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SUBSURFACE STRATIGRAPHIC RELATIONSHIPS OF THE UPPER SILURIAN AND DEVONIAN ROCK OF MILWAUKEE COUNTY, WISCONSIN

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ABSTRACT

The lithology, distribution, and stratigraphic relationships of Upper Silurian and Devonian strata in Milwaukee County, Wisconsin, have been clarified by new subsurface data. The contact between Silurian nonreef Racine Dolomite, deposited under normal-marine conditions, and the overlying Silurian Waubakee Dolomite, deposited in a hypersaline supratidal environment, is gradational. A prominent unconformity marks the contact between the Waubakee Dolomite and the overlying Middle Devonian Thiensville Formation. Some Racine Dolomite reefs project through the Waubakee Dolomite to the unconformity at the base of the Thiensville Formation. Partial contemporaneity of reef development and Waubakee Dolomite deposition cannot be discounted at this time; however, limited evidence suggests that reef development ceased prior to Waubakee Dolomite deposition. Devonian strata drape over the tops of the reefs, exhibiting no change in thickness or lithology. The Thiensville Formation was deposited under arid, hypersaline conditions, probably in a coastal sabkha environment. A return to normal-marine conditions took place during deposition of the Middle Devonian Milwaukee Formation. Present distribution of some Devonian strata is controlled by a syncline in the northeastern part of the county.

INTRODUCTION

Upper Silurian and Devonian strata in eastern Milwaukee and Ozaukee Counties constitute the youngest Paleozoic rock in Wisconsin and the westernmost occurrence of that age strata in the Michigan Basin. Presence of the rock first was reported by Lapham in 1851, but because the rock is poorly exposed only a general understanding of stratigraphy and distribution was possible. It was not until Raasch's (1935) Devonian study that any significant use of subsurface data, then limited to water-well logs, was made. Examination of new cores drilled by the Milwaukee Metropolitan Sewerage District has greatly improved our knowledge of bedrock geology in Milwaukee County. The appendix of the geologic logs is published separately (Mikulic and Kluessendorf, 1988) as Wisconsin Geological and Natural History Survey Open-file Report WOFR 88-1.

This paper describes the general lithology, distribution, and stratigraphic relationships of the Upper Silurian and Devonian strata in the northern half of Milwaukee County. We logged these cores independently of the work being conducted by the Milwaukee Metropolitan Sewerage District, and our stratigraphic determinations may differ from theirs. More detailed studies of the stratigraphy, petrology, and paleontology of the Devonian and Silurian rock of Milwaukee and surrounding counties are in progress.

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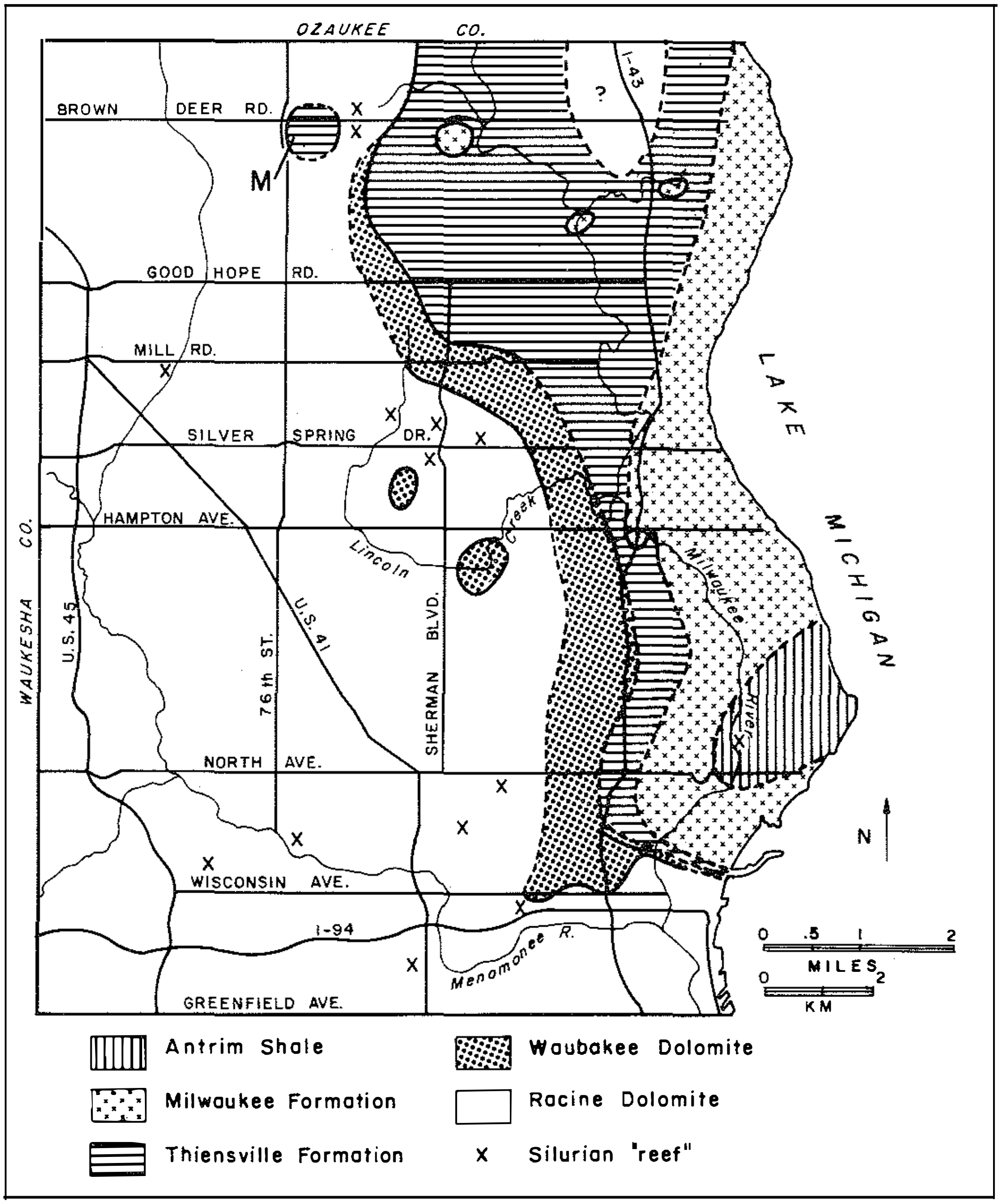

Figure 1. Bedrock geology map of the northern half of Milwaukee County, Wisconsin. M-small outlier of Milwaukee Formation (I, fig. 8) described by Chamberlin (1877) and Raasch (1925, unpublished fieldnotes).

BEDROCK SURFACE

Silurian Racine Dolomite forms the bedrock surface throughout most of Milwaukee County except in the northeastern quarter of the county where it is overlain by the Silurian Waubakee Dolomite and Devonian strata (fig. 1).

Although a thick cover of Quaternary sediments, ranging from 0 to 73 m and averaging 33 m in thickness, masks most of the bedrock surface, subsurface information discloses several important features. Most prominent of these is the 46 to 73 m deep bedrock valley, first noted by Foley, and others (1953), that underlies the present-day Menomonee River valley. Although this bedrock valley may control the course of the Menomonee River at this location, most other surface features, including the Milwaukee River, apparently are unrelated to bedrock topography.

Rock crops out primarily where stream erosion has uncovered the tops of buried bedrock hills. In the southern and western parts of the county these bedrock hills commonly consist of erosionally-resistant Racine Dolomite reefs. In the northeastern part of the county less resistant Devonian rock form several buried bedrock hills with as much as 15 m of relief.

STRATIGRAPHY

The general stratigraphic succession of the Silurian and Devonian strata in Milwaukee County is presented in figure 2. Pre-Racine Dolomite Silurian strata are similar to that in surrounding counties (Mikulic, 1977, 1979) and will not be discussed here.

Racine Dolomite

The Racine Dolomite, which forms the bedrock surface throughout much of Milwaukee County, is Late Silurian (Wenlockian-Ludlovian) (Berry and Boucot, 1970) in age. Generally the Racine Dolomite is about 52 m thick, but locally, where reefs are present, the unit is as much as 87 m thick. Contact with the underlying dense, cherty Waukesha Dolomite is sharp but conformable. The Racine Dolomite probably was deposited under predominantly subtidal, normal-marine conditions.

The basal 2 to 3 m of the Racine Dolomite is massive- to thick-bedded, porous, slightly vuggy, stylolitic, crystalline, pelmatozoan-rich, light- to dark-gray dolomite. These strata are overlain by 6 m of well-bedded, thin- to thick-bedded, less porous and less crystalline dolomite that is cherty in places. Most of the remaining nonreef Racine Dolomite is well-bedded, nonporous, even-textured, finely crystalline, slightly argillaceous, light olive-gray dolomite. Thin

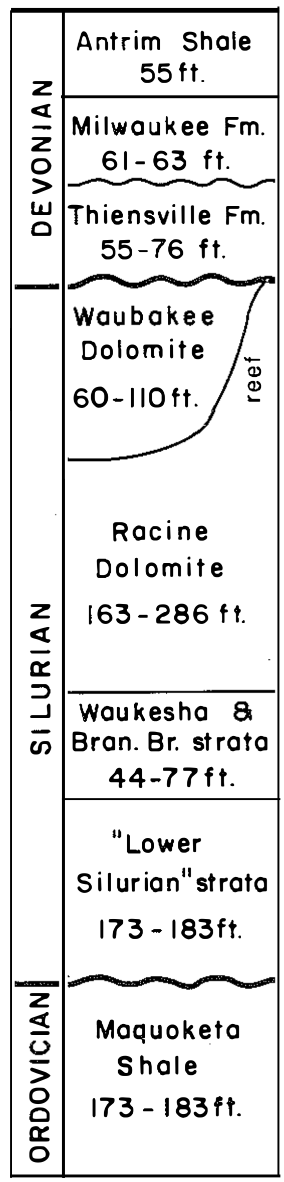

Figure 2. Generalized stratigraphic column for the Devonian, Silurian and Upper Ordovician strata in Milwaukee County, Wisconsin, showing relationship between the Waubakee Dolomite and Racine Dolomite reef.

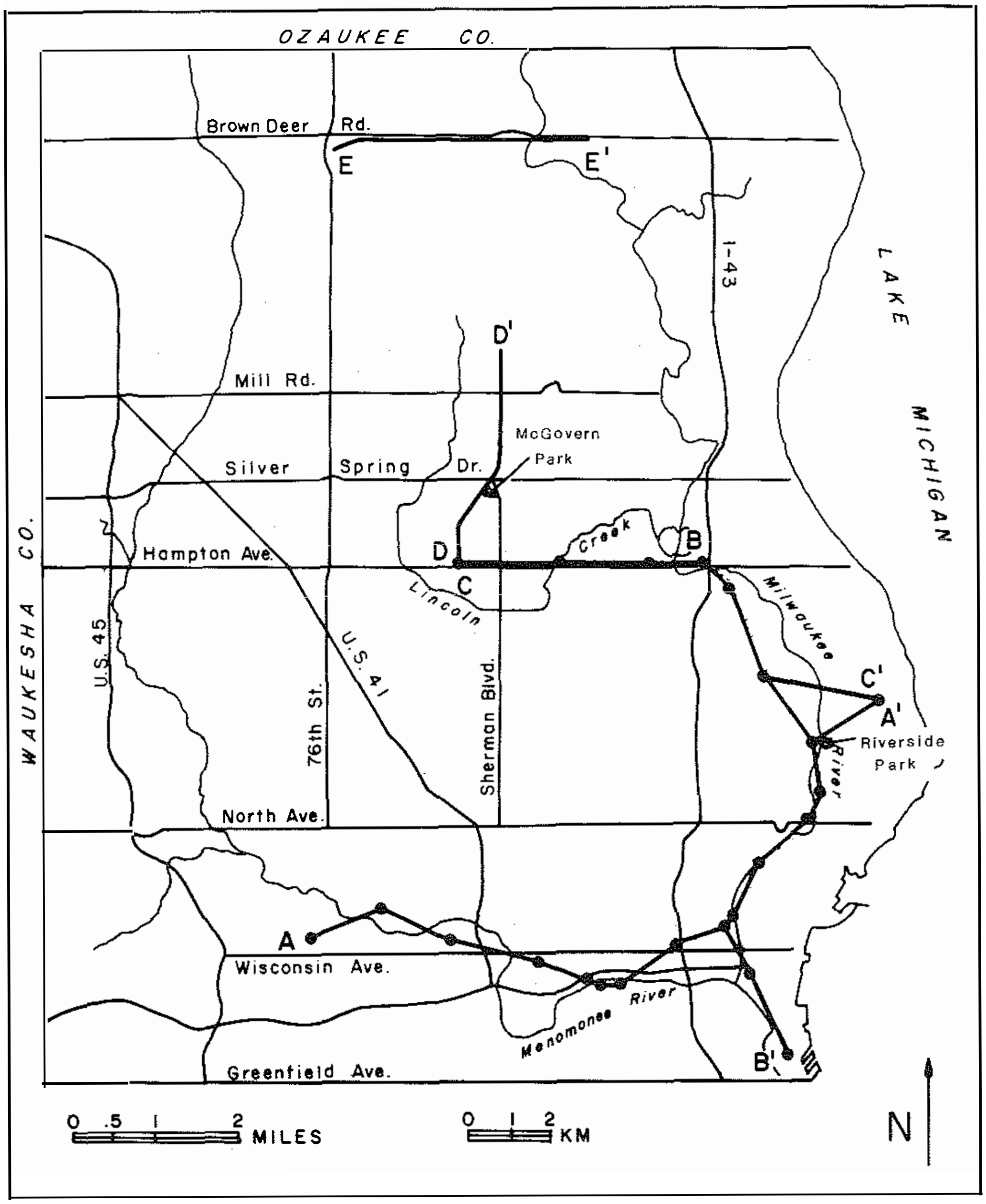

Figure 3. Map of the study area showing location of cross-sections in figures 4 through 8. Closed circles-location of cores on cross-sections A-A', B-B' and C-C'.

zones of dark-gray argillaceous partings and highly compacted, predominantly horizontal burrows, some pyrite-filled, are common. Orthoconic natutiloid cephalopods are scattered throughout these strata; certain layers contain a more diverse fauna of brachiopods, trilobites (especially *Sthenarocalymene celebra*) and pisocrinid crinoids (Mikulic, 1979).

A few layers displaying a prominent mottled fabric of crystalline and argillaceous dolomite interbed with this typical nonreef Racine Dolomite.

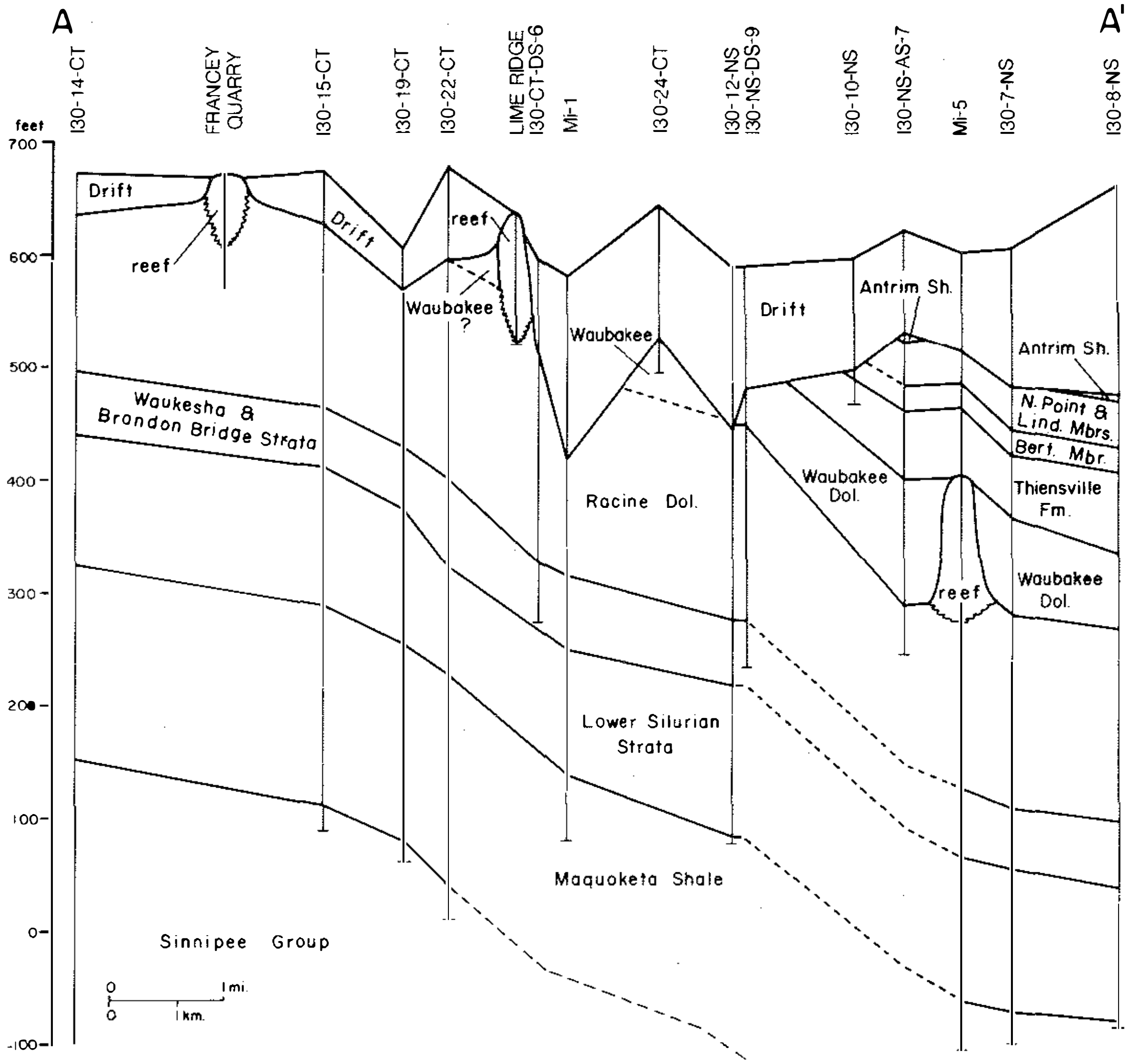

Figure 4. Cross-section A-A' showing the Riverside Park (Mi-5) and Lime Ridge (west of I30-CT-DS-6) Racine Dolomite reefs and their relationship with surrounding Silurian and Devonian strata. The now-filled Francey Quarry was located northeast of the intersection of North 68th and West State Streets. Data on Lime Ridge derived from former quarries, outcrops, and boring C10-13-CT5/6. On this and all other cross-sections surface topography between data points generally was not corrected to other surveyed elevations.

Mottling and segregation of sediment grain size is probably due to bioturbation.

Reefs occur sporadically within the Racine dolomite (figs. 3, 4, 5 and 9). Generally the reefs are mound-shaped and reach thicknesses of as much as 30 m and diameters of over 300 m. The reefs consists of massive, coarsely crystalline, porous, vuggy, fossiliferous, mottled gray to brownish-gray dolomite, which grades laterally into typical nonreef Racine Dolomite (fig. 9). Slickensides are common locally. Some of the reefs project above the surface of nonreef Racine Dolomite strata, accounting for the significant increase in overall thickness of the unit (figs. 4 and 5).

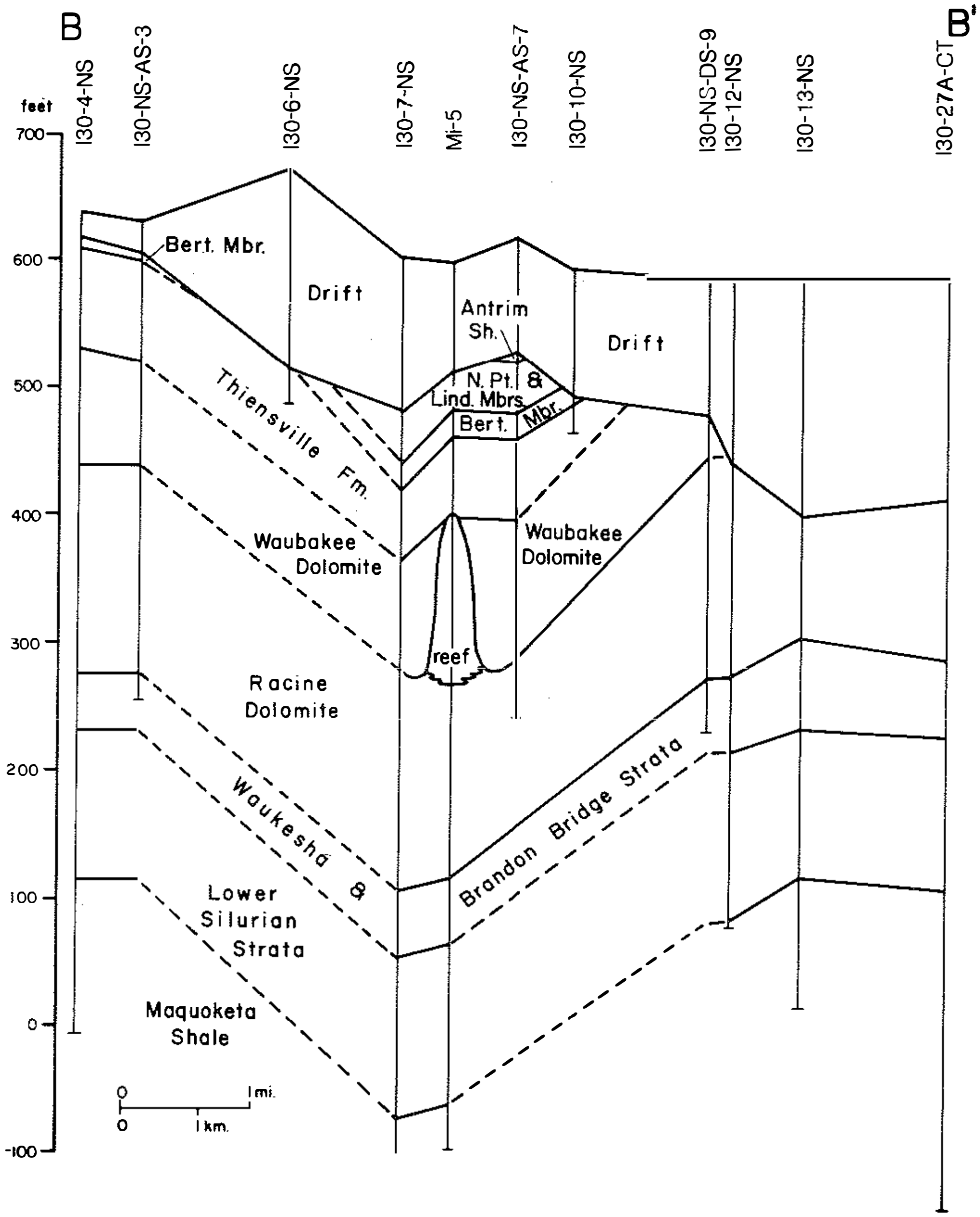

Figure 5. Cross-section B-B' along the Milwaukee River, showing the syncline at North Point and the Riverside Park Racine Dolomite reef (Mi-5) and its relationship with surrounding strata.

Reef strata in the northern half of the county contain a diverse and abundant fauna of brachiopods, bryozoans, corals, cephalopods, trilobites, gastropods, stromatoporoids, and bivalves. The scarcity and low diversity of echinoderms in these units contrasts sharply with the great abundance and diversity of echinoderms in Racine Dolomite reefs to the south and north (Mikulic, 1979).

The contact between the nonreef Racine Dolomite and the overlying Waubakee Dolomite is gradational. The contact between Racine Dolomite reefs and the Waubakee Dolomite may be unconformable. The tops of the reefs are overlain unconformably by the Devonian Thiensville Formation.

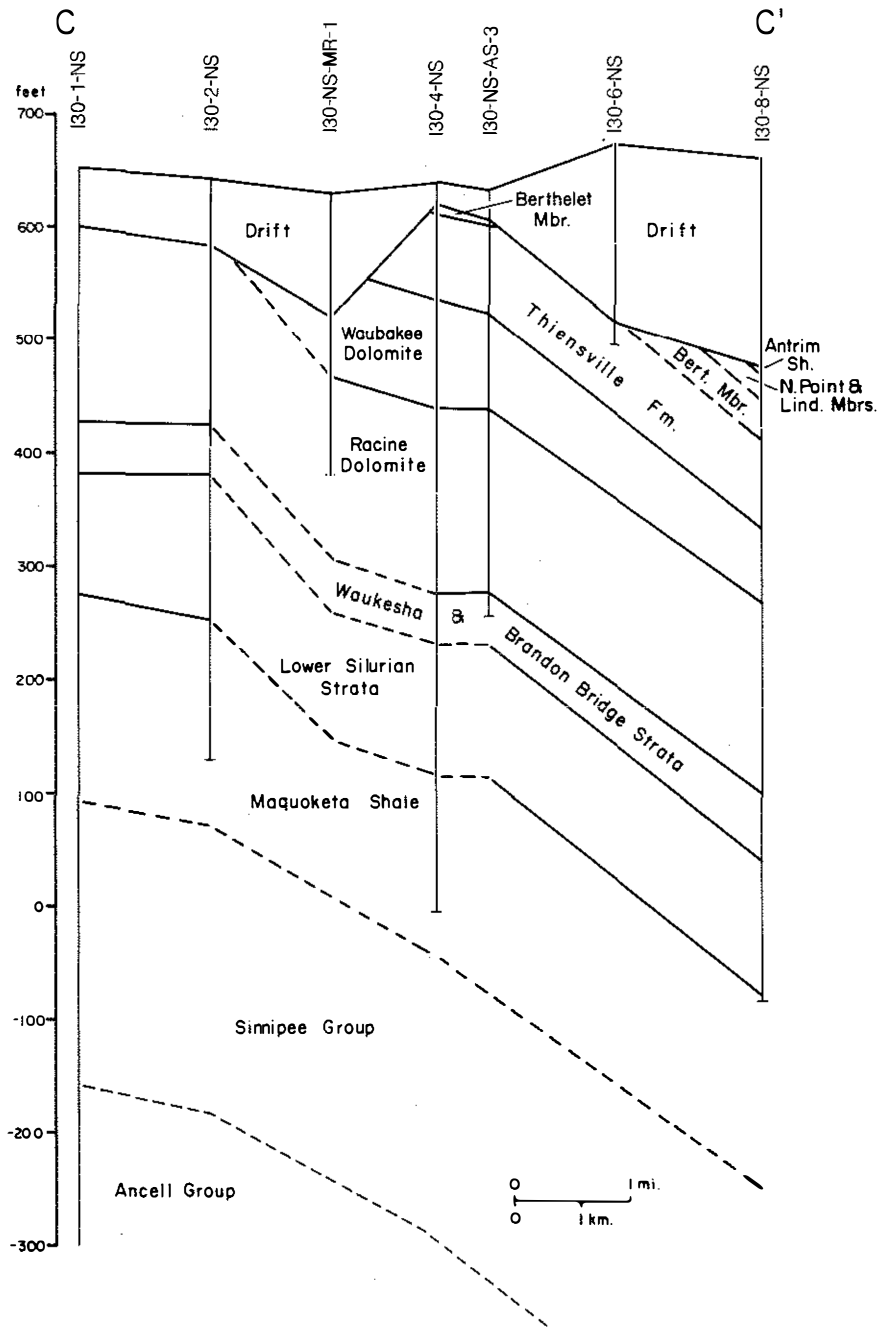

Figure 6. Cross-section C-C' showing the increase in dip of the Silurian and Devonian rock at the western edge of the North Point syncline.

Waubakee Dolomite

Overlying the Racine Dolomite in northeastern Milwaukee County is a conspicuous laminated dolomite that Alden (1906) identified as the Waubakee Dolomite based on lithologic similarity to the type Waubakee Dolomite section in Ozaukee County. In Milwaukee County this unit consists of dense, laminated to thin-bedded, slightly argillaceous, light- to dark-gray dolomite (fig. 10). Generally laminae are very thin, relatively flat-lying and laterally

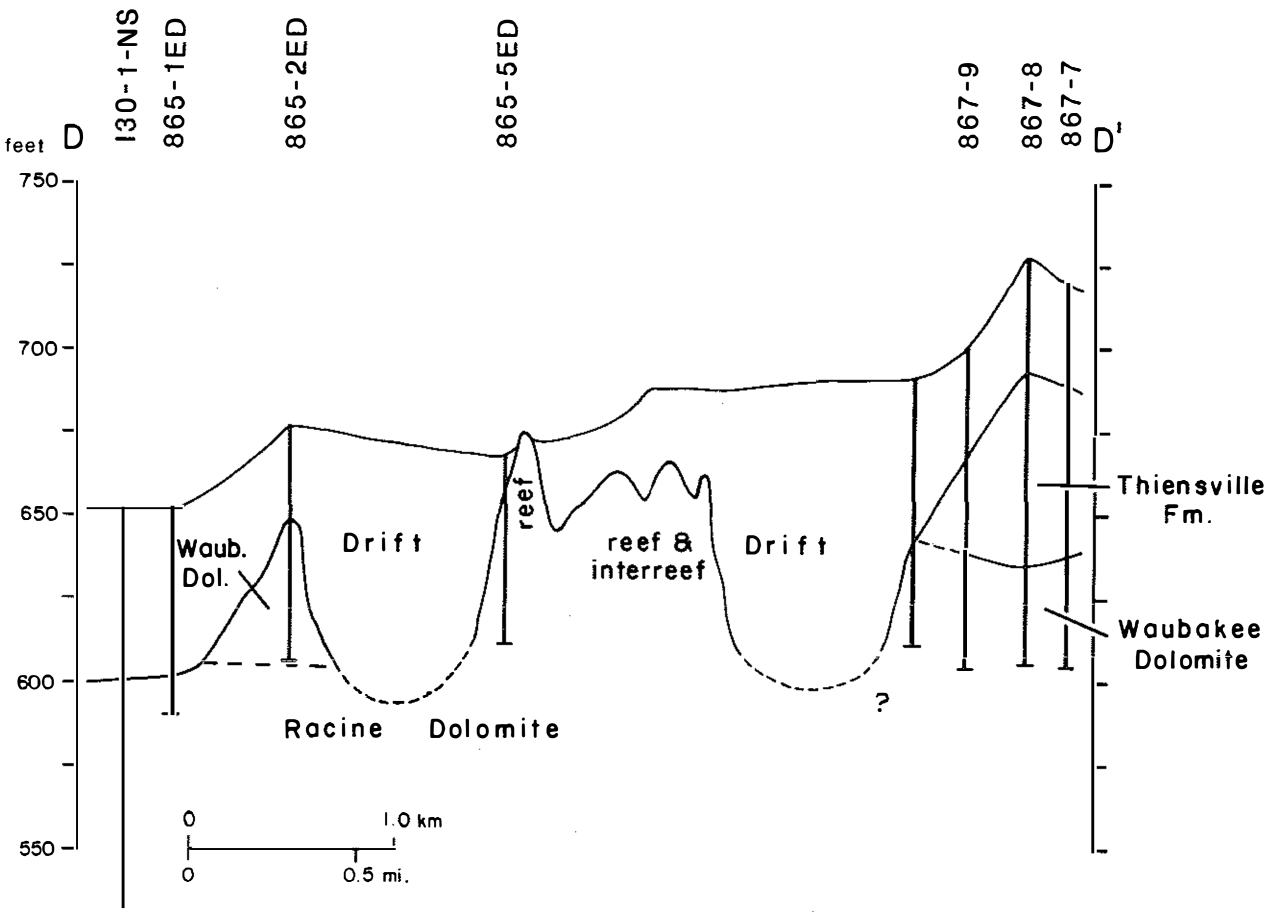

Figure 7. Cross-section D-D' constructed from shallow borings in the vicinity of McGovern Park which show the relationship between the Zautke reef (boring 865-5ED) and surrounding Waubakee Dolomite and Thiensville Formation. Topography between 865-5ED and 867-9 was determined from shallow borings that reached top of bedrock. Lithologies were determined from samples from sewer tunnel excavations.

persistent, although locally they may be wavy or discontinuous. Smooth flat bedding surfaces containing little argillaceous material impart a platy appearance to most of the Waubakee Dolomite; in some engineering logs the unit is described as hasving a poker-chip appearance in cores. Very fine laminoid fenestrae are common. Some strata are more crystalline, nonlaminated, porours, vuggy and nonplaty, and show evidence of bioturbation. When freshly broken, the Waukakee Dolomite emits a strong petroliferous odor.

Evidence for periodic desiccation and hypersalinity includes rare small intraclasts and shrinkage cracks. Calcitized pseudomorphs of skeletal halite (Southgate, 1982) are common locally (fig. 11); rare pseudomorphs of gypsum crystals and anhydrite nodules occur. A few brachiopods have been found in the Waubakee Dolomite in Milwaukee County, first by Chamberlin (1877) at the Petzold Quarry and more recently in sewer tunnel excavations. Nevertheless, the unit generally is unfossiliferous.

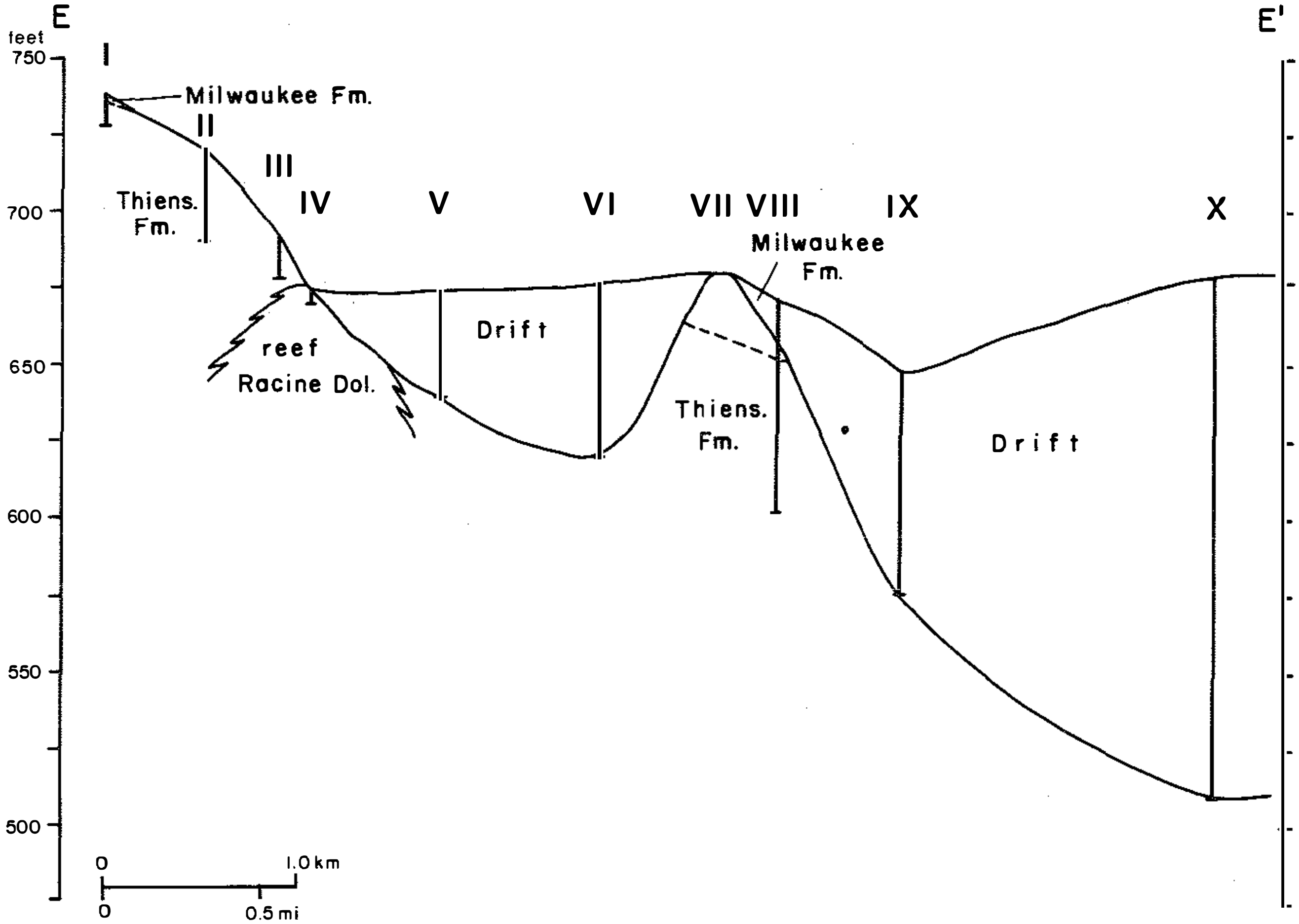

Figure 8. Cross-section E-E' along West Brown Deer Road from North 76th Street east to the Milwaukee River. I=excavations in the vicinity of St. Catherine's Catholic Church described by Chamberlin (1877) and Raasch (1925, unpublished fieldnotes). II=sewer excavations exposed in 1971. III=ditch along North 68th Street described by Raasch (1925, unpublished fieldnotes). IV=outcrops and shallow excavations in the vicinity of North 67th Street. V, VI, IX, X=soil borings showing topography of bedrock surface with no available bedrock information; VII=outcrops at the Badger Meter Company; VIII=boring 289-NB12.

Sedimentary features suggest that the Waubakee Dolomite was deposited in an intertidal-supratidal setting that was subjected to periods of drying. Hypersalinity most likely excluded most organisms, allowing for preservation of laminae and accounting for the paucity of fossil benthos. Only rare strata, which contain no evidence of hypersalinity, were bioturbated. Laminae may be due to algal mat growth, but because algal fossils are absent and evidence of doming is lacking, origin of the laminae is inconclusive.

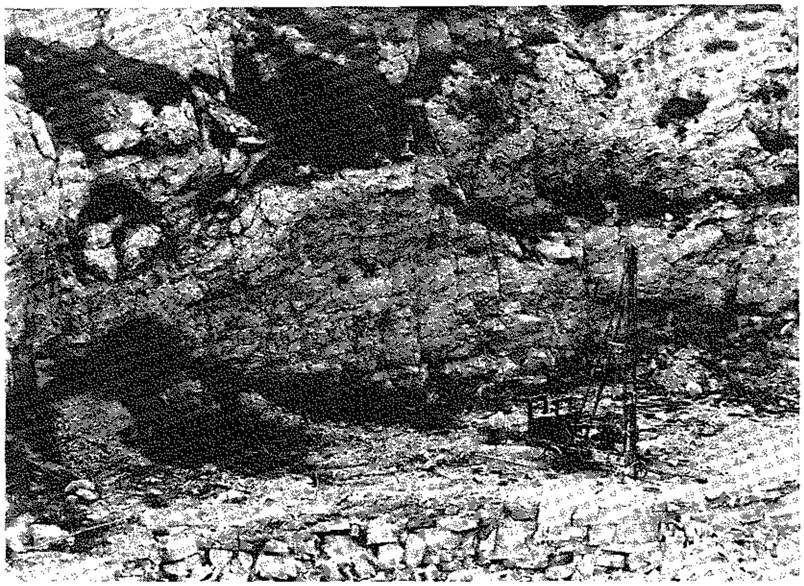

Figure 9. Massive Racine Dolomite reef strata overlying well-bedded nonreef Racine Dolomite in the northwest corner of the now-filled Francey Quarry, SW1/4SW1/4SE1/4 sec. 22, T. 7 N., R. 22 E., Milwaukee 7.5-minute quadrangle, Wauwatosa, Milwaukee County, Wisconsin. Photo circa 1915, courtesy of Milwaukee Public Museum, Photo No. 47367.

Where overlain by Devonian strata, the Waubakee Dolomite varies from 18 to 33 m in thickness, probably as a result of pre-Middle Devonian erosion. The contact between the Waubakee Dolomite and the overlying Thiensville Formation is unconformable. Locally the Waubakee Dolomite thins and disappears over Racine Dolomite reefs which project upward to the base of the Devonian (figs. 4 and 5).

Correlation of this unit with the type section of the Waubakee Dolomite in Ozaukee County is based primarily on lithologic similarity, as previously mentioned. Conclusive evidence that these strata are of the same age and in the same stratigraphic position is lacking (Mikulic, 1979). Berry and Boucot (1970) suggested that the Waubakee Dolomite is a *Leperditia*-rich lens within the Racine Dolomite. Although this interpretation cannot be discounted for the Waubakee Dolomite at the type section, subsurface data show this is not the case for the Waubakee Dolomite in Milwaukee County (Mikulic, 1979).

The Waubakee Dolomite is assigned a Late Silurian age based on its stratigraphic position above the Racine Dolomite and its lithologic similarity to Late Silurian hypersaline carbonates in Michigan (A-1 Carbonate), Indiana (Kokomo Limestone) and Iowa (Anamosa Member of the Gower Formation). Klug (1977) found no conodonts in the Waubakee Dolomite from the Lincoln Creek exposures. This lack of biostratigraphically useful fossils prohibits a more precise age determination.

Thiensville Formation

The Thiensville Formation unconformably overlies the Waubakee Dolomite and, rarely, the tops of Racine Dolomite reefs throughout most of northeastern

Figure 10. Waubakee Dolomite, well-laminated light olive-gray (5 Y 6/1) and olive-gray (5 Y 4/1) argillaceous dolomite with common very fine laminoid fenestrae (arrow). Laminae conform to irregularities on the surface of underlying thin bed of nonlaminated light olive-gray dolomite with faint argillaceous streaks. Core slab from boring I30-NS-4 (Mikulic and Kluessendorf, 1988), top of slab from depth of 48.2 m; bar scale 2.54 cm.

Milwaukee County. The unconformable contact between the Thiensville Formation and the overlying Milwaukee Formation is sharp, irregular, and mineralized (fig. 12). Although the Theinsville Formation is considered Middle Devonian (Givetian) (Schumacher, 1971a), diagnostic fossils have not been discovered in the county.

The Thiensville Formation ranges from 17 to 23 m in thickness and is lithologically complex. In general, the unit grades upward from argillaceous sediments at the base to purer carbonate at the top. The lowest 3 m is composed of poorly lithified sediments, including clay, silt and, in places, thin layers of dense to porous dolomite. Core recovery from this part of the unit is poor and the precise lithologic sequence is uncertain. The remainder of the Thiensville Formation is dolomite with minor amounts of limestone, claystone, and mudstone. The dolomite ranges from fine-grained, dense, and nonporous to vuggy, coarse-grained or granular, and friable. Although strata vary in color, shades of yellowish brown dominate. Much of the rock gives off a strong petroliferous odor when freshly broken.

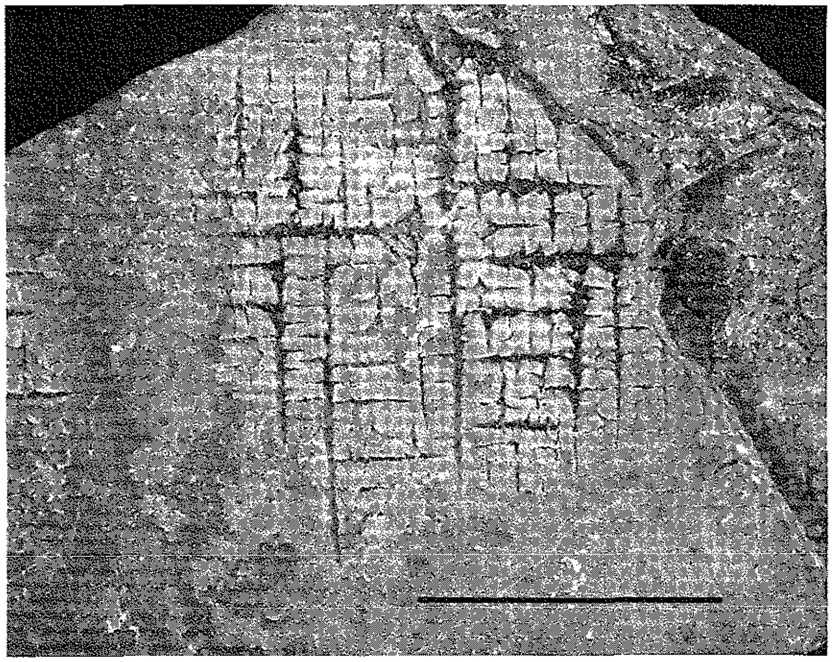

Figure 11. Waubakee Dolomite showing pseudomorphs of skeletal halite. Predominant reticulate ridge pattern indicates preferential precipitation of halite on cub edges and corners on the floors of very shallow brine pools that evaporated due to dryness (Southgate, 1982). Sample from sewer tunnel excavation at North 51st Street and West Villard Avenue, Milwaukee, Milwaukee County, Wisconsin. Bar scale=1.3 cm.

Some strata display evidence of hypersaline depositional conditions. Calcitized pseudomorphs after anhydrite nodules and rare gypsum crystal molds are present. Small diapiric desiccation structures caused by displacive growth of evaporites occur (fig. 12). These strata typically exhibit pronounced brecciation which probably resulted from collapse after dissolution of evaporites by meteoric waters.

Several intervals of granular, crystalline, porous, yellowish-brown to dark-brown, laminated, silty dolomite show evidence of desiccation, including intraclasts, desiccation cracks, and collapse breccias (fig. 13). Laminae are irregular and inclined; locally they may be nodular, possibly due to incipient growth of anhydrite nodules. Exposures in Estabrook Park demonstrate that these laminae are related to low domes as much as 1 m in diameter and up to 0.3 m in height that are probably of algal origin (fig. 14).

Presence of nodular anhydrite pseudomorphs and desiccation features point to an arid supratidal depositional environment, probably a coastal sabkha. Brownish coloration of the sediments suggests oxidation in such a setting. Periodic vadose conditions are indicated by collapse breccias, and proximity to continental conditions is suggested by presence of quartz silt, possibly windblown from nearby dunes. Quartz grains composing the dunes were

Figure 12. Milwaukee Formation-Thiensville Formation contact. Light olive-gray (5 Y 6/1) dolomitic mudstone of the Milwaukee Formation contains small rip-up clasts (arrow) of the underlying Thiensville Formation, which is a mottled light olive-gray (5 Y 6/1) and medium-gray (N5) dolomite. The darker patches appear to be anhydrite nodule pseudomorphs; growth of one nodule has caused a small diapiric desiccation structure (d). Collapse brecciation occurs in the upper Thiensville Formation; resulting vugs are lined with pyrite and ?celestite. In places pyrite coats the Thiensville surface. Core slab from boring NB-24 (Project MW79-661), North Sherman Boulevard between West Parkland and West Woodale Avenues, west edge of SW1/4NW1/4NW1/4 sec. 13, T. 8 N., R. 21 E., Thiensville 7.5-minute quadrangle, Brown Deer, Milwaukee County, Wisconsin. Surface elevation: 217.8 m. Top of slab from depth of 30.7 m; bar scale = 2.54 cm.

most likely derived from older (Cambrian and Ordovician) sandstone on the emergent Wisconsin upland (Summerson and Swann, 1970).

The only fossiliferous zone occurs near the middle of the Thiensville Formation in Milwaukee County, and represents a period of more normal salinity in shallow-marine conditions. Fossils, predominantly brachiopod and rugosid coral, are abundant and preserved as internal and external molds in a dark-brown, slightly porous, silty dolomite. The bioclastic wackestone-packstone fabric is characterized by a distinctive swirled pattern imparted by bioturbation. This zone is lithologically and paleontologically very similar to the fossiliferous Lake Church Dolomite as exposed at its type

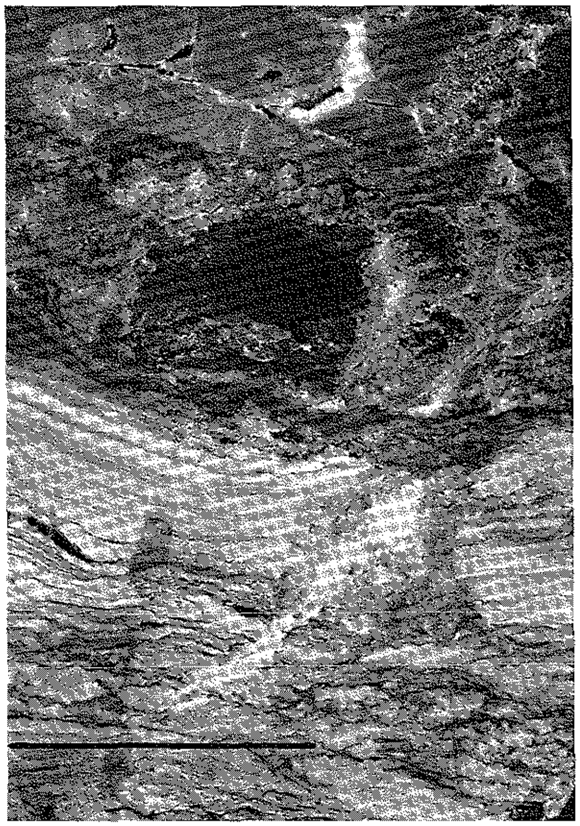

Figure 13. Thiensville Formation, vuggy brecciated yellowish brown (10 YR 5/2) limestone overlying grayish orange (10 YR 6/2) brecciated laminated to nodular dolomite and limestone. Small nodules in the laminated lithology probably are due to growth of anhydrite nodules. Laminae are inclined and are known from outcrop evidence to be related to possible algal domew (fig. 14). Core slab from boring EB-44 (Project MW79-662), Northeast Side Relief Sewer System-East Branch, between Indian Creek and Indian Creek Parkway, just east of Port Washington Road, SE1/4NW1/4SE1/4 sec. 8, T. 8 N., R. 22 E., Thinsville 7.5-minute quadrangle, Fox Point, Milwaukee County, Wisconsin. Surface elevation 200.8 m; bottom slab from depth of 12.5 m; bar scale = 2.54 cm.

section in Ozaukee County (Kluessendorf and Mikulic, 1985). The Lake Church Dolomite may be a facies of the Thiensville Formation, or, on the other hand, the Thiensville Formation as it is described in Milwaukee County may be equivalent to both the Lake Church Dolomite and the Thiensville Formation as they are described in Ozaukee County. More subsurface data from Ozaukee County are needed to clarify this relationship.

Milwaukee Formation

The Milwaukee Formation, which is considered Middle Devonian (upper Givetian) based on conodonts (Schumacher, 1971a), overlies the Thiensville Formation disconformably. Where overlain by Antrim Shale, the Milwaukee Formation is 18.5 to 19.2 m thick. The lower 9 m formerly were exposed in the

Figure 14. Probable algal dome in the upper Thiensville Formation about 1 - 2 m below the Milwaukee Formation-Theinsville Formation contact, north side of Milwaukee River, 90 m west of the dam, 274 m east of the Port Washington Road bridge, Estabrook Park, NE1/4NW1/4NE1/4 sec. 5, T. 7 N., R. 22 E., Milwaukee 7.5-minute quadrangle, Milwaukee County, Wisconsin.

Milwaukee Cement Company quarries and mines located along the Milwaukee River in present-day Estabrook Park. This part of the unit recently was described by Schumacher (1971a) and Klug and Nelson (1977).

The Milwaukee Formation comprises three members. The lowest, the Berthelet Member, is a gray, fossiliferous, argillaceous dolomite. This member, named by Raasch (1935), consists of Units A and B of Cleland (1911). The upper 2 m of this member (Unit B) is thick-bedded, highly fossiliferous, more dolomitic than the lower strata, and contains asphalt-filled vugs. Fossils in the Berthelet Member are preserved as internal and external molds, typically iron-stained, with the exception of phosphatic vertebrate and invertebrate remains. Highly compressed, pyritized burrows and trails are scattered throughout the member. Thickness of the Berthelet Member is notably consistent, ranging from 6.2 to 6.5 m.

The Lindwurm Member (Unit C of Cleland, 1911) succeeds the Berthelet Member (Raasch, 1935). It is an argillaceous dolomite that grades upward into slightly dolomitic siltstone. This member is highly fossiliferous but, in contrast to the Berthelet Member, the fossils are calcitic. Common wispy argillaceous partings may be due to pressure solution, although bioturbation is evident.

Approximately 5 to 6 m above the base of the Lindwurm Member a marked faunal change takes place. Below this horizon fossils are diverse and abundant, especially pelmatozoan debris and bryozoans. Above this horizon, however, pelmatozoan debris is rare or absent, overall faunal diversity decreases dramatically, and chonetid brachiopods and tentaculitids become the most common faunal element. These upper strata, which constitute the North Point Member (Raasch, 1935), contain a few thin zones of silicified fossil allochems in chert within a dolomitic siltstone. The diverse and abundant fossils in these zones are disarticulated and exhibit no preferred orientation except where imbricated locally. These zones probably represent storm deposits; the porous grainstone fabric may have favored preferential silicification. Contact between the Lindwurm and North Point Members is gradational. In general, the Milwaukee Formation appears to have been deposited in shallow subtidal, normal-marine conditions.

Antrim Shale

The Antrim Shale occurs only in a limited part of eastern Milwaukee County in the vicinity of Lake Park and west to the Milwaukee River (fig. 1). Apparently distribution of the Antrim Shale is related to the syncline in the North Point area (fig. 15).

Contact with the underlying Milwaukee Formation is sharp and irregular in boring I30-NS-AS-7 (Mikulic and Kluessendorf, 1988) and appears to be unconformable. The basal Antrim Shale, a gray silty mudstone, was observed in two borings (I30-NS-8 and I30-NS-AS-7) where it is 1.7 and 4.0 m thick, respectively. At both localities, the unit occurs at the bedrock surface; much of it apparently has been eroded away here as Raasch (1935) reported a maximum thickness of 17 m for the Antrim Shale at North Point. The name Antrim Shale tentatively replaces the formerly utilized, but preoccupied, Kenwood Shale, as suggested by Schumacher (1971b) and Klug and Nelson (1977).

Linguliid brachiopods are the only macrofossils observed in the Antrim Shale in the new cores. Schumacher (1971b) found Late Devonian (middle Frasnian to early Famennian) conodonts in the unit, making it the youngest Paleozoic unit in Wisconsin.

STRATIGRAPHIC PROBLEMS RELATED TO REEFS

T.J. Hale (1860, unpublished fieldnotes) observed that the Racine Dolomite reef exposures near the present-day McGovern Park occurred at the same elevation as the Waubakee Dolomite on nearby Mud (Lincoln) Creek. Outcrops and water-well logs indicate that the Waubakee Dolomite or the Thiensville Formation occur at the same elevation as Racine Dolomite reefs at other localities. Misunderstanding of the nature of these relationships led to misidentification and miscorrelation of rock units at certain localities (for example, Chamberlin, 1877). Until the new subsurface information became available, outcrop correlation was uncertain and determination of whether these relationships were structural or depositional in nature was difficult. The new cores indicate that these relationships are depositional in nature, as demonstrated at the following localities.

Riverside Park

Subsurface data reveal the presence of a Racine Dolomite reef near the southwest corner of Riverside Park (figs. 3, 4 and 5). In boring Mi-5 (Mikulic and Kluessendorf, 1988) 88 m of Racine Dolomite, of which the upper 24 m is reef rock, is overlain by a normal sequence of Thiensville and Milwaukee Formations. No Waubakee Dolomite is present, but surrounding borings show a normal sequence of Waubakee Dolomite, with a maximum thickness of 33 m in boring I30-NS-AS-7, succeeding nonreef Racine Dolomite and overlain by Devonian strata. The Devonian strata in boring Mi-5, occurring at an anomalous elevation for the area, drape over the reef. No lithologic or paleontologic changes are recognizable in the Thiensville or Milwaukee Formations at this locality. The contact between the reef and the Thiensville Formation is sharp and unconformable; the contact between the reef and the Waubakee Dolomite appears to be sharp, although some interbedding may occur.

Lime Ridge Reef

Scattered outcrops of Racine Dolomite reef strata formerly were present along the north side of the Menomonee River valley from North 25th Street to North 27th Street in an area of Milwaukee once known as Lime Ridge. Subsurface data indicate that these exposures are reef-controlled bedrock hills that are mostly buried by Quaternary sediments (fig. 4). A short distance to the northeast, 5 m of Waubakee Dolomite overlies apparent reef strata in the Eagles Club water well (Wisconsin Geological & Natural History Survey log ML-58), occurring at the same elevation as the Lime Ridge reef exposure at North 25th Street and St. Paul Avenue along the Menomonee River valley.

Zautke Reef Area

Racine Dolomite reef strata have been exposed intermittently in outcrops and sewer tunnel excavations along West Silver Spring Drive between McGovern Park and North 35th Street (fig. 3) and at the now-filled Zautke Quarry north of North 51st Boulevard (fig. 7). Elevation at the top of reef rock ranges from 205 m on the west to 195 m on the east. Reef rock is at least 18 m thick (boring 865-5ED, fig. 7), and it is lithologically and paleontologically identical to Racine Dolomite reefs exposed to the south along the Menomonee River.

Approximately 1.6 km north of these reef exposures, in the vicinity of West Mill Road and North Sherman Boulevard (fig. 3; boring 867-9, fig. 7), the Waubakee Dolomite extends down to an elevation of 184 m—about 21 m lower than the top of the highest reef exposure. The Thiensville-Waubakee contact dips to the north and east, occurring at an elevation of 195 m about 0.2 km north and 183 m about 0.8 km east at the intersection of West Mill Road and North Teutonia Avenue.

A small buried bedrock hill occurs southwest of McGovern Park where Waubakee Dolomite is present in shallow borings near the intersection of North 51st Street and West Villard Avenue (figs. 1 and 3; boring 865-2ED, fig. 7). The Waubakee Dolomite ranges in elevation from 197 m down to at least 184 m giving it a thickness of more than 12 m here. At the intersection of West Stark and North 51st Streets (boring 865-1ED, fig. 7), the occurrence of nonreef Racine Dolomite at the bedrock surface at an elevation of 183 m indicates that the Racine-Waubakee contact in this area lies between 183 and 184 m--an elevation almost 21 m below the top of the Racine Dolomite reef at McGovern Park.

Approximately 1.6 km southeast of McGovern Park a large, mostly buried bedrock hill of Waubakee Dolomite with a top elevation of 194 m is partially exposed in Lincoln (Mud) Creek (fig. 1). Subsurface data indicate that the Waubakee-Racine contact occurs at an elevation of 185 m.

The stratigraphic relationships in the Zautke reef area show that the Waubakee Dolomite and Racine Dolomite reef strata overlap in elevation for more than 18 m.

Brown Deer Area

An outlier of Devonian rock, which occurs along the south side of West Brown Deer Road from North 68th Street to North 76th Street (fig. 1), forms a bedrock hill that rises 15 m above the surrounding area. This bedrock hill is covered thinly by soil on the north side, and rock has been exposed intermittently in shallow stone pits and other excavations. Chamberlin (1877) observed "Hamilton Cement Rock" (Milwaukee Formation) in stone pits near St. Catherine's Catholic Church on North 76th Place (NW1/4 sec. 10, T. 8 N., R. 21 E.) (I, fig. 8). He assigned underlying strata, now known to belong to the Thiensville Formation, to the Silurian. Near the top of the hill, just east of the church, Raasch (1925, unpublished fieldnotes) observed about 0.3 m of Milwaukee Formation underlain by about 4 m of Thiensville Formation. The contact between these units is at an elevation of about 225 m (fig. 8). Raasch also described a 12 m section of Thiensville Formation (top elevation of about 218 m) in a ditch south of Brown Deer Road along North 68th Street (III, fig. 8). At this same locality rubble from a 1986 sewer tunnel consisted of Racine reef rock at approximately the level of Brown Deer Road and Thiensville lithology ascending the hill to the south. No Waubakee lithology was observed. Subsequent excavations between these sites have uncovered Thiensville Formation strata also.

Racine Dolomite reef strata wtih a maximum top elevation of 207 m was encountered about a meter below ground surface along West Brown Deer Road between North 60th and 68th Streets and in a small creek to the south (IV, fig. 8). Approximately 1.6 km east, the Milwaukee Formation outcrops in a low hill behind the Badger Meter Company plant on the south side of West Brown Deer Road (VII, fig. 8); here the contact between the Lindwurm and Berthelet Members is at an elevation of 206 m. The Milwaukee Formation formerly was exposed in the Brown Deer railroad cut just east of the plant (Chamberlin, 1877). A short distance east, shallow borings show that the contact between the Thiensville and Milwaukee Formations is at an elevation of 198 m (VIII, fig. 8). Other borings about 4.4 km farther east show this contact at 187 m.

These data indicate that Racine Dolomite reef strata probably are at a higher elevation than the base of the Thiensville Formation, and suggest a relationship similar to that seen at Riverside Park (fig. 5). The Waubakee Dolomite has not been observed in any of these shallow borings or excavations, and its presence in the area is uncertain.

Evidence from the Riverside Park area, supported by these three other localities, indicates that Devonian strata drape over some Racine Dolomite reefs, which, in turn, are adjacent to the Waubakee Dolomite. It is unclear, however, if the Racine Dolomite reef strata are at least in part contemporaneous with the surrounding Waubakee Dolomite and, if so, how these units are related depositionally.

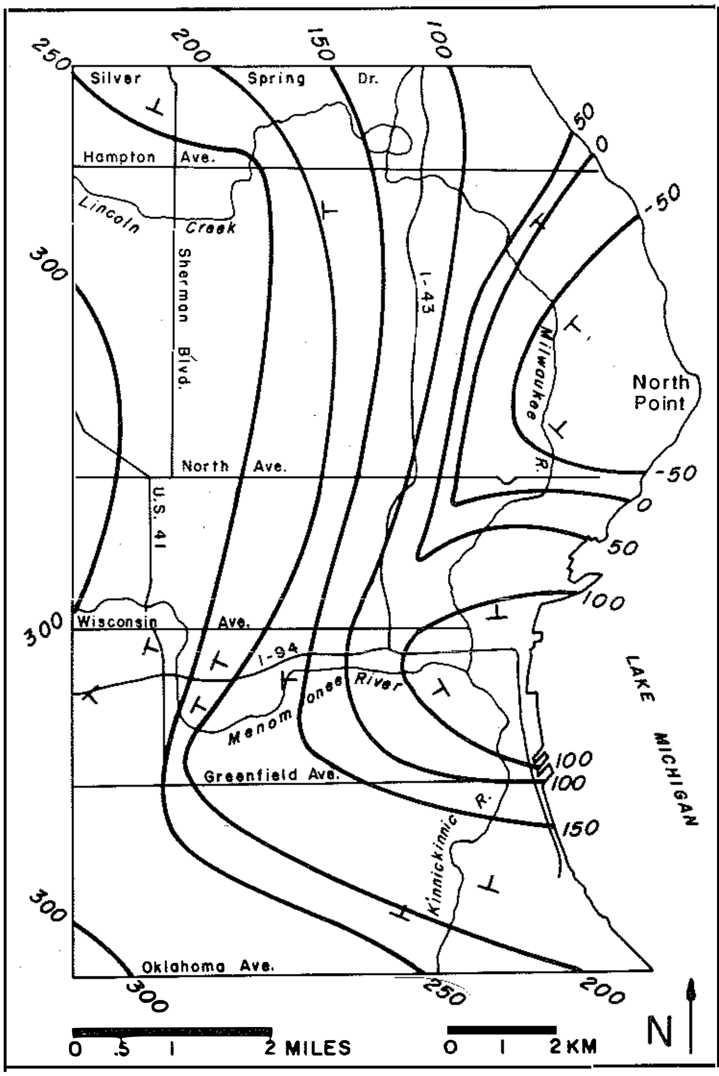

Figure 15. Structure-contour map of the base of the Silurian in east-central part of Milwaukee County, Wisconsin. Each dip symbol represents data derived from a three-point problem utilizing core or water-well log information. Contour interval in feet.

STRUCTURAL FEATURES

The Paleozoic strata of eastern Wisconsin dip gently eastward from the Wisconsin Arch towards the Michigan Basin. Distelhorst (1967) reported a northeasterly dip of 3.8 to 5.7 m per km in Milwaukee County based on water-well logs. Using better-defined horizons in the new cores, we found that the dip of Paleozoic strata in the county ranges from 1.1 to 17.1 per km, and it is more variable in direction than reported by Distelhorst (1967) (figs. 2 through 8 and 15).

A small syncline trends from North Point to the southwest, where it narrows rapidly near the intersection of Interstate Highways 94 and 43 (fig. 13). Present distribution of some Devonian strata, particularly the Antrim Shale, appears to be controlled in part by this structure. The syncline probably formed after deposition of the Milwaukee Formation as is suggested by the uniform thickness and lithology of that unit.

Distelhorst and Milnes (1968) reported a fault zone trending northeast-southwest through the mouth of the Milwaukee River; existence of the fault zone was not substantiated by new subsurface information. Additional minor faults with only a few cm of vertical displacement were observed in the study area by Alden (1906).

DEPOSITIONAL HISTORY

The Racine Dolomite probably was deposited under normal-marine subtidal conditions on a shallow carbonate platform at the edge of the proto-Michigan Basin. During Racine Dolomite deposition, many isolated reefs, which had relief of several tens of feet above the seafloor, developed on the platform. Towards the end of Racine Dolomite deposition, sea level fell, circulation became restricted, and salinity increased--a change marked by the gradational contact between the nonreef Racine Dolomite and the overlying Waubakee Dolomite.

Although Racine Dolomite reefs are surrounded by the Waubakee Dolomite at several localities, the depositional relationship between these two units is unclear. It is unknown whether the reefs developed only during deposition of the Racine Dolomite, were later killed off by salinity changes, and the Waubakee Dolomite was deposited around the topographically high, dead reefs, or, alternatively, whether the reefs continued to grow after the onset of Waubakee Dolomite deposition. It is certain that initial reef development took place during Racine Dolomite deposition and that the lower parts of the reefs do not differ lithologically or paleontologically from the upper parts that are surrounded by the Waubakee Dolomite. The contact between the Waubakee Dolomite and a reef was observed in only one core (I30-NS-MR-4D) where it appears to be unconformable, but may interbed. The absence of a known erosional conglomerate of Racine Dolomite within, or at the base of, the Waubakee Dolomite indicates that the reefs were not eroded significantly prior to Waubakee Dolomite deposition. Some authors have suggested that Silurian reef deposition was contemporaneous with hypersaline conditions in the Michigan Basin (Droste and Shaver, 1977) and in Iowa (Witzke, 1981). The possibility that Racine Dolomite reefs and the surrounding Waubakee Dolomite may be totally or partially contemporaneous cannot be discounted at this time.

The unconformity at the top of the Waubakee Dolomite developed following a Late Silurian regression during a prolonged period of emergence and erosion. The oldest Devonian rock is represented by the Thiensville Formation, a complex transgressive sequence that was deposited predominantly under arid supratidal conditions, probably in a coastal sabkha. The Milwaukee Formation marks a return to normal-marine subtidal conditions.

SUMMARY

Several important features of the Silurian and Devonian strata in Milwaukee County, Wisconsin, have been clarified by new subsurface data.

1. Some reefs, which developed initially during Racine Dolomite deposition, project upwards through the Waubakee Dolomite to the base of the Thiensville Formation.

2. The contact between the nonreef Racine Dolomite and the overlying Waubakee Dolomite is gradational.

3. The contact between Racine Dolomite reefs and the adjacent Waubakee Dolomite may be unconformable. Partial depositional contemporaneity of the Waubakee Dolomite and reefs cannot be discounted or proved by available data.

4. The contact between the Waubakee Dolomite and the overlying Thiensville Formation is unconformable and irregular, as is the contact between the Thiensville Formation and the Racine Dolomite reefs.

5. Thiensville and Milwaukee Formations strata drape over the Racine Dolomite reefs; however, thickness and lithology of the Milwaukee Formation remain uniform, indicating that the presence of underlying reefs had no influence on deposition of that unit.

6. The syncline at North Point in northeastern Milwaukee County controls present distribution of at least some Devonian strata, particularly the Antrim Shale.

7. Upper Silurian strata in the study area represent a regressive shallowing-upward sequence. Following emergence and erosion, the Middle Devonian strata were deposited during a marine transgression.

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