunleith strata indicate the sea in which upper Dunleith strata was deposited was clear, warm, calm and of normal marine salinity. However, the strata of the upper Dunleith Formation at Mantorville, Minnesota, suggest a different environment, one of which was likely hypersaline, as evidence from the lack of stenohaline organisms and the presence of euryhaline organisms and dolomitic strata.

The members of the upper Dunleith Formation can be precisely correlated by the use of argillaceous horizons, fossil zones, chert nodule horizons, corrosion zones, bentonite beds, stylolites, mottled zones and other sedimentary features. The differentiation of the members in the upper Dunleith Formation is usually determined by the presence of distinct argillaceous horizons that occur at the top of each member. Where the argillaceous horizons are less prominant, other features of the member are useful in locating an approximate contact.

Corrosion surfaces or zones are features of both local and large lateral extent within the carbonate strata. These surfaces represent a period of non-deposition and/or errosion. Corrosion zones probably indicate a sedimentary environment when the chemistry of the sediment-water interface favored solution rather than deposition of carbonate, associated with mechanical erosion.

Four bentonite horizons are present within the upper Dunleith Formation and are useful time stratigraphic features. These horizons occur 3 to 7 feet below the Rivoli Member top, at the Rivoli-Sherwood contact, 3 to 6 feet into the Sherwood Member and approximately in the middle of the Wall Member. The mineralogy of the bentonites is different than those of the shales and clays. Bentonites are usually composed of euhedral (or subhedral) zircon, apatite and hornblende grains. Other heavy minerals of biotite, garnet and tourmaline also occur in some samples in minor amounts. The source of the bentonites as determined from paleomagnetic data (Dott and Batten, 1976) was probably the northeastern portion of the Appalachian mobile belt.

INTRODUCTION

The upper Dunleith Formation of middle Ordovician (Champlainian) age is subdivided into four members; the Rivoli at the base, Sherwood, Wall and Wyota. These four members are stratigraphic equivalents of the Prosser Member of the Galena Formation. The latter is the terminology currently used by the Minnesota Geological Survey (Figure 1).

Differentiation of the upper Dunleith Formation into members requires detailed study to become familiar with minor lithologic features that seem subtle on preliminary observation. Since the upper Dunleith Formation is about 75 feet thick in regions where topographic relief does not exceed 50 feet, it is the only formation exposed over large areas. Consequently, the need to recognize stratigraphic position within the upper Dunleith justifies the differentiation of members for precise position in the section. Member differentiation is useful in determining depths to units such as cherty or argillaceous zones and for detailed studies of geological structures.

The objectives of this study are to:

1) Correlate stratigraphy of the Rivoli, Sherwood, Wall and Wyota Members of the Dunleith Formation

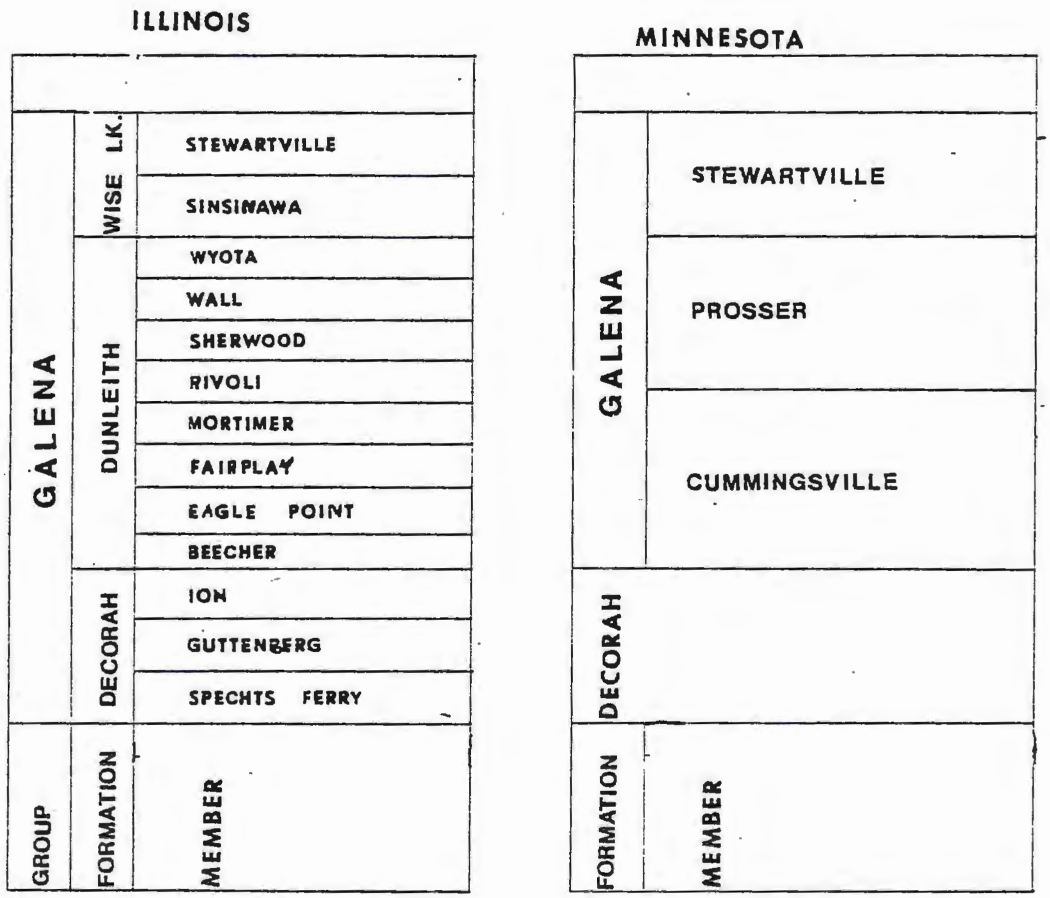

Figure 1— Correlation of Galena stratigraphy of Illinois and Minnesota (Weiss, 1957; Templeton and Willman, 1963; Levorson and Gerk, 1973).

using all criteria from this and previous studies in Iowa and Illinois. 2) Determine the lithology of the different members. 3) Determine facies changes within the members. 4) Analyze sedimentary structures and their relationship to thinning and thickening of strata. 5) Use fossil types to determine environments of deposition.

Location and Extent of Area

The area where the Rivoli, Sherwood, Wall and Wyota Members were studied covers approximately 6,000 square miles in southeastern Minnesota and northeastern Iowa. The outcrop boundary extends south to Burr Oak, Iowa, north to Cannon Falls, Minnesota, west to Mantorville, Minnesota, and east to Eyota, Minnesota (Figure 2).

Methods of Study

The investigation included field work to determine member correlation by the use of bentonite beds, corrosion surfaces, clay horizons, scour surfaces, chert horizons, faunal content, and argillaceous zones at the tops of the members. Thin sections and heavy mineral analyses done on rocks and bentonites were also useful in member correlations.

Outcrops were located by use of Levorson and Gerk's (1972 and 1975) Iowa Geologic Field Guides, Weiss' (1957) published doctoral thesis, and Sloan's (1958-1960) field geology maps in southeastern Minnesota.

Thirty-two outcrops were studied and stratigraphic sections constructed on a scale of one-quarter inch to

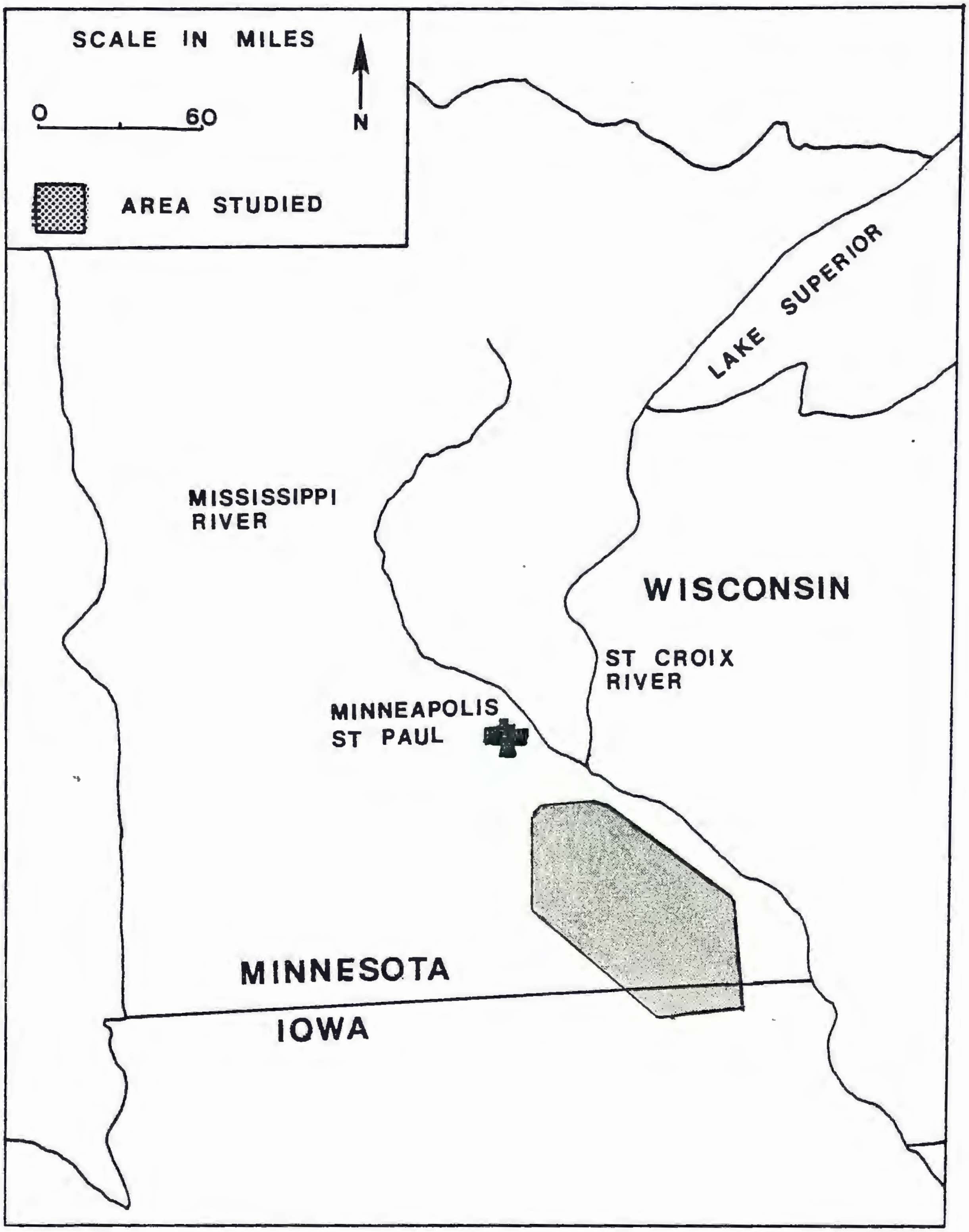

Figure 2-- Map showing where the upper Dunleith Formation was studied.

the foot. Extreme detail is necessary to establish correlations and to maintain stratigraphic control. Detailed descriptions and locations are listed in Apendix A.

Lab Methods

Thin sections were made from 90 rock samples collected from the Rivoli, Sherwood, Wall and Wyota Members of the Dunleith Formation and point counted. Thin section heels were stained for calcite using a solution of 0.2 grams of Alizarin Red S. dissolved in 100 milliliters of hydrochloric acid. Heels were usually immersed in the solution for 45 seconds and then rinsed in running water. The presence of calcite was indicated by a pink color while dolomite was not stained. Staining was useful in determining rough percentages of the mineral composition of the lithologies in the strata.

Heavy mineral mounts were prepared from 40 clay samples believed to be bentonites. Clay samples were crushed by mortar and pestle to reduce large clusters of consolidated clay. The clay fraction was then washed through a 230 mesh sand/silt-clay sieve. Heavy minerals from the remaining coarse fraction were then separated by using tetrabromoethane in separatory funnels. The heavy mineral residue was then washed in acetone, dried and mounted in Piccolite.

Previous Works

The stratigraphic interpretation of the most significant papers dealing with the middle Galena Formation in Minnesota, or upper Dunlieth Formation in Iowa and Illinois is summarized in Figure 3.

Hall (1851) proposed the name Galena for the drab limestone that overlaid the 'Trenton' Limestone (Platteville and lower Decorah) in Illinois, Iowa and Wisconsin. The present-day Dubuque Formation was also included in the Galena.

The first reference to the name Prosser was by Winchell and Ulrich in 1897, when they measured a section in Galena limestone at Prosser's Ravine in Fillmore County, Minnesota. Ulrich (1911) designated the Prosser "Formation" of Galena as a "Prosser Limestone Fauna" comprised of beds of brachiopods Clitambonites and Fusispira, and the bryozoan Nematopora.

Kay (1935) adopted the Prosser as a formation in the Galena Group. Kay placed the lower contact of the Prosser at the top of the shaley Decorah above the Prasopora zone and placed the upper contact at the upper Receptaculites zone in the vuggy dolomitic Stewartville. Kay cited 135 feet as the thickness of the Prosser at Prosser's Ravine.

Stauffer and Thiel (1941), described a new measured section of Prosser in the valley of Mahood's Creek at Wykoff, Minnesota. This was done because the original type outcrop of Ulrich (1911) had never been properly located. The lithologic boundaries of Stauffer and Thiel were the same as Kay's, but total thickness of the Wykoff section was given as 180 feet. Weiss, in measuring

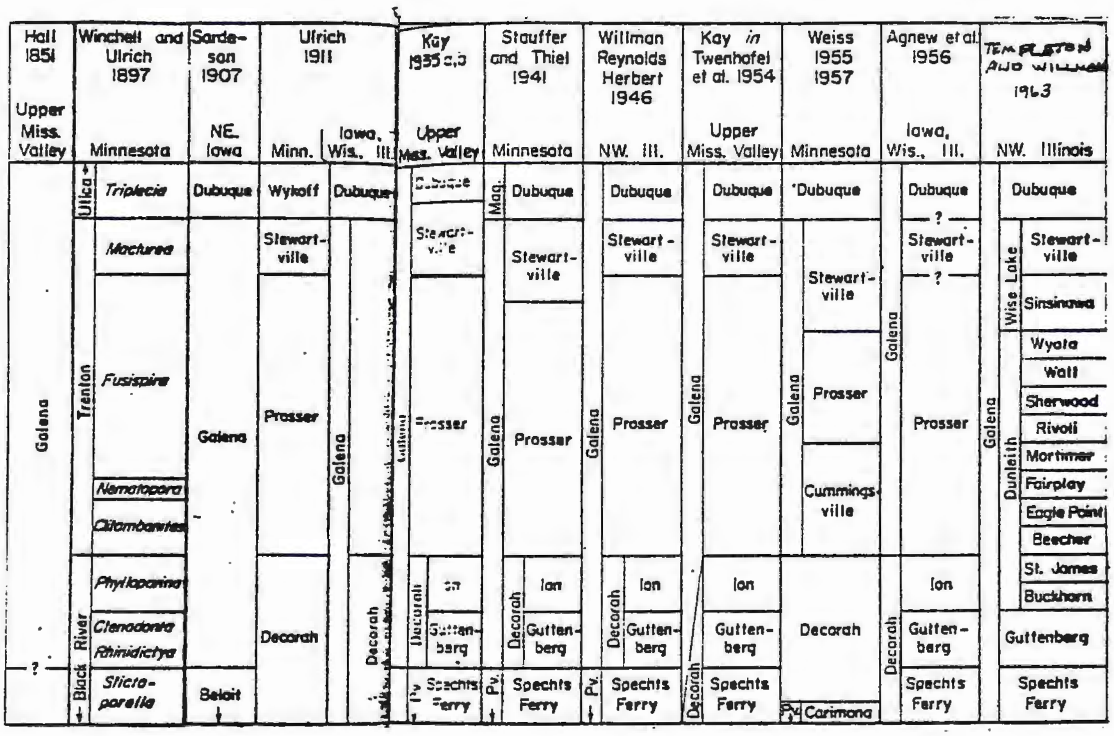

Figure 3-- Development of the Galena Group from 1851 to 1963 (from Templeton and Willman, 1963).

the same section in 1955, also found the Prosser to be 180 feet thick, concluding that Kay's thickness of the Prosser was incorrect since both sections are only a few miles apart.

Weiss (1957) redefined the Prosser as a member of the Galena Formation. Weiss divided the Galena Formation into three members; the Cummingsville at the base, the Prosser as the middle member, and the Stewartville at the top.

The Cummingsville Member, of approximately 60 feet, is equivalent to the 'Galena shales' as Kay described in 1935. The Prosser Member is bounded by the very argillaceous shaley limestones below and the mottled dolomitic limestones above. The Stewartville Member, which overlies the Prosser, is approximately 70 feet thick. The Stewartville is described as a dolomitic limestone with abundant Receptaculites.

Templeton and Willman (1963) in Illinois reclassified the Galena Formation and its members into the Dunleith and Wise Lake Formations of the Galena Group. The Dunlieth Formation is divided into ten members: the lower two equivalent to the upper Decorah (Ion Member) in Minnesota, the middle four equivalent to the Cummingsville of Minnesota, and the upper four, namely the Rivoli, Sherwood, Wall and Wyota, equivalent to the Prosser Member as described by Weiss. The Wise Lake Formation is equivalent to the Stewartville Member as described by Weiss.

Levorson and Gerk (1973) slightly modified the classification of Templeton and Willman (1963) by incorporating the lower two members of the Dunleith Formation into the Decorah Formation on the basis of a continuing shale lithology in Iowa and Minnesota.

Present Stratigraphy

The Dunleith of Galena Formation is of Upper Middle Ordovician (Trentonian) age and is incorporated into the Champlainian Series.

Stratigraphic nomenclature currently in use by the Minnesota Geological Survey is Weiss' (1957) classification as modified by Austin (1970). Austin's stratigraphic interpretation, as determined from the Hollandale test hole, notes a lithologic intertonguing between the limestone dominant Prosser Member and the overlying dolomitic Stewartville (Figure 4).

The names: Dunleith and Wise Lake in Illinois and Iowa apply to the same strata as the Galena Formation in Minnesota. Figure 5 is a stratigraphic and lithologic column showing the correlations among the formations.

Structural Setting

The Paleozoic strata of southeastern Minnesota, northern Iowa and southwestern Wisconsin were formed on a marine shelf. Within this shelf area lies the Hollandale Embayment, a shallow depression that extends northward from the ancestral Forest City Basin into southeastern Minnesota and southwestern Wisconsin (Figure 6).

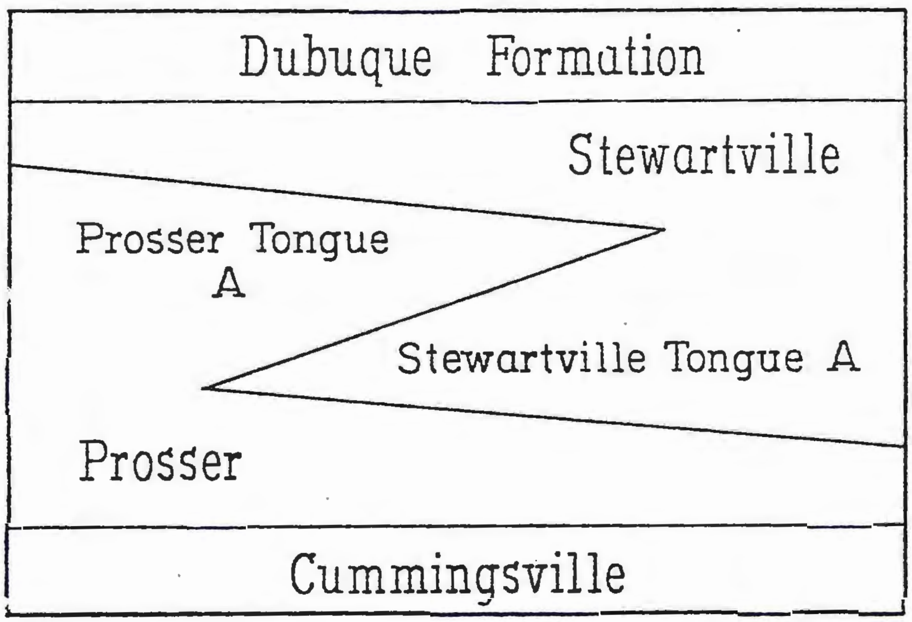

Figure 4-- Intertongued relationship between Stewartville and Prosser lithologies (Austin, 1970).

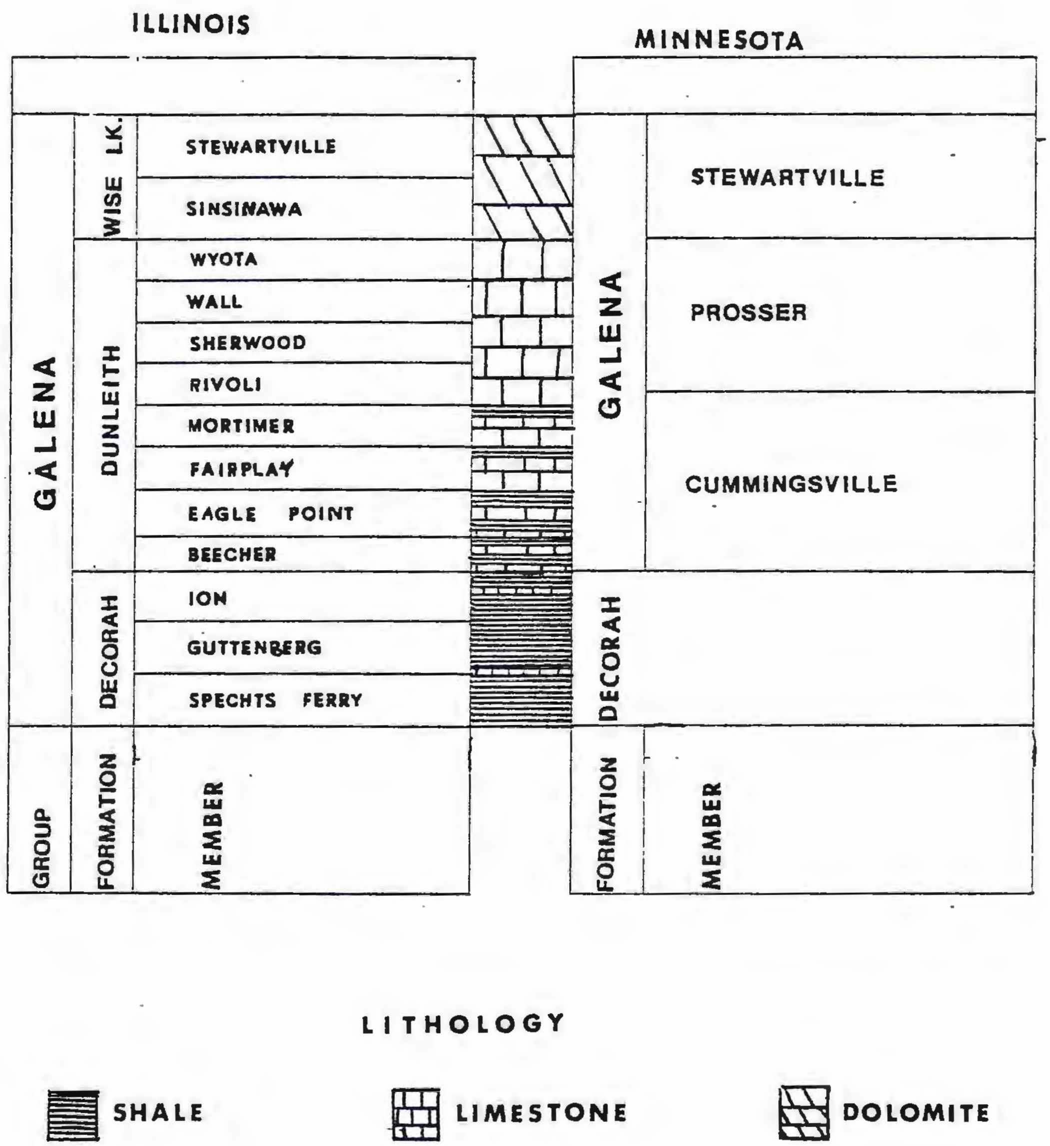

Figure 5-- Stratigraphic and lithologic column correlating Galena stratigraphy of Illinois and Minnesota.

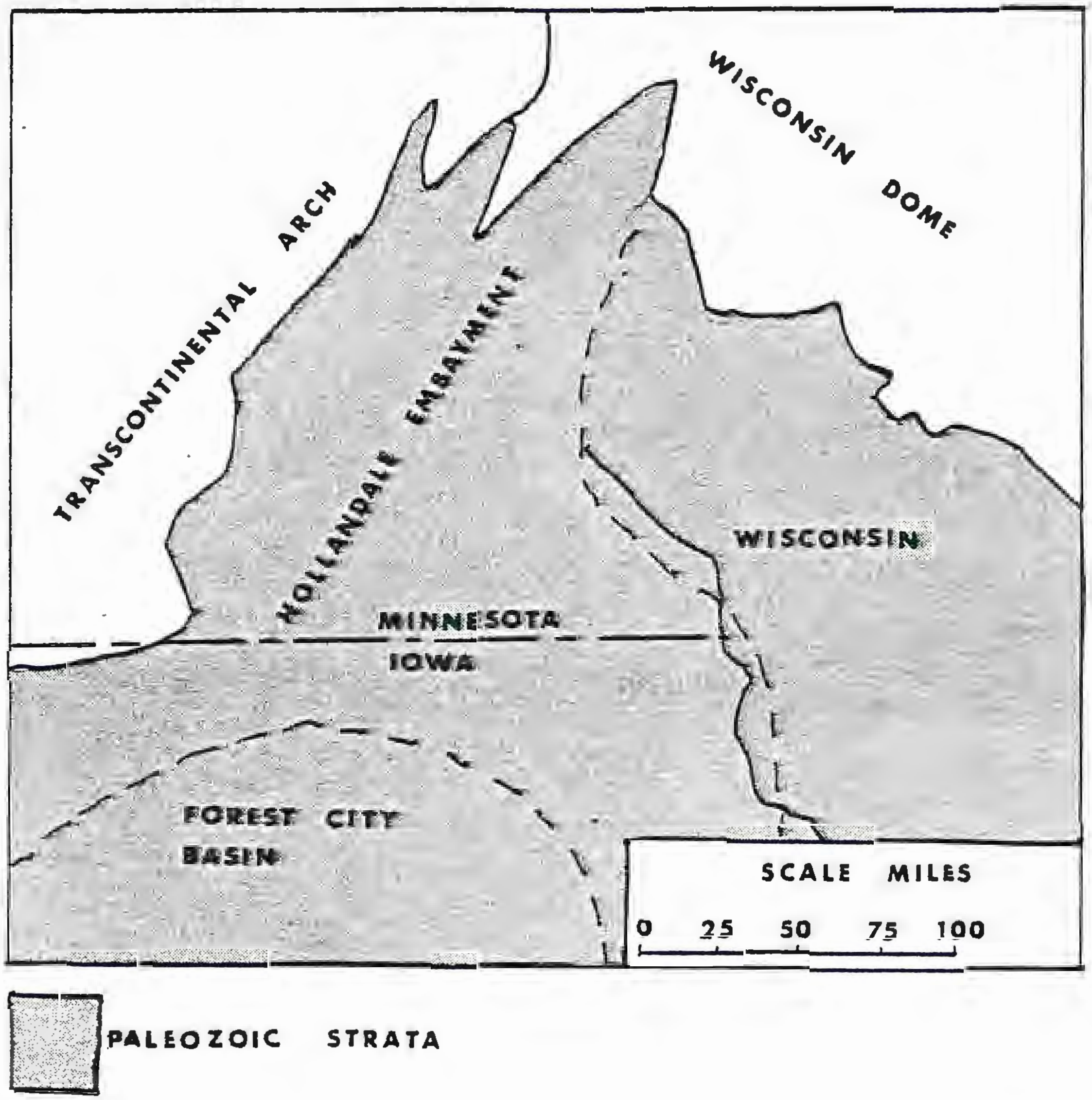

Figure 6-- Map showing Location of the Hollandale Embayment and exposure of Paleozoic strata (Austin,1970).

The marine rocks that remain today within the embayment are bounded to the east, north and west by the Precambrian rocks that constitute the Wisconsin Dome and the Transcontinental Arch (Austin, 1979). Smaller subbasins within the embayment, such as the Twin Cities Basin (Austin, 1972), were formed by irregularities on the underlying Precambrian surface.

The Hollandale Embayment overlies Precambrian basement rocks of basaltic and granitic composition which have been faulted, forming a graben into which Paleozoic sediments were deposited. Post-Precambrian movements along fault planes have produced minor though significant disruptions in the embayment such as the Red Wing-Rochester Anticline and the Belle Plain Fault. Austin (1972) believes the Red Wing-Rochester Anticline is a post-Ordovician feature produced by gentle warping of Paleozoic strata during further subsidence of the Hollandale Embayment.

The lower four members of the Dunleith Formation represent a gradual change in depositional conditions, resulting from a transgressing sea within the Hollandale Embayment. The Transcontinental Arch to the west which supplied the fine clastics to the Decorah, continued to supply clastics to the lower Dunleith Formation on a reduced and intermittent scale. As the Transcontinental Arch subsided and the seas transgressed, the alternating limestone and shale lithology gradually became a clastic deficient limestone-dominated environment, in the upper

Dunleith, establishing a carbonate bank (Webers, 1972). This carbonate bank is dominated by articulate brachiopods such as *Sowerbyella* and *Resserella*. Thus, the bottom communities of the upper Dunleith Formation are dominated by filter feeders indicative of quiet clear water of normal marine salinity.

The Transcontinental Arch continued to subside during deposition of the Wise Lake Formation. The top of the Wise Lake Formation is marked by increasing clastics indicating a mild uplift of the Transcontinental Arch.

LITHOSTRATIGRAPHY

Introduction

The upper Dunleith Formation contains four different members, each having unique characteristics that separates it from other members in the formation. With stratigraphic columns constructed on a scale of one quarter inch to the foot, sedimentary structures such as corrosion zones, argillaceous zones and chert horizons, can be traced from outcrop to outcrop. The following are sedimentary and lithologic features useful in distinguishing the members of the upper Dunleith Formation.

Rivoli Member

The Rivoli Member in Minnesota is easily distinguished from overlying and underlying members. The Rivoli usually averages 12 to 13 feet in thickness, much thinner than the 17 to 20 feet recorded near Decorah, Iowa (Levorson and Gerk, 1972), and at the type section in Dubuque, Illinois (Templeton and Willman, 1963). Figure 7 is an isopach map of the Rivoli. Features useful in identifying Rivoli strata are:

A) The Rivoli is a biomicrite with a detrital content of 10 to 15 percent, mostly of silt-size quartz and clay. The lower part of the member below the Calmar Bentonite contains the greatest detrital fraction (Figure 8).

B) Weathered outcrop exposures usually show a nodular pattern which is the result of disseminated clay which weathers recessively (Figure 9).

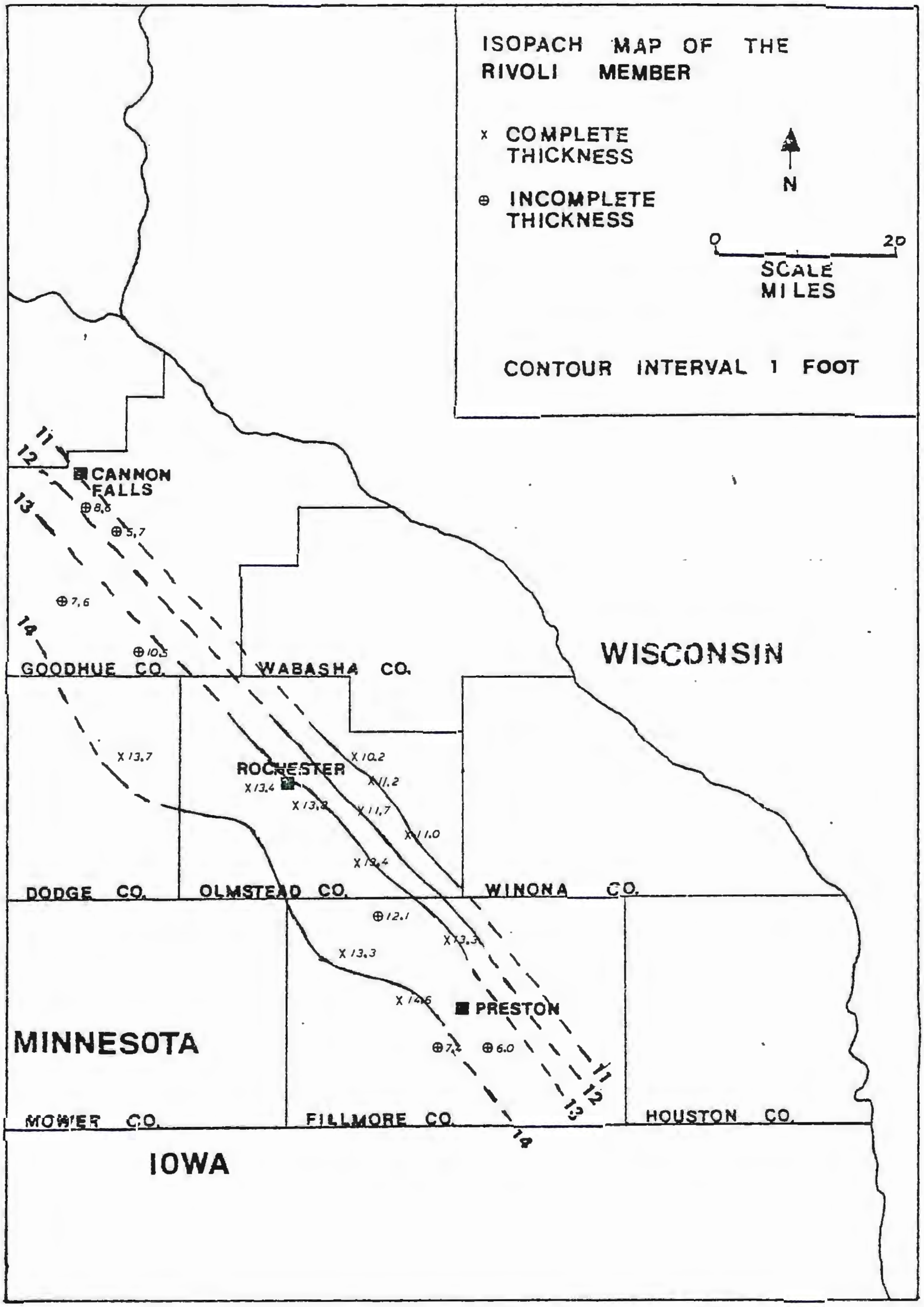

Figure 7-- Isopach map of the Rivoli Member.

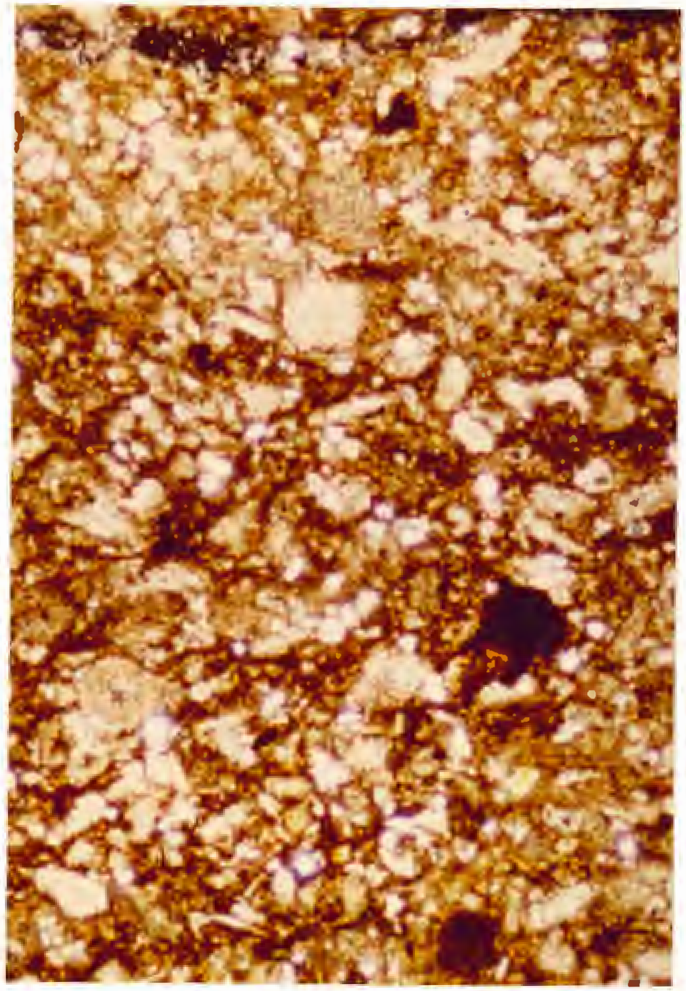

Figure 8-- Photomicrograph of Rivoli stratum. High quartz content (white grains), and high clay content. Stratum is a biomicrite. Field of view is 0.5 mm. wide.

Figure 9-- Outcrop exposure of Rivoli strata showing nodular horizons. Locality #24, Roscoe, Minnesota.

Figure 10-- Branching fucoids on bedding plane in Rivoli stratum. Locality #24, Roscoe, Minnesota.

C) Bedding surfaces may contain branching fucoids showing a dendroid pattern (Figure 10).

D) Rivoli strata are usually non-cherty; however, at locality #3, Greenleafton, Minnesota, chert nodules are present in the upper two feet of the member.

E) Receptaculites oweni and Ischadites iowensis (refer to Figure 16) are very abundant in the upper one-third of the Rivoli Member.

F) Two bentonite beds are present in the Rivoli Member in Minnesota and Iowa. The lower bentonite, named the Calmar, from Calmar, Winneshiek County, Iowa (Willman and Kolata, 1978), occurs 4 to 7 feet below the top of the member. This bentonite is easily recognized in fresh outcrop in Fillmore County, Minnesota, as a one inch thick orange swelled clay. The second bentonite, named the Conover, from Conover, Winneshiek County, Iowa (Willman and Kolata, 1978), occurs at the Rivoli-Sherwood member contact (refer to Figure 20, page 35).

G) The Cummingsville-Prosser boundary in Minnesota (Weiss, 1957) is located approximately 7 feet up from the base of the Rivoli Member. The Cummingsville-Prosser contact is determined by a decrease in detrital content within the rocks.

Rivoli-Sherwood Contact

The Rivoli-Sherwood contact is not marked by a distinct lithologic change. Compositionally the upper 3 to 5 feet of the Rivoli resembles the overlying Sherwood Member. In Goodhue County, Minnesota, the Rivoli-

Sherwood contact is distinguished by the presence of a 6 inch shale horizon at the top of the Rivoli which contains flakes of bentonite (Figures 11 and 12). Elsewhere the shale horizon thins to 1 to 2 inches. At some localities where the bentonite was not seen, close observation revealed an 8 to 12 inch argillaceous zone in the Rivoli at the Rivoli-Sherwood boundary.

Sherwood Member

The Sherwood Member ranges in thickness from 16 to 22 feet, increasing northward from 14 feet described at the type section in Dubuque, Illinois (Templeton and Willman, 1963) (Figure 13). Listed below are sedimentological and lithological features useful in identifying Sherwood strata.

A) The Sherwood Member is a biomicrite with fossil allochems ranges from 3 to 30 percent. Quartz and clay content averages about 5 percent (Figure 15). The Sherwood is thicker bedded (1 to 3 feet), lighter colored and less silty than the Rivoli (Figure 14).

B) The Sherwood is commonly cherty in Fillmore County, Minnesota. Chert nodules occur further north (localities #6 and 31), than those of the Wyota Member. This chert horizon was designated Chert Horizon #3 by Levorson and Gerk (1972).

C) Ischadites iowensis and Receptaculites oweni commonly are associated with the member (middle Receptaculites zone of Templeton and Willman, 1963) (Figure 16).

Figure 11-- Fresh surface of Rivoli and Sherwood strata. The Rivoli-Sherwood contact is placed above the red line at the number 3. Locality #24 Roscoe, Minnesota.

Figure 12-- Quarry exposure of Rivoli and Sherwood strata. Person's hand is positioned at contact between the two members at the 5 inch shale horizon. Locality #20 Goodhue County, Minnesota.

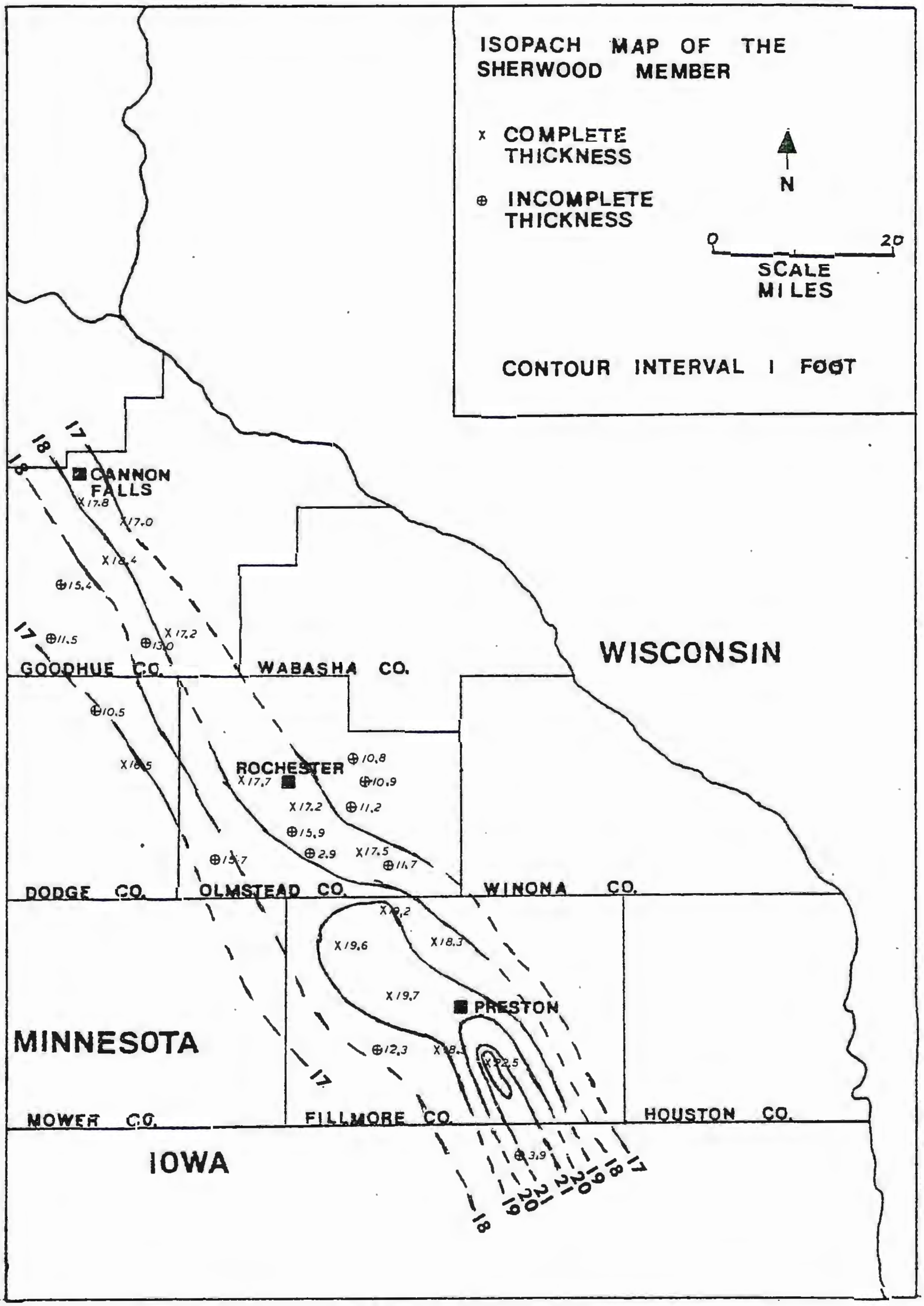

Figure 13-- Isopach map of the Sherwood Member.

Figure 14-- Exposure of Sherwood, Wall, Wyota and Sinsinawa Strata. Locality #32 Rochester, Minnesota

D) A prominent bentonite occurs 3 to 6 feet up from the base of the member. This bentonite was identified by Mossler and Hayes (1966) and is named the Nasset Bentonite by Willman and Kolata (1978).

E) The Sherwood in Fillmore County contains numerous corrosion zones (refer to page 45, Figure 26) which, northward in Olmstead and Goodhue counties, are replaced by sparry calcarenite bands (refer to page 61). The calcarenite bands are easily recognizable on weathered surfaces.

F) A prominent crinoid horizon occurs at the top of the member which contains abundant columnals and stems. This horizon extends from locality 7 in Iowa to locality 28 at Cannon Falls, Minnesota. Complete crinoid crowns have been collected from this horizon.

G) The top of the Sherwood is usually marked by a distinct argillaceous zone which is a light yellow-brown color, thinly bedded, recessively weathered and 2 to 3 feet in thickness. In Fillmore and Olmstead counties, a distinct corrosion surface is present at the top of the member.

Sherwood-Wall Contact

The Sherwood-Wall contact is placed at the top of the argillaceous zone in the Sherwood. In fillmore County, Minnesota, numerous chert nodules occur in the upper 5 to 7 feet of the Sherwood, associated with crinoid and cystoid remains, which assist in placing the Sherwood-Wall contact.

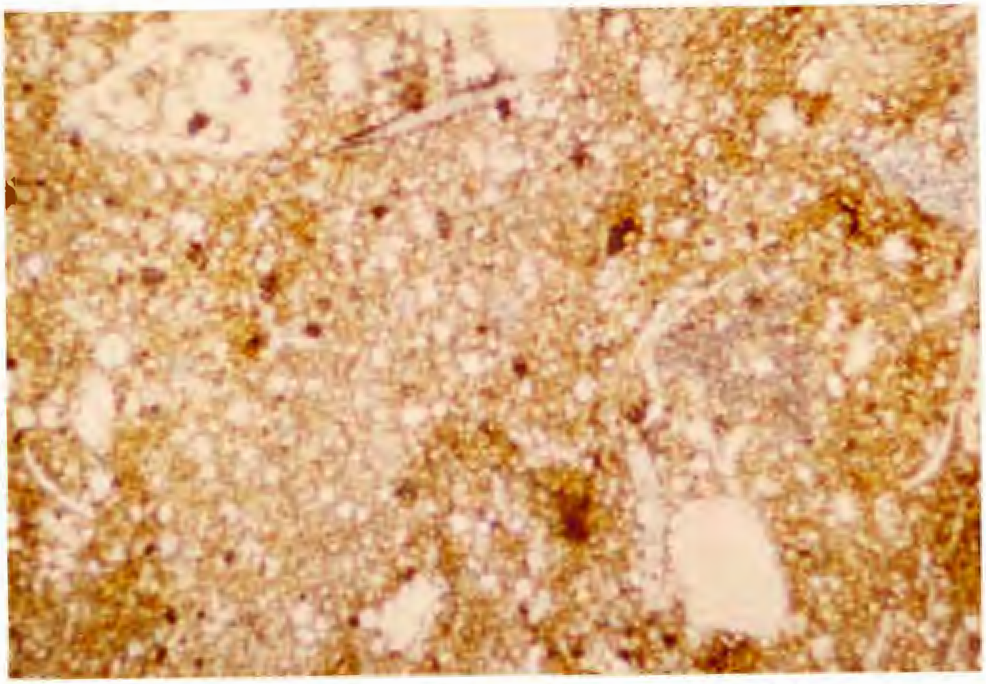

Figure 15--Photomicrograph of Sherwood Member. Biomicrite with sparry calcite. Quartz is present in minor amounts. Photograph is 1.0 mm. in width. Crossed nicols.

Figure 16-- Photograph of <u>Receptaculites oweni</u> from the Sinsinawa Member.

Wall Member

The Wall Member in Minnesota varies in thickness from 8 to 14 feet (Figure 17). The Wall is approximately 10 feet thick at the type section in Dubuque, Illinois. Features useful in identifying Wall strata are:

A) The Wall Member is a light brown or buff colored, thick bedded biomicrite with a low detrital content, averaging about 5 percent. The Wall is more dolomitic than the underlying Sherwood, averaging 30 percent dolomite (Figure 18).

B) Wall strata are non-cherty in Minnesota, except at locality #3. In northern Iowa, chert nodules exist in the upper and lower foot of the member.

C) In southern Fillmore County and northern Iowa, a bentonite exists in the middle of the Wall Member. This bentonite was designated I-6 by Mossler and Hayes (1966) and was named the Haldane Bentonite by Willman and Kolata (1978).

Wall-Wyota Contact

The contact of the Wall Member with the overlying Wyota Member is not sharply distinguished by a lithologic change. General characteristics of the Wall, however, can assist in locating an approximate contact. At most localities, the contact is marked by an argillaceous zone of 8 to 10 inches, commonly associated with a 2 inch clay or shale horizon. At localities 2, 3, and 5 the clay horizon resembles a bentonite, but none previously has been identified at this position. In Goodhue County,

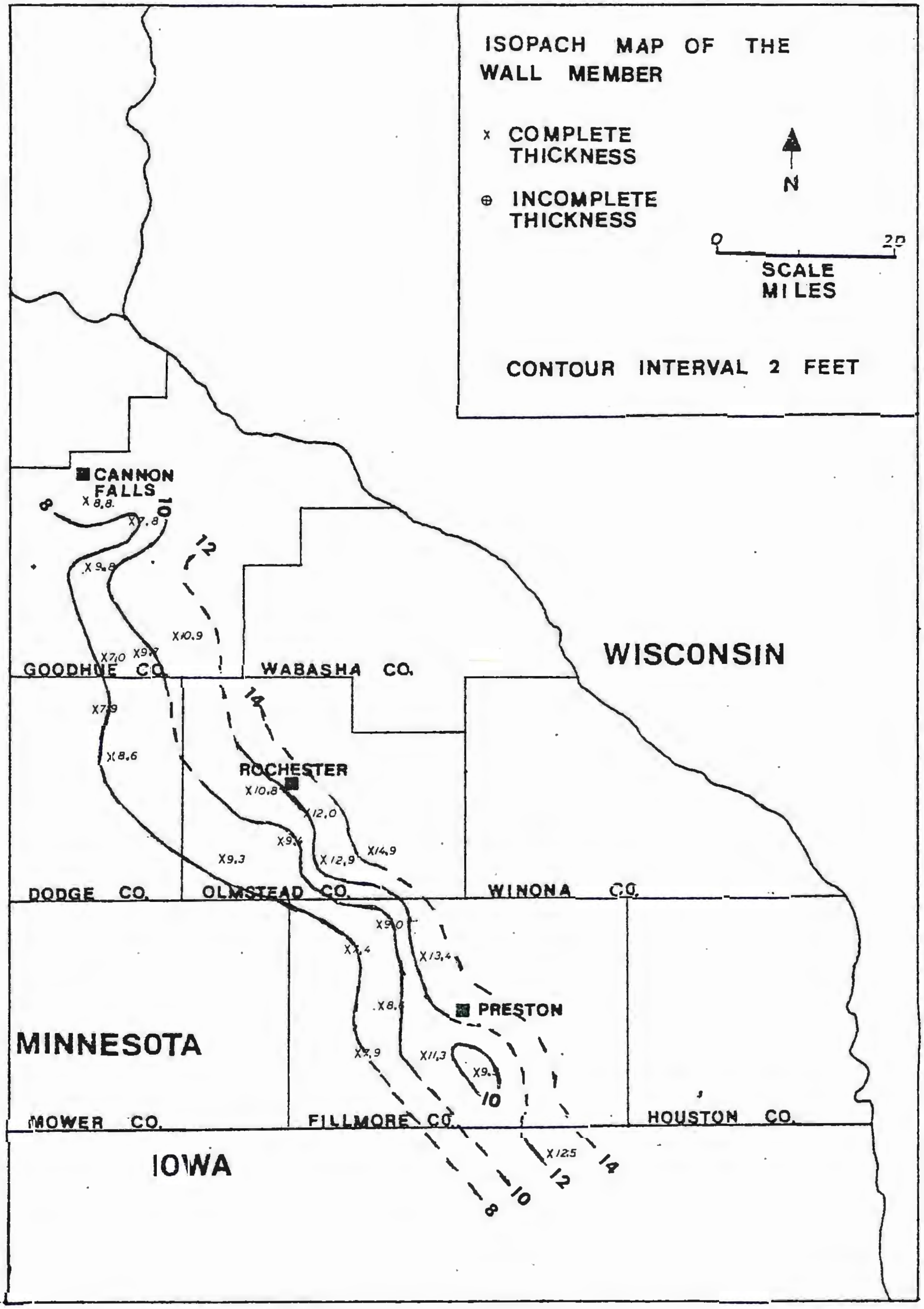

Figure 17-- Isopach map of the Wall Member.

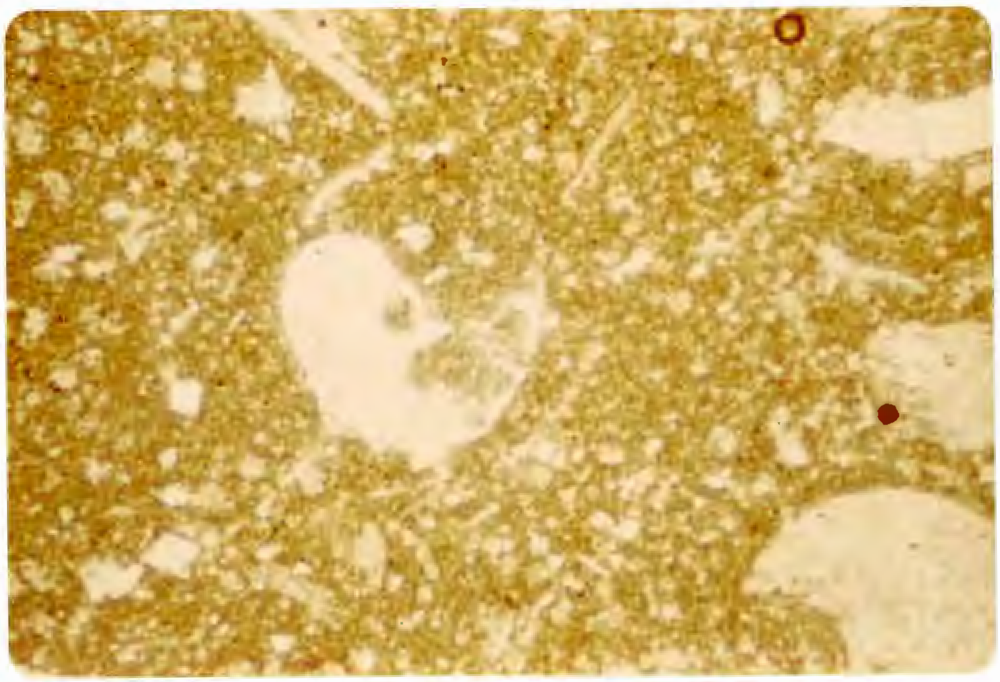

Figure 18-- Photomicrograph of Wall stratum. Lithology is a biomicrite with numerous dolomite rhombs. Lithology of Wall Member is similar to the Wyota Member. Fossil fragments are echinoderm plates and gastropod fragments. Field of view is 1.0 mm. wide, uncrossed nicols.

Minnesota, the Wall-Wyota contact is marked by a lithology change, the Wyota strata are more dolomitized than the underlying Wall.

Wyota Member

The Wyota Member ranges in thickness from 22 feet in northern Iowa to 14 feet northward in Olmstead County, Minnesota (Figure 19). At the type section in Dubuque, Illinois, the Wyota is 19 feet thick (Templeton and Willman, 1963). Listed below are features useful in identifying Wyota strata:

A) The Wyota in Minnesota is a pure (less than 5 percent silt and clay), tan-colored, medium bedded, biomicrite. Northward, the strata becomes buff-colored due to the increasing dolomitic content. Figure 15 shows Wyota strata in outcrop.

B) In central and southern Fillmore County, the Wyota contains chert nodules similar to those in Sherwood strata. These chert nodules disappear northward as the member increases in argillaceous content. This cherty horizon was designated Chert Horizon #4 by Levorson and Gerk (1972).

C) Beds in the Wyota are thinner (3 to 12 inches) than the subjacent Wall Member. Lithologically the two members are similar.

Wyota-Sinsinawa Contact

The contact of the Wyota with the Sinsinawa is the same as the Prosser-Stewartville contact as described in the stratigraphy of the Minnesota Geological Survey.

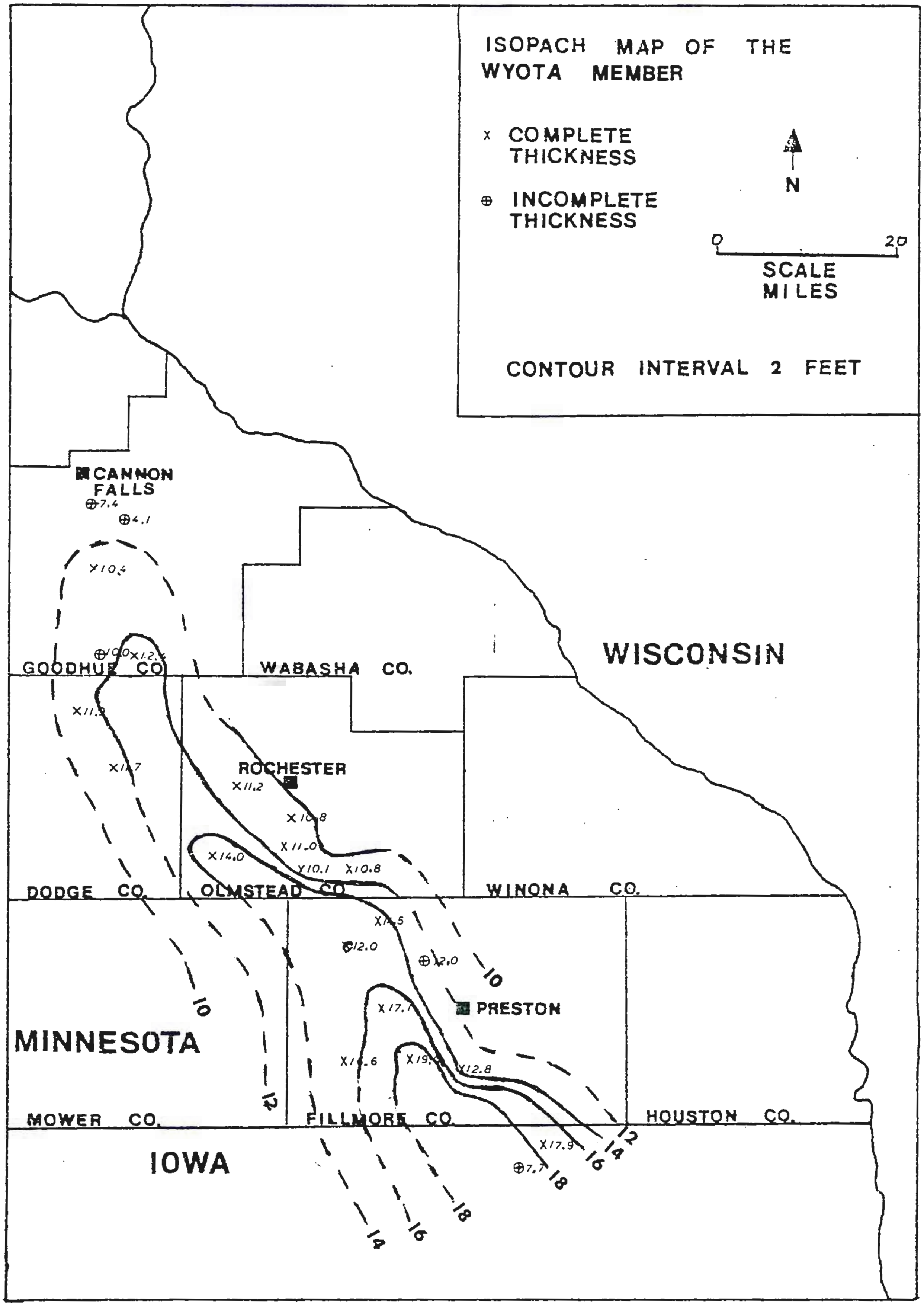

Figure 19-- Isopach map of the Wyota Member.

In Fillmore County, Minnesota, the Wyota-Sinsinawa contact is distinguished by the presence of chert at the Wyota top. The Sinsinawa is devoid of chert. A distinct oxidized corrosion surface at the top of the Wyota chert horizon marks a definite contact that can be correlated throughout Fillmore County, Minnesota, and northern Iowa.

Northward in Olmstead and Goodhue counties, placing the Wyota-Sinsinawa contact is difficult due to an interfingering of lithologies. This interfingering was noted by Austin (1969) at the equivalent Prosser-Stewartville contact (see Figure 4). The interfingering of lithologies caused the thickness of the Wyota Member to vary as much as 12 feet in Olmstead County, Minnesota at localities 9 and 10.

While the Wyota-Sinsinawa contact may not be sharply defined everywhere, lithologic and sedimentological features of Sinsinawa strata permit an arbitrary contact to be chosen. Sinsinawa strata are dolomitic, have a mottled texture, contain three closely spaced corrosion surfaces near the base in Fillmore County, Minnesota, are crinoidal in the lower one-third, and contain abundant _Receptaculites_ (upper _Receptaculites_ zone of Templeton and Willman, 1963) 10 to 15 feet up from the base of the member.

BENTONITE HORIZONS

Introduction

Ordovician bentonites are useful horizons for correlation within limited areas in northeastern Iowa and southeastern Minnesota. Templeton and Willman (1963), Mossler and Hayes (1966), and Levorson and Gerk (1973), identified four volcanic ash layers (bentonites) in the Rivoli, Sherwood and Wall strata in Minnesota, Iowa and Illinois. Field identification of bentonites was generally correct, but laboratory analyses was used for confirmation. Field samples of presumed bentonites were subjected to heavy mineral analyses as suggested by Weaver (1953). Results are listed in Table 1.

Composition

Ordovician volcanic ash which devitrified *in situ* initially altered to montmorillonite. Owing to compaction and diagenesis after burial, the expandable layers of the montmorillonite partially collapsed and the potassium content increased producing a mixed-layer illite-montmorillonite structure (Willman and Kolata, 1978). Since Ordovician ash beds no longer have the montmorillonite composition of the original bentonite, they have been referred to as meta-bentonite, Ordovician bentonite, potash bentonite or K-bentonite.

Field Description

Bentonites in Minnesota and Iowa appear as beds of orange-yellow plastic clay, ranging in thickness from

BENTONITE HEAVY MINERALS

Location	Bentonite	Zircon	Apatite	Hornblende	Pyroxene	Biotite	Misc.
Wykoff #1	Ca	47	13	99	10	13	15
Greenleafton #3	Ca	41	52	4	0	17	10
Fountain #4	Ca	25	15	33	0	0	3
Total	Ca	113	80	136	10	30	28
Rochester #10	Co	4	1	17	6	4	10
Pleasant Grove #11	Co	142	24	5	15	0	0
Roscoe #24	Co	15	14	3	0	8	2
Rochester #30	Co	41	29	26	0	2	30
Spring Valley #31	Co	10	15	1	0	0	6
Total	Co	212	83	52	21	14	48
Leon #21	N	12	11	13	0	20	1
Mantorville #2	N	18	10	13	0	2	2
Cannon Falls #28	N	13	7	17	0	1	1
Total	N	43	28	43	0	23	4
Rifle Hill #2	H	10	3	10	0	3	4
Total	H	10	3	10	0	3	4

Ca-Calmar Co-Conover N-Nasset H-Haldane

Table 1-- Results of heavy mineral analyses from bentonites from the upper Dunleith Formation in Minnesota.

1/4 to 1 inch (Figure 20). When wet, bentonite beds appear as orange colored, swelled, pliable clay, identifiable at a distance. Shale partings within the same strata do not react in this manner when wet. The orangish stain of a wet bentonite on one's fingers is also a useful field test for identification. When dry, these bentonites have a tendency to withdraw from the face of an exposure, with the positions of the bentonites marked by sharp reentrants in the limestone beds. Dry bentonites have a 'greasy' or smooth feeling when rubbed between one's fingers.

Most bentonites were found in fresh quarry faces and roadcuts. Since bentonites are easily eroded, they could not normally be recognized in old exposures.

Bentonite Stratigraphy

The four bentonites which occur in the upper Dunleith Formation (Figure 20)(Prosser of Weiss, 1955) are as follows:

A) The Calmar Bentonite (named for Calmar, Winneshiek County, Iowa: Willman and Kolata, 1978) occurs in the Rivoli Member 4 to 7 feet below the top. This bentonite was the easiest to recognize in the field since it was usually the thickest (one inch). The Calmar Bentonite was seen at 10 localities.

B) The Conover Bentonite (named for Conover, Winneshiek County, Iowa; Willman and Kolata, 1978) is at the Rivoli-Sherwood contact. This bentonite was seen at 6 localities.

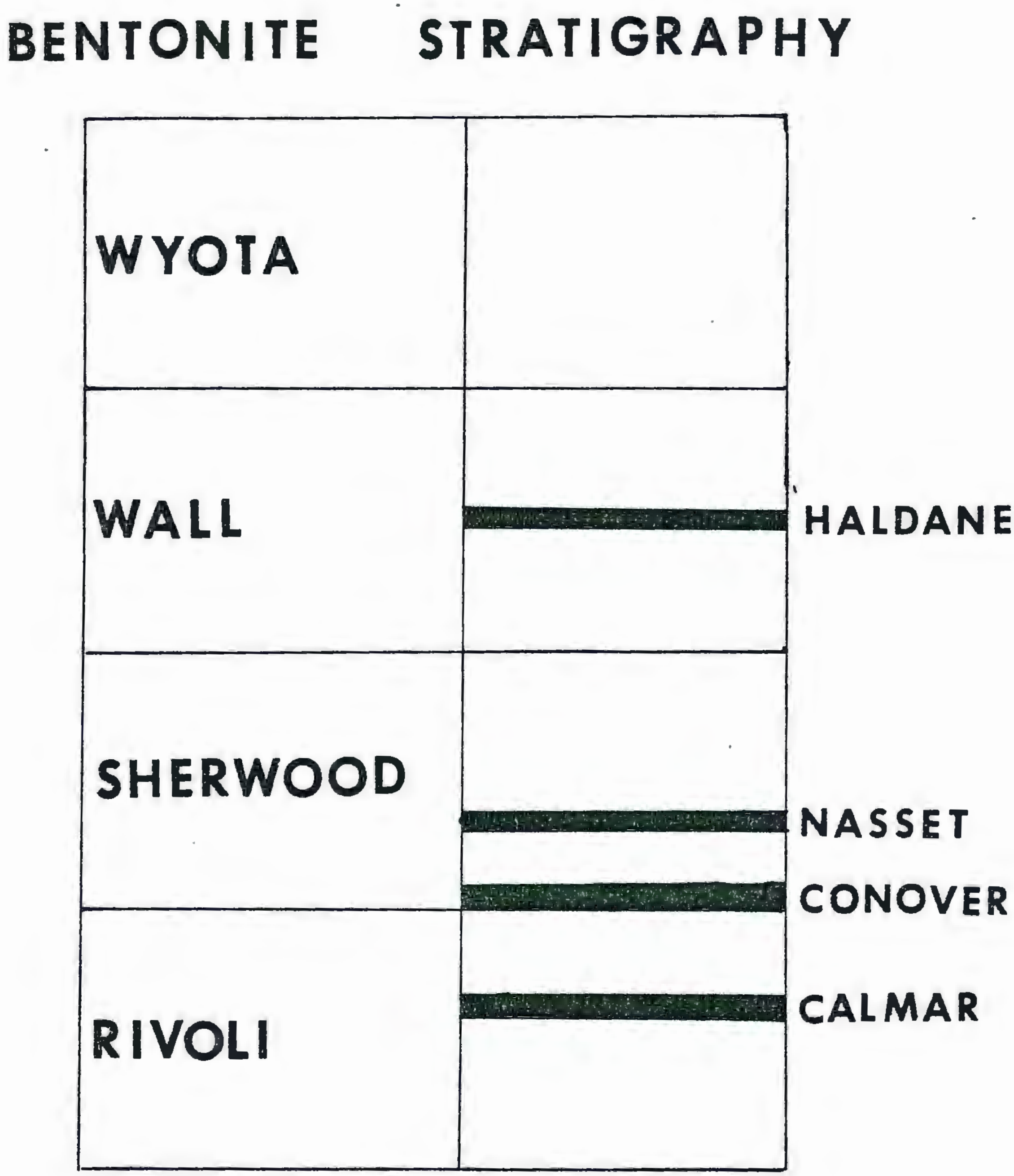

Figure 20-- Bentonite stratigraphy in the upper Dunleith Formation.

C) The Nasset Bentonite (named for Nasset, Winneshiek County, Iowa; Willman and Kolata, 1978) occurs in the Sherwood Member 3 to 6 feet above the base. This bentonite was seen at 6 localities.

D) The Haldane Bentonite (named for Haldane, Ogle County, Illinois; Willman and Kolata, 1978) is approximately in the middle of the Wall Member. This bentonite was seen at 2 locations.

The four bentonite horizons may not be present at all exposures because of local resedimentation of ash which destroyed the continuity of the ash blanket.

Bentonite (Heavy) Mineralogy

Ordovician K-bentonite horizons have been found to contain non-opaque heavy minerals including zircon, apatite, hornblende and biotite. Volcanic ash of intermediate composition also contains hypersthene and augite. Normal marine shales and clays usually do not contain euhedral or subhedral grains of apatite, zircon and hornblende, but usually contain rounded zircons, garnets, tourmalines, rutiles and authigenic pyrite (Weaver, 1953; Mossler and Hayes, 1966; Allen, 1926). A contrast in mineralogy therefore exists between bentonites and normal shales and clays.

Heavy mineral analyses were done on forty clay samples. Of these samples, fourteen contain the euhedral apatite, zircon and hornblende grains typical of bentonite (Table I). The mineralogies of the remaining twenty-six samples are similar to that of normal shales and clays.

Heavy Mineral Descriptions

Zircon

Zircon composes approximately 33 percent of the heavy minerals extracted from these bentonites. Grains are euhedral to subhedral in shape, usually clear, and contain inclusions parallel to the c-axis. Zircon grains average 0.15 millimeters in length. Figure 22 shows a typical zircon grain.

Apatite

Apatite accounts for approximately 19 percent of the heavy minerals extracted from bentonites. Grains are usually euhedral, colorless and average 0.10 millimeters in size. Inclusions are found in apatite grains at localities 3, 11, and 21 (Figure 23).

Hornblende

Hornblende accounts for 32 percent of the heavy minerals extracted from bentonites. Hornblende grains vary in shape from euhedral crystals to elongated grains averaging 0.20 millimeters in size. Different orientations of grains allow for variations in pleochroic colors of green. Figure 24 shows a typical hornblende grain.

Biotite

Biotite grains account for 9 percent of the heavy minerals extracted from bentonites. Biotite grains occur as anhedral flakes, approximately the same size as hornblende grains. Pleochroism of biotite flakes is usually brown to light brown.

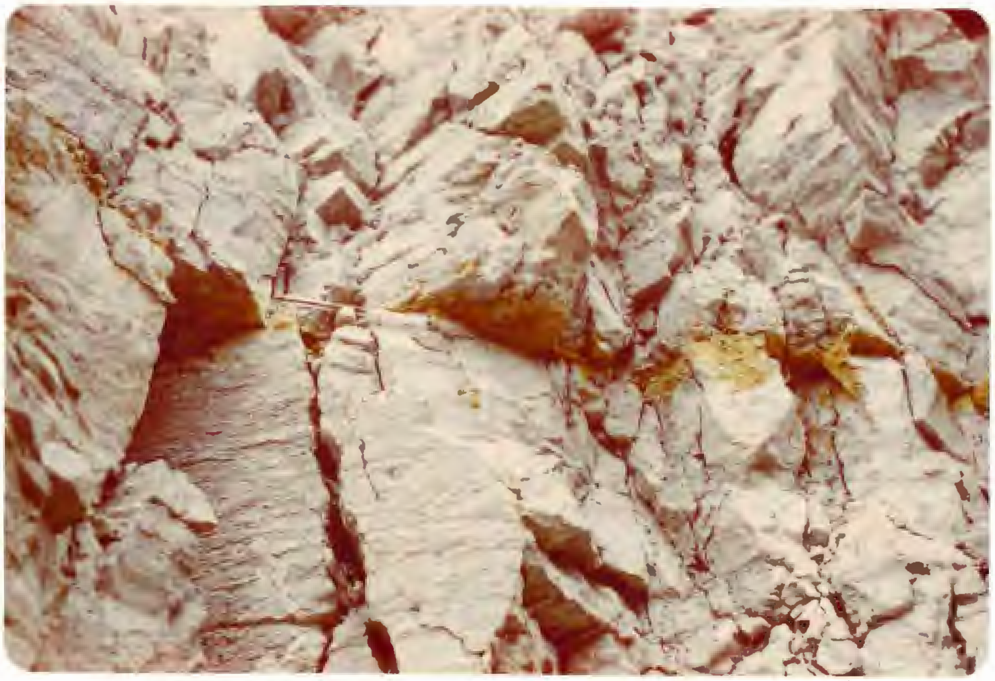

Figure 21-- Outcrop exposure of the Calmar Bentonite (wet). Locality #4, Fountain, Minnesota. Pen for scale.

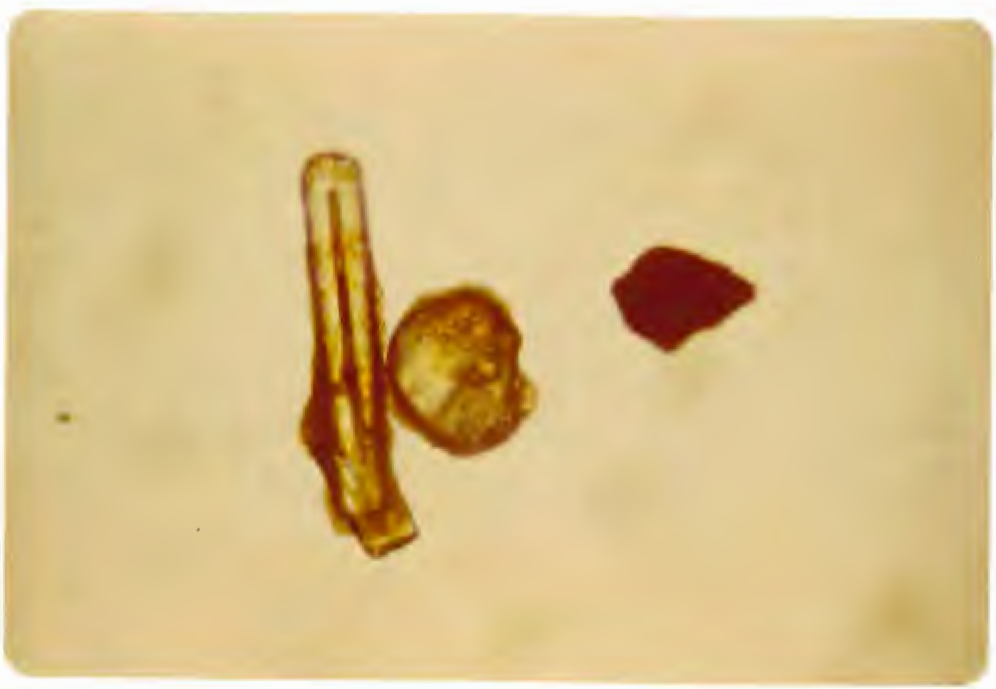

Figure 22-- Photomicrograph of two zircon grains, one with inclusion. Field of view is 1.0 mm. in width, uncrossed nicols.

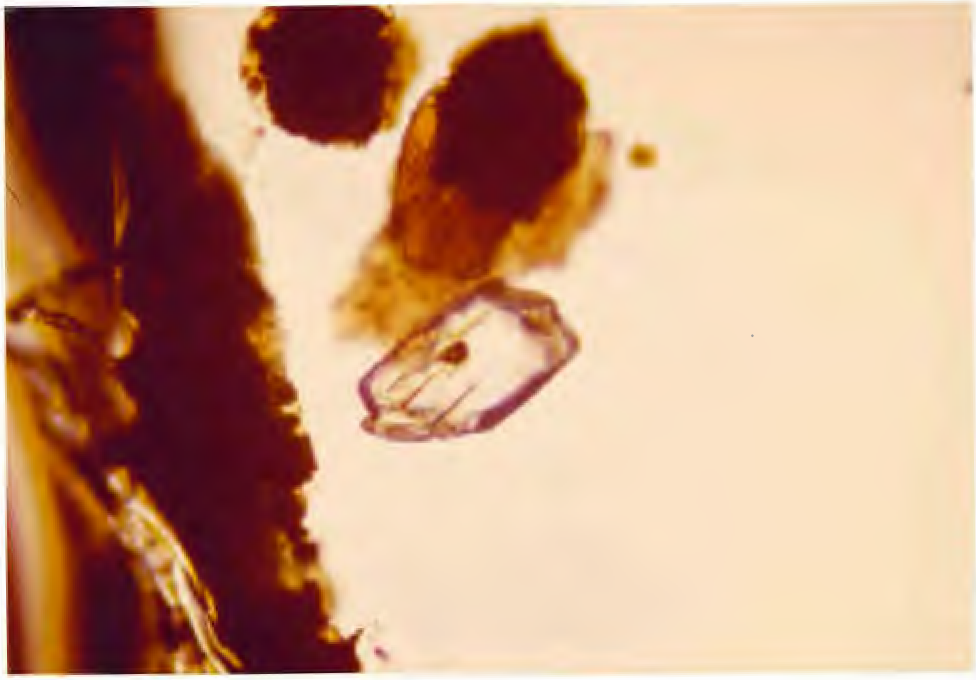

Figure 23-- Photomicrograph of apatite grain. Field of view is 1.0 mm. in width, uncrossed nicols.

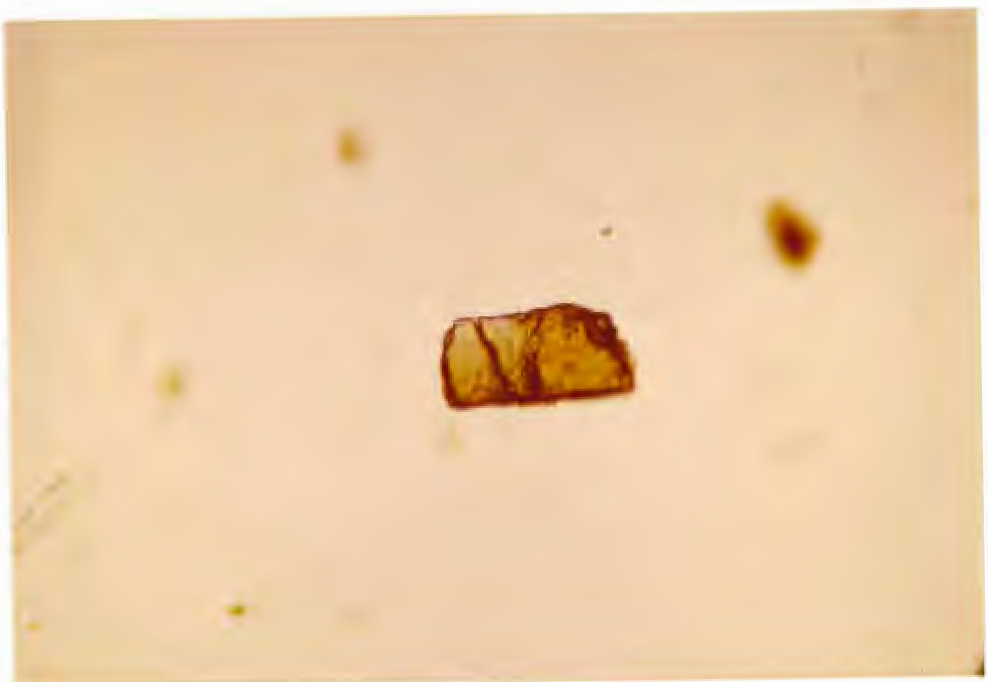

Figure 24-- Photomicrograph of hornblende grain. Field of view is 1.0 mm. in width, uncrossed nicols.

Pyroxene

Pyroxene grains of augite are found in the Calmar and Conover bentonite at localities 11 and 1. Augite grains are euhedral to subhedral in shape, approximately 0.15 millimeters in size and colorless. Pyroxene grains account for 2 percent of heavy minerals extracted from bentonites.

Miscellaneous

Tourmaline and garnet grains account for 5 percent and 2 percent of heavy minerals extracted from bentonites. Tourmaline grains are usually subrounded, blue and green in color with pleochroic variations. Garnet grains appear slightly etched, colorless and subrounded. Tourmaline and garnet grains are indicative of contamination of bentonite beds after deposition (Weaver, 1953).

Collophane

Collophane, a massive form of apatite, occurs as subrounded light brown grains extracted from samples of bentonite at localities 2 and 28. Collophane grains usually appear isotropic, with some grains showing very low birefringence (0.005). The presence of collophane indicates some degree of contamination of the bentonite (Weaver, 1953). Weiss (1954) noted scattered patches of collophane in a bentonite horizon within the Stewartville Member of the Galena Formation. Weiss believed the collophane to be fragments of graptolites.

Bentonite Interpretation

The Calmar Bentonite and the Nasset Bentonite are mineralogically similar. Both bentonites contain 27 percent zircon and very high amounts of hornblende (36 and 43 percent). The Haldane bentonite also contains a high amount of hornblende. The heavy mineralogy of the Conover Bentonite is different from the other bentonites, containing a high amount of zircon and a lesser amount of hornblende. Augite is also present in the Conover Bentonite.

The mineralogy of the Conover Bentonite may suggest a source of slightly different mineralogy, possible of intermediate composition. However, the lack of hornblende may be the result of interstratal solutions which may have dissolved the hornblende grains.

Mossler and Hayes' (1966) heavy mineral analyses on the bentonites in the middle Ordovician strata in Minnesota and Iowa did not indicate any special source area for the bentonites of the upper Dunleith Formation. They found the bentonites of the middle Ordovician in Minnesota and Iowa to be of approximately the same composition.

Volcanic Ash Source

The volcanic source for the Ordovician bentonites in southeastern Minnesota and northern Iowa is believed to be the Appalachian mobile belt, according to Mossler and Hayes (1966) and Dott and Batten (1976).

K-bentonites which were studied show similar mineralogic compositions and probably were derived from close source areas. The use of paleowind currents and thickening of bentonite horizons toward the source area is useful in determining a general region from which the bentonites were likely derived.

Palemomagnetics have been used to determine the position of the equator during middle Ordovician time (Figure 25; Dott and Batten, 1976). If this position of the equator is correct, the northeastern portion of the Appalachian mobile belt would be located within the southeast trade wind belt. Volcanic ash distribution would thicken towards the source, which Eaton (1963) found to be the case in studies of other Ordovician bentonites in the northeastern United States.

Conclusions

1) Volcanics in the northeastern portion of the Appalachian mobile belt were the source of the volcanic ash that trade winds deposited to Iowa and Minnesota during Ordovician time.

2) Heavy mineral analyses are useful in determining bentonite horizons, which have a mineralogy different from that of typical marine shales and carbonate rocks.

3) Bentonite horizons are useful in correlating stratigraphy within limited areas, especially if other criteria for stratigraphic control are available.

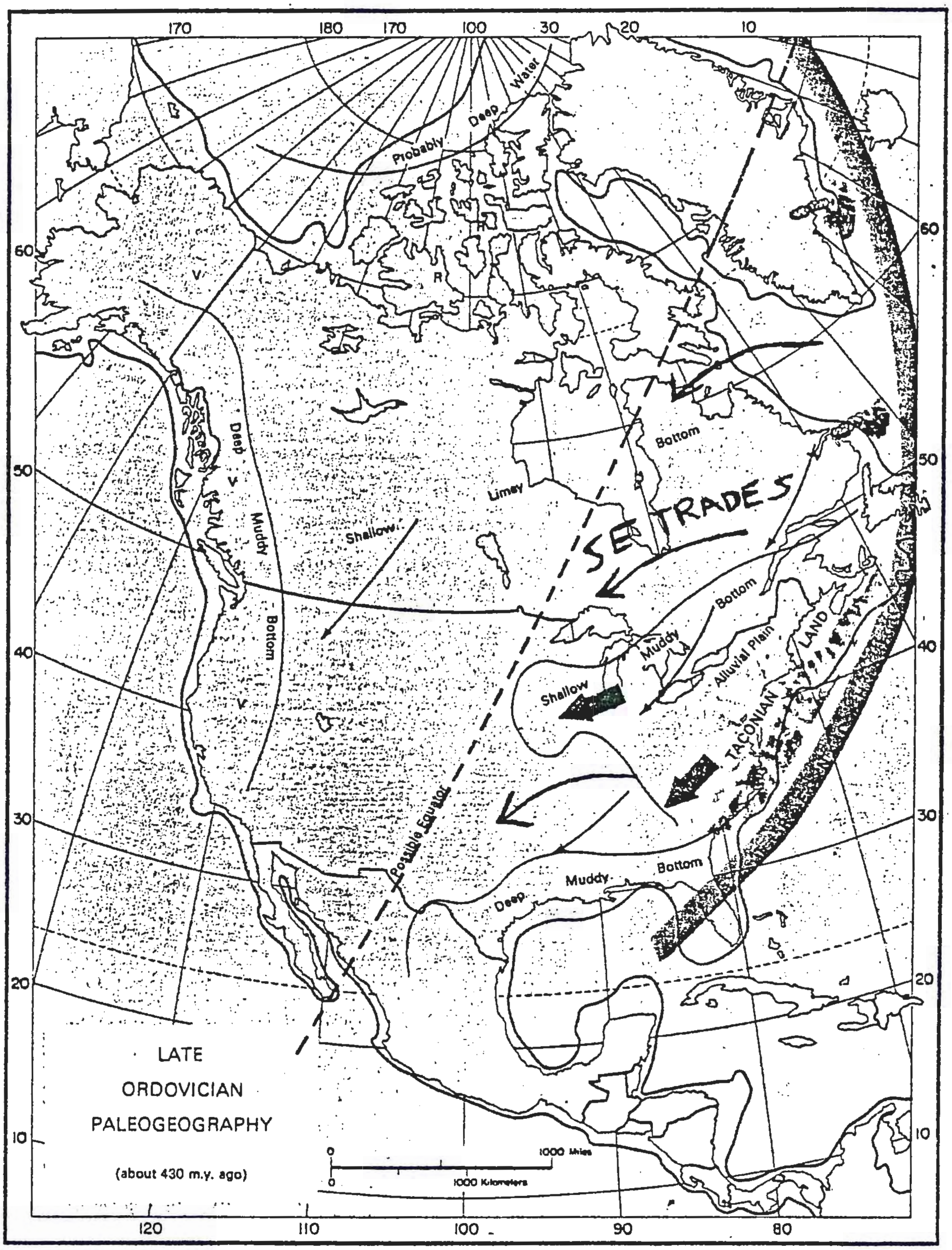

Figure 24-- From Dott and Batten (1976), showing probable position of the equator during late Ordovician time. Arrows indicate direction of southeast trade wind currents in which volcanic ash was carried.

SEDIMENTARY STRUCTURES

Corrosion Zones

Corrosion surfaces or corrosion zones (Weiss, 1958) are distinctive surfaces parallel to bedding, formed by solution rather than deposition of calcium carbonate. These surfaces commonly occur in middle Ordovician strata of Minnesota and Iowa. Surfaces of corrosion zones are relatively flat, usually broken by steep-sided irregular pits as much as four inches deep, but usually 1/4 to 1/2 inch deep. Sections cut perpendicular to the corrosion zone show that the carbonate stratum that overlies the corrosion surface commonly fills the irregular pits. Silt size quartz, dolomite rhombs, clay particles and sparry fossil fragments are commonly the material that fills most of the irregular pits of the corrosion zones (Figure 26).

In the region of Fillmore County, Minnesota and northern Iowa, corrosion surfaces have black rims that stand out prominently (Figure 27). The black rim is usually fine-grained disseminated pyrite that can be as much as two inches thick. In Olmstead, Goodhue and Dodge counties in Minnesota, the black rim is not as prominent, and close examination is required to find the corrosion surface or zone.

Corrosion zones of the Sherwood, Wall and Wyota Members have horizons of sand-size material that overlie the corrosion surface. These horizons are usually 2 to 3 inches thick and are composed of a calcareous,

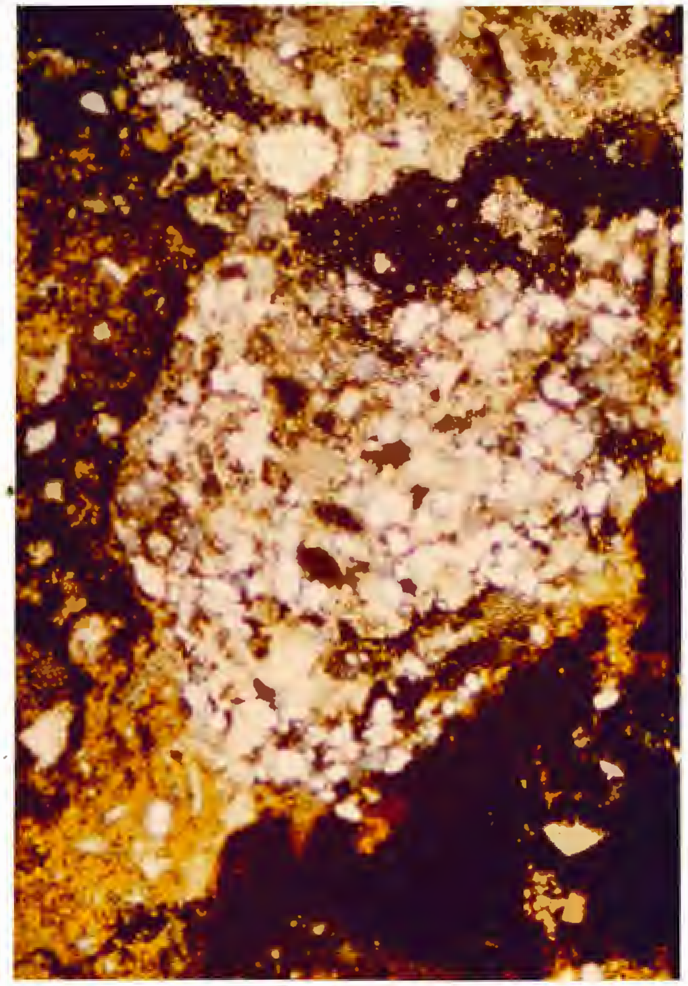

Figure 26-- Photomicrograph of corrosion zone, showing filling of eroded pits with overlying detrital material. From Wall Member, Locality #5, Harmony, Minnesota. Field of view is 0.5 mm. in width, crossed nicols.

Figure 27-- Corrosion zone from upper portion of the Sherwood Member (locality #7, Burr Oak, Iowa). Note black disseminated pyrite, and syneresis cracks on the corrosion surface.

Figure 28-- Corrosion zone from upper Sherwood Member with microconglomeratic zone composed of sand-size fossil fragments and other clastics filling the eroded pits. Locality #3, Bristol Township, Filmore County, Minnesota.

dolomitic, or shaley matrix containing clasts of fine quartz, phosphatic grains and small fragments of limestone (Figure 26). Corrosion surfaces are also covered with fucoidal trails and burrows.

Shrinkage (syneresis) cracks are present within corrosion surfaces as small (1/8 inch) v-shaped cracks. These shrinkage cracks may not be the result of subaerial exposure. Small scale slumpage of lithified material along the corrosion zones itself, after carbonate deposition resumed, may have been related to weaknesses created by the shrinkage cracks (Figure 27).

Origin

Different theories have been presented by various authors regarding the origin of corrosion zones. Authors such as Prokopovich (1955), Weiss (1958), Conkin and Conkin (1975) and Levorson and Gerk (1973) believe corrosion zones represent discontinuities within the rock with different processes possibly responsible for their origin and development.

Prokopovich (1955) believes corrosion zones are partially the result of bottom currents which provide the energy for possible mechanical erosion and abrasion of the sea floor and for subsequent deposition of the overlying clastic horizons. Simultaneously with mechanical erosion the solution of calcareous mud also occurs. The solution of carbonate mud may be caused by a number of factors such as stagnation of waters, decreasing temperatures, or by decreasing the pH of the water. Thus corrosion zones may have formed when the chemistry at the sediment-water interface favored solution rathar than deposition of carbonates and mechanical erosion occurred.

Weiss (1958) postulates that corrosion zones are developed by solvent action of sea water in the intertidal zone. Weiss noted that in other studies that normal sea water can dissolve limestone in the intertidal zone. Thus an intertidal origin for corrosion zones could account for both chemical corrosion and mechanical erosion.

Disseminated pyrite on the corrosion surfaces may have formed under reducing (anaerobic) conditions. Pyrite may have formed after the corrosion zone was lithified and a thin horizon of sand-size material was deposited over the corrosion surface. Since anaerobic conditions can exist in fine-grained sediment a few inches below an oxigenated interface (D. G. Darby, 1980 personal communication), it may be possible for disseminated pyrite to form while the corrosion surface was in or near the intertidal zone. Weiss (1958) believes the pyrite found within the corrosion zone is of diagenetic origin; however, this would not account for the concentration of pyrite along the corrosion surface and not elsewhere in the strata.

The amount and intensity of corrosion and abrasion by chemical and mechanical energy varied over the sea floor. Where corrosion and abrasion were widespread, extensive corrosion zones formed. Some of these zones are traceable over a distance of 75 miles. Some corrosion zones are less extensive, disappearing within single outcrops. Usually these local corrosion zones grade laterally into sparry cemented calcarenite bands (refer to page 61). These bands probably represent a continuation of current activity, without chemical corrosion.

In summary, the intensity of corrosion on the sea floor varied in different localities during different periods of time according to the special circumstances of the environment. Since carbonate deposition would not have occurred during corrosion on the sea floor, each corrosion zone would be a minor diastem which could account for minor thinning of members in the upper Dunleith Formation. However, the variation of intensity of corrosion on the sea floor does not allow isopach maps to be useful in relating the thinning of members to corrosion surfaces.

Stylolites

Stylolite surfaces are prominent sedimentary features in the Wyota Member of the Dunleith Formation and in the Sinsinawa Member of the Wise Lake Formation (Figure 29), resulting from interpenetration of beds by solution. Stylolite surfaces studied have a relief of approximately 1/8 inch, and are parallel to bedding. An increase in argillaceous content usually occurs at the stylolite surface.

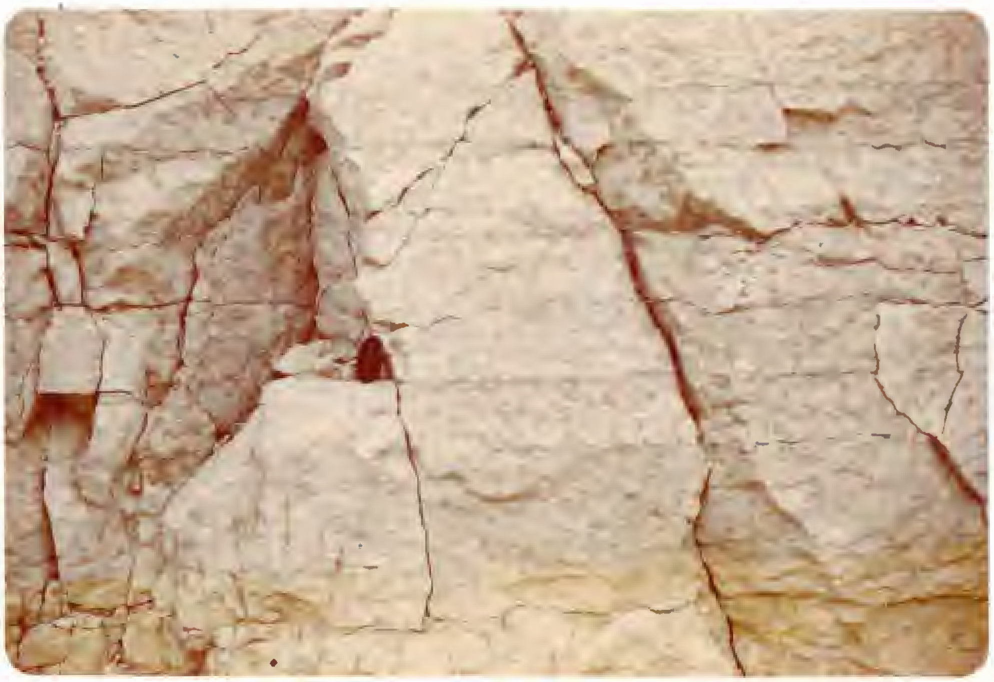

Figure 29-- Exposure in the Sinsinawa Member showing corrosion zones, stylolites, and mottling. Locality #2, Rifle Hill Fillmore county, Minnesota.

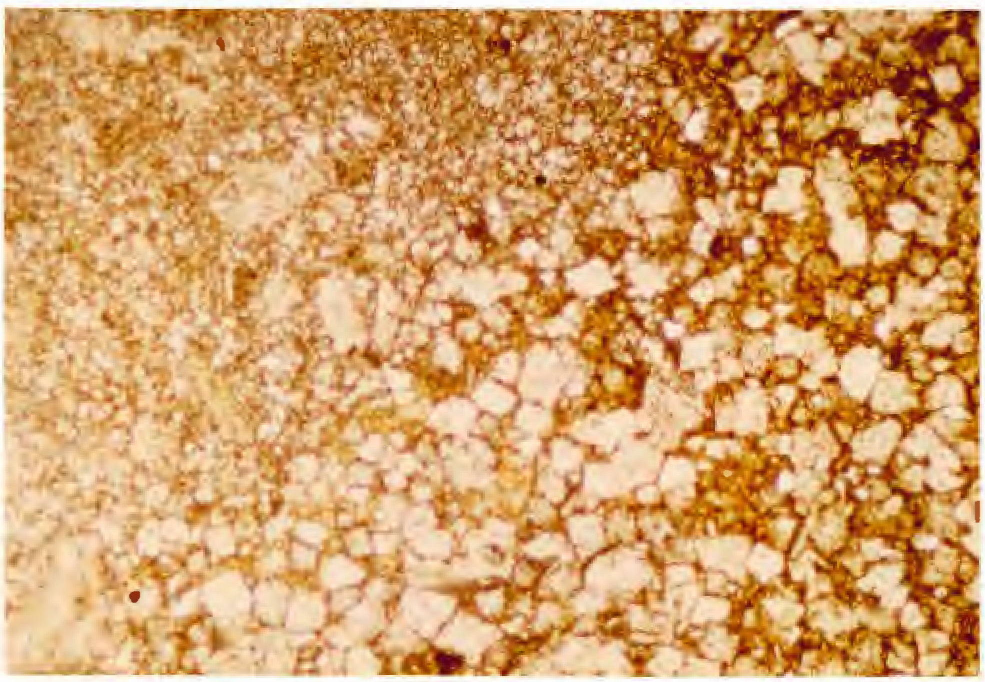

Figure 30-- Photomicrograph of a mottled zone. Coarse dolomite rhombs indicate the mottled zone. From Sinsinawa Member, locality #2, Rifle Hill Fillmore County, Minnesota. Field of view is 1.0 mm., crossed nicols.

Mottling

Mottling is a term used primarily to describe the appearance of patchy areas of dolomite in a dominantly limestone stratum. On fresh outcrop surfaces studied, the patchy dolomite appears tan in color while the limestone appears dark gray in color. On weathered surfaces the dolomite appears rusty brown and the limestone appears light brown. Dolomite patches are usually lenses and tubes of various shapes, approximately 1/2 to 2 inches in cross-section with no preferred orientation (Figure 29).

Mottled surfaces are prominent in the Sinsinawa Member of the Wise Lake Formation. In Fillmore County, Minnesota, and in northern Iowa, the mottling feature in the Sinsinawa Member is useful in placing the Wyota-Sinsinawa contact since the Wyota is not mottled. In Goodhue County, Minnesota, mottling texture is present, but faint, in Sherwood, Wall and Wyota strata.

Thin section petrology done on mottled surfaces show large crystals of dolomite invading the carbonate matrix, indicating replacement of the carbonate after its consolidation (Figure 30). Willman and Kolata (1978) believe the mottling in the Ordovician of the upper Mississippi Valley is of two origins. The mottling may be due to dolomite replacement of material filling burrows, or the mottling can be a result of dolomitization of porous areas in the limestone.

Dolomitization of the entire section exposed at locality #22; Mantorville, Minnesota, created ghosts of the initial mottled surface. The original mottled surface is recognizable by the larger dolomite rhombs while the dolomite rhombs are much smaller in the surrounding matrix (within studied thin sections).

Chert Horizons

Chert occurs in the upper Dunleith Formation as horizons of smooth, rounded, elongated nodules. The nodules are usually about 1 inch in width, 3 inches in length, and 3 inches thick, varying in color from gray to tan, with a white exterior (Figure 31). Most nodules are distributed within the beds, not crossing major bedding planes.

The number and thickness of chert nodule horizons increase southwestward in Fillmore County toward the mineral district in Illinois (Weiss, 1955). Chert nodules are not present within any strata studied north of Fillmore County, Minnesota.

In thin section, chert appears as dense microcrystalline quartz associated with dolomite rhombs and calcareous fossil fragments (Figure 32). Silicified fossils are present in some chert nodules. Fossil fragments in thin sections from cherty strata show replacement of the carbonate by chalcedony.

There is controversy regarding the origin of chert nodules. In the nodules there is evidence both for and

Figure 31-- Chert nodules in the Sherwood Member. Locality #1, Wykoff, Minnesota.

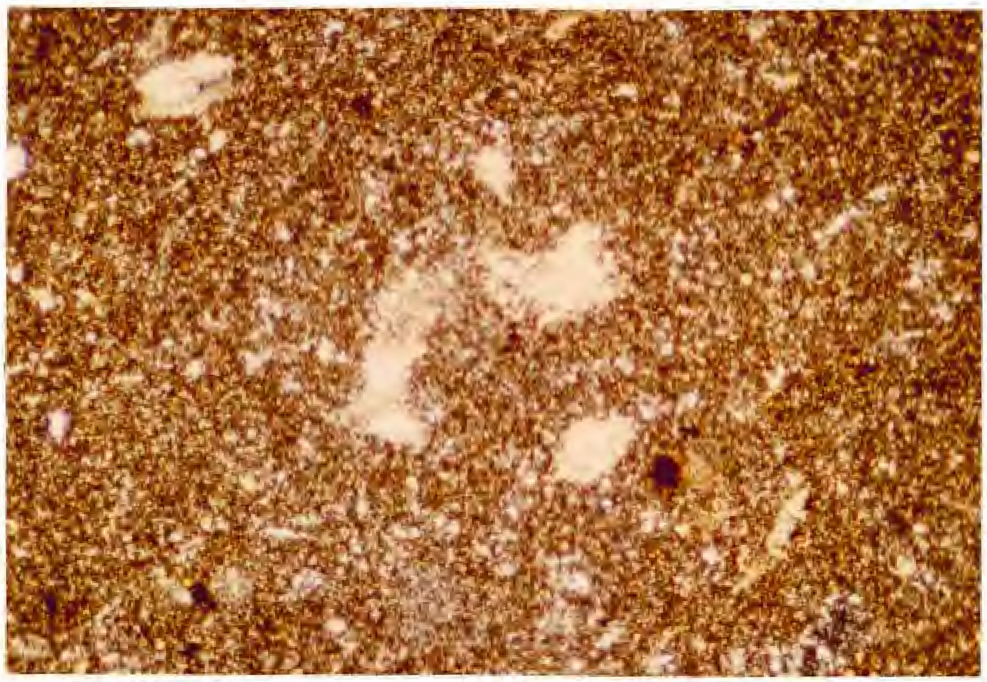

Figure 32-- Photomicrograph of chert nodule with traces of carbonate material (brown color). Field of view is 1.0 mm., crossed nicols.

against primary and replacement chert. Evidence for primary chert which is believed to be formed by direct precipitation of masses of silica gel on the sea floor (Pettijohn, 1975) in relation to the chert nodules in the Sherwood and Wyota Members is as follows:

A) Smooth, rounded nodules are tight against the limestone matrix.

B) Nodular chert beds occur parallel to the bedding.

C) Laminae of the limestone matrix are bent around some nodules of chert.

Evidence for replacement chert, with silica as a post-depositional replacement of the host rock (Pettijohn, 1975), in relation to the chert nodules in the Sherwood and Wyota Members is:

A) Irregular shapes of some chert nodules.

B) The presence of patches of limestone and dolomite rhombs within some chert nodules.

C) Many fossils close to the chert nodule horizons show replacement by chalcedony, likely associated with chert nodule formation.

D) Beds in the host limestone more susceptible to replacement by disseminated silica would explain the concentration of nodules in horizons, with greater ease of replacement parallel to bedding.

Evidence against primary origin of chert nodules by precipitation has been found by Cressman (1962) in experimental studies. The studies revealed that normal sea water is unsaturated with silica making it unlikely that silica gel globules would form under normal open marine conditions which existed during deposition of the upper Dunleith Formation.

The origin of the chert nodules based on evidence found in thin sections was probably replacement. According to Pettijohn (1975) secondary chert forms by precipitation from water which contains dissolved silica which originally was secreted by radiolarians, diatoms, and sponges. Later the silica may be concentrated by diffusion of silica in solution towards the direction of diffusion through the unlithified limey sediment, and was reprecipitated as nodules that replaced the limestone. The nodules would be precipitated parallel to bedding since the original waters with dissolved silica were also somewhat concentrated parallel to bedding.

Weiss(1955) believes that chert nodule formation may be part of a phase of mineralization that produced the lead-zinc ores in Illinois and Wisconsin. This would agree with the dissappearance of chert nodules north of Fillmore County, away from the lead-zinc mineralized area.

<u>Bedding</u>

Bedding plane thicknesses in upper Dunleith strata range from 3 inches to very thick beds (greater than 3 feet). The Rivoli is the thinnest bedded member, with horizons of shale. The Sherwood, Wall and Wyota Members are usually thick bedded on the order of 1 to 3 feet.

Some bedding surfaces are interpreted as stylo-litic. Stylolitic bedding is shown by a roughness on the bedding surface which would have been produced by solution interpenetration under pressure. At several places these bedding surfaces can be traced to stylo-lites at different locations in the outcrop.

LITHOLOGY

Introduction

Several different lithologies are present within the upper Dunleith Formation. Rock units are very thin (3 inches) to very thick (greater than 36 inches) bedded and most units can be traced throughout an outcrop.

Rocks are named using Folk's (1962) carbonate textural spectrum (Figure 33) in which carbonate rocks are divided into eight field and petrographic units. They are (with Dunham's, 1962, classification according to depositional texture in parentheses): micrite (mudstone), fossiliferous micrite (mudstone), sparse biomicrite (wackestone), packed biomicrite (packstone) and biosparite of various sortings (grainstone). Dolostones and shales are also present.

Micrite and Fossiliferous Micrite

By Folk's (1962) definition, fossiliferous micrites have 1 percent to 10 percent allochems and micrites have less than 1 percent allochems. In this study, micrite and fossiliferous micrite vary in composition by only one to two percent of allochems and will be discussed as one unit.

Fossiliferous micrites are composed of both whole and fractured shell material and are frequently burrowed. Fossiliferous micrites which are burrowed have small filled tubes in which the shell material is finely fragmented and the micritic burrow filling is lighter

CARBONATE TEXTURAL SPECTRUM

	OVER 2/3 LIME MUD MATRIX				SUBEQUAL SPAR & LIME MUD	OVER 2/3 SPAR CEMENT		
Percent Allochems	0-1%	1-10%	10-50%	OVER 50%		SORTING POOR	SORTING GOOD	ROUNDED & ABRADED
Representative Rock Terms	MICRITE & DISMICRITE	FOSSILI-FEROUS MICRITE	SPARSE BIOMICRITE	PACKED BIOMICRITE	POORLY-WASHED BIOSPARITE	UNSORTED BIOSPARITE	SORTED BIOSPARITE	ROUNDED BIOSPARITE
1959 Terminology	Micrite & Dismicrite	Fossiliferous Micrite	Biomicrite			Biosparite		
Terrigenous Analogues	Claystone		Sandy Claystone	Clayey or Immature Sandstone		Submature Sandstone	Mature Sandstone	Supermature Sandstone

LIME MUD MATRIX
SPARRY CALCITE CEMENT

Figure 33-- Folk's Carbonate Textural Spectrum

in color than the surrounding micrite matrix. Shells that are present in unburrowed strata are predominantly of brachiopods, and are generally whole and articulated. Very fine sand-size quartz and opaques are also present in trace amounts.

These fossiliferous micrites appear to have been deposited in a relatively low energy environment. The condition of the shells (whole and articulated) suggest that they were buried during normal sedimentation and not transported. Micrite was being deposited at the same time as the shells and the deposition of one bed was a gradual process. The preservation of micrite indicates that current energy was low or the carbonate mud would have been winnowed away.

Micrite and fossiliferous micrite compose approximately 30 percent of the lithology of the upper Dunleith Formation.

Sparse Biomicrite

By Folk's definition, sparse biomicrites have 10 percent to 50 percent allochems. Sparse biomicrites comprise 60 percent of the upper Dunleith Formation.

Shells of brachiopods and gastropods occur both fragmented and whole. Trilobite, bryozoan and crinoid remains appear as debris or disarticulated or molt fragments. Shell orientation is usually parallel to bedding, but some shells are at some angle to bedding. Shells are mostly mud support, but a few shells were grain supported. Curved shells of brachiopods and trilobites are usually oriented concave downward.

Sparse biomicrites are thought to be deposited in low energy environments periodically washed by weak currents. Evidences of current action are: broken shells, grain support of some shells, shells oriented parallel to bedding and curved shells oriented concave downward. Further evidence of weak current activity is the presence of carbonate intraclasts and silt-size quartz within sparse biomicrites.

Packed Biomicrite

Packed biomicrites, or coquinas, are composed of greater than 50 percent skeletal material with the remaining fraction being micrite. Packed biomicrites occur in the stratum as 1/4 to 3/4 inch lenses cement by micrite, usually of little lateral extent. Skeletal remains show little fragmentation, abrasion, or sorting and are composed mostly of shells or gastropods, brachiopods and crinoidal material.

Packed biomicrites are probably quiet water deposits in which various types of organisms produce shell material and die at a faster rate than carbonate mud is accumulating. The resulting deposit is a packed biomicrite or coquina with abundant skeletal material with little evidence of abrasion.

Packed biomicrites probably formed under the same depositional energy conditions as sparse biomicrites, resulting from very low currents which produced these small irregular horizons.

Biosparite

Biosparite is a term used to describe carbonates composed mostly of fossil material cemented by sparry calcite. Biosparites occur in the upper Dunleith Formation as 'bands' usually 1 inch to 5 inches thick, within beds of biomicrite (Figure 34). These horizons have previously been termed sparry calcarenite bands (Willman and Kolata, 1978; Levorson and Gerk, 1973). Biosparites are composed of moderately well sorted sparry fossil fragments which are grain supported, micrite clasts, pellets, sand-size quartz and opaques (Figure 35). Sparry calcite is the cementing agent. Identifiable fossils are crinoid columnals, brachiopods, bryozoans and trilobite fragments. Shell fragments do not have a preferred orientation.

Micrite is present in some biosparites surrounded by shell material which protected it from currents (geopetal fabric).

Biosparites may have been deposited in a moderate energy environment of vigorous winnowing action. This is evident by shells which are highly fragmented and slightly rounded by current activity, geopetal textures, the presence of intraclasts and an abundance of detrital quartz. The association of biosparites with corrosion zones (which may have formed in or near the intertidal zone) is further evidence for a moderately high energy depositional environment.

Figure 34-- Handsample of a biosparite overlain and underlain by biomicrite.

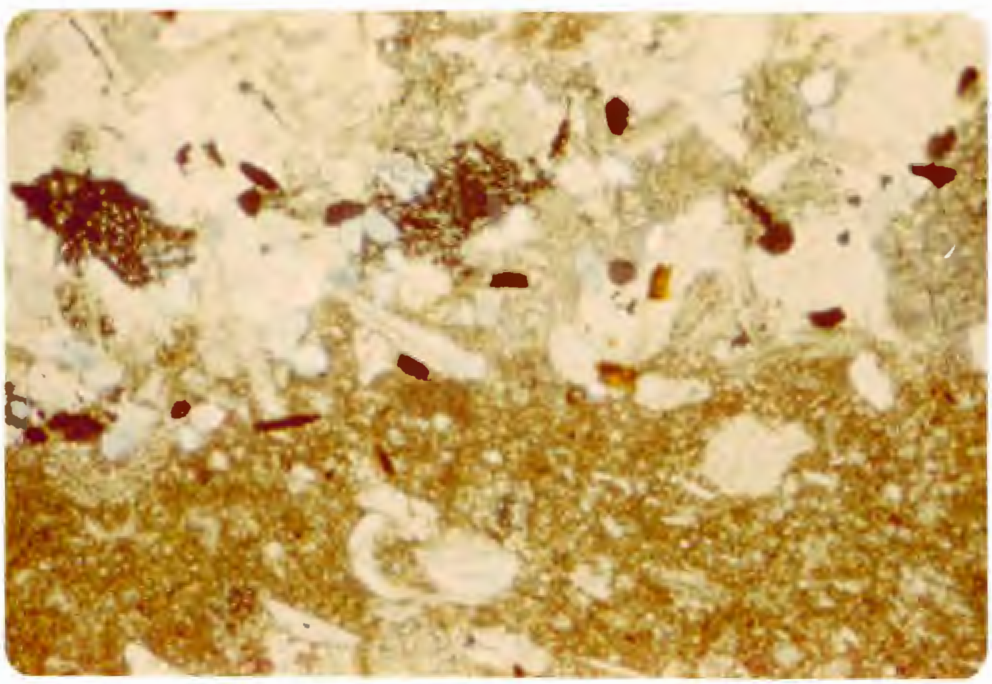

Figure 36-- Photomicrograph of a biosparite in sharp contact with an underlying biomicrite. Biosparite is composed of fossil fragments, opaques, quartz and sparry calcite. Field of view is 1.0 mm., crossed nicols.

Dolostone or Dolomite

Dolostone is the term used to describe samples composed primarily of dolomite. Dolomite constitutes over 90 percent of the mineralogic volume of the Sherwood, Wall and Wyota Members in Dodge County, Minnesota, and is secondary in origin. Dolomitization of the original matrix destroyed many biological and lithological features; however, ghosts of some fossils and sedimentary structures can be seen in outcrop and thin section.

Shale

Lenses and beds of platy, fissile, dark blue-gray shale, ranging from 1/2 inch to 10 inches in thickness, occur predominantly within the Rivoli Member. Shale also occurs in the Sherwood, Wall and Wyota Members, but is usually present as very thin beds or wavy bed partings. The shales are composed dominantly of illite with lesser amounts of layer mixed-clays (Austin, 1971; Willman and Kolata, 1978), silt-size quartz, feldspar, pyrite and micrite. Shale horizons may contain brachiopod shells, graptolites and trilobite debris, usually occurring on bedding planes. Shale horizons may also be horizontally burrowed.

Webers (1972) attributes the source of the clays and other fine clastics that compose the shales to subaerial exposure of the Transcontinental Arch. The thick shales of the Rivoli Member, especially in Goodhue County, Minnesota, reflect a high influx rate of clastics. The very thin beds of shales and wavy shale partings reflect minor pulsations in the rate and supply of silt and clay from the Transcontinental Arch (refer to Figure 6, page 12).

THIN SECTION PETROLOGY

Introduction

Eighty-seven thin sections were petrographically analyzed. Folk's (1959) mineralogic classification was used in describing the carbonates.

Thin Section Mineralogy

Micrite

Micrite is the most common constituents, composing the matrix of studied samples. Micrite is a term designated by Folk (1959) to describe microcrystalline calcite one micrometer (micron) to four micrometers in size. Micrite was observed as equant grains with very high birefringence. The composition of the micrite was determined usually to be calcite rather than dolomite (dolomicrite) by staining slabs cut for thin sections with Alizarin Red S.

Different processes may be responsible for the origin of micrite. Micrite may be formed by the alteration of aragonite to calcite, with the original aragonitic ooze being either a chemical precipitate or more commonly, a product formed by the release of minute aragonitic needles by degradation of carbonate algae. Micrite may also be the finest product of shell attrition and thus can be mechanical in origin. Some forms of micrite may also be a diagenetic product resulting from boring organisms which decrease the size of fossils and other sedimentary particles (micritization) (Pettijohn, 1975).

Sparry Calcite

Sparry calcite or sparite is clear, coarsely crystalline (greater than 40 micrometers) calcite which shows well defined crystal boundaries and cleavage traces. In studied thin sections, sparry calcite occurs either as a pore-filling cement or as a result of crystallization of finer-grained micritic carbonate. In studied thin sections of biosparites, sparry calcite fills the pores of a framework composed of fossil fragments, quartz grains, dolomite rhombs and intraclasts. Sparry calcite also occurs in biosparites as rounded clasts derived from other sources.

Sparry calcite also occurs as cavity fillings of fossil molds (drusy mosaic). This is evident by the partial collapse of the rim or "micrite-envelope" of the original shell.

Dolomite

Dolomite appears as clouded rhombs, some with hematite halos, ranging in size from 5 micrometers (microns) to 30 micrometers. The rhombs occur either as scattered individual grains or as clusters associated with the mottling of limestones.

Dolomite, from evidence in thin section, is likely a diagenetic replacement of the original limestone. Scattering of dolomite euhedra in an unaltered calcitic matrix (porphyroid texture), is the result of incomplete dolomitization. Pettijohn (1975) attributes partial dolomitization to the unmixing of high-magnesium calcites of organic origin. Exsolution of the high-magnesium calcites was not sufficient to totally convert limestone to dolomite, but would have been enough to form a scattering of dolomite crystals within the limestone. In thin sections where porphyroid textures are common, dolomite rhombs commonly enclose small grains of quartz and transect primary structures such as fossils, indicating a diagenetic origin of dolomite.

Patches or clusters of dolomite rhombs (mottling) may also be a result of incomplete dolomitization (refer to page 51), reflecting control of pre-existing structures such as burrows.

At locality #22, Mantorville, Minnesota, in western Dodge County, dolomite composes more than 90 percent of the carbonate strata. The dolomite forms a medium-to coarsely-crystalline mosaic, with the dolomite crystals in euhedral form (idiotopic fabric of Friedman, 1965).

Quartz

Quartz grains occur as fine sand to coarse silt within biomicrites and biosparites. Grains are usually subangular to subrounded, well sorted, and make up about 2 percent of the upper Dunleith Formation.

Silt-size quartz grains that occur in the micrites of the upper Dunleith Formation may have been wind transported, since no evidence of current action was found in micrite samples that contain minor quartz. Quartz grains that make up to 25 percent of the volume of some biosparites and argillaceous micrites are likely current related deposits.

Chert

Chert appears in thin sections as chalcedony, replacing skeletal material. Chert, in nodules, appears as microcrystalline quartz, possibly replacing the carbonate material. Chert formation is discussed on page 52.

Feldspar

Plagioclase is recognized by albite twinning while microcline is recognized by polysynthetic "grid" twinning or tapering "spindle-shaped" lamellae. Both types of feldspar appear unaltered under plane polarized light. Feldspars are approximately the same size as quartz grains, rarely comprising greater than 1 percent of any sample.

Feldspars are likely of the same origin as quartz grains; however, euhedral shapes of some microcline grains may indicate authigenic growth.

Opaques

Pyrite is the most common opaque and is present as silt-size scattered grains. These silt-size grains are sometimes concentrated either along the borders of fossil fragments or as replacement of fossil fragments. Authigenic pyrite is usually concentrated along corrosion surfaces.

Hematite, in trace amounts, occurs as bright red fringe halos around dolomite rhombs. Hematite is likely an alteration product of the iron-rich dolomite.

Intraclasts

Intraclasts are particles of penecontemporaneous material, usually of weakly consolidated carbonate sediment that has been eroded by currents from within the basin of deposition and redeposited. Intraclasts vary in size from fine to coarse sand and consist of micrite and/or biomicrite plus silt-size quartz grains. Intraclasts may indicate a tearing up of the sea bottom by an increase in current activity such as storms, or as possible tectonic changes in the depositional basin in which partial emergence of the basin occurred, allowing erosion of the weakly lithified sediments.

Fossils

Fossil fragments comprise the major portion of allochems within studied samples. Fossil fragments which are present in strata composed mostly of micrite are usually unabraded and identifiable, while fossil material found in biosparites and argillaceous biomicrites is abraded and less recognizable. The most common fossils are brachiopods, crinoids, bryozoans, corals, trilobites and sponges. Fine fragments of trilobites, bryozoans and crinoids have distinctive shapes and internal structures (if not recrystallized) and stand out well in polarized and unpolarized light. Sponges are present as fine calcareous spicules.

SEDIMENTATION AND DEPOSITIONAL ENVIRONMENTS

Introduction

The upper Dunleith Formation (Prosser Member of the Galena Formation in Minnesota) was deposited in a normal marine subtidal environment, below the general wave base, in a broad epeiric sea. The upper Dunleith and Wise Lake Formations and their correlatives, can be found over much of North America and probably represent a portion of time of the greatest submergence ever experienced by the North American continent (Templeton and Willman, 1963). The similar lithologies throughout the Rivoli, Sherwood, Wall and Wyota Members indicate similar environments existed throughout the study area, with minor variations.

Sea Depth

Epicontinental or epeiric seas typically attain depths of only 100 feet, with a maximum of perhaps 600 feet (Shaw, 1964). Bottom slopes of epeiric seas according to Shaw (1964) and Irwin (1965) are usually less than 1 feet per mile, averaging 0.1 to 0.6 foot per mile.

The depth of the epeiric sea in which the upper Dunleith Formation was deposited can be estimated by examining the fossil fauna. Major fossil groups such as brachiopods, crinoids, bryozoans and pelecypods are usually indicative of shallow marine waters. In addition the inarticulate brachiopod *Lingula*, which is common in upper Dunleith strata, is evidence of shallow subtidal marine waters of depths from 20 feet to 80 feet (Heckel, 1972).

Salinity

Normal salinity for marine waters is a typical circulated sea averages about 35 parts per thousand. Since distribution of organisms is limited by salinity and variations in it, fossils are a useful tool for determining salinity conditions, especially those organisms which are known to be stenohaline (35 to 40 parts per thousand).

Fossil assemblages of brachiopods, crinoids and corals, which are usually stenohaline, comprise most of the fauna that is found in the upper Dunleith Formation. Fewer species of organisms are present in the overlying Wise Lake Formation (upper Galena Formation in Minnesota stratigraphic nomenclature) and those organisms that are present, such as gastropods and cephalopods, could live in more diverse saline conditions. Webers (1972) noted that in a study of the Permian Reef Complex, the fauna of the hypersaline backreef environment was dominated by gastropods and devoid of stenohaline organisms. This ecological picture generally fits the Wise Lake Formation. Thus, a prominent change in salinity occurred in the environment between the deposition of the upper Dunleith Formation and the overlying Wise Lake Formation. Other authors such as Pearse and

Gunter (1957) have noted from biological observation, that the number of species of organisms is greatest at normal marine salinity and declines under conditions of either higher or lower salinity. Webers (1972) noted that the Prosser Member of the Galena Formation in Minnesota (upper Dunleith Formation) contains abundant species, indicating an environment of normal marine salinity.

Substrate

The firmness of the substrate may be determined by considering the types of organisms which attach themselves to the bottom of the sea floor. Organisms prominent in the upper Dunleith Formation such as solitary corals (Streptelasma) and crinoids are evidence for a moderate to firm substrate. Corrosion surfaces (see page 44) are somewhat lithified surfaces; they too provided attachment sites for corals and crinoids (Hopper, 1978).

Other organisms, such as brachiopods, which are numerous in the strata studied, live on either a hard or soft substrate. Some brachiopods cement their shells to hard objects, but most are attached by their pedicle to shells or to the substrate.

Water Turbidity

Consideration of feeding methods of organisms is useful to determine if an environment was characterized by clear or turbid water. Filter feeders such as brachiopods (e.g. Strophomena, Sowerbyella. Rafinesquina), and corals, dominate the fossil assemblages that are present in the upper Dunleith strata. These organisms indicate an environment of clear water containing the microorganisms on which they feed. Moreover, these filter feeders are restricted to clear water, because too much suspended clay and silt will choke their feeding apparatuses.

Sedimentation Summary

Micrites and sparse biomicrites are the most common lithologies in the upper Dunleith Formation, appearing as interbedded horizons representing low energy environments. In micrites, the orientation and condition of the fossil shells present (unabraded) suggest little or no transport. Current activity was minimal or non-existant, or the lime muds would have been winnowed away, leaving coarser sediment behind.

In sparse biomicrites, many of the fossil allochems are broken, with some curved shells oriented concave downward. This may be evidence for weak current activity, but may also be partially due to the activities of predator organisms which grind shells in search of food.

Biosparites occur in the strata as 1/2 inch to 5 inches thick (sparry calcarenite) bands, possibly deposited by moderately high energy currents. These currents winnowed away the carbonate mud as evidenced by geopetal textures, while depositing moderately sorted and abraded sparry fossil allochems and fine sand-size quartz grains. Fossil allochems are composed of fragments of crinoids, brachiopods and other organisms possibly brought in from other environments, unlike fossil allochems found in sparce biomicrites which likely lived in the deposition site. Since most biosparites occur as small distinct bands and have little lateral extent, they may be interpreted as local influxes of high energy, possibly resulting from storm activity.

Generally, significant current action was lacking during deposition of upper Dunleith strata, since biosparites compose no more than a few percent of the lithologies present.

Shales, which occur mainly in the Rivoli Member in Goodhue County, Minnesota, are evidence for a quiet water environment which is being supplied with terrigenous materials. The source of the terrigenous material was likely the Transcontinental Arch, since terrigenous detrital material within the strata increases toward the west and northwest and decreases toward the southeast.

Environmental Changes

Vertical

Vertically, in the upper Dunleith Formation, the lithology changes upward gradually from biomicrites of high detrital content alternating with shale beds in the Rivoli Member, to biomicrites with little detrital content in the Wyota Member. This change in lithology may reflect the subsidence of the Transcontinental Arch, thus decreasing the detrital material supplied to the upper Dunleith Formation.

Smaller lithologic changes also occur in the strata, reflecting minor changes in the source area and depositional environment. These lithologies, such as interbedded shales and thin argillaceous horizons, may be explained by storm activity or intense periods of rainfall, eroding the Transcontinental Arch, with the terrigenous material being deposited into the depositional basin.

Lateral

The lithologies of the upper Dunleith Formation change laterally from northern Iowa to Goodhue County, Minnesota. At locality #28, northern Goodhue County, the Rivoli Member is very shaley, reflecting a large amount of detrital material. At locality #5, southern Fillmore County, the Rivoli Member contains little detrital material, and is devoid of shale beds. Figure 36 correlates three lithologic sections, by the use of bentonite horizons.

Argillaceous content increases northward throughout the members of the upper Dunleith Formation. The amount of disseminated clay within the strata is greatest in Goodhue County, Minnesota. Since Goodhue County is closer to the Transcontinental Arch than any other

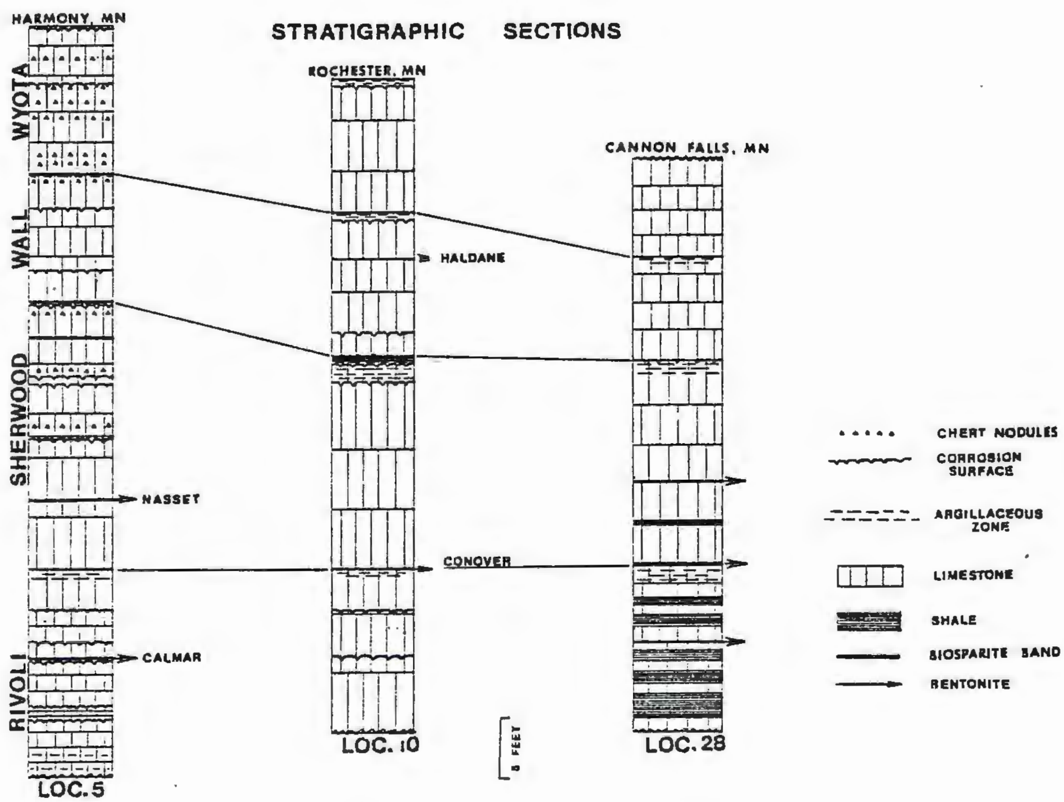

Figure 36— Correlation of three stratigraphic sections.

studied location, it would likely receive the most clay. The least amount of disseminated clay, as determined from insoluble residues (refer to Appendix B), within upper Dunleith strata occurs in southern Fillmore County, Minnesota and northern Iowa. Thus, it is unlikely the Wisconsin Arch was supplying detrital material during deposition of upper Dunleith strata, since localities in southern Fillmore County and northern Iowa contain little terrigenous material. These southern most localities are close to the possible position of the Wisconsin Arch, thus, the Wisconsin Arch was not contributing terrigenous material during deposition of upper Dunleith strata.

At Mantorville, Minnesota

The lithology of the upper Dunleith Formation is different at Mantorville, Minnesota (Dodge County) than at any other location in Minnesota. The upper Dunleith strata at Mantorville are completely dolomitized, to the extent that in thin section dolomite is an interlocking mosaic of large crystals (Figure 37). Fossils are rare in the section, not because of dolomitization, since those that are present such as *Receptaculites* and *Hormotoma* are readily distinguishable, but more probably due to variations in salinity.

The lack of stenohaline organisms, the abundance of gastropods and the complete dolomitization of the strata at Mantorville, Minnesota suggest hypersaline conditions existed during sedimentation. At Mantor-

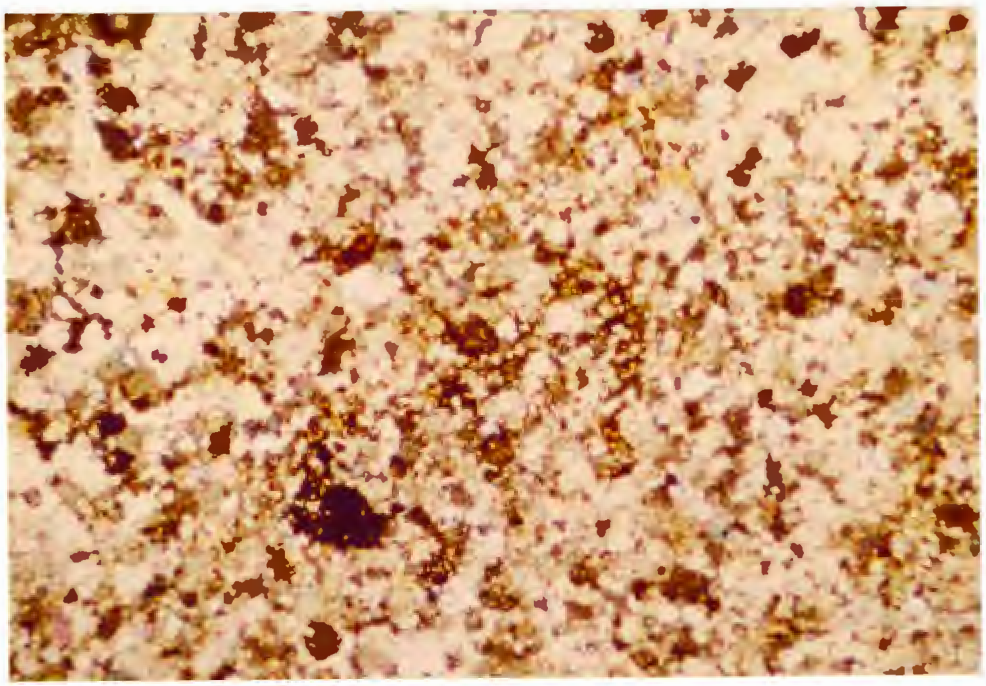

Figure 37-- Photomicrograph of Sherwood stratum at locality #22 Mantorville, Minnesota. Mineralogy is entirely composed of dolomite with traces of pyrite. Field of view is 1.0 mm. in size, crossed nicols.

ville, Minnesota, water circulation may have been restricted, allowing hypersaline conditions to possibly be developed as a result of evaporation and poor circulation.

Indirectly, hypersaline conditions may account for the later dolomitization of the strata at Mantorville, Minnesota. According to Pettijohn (1975) dolomite tends to be associated with evaporites which form in stagnant waters.

SUMMARY

After completion of this study of the upper Dunleith Formation (Prosser Member, Galena Formation), I suggest the following general conclusions:

1) The Rivoli, Sherwood, Wall and Wyota Members are useful subdivisions of the upper Dunleith Formation in southeastern Minnesota and can be recognized and precisely correlated by lithologic and biostratigraphic features if detailed stratigraphy is used.

2) The argillaceous content within upper Dunleith strata increases northwestward and westward towards the Transcontinental Arch. Thus the clastics supplied during deposition of upper Dunleith strata are likely derived from the Transcontinental Arch, as determined from insoluble residues.

3) The seas were transgressing slightly during deposition of upper Dunleith strata as evident by a diminishing of clastics upward in section to purer carbonate strata.

4) The depositional environment of the upper Dunleith Formation was one of quiet clear water of normal salinity, with water depths likely less than 80 feet, with a moderately hard to soft substrate which allowed attachment for various organisms. The salinity of the sea likely increased towards the Transcontinental Arch, possibly due to a decrease in water circulation.

The increase in salinity may be responsible for the dolomitization of the strata at Mantorville, Minnesota.

5) Variations in current activity occurred during sedimentation of upper Dunleith strata. Sparry calcarenite horizons composed of fossil fragments and abundant quartz grains indicate high current activity. The source of the quartz was likely the Transcontinental Arch.

6) Corrosion zones are useful features in correlating strata over large distances. These zones reflect major changes in sedimentation, causing variations in strata thickness within the members of the upper Dunleith Formation.

7) Chert nodules are likely replacement in origin and increases in numbers southeastward towards the mineral district.

8) Bentonite beds are excellent time stratigraphic features useful in correlating strata over large regions. The mineralogy of these horizons is different from that of shales and clays. The source area of the ash responsible for the bentonites, as determined from paleomagnetic data, was likely the Appalachian mobile belt.

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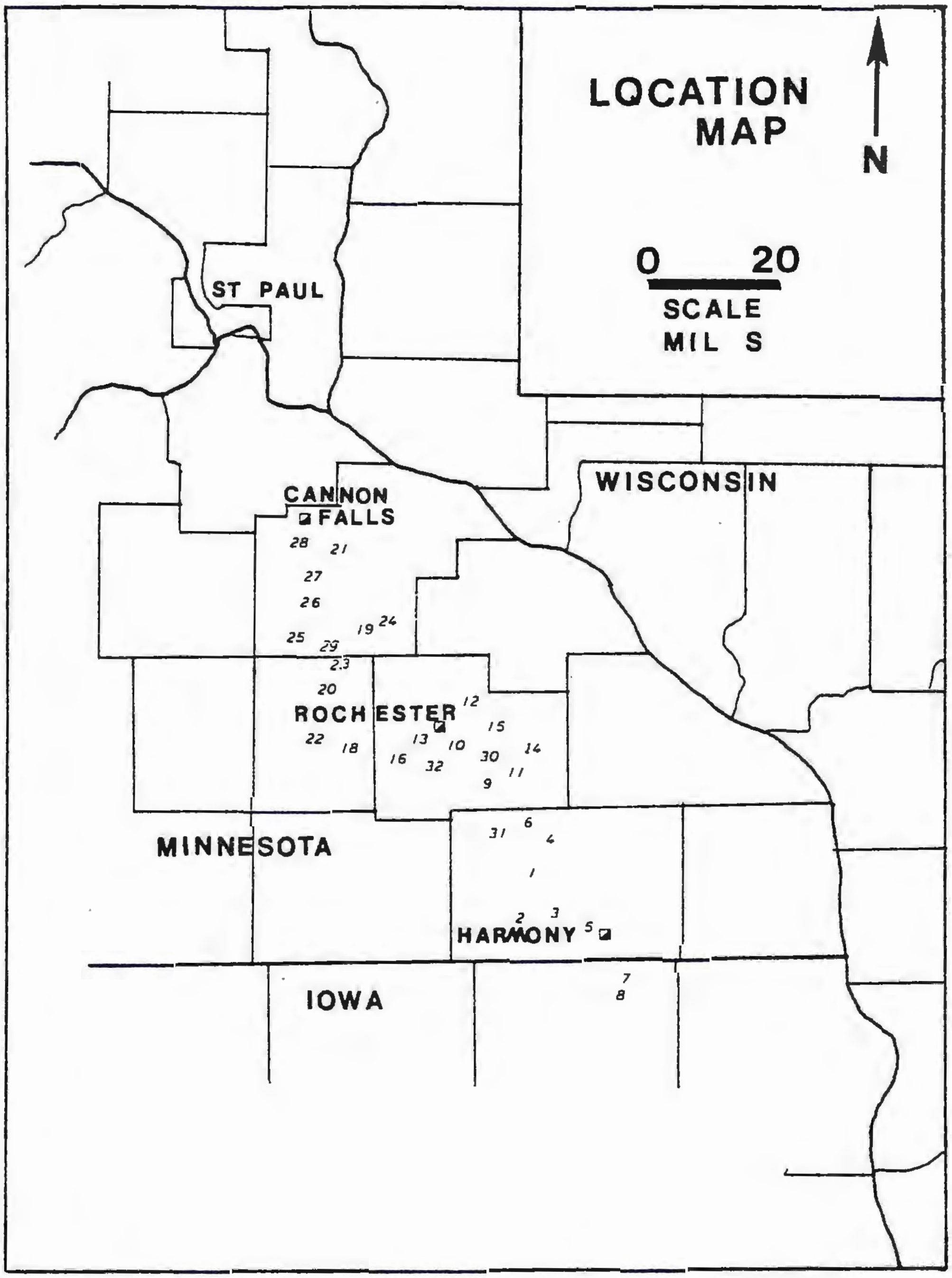
APPENDIX A

Outcrops, Descriptions and Locations



Map showing outcrop locations.

Location: #1 quarry 2 miles east and 1 mile south of Wykoff, Minnesota, NE¼, SW¼, sec. 25, T1 30N, R12W, Fillmore County.

<u>Thickness in feet</u>

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
68.5	17	Biomicrite, thin bedded, light brown, inaccessible.
51.5	3.1	Micrite, irregular weathering, mottled, interbedded thin shale partings.
		WALL MEMBER
48.5	8.7	Biomicrite, medium bedded, with lenses of coquinas one inch thick. Upper 3 feet very argillaceous, with interbedded thin shale horizons, chert nodules 12 inches up from unit base.
		SHERWOOD MEMBER
39.8	.5	Clay horizon.
39.3	4.3	Biomicrite, light tan, medium bedded, chert nodules, numerous crinoidal debris, <u>Hormotoma</u>, <u>Resserella</u>.
35.0	1.0	Biomicrite, pyritic stained, numerous corrosion surfaces.
34.0	.3	Clay horizon.
33.7	8.0	Biomicrite, tanish, thin bedded, chert nodules, thin sparry calc-arenite bands, burrowed, <u>Lingula</u>, <u>Ischadites iowensis</u>, <u>Maclurites</u>.
25.7	5.7	Biomicrite, medium bedded, arg-illaceous, crinoidal remains.
20.0	.5	Shale, green, platy, fissle.

Thickness in feet			
From base	Of unit		
		RIVOLI MEMBER	
19.5	7.0		Biomicrite, medium to thick bedded, upper 3 feet more argillaceous than remainder of unit, sparry calcarenite bands 1.5 inches thick 30, 60, and 80 inches from base of unit, *Rafinesquina*, *Ischadites iowensis*, *Sowerbyella*.
12.5	.2		Bentonite horizon, orange clay.
12.3	6.6		Micrite, thick bedded, numerous corrosion surfaces in middle of unit.
		MORTIMER MEMBER	
5.7	5.7		Biomicrite, light gray, thick bedded, argillaceous, lower 2 feet covered.

Location: #2 Rifle Hill quarry, 7 miles south of Wykoff, Minnesota, NE¼, NW¼, sec. 35, T102N. R12W, Fillmore County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
49.0	12.2	Biomicrite, mottled, buff colored, dolomitic, thick bedded, *Receptaculites oweni*, *Hormotoma*.
		Dunleith Formation WYOTA MEMBER
36.8	16.6	Biomicrite, light gray, thick bedded, chert nodules, numerous (9) corrosion zones 4 to 10 feet below unit top, sparry calcarenite bands 1" thick prominent in lower 5 feet of unit.
		WALL MEMBER
20.2	.2	Clay horizon-bentonite.
20.0	7.6	Micrite, non-cherty, thick bedded, light gray, silty bands approximately ½ inch thick throughout.
		SHERWOOD MEMBER
12.4	3.3	Biomicrite, light gray, thick bedded, silty top 1' argillaceous, prominent corrosion surface at top (pyritic), *Isotelus*, *Flexicalymene*.
9.1	2.4	Biomicrite, chert nodules, numerous corrosion zones.
6.7	.7	Biosparite, dark blue, crinoidal remains.
6.0	6.0	Biomicrite, thick bedded, with small lenses of coquinas ½ inch thick, bottom 3.5 feet covered.

Location: #3 Scheevel quarry, 3 miles north and 6 miles west of Harmony, Minnesota, SE$\frac{1}{4}$, NW$\frac{1}{4}$, sec. 2, T101N, R11W, Fillmore County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
66.8	10.0	Dolomite, thin bedded, vuggy, buff colored, fine grained, *Receptaculites oweni*.
		Dunleith Formation WYOTA MEMBER
56.8	10.0	Biomicrite, 3 inch thin crinkly beds with shale partings, buff colored, chert nodules 3 feet from unit base.
46.8	9.0	Biomicrite, medium bedded, light gray to buff colored, slightly argillaceous, chert nodules, burrowed.
		WALL MEMBER
37.8	.4	Clay horizon with flakes of bentonite.
37.4	1.0	Biomicrite, very argillaceous with intermingled shales, weathers recessive.
36.4	6.3	Biomicrite, medium bedded, light brown, cherty nodules, slightly mottled, and burrowed, thin lenses of coquinas.
30.1	.3	Shale, green, fissile, burrowed.
29.8	3.3	Micrite, medium bedded, light gray, small clasts of dark gray micrite 1 to 2 inches.
		SHERWOOD MEMBER
26.5	2.8	Biomicrite, cherty, argillaceous, weathering recessive, prominent corrosion surface (pyritized) at unit top.

Thickness in feet		
From base	Of unit	SHERWOOD MEMBER (continued)
23.7	5.7	Biomicrite, medium bedded, light gray, cherty, wavy bedding surfaces, numerous crinoidal debris, Ischadites iowensis, Receptaculites oweni, Sowerbyella.
18.0	10.0	Biomicrite, light gray, thin to medium bedded, argillaceous with thin lenses of shale, small ¼ inch bands of biosparite, chert nodules in lower 2 feet.
		RIVOLI MEMBER
8.0	1.0	Micrite, very argillaceous with shale intermixed, chert nodules, weathers recessive.
7.0	6.7	Biomicrite, light gray, medium to thin bedded, Atrypa, Rafinesquina.
.3	.3	Bentonite, orange clay (Calmar).

Location: #4 quarry ½ mile west of Fountain Minnesota, SW¼, sec. 3, T103N, R11W, Fillmore County

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
80	12	Biomicrite, thin bedded, buff colored, weathered, inaccessible.
		WALL MEMBER
68	13	Biomicrite, thin bedded, buff, top 2 feet of unit weathers recessive inaccessible.
		SHERWOOD MEMBER
55	7.3	Biomicrite, thick bedded, light brown to tan, irregularly fractured and weathered, abundant brachiopod and crinoidal debris, *Sowerbyella*, *Endoceras*.
47.7	4.0	Biomicrite, light gray, silt partings, crinoidal debris.
43.7	.3	Coquina, crinoid and gastropod remains, sparry cement, weathers recessive.
43.4	2	Biomicrite, pyrite concretions, small intraclasts of micrite.
41.1	6.1	Biomicrite, light gray, medium bedded, nodular texture, burrowed *Flexicalymene*, *Strophomena*, *Rafinesquina*, *Lingula*.
		RIVOLI MEMBER
35.0	1.0	Biomicrite, light brown, very argillaceous, weathers recessive, flakes of bentonite with intermixed clay.
34.0	6.0	Biomicrite, medium bedded, light gray, pyritic staining, *Ischadites iowensis*.

Thickness in feet			
From base	Of unit		RIVOLI MEMBER (continued)
28.0	.2		Clay horizon.
27.8	5.2		Biomicrite, light gray, numerous crinoidal debris, thin shale partings.
			MORTIMER MEMBER
22.6	.6		Shale, buff, fissile, burrowed, recessive.
15.7	3.0		Biomicrite, with thin shale interbeds, blue-green weathers recessive.
12.7	2.4		Micrite, argillaceous, numerous corrosion surfaces.
			FAIRPLAY MEMBER
10.3	1.6		Shale, green, fissile.
8.7	2.8		Biomicrite, blue-green, high detrital content, thin interbedded shales, burrowed, stylolites, bryozoan fragments, numerous corrosion surfaces.
5.9	4.0		Shale, light gray to green, platy, bentonite horizon 5 inches from unit top, Fairplay Bentonite.
1.9	1.9		Biomicrite, with interbedded shales, light gray, mottled chert nodules 6 inches from base.

Location: #5 Peterson quarry, $1\frac{1}{2}$ miles northwest of Harmony, Minnesota, NE$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 9, T101N, R10W, Fillmore County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
61.0	10	Dolomite, thin bedded buff mottled, inaccessible.
		Dunleith Formation WYOTA MEMBER
51.0	4.0	Biomicrite, light brown to buff, medium bedded, inaccessible.
47.0	8.0	Biomicrite, thick bedded, buff gray, argillaceous, numerous chert nodules, thin lenses of biosparite.
		WALL MEMBER
39.0	.2	Clay horizon, brown.
38.8	10.3	Biomicrite, dark gray, thick bedded, slightly argillaceous, upper 1 foot is cherty, oxidized corrosion surfaces.
		SHERWOOD MEMBER
28.5	5.4	Biomicrite, medium bedded, dark gray, chert nodules, thin interbedded lenses of biosparite, prominent corrosion surface at top unit, Receptaculites oweni, Pleurocystites.
23.1	3.7	Biomicrite, dark gray, numerous 1 inch horizons of biosparite, corrosion surfaces, branching fucoids.
19.4	.3	Biosparite, dark blue, quartzose well sorted.
19.1	3.6	Biomicrite, dark gray, chert nodules, glassy texture, numerous crinoidal debris.

Thickness in feet From base	Of unit	
		SHERWOOD MEMBER (continued)
15.5	3.0	Micrite, dense, dark to light gray, ½ inch coquinoid beds, small ¼ inch micrite intraclasts.
12.5	.1	Nasset Bentonite, yellow-orange clay.
12.4	6.4	Micrite, light gray, thick bedded.
		RIVOLI MEMBER
6.0	.7	Argillaceous micrite, light brown, recessive, 1 inch clay horizon at top.
5.3	5.3	Biomicrite, thick bedded light brown oxidized surface, Calmar Bentonite on quarry floor.

Location: #6 Bear Creek quarry, 5½ miles west of Chatfield, Minnesota, NW¼, SE¼, sec. 9 T104N, R12W, Fillmore County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
69.5	11.0	Dolomite, medium crinkled bedded, buff, fine grained, iron stained, vuggy, crinoidal, brachiopod and gastropod remains, *Receptaculites oweni*.
58.5	4.0	Dolomite, thin bedded mottled, buff, fine grained interbedded thin shale horizons, graptolites, cephalopod fragments.
		Dunleith Formation WYOTA MEMBER
54.5	1.7	Shale, red-green, platy contains 1 inch micrite clasts, burrowed.
52.8	12.5	Dolomite, fine grained, buff, thick bedded.
		WALL MEMBER
40.3	1.1	Biomicrite, light brown, platy, very argillaceous, weathers recessive.
39.2	5.0	Biomicrite, dark gray, nodular texture, thin sparry calcarinite bands, oxidized corrosion zones (3).
34.2	.2	Shale, green, platy.
34.0	2.7	Biomicrite, dark gray, thick bedded, chert nodules 19 inches up from unit base.
		SHERWOOD MEMBER
31.3	5.0	Biomicrite, thick bedded, light to dark gray, chert nodules, brachiopod fragments, *Sowerbyella*, *Strophomena*.

Thickness in feet

From base	Of unit	
		SHERWOOD MEMBER (continued)
26.3	7.0	Biomicrite, thick bedded, light gray, homogeneous throughout, abundant Sowerbyella.
19.3	.2	Nasset Bentonite, orange clay within green shales.
19.1	6.4	Biomicrite, very thick bedded, light gray, homogeneous, small thin sparry calcarenite bands. numerous Sowerbyella, Receptaculites oweni, Rafinesquina, Lingula.
12.7	.6	Biosparite, dark blue-gray, numerous brachiopod and crinoid remains.
		RIVOLI MEMBER
12.1	.2	Conover Bentonite, clay horizon.
11.9	6.0	Biomicrite, dark gray, medium bedded, thin shale partings weathering slightly recessive, thin lenses of sparry calcarenite bands.
5.9	.1	Calmar Bentonite, orange clay.
5.8	5.8	Micrite, dark gray, argillaceous, thin shales interbedded, iron stained, pitted surface, weathers recessive.

Location: #7 quarry, $1\frac{1}{2}$ miles north of Burr Oak, Iowa, SW$\frac{1}{4}$ sec. 14, R9W, Winneshiek County.

<u>Thickness in feet</u>

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
42.5	8.0	Dolomite, thin bedded, buff, inaccessible.
		Dunleith Formation WYOTA MEMBER
34.5	6.0	Biomicrite, thin crinkled beds, brown mottled, inaccessible.
28.5	5.0	Biomicrite, thin crinkled beds light brown, chert nodules calcite stained surface.
23.5	1.4	Biomicrite, very thin bedded, gray brown, recessive unit.
22.1	2.0	Micrite, light brown, chert nodules.
20.1	.7	Micrite, thin bedded, dark brown, very argillaceous, breaks in plates, recessive.
19.4	3.0	Micrite, nodular wavy thin bedding, yellow brown, chert nodules.
		WALL MEMBER
16.4	1.0	Micrite, very thin bedded, light brown, very argillaceous, weathers recessive, chert nodules.
15.4	2.7	Micrite, medium bedded (crinkled) yellow-brown iron stained, small $\frac{1}{2}$ inch micrite clasts.
12.7	.2	Clay horizon, yellow orange.
12.5	7.3	Biomicrite, thick bedded, light gray, prominent corrosion surface in middle of unit, chert nodule horizon in lower one foot, <u>Streptalasma</u>, <u>Hormotoma</u>.

<u>Thickness in feet</u>

From base	Of unit	SHERWOOD MEMBER
5.2	5.2	Biomicrite, thick bedded, light gray, numerous corrosion surfaces (5), prominent oxidized corrosion surface at unit top, numerous chert nodule horizons in lower 3 feet, abundant crinoidal debris in middle of unit, abundant *Ischadites iowensis*.

Location: #8 quarry, ¼ mile east of Burr Oak, Iowa, SW¼, sec. 23, T100N, R9W, Winneshiek County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation STEWARTVILLE MEMBER
42.8	5.0	Dolomite, thick bedded, buff, vuggy, inaccessible.
		SINSINAWA MEMBER
37.8	18.5	Dolomite, medium to thick bedded, buff, mottled, inaccessible.
19.3	11.5	Biomicrite, highly dolomitic, medium to thick bedded, dark gray to buff colored, numerous (8) corrosion surfaces throughout unit, abundant crinoids. *Hormotoma*.
		Dunleith Formation WYOTA MEMBER
7.8	7.8	Biomicrite, thick bedded, light gray, dense, numerous chert nodule horizons, top of unit prominent corrosion surface.

Location: #9 Fugle's Mill, 2 miles south of Simpson, Minnesota, SW¼, SE¼, sec. 17, T105N, R13W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
26.0	.6	Clay horizon, with shales, black green, burrowed.
25.4	1.1	Micrite, brown, very argillaceous, platy.
24.3	8.4	Biomicrite, medium to thick bedded, light to dark gray, silty nodular texture, small ½ inch micrite clasts in lower 2 feet of unit.
		WALL MEMBER
15.9	4.0	Biomicrite, thick bedded, light gray, wavy silt layer texture, thin ¼ inch sparry calcarenite bands.
11.9	.2	Shale, green-brown, very prominent horizon.
11.7	8.7	Biomicrite, medium to thick bedded, light gray, thin ¼ inch coquina horizons, numerous fragments of brachiopods and crinoids.
		SHERWOOD MEMBER
3.0	3.0	Biomicrite, thick bedded, white-brown to gray, thin interbedded shales.

Location: #10 Quave-Anderson quarry, 2 miles south of Rochester, Minnesota, SW¼, NE¼, sec. 35 T106N, R14W, Olmstead county.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
78.0	14	Dolomite, fine grained crinkly bedded, buff, vuggy, mottled, crinoidal, *Receptaculites*.
		Dunleith Formation WYOTA MEMBER
64.0	10.5	Biomicrite, medium bedded, yellow gray to buff, mottled, *Macurites*, *Hormotoma*, single *Receptaculites oweni*.
53.5	10.7	Biomicrite, (crinkled) thick bedded, yellow gray to buff, crinoidal, surface oxidized from pyrite staining.
		WALL MEMBER
42.8	4.8	Biomicrite, thick bedded, light gray, crinoidal, thin ¼ inch coquina bands, gastropod fragments, *Streptalasma*.
38.0	.3	Clay horizon, bentonite of Wall Member (Haldane).
37.7	7.0	Biomicrite, thick bedded light blue gray, slightly mottled, silty, corrosion zones lower 1 foot of unit.
		SHERWOOD MEMBER
30.7	2.0	Biomicrite, thin bedded, platy, light brown, very argillaceous to shaley, burrowed, prominent corrosion surface at top.
28.7	5.2	Biomicrite, very thick bedded, light gray, dense, thin lenses of biosparite, lower 1 foot slightly argillaceous, *Strophomena*, *Rafinesquina*.

Thickness in feet		
From base	Of unit	SHERWOOD MEMBER (continued)
23.5	.3	Clay horizon, prominent, Haldane Bentonite, orange colored.
23.2	9.5	Biomicrite, thick bedded to very thick bedded, light gray, fractured, thin ¼ inch bands of biosparite, Lingula, Vellamo.
		RIVOLI MEMBER
13.7	.1	Clay horizon, green-orange.
13.6	4.3	Biomicrite, thick bedded, dark gray, small ¼ inch micrite clasts, corrosion surfaces (3) lower 2 feet of member, Lingula.
9.3	9.3	Biomicrite, medium to thick bedded, dark gray, thin shale partings weathering recessive, wavy texture, iron stained surface from pyrite weathering, lower 5 feet covered.

Location: #11 quarry, 3 miles east and 1 mile north of Cummingsville, Minnesota, NE¼, SW¼, sec. 13, T105N, R13W, Olmstead County.

Thickness in feet

From base	Of units	Wise Lake Formation SINSINAWA MEMBER
70.3	6.6	Dolomite, thick bedded, buff to gray, fine grained, glassy texture, mottled, gastropods, horn corals.
		Dunleith Formation WYOTA MEMBER
63.7	11.2	Biomicrite, thick bedded to very thick bedded, buff to gray, silty, pitted, lower 2 feet shows nodular texture, pyrite concretions, Hormotoma.
		WALL MEMBER
52.5	5.2	Micrite, thick bedded, light brown, thin ¼ inch biosparite lenses, top 2 inches very argillaceous.
47.3	.5	Shale, blue, fissile, platy, flakes of bentonite (Haldane), orange colored.
46.8	8.0	Biomicrite, very thick bedded, light to dark blue, ¼ inch micrite clasts, abundant brachiopods and crinoidal debris, Strophomena, Sowerbyella.
		SHERWOOD MEMBER
38.8	.9	Biomicrite, same as above, horizon of numerous prominent (4) corrosion surfaces.
37.9	3.7	Biomicrite, same as above.
34.2	.3	Shale, blue, fissile, burrowed, surface fossil debris, crinoidal, Rafinesquina, Sowerbyella.
33.9	2.0	Biomicrite, dark blue.

Thickness in feet

From base	Of unit	
		SHERWOOD MEMBER (continued)
31.9	.2	Clay horizon, Nasset Bentonite.
31.7	10.5	Biomicrite, very thick bedded, light brown to gray, thin lenses of coquinas, much crinoidal debris.
		RIVOLI MEMBER
21.2	.3	Shale, blue, fissile, platy, burrowed, small $\frac{1}{4}$ inch micrite clasts.
20.9	6.6	Biomicrite, thick bedded, dark blue gray, wavy texture, high detrital content lower 2 feet.
14.3	.1	Clay horizon.
14.2	4.7	Biomicrite, thick bedded, dark blue, interbedded shales, silt partings, weathers recessive, very fractured.
		MORTIMER MEMBER
9.6	9.6	Shaley with intermixed micrite, dark blue, flaggy, recessive, nodular texture.

Location: #12 roadcut, 8 miles east of Rochester, Minnesota, SE¼, NE¼, sec. 25, T107N, R13W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation
		SHERWOOD MEMBER
31.5	4.7	Biomicrite, thin crinkly bedding, iron stained, thin sparry calcarenite bands.
		RIVOLI MEMBER
26.8	.2	Clay horizon, yellow orange, laminated.
26.6	6.0	Biomicrite, medium bedded, oxidized brown, silt partings.
20.6	.1	Clay horizon, orangish Calmar Bentonite.
20.5	6.7	Micrite, medium bedded, light brown to buff, silt partings.
		MORTIMER MEMBER
13.8	.8	Shale, blue green, recessive, fissile, burrowed, fossil fragments.
13.0	2.5	Micrite, light gray, nodular texture.
10.5	2.5	Shale, blue-gray, fissile, recessive.
8.0	.9	Micrite, light gray, with shale partings.
7.1	.7	Shale, blue-gray, fissile platy.
6.4	.7	Micrite, light gray, shale partings.

<u>Thickness in feet</u>

From base	Of unit	FAIRPLAY MEMBER
5.7	5.7	Shale, light blue gray, platy, fissile, mottled corrosion surfaces, more resistant to weathering than shales above, *Receptaculites oweni*.

Location: #13 quarry, $2\frac{1}{2}$ miles southwest of Rochester, Minnesota, SW$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 16, T106N, R14W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation WYOTA MEMBER
64.7	10	Biomicrite, thin bedded, crinkly, buff, mottled, inaccessible.
		WALL MEMBER
54.7	4.4	Biomicrite, medium bedded, yellow-light gray.
50.3	.3	Clay horizon, orange-green.
50.0	6.1	Biomicrite, thin crinkled beds, light gray, oxidized, silt partings, gastropod and brachiopod fragments.
		SHERWOOD MEMBER
43.9	1.0	Clay horizon top 2 inches, lower 11 inches argillaceous micrite, light yellow, recessive.
42.9	8.4	Biomicrite, thick bedded, light gray, small $\frac{1}{4}$ inch micrite clasts in lower 1 foot, corrosion zones (3) upper 1 foot of unit.
34.5	.3	Biosparite, oxidized, brown, graded bedding.
34.2	2.5	Biomicrite, thick bedded, light gray.
31.7	.1	Clay horizon, gray.
31.6	.4	Biosparite band, dark blue-gray.
31.2	5.0	Micrite, thick bedded, wavy bedding plane, light gray.

Thickness in feet		
From base	Of unit	RIVOLI MEMBER
26.2	.3	Clay horizon, gray with orange flakes, iron stained bentonite (Conover).
25.9	.4	Micrite, very argillaceous, light brown.
25.5	5.8	Biomicrite, very thick bedded, light gray, dense.
19.7	.1	Clay horizon, gray.
19.6	6.8	Biomicrite, thick bedded, light gray, high shale content, thin ½ inch sparry calcarenite bands, numerous brachiopod fragments, Rafinesquina.
		MORTIMER MEMBER
12.8	.5	Shale, green, platy, recessive.
12.3	6.0	Biomicrite, medium to thick bedded with 1 to 2 inch interbedded shale horizons, blue-gray colored, shales weather recessive, numerous corrosion surfaces (4).
6.3	6.3	Shale, blue-gray, brittle, fissile, platy, small horizons of more resistant micrite with high clastic content.

Location: #14 quarry, 3½ miles south of Eyota, Minnesota, NW¼, NE¼, sec. 2, T105N, R12W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
54.0	4.3	Micrite, thin bedded, crinkly, buff, inaccessible.
		WALL MEMBER
49.7	9.4	Biomicrite, medium bedded, buff to gray, inaccessible.
		SHERWOOD MEMBER
40.3	6.1	Biomicrite, medium bedded, light gray, inaccessible.
34.2	7.8	Biomicrite, thin to medium crinkled beds, brownish gray, small ½ inch micrite intraclasts crinoidal debris.
26.4	.1	Clay horizon, yellow-brown.
26.3	2.3	Biomicrite, thick bedded, nodular texture, brachiopod and crinoidal debris, thin ¼ inch coquina lenses.
24.0	.1	Clay horizon, yellow white.
23.9	2.3	Biomicrite, light gray, thin ½ inch sparry calcarenite bands.
		RIVOLI MEMBER
21.6	.6	Argillaceous micrite, light brown, recessive, platy.
21.0	1.4	Micrite, light gray, dense, oxidized weathered surfaces.
19.6	3.3	Micrite, medium bedded, light to dark gray, interbedded shale partings, nodular texture, 1 inch micrite intraclasts.

<u>Thickness in feet</u>

From base	Of unit	RIVOLI MEMBER (continued)
16.3	.5	Shale, blue gray, fissile, platy, burrowed.
15.8	2.1	Biomicrite, medium bedded, dark gray, silty partings.
13.7	.1	Clay horizon, gray.
13.6	2.7	Biomicrite, thick bedded, dark gray, numerous shale partings lower 1 foot weathers recessive.
		MORTIMER MEMBER
10.9	.4	Clay horizon, yellow green, iron stains.
10.5	3.1	Micrite, thick bedded, dark gray, high shale content.
7.4	.4	Shale, blue gray, fissile, platy.
7.0	6.0	Micrite, thick bedded, dark gray, high shale content, weathers recessive, numerous prominent corrosion surfaces (4), lower one foot mottled.
		FAIRPLAY MEMBER
1.0	1.0	Shale, blue gray, platy, fissile, recessive.

Location: #15 Patterson quarry, 9 miles east of Rochester, Minnesota, SW¼, NE¼, sec. 8, T106N, R12W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation SHERWOOD MEMBER
30.1	5.2	Micrite, thin crinkled beds, yellow brown, pitted, vuggy surface, badly weathered.
24.9	.3	Shale, oxidized.
24.6	.8	Micrite, as above.
23.8	.5	Shale, oxidized.
23.3	4.0	Biomicrite, thin crinkled beds, light brown, abundant crinoidal debris, thin 1 inch coquina beds.
		RIVOLI MEMBER
19.3	.8	Argillaceous micrite, thin bedded, light brown, platy, thin interbedded clay horizons.
18.5	1.0	Micrite, yellow brown.
17.5	.3	Clay horizon, yellow-orange.
17.2	2.1	Biomicrite, thin to medium bedded, nodular texture, light brown, 1¼ inch coquina bands.
15.1	.2	Clay horizon, laminated, Calmar Bentonite?, prominent horizon.
14.9	8.8	Biomicrite, thick bedded, light brown, high detrital content, crinoidal debris, brachiopods, *Sowerbyella*, *Rafinesquina*.
6.1	2.0	Biomicrite, light to dark gray, interbedded shales, wavy texture, ½ inch micrite intraclasts.

Thickness in feet		
From base	Of unit	MORTIMER MEMBER
4.1	4.1	Biomicrite with interbedded shales, medium bedded, platy, corrosion surfaces in lower 2 feet.

Location: #16 Rock Dell quarry, 1 mile east of Rock Dell, Minnesota, NE¼, NW¼, sec. 9, T105N R15W, Olmstead County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
59.0	20	Dolomite, thick bedded, buff, mottled, vuggy, abundant Receptaculites oweni, inaccessible.
		Dunleith Formation WYOTA MEMBER
39.0	8.6	Dolomite, fine grained, thick bedded, buff to gray, top 3 feet argillaceous, brachiopods, Sowerbyella, Resserella.
30.4	5.5	Biomicrite, highly dolomitic, thick bedded, buff to gray, iron stained, Receptaculites oweni.
		WALL MEMBER
24.9	9.2	Biomicrite, thick bedded (more so than above), light gray, ½ inch iron concretions, dense thin ½ inch sparry calcarenite bands, Receptaculites oweni.
		SHERWOOD MEMBER
15.7	.5	Argillaceous micrite, light brown.
15.2	4.2	Biomicrite, thick bedded, light gray, dense, burrowed, gastropods horn coral, Streptalasma.
11.0	.3	Clay horizon, blue gray.
10.7	4.0	Biomicrite, same as above, Ischadites iowensis.
6.7	.2	Clay layer, yellow orange, Haldane Bentonite?
6.5	6.5	Biomicrite, very thick bedded, light gray, Sowerbyella, Rafinesquina, Receptaculites oweni.

Location: #18 quarry, 2½ miles east of Mantorville, Minnesota, SW¼, NW¼, sec. 23, T107N, R16W, Dodge County.

Thickness in feet

From base	Of unit	Dunleith Formation SHERWOOD MEMBER
21	21	Dolomite, medium to thin bedded, fine grained, flaggy, buff, iron stained, strata uniform, differentiation of member by presence of brachiopods, Rafinesquina, and Ischadites iowensis.

Location: #19 quarry, 6 miles southwest of Zumbrota, Minnesota, NW¼, SW¼, sec. 29, T109N, R16W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
34.0	11.3	Dolomite, fine grained, medium bedded, buff, iron stained.
		WALL MEMBER
22.7	6.8	Biomicrite, medium bedded, buff to gray, small ½ inch intraclasts.
15.9	2.8	Biomicrite, thick bedded, light gray, dense, small ½ inch sparry calcarenite bands, brachiopods, *Lingula*.
		SHERWOOD MEMBER
13.1	3.1	Biomicrite, thick bedded, top 8 inches very argillaceous, light gray, pyrite concretions numerous.
10.0	5.2	Biomicrite, thick bedded, light gray, pyrite concretions, corrosion surfaces not pyrite stained.
4.8	.4	Clay horizon, gray brown.
4.4	4.4	Biomicrite, medium bedded, dark gray to blue, large detrital composition, thin shale partings, brachiopods, *Sowerbyella Lepidocyclus*.

Location #20 Granger quarry, ½ mile northeast of Concord, Minnesota, SE¼, SE¼, sec. 14, T108N, R17W, Dodge County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
30.1	11.9	Dolomitic micrite, thick bedded buff to gray, mottled, inaccessible.
		WALL MEMBER
18.2	7.9	Micrite, thick bedded, gray to buff, lower 2 feet iron stained.
		SHERWOOD MEMBER
10.3	.1	Clay horizon, gray.
10.2	4.6	Biomicrite, medium to thick bedded, slightly argillaceous, light gray, corrosion surfaces (2), thin ½ inch coquina lenses, crinoidal debris, brachiopod fragments, *Receptaculites oweni*.
5.6	.2	Clay horizon, orange-yellow, bentonite?
5.4	5.4	Biomicrite, thick bedded, light to dark gray, dense, 1 inch micrite intraclasts, corrosion surfaces (3), specimen *Hormotoma*.

Location: #21 quarry, 7 miles southeast of Cannon Falls, Minnesota, SW$\frac{1}{4}$, SW$\frac{1}{4}$, sec. 14, T111N, R17W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYCTA MEMBER
34.3	4.6	Biomicrite, thin crinkled beds, light yellow, iron stained, burrowed.
		WALL MEMBER
29.7	.1	Shale, blue gray.
29.6	6.8	Micrite, thin to medium bedded, light yellow, thin sparry calcarenite bands.
		SHERWOOD MEMBER
22.8	.9	Argillaceous micrite, light brown to white, weathers recessive.
21.9	3.9	Biomicrite, medium to thick bedded, light gray, dense, *Sowerbyella*.
18.0	2.0	Biomicrite, as above, corrosion surfaces (3), pyritized.
16.0	6.6	Biomicrite, thick bedded, light gray, small coquina beds $\frac{1}{2}$ inch, *Rafinesquina*, *Receptaculites oweni*.
9.4	.1	Clay horizon, gray.
9.3	3.5	Micrite, thick bedded, light gray, pyrite concretions, lower 1 foot contains shale partings.

Thickness in feet

From base	Of unit	RIVOLI MEMBER
5.8	.4	Shale, dark blue gray, fissile orange bentonite flakes (Conover Bentonite), prominant horizon, corrosion surface at base of unit.
5.4	5.4	Biomicrite, thick bedded, dark gray, wavy texture, high shale content, argillaceous, burrowed.

Location: #22 Stussy's quarry, 3/4 mile southwest of Mantorville, Minnesota, SW¼, SW¼ sec. 21, T107N, R16W, Dodge County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
71.2	11.2	Dolomite, fine grained, thick bedded, buff.
		Dunleith Formation WYOTA MEMBER
60.0	.9	Argillaceous dolomite, light brown, recessive.
59.1	7.6	Dolomite, medium grained, thick bedded, buff, pyrite concretions lower 2 feet.
51.5	.5	Clay horizon, orange, prominent bentonite?
51.0	3.4	Dolomite, medium grained, thick bedded, buff.
		WALL MEMBER
47.6	8.6	Dolomite, medium grained, very thick bedded, buff to gray, lower 1 foot burrowed, corrosion surface 2 feet from base.
		SHERWOOD MEMBER
39.0	.5	Argillaceous micrite with interbedded clay horizons, light brown, recessive.
38.5	5.2	Dolomite, medium grained, very thick bedded, light gray to buff, mottled, burrowed, recrystallized brachiopods, <u>Resserella</u>.
33.3	.3	Clay horizon, orange yellow.
32.0	4.0	Dolomite, as above, vuggy, <u>Receptaculites oweni</u>, <u>Ischadites iowensis</u>.
28.0	.1	Clay horizon, orange, Nasset Bentonite.

Thickness in feet		
From base	Of unit	SHERWOOD MEMBER (continued)
27.9	6.7	Dolomite, medium grained, light gray to buff, mottled, vuggy.
		RIVOLI MEMBER
21.2	.1	Clay horizon, orange, Conover Bentonite.
21.1	13.6	Dolomite, medium grained, medium bedded, dark gray, thin shale partings, wavy texture, possible current activity, slump structures, mottled, pyrite concretions, burrowed, abundant *Sowerbyella*, *Strophomena*, specimen *Receptaculites oweni*.
		MORTIMER MEMBER
7.5	.2	Shale, dark gray, fissile burrowed.
7.2	7.2	Dolomite, medium grained, thick bedded, dark gray, wavy texture, mottled, numerous (4) corrosion surfaces, pyrite concretions.

Location: #24 quarry, 2 miles east of Roscoe, Minnesota, NW¼, sec. 28, T109N, R16W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WALL MEMBER
38.5	10.8	Biomicrite, thin to medium bedded, buff to gray, thin ½ inch coquina horizons, crinoid debris lower 2 feet, _Receptaculites oweni_, _Ischadites iowensis_.
		SHERWOOD MEMBER
27.7	8.2	Biomicrite, thin to medium bedded, light brown, top 6 inches of unit argillaceous, crinoidal debris upper 2 feet, burrowed, top 1 foot iron stained, specimen _Endoceris_, _Hormotoma_.
19.5	.1	Clay horizon, gray.
19.4	2.6	Biomicrite, as above.
16.8	.5	Shale, yellow green, with flakes of bentonite (Nasset Bentonite), vegetation.
16.3	5.8	Biomicrite, thick bedded, light gray, thin shale partings, high silt content, thin ½ inch lenses of biosparite.
		RIVOLI MEMBER
10.5	.5	Shale, blue gray, bentonite flakes (Conover Bentonite).
10.0	5.3	Biomicrite, dark gray, thick bedded, nodular texture, thin ½ inch shale horizons, crinoidal debris.
4.7	.1	Clay horizon, orange Calmar Bentonite.
4.6	4.6	Biomicrite, medium to thick bedded, dark gray, high shale content, argillaceous, weathers recessive, nodular texture.

Location: #25 roadcut, 3 miles south of Kenyon, Minnesota, SW$\frac{1}{4}$, NE$\frac{1}{4}$, sec. 8, T109N, R18W, Goodhue County.

<u>Thickness in feet</u>

From base	Of unit	Dunleith Formation SHERWOOD MEMBER
11.5	4.3	Micrite, thin to medium bedded, brown.
7.2	.1	Clay horizon, gray.
7.1	7.1	Biomicrite, medium to thick bedded, light brown, nodular texture, lower 4 feet argillaceous.

Location: #26 quarry, 8 miles northeast of Kenyon, Minnesota, E½, sec. 6, T110N, R17W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation SHERWOOD MEMBER
22.9	9.0	Micrite, thin crinkled beds, buff to gray, iron stained, fractured, weathered, inaccessible.
13.9	.1	Clay horizon, yellow green.
13.8	6.3	Biomicrite, thick bedded, light gray, silty partings, small calcite concretions?
		RIVOLI MEMBER
7.5	.6	Shale, blue, platy, fissile, flakes of bentonite (Conover Bentonite), graptolites, burrowed.
6.9	6.9	Micrite, medium bedded, dark blue, ½ to 3/4 inch shale horizons, weathers recessive, mottled, shales are burrowed, pyrite stained.

Location: #27 quarry, 3 miles south of Hader, Minnesota, W½, sec. 8, T110N, R17W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
38.7	10.3	Micrite, medium bedded, buff to gray, mottled, inaccessible.
		WALL MEMBER
28.4	1.0	Argillaceous micrite, light brown, recessive, inaccesible.
27.4	9.0	Biomicrite, medium bedded, light brown, numerous (6) coquina lenses, *Ischadites iowensis*.
		SHERWOOD MEMBER
18.4	5.4	Biomicrite, thick bedded, light gray, dense, pyrite concretions, top 1 foot burrowed.
13.0	.3	Argillaceous micrite, light brown, burrowed, interbedded clay horizon.
12.7	5.7	Biomicrite, thick bedded, light gray, lower 2 feet with thin shale partings, *Receptaculites oweni*.
7.0	.1	Clay horizon, orange, Nasset Bentonite.
6.9	6.3	Biomicrite, thick bedded, light to dark gray.
		RIVOLI MEMBER
.6	.6	Shale, blue gray, fissile, platy, floor of quarry.

Location: #28 roadcut, on east bank of U.S. Highway 52, 5 miles south of Cannon Falls, Minnesota, NW¼, sect. 8, T111N, R17W, Goodhue County.

<u>Thickness in feet</u>

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
34.0	7.4	Biomicrite, medium bedded, buff, mottled, badly weathered.
		WALL MEMBER
26.6	8.8	Biomicrite, medium to thick bedded, buff, top 1 foot very argillaceous, lower 2 feet has 1 inch sparry calcarenite bands (2), specimen <u>Receptaculites oweni</u>, <u>Prasopora</u>.
		SHERWOOD MEMBER
17.8	.9	Argillaceous micrite, light brown, recessive prominent horizon.
16.9	9.8	Biomicrite, thick bedded, light gray, top 2 feet numerous crinoidal debris, pyrite concretions, lower 2 feet has thin shale partings, <u>Ischadites iowensis</u>, <u>Receptaculites oweni</u>, <u>Sowerbyella</u>, <u>Resserella</u>, <u>Streptalasma</u>, <u>Prasopora</u>.
7.1	.1	Clay horizon, bentonite (Nasset).
7.0	6.5	Biomicrite, thick bedded, dark to light gray, wavy texture, thin 1 inch shale horizons, lower 2 feet weathers recessive.
		RIVOLI MEMBER
.5	.5	Shale, blue gray, fissile, prominent horizon, flakes of bentonite (Conover).

Location: quarry approximately 2 miles west of location #28, continuation of Rivoli Member from shale horizon.

Thickness in feet

From base	Of unit	Dunleith Formation RIVOLI MEMBER
6.0	.5	Shale, same horizon as above, Conover Bentonite.
5.5	5.5	Biomicrite, medium to thick bedded, dark gray, high shale content, weathers recessive.

Location: #29 quarry, 4 miles southwest of Roscoe, Minnesota, SW¼, SE¼, sec. 34, T109N, R17W, Goodhue County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
23.9	9.8	Dolomite, fine grained, medium to thick bedded, buff, vuggy.
		WALL MEMBER
14.1	.1	Clay horizon, gray.
14.0	1.0	Argillaceous dolomite, buff, recessive.
13.0	4.9	Biomicrite, slightly dolomitic, medium to thick bedded, light brown to blue gray, burrowed, graptolites on thin shale horizons.
		SHERWOOD MEMBER
8.1	8.1	Micrite, slightly dolomite, medium to thick bedded, thin 1 inch burrowed shale horizons in lower 3 feet.

Location: #30 roadcut on Interstate 90, 2 miles northeast of Simpson, Minnesota, SW$\frac{1}{4}$, SE$\frac{1}{4}$, sec. 27, T106N, R13W, Olmstead County.

Thickness in feet

From base	Of unit	Dunleith Formation
		SHERWOOD MEMBER
36.1	8.6	Biomicrite, medium bedded, light brown, badly weathered
27.5	.1	Clay horizon, gray vegetation, bentonite (Conover)
27.4	2.4	Biomicrite, light brown, slightly mottled.
		RIVOLI MEMBER
25.0	.2	Clay horizon, brown gray, oxidized, very prominent.
24.8	3.2	Biomicrite, thick bedded, dark blue, crinoidal debris.
21.6	.1	Clay horizon, orange yellow.
21.5	4.8	Micrite, medium bedded, dark gray, mottled, thin shale horizons in lower 2 feet.
16.7	.3	Shale, clay, gray.
16.4	3.2	Micrite, thin bedded, dark blue, platy, high detrital content.
		MORTIMER MEMBER
13.2	.5	Shale, blue gray, burrowed.
12.7	.8	Micrite, dark blue.
11.9	1.3	Shale, blue, fissile, platy, burrowed.
10.6	1.1	Micrite, dark blue, high shale content, weathers recessive, corrosion surfaces (2).
9.5	.1	Clay horizon, gray.

Thickness in feet		
From base	Of unit	MORTIMER MEMBER (continued)
9.4	2.1	Shale, dark blue, platy, burrowed, prominent corrosion surfaces (3).
7.3	2.4	Micrite, dark blue, high detrital content, shaley, burrowed, corrosion zones (3).
		FAIRPLAY MEMBER
4.9	2.9	Shale, blue, platy, burrowed.
2.0	2.0	Micrite, dark blue, shaley, burrowed, prominent mottling, vuggy, *Receptaculites oweni*.

Location: #31 Albrecht's Ravine roadcut, 5 miles north of Wykoff, Minnesota, NE¼, NE¼, sec. 5, T103N, R12W, Fillmore County.

Thickness in feet

From base	Of unit	Dunleith Formation
		WYOTA MEMBER
57.0	12.0	Micrite, thick bedded, buff badly weathered.
		WALL MEMBER
45.0	2.0	Micrite, thick bedded, buff, badly weathered, prominent corrosion zone at unit top.
43.0	.1	Clay horizon, orange yellow.
42.9	4.3	Micrite, as above, badly weathered.
		SHERWOOD MEMBER
38.6	2.3	Biomicrite, thick bedded, light gray, prominent corrosion zone at unit top, weathered.
36.3	10.8	Biomicrite, thick bedded, light gray, chert nodules in horizons, corrosion zones (2), abundant brachiopods and trilobite fragments, *Sowerbyella*, *Rafinesquina*, *Isotelus*, old exposure weathered.
25.5	6.2	Biomicrite, medium bedded, buff to gray.
		RIVOLI MEMBER
19.3	.2	Clay horizon, gray, prominent.
19.1	13.1	Micrite, medium bedded, brown, badly weathered, lower 2 feet argillaceous.
		MORTIMER MEMBER
6.0	6.0	Micrite, with interbedded shales, medium bedded, buff to brown, recessive, bad exposure.

Location: #32 quarry, ½ mile north of Rochester Airport, Minnesota, NW¼, SW¼, sec. 4, T105N, R14W, Olmstead County.

Thickness in feet

From base	Of unit	
		Wise Lake Formation SINSINAWA MEMBER
44.7	3.3	Dolomite, fine grained, thin crinkled beds, (dark) buff, vuggy, mottled, Hormotoma, Receptaculites oweni, specimen Lambeophyllum.
		Dunleith Formation WYOTA MEMBER
41.4	11.0	Micrite, slightly dolomitic, medium bedded, light brown, mottled, inaccessible.
		WALL MEMBER
30.4	5.0	Micrite, medium to thick bedded, light gray to buff, inaccessible.
25.4	4.4	Biomicrite, thick bedded, light gray, small thin ½ inch coquina beds.
		SHERWOOD MEMBER
21.0	1.0	Argillaceous micrite, light brown, prominent horizon, recessive.
20.0	7.2	Biomicrite, thick bedded, light to dark gray, pyrite concretions, stylolites, abundant brachiopod fragments, Resserella, abundant Receptaculites oweni, Hormotoma.
12.8	7.8	Biomicrite, medium to thick bedded, dark gray, numerous (6) ½ to 1 inch coquina beds, thin ½ inch shale horizons lower 4 feet, burrowed, Atrypa, Sowerbyella, Lingula, Receptaculites oweni.
		RIVOLI MEMBER?
5.0	5.0	Covered interval, which is recessive from weathering of shales.

APPENDIX B

Insoluble Residues

INSOLUBLE RESIDUES

Location	Member	% Insoluble
Harmony #5	Rivoli	6%
Harmony #5	Sherwood	5%
Harmony #5	Wall	4%
Harmony #5	Wyota	4%
Rochester #10	Rivoli	8%
Rochester #10	Sherwood	6%
Rochester #10	Wall	7%
Rochester #10	Wyota	6%
Cannon Falls #28	Rivoli	16%
Cannon Falls #28	Sherwood	9%
Cannon Falls #28	Wall	7%
Cannon Falls #28	Wyota	7%
Eyota #14	Rivoli	10%
Eyota #14	Sherwood	6%
Eyota #14	Wall	6%
Rock Dell #16	Sherwood	6%
Rock Dell #16	Wall	7%
Rock Dell #16	Wyota	6%

APPENDIX C

Conodonts

CONODONTS

Identification	Amount	Location	Member
Panderodus sp.	6	#22	Sinsinawa
Scolopodus sp.	3	#22	Wyota (top)
Paroistodus sp.	5	#19	Wyota (top)
Paltodus sp.	3	#9	Sinsinawa
Oistodus sp.	6	#32	Wyota
Dislacudonlidae	2	#32	Wyota (top)
Drepanodus sp.	5	#32	Sinsinawa
Acontiodus sp.	3	#5	Sherwood
Pravagrathus sp.	3	#16	Wyota (top)