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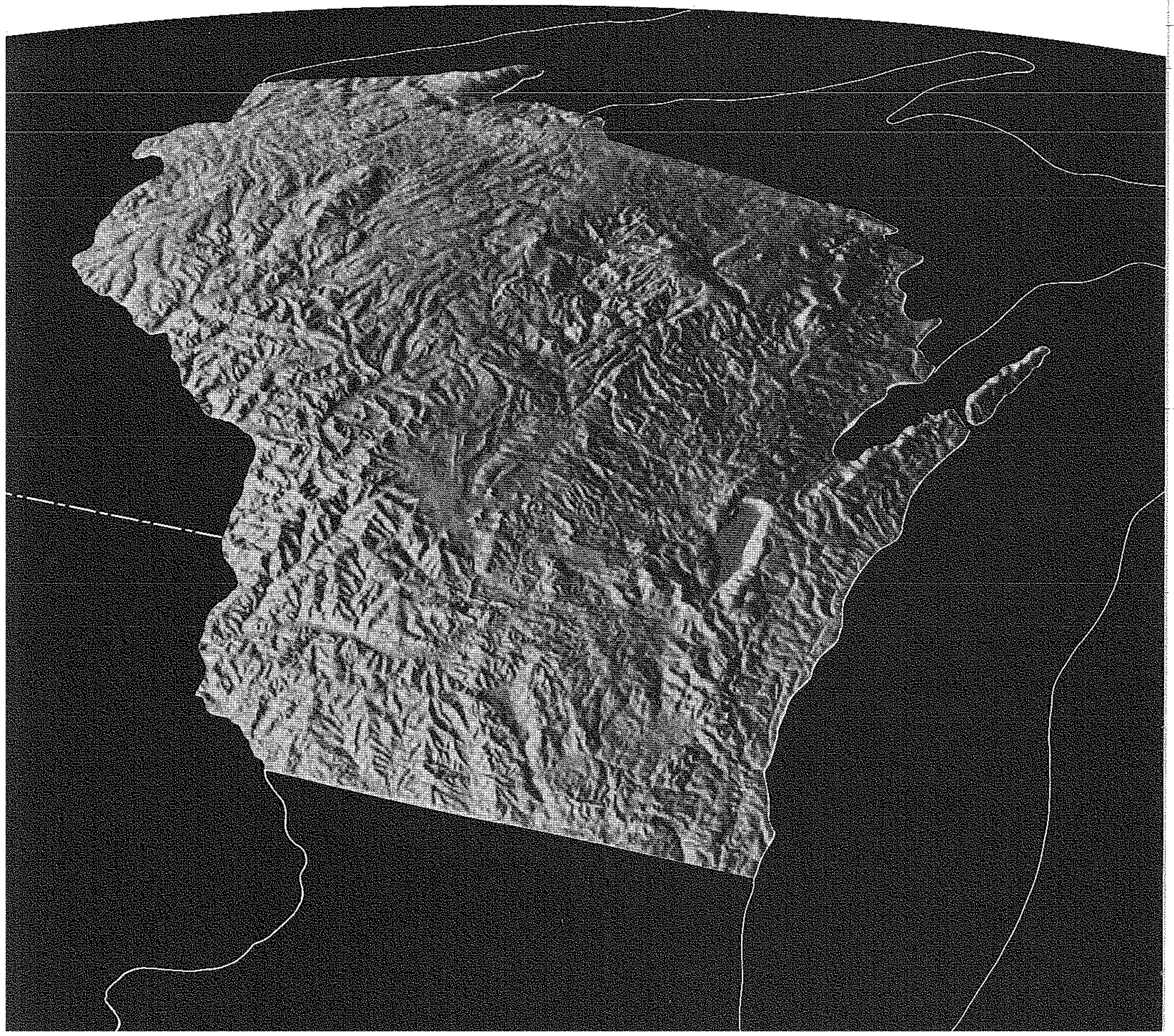

Geoscience Wisconsin

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PREFACE

"Geoscience Wisconsin" is a serial that addresses itself to the geology of Wisconsin -- geology in the broadest sense to include rock and rock as related to soil, water, climate, environment, and so forth. It is intended to present timely information from knowledgeable sources and make it accessible with minimal time in review and production to the benefit of private citizens, government, scientests, and industry.

Manuscripts are invited from scientists in academic, government, and industrial fields. Once a manuscript has been reviewed and accepted, the authors will submit a revised copy of the paper, and the Geological and Natural History Survey will publish the paper as funds permit, distribute copies at nominal cost, and maintain the publication as a part of the Survey list of publications. This will help to insure that results of research are not lost in the archival systems of large libraries, or lost in the musty drawers of an open-file.

The papers in this volume cover a wide range of geologic problems, and diverse areas in Wisconsin. Don Mikulic and Joanne Kluessendorf present a comprehensive geologic description of the bedrock geology in Milwaukee County. Bill Mode and John Attig summarize the Pleistocene geology and history of Marathon County. Greg Mursky and William Bailey present detailed geochemical data on granitic rock in northeastern Wisconsin. Emeka Okwueze and C.S. Clay describe the thickness of Pleistocene material in Vilas County using geophysical techniques in an area being intensively studied by others for the effects of acidic deposition. Sara Heller summarizes geochemical aspects of some spring water in Grant County.

We encourage submission of manuscripts relating to Wisconsin Geology. Special consideration will be given to papers which deal with timely topics, present new ideas, and have regional or statewide implications.

M.G. Mudrey, Jr.
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SUBSURFACE STRATIGRAPHIC RELATIONSHIPS OF THE UPPER SILURIAN AND DEVONIAN ROCK OF MILWAUKEE COUNTY, WISCONSIN

Donald G. Mikulic[1] and Joanne Kluessendorf[2]

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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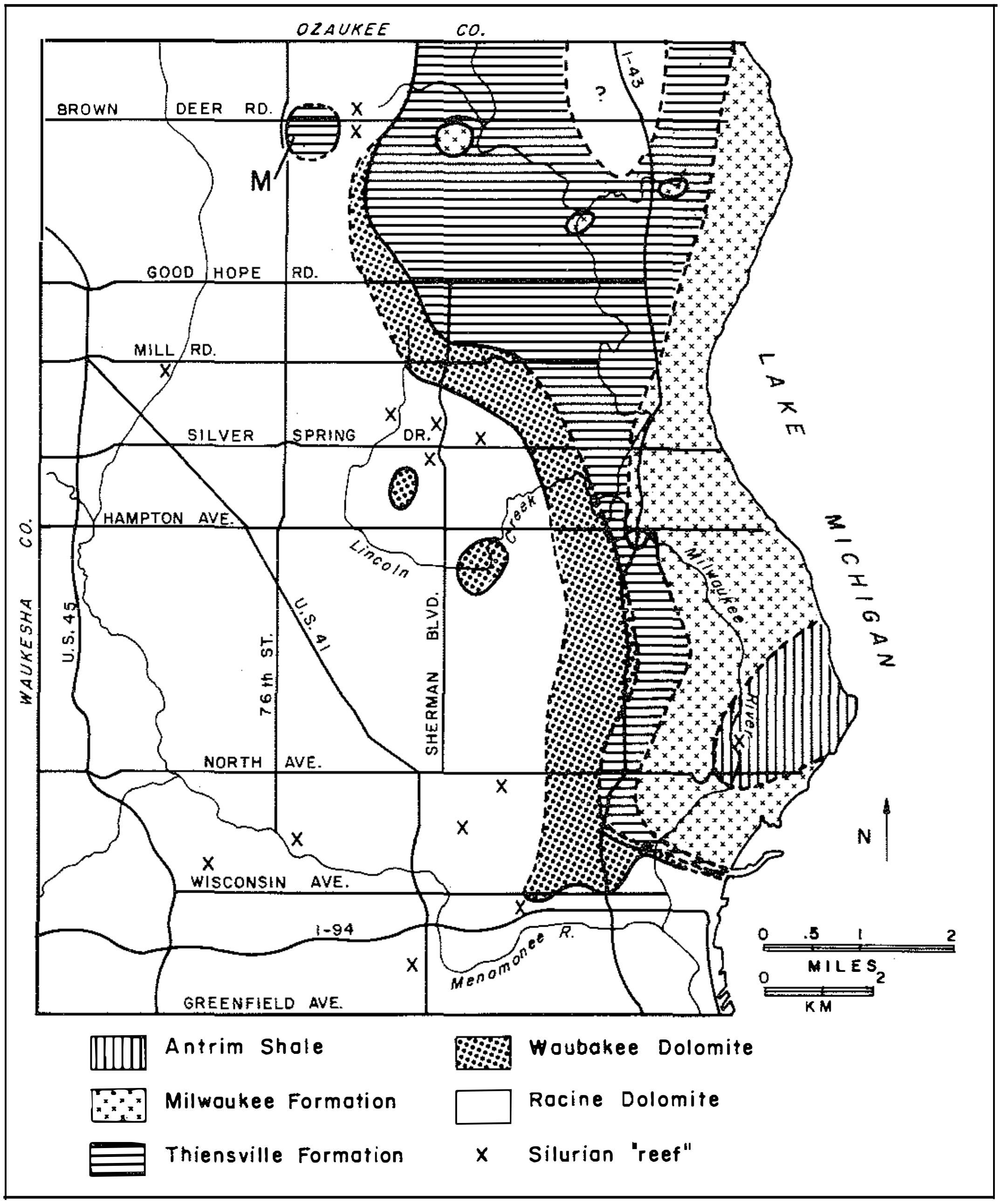

Figure 1. Bedrock geology map of the northern half of Milwaukee County, Wisconsin. M-small outlier of Milwaukee Formation (I, fig. 8) described by Chamberlin (1877) and Raasch (1925, unpublished field-notes).

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

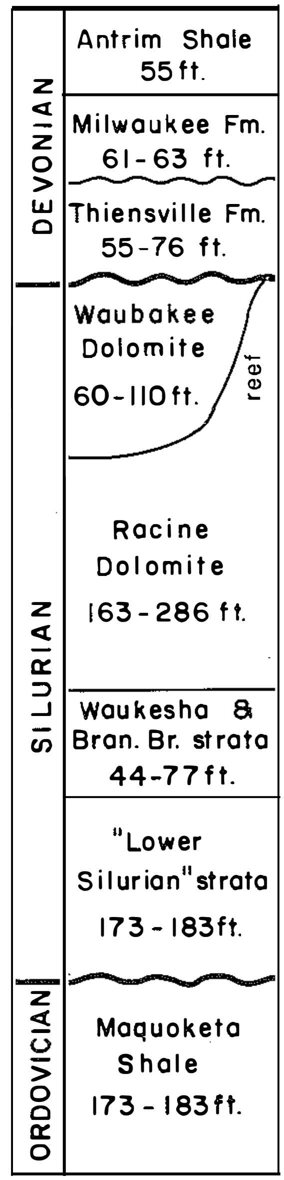

Figure 2. Generalized stratigraphic column for the Devonian, Silurian and Upper Ordovician strata in Milwaukee County, Wisconsin, showing relation ship between the Waubakee Dolomite and Racine Dolomite reef.

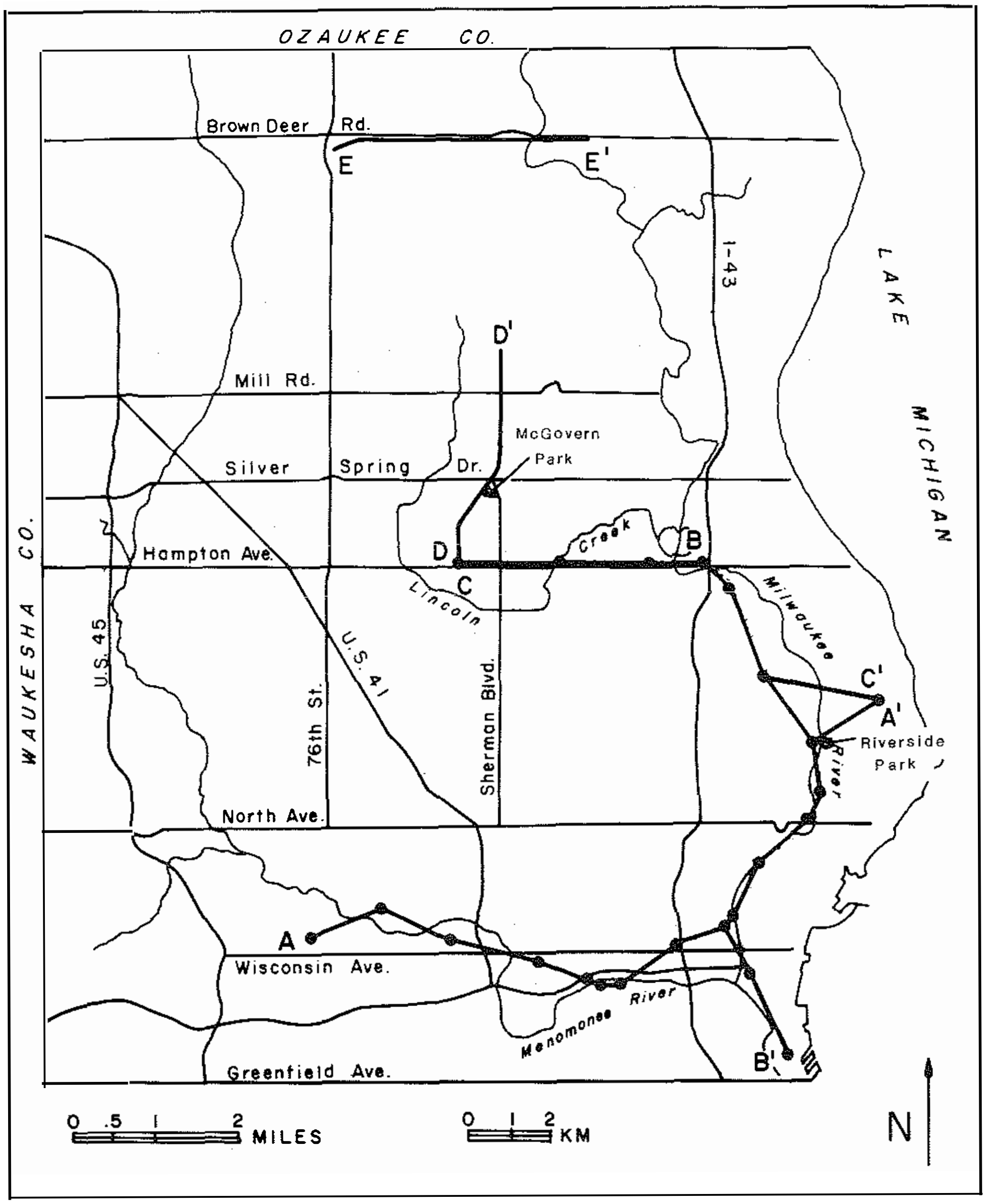

Figure 3. Map of the study area showing location of cross-sections in figures 4 through 8. Closed circles-location of cores on cross-sections A-A', B-B' and C-C'.

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.

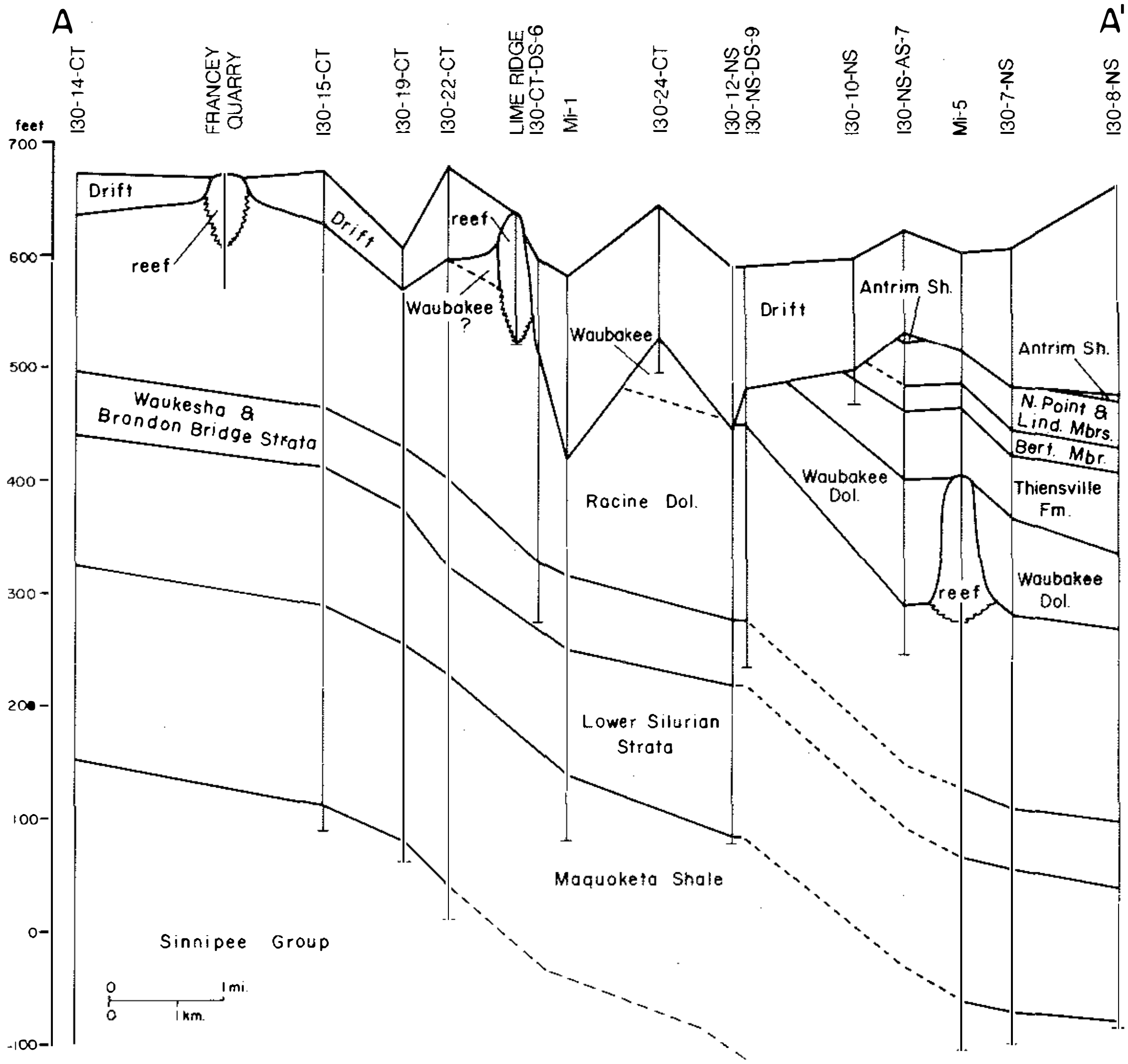

Figure 4. Cross-section A-A' showing the Riverside Park (Mi-5) and Lime Ridge (west of I30-CT-DS-6) Racine Dolomite reefs and their relationship with surrounding Silurian and Devonian strata. The now-filled Francey Quarry was located northeast of the intersection of North 68th and West State Streets. 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).

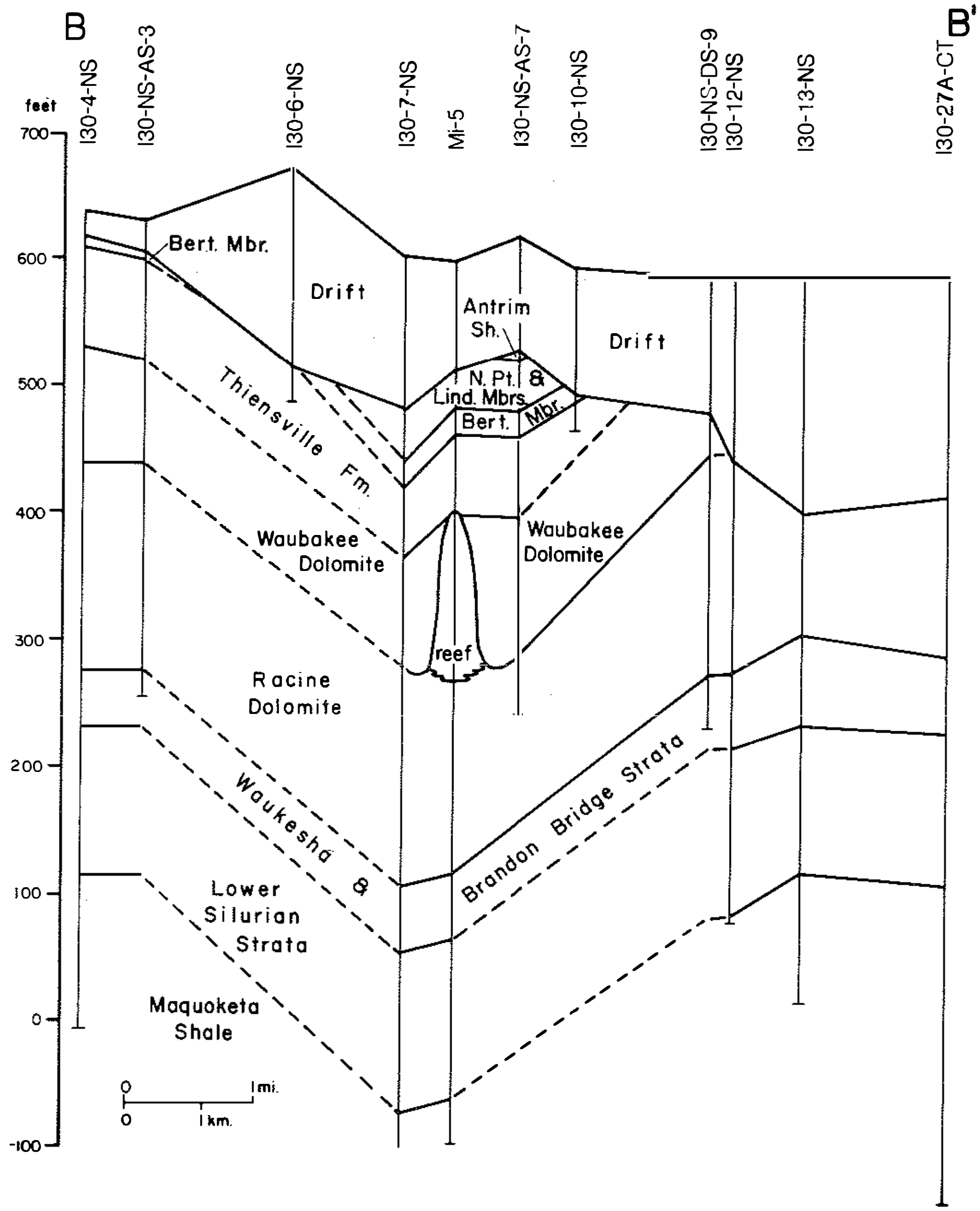

Figure 5. Cross-section B-B' along the Milwaukee River, showing the syncline at North Point and the Riverside Park Racine Dolomite reef (Mi-5) and its relationship with surrounding strata.

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.

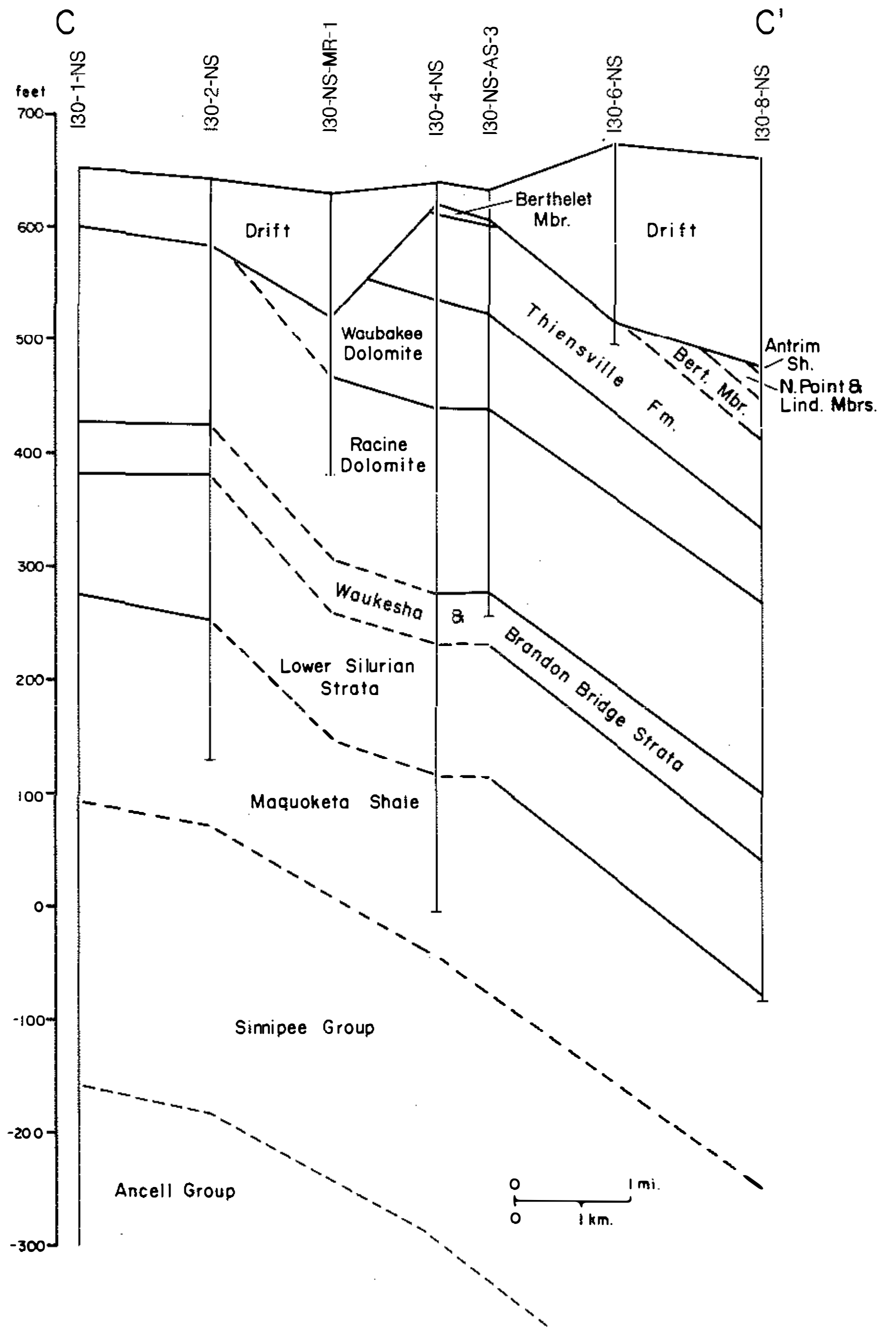

Figure 6. Cross-section C-C' showing the increase in dip of the Silurian and Devonian rock at the western edge of the North Point syncline.

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

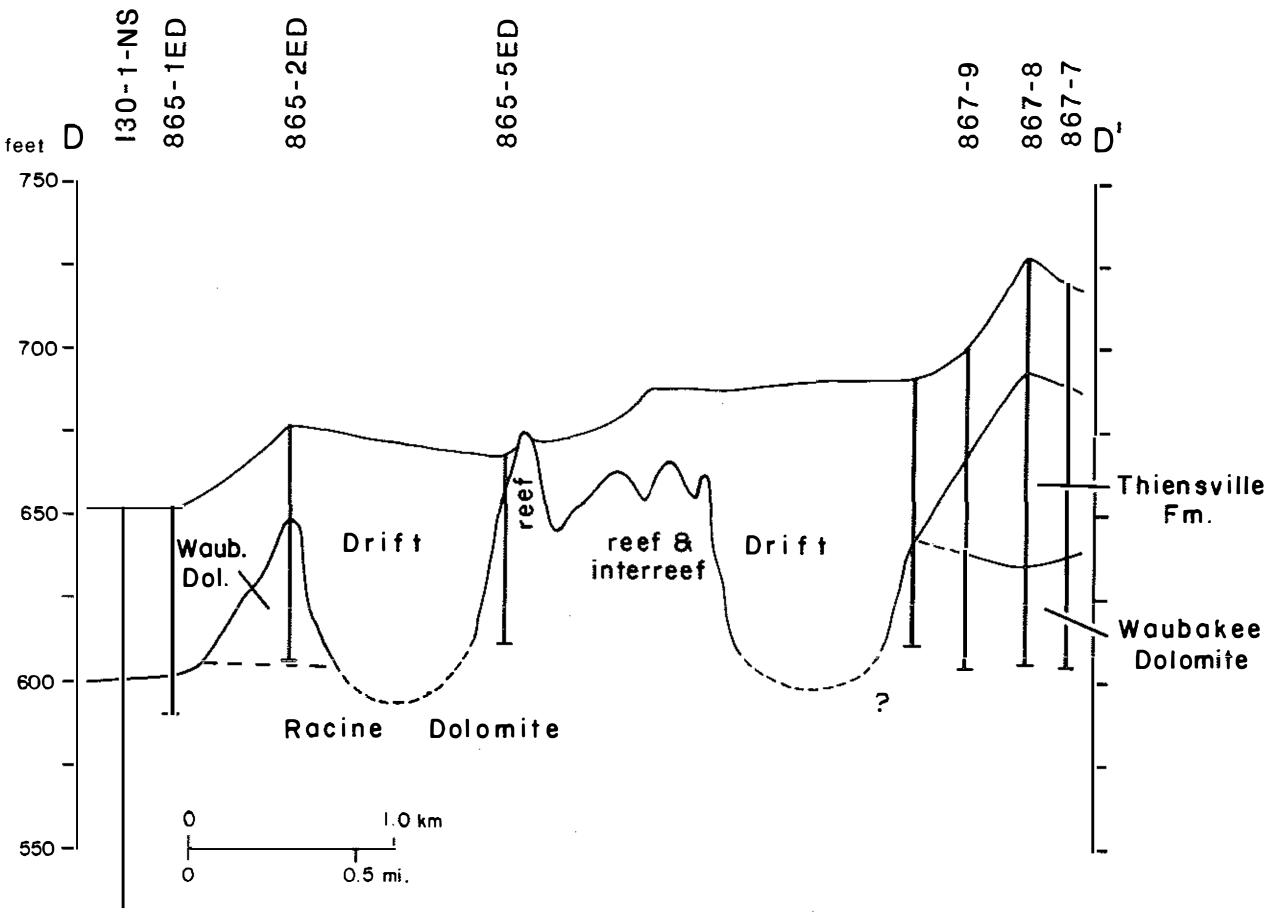

Figure 7. Cross-section D-D' constructed from shallow borings in the vicinity of McGovern Park which show the relationship between the Zautke reef (boring 865-5ED) and surrounding Waubakee Dolomite and Thiensville Formation. Topography between 865-5ED and 867-9 was determined from shallow borings that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

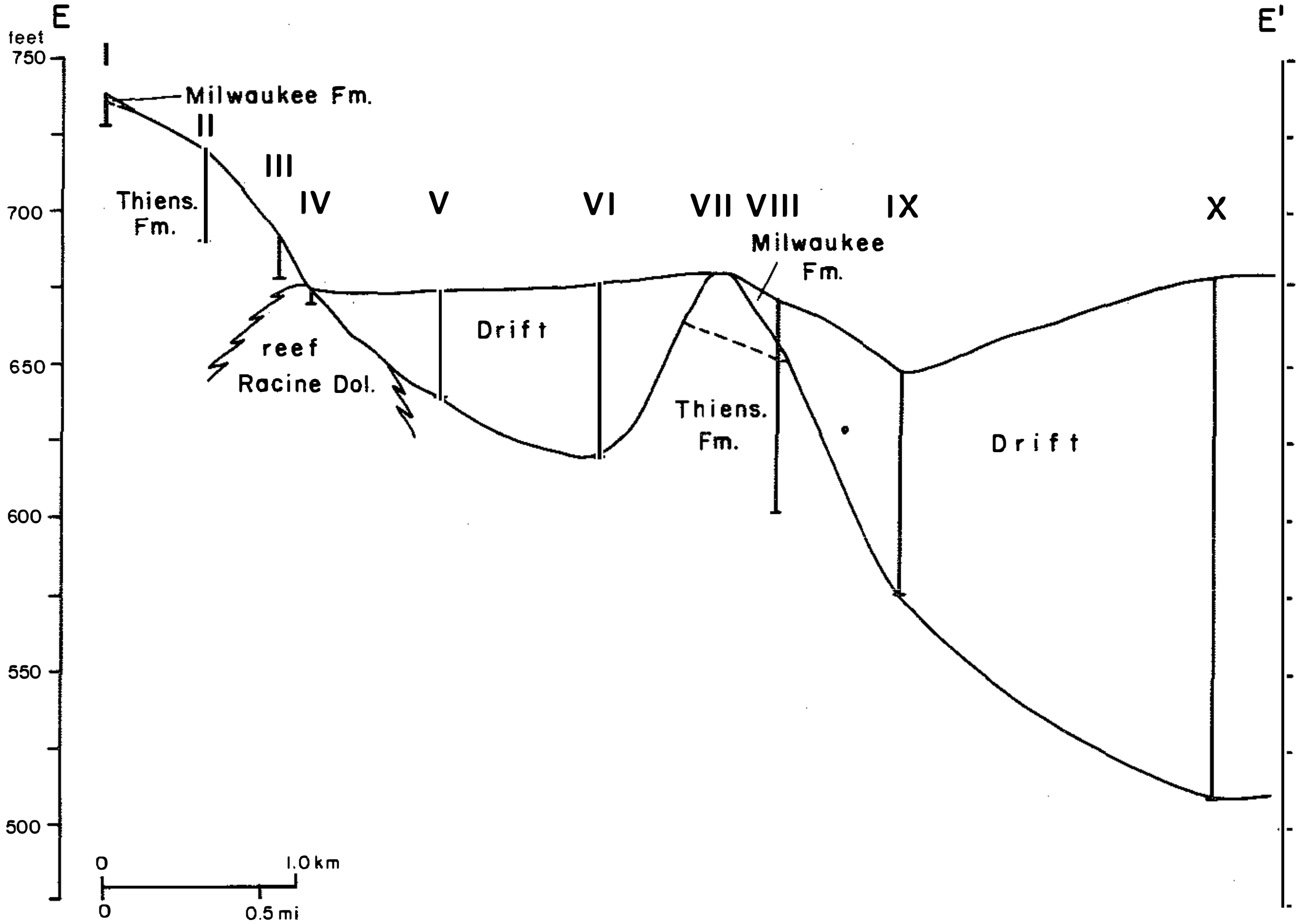

Figure 8. Cross-section E-E' along West Brown Deer Road from North 76th Street east to the Milwaukee River. I=excavations in the vicinity of St. Catherine's Catholic Church described by Chamberlin (1877) and Raasch (1925, unpublished fieldnotes). II=sewer excavations exposed in 1971. III=ditch along 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.

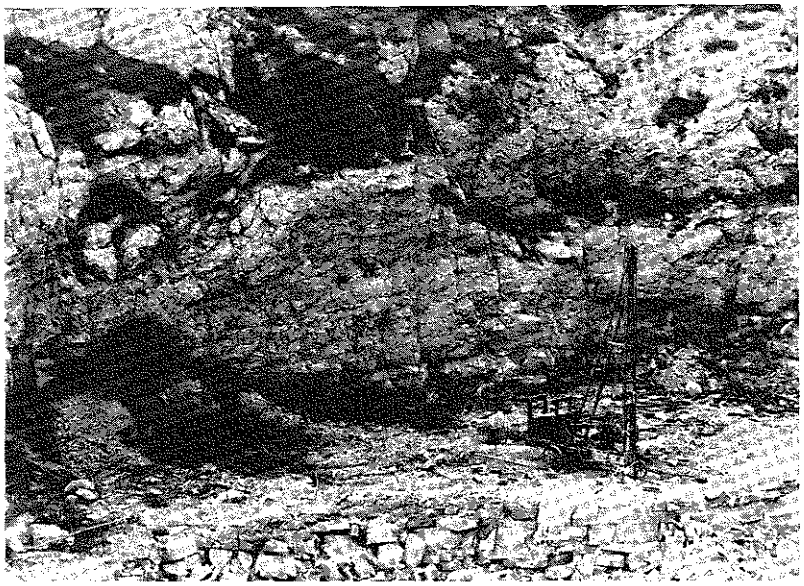

Figure 9. Massive Racine Dolomite reef strata overlying well-bedded nonreef Racine Dolomite in the northwest corner of the now-filled Francey Quarry, SW1/4SW1/4SE1/4 sec. 22, T. 7 N., R. 22 E., Milwaukee 7.5-minute quadrangle, Wauwatosa, Milwaukee County, Wisconsin. Photo circa 1915, courtesy of Milwaukee 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.

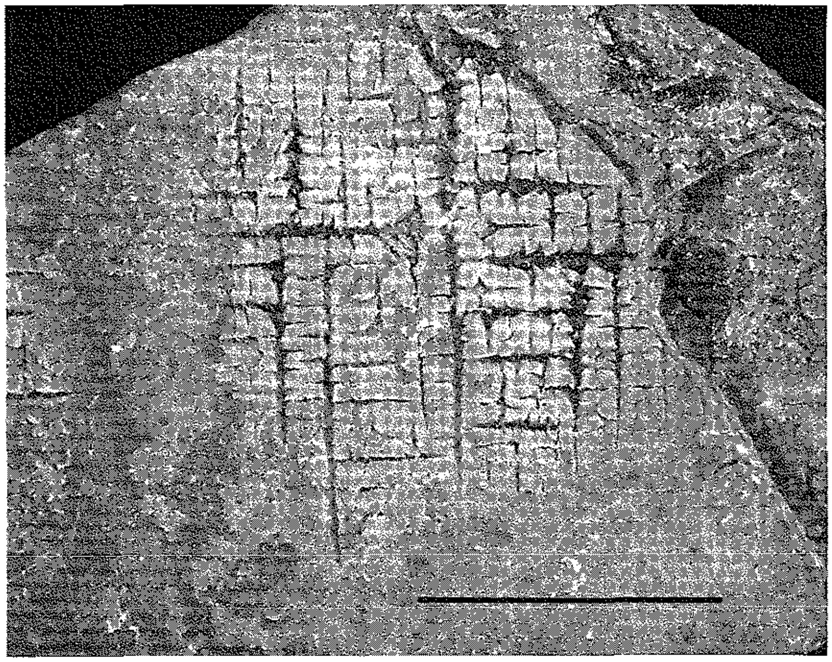

Figure 11. Waubakee Dolomite showing pseudomorphs of skeletal halite. Predominant reticulate ridge pattern indicates preferential precipitation of halite on cub edges and corners on the floors of very shallow brine pools that evaporated due to dryness (Southgate, 1982). Sample from sewer tunnel excavation 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

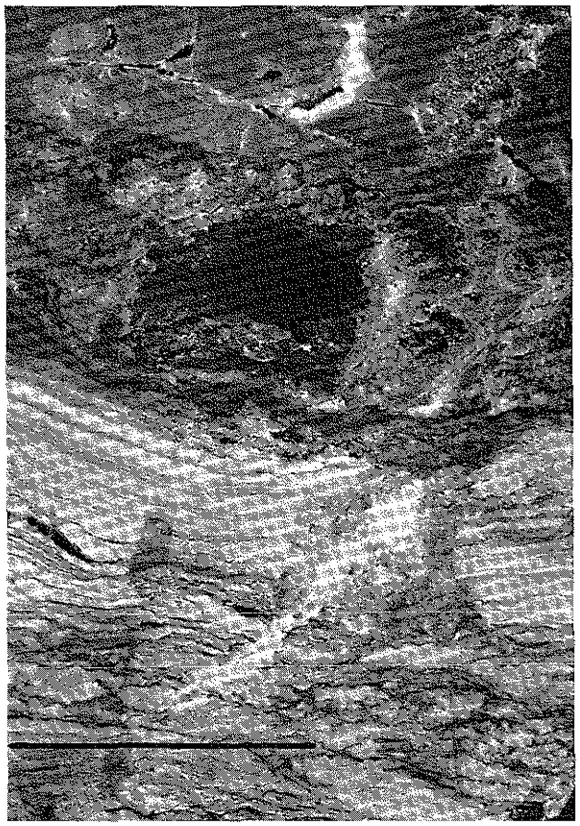

Figure 13. Thiensville Formation, vuggy brecciated yellowish brown (10 YR 5/2) limestone overlying grayish orange (10 YR 6/2) brecciated laminated to nodular dolomite and limestone. Small nodules in the laminated lithology probably are due to growth of anhydrite nodules. Laminae are inclined and are 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.

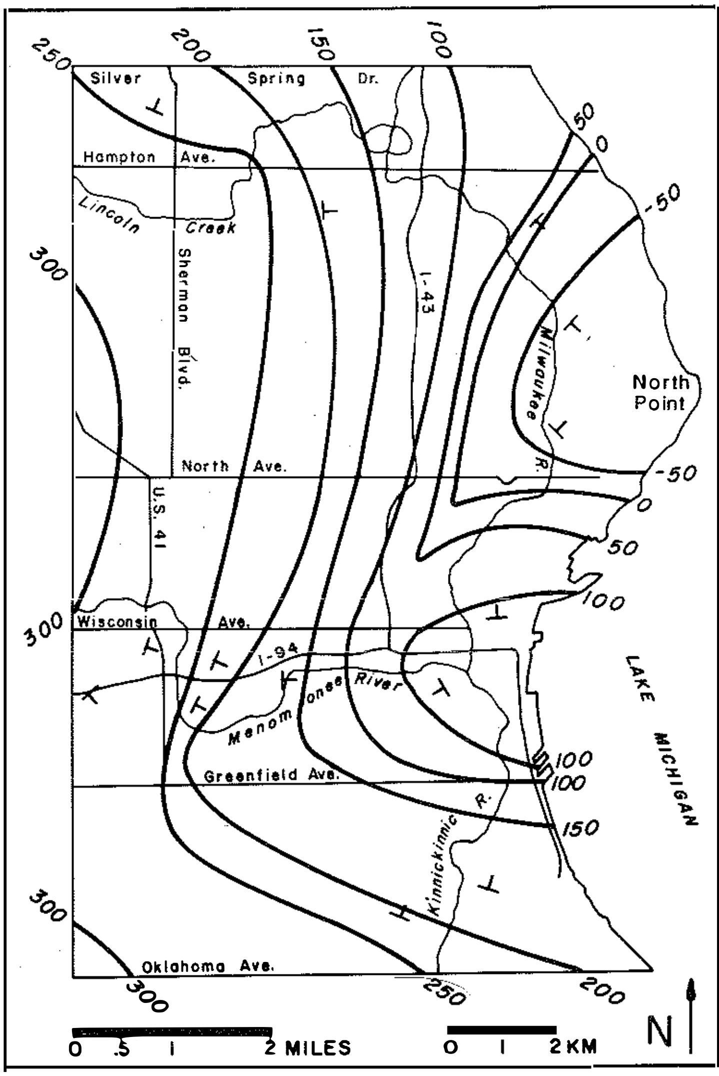

Figure 15. Structure-contour map of the base of the Silurian in east-central part of Milwaukee County, Wisconsin. Each dip symbol represents data derived from a three-point problem utilizing core or water-well log information. Contour interval in feet.

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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PLEISTOCENE GEOLOGY OF THE MARATHON COUNTY AREA OF CENTRAL WISCONSIN

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ABSTRACT

Five geomorphic areas, each with distinctive topography and surficial materials, are present in the Marathon County area. The entire area was glaciated during the Pleistocene, but well-preserved glacial topography occurs only on geomorphic area 5, the area which was glaciated during the late Wisconsin. In the other areas erosion has removed glacial landforms, and the degree of dissection increases with the age of surficial materials. Each geomorphic area represents the surficial exposure of a different glacial sedimentary unit. Glacial sedimentary units have been designated as formations and members ranging in age from pre-Illinoian (Marathon Formation) through late Wisconsin (Mapleview Member).

INTRODUCTION

Marathon and northern Wood Counties are located in central Wisconsin (fig. 1), most of which was glaciated before the last part of the Wisconsin Glaciation (before about 25,000 years ago). Only the easternmost part of Marathon County was glaciated during the last part of the Wisconsin Glaciation about 25,000 to 10,000 years ago in Wisconsin. A number of aspects of earlier Pleistocene history have been studied (see for example Chamberlin, 1882; Leverett, 1899; Weidman, 1907; Hole, 1943b; Thwaites, 1943; Black, 1962; Stewart, 1973; Mode, 1976; LaBerge and Myers, 1983). Although much work has been done, the answers to many questions regarding the Pleistocene history of the area remain incomplete. This summary paper is a revised version of a paper prepared for the 50th Annual Tri-State Field Conference (Mode and Attig, 1986).

For discussion purposes Marathon County and the northern part of adjacent Wood County can be divided into five areas, each of which contains a characteristic landscape and characteristic Pleistocene sediment (fig. 2; table 1; Attig and Muldoon, in preparation; Clayton, in preparation). In this paper we discuss each of the five areas, their landscape, the nature of underlying Pleistocene sediment, and various aspects of Pleistocene stratigraphy and history.

PREVIOUS INVESTIGATIONS

Most workers have interpreted the relative thinness of Pleistocene sediment beyond the outer late Wisconsin moraine to be the result of extensive erosion and therefore treated the thinness as evidence of great age. Some (for example Hole, 1943a, b) have suggested that the sediment was deposited by a thin, debris-poor glacier that was short-lived. One reason for such interpretations is the paucity of exposures in central Wisconsin, especially

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Table 1. Characteristics of geomorphic areas in Marathon County and adjacent Wood County.

AREA	GEOMORPHIC CHARACTER	PLEISTOCENE MATERIALS (Excluding valley-fill deposits)
1.	Low relief, rolling topography; Pleistocene sediment is thin and discontinuous on Precambrian or Cambrian rock	Undifferentiated Marathon Formation including the Wausau Member of the Marathon Formation
2.	Gently rolling topography on uplands; Precambrian or Cambrian rock rarely crops out except where streams have incised through the Pleistocene sediment	Edgar Member of the Marathon Formation
3.	Broad ridge with no small-scale glacial features	Bakerville Member of the Lincoln Formation overlying sand and gravel (calcareous) and the Edgar Member of the Marathon Formation
4.	Gently rolling topography with some subdued glacial topography, including moraine ridges and areas of hummocky topography	Merrill Member of the Lincoln Formation
5.	High-relief hummocky topography in moraines; very fresh glacial landscape with much collapse topography and many undrained depressions	Mapleview Member of the Horicon Formation

those containing more than one stratigraphic unit. Recent studies of the stratigraphy of the area using a power auger have added to our knowledge of the nature and distribution of lithostratigraphic units present (Attig and Muldoon, in preparation).

The earliest geologic map of the area showed Pleistocene material beyond the outer late Wisconsin moraine as an Older Drift of the First Glacial Epoch, bounded on the south by the Driftless Area, and bounded on the north by the prominent moraine of the Younger Drift of the Second Glacial Epoch (fig. 3a; Chamberlin and Salisbury, 1885; Chamberlin, 1882, 1883). The main distinction for these workers between late Wisconsin material and older Pleistocene material was thickness, but they also noted the advanced degree of decay of pebbles in the older material.

Chamberlin (1882) opened the debate about interpretation of the area of older glacial deposits when he stated that the topography was mainly preglacial and had only been slightly modified by deposition of a thin veneer of glacial sediment. He apparently did not feel this was the sole reason for the topography, however, because he was later cited by Weidman (1907; through personal communication) as having noted that the advanced state of erosion of the older deposits was comparable to that of material deposited during the Kansan Glaciation in Iowa.

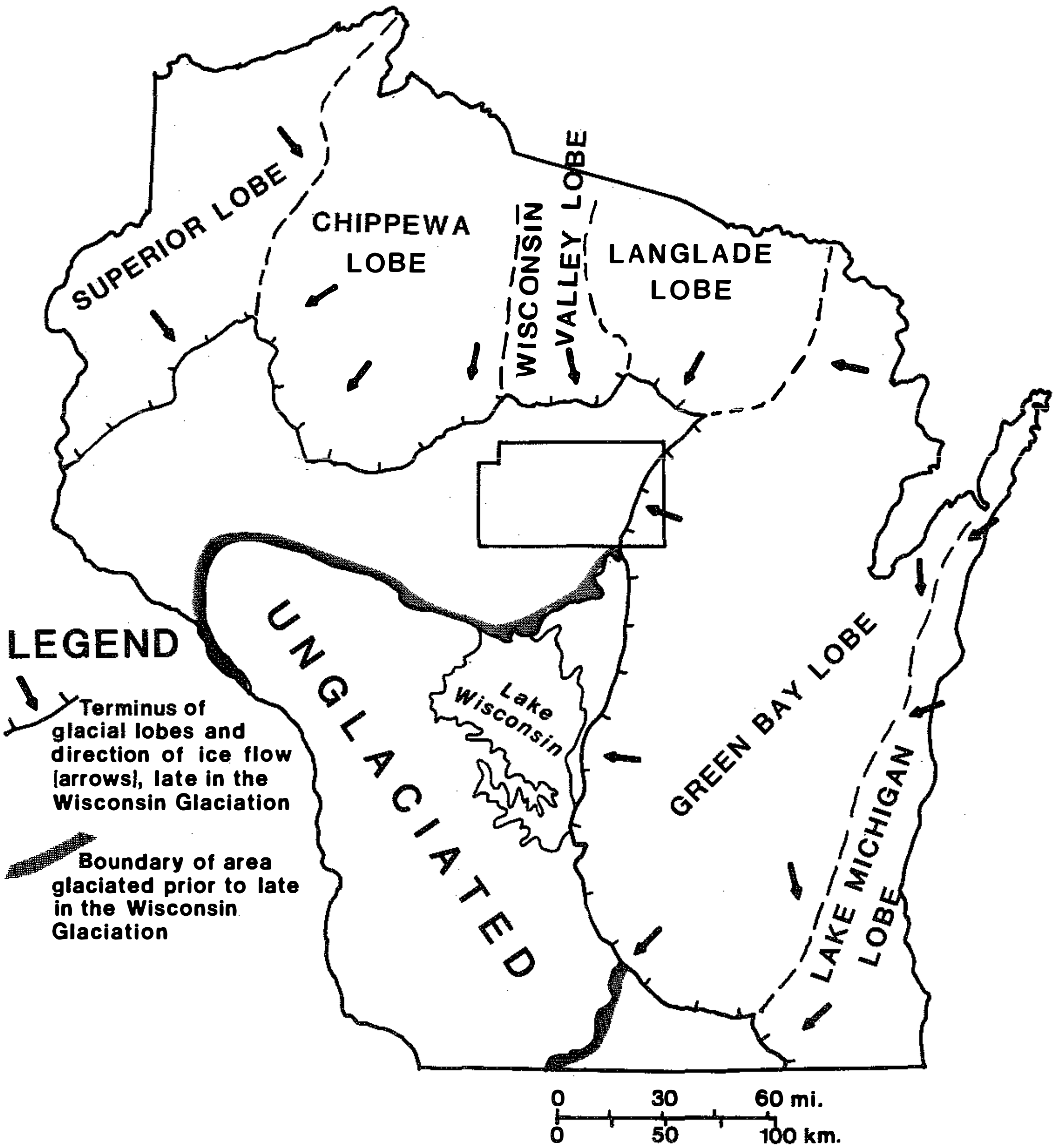

Figure 1. Location of glacial lobes in Wisconsin. Marathon County is outlined and Wood County adjoins its southern boundary.

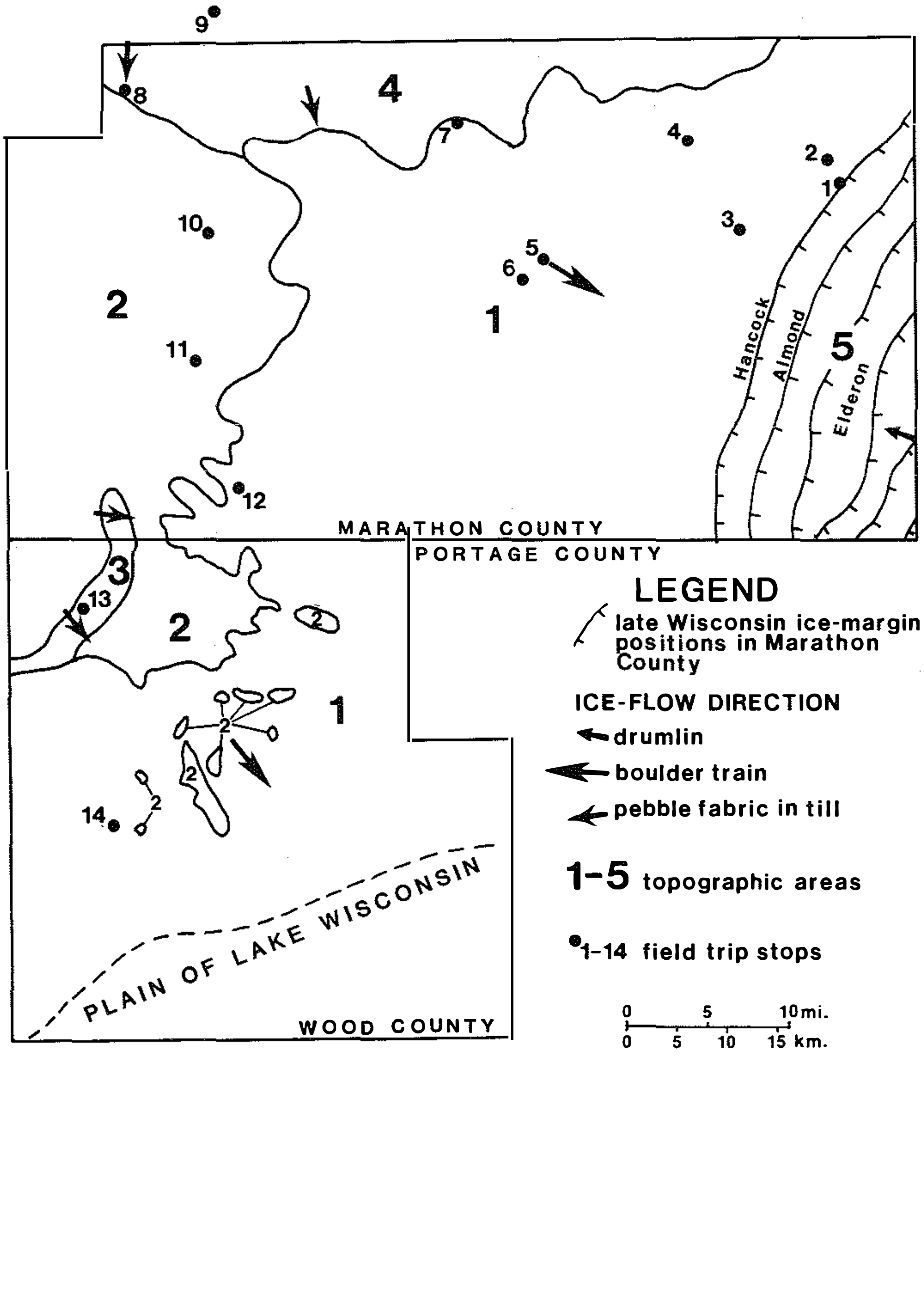

Figure 2. Geomorphic areas in Marathon (Attig and Muldoon, in preparation) and Wood Counties (Clayton, in preparation).

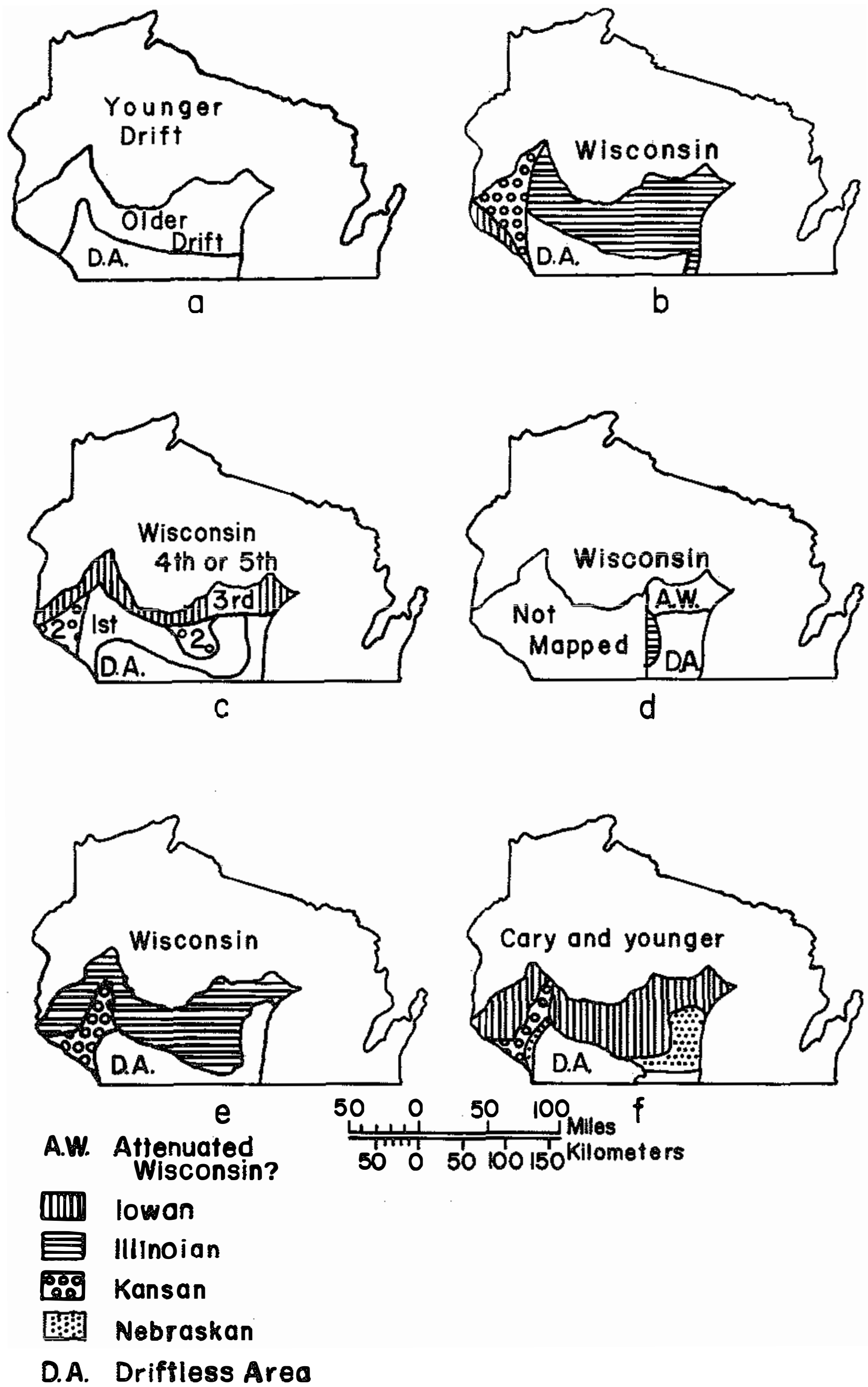

Figure 3. Interpretations of the age of older glacial deposits in central Wisconsin. a) Chamberlin and Salisbury (1885); b) Leverett (1899); c) Weidman (1907, 1913); d) Leverett and Taylor (1915); e) Leverett, in Antevs (1929); and, f) Thwaites (1955).

Leverett (1899) distinguished one pre-Wisconsin unit in central Wisconsin and assigned it an Illinoian age on the basis of color, clay content, pebble lithology, and degree of weathering (fig. 3b).

Weidman (1907) mapped First, Second, and Third Drifts in the area of older materials, with the First Drift being oldest and farthest south (fig. 3c), but he thought that central Marathon County was unglaciated. He used weathering to distinguish units and as an index of relative age. Feldspar grains in igneous clasts are weathered to kaolinite at depths of 10 to 15 feet in the First Drift and 10 to 20 feet in the Second Drift. The yellowish-brown color of oxidized First and Second Drifts results from extensive oxidation and disintegration of iron-bearing minerals to a greater degree than has occurred in the reddish brown Third and Fourth Drifts. Abundant clay and compaction were also thought to reflect the greater age of the First and Second Drifts.

According to Weidman, the Third Drift was intermediate in age between the Fourth (Wisconsin) Drift, and the First and Second Drifts. Though more dissected than the Fourth Drift, it has discontinuous, ice-marginal ridges and hummocky topography, and the degree of weathering is much less than in the First and Second Drifts. Weidman (1913) correlated the Second Drift with the Kansan of Iowa and the Third Drift with the Iowan of northeastern Iowa.

Weidman also discussed the origin of the topography. He believed that the topography in areas of extensive postglacial stream trenching was no longer influenced by the older materials, but in areas where the streams were not deeply entrenched, the older materials did influence topography. This interpretation was based on his observations of overburden thickness. The average thicknesses of till of the First, Second and Third Drifts are 8, 30, and 5 feet, respectively, and Weidman found that each drift thickened at its edge, which he interpreted as remnants of end moraines. However, other workers (Chamberlin and Salisbury, 1885; Hole, 1943a,b) found that the older glacial deposits thin continuously and gradually from north to south.

In a map drafted in 1913 Leverett and Taylor called Weidman's First and Second Drifts both Illinoian, and did not distinguish them from each other. The map also showed Weidman's Third Drift as "Attenuated Drift, Wisconsin?" (fig. 3d). Leverett (in Antevs, 1929) correlated virtually all of the older materials with the Illinoian (fig. 3e).

Hole (1943a, b) concluded that the older materials were only one rock unit and that it was probably Wisconsin (Cary) in age. He saw no strong evidence for more than one glacial event because there were no multiple-till exposures, no till beneath buried soils, and nothing but gradual changes in till lithology, which he thought reflected local differences in bedrock. He found that the older material was not more deeply weathered than late Wisconsin (Cary) deposits, and suggested that Cary ice first advanced to the edge of the Driftless Area and then retreated rapidly before coming to a prolonged halt and depositing prominent end moraines.

Thwaites (1943) found no unglaciated area in Marathon County and stated that moderate erosion and weathering and immature soil profiles in the older materials indicate an Iowan age. His map (1955) showed most of the older sediment as Iowan, but some was mapped as Nebraskan (fig. 3f).

Black (1962) introduced the term Rockian for the period of glaciation in Wisconsin that began around 30,000 B.P. At that time he felt that there were no Pleistocene deposits in Wisconsin that were older than Rockian, that the older materials in central Wisconsin were Rockian, and that it was Rockian ice which glaciated the Driftless Area. He was later to agree with others that there may have been some pre-Rockian glaciation of the state (Frye and others, 1965; Black and others, 1965; Black and Rubin, 1968).

Based on lithologic and weathering studies in northern Marathon County, Olup (1969) supported Hole's (1943a, b) conclusion that the First, Second, and Third Drifts of Weidman (1907) are petrologically the same, and he assigned this single unit a Rockian age.

LaBerge and Myers (1983) defined two old glacial units in eastern Marathon County in the area beyond the outer late Wisconsin moraine and informally named the two till units the Wausau and the Merrill. The Merrill corresponds to Weidman's (1907) Third Drift, and the Wausau is found in Weidman's Driftless Area near the Wisconsin River and in the area of the First Drift. It is extremely thin, and its distribution is patchy. Stewart (1973) differentiated three till units, the Merrill, Wausau, and late Wisconsin using color, grain-size distribution, and clay mineralogy. The Wausau and Merrill units have much higher vermiculite contents than late Wisconsin till. The Wausau unit, which was found beneath the Merrill unit in one locality, has abundant smectite. A radiocarbon date of 40,800 2,000 B.P. (ISGS-256) on organic sediment overlying the Merrill (Stewart and Mickelson, 1976) was the first conclusive evidence that the older materials were deposited before late Wisconsin time.

Mode (1976) informally named two additional old till units, the Bakerville and Edgar (fig. 4). In power auger holes he found the Bakerville overlying the Edgar and the Edgar overlying the Wausau. Dark gray, organic-rich sediment (till?) was also found underlying the Edgar in several drill holes. Drilling logs of Bell and Sherrill (1974) also recorded this dark gray material in the subsurface. The distinctive feature of till of the Edgar unit is that it contains abundant calcite.

Mickelson and others (1984) formalized the Pleistocene rock stratigraphy of Wisconsin. Units that are found in the area described here are shown in figure 5. The Pleistocene geology of Marathon County (Attig and Muldoon, in preparation) and Wood County (Clayton, in preparation) are now being studied by the Wisconsin Geological and Natural History Survey.

The emphasis of this review has been upon the older glacial deposits. Attig and others (1985) reviewed the late Wisconsin glacial history and designated the St. Croix-Hancock Phase as the time when the outer moraine (Hancock moraine of Clayton, in press) of the Green Bay Lobe formed, about 18,000 to 15,000 B.P.

GEOMORPHIC AREAS

The landscape of Marathon County and part of Wood County can be divided into five areas, each of which has distinctive topography and surficial materials (fig. 2; table 1). The topographic character of each area is

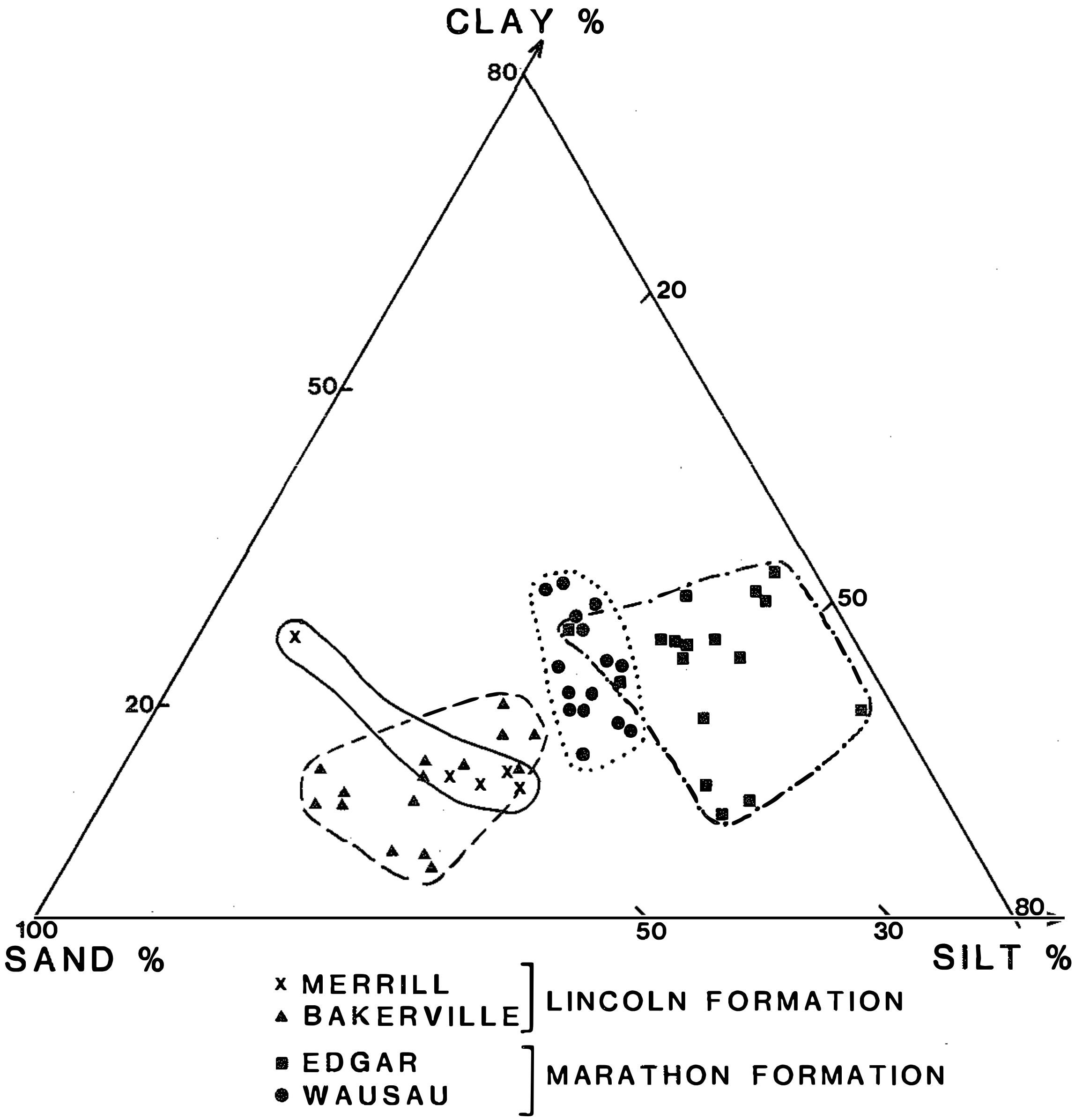

Figure 4. Grain-size distribution of the less-than-2 mm fraction of till samples from Marathon County and adjacent areas (Mode, 1976).

MEMBERS	FORMATIONS
MAPLEVIEW	HORICON
MERRILL	LINCOLN
BAKERVILLE	
EDGAR	MARATHON
?—?—	
UNNAMED(?)	
WAUSAU	

Figure 5. Pleistocene stratigraphic units in Marathon County (Mickelson and others, 1984).

primarily related to the time since the area was last glaciated, but it is also related to the proximity of major drainage and the nature, thickness, and distribution of Pleistocene material.

Area 1

Area 1 occupies central Marathon and Wood Counties (fig. 2) and is characterized by rolling topography developed on Precambrian igneous and metamorphic rock and Cambrian sandstone (fig. 6). This is approximately the same area that Weidman (1907) interpreted to be unglaciated, but that was later recognized as being glaciated (Thwaites, 1943; LaBerge and Myers, 1983). Soils are poorly drained because Precambrian rock is near the surface and the overburden has abundant clay. Many rock outcrops occur and the highest points in the landscape are typically underlain by resistant lithologies such as the quartzite underlying Rib Mountain. No glacial topography is preserved except for late Wisconsin outwash surfaces in the valleys of the Wisconsin, Eau Claire, and Rib Rivers.

Attig and Muldoon (in preparation) have mapped the thin surficial materials of this area as undifferentiated Marathon Formation, a map unit which includes till of the Wausau Member, possible other old till units, residuum, and slope deposits. These individual constituents cannot be differentiated because outcrops are few and the materials are not readily distinguishable from

Table 2. Till characteristics, Marathon County. Clay minerals are illite (I), kaolinite-chlorite (K), vermiculite (V), and smectite (S). Calc? indicates whether the till is calcareous. NA means no data are available.

Formation & Member	Color	Sand/silt/ clay (%)	Clay Mins (%) I	K	V	S	Calc?
Horicon							
Mapleview	brown (7.5 YR 4/4) to reddish brown (5 YR 4/4)	83/13/4	69	13	5	14	no
Lincoln							
Merrill	dark reddish brown (5 YR 3/4 to 2.5 YR 3/4)	62/28/10	53	9	22	16	no
Bakerville	reddish brown (5 YR 4/4)	62/25/13	53	8	14	25	no
Marathon							
Edgar	variable; yellowish brown (10 YR 5/6) to reddish brown (5 YR 4/4)	33/43/24	44	6	17	33	yes
unnamed member	brownish black (10 YR 2/2)	NA	NA				yes
Wausau	brown (7.5 YR 4/4)	43/34/23	44	5	18	32	no

one another in the field. Scattered erratics derived from the Lake Superior region, especially clasts of Keweenawan volcanic rock, and loess are widespread at the surface. Wind polished and faceted cobbles are common in this area.

Till of the Wausau Member is found directly overlying Precambrian rock. The Wausau Member of the Marathon Formation is the oldest Pleistocene unit in Marathon County (fig. 5). It contains brown, pebbly loam to clay loam till (fig. 4), which has a clay mineral assemblage dominated by expandable clays, essentially identical to the clay mineral assemblage of till of the Edgar Member (table 2). The reason that till units of the Marathon Formation contain larger amounts of expandable clay than till units of the Lincoln and Horicon Formations is one or more of the following: they were derived from a different source region; they were derived from deeply weathered source materials, which, when removed by glacial erosion, exposed fresh rock to erosion by subsequent advances; or, they have become more deeply weathered since they were deposited. Systematic change in clay mineralogy occurs with increasing depth in Marathon Formation till (Stewart, 1973; Mode, 1976), which demonstrates that weathering has caused at least some of the difference in clay mineralogy

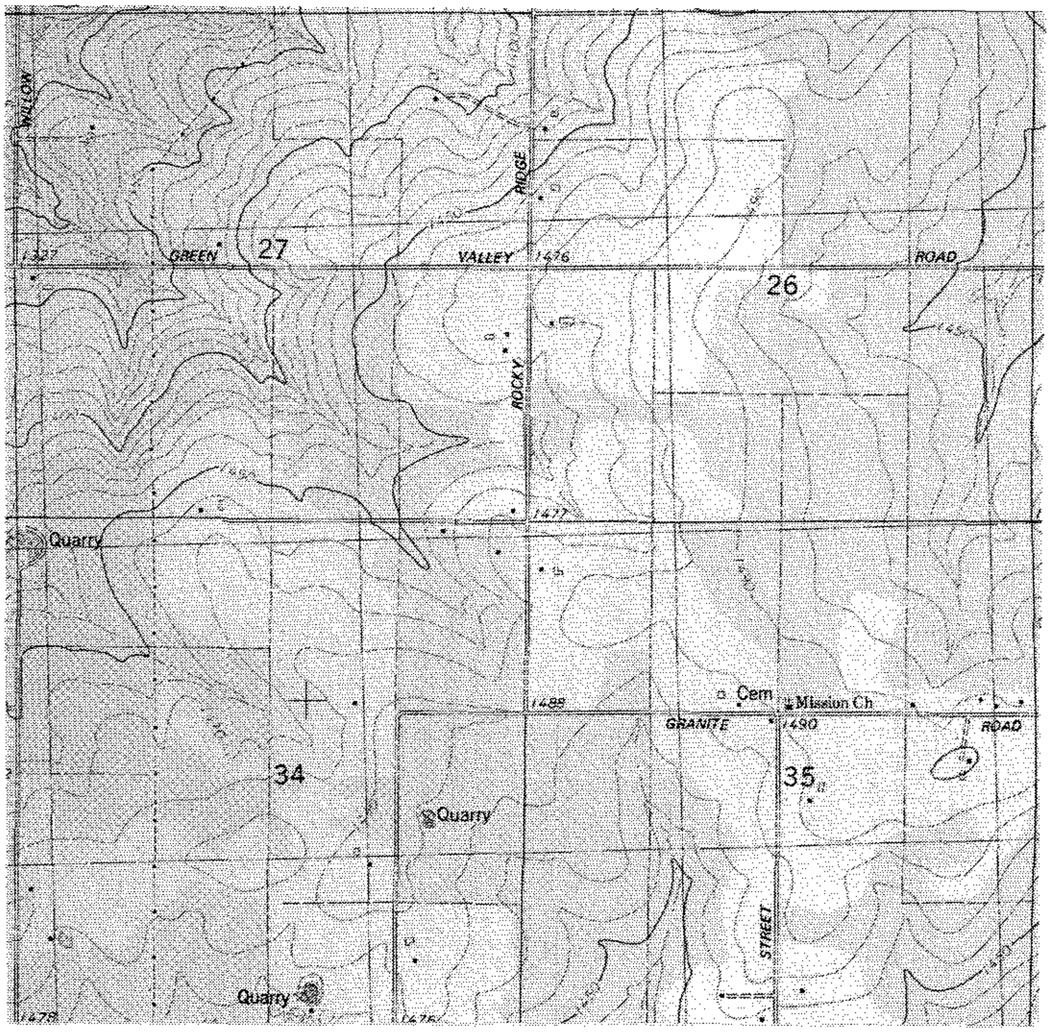

Figure 6. Topography of area 1, undifferentiated Marathon Formation (Attig and Muldoon, in preparation) in north-central Marathon County, Nutterville 7.5-minute quadrangle, T. 30 N., R. 8 E.

between the Marathon Formation and the Lincoln and Horicon Formations. Boulder trains (fig. 2) indicate that ice-flow direction across area 1 was southeast to east-southeast (Weidman, 1907; LaBerge and Myers, 1983; Clayton, in preparation).

Area 2

Western Marathon County and northwestern Wood County are included in area 2 (fig. 2). This area roughly corresponds to the area of Weidman's (1907) Second Drift. Flat to gently rolling uplands with a few deeply incised valleys are the most obvious topographic characteristics. Outcrops of rock in upland areas are uncommon. No glacial topography is preserved (fig. 7). Drainage is well integrated, and no lakes and few bogs occur. Soils are better drained than in area 1, resulting in considerably more cultivation in area 2.

The surficial material in area 2 is the Edgar Member of the Marathon Formation (Attig and Muldoon, in preparation). Its thickness reaches 25 m on uplands and is commonly 15 m. The brown, loam till of the Edgar Member is similar to that of the Wausau Member except that it is calcareous and contains more silt (fig. 4; table 2). It is leached of carbonates to depths of as much

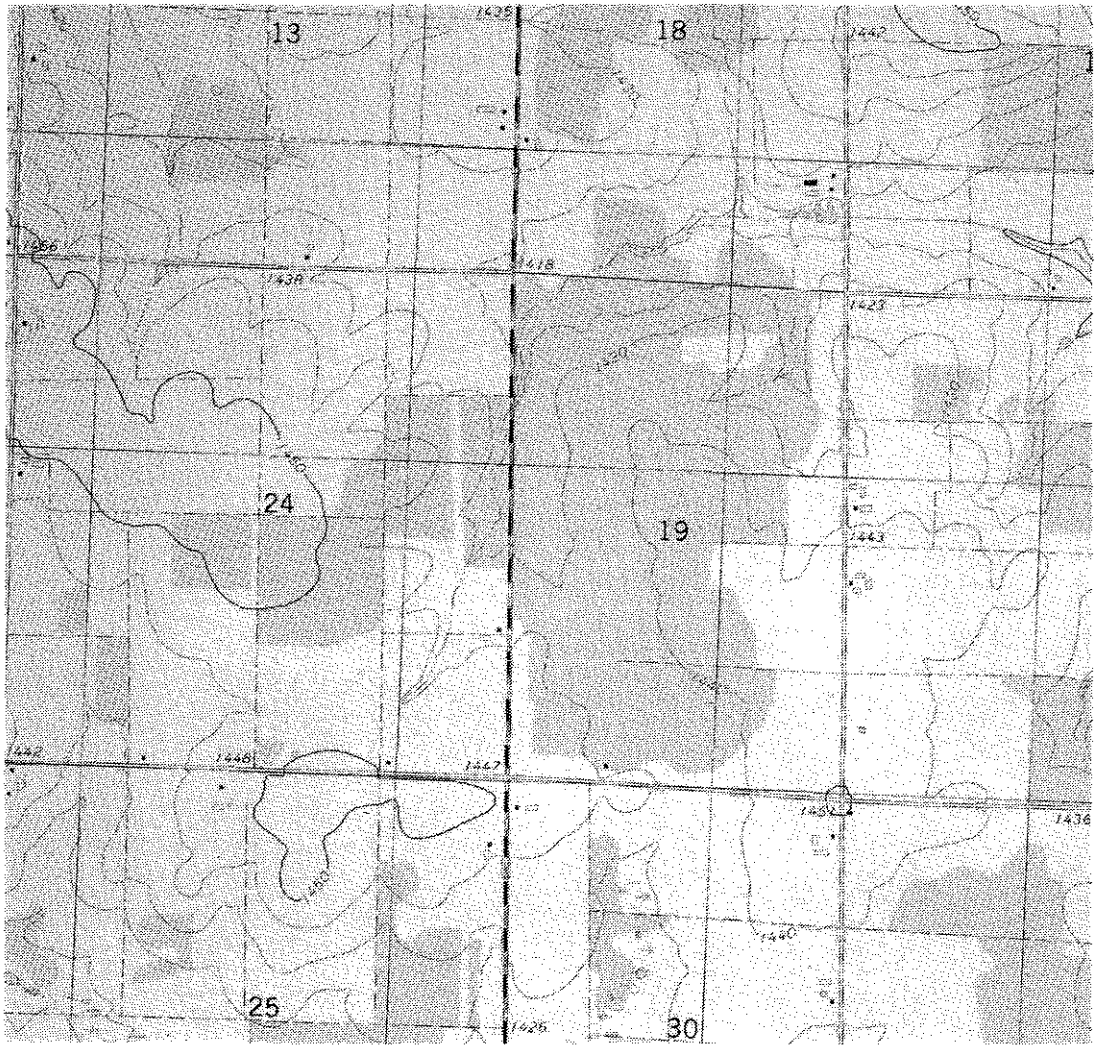

Figure 7. Topography of area 2, the Edgar Member of the Marathon Formation (Attig and Muldoon, in preparation) in northwestern Marathon County, Wein 7.5-minute quadrangle, T. 29 N., R. 3 and 4 E.

as 3 m, but below this level pebbles of fossiliferous limestone are present. In a few areas calcareous material is present within 1 m of the surface. Mode (1976) measured one pebble fabric in till that indicated southward ice flow.

Till of the Edgar Member overlies the Wausau Member, organic sediment, and weathered rock. Organic sediment may also be interstratified with till of the Edgar Member. Though Mickelson and others (1984) distinguished organic sediment as an unnamed member of the Marathon Formation, it may be part of the Edgar Member. Attig and Muldoon (in preparation) report that till of the Edgar Member was deposited by more than one glacial advance. A zone of leached till and organic materials has been encountered within the till section in several power-auger holes.

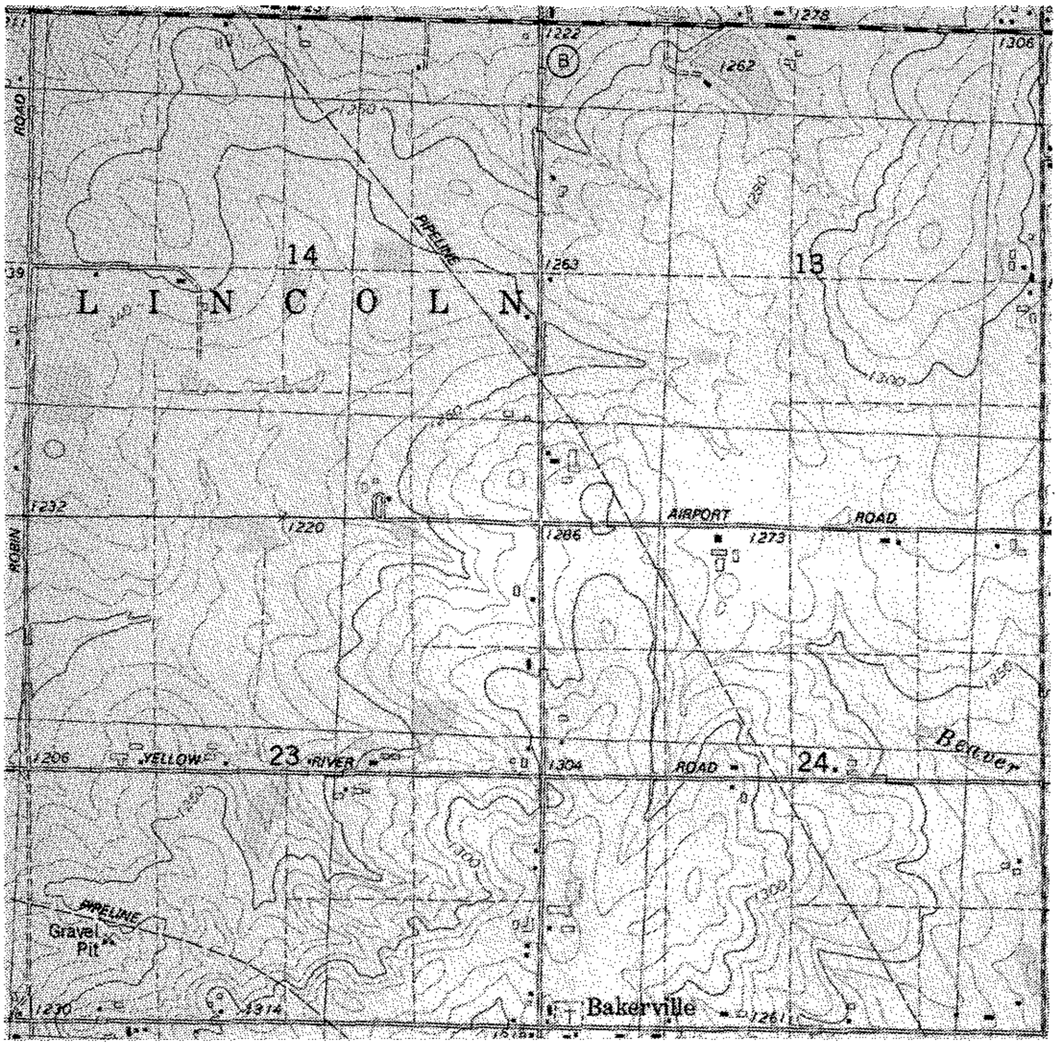

Figure 8. Topography of area 3, the Bakerville Member of the Lincoln Formation (Attig and Muldoon, in preparation) in northwestern Wood County (Clayton, in preparation), Marshfield 7.5-minute quadrangle, T. 25 N., R. 2 E.

Area 3

Area 3 is a broad ridge (fig. 8) in southwestern Marathon and northwestern Wood Counties that has been called the Marshfield moraine (Weidman, 1907), though it has no small-scale glacial topography (fig. 2). Weidman (1907) interpreted this ridge as an end moraine at the southern edge of his Second Drift. The Black and Yellow River valleys are deeply incised where they cut across this ridge. Soils are well drained because of deeply buried rock and permeable surficial material. Surficial material on the crest of the ridge is the Bakerville Member of the Lincoln Formation (Mode, 1976), and it is as much as 30 m thick.

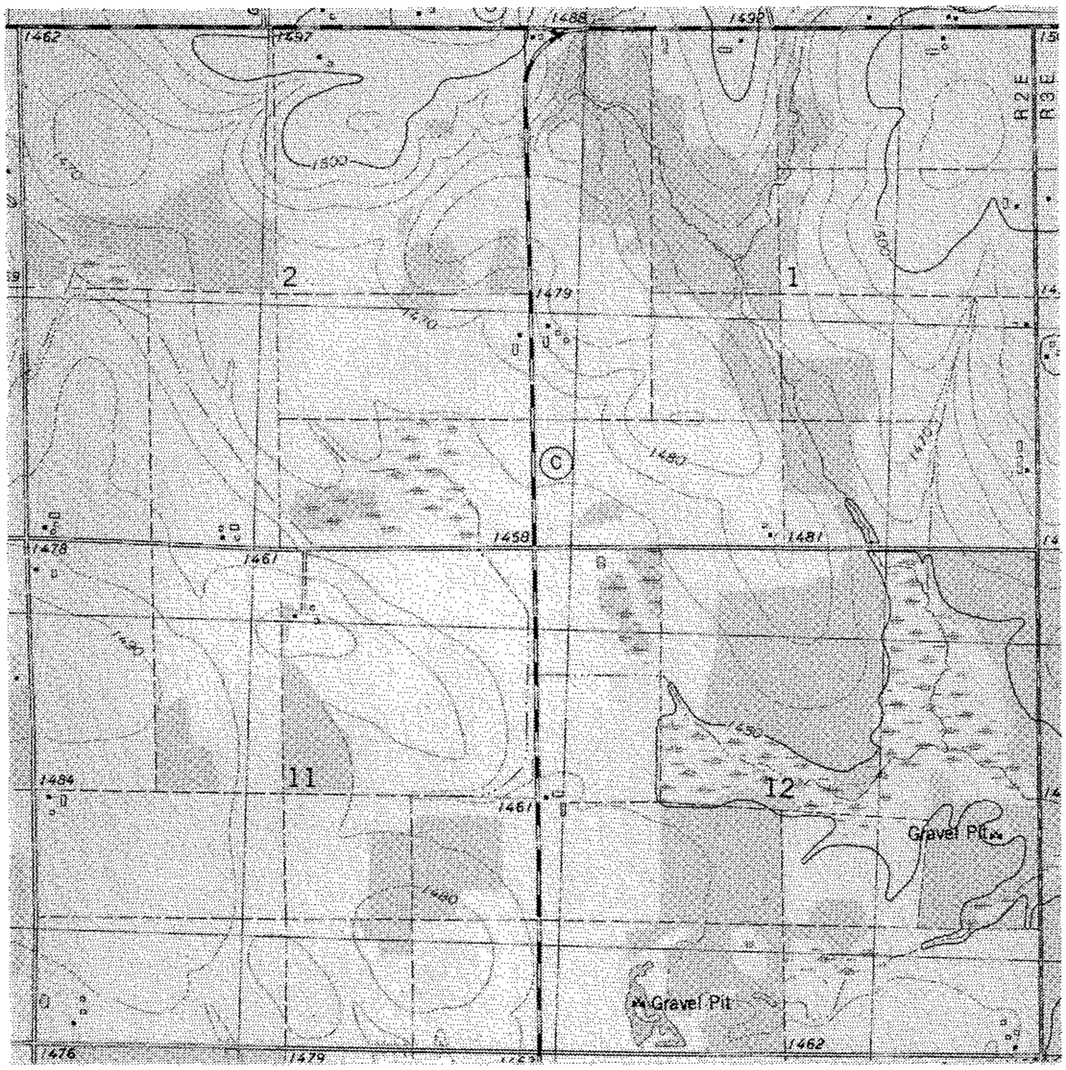

Figure 9. Topography of area 4, the Merrill Member of the Lincoln Formation (Attig and Muldoon, in preparation) in southeastern Taylor County adjacent to northwestern Marathon County, Corinth 7.5-minute quadrangle, T. 30 N., R. 2 E.

Till of the Bakerville Member is reddish brown, sandy loam and consistently redder, sandier (fig. 4), and more illite-rich than till of the Marathon Formation (table 2). It contains erratics from the Lake Superior region. Pebble fabrics in till indicate southeastward and eastward ice-flow directions (fig. 2). This till is lithologically very similar to that of the Merrill Member of the Lincoln Formation (table 2), but the Bakerville Member pinches out 35 km south of the edge of the Merrill Member. Though it has not been found underlying the Merrill Member, it is probably the older of the two because of its position south of the Merrill Member and its greater degree of dissection and lack of glacial constructional topography. The relationship of the Bakerville Member to the Merrill Member will probably not be clear until the area adjacent to Marathon County to the west (Clark County) is studied in detail. Beneath the Bakerville Member, sand and gravel, the Edgar Member, organic sediment, the Wausau Member, and weathered rock may be present. Pleistocene sediment reaches 40 m in thickness in this area.

The deep dissection of area 3 and the absence of hummocky topography, make it difficult to determine whether it originated as an end moraine or is an erosional remnant of a formerly more extensive body of glacial sediment. The ridge is locally underlain by a rock high (Bell and Sherill, 1974), and both the Bakerville and the Edgar Members are thick (Clayton, in preparation; Mode, 1976). The calcareous sand and gravel that separates these two members occurs above the surrounding landscape, and if it represents an outwash surface developed during deposition of till of the Edgar Member, a great deal of that surface and nearly all of the overlying Bakerville Member have been subsequently removed.

Area 4

Area 4 occupies the northern one-fourth of Marathon County (fig. 2), roughly the area of Weidman's (1907) Third Drift, and the Merrill Member of the Lincoln Formation is the surficial material (Attig and Muldoon, in preparation). The landscape is less dissected than area 1, 2, or 3, and constructional glacial landforms, such as ice-marginal ridges, are present in places. Gently rolling topography occurs throughout the area, and undrained depressions are common (fig. 9).

The dark reddish brown, sandy loam till of the Merrill Member is sometimes darker than, but otherwise indistinguishable from, till of the Bakerville Member (fig. 4; table 2). The Merrill Member is much less dissected, and therefore more continuous in its distribution, than any other unit discussed so far. It was this contrast plus the presence of recessional moraines near the northern edge of its area that suggested a late Wisconsin age to many early workers. The Merrill Member reaches a thickness of over 20 m beneath recessional moraines and gradually becomes thinner southward, pinching out 35 km north of the northernmost occurrence of the Bakerville Member in Marathon County. In the absence of a stratigraphic section containing both the Bakerville and Merrill Members, and considering the similarity of the till each contains, it is possible that they are one unit. The Wausau Member or the Edgar Member underlies the Merrill Member in roadcuts near the margin of the latter and in the subsurface.

Two radiocarbon dates on organic sediment overlying till of the Merrill Member suggest it was deposited before late Wisconsin time (earlier than 36,000 B.P. (ISGS-262) and 40,800 2,000 B.P. (ISGS-256); Stewart and Mickelson, 1976).

Area 5

Late Wisconsin end moraines characterize the topography of area 5 (fig. 2 and 10). These ridges are narrow and continuous end moraines. Drainage in area 5 is poorly integrated; many undrained depressions occur, and moraine ridges contain high-relief, hummocky topography. The Eau Claire River valley contains outwash terraces that grade to the outer end moraine. The Plover River, which formed during deglaciation as an ice-marginal stream, drains the proximal side of the outer moraine. Glacial landforms include

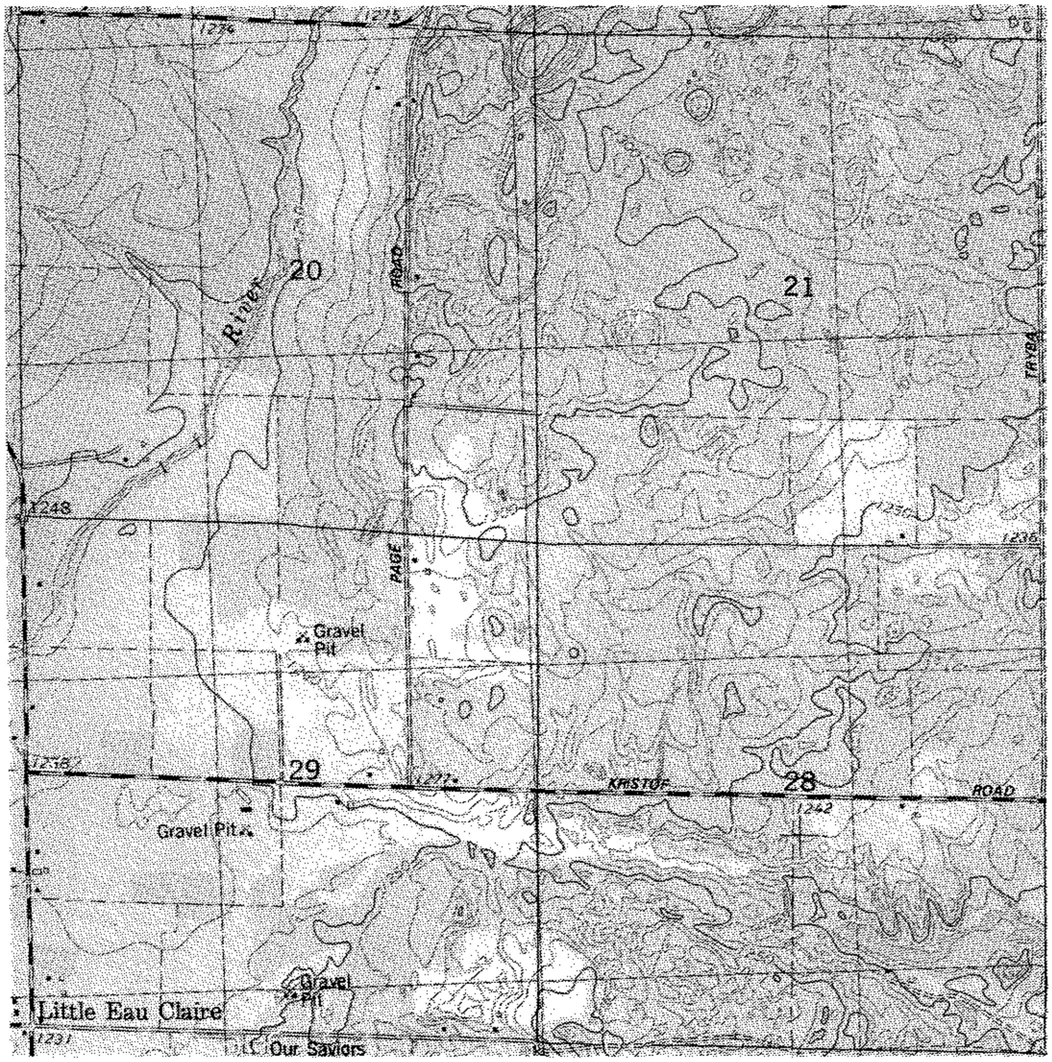

Figure 10. Topography of area 5, the Mapleview Member of the Horicon Formation (Attig and Muldoon, in preparation) in southeastern Marathon County, Bevent 7.5-minute quadrangle, T. 27 N., R. 9 E.

collapsed fluvial deposits, ice-walled-lake plains, and tunnel channels. Surficial materials of area 5 are mapped as the Mapleview Member of the Horicon Formation (Attig and Muldoon, in preparation).

The Mapleview Member includes brown, dolomitic till and associated sediment, which, because of their eastern source, are distinctly different from other Pleistocene deposits in Marathon County. The Mapleview Member is generally thick in Marathon County, and in the few places where its lower contact is exposed, it overlies weathered or fresh Precambrian rock. Till of the Mapleview Member is loamy sand and contains a clay mineral assemblage dominated by illite (table 2). Orientations of moraines and drumlins indicate that ice flow was west-northwestward (fig. 2).

The outer moraine (Hancock moraine; Clayton, in press) and the next moraine to the east (Almond moraine; Clayton, in press) were deposited during the St. Croix-Hancock Phase, between 18,000 and 15,000 yr B.P. (Attig and others, 1985). Ice retreated from Marathon County by 13,000 B.P., and was east of the drainage divide. A a result, meltwater was flowing south along the ice margin and not into Marathon County.

PLEISTOCENE HISTORY AND REGIONAL CORRELATION

The oldest Pleistocene unit in Marathon County is the Wausau Member of the Marathon Formation (fig. 5; Mickelson and others, 1984). The till was derived from the Lake Superior region, and ice-flow indicators reflect southeastward flow. Overlying the Wausau Member are organic sediment and the Edgar Member of the Marathon Formation. Limestone in the Edgar Member indicates a different source from the Wausau Member, and it is probable that an interval of weathering and erosion separated deposition of till of these two members.

The Edgar Member is correlated with the Pierce Formation of western Wisconsin (table 3) (Baker and others, 1983; Baker, 1984) because both members contain limestone. If this correlation is correct, the Edgar Member and the entire Marathon Formation are pre-Illinoian because reversed magnetic polarity indicates that the Pierce Formation is pre-Illinoian (Baker, 1984). The degree of weathering of the Marathon Formation, indicated by magnetite depletion (Johnson, 1984) and the clay mineral assemblage (Mode, 1976), supports this age assignment.

Deposition of till of the Edgar Member was followed by an interval of weathering and erosion; a deep weathering profile occurs in the Edgar Member where it underlies the Lincoln Formation.

The Lincoln Formation was deposited by ice flowing south and southeastward from the Lake Superior basin. This is indicated by derivation of sediment from the Lake Superior region and pebble fabrics in tills. The Lincoln Formation probably is correlative with the River Falls Formation of western Wisconsin (table 3) (Baker and others, 1983; Baker, 1984) because of its similar stratigraphic position and lithology. However, Johnson (1984) found the Merrill Member of the Lincoln Formation to be less weathered than the Prairie Farm and unnamed members of the River Falls Formation. The Lincoln Formation was probably deposited in early Wisconsin time (more than 40,800 + 2,000 B.P.; IGSG-256), but may be partly or wholly Illinoian.

The Mapleview Member of the Horicon Formation was deposited during late Wisconsin following an interval of weathering and erosion. Westward flowing ice of the Green Bay Lobe brought dolomitic sediment into eastern Marathon County between about 18,000 and 13,000 B.P. and constructed a series of end moraines. Ice from the Lake Superior basin did not reach Marathon County during late Wisconsin, but outwash derived from the Lake Superior region was deposited in the valleys of the Rib, Wisconsin, and Eau Claire Rivers.

The Mapleview Member has been correlated with the Mikana and Sylvan Lake Members of the Copper Falls Formation in western Wisconsin (Johnson, 1984; table 3; Attig and others, 1985; fig. 4).

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PETROCHEMISTRY OF PRECAMBRIAN GRANITIC ROCK FROM NORTHEASTERN WISCONSIN

Gregory Mursky[1] and William Bailey[1]

ABSTRACT

Precambrian granitic rock from northeastern Wisconsin appears to have been emplaced mesozonally between 1.6 and 1.9 Ga. Granite to quartz diorite are represented, yet mineralogy is quite similar. The rock is calc-alkalic in nature and displays a relatively high K_2O/Na_2O ratio which supports a syntectonic to late tectonic origin.

The close correlation between the results of this study and experimental results for the system Ab-Q-Or-H_2O and Ab-An-Or-H_2O imply that the granitic rock has formed through crystallization of a magma derived from the melting of downfolded crustal rock, possibly along a subducting zone. Most rock units appear to have formed between 670 °C and 750 °C and from 1 to 3 Kbar pressure.

INTRODUCTION

The main purpose of this study is to provide information, primarily of a petrological and chemical nature, about granitic rock from a twenty thousand square kilometer area in northeastern Wisconsin (fig. 1). Because of the enormous size of the area and the relative scarcity of outcrop detailed fieldwork was not attempted. It is hoped, however, that much of the information presented here will be of use to future investigators involved with more detailed studies. The data are published separately (Mursky and Bailey, 1988) as Wisconsin Geological and Natural History Survey Open-file Report WOFR 88-2.

PREVIOUS STUDIES

The first detailed investigations of granitic rock in the region was done by Cain (1962) and Wadsworth (1962). Cain described several granitic units of the Athelstane area, including the Amberg granite, Newingham granodiorite, Hoskin Lake granite, and the Dunbar gneiss. Cain and Banks dated several of these units, and obtained zircon ages of between 1.85 and 1.95 Ga. Wadsworth (1962) studied the chemistry and petrology of the Twelve Foot Falls quartz diorite pluton located at Pembine, and Myles (1972) investigated the area near the contact of the Wolf River batholith and the Athelstane quartz monzonite, mainly through chemical analyses of both rocks and minerals. Cudzilo (1978) studied approximately the same region as Cain, concentrating primarily on the chemical relationships of the units described by Cain. Petrochemical work in east central Wisconsin was also done by Anderson, and others (1980). Recently, the geologists from the Wisconsin Geological and Natural History Survey have been doing large scale mapping in northeastern Wisconsin and in 1984 the Survey published a geological map of the area (Greenberg and Brown, 1984).

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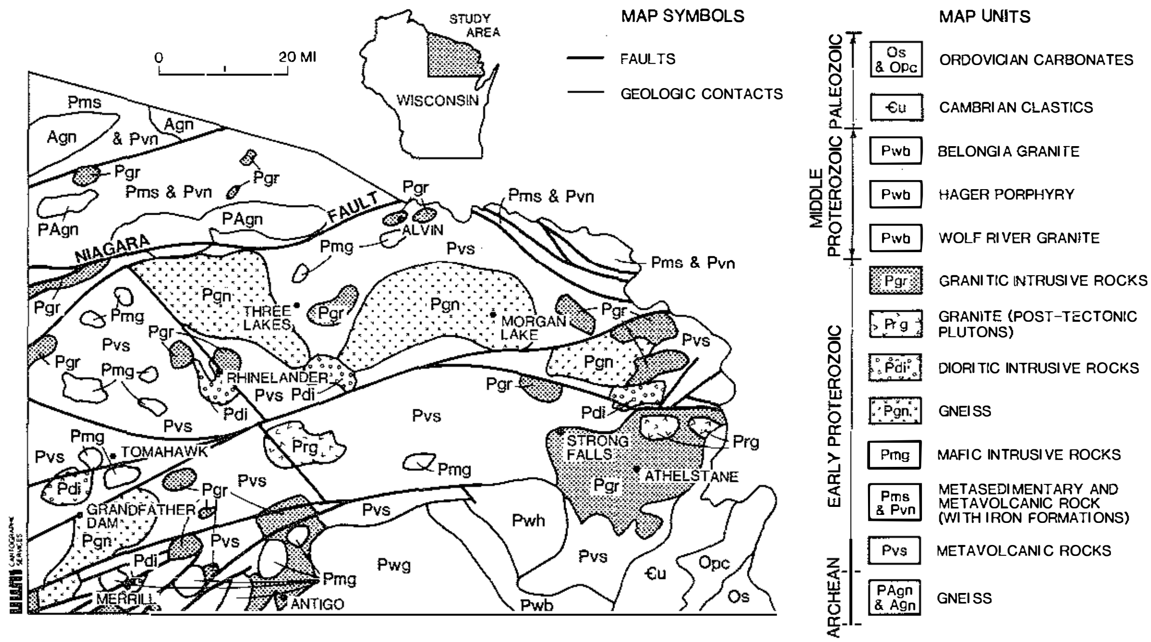


Figure 1. Geologic map of northeastern Wisconsin showing locations of granitic rock units from this study (simplified from Greenberg and Brown, 1984).

METHODS

Eighty thin sections were made, at least one for each outcrop. The anorthite content of plagioclase was determined with the aid of four axis Zeiss universal stage according to Michel-Levy method. Modal analyses were obtained from rock slabs after staining of feldspar according to the method of Bailey and Stevens (1960) and Hutchison (1974). Whole rock chemical analyses for Si, Al, K, Ca, and Fe were determined using a Phillips PW 1410 X-ray spectrometer (XRF) whereas Na and Mg were determined by atomic absorption. X-ray spectrometry (XRF) was carried out according to the procedure described by Jenkins (1976) and atomic absorption techniques were similar to those advanced by Andigo and Billings (1972).

GENERAL GEOLOGY

The majority of plutonic rock in the study area ranges in composition from granite to quartz diorite but mineralogy is quite similar (fig. 2). The predominant alkali feldspar is microcline, ranging from nonperthitic or slightly perthitic in the more basic rock to very perthitic in some of the true granite. Orthoclase was occasionally observed. Quartz is ubiquitous, occuring in large amounts even in some quartz diorites (up to 35 percent). Plagioclase ranges between oligoclase and andesine in composition, and is almost always altered more than the other major minerals. Biotite is invariably pleochroic in dark brown and yellow and hornblende in dark green and yellow. The most common accessory mineral in the more basic rocks is sphene and in the more acidic, zircon. Apatite was frequently observed and epidote, allanite and various opaques were occasionally seen.

Although primary textures, due to cataclastic effects, are commonly obscured, most rock is medium grained, hypidiomorphic granular to allotriomorphic granular. Microcline and quartz are usually anhedral, but microcline is more commonly interstitial and quartz is often polycrystalline. Plagioclase is usually zoned, subhedral and polysynthetically twinned. Biotite and hornblende are commonly subhedral. The paragenetic sequence of minerals for each area is shown in figure 2.

Most of the granitic rock can be tentatively classified as mesozonal, because features associated with katazonal or epizonal emplacement were not readily observed. For instance, migmatization and high-grade regional metamorphic rock associated with greater depths and pressures were lacking.

Metamorphic effects in the samples are not uncommon, but it is nearly always low grade, and commonly retrograde. For instance, many samples contain saussuritized plagioclase, and potash feldspar in the granite is commonly kaolinized or sericitized. In a few extreme cases granite has been metamorphosed to the low-grade mineral assemblage quartz, muscovite, albite, chlorite, and epidote, but still retain the original granitic texture.

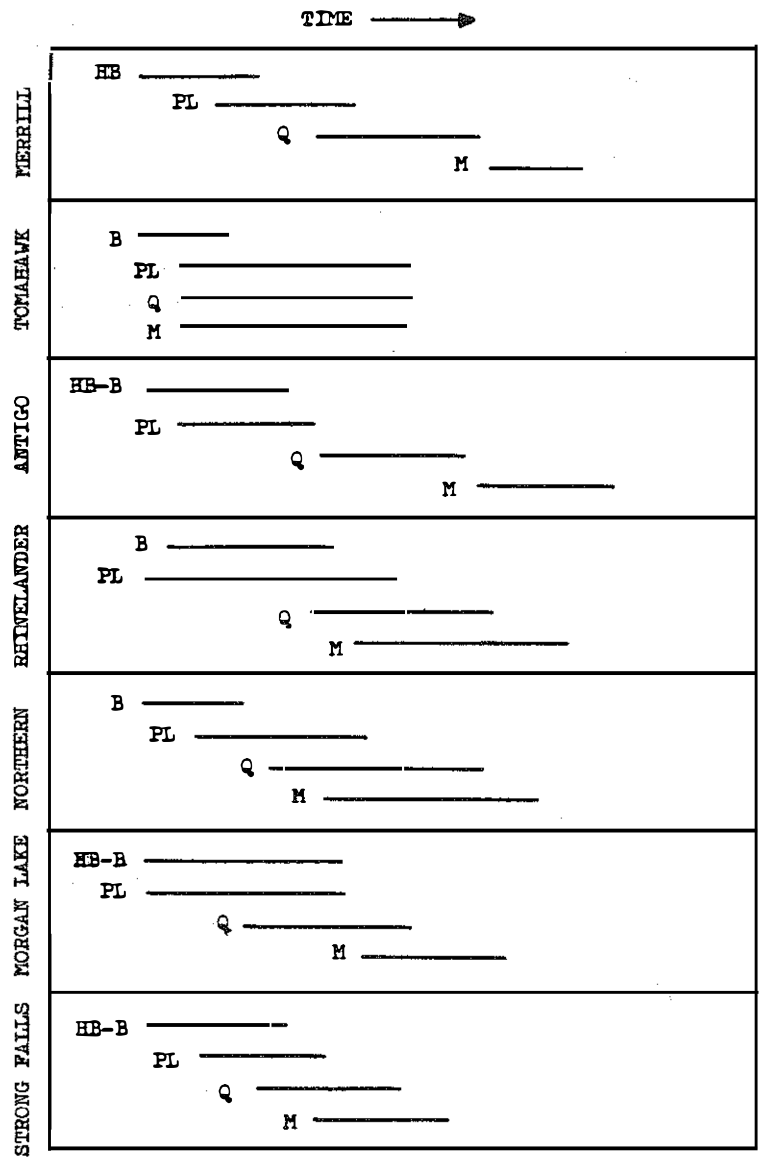
Samples which have been metamorphosed to higher grades are relatively few. Quartz diorite samples of the Twin Lakes area have been changed to amphibolite, and the rock collected at Argonne contain almandine garnet and are possibly paragneissic. The other Twin Lake rock may also be metasedimentary, but this is uncertain since strictly metamorphic minerals were not observed and the texture, though granular, was not necessarily relict. Contact metasedimentary rock found at Grandfather Dam is part of a roof pendant which has been metamorphosed to the sanidine facies.

In some cases, the original texture of the rock has been modified and obscured by cataclastic effects. Although pronounced changes can be seen in hand specimen, they can be most easily observed under the microscope. As strain increases, textural changes appear in a progressive sequence. Initially, trains of inclusions and undulatory extinction appear in quartz, and occasionally twin lamallae of plagioclase are bent. As strain increases, mortar texture is observed around quartz grains until finally quartz is apparently transformed into polycrystalline aggregate and feldspars appear as lenticles outlined by micas. Complete mylonitization was not observed.

PETROGRAPHY

Antigo Area

The samples for this area were collected on Highway 64 west of Antigo and on county roads in the vicinity of Antigo. The rock commonly shows exfoliation, and vary from fine to coarse grained and from granite to quartz diorite. Color is also quite variable. The mineralogy of most of the samples is typical of granitic rock. Quartz (25 to 45 percent), slightly perthitic to nonperthitic microcline (0 to 10 percent), biotite (20 percent), zoned



B=biotite, HB=hornblende, M=microcline, PL=plagioclase, Q=quartz

Figure 2. Mineral paragenesses in granitic rock from northeastern Wisconsin.

plagioclase An_{15-35} (25 to 65 percent) and hornblende (trace to 30 percent) are the primary minerals. Apatite, sphene, zircon, and allanite are accessories.

Athelstane Area

Athelstane area has been studied previously (Cain 1962, Cudzilo 1978); however, new outcrop, particularly along external contacts, is being looked at for the first time. The unit underlies about 200 squre kilometers of northeastern Wisconsin and has been dated at 1810 50 Ma (Van Schmus, 1973). Typical Athelstane area rock is medium- to coarse-grained granite to granodiorite composed of anhedral quartz (25 to 35 percent), anhedral and perthitic microcline (20 to 40 percent) and subhedral to anhedral plagioclase (20 to 40 percent) with anorthite content varying from An_{25} to An_{35}. Ubiquitous albite twinning in plagioclase is very fine and often obscured by a dusty appearance or saussuritization. Biotite is pleiochroic in red brown to dark brown and yellow, and hornblende in green and yellow (5 to 15 percent). Typical accessories include apatite, zircon, and strings of anhedral sphene. Overall, the texture is hypidiomorphic granular and occasionally slightly porphyritic.

Rhinelander Area

The samples studied were collected in and around the city of Rhinelander. They are generally altered granitic rocks which vary slightly in texture and color, from medium to coarse grained and from pink to beige. The Rhinelander rock varies considerably in mineral abundance. Plagioclase varies from An_5 to An_{35} and makes up 15 to 50 percent of the rock. Quartz (30 to 50 percent), nonperthitic microcline (0 to 30 percent), biotite (5 to 15 percent), and a little orthoclase are the primary minerals. Metasomatism was observed at the contact with mafic porphyry indicated by microcline development in the porphyry and depletion of potassium in the adjoining granite.

Northern Area

Although the samples from this area are further apart than the rock of the other areas, they are uniformly beige medium-grained, biotite granite. However, in the far north of the area pegmatite was observed intruding granite gneiss, probably near contact with country rock. The northern rock consists of quartz (25 to 35 percent), zoned and corroded anhedral to subhedral plagioclase (15 to 25 percent), slightly perthitic microcline (35 to 40 percent), and biotite and muscovite (10 percent). Myrmekite is a common constituent and may be due to reaction between contacting K-feldspar and plagioclase. The pegmatites are composed almost entirely of quartz and microcline with a little almandine garnet.

Grandfather Dam Area

Outcrop from this area was found on Highway 107 between Merrill and Tomahawk in the Grandfather Dam area. The rock varies from granite to diorite and most is foliated. The rock varies from fine to coarse grained and locally is cut by quartz veins about 5 cm thick. The diorite consists of 50 percent pale green uralite, formed from the alteration of clinopyroxene, and 50 percent plagioclase (An_{40-45}). Chlorite and epidote occur as alteration products of the clinopyroxene. Quartz rich tonalite is composed of biotite and hornblende (15 percent), quartz (45 percent), plagioclase An_{25-30} (20 to 30 percent) and microcline (10 percent).

Tomahawk Area

Rock was collected on town roads a few kilometers north of Merrill. All are granitic in composition varying from predominantly red, coarse-grained granite to subordinate tan, fine-grained granite in contact with and commonly contains greenstone inclusions. The coarse-grained, red granite contains quartz (30 to 35 percent), anhedral to subhedral saussuritized plagioclase An_{10-15} (20 to 25 percent), slightly perthitic microcline (40 to 45 percent), biotite (5 to 10 percent), and minor hornblende. Sphene, apatite and epidote are the accessories. The finer grained granite phase is similar to the above, but is less strained. Accessories include epidote, zircon and allanite. Myrmekite was present in all the samples from this unit.

Three Lakes Area

The rock from this vicinity is mainly foliated, east-west striking medium-grained quartz diorite gneiss. There is a distinct change in the petrology to more mafic diorite gneiss in the southern part of the area, possibly representing a separate unit. The quartz diorite gneiss is composed of quartz (25 to 30 percent), plagioclase An_{30-35} (55 to 60 percent) a little microcline (5 percent) and less than 15 percent biotite and hornblende. Accessories include chalcopyrite. The more mafic samples contain about 50 percent hornblende, and 50 percent plagioclase (An_{40-45}) and had been metamorphosed to the amphibolite facies.

Morgan Lake Area

The Morgan Lake rock samples were collected from a very small area and are almost identical petrologically. They are beige, medium- to coarse-grained granite composed of quartz (25 to 35 percent), altered, and zoned subhedral to euhedral plagioclase An_{20-25} (15 to 30 percent), slightly perthitic microcline (25 to 45 percent), brown biotite and muscovite. Zircon is the major accessory, prominently appearing in a variety of shapes. The Morgan Lake rocks display fewer characteristics of strain than the rock from most other areas.

Strong Falls Area

As with the Morgan Lake granite, samples were collected in a very small area. They are pink, coarse- to medium-grained granite consisting of quartz (20 to 30 percent), anhedral to subhedral plagioclase An_{10-15} (20 percent), microcline perthitie (35 percent), biotite (15 percent) and a little hornblende intergrown with biotite. Very distinctive zircon, displaying variable appearance is the major accessory.

Merrill Area

The rock underlying this area is medium-grained quartz diorite. Locally, this unit is foliated in an east-west direction and is cut by pegmatite dikes. Mineralogically, the Merrill rock is composed of plagioclase An_{40-45} (50 to 60 percent), hornblende (20 to 30 percent), quartz (20 to 30 percent) and a trace of interstitial microcline. Texturally, it varies from massive to foliated. Small clumps of hornblende crystals wrap around larger grains of plagioclase in the foliated samples. Chlorite, epidote, and apatite are present as accessory minerals.

Miscellaneous

The miscellaneous grouping includes those areas about which there is limited information. The Alvin area rock is granite with mineralogy and texture similar to those found in many other areas of this study. Those granite gneisses cropping out north of Argonne, however, are paragneisses with a granoblastic texture. The mineralogy includes plagioclase, microcline, biotite, quartz, hornblende and almandine garnet. Diorite located at Laona Junction has locally been metamorphosed to the greenschist facies. The rocks of the Carter area are granites which vary in color gradually between grayish green and pink and under the microscope it appears that they were formed by metamorphism and possibly metasomatism of medium grained sandstone. It is probably significant that Carter is only two miles north of the contact with the Wolf River batholith. The areas about ten miles west of Strong Falls and at Armstrong, are underlain by quartz monzonite similar petrologically to the majority of other granites in this study. For a more detailed petrography of these rocks, see Appendix II in Mursky and Bailey (1988).

CHEMISTRY

Introduction

Forty-eight rock samples were chemically analyzed for seven major elements: Fe, Ca, Si, Al and K were analyzed by X-ray fluorescence; and Na and Mg by atomic absorption. In most cases the results were reasonable and satisfactory, but the oxide sum was uniformly low for the more mafic rocks. One possible explanation for this is that H_2O and TiO_2 are not accounted for. Another reason may be that some divitrification of the glass discs, used in X-ray fluorescence, took place, resulting in heteorgeneity of the samples (Jenkins, 1976). However, for the purposes of this comparative study the results seem to be satisfactory.

The chemical analyses were used to calculate Niggli molecular norms and to calculate and plot variation diagrams and fractionation indices. Norms for the bulk of the rocks were calculated with a program written in BASIC for a Sinclair ZX81 computer. These norms were then compared with the modal analyses.

Variation diagrams were used to compare the chemical trends. Among the diagrams prepared were Harker diagrams (Harker, 1909), (Na + K) - Fe - Mg and Na - K - Ca triangular diagrams, the Peacock Diagram, Ab - Q - Or, Ab - An - Or triangular diagrams, and K_2O vs Na_2O.

Molecular Norms

Niggli molecular norms (figs. 3 and 4) are corundum normative (peraluminous) and quartz normative but comparison of norms with modes discloses some discrepancies. Orthoclase, in particular, is usually higher in the mode than in the norm. This is possibly due to incorporation of Na in the alkali feldspar not accounted for by the normative calculations. Quartz is usually higher in the norm than in the mode, and this is probably due to the presence of other silicate minerals in the analysis. Minor errors in these norms can be accounted for by the limited number of elements analyzed for.

Norms were used to calculate the Differentiation Index (DI) (Bowen and Tuttle 1958), which gives some clue to the stage of fractionation of a rock. In this scheme the DI of the average granite = 93, average granodiorite = 67, average diorite = 48.

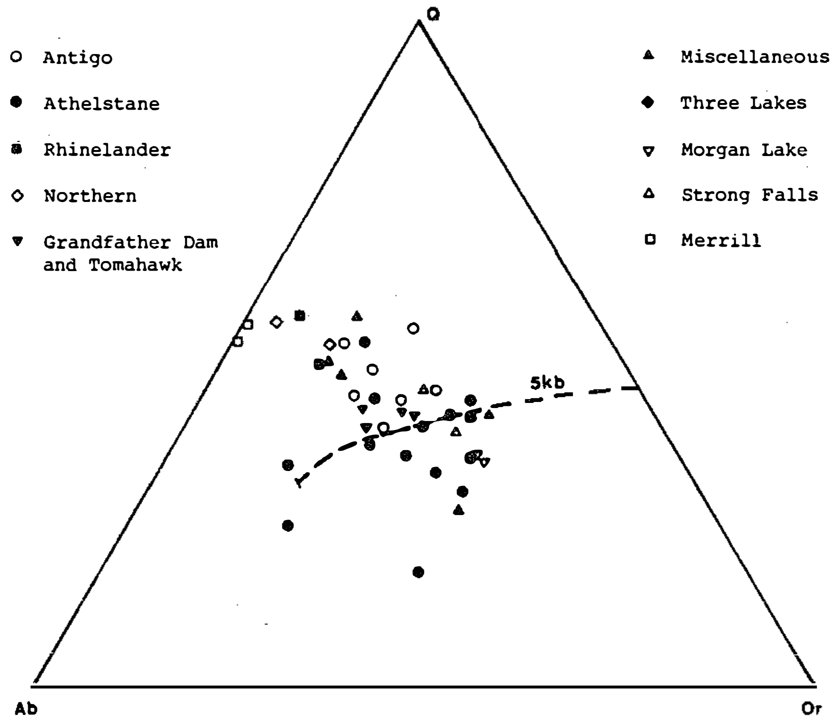


Figure 3. Ternary diagram of the normative components albite (Ab)-quartz (q)-orthoclase (Or) for the individual sample areas with the approximate position of the cotectic line drawn in.

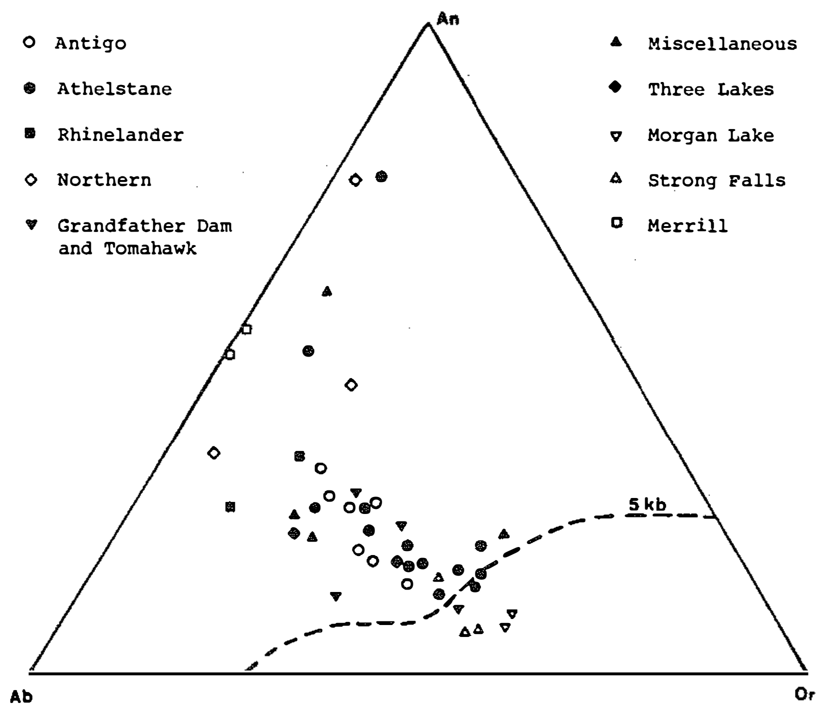


Figure 4. Ternary diagram of the normative components albite (Ab)- anorthite (An)-orthoclase (Or) for the individual sample areas with the approximate position of the cotectic drawn in.

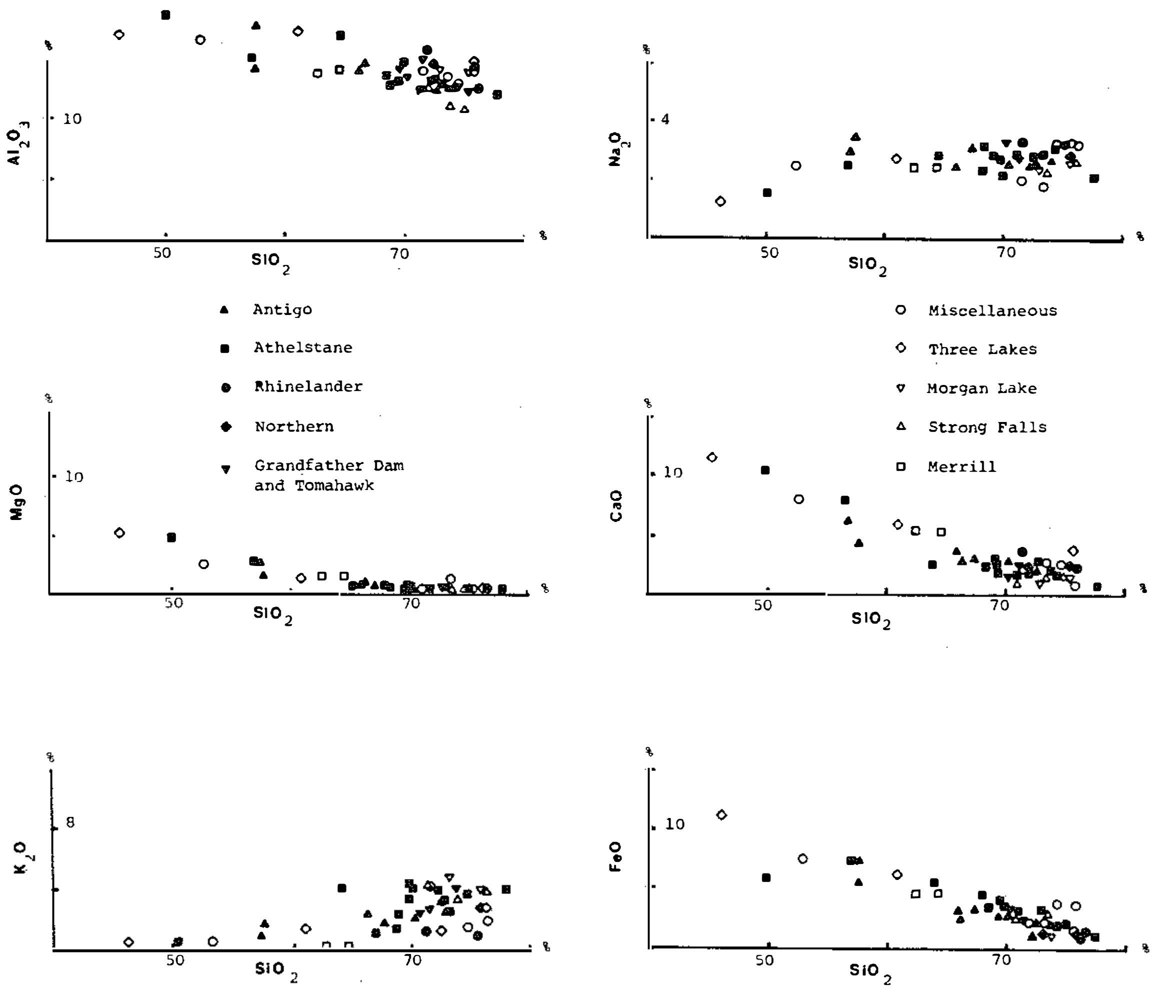


Figure 5. Harker variation diagrams for granitic rock from northeastern Wisconsin.

Variation Diagrams

Harker Diagrams are displayed in figure 5 and their study discloses several interesting trends. In the sodium diagram the points define a line nearly parallel with the silica axis. This implies that there is no correlation between sodium and silica content. However, on the calcium and iron curves, which nearly coincide, one can see a definite increase with decreasing silica. The same trend can be seen on the alumina curve, but not as pronounced and with greater point scatter. The magnesia curve maintains a correlation with silica with little point scatter, however, this latter condition is probably due to the small amounts of magnesia in the silica rich rocks. On the potassium diagram one can observe the greatest amount of scatter and a definite increase of potash with increased silica. The scatter possibly implies greater mobility of the potassium than the other oxides.

It is instructive to compare the trends from the individual geographical areas on the same diagrams. For example, on the calcium curve the Athelstane and Antigo group of rocks define slightly different trends, as does the combination of Three Lakes, Merrill and the miscellaneous samples nearest Cavour, all of which are diorites or quartz diorites. This may be due to the derivation from different magmas, or heterogeneity within the same magma.

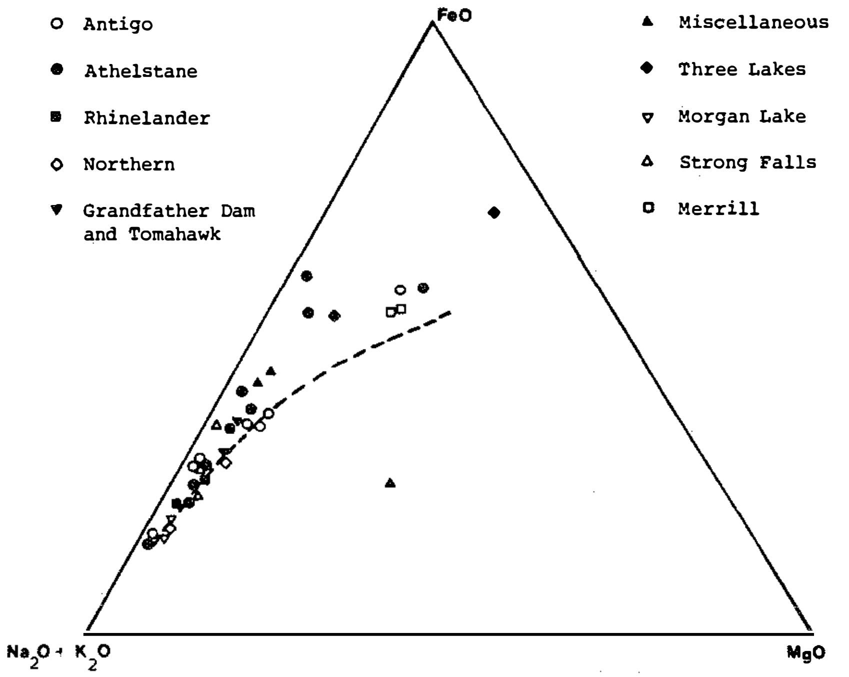


Figure 6. Ternary diagram of the components FeO (total iron) - MgO - Na_2O + K_2O) in weight per cent for the individual sample areas also showing the trend of the Southern California batholith (Nockolds and Allen, 1953, dashed line.

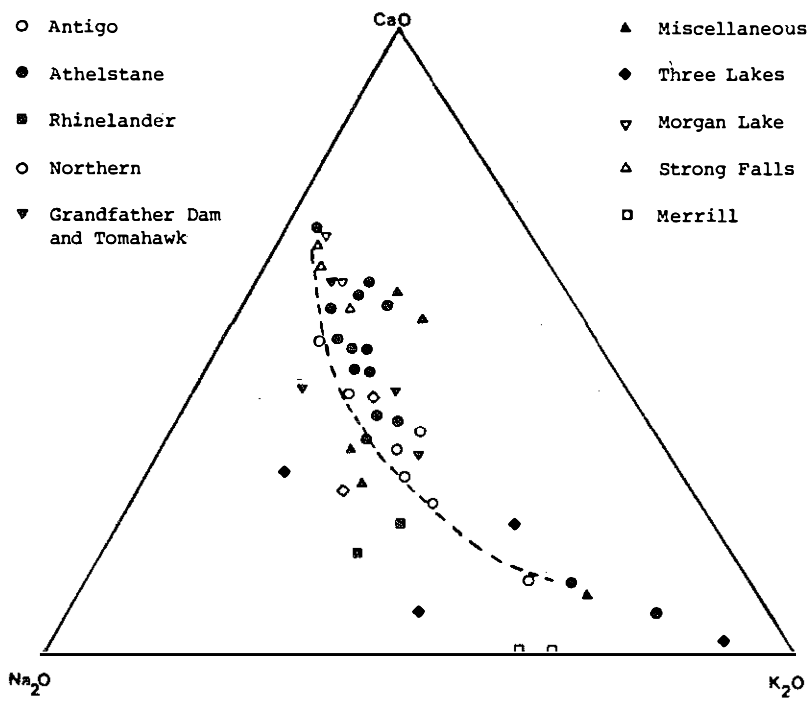


Figure 7. Ternary diagram of the components Na_2O-K_2O-CaO in weight percent for the individual sample areas including the trend for the Southern California batholith (Noxckolds and Allen, 1953, dashed line).

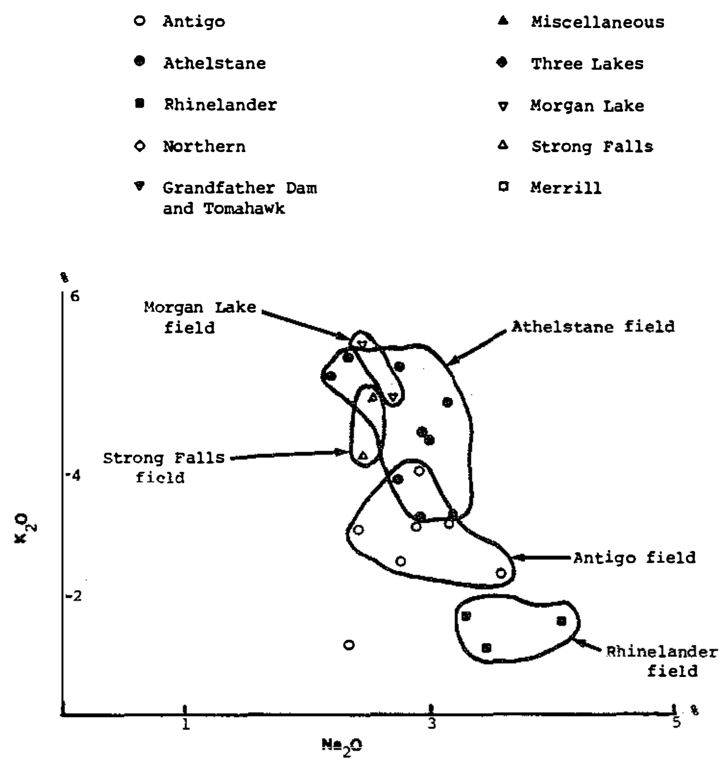


Figure 8. Plot of Na_2O versus K_2O showing the separate fields delineated for the individual sample areas.

On the iron curve the trends are very similar to those of the calcium curve, but on this plot the Athelstane rocks have slightly more iron than the Antigo rocks. Because of the small amount of Mg in the more acidic samples, distinction between different trends cannot be made.

The points on the potassium curve show the most scatter, particularly in the silica rich samples. This could be due to metasomatism or assimilation. Comparing potassium to sodium for acid rocks in any of the areas discloses discloses that these rocks are high in potassium which is typical of late tectonic granites (Barth 1962), although the Rhinelander rocks are noticeably deficient in potassium.

In figure 6 one can see a distinct trend, defined by the position of the plotted points from the recalculated chemical analyses. The trend of this curve and distribution of the individual points are similar to that for calc-alkalic suites, that is. The Southern California Batholith (Nockolds and Allen 1953). Areal trends are also evident. The points representing the Athelstane quartz monzonite traces out the main curve, as do those representing the Antigo samples. However, it is not possible to separate the individual trends with confidence for other areas.

The data in Na_2O - K_2O - CaO (fig. 7) defines a trend similar to those observed for calc-alkalic suites of rocks. On this diagram the points nearest the K_2O corner are the most granitic, while those at the top are the most mafic, and the Athelstane rocks are more potassic than the Antigo rocks for a given Na_2O/CaO ratio. The Merrill rocks do not lie on the main trend, but are scattered near the bottom of the diagram.

Another ternary diagram useful in differentiating units or, in interpreting conditions of formation is one whose corners are normative albite (Ab) - quartz (Q) - orthoclase (Or) (fig. 3). The Athelstane and Antigo samples can be distinguished as separate units in this diagram because the Athelstane samples have a higher Or content for a given Q/Ab ratio. The points from the Merrill, Morgan Lake, and Strong Falls rocks all group as individual units also. The Athelstane points which do not group nicely represent samples near external contacts. The other areas cannot be differentiated as easily from this diagram.

If normative Ab-An-Or are plotted as components on a ternary diagram (fig. 4) the Strong Falls rocks (low An, Ab/Or ratio = 1) and the Rhinelander rocks (low Or, Ab/An = 1.5) can be distinguished as separate units. The Athelstane and Antigo area rocks are not as easily distinguished in this diagram due to variable An content.

Figure 8 is a plot of Na_2O versus K_2O and it has been used to assist in differentiating the plutons of far northeastern Wisconsin (Cudzilo 1978). The samples from many of the areas delineate separate fields. The Rhinelander rocks have the highest Na_2O/K_2O ratio, the Morgan Lake and Athelstane rocks the lowest.

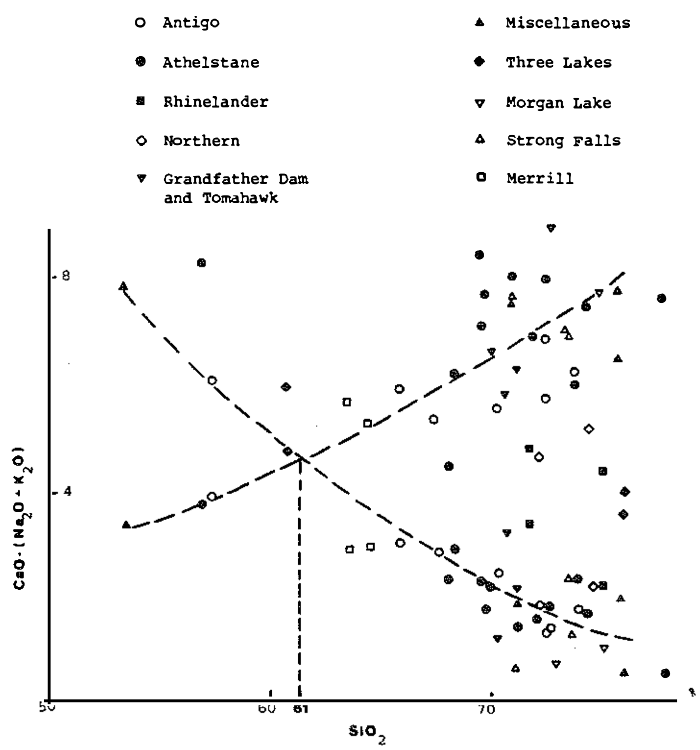


Figure 9. Peacock diagram of individual sample areas with inferred trends (dashed lines).

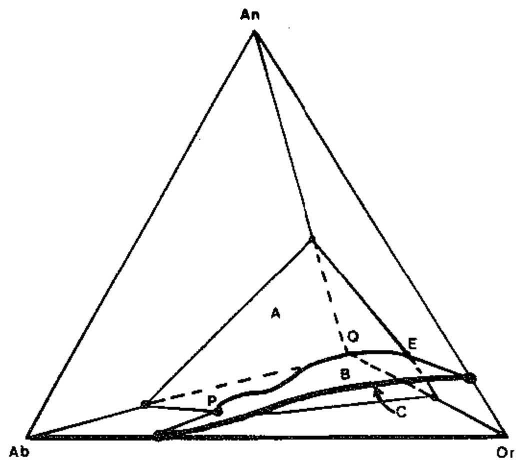
The Peacock diagram (fig. 9) can be used to identify the rock series to which a cogenetic group of rocks belongs (Hyndman 1972). The plot defines two intersecting concave upward lines and the SiO_2 value at the point of intersection defines the type of magma from which the rocks were derived. Inspection of the plotted points for the rocks of the study area in figure 9 makes it apparent that some interpretation is necessary to determine the position of the two lines. The dotted lines appear to be the best choices and intersect at a SiO_2 value of 61.0 which indicates a borderline calcic or calc-alkalic rock series. Such series are usually associated with orogenic areas. Note should be made that the Rhinelander and Three Lakes samples are relatively deficient in alkalis.

CONCLUSIONS

The majority of rocks in this study were probably emplaced during the Penokean Orogeny about 1.6 to 1.9 Ga. The Athelstane quartz monzonite has been dated at 1810 50 Ma (Van Schmus 1973) and many of the other units show evidence of a similar age. For example, some units are foliated in a direction approximately parallel to the tectonic axis of the Penokean mobile belt (that is Merrill, Grandfather Dam and Three Lakes) and some units contain greenstone inclusions presumably belonging to the belt. Therefore, these units are mainly late tectonic and syntectonic. The calc-alkalic to calcic chemistry of the units, the relatively high K_2O/Na_2O ratio, and apparent mesozonal emplacement of these units support a mainly late tectonic origin. Detailed radiometric dates would be useful to substantiate the probable relationship to the Athelstane quartz monzonite and the previously studied plutons of northeastern Wisconsin.

Many of the plutonic units of this study can be classified as I-type granites (compositionally expanded), as opposed to S-type (compositionally restricted)(Pitcher 1979). I-type granites are thought to be mainly derived from anatexis of upper mantle rocks formed over a subduction zone at an oceanic plate and continental plate boundary similar to the geological setting on the west coast of South America (Pitcher 1978). Analogously, the study area was probably an ancient continental margin underlain by subducting oceanic crust. Some of the granites in the study area may be of crustal origin and this would be similar to S-types. Furthermore, many features of an I-type granite geological setting (Pitcher 1978) are not present in this study. Initial $^{87}Sr/^{86}Sr$ ratio would help to resolve this question.

From experimental studies of the Ab-An-Or-Q-H_2O system (Winkler, 1979), the relationship of the phases with changing temperature at constant pressure has been clarified (fig. 10). The important features of this diagram are the cotectic line PE, the cotectic surfaces A, B, and C, and the spaces beyond each of these surfaces. In fusion studies of paragneisses, containing the components Ab-Or-Q-An, and enough H_2O to maintain constant pressure throughout fusion, melting begins on the cotectic line PE, and upon raising temperature the melt composition moves up the line until all the alkali feldspar in the paragneiss is melted, then it moves onto one of the cotectic surfaces. Finally, after raising the temperature even higher, one of the remaining phases completely melts, and the composition of the melt moves into one of the spaces above or below the cotectic surface. From the experimental studies it was found that the position of the cotectic line changes only



Explanation

PE = cotectic line

A = cotectic surface separating quartz space from plagioclase space

B = cotectic surface separating plagioclase space from alkali feldspar space

C = cotectic surface separating quartz space from alkali feldspar space

Figure 10. Phase relations in the system Ab-An-Or-Q at a given H_2O pressure (after Winkler, 1979).

slightly with regard to pressure and a change in the composition of the paragneiss. Providing the initial material contains the preceding major components the above sequence is followed upon melting.

As discussed previously, the rocks of this study have been projected onto the triangular diagrams Ab-Q-Or and Ab-An-Or of the tetrahedron in figures 3 and 4. Most of the Athelstane samples plot on or close to the cotectic line and because of their low An content may represent a "minimum melt" derived from anatexis of paragneisses with an Ab/An ratio of between 2.5 and 8 at H_2O pressures of less than 3 kb and temperatures of about 670 to 700 C or as late differentiates under the same pressure- temperature conditions. The Strong Falls and Morgan Lake units could have been formed in essentially the same way and the Antigo, Rhinelander and Northern units possibly formed at temperatures 50 to 80 °C higher as later melts, or earlier differentiates. Most of the points on the diagram can be interpreted as originating in either of these two ways and it is possible that nearly all the rocks could have originated mainly by partial melting of rocks of appropriate composition, followed by crystallization from a magma.

Conclusions regarding the temperatures and pressures of formation of the rock units, based on figures 3 and 4, indicate that most units formed between about 670 and 750 °C from 1 to 3 Kbar H_2O pressure. Support for this hypothesis includes the mineralogy of the samples. The primary minerals found in these rocks are stable within this range, and maximum microcline in particular indicates formation near the low temperature limit proposed. The roof pendant, at Grandfather Dam, which belongs to the sanidine facies, was probably metamorphosed near the upper temperature limit, possibly by underlying dioritic magma.

The study area is not unique among Proterozoic areas of the world. Mobile belts and associate plutons of this age exist in several places, but the one best studied is the Svecofennide Province in southwestern Finland and Sweden (Read and Watson 1975).

ACKNOWLEDGMENTS

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SEISMIC REFRACTION MEASUREMENTS IN BEDROCK OF THE TROUT LAKE REGION OF VILAS COUNTY, NORTHERN WISCONSIN

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ABSTRACT

A seismic refraction survey of bedrock and water table elevations in the Trout Lake region were made as part of a long-term ecological research project on lake ecosystems in Vilas County, Wisconsin. The area lies within the glaciated region of Wisconsin and the glacial material directly overlies Precambrian crystalline bedrock.

Sixty-four seismic refraction spreads were completed in a grid form and covered about 110 km^2. Basically the structure is glacial till over bedrock. Analysis of the data gave a three-layer seismic structure. A top unsaturated layer with a velocity of 0.45 km/s and an average thickness of 5 m overlies a water saturated layer with a velocity value of about 1.7 km/s and an average thickness of 35 to 40 m. This saturated layer directly overlies the crystalline bedrock. Most of the bedrock velocity values obtained range from 4.0 to 6.0 km/s indicating that the bedrock lithology is probably granite with intrusions of gabbro and a sparse distribution of gneiss. Bedrock valleys were located and an east-to-west bedrock dip of less than 1° was detected. A water table map showed a regional east-to-west groundwater flow. Recharge, discharge and flow-through lakes were identified.

INTRODUCTION

Hydrogeological studies for the long-term ecological research project in Vilas County require bedrock topography. We used the seismic refraction method to determine bedrock and water table elevations and, if possible, bedrock lithology. The bedrock velocity and water table contour maps are interpreted in terms of bedrock lithology and groundwater flow directions, respectively. Details are given in Okwueze (1983).

It is well known that geophysical methods can be used to map the structure and the physical properties of earth materials. Various geophysical methods have been used in mapping basement-bedrock topography and water table elevation but the most commonly used and recommended is the seismic refraction survey (Eaton and Watkins, 1970; Fetter, 1980). This is because in most basement areas, bedrock is shallow and the contrast in the elastic properties of the subsurface rocks and the overburden is usually high. One can also use seismic methods to measure the water table when the contrast between the elastic properties of saturated and unsaturated rock is high. The contrast between the seismic velocities of saturated and unsaturated glacial materials is high in this area.

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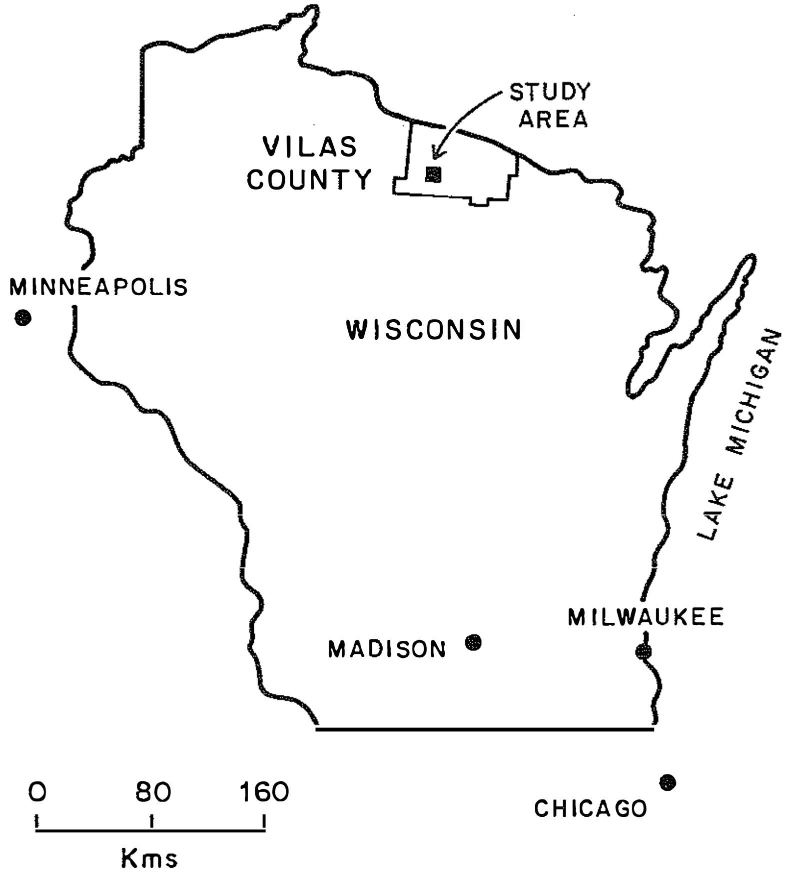

Figure 1. Location map of the study area.

LOCATION AND GEOLOGY

The survey was carried out in Vilas County, Wisconsin. Around 46°N and 89°40'W (Okwueze, 1983). The area is located about 400 km north of Madison (fig. 1), and covers an area of about 110 km^2. The surface elevation is irregular, ranging from a minimum of 493 m to a maximum of 563 m above sea level.

The geology is poorly known because glacial deposits cover the bedrock completely within the study area. The basement rock in northern Wisconsin is broadly classified into two Archean terranes: a granite- greenstone terrane and a gneiss terrane. These lie within the southern edge of the North American Shield in an area called the Wisconsin Dome (Lapedes, 1978). The bedrock within the area of the survey seems to be entirely crystalline (Thwaites, 1929) and composed of lower Proterozoic igneous and metamorphic rock units represented by granite intrusives, diorite, and gneiss (Greenberg and Brown, 1984).

The glaciation processes of the Pleistocene modified the land surface (present bedrock surface) by carving and gouging out soft rock and depositing hills and ridges of sand, gravel, silt, and clay (Attig, 1985).

MEASUREMENT AND INSTRUMENTATION

The seismic equipment consisted of a compact Nimbus ES-1210 F multi-channel signal enhancement seismograph from EG&G Geometrics with recording, filtering, stacking, storage, display, and hard copy options. Repeated signals can be stacked to reduce random noise relative to the signal and to increase the signal-to-noise ratio. This is ideal for small energy sources like sledge hammer blows, which were the energy sources in this work. The Nimbus seismograph is powered by a 12 V DC battery. A single 12-geophone string with a total spread of 100 m was used during the survey. The geophones were vertical, 12-Hz types.

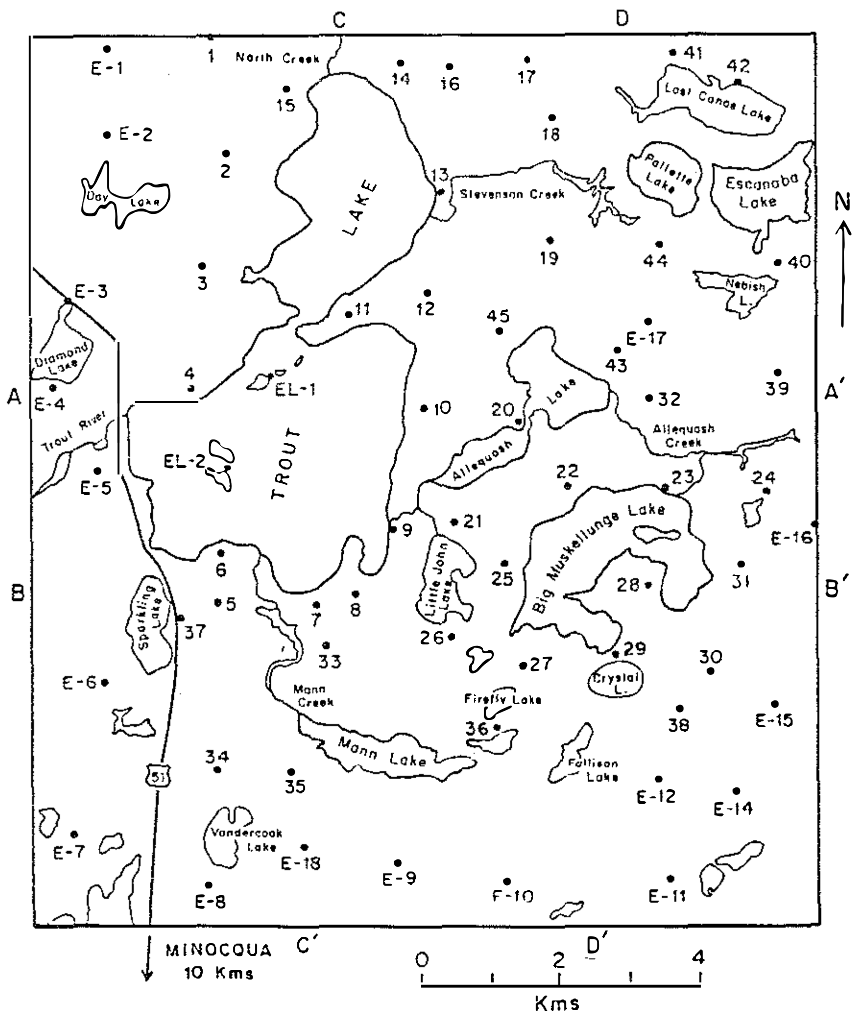

Figure 2. Map of the study area with seismic spread locations.

A total of 64 seismic refraction spreads were completed during the survey (fig. 2). The field situation did not permit a regular grid due to the inaccessibility of some pre-selected stations. The inter-station distance was an average of 1.6 km with a maximum of about 2.5 km and a minimum of 0.5 km. Reversed profiles were used in all cases. The surface elevations of all the station points were obtained by the altimeter leveling method.

DATA PROCESSING AND INTERPRETATION

A typical seismic record and its reversal are shown in figure 3. The times of arrival of seismic wavelets from subsurface refractors for the various source-receiver distances were picked directly from the records. These travel times were plotted against source-receiver distances for both forward and reverse profiles. The compressional wave velocities of various layer, depths to refractors, and dips (where applicable) were obtained from the resulting time-distance (T-X) curves. The time intercept method as developed by Hawkins (1961) was used in the calculation of the seismic parameters. For dipping refractors, the forward and reverse delay-times originating from the same point on the refractor were not equal. The formulae used in obtaining true velocities, depths, and dips in these circumstances were adapted from Mooney (1973). These estimates were used as initial values for seismic refraction modeling.

A computer program by Clay (1981), which uses the generalized reciprocal method (GRM)(Palmer, 1980), was used for the modeling. Each plot of the model curves was compared with field data. By varying and adjusting the parameters of the theoretical models, visual best fits were obtained (fig. 4). Errors were calculated by using the least squares method. Almost all of the stations had negligible dips and errors of seismic velocities were less than 1 percent. The thickness of layer 2 and the top of the bedrock are sensitive to the velocity of the layer. As shown in figure 4, first arrivals from the top of layer 2 extend from about 20 m to 60 m on both profiles. This gives good estimates of layer 2 velocities. A 1 percent velocity error gives a 1 percent depth error. For a 40 m thick layer and 1 percent error, errors of depths to the top of bedrock are $\pm$ 0.4 m. Profiles over dipping layers had larger errors and in the worst case the estimated errors of the bedrock depths were $\pm$ 4 m.

The data from the 64 stations were interpreted to determine the seismic velocity and thickness of the layers (table 1). The interpretation gave a three-layered structure. A simplified description of the results follows.

A top layer with a velocity of about 450 m/s and an average thickness of 5 m overlies a second layer with an average velocity of about 1700 m/s and an average thickness of 35 m. The change of seismic velocities from layer 1 to layer 2 are consistent with an interpretation that layer 1 and layer 2 are sand and gravel. Water saturation increases the seismic velocity from 450 m/s to 1700 m/s and layer 2 is water saturated gravel. The bottom refractor, whose velocity ranges from 3838 to 7000 m/s, corresponds to velocities generally associated with crystalline rock. The bedrock underlies layer 2 at an average depth of 40 m but varies between a minimum of 28 m to a maximum of 64 m below the surface.

The depth of the bedrock and top of layer 2 varied widely throughout the survey area and maps have been prepared to show this variation distinctly. An

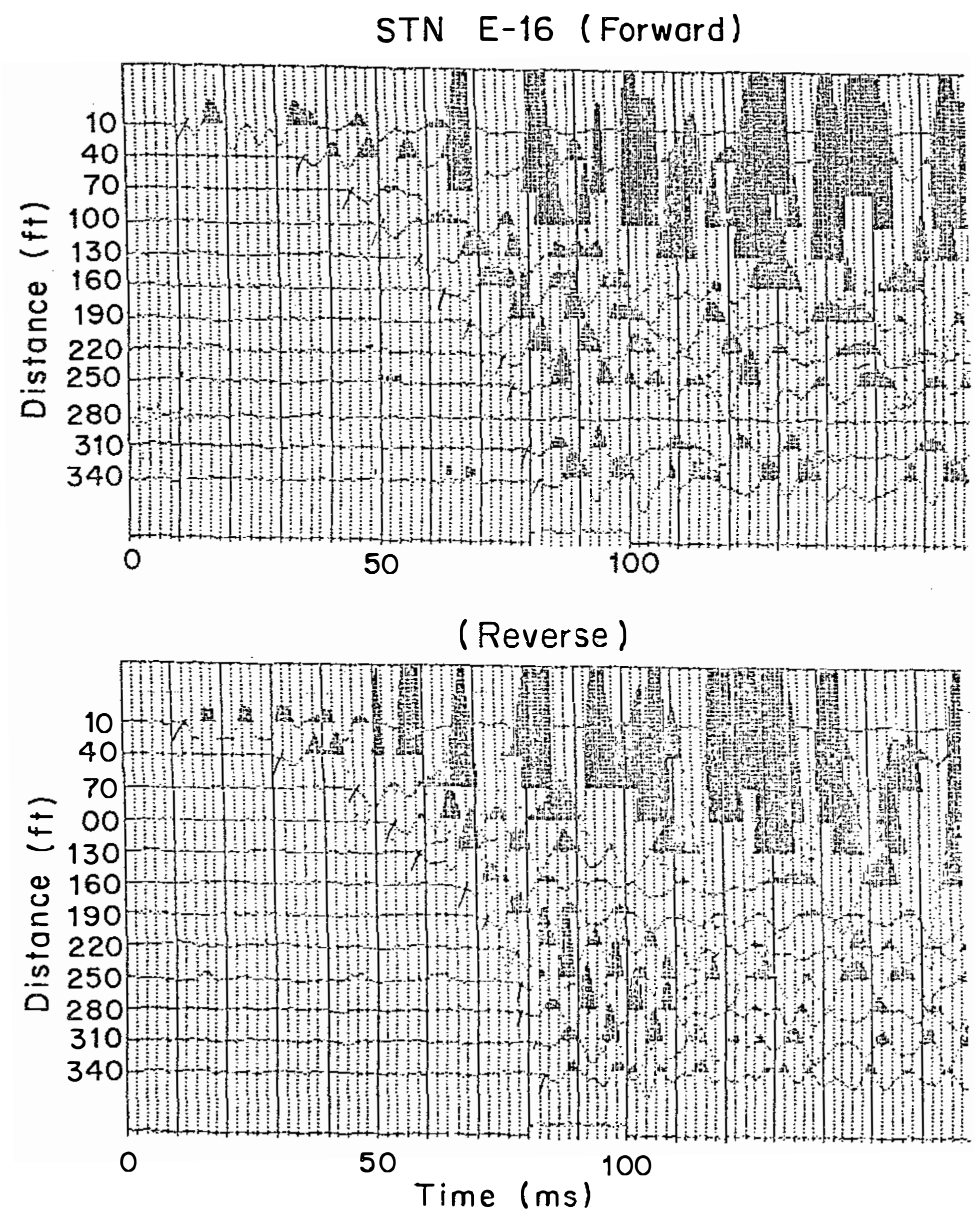

Figure 3. Typical refraction records obtained during the survey for station E-16. The original measurements were in feet along the spread. We retain these distances for simplicity in the figure.

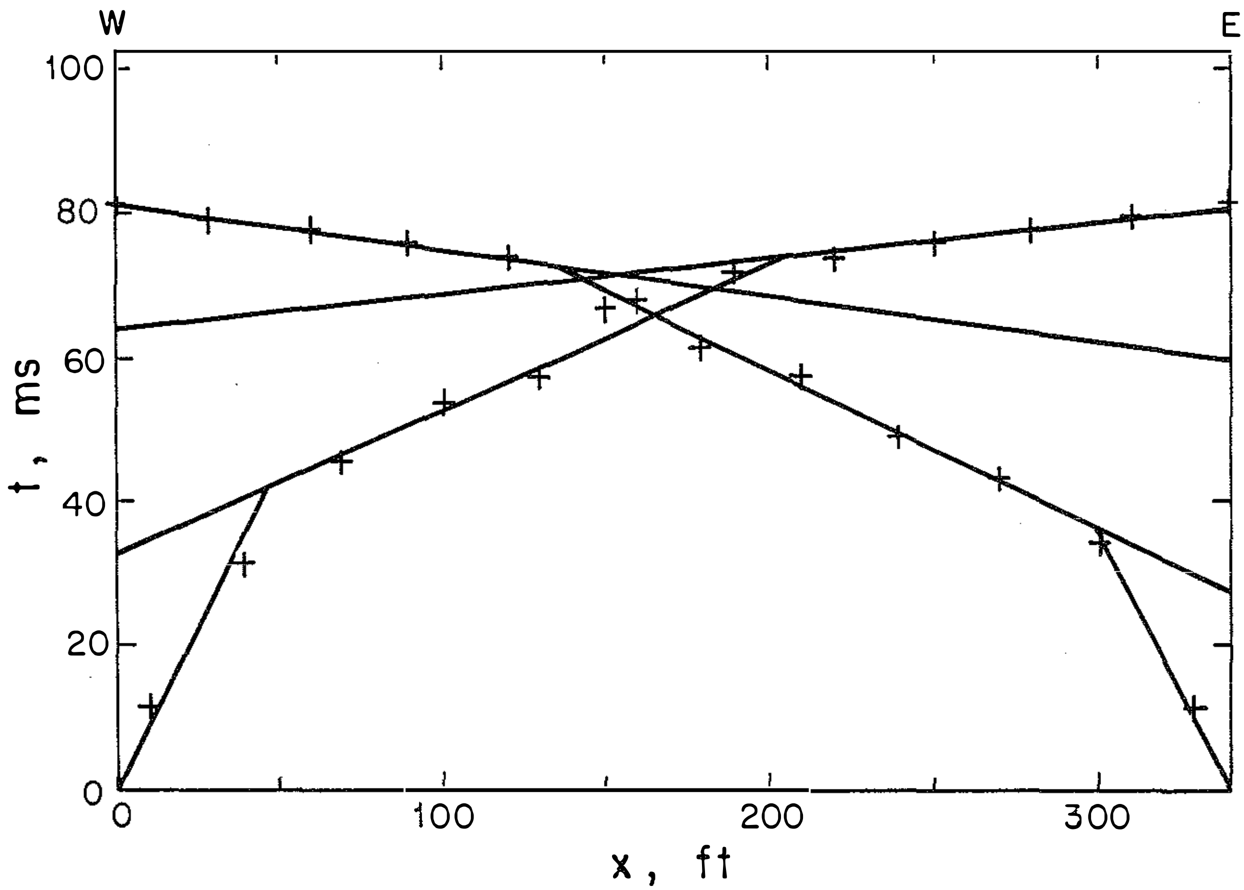

Figure 4. Typical time-distance (T-X) curve from station E-16.

elevation contour map of the top of layer 2 has been presented as a water table map showing the variation of the water table elevations at the various stations and the groundwater flow directions (fig. 5). The map showed a regional east-to-west groundwater flow. Trout Lake was identified as a discharge lake; Escanaba, Lost Canoe and Crystal as recharge lakes; and the rest as flow-through lakes.

Direct measurements of water table elevations were made at 8 of the seismic stations (Galen Kenoyer, verbal communication, 1982; Gary Patterson; verbal communication, 1982). Table 2 shows a comparison of the refraction data and the direct measurements. The seismic measurements were made a year earlier. Even so, the largest difference is a meter.

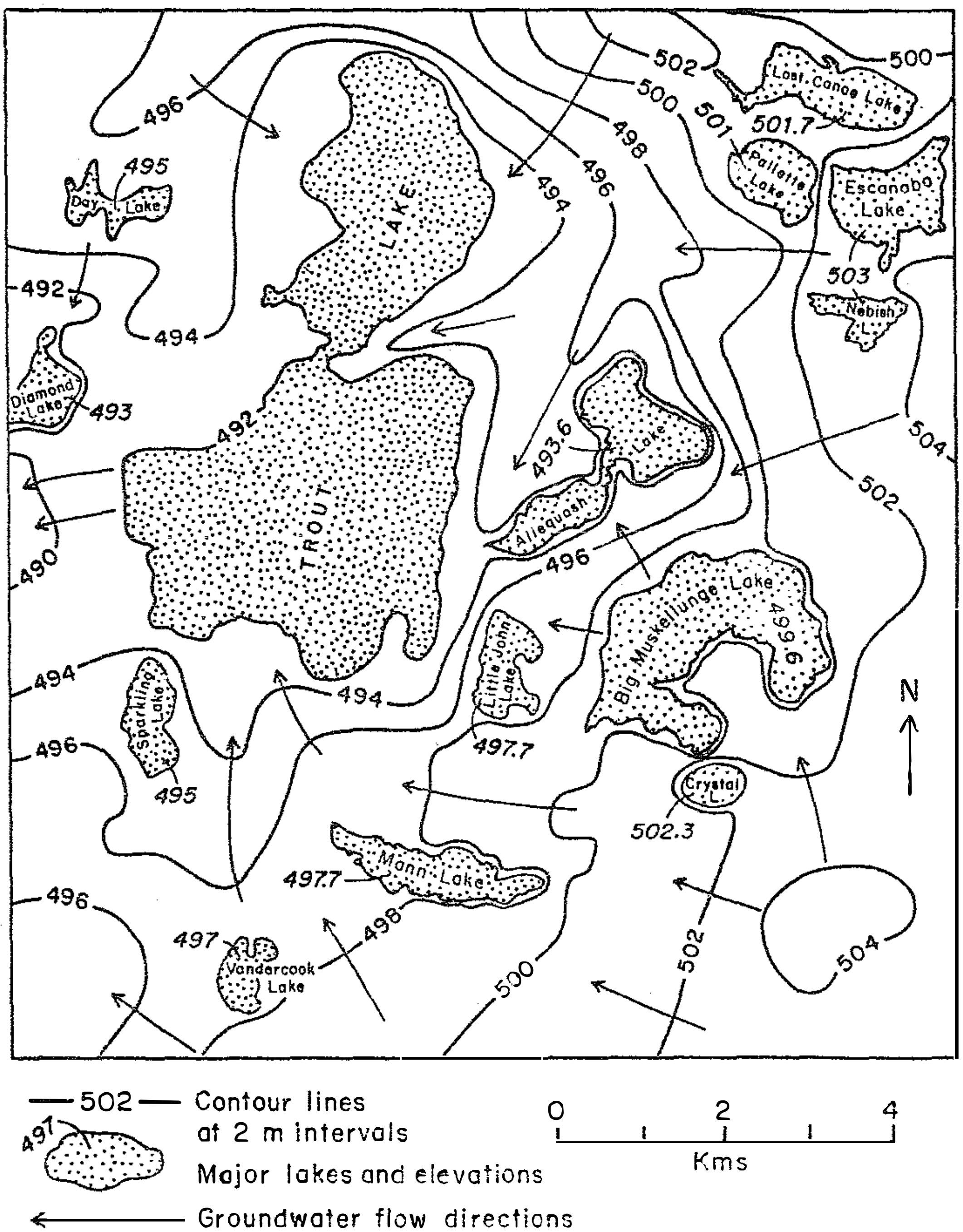

Figure 5. Water table elevation map from refraction data, Trout Lake area, northern Wisconsin, summer of 1982.

Table 1. Summary of results from refraction survey (Summer 1981 and 1982).

Station	Surface Elevation (m)	Water Table Elevation (m)	Bedrock Elevation (m)	Bedrock Velocity (m/s)
1	505	497	463	5425
2	505	494	461	4724
3	516	495	459	5486
4	499	492	440	5822
5	499	493	457	4877
6	497	492	462	4689
7	504	494	453	4724
8	504	493	451	5410
9	494	492	463	4572
10	499	494	455	5080
11	500	494	459	6096
12	500	495	459	5125
13	494	492	452	4570
14	503	497	463	4570
15	498	492	466	4907
16	504	499	473	5212
17	507	502	469	4663
18	506	499	467	4397
19	511	497	475	5791
20	497	494	465	5182
21	504	497	470	5273
22	510	498	473	5334
23	504	500	458	4877
24	504	501	476	4877
25	507	497	465	4572
26	508	499	461	4570
27	505	500	455	4953
28	506	501	462	4816
29	504	501	454	4877
30	509	502	466	5182
31	509	502	479	4877
32	512	500	477	5486
33	501	497	448	4785
34	512	496	448	5624
35	512	497	457	5029
36	505	500	447	6096
37	498	494	447	6020
38	510	503	470	5639
39	515	504	482	4877
40	520	505	475	3992
41	512	501	464	5525
42	509	500	464	4511
43	506	499	475	6218
44	506	499	476	4648
45	506	496	473	5517
E-1	501	495	471	3658

Table 1. Continued.

Station	Surface Elevation (m)	Water Table Elevation (m)	Bedrock Elevation (m)	Bedrock Velocity (m/s)
E-2	504	496	473	3962
E-3	497	490	461	6066
E-4	495	491	460	5182
E-5	494	491	458	4572
E-6	503	497	463	3818
E-7	508	494	460	4572
E-8	508	498	463	4633
E-9	524	-	474	4224
E-10	530	-	474	4267
E-11	512	503	473	5700
E-12	527	504	478	4572
E-14	515	506	479	6096
E-15	518	503	459	4724
E-16	508	503	480	5396
E-17	507	501	471	6197
E-18	513	-	471	4572
EL-1	492	492	457	7000
EL-2	429	492	452	4932

Table 2. Comparison of head values obtained from direct measurement and seismic measurements, summer 1981.

Station	Water table elevation (m) Observed	Geophysical
4	492.6**	492
23	500.8*	500
24	502*	501
25	498.6*	499
27	500.5*	500
29	501.7*	501
30	502*	502
41	501.5**	501

* Galen Kenoyer, measurements - summer 1982
**Gary Patterson, measurements - fall 1982

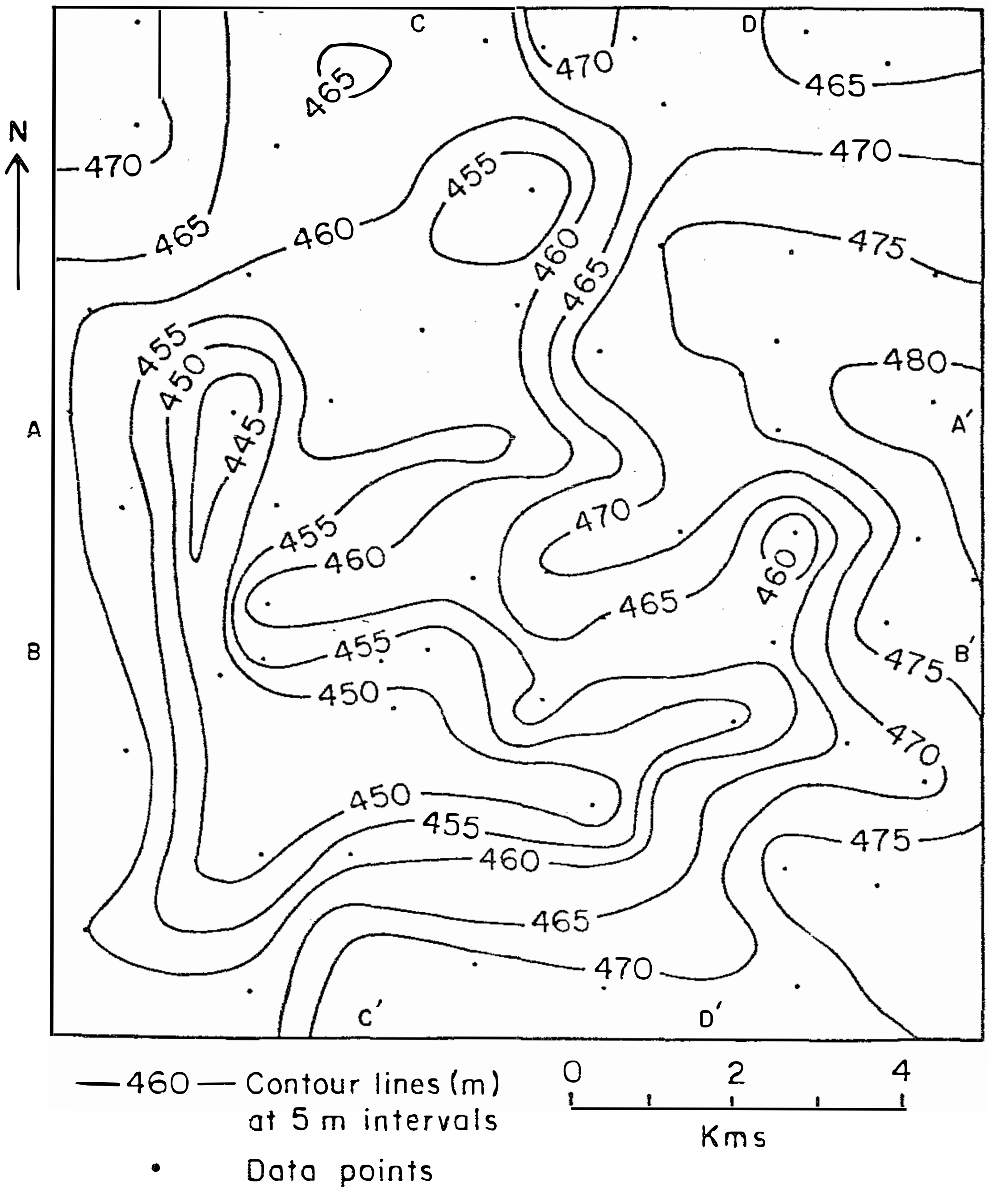

Figure 6. Bedrock elevation map from refraction data, Trout Lake area, northern Wisconsin.

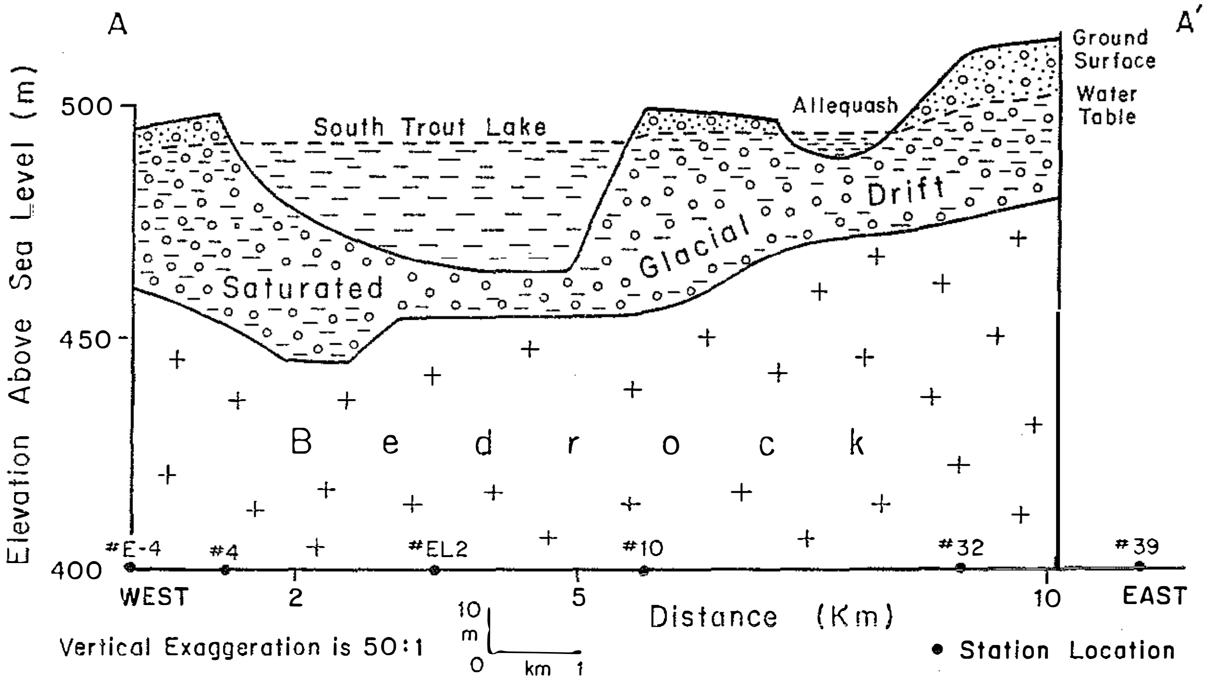

Figure 7. Geologic cross-section along AA' (fig. 2).

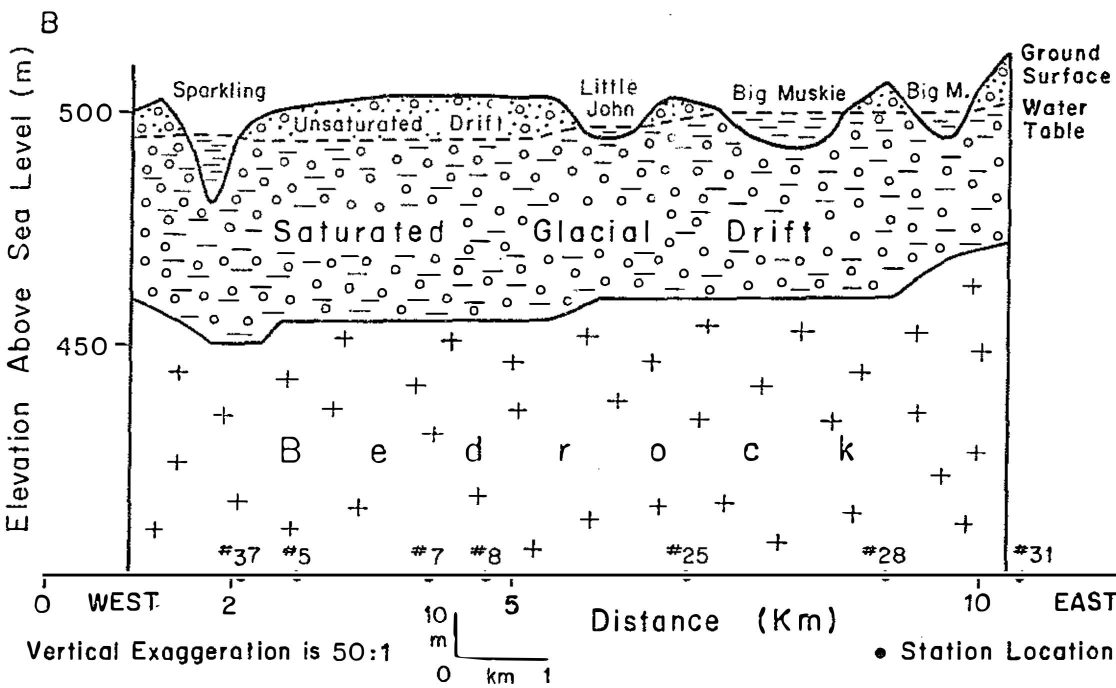

Figure 8. Geologic cross-section along BB' (fig. 2).

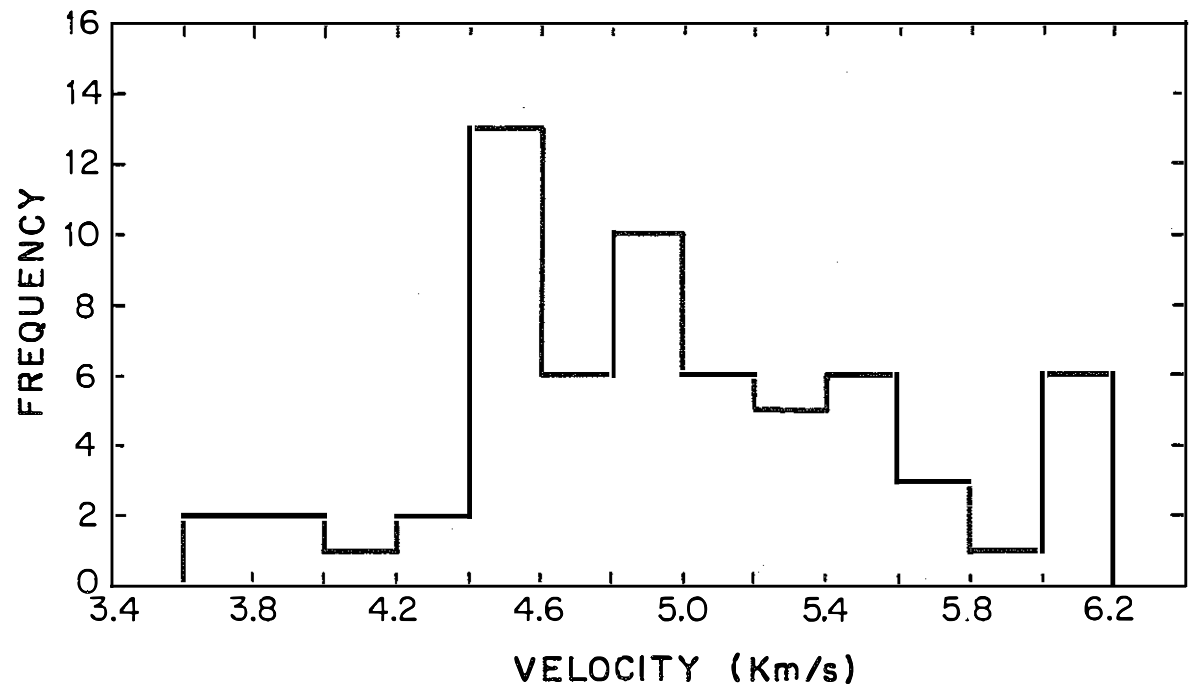

Figure 9. Frequency distribution of bedrock velocities in the study area.

Figure 6 shows the elevation contour map of the bedrock. Bedrock valleys are distinctly present on the map. An east-to-west dip of about 1° was calculated for the study area. Two seismic cross-sections (fig. 7 and 9) prepared from AA' and BB' traverses (fig. 2) show the bedrock surface and the layer 1-layer 2 structure in an east-west direction.

A wide range of bedrock velocities were obtained during the survey. A frequency distribution of the velocities is shown in figure 9. A contour map of bedrock velocities is shown in figure 10. Most of the stations had bedrock (layer 3) velocities in the 5 km/s range. Some stations were 5.5 km/s and greater and some were less than 4.5 km/s. Associations of rock types and seismic velocities are speculative. Using representative velocity values for different rock types (Mooney, 1973), three possible rock types are granite, gabbro, and gneiss. The identifications in figure 10 are based on this association. Whether these particular identifications are correct or not is not important. The data show significant differences in bedrock velocities in the area. These indicate that the rocks have significant differences in the physical properties.

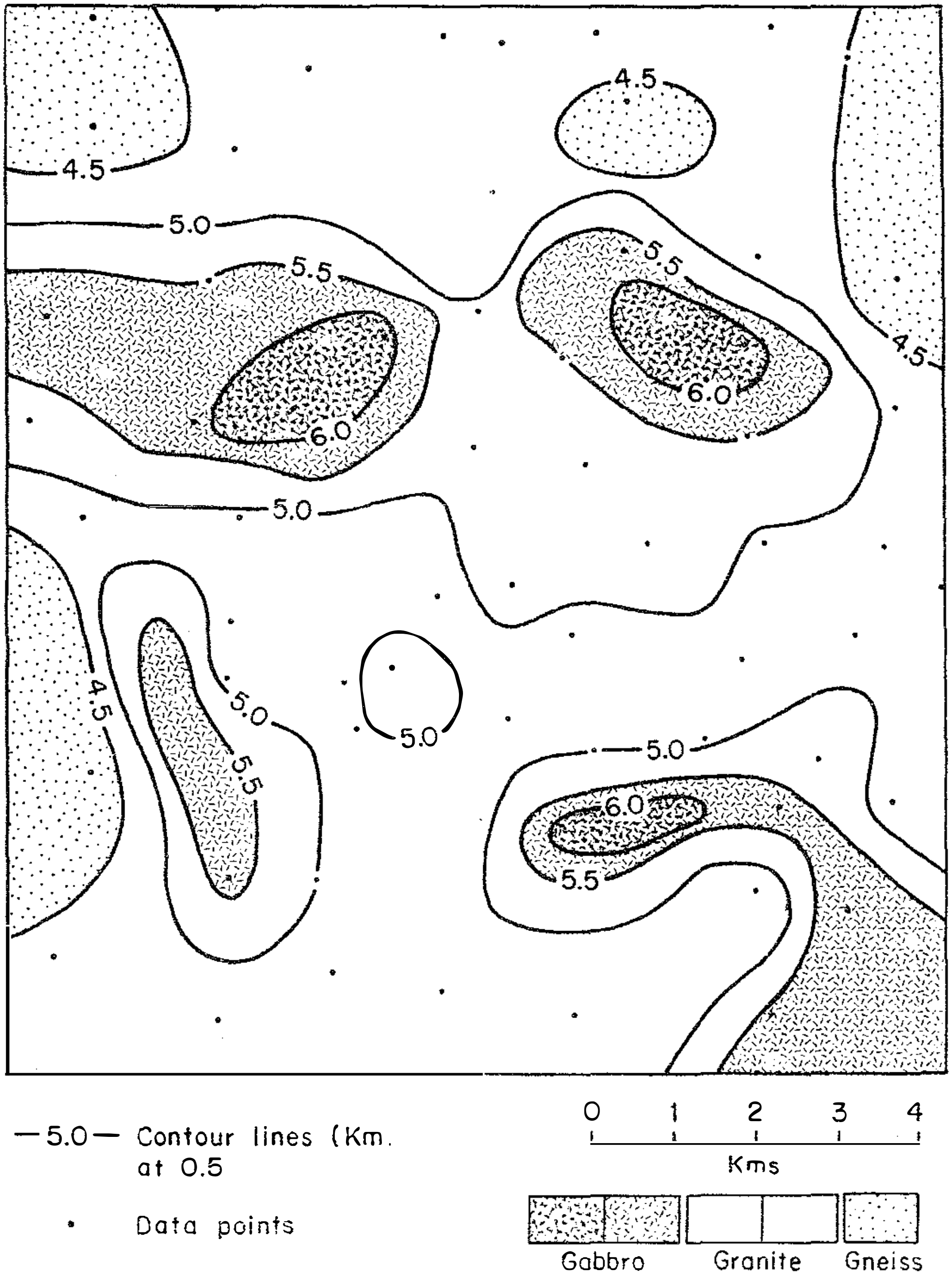

Figure 10. **Bedrock velocity contour map of the study area showing probable lithology of the crystalline rock.**

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SEASONAL GEOCHEMISTRY OF TWO TUFA-DEPOSITING SPRINGS IN SOUTHWESTERN WISCONSIN

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ABSTRACT

Two small springs in southwestern Wisconsin, which emerge from Middle Ordovician dolomite, form water falls flowing over massive tufa mounds. Both springs were sampled in summer and winter at the spring outlet and at the base of the falls. Both springs contain hard water of a calcium-magnesium-bicarbonate type which is supersaturated with carbon dioxide in comparison to the atmosphere. Seasonal comparison of the water quality at the spring outlets shows a summer decrease in pH, saturation with respect to calcite and dolomite, and bicarbonate concentration; and a summer increase in temperature and pCO_2. These effects are due to carbonic-acid recharge available during the growing season. As the spring water emerges and travels over the algae- and ice-covered tufa mound or both and downward, carbon dioxide is rapidly lost to the atmosphere. This causes a dramatic increase in carbonate mineral saturation and pH. Calcite or aragonite is precipitated and results in a subsequent loss of dissolved calcium, bicarbonate, total hardness, and conductivity. Contrary to other studies, for these springs the greatest loss of calcium carbonate occurs in the winter. The top-to-bottom increase in carbonate mineral saturation in the summer indicates that deposition is inhibited during that season, perhaps because of the effects of magnesium ions retarding calcite precipitation at higher temperatures. Evaporation does not play a significant role in tufa deposition at this locality.

INTRODUCTION

Many previous studies have indicated that tufa deposition of non-thermal springs, as well as speleothem deposition in caves, occurs mainly during periods of comparatively warm weather such as summer or interglacial periods. Enhanced tufa deposition during warm weather is thought to be due to greater evaporation, plant growth, and higher concentrations of carbonate minerals during low flow conditions (Pitty, 1971; Moore, 1962).

Springs which deposit tufa are not abundant in Wisconsin. Two such springs, however, are locally well known. Both of these emerge from Middle Ordovician dolomite where thin shales locally concentrate ground-water flow. This study examines the seasonal variation in the carbonate geochemistry of these two springs and how it pertains to tufa deposition. Unlike previous studies, both of these springs were found to have enhanced tufa deposition in winter.

SPRING DESCRIPTION

The spring locally known as Platteville tufa falls is located 7 kilometers southwest of the town of Platteville, Wisconsin (NE1/4NW1/4 sec. 5.

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T. 2 N., R. 1 W., Dickeyville quadrangle). The water issues from a sand-choked opening in the base of the Middle Ordovician Guttenberg Dolomite on the steep south bank of Blockhouse Creek, and flows over a massive mound of tufa which overhangs the creek. The total vertical drop of the water is approximately 15 m. Potosi tufa falls is located 14 km northwest of the town of Potosi, Wisconsin, 300 m. south of the bridge over the Grant River formed by Camel Ridge Road (NW1/4NE1/4 sec. 17 T. 3 N. R. 4 W., Balltown quadrangle). In this location the water emerges from the base of the Pecatonica Dolomite, at a vertical cliff formed by the erosion of the Grant River through the St. Peter Sandstone. A large mound of tufa overhangs the river here as well, with the total vertical drop from the spring to the river approximately 20 meters. In this location the river bottom is littered with large irregular blocks of tufa which have fallen off the mound in the past.

Both springs have a relatively uniform year-round flow of approximately 40 and 60 liters per minute, respectively. The water of both springs are clear and sediment-free. Both Tufa mounds support the abundant growth of filamentous algae, mosses, and grasses. Ice buildup on the tufa mounds is considerable in the winter.

Tufa accumulation is most rapid at the top of the tufa mound where a thin water layer passes over the tufa barrier before falling to the river below. The fall of the mineral-laden spring water causes aeration and turbulence which results in the loss of carbon dioxide, evaporation, and plant growth. All of these promote carbonate mineral precipitation on the tufa mound.

METHODS

Water samples were taken at both springs as close to their respective outlets as possible, and also at the base of the falls. The springs were sampled in June 1981 (air temperature approximately 20 °C) and again in February 1982 (air temperature approximately 5 °C). Conductivity, temperature, and pH were measured in the field. Bicarbonate concentration was measured (standard HCl titration) on the chilled unfiltered samples within several hours of collection. The samples were then acidified with nitric acid, and the remainder analyses were performed in the laboratory several days later. Computer analysis of the data (from a program designed by Jacobson, 1973, and modified by E. Werner) was used to calculate the theoretical electrical conductivity at 25 °C, the saturation indices for calcite and dolomite, the theoretical aqueous partial pressure of carbon dioxide, the calcium to magnesium equivalence ratio, and the ion charge-balance error. The results are shown in table 1.

DISCUSSION OF CHEMICAL DATA

The geochemistry of both the Platteville and Potosi springs shows very hard water of a calcium-magnesium-bicarbonate type, as would be expected from a dolomite aquifer. The calcium-to-magnesium equivalence ratio is also typical of dolomite dissolution. The water is very close to saturation with carbonate minerals as it emerges, and exceeds the carbon dioxide partial pressure in equilibrium with the atmosphere (log pCO_2 = -3.5).

Table 1. Results of chemical analyses for seasonal comparison of top (spring outlet) and bottom (base of falls) of Potosi and Platteville tufa falls springs. Symbols and units used: SPC- conductivity in mhos/cm at 25 °C (calculated); TH- total hardness in mg/l $CaCO_3$; pCO_2- base 10 logarithm of the theoretical aqueous carbon dioxide partial pressure; SIc- log saturation index for calcite; SId- log saturation index for dolomite; Ca/Mg- calcium to magnesium equivalence ratio; all other parameters in mg/l except for pH and T°C. ERR- analysis charge-balance error (percent).

	Summer Potosi 6-16-81		Winter Potosi 2-27-82		Summer Platteville 6-7-81		Winter Platteville 2-27-82		
	top	bottom	top	bottom	top	bottom	top	bottom	Analytical error
pH	7.20	7.95	7.30	8.00	7.20	7.90	7.30	7.90	0.05
T°C	10.0	12.5	9.0	7.0	9.0	9.8	8.0	5.0	.2
SPC	771	708	747	679	749	750	770	755	--
HCO_3^-	437	418	439	396	435	431	450	439	5
TH	364	348	364	327	364	366	373	369	20
Ca^{+2}	88.3	80.8	80.8	67.3	80.6	82.1	87.9	79.1	4
Mg^{+2}	34.8	35.4	39.4	38.6	39.4	39.2	37.2	41.5	2
Cl^-	5.6	4.9	5.9	5.9	3.9	4.2	4.5	5.2	.5
SO_4^{-2}	14	14	10	10	35	31	31	30	2
Fe_{TOT}	0.005	0.005	0.009	0.009	0.006	0.012	0.009	0.060	0.02
Na^+	5	5	5	5	5	5	5	5	
Ca/Mg	1.54	1.38	1.24	1.06	1.24	1.27	1.43	1.16	--
SIc	0.09	0.83	0.14	0.70	0.04	0.75	0.17	0.67	0.05
SId	-0.05	0.72	0.04	0.61	-0.07	0.65	0.03	0.56	0.05
PCO_2	-1.65	-2.41	-1.75	-2.50	-1.66	-2.36	-1.75	-2.37	0.05
ERR	5.4	2.8	3.5	4.2	3.6	2.9	3.8	3.3	--

Seasonal comparison of the chemical quality of the water at the outlet of both springs shows a summer decrease in pH, decrease in saturation with respect to calcite and dolomite, decrease in bicarbonate concentration, and an increase in temperature and theoretical aqueous carbon dioxide partial pressure. During the summer growing season, the carbon dioxide partial pressure in the soil zone should be greater because of the higher temperature, rate of organic matter decay, and plant root respiration. Percolation of water through this zone would tend to increase the carbon dioxide partial pressure of the shallow ground water during the summer. This results in a pH decrease because of the formation of carbonic acid, which then partially dissociates to bicarbonate. The summer recharge of carbonic-acid rich ground waters causes a decrease in the degree of carbonate saturation because greater bicarbonate and hardness values are needed in the ground water to achieve saturation at the lowered pH levels. The summer decrease in bicarbonate concentration in the springs is harder to explain, as a summer increase should be expected due to the dissociation of carbonic-acid recharge. The slight summer decrease may be a result of the lower bicarbonate solubility in warmer water.

Comparison of water quality between the spring outlet at the top and the bottom of the falls shows that as the water travels out of the opening, over the tufa mound and downward, its conductivity, total hardness, calcium and bicarbonate concentrations, and theoretical aqueous carbon dioxide partial pressure all decrease, especially for the Potosi spring in the winter. The pH and saturation indices for calcite and dolomite both increase dramatically. The increase in carbonate mineral saturation between the top and the bottom of the falls is especially noticeable in the summer for both springs. As would be expected the temperature of the spring water increases in summer and decreases in the winter as the water reacts with ambient atmospheric temperatures, or flows over the winter ice accumulation.

As water travels over the tufa mound it approaches equilibrium with the atmospheric partial pressure of carbon dioxide, which is much lower than the carbon dioxide content of the spring water. This rapid degassing causes a sudden rise in pH and subsequent precipitation of calcium carbonate, which removes calcium and bicarbonate ions from solution, thereby decreasing the total hardness and electrical conductivity. If calcite precipitation were rapid enough to keep pace with degassing, the spring water would reach the bottom of the falls at equilibrium with carbonate minerals. However, the water actually arrives at the base of the falls in a supersaturated state, indicating that the rate of carbon dioxide degassing is much faster than the rate of tufa deposition. Similar results have been found by Dunkerley (1981) and Barnes (1965) for tufa-depositing springs in Queensland, Australia, and Brich Creek, California, respectively.

The chemical results shown in Table 1 also indicate that tufa deposition is occurring by a precipitation of calcite or aragonite only. The small gains or losses in dissolved magnesium shown are within experimental error and are not significant. The loss of calcium and preservation of dissolved magnesium from the top to the bottom of the falls causes the calcium-to-magnesium equivalence ratio to approach unity at the bottom.

The most interesting problem with both the Potosi and Platteville tufa falls springs is that most of the calcite deposition occurs in the winter rather than in the summer, as would be expected. Table 2 indicates direct

Table 2. Top-to-bottom gain (+) or loss (-) in selected aqueous geochemical species. Symbols and units are the same as for table 1.

	Summer Potosi 6-16-81	Winter Potosi 2-27-82	Summer Platteville 6-7-81	Winter Platteville 2-27-82
pH	+0.75	+0.70	+0.70	+0.60
T°C	+2.5	-2.0	+0.8	-3.0
SPC	-63	-68	+1	-15
HCO^-_3	-14	-43	-4	-11
TH	-16	-37	+2	-4
Ca^{+2}	-7.5	-13.5	+1.5	-8.8
Mg^{+2}	+0.6	-0.8	-0.2	+4.3
Ca/Mg	-0.16	-0.18	+0.03	-0.27
SIc	+0.74	+0.56	+0.71	+0.50
SId	+0.77	+0.57	+0.72	+0.53
PCO_2	-0.76	-0.75	-0.70	-0.62

gains and losses of relevant dissolved species between the top and bottom of the falls. The greatest loss in dissolved calcium and bicarbonate occurs in the winter. The slight gain in calcium for Platteville tufa falls in the summer is insignificant. The greatest gain in carbonate mineral saturation from top to bottom occurs in the summer because less calcite is deposited during that season.

Previous research has indicated that tufa deposition from non-thermal springs occurs mainly in the summer due to greater evaporation and plant growth during the warm season (Pitty, 1971). In addition, Moore (1962) indicates that stalactite growth in caves is greater in the warm season and in warm climates because ground water contains more carbon dioxide from organic matter decay and plant root respiration in the soil zone. This lowers its pH and allows it to dissolve more carbonate minerals from the bedrock. When this slowly percolating ground water eventually reaches saturation and subsequently migrates to an air-filled cave passage, carbon dioxide is rapidly lost and stalactite growth results. However, stalactite growth will not occur if percolation is so rapid that the water cannot reach saturation. In the winter, on the other hand, the ground water has less ability to dissolve (and hence precipitate) minerals because less carbon dioxide is available. Platteville tufa falls shows higher concentrations of carbonate minerals in the summer, as predicted by this model, as do other springs in the area (Heller, manuscript in preparation). However, deposition of calcite occurs as a function of calcite saturation rather than total concentration. As noted previously, both tufa falls springs are more saturated with carbonate minerals, and hence more likely to deposit tufa, in the winter.

Moore's model has been challenged by Atkinson (1981), who has studied stalactite growth in Castleguard Cave, British Columbia, which is located beneath the Columbia Icefield. Atkinson maintains that the abundant speleothems in this alpine cavern are a result of supersaturation of ground water caused by complex mineral dissolution of dolomite and sulfates rather than loss of carbon dioxide. If this is true then the speleothem deposition in Castleguard Cave is not strictly climatically controlled.

Herlinger (1977) notes that tufa deposition along Fall Creek, Idaho, occurs as spherical granules attached to algal filaments in the summer, and denser, non-granular zones deposited in the winter when darkness and cold preclude or inhibit algal activity. Examination of eroded, inactive tufa mounds reveals cycles of porous, granular layers alternating with denser, non-granular zones.

In contrast to the studies above, Hennig, and others (1982) plotted age data for 660 speleothems and 140 spring-deposited travertines. The plots clearly show periods of increased speleothem/travertine growth between approximately 130,000 and 90,000 years ago and since about 15,000 years ago, periods which correspond to warm, humid interglacial climatic phases.

CONCLUSION

The results of this study and the research cited above show that climatic controls of tufa (or stalactite) deposition are far from simple. For whatever reason, calcite tufa deposition at Platteville and Potosi tufa falls occurs mainly in the winter. The top-to-bottom increase in carbonate mineral saturation in the summer indicates that deposition is inhibited during that season, perhaps because of the effects of magnesium ions retarding calcite precipitation at higher temperatures. Evaporation of the water is not thought to play a significant role in the tufa deposition for two reasons: 1) tufa deposition occurs mainly in the winter while evaporation is strongest in the summer, and 2) in order to cause calcite supersaturation to occur by evaporation, an increase or at least maintenance of solute concentrations should be expected from top to bottom of the falls. This does not occur.

The conclusions of this study are based on a total of eight water samples, so the results should be considered preliminary. Unfortunately, because of the exposed locations of the springs, obtaining water samples from them at all is physically challenging, particularly in winter.

ACKNOWLEDGMENTS

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Geoscience Wisconsin Editorial and Publication Policy

General Information

"Geoscience Wisconsin," a report series covering significant geoscience research pertaining to Wisconsin geology, is published by the Wisconsin Geological and Natural History Survey, University of Wisconsin—Extension. The purpose of the series is to provide increased awareness of the geoscience research done in Wisconsin and to provide a vehicle for the communication of scholarly geologic reresearch pertinent to Wisconsin. Although compilations and review papers will be considered for publication, the main object of the series is to publish high-quality, original research papers of general interest on all phases of the geology of Wisconsin.

Scope and Length of Papers

All phases of geoscience research done in Wisconsin or very closely related to Wisconsin interests will be considered for publication. All members of the professional geoscience community are encouraged to submit their scholarly papers for publication in "Geoscience Wisconsin." Students are also encouraged to submit papers on their completed thesis research.

Papers should be no longer than 25 pages including all figures, references, abstracts, and so forth. Manuscripts exceeding 25 pages must have the approval of the editor before submission to "Geoscience Wisconsin." Draft copies for review will be double spaced with ample margins; this includes references cited. For final publication, camera-ready copy of all papers will be prepared by the Wisconsin Geological and Natural History Survey. Originals or photographs of all illustrations will be submitted at this time. Photocopies (xerographies) will not be accepted for printing. General style follows that of the U.S. Geological Survey and the Geological Society of America. Manuscripts not meeting style will be returned to the authors without review. There are no page charges.

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Michael G. Mudrey, Jr., is the editor and is responsible for receiving manuscripts which are submitted. He will examine manuscripts for general style and length requirements, and he will make recommendation as to suitability for publication in "Geoscience Wisconsin." The recommendation will be submitted to the Director for a decision and the manuscript will either be rejected, returned to the author for modification, or sent to one of the associate editors for review.

After the manuscript has been reviewed by an associate editor and reviewers (specialists in the field addressed by the paper) a final decision on acceptance or rejection will be made by the editor. The manuscript, if accepted, will be returned to the author for modification, based on the recommendations of the associate editor and reviewers, and for preparation of the final copy. The final manuscript will then be submitted to the editor who will see the manuscript through its publication stages.

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