GEOLOGY OF THE NIAGARA ESCARPMENT IN WISCONSIN

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ABSTRACT

The Niagara Escarpment is a 650-mile (1,050 km) long discontinuous bedrock ridge that runs from western New York near Niagara Falls, through southern Ontario and the Upper Peninsula of Michigan into eastern Wisconsin. In Wisconsin, the escarpment runs from Rock Island on the tip of Door County all the way south to Ashippun in Dodge County and is the most prominent topographic feature in the eastern part of the state. It includes the mainly west and northwest-facing escarpments that have developed on resistant eastward-dipping Silurian dolostones that overlie the much softer Ordovician Maquoketa Shale. The geologic feature we see today was a culmination of many depositional, tectonic, and erosional processes that have operated over hundreds of millions of years. Together, these events have produced spectacular cliffs and ledges that overlook lowlands to the west beginning at Horicon Marsh in the south all the way north to the bay of Green Bay west of the Door Peninsula. This article is intended as a comprehensive review of the geologic history of this region as it pertains to the Niagara Escarpment.

INTRODUCTION

The Niagara Escarpment is the topographic expression of a bedrock unit that extends at least 650 mi (1,046 km) from eastern Wisconsin through the Upper Peninsula of Michigan, through Manitoulin Island and the Bruce Peninsula into southern Ontario and into the Niagara area of New York. This internationally recognized geologic feature was named for the region around Niagara Falls in New York and Ontario where the Niagara River plunges over the Silurian Lockport Dolostone into a gorge cut through the underlying lower Silurian and uppermost Ordovician mudstones and sandstones.

The Niagara Escarpment is eastern Wisconsin's most prominent topographic feature. It runs for approximately 230 mi (370 km) from the tip of Door County southward to Dodge County (fig. 1), with sporadic exposures further to the south in Waukesha County where the bedrock escarpment is mostly concealed beneath glacial sediments (Kasprzak and Walter, 2001). It is the best developed in a series of parallel escarpments in eastern Wisconsin that are present along the western margin of the ancestral Michigan basin. The Niagara Escarpment is defined by the western edge of a discontinuous topographic ridge of eastward dipping Silurian dolostone, formally known as a cuesta. It ranges in height from small ledges a few feet (meters) high to cliffs over 200 ft (60 m) high in parts of Door County. The cuesta exists because of a complex interplay between ancient marine sedimentary environments, development of the Michigan structural basin to the east, and subsequent erosion by rivers and glaciers. The Niagara Escarpment's importance to the region's ecology, materials industry, and tourism industry has long been recognized (Anderson and others, 2002; Kasprzak and Walter, 2001; Kluessendorf and Mikulic, 1989; Mikulic and others, 2010; this issue). In 1852, T.C. Chamberlin (1877) used the term "ledge" to describe the Niagara Escarpment throughout eastern Wisconsin. Local vernacular names for rocks along and near the Niagara Escarpment include "the ledge" in areas to the south between Green Bay and Fond du Lac, as well as "the bluff" to the north in Door County, reflecting the important relationship between local culture and the escarpment in Wisconsin. Others in northeastern Wisconsin have used the term "the ridge" (for example, Kox, 1985).

Despite this recognition, there has not been a comprehensive peer-reviewed scientific review article dedicated to the geology of the Niagara Escarpment in Wisconsin. With a few exceptions, limited

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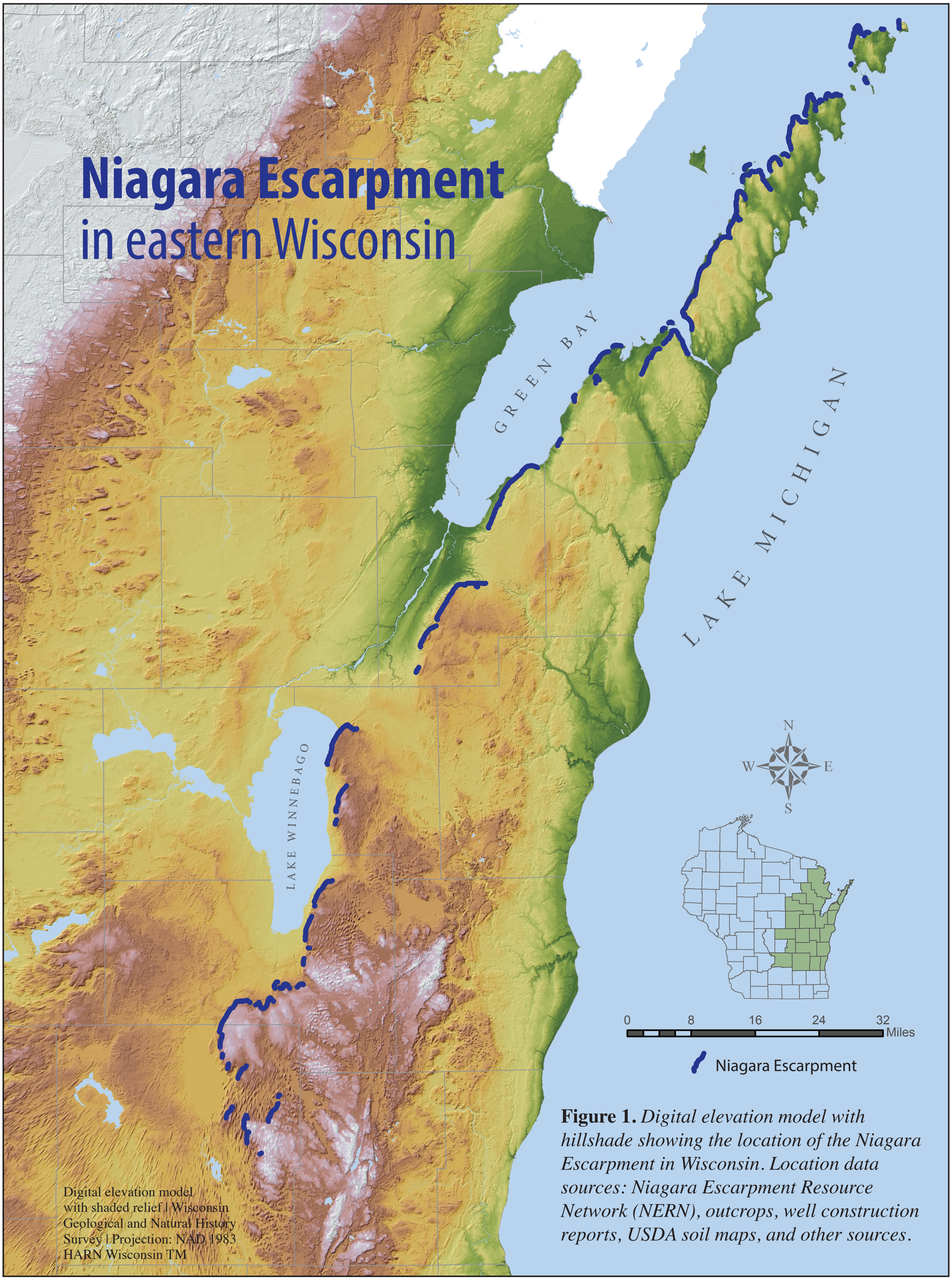

Figure 1. *Digital elevation model with hillshade showing the location of the Niagara Escarpment in Wisconsin. Location data sources: Niagara Escarpment Resource Network (NERN), outcrops, well construction reports, USDA soil maps, and other sources.*

attention has been paid to the bedrock of northeastern Wisconsin in peer-reviewed literature, especially outside of groundwater and paleontological investigations. For example, the North Central Section of the Geological Society of America's Centennial Field Guide (Volume 3) contains descriptions for eleven different locations in Wisconsin, but none for eastern Wisconsin (Biggs, 1987). The Wisconsin Geologic and Natural History Survey also maintains a list of over 100 descriptions of outcrops to illustrate various geologic formations, features, and characteristics in Wisconsin. However, there is only one outcrop description listed for Door, Brown, or Calumet counties, where the bulk of the Niagara Escarpment is located in Wisconsin. This article, along with others in this special issue of Geoscience Wisconsin, will help to close this gap by providing a general review of existing literature and set the stage for new research being conducted in the region.

GEOLOGIC SETTING AND STRATIGRAPHY

Chamberlin (1877) noted that although Wisconsin could not properly be described as either mountainous or sunk to a dead level (below sea level), it was "the golden mean in a gently undulating diversified surface." The relatively modest topography he described is the product of hundreds of millions of years of mountain building, intense erosion, encroachment of the oceans, and influx of glacial ice. Today, the eastern Wisconsin region lies on the western flank of the ancestral Michigan basin and is bordered by the Wisconsin arch to the west, the Canadian shield to the north, and the Illinois basin to the south. The relatively thin sequence of 2,300 ft (<700 m) of Paleozoic rocks in northeastern Wisconsin gently dips to the east into the ancestral Michigan basin, where the thickness of the sedimentary section increases substantially to over 15,700 ft (4,800 m). It is the eastward dip of these sedimentary rocks, especially those of the Silurian System, which allowed for later erosion to produce the Niagara Escarpment.

Research on the rocks in northeastern Wisconsin has been long lived, but restricted in scope because of the limited number of natural exposures of bedrock. The most comprehensive publication that covers the geology of eastern Wisconsin is that of Chamberlin (1877), but others have also published on the sedimentology and stratigraphy of Silurian rocks in the region (for example, Shrock 1939, 1940; Sherrill, 1978; Kluessendorf and Mikulic, 1989; Harris and Waldhuetter, 1996; Harris and others, 1998; Kluessendorf and Mikulic, 2004; Mikulic and others, 2010). Most of the region is covered by Pleistocene glacial sediments, ranging in thickness from less than a meter to over 330 ft (100 m) in buried bedrock valleys. As a result, outcrop exposures and even road cuts are spotty, at best, except in the Door Peninsula region in northeastern Wisconsin or along the escarpment edge in other counties. Most information known about the bedrock in the region has been gathered from stone quarries, a small number of road cuts, water well construction reports, and a few drill cores.

Wisconsin's geologic history is preserved in rocks and sediments from three distinctly different periods of time, with long intervals of erosion or nondeposition occurring between each. Rocks from the first of these three time intervals are generally referred to as Precambrian rocks. This refers to the part of Earth's past that occurred before the Cambrian Period, which began 541 million years ago (Ma). Rocks that make up the foundation of all continental landmasses are mostly made of these older igneous and metamorphic rocks and are collectively termed "Precambrian basement." The second interval of Earth's history that is recorded in Wisconsin includes mainly sedimentary rocks of the Early to Middle Paleozoic Era. The youngest of the three intervals was recorded during the later part of the Quaternary Period (2.6 Ma to 11,800 years ago). Figure 2 shows a generalized bedrock geologic map for Wisconsin and Michigan. A brief summary of each of these parts of the geologic record is presented below because the history and character of these rocks has been important in the development and evolution of the Niagara Escarpment in Wisconsin.

Precambrian history

Although there are ancient Archean age rocks preserved in our region, the part of North America we call Wisconsin was assembled during the Proterozoic Eon during a mountain building event known as the Penokean Orogeny. The Penokean Orogeny occurred over a 50 million year stretch of time 1,880 to 1,830 Ma. A collision involving three separate landmasses that accreted together formed what is now the northern half of Wisconsin (fig. 3). The first of two collisions involved the older, and much larger, Archean Superior

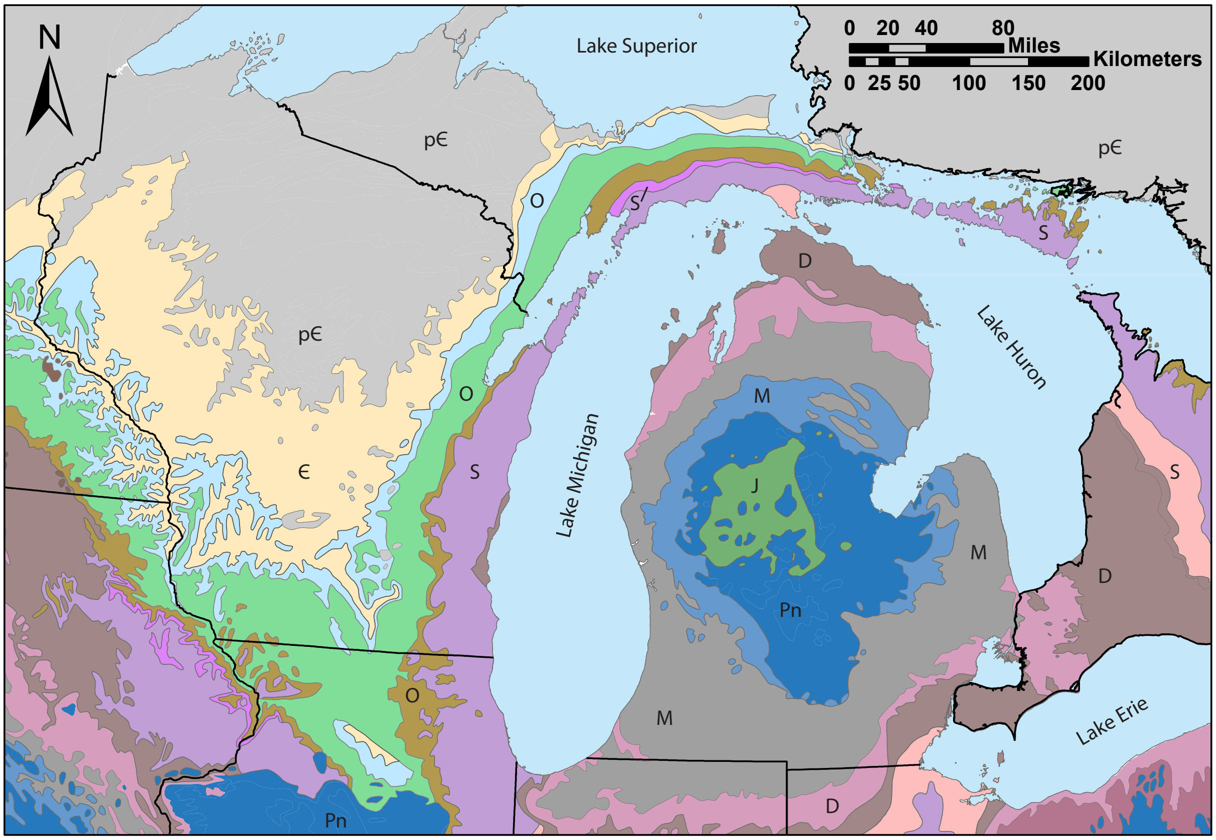

Figure 2. *Bedrock geologic map showing eastern Wisconsin and the ancestral Michigan basin (bullseye pattern). Geologic rock systems (periods): p€ = Precambrian, € = Cambrian, O = Ordovician, S = Silurian, D = Devonian, M = Mississippian, Pn = Pennsylvanian, J = Jurassic. Base map data modified after Schruben and others (1994) and Ontario Geological Survey (1993).*

craton (older than 2,500 Ma) and a Proterozoic (1,889 to 1,860 Ma) volcanic island arc known as the Pembine-Wausau terrane as the ocean basin between them was closed by subduction (Schulz and Cannon, 2007). As the island arc approached, this collision preserved a sedimentary sequence in the Penokean foreland that records a cycle of continental rifting and ocean opening, followed by deep-water sedimentation that was incorporated into the foreland fold and thrust belt. Rocks of the Superior craton are found today from northernmost Wisconsin northward into Canada and are separated from the Pembine-Wausau terrane to the south by an east-west suture zone that runs across northern Wisconsin and the southern portion of the Upper Peninsula of Michigan. This suture zone is known as the Niagara fault zone, but is not related to the Niagara Escarpment. A second collision occurred when the Archean Marshfield terrane was accreted to the Pembine-Wausau terrane by a similar process. This terrane appears to be a piece of Archean continental crust that may have once rifted away from another continent.

Two later orogenic events were responsible for building central and southern Wisconsin. These events, known as the Yavapai and Mazatzal orogenies, are well documented in the southwestern United States and have recently been assigned to this portion of North America. The Yavapai Orogeny (1,800 to 1,700 Ma) further added material to the continent (fig. 3), forming the basement upon which the 1,750 Ma rhyolites and subsequent quartzites were deposited. This event was also responsible for regional metamorphic overprinting that produced high grade metamorphic rocks along a gneiss dome corridor in areas as far north as the Upper Peninsula of Michigan (NICE Working Group, 2007).

The Baraboo Hills and other quartzite units in Wisconsin were deposited after the Yavapai Orogeny

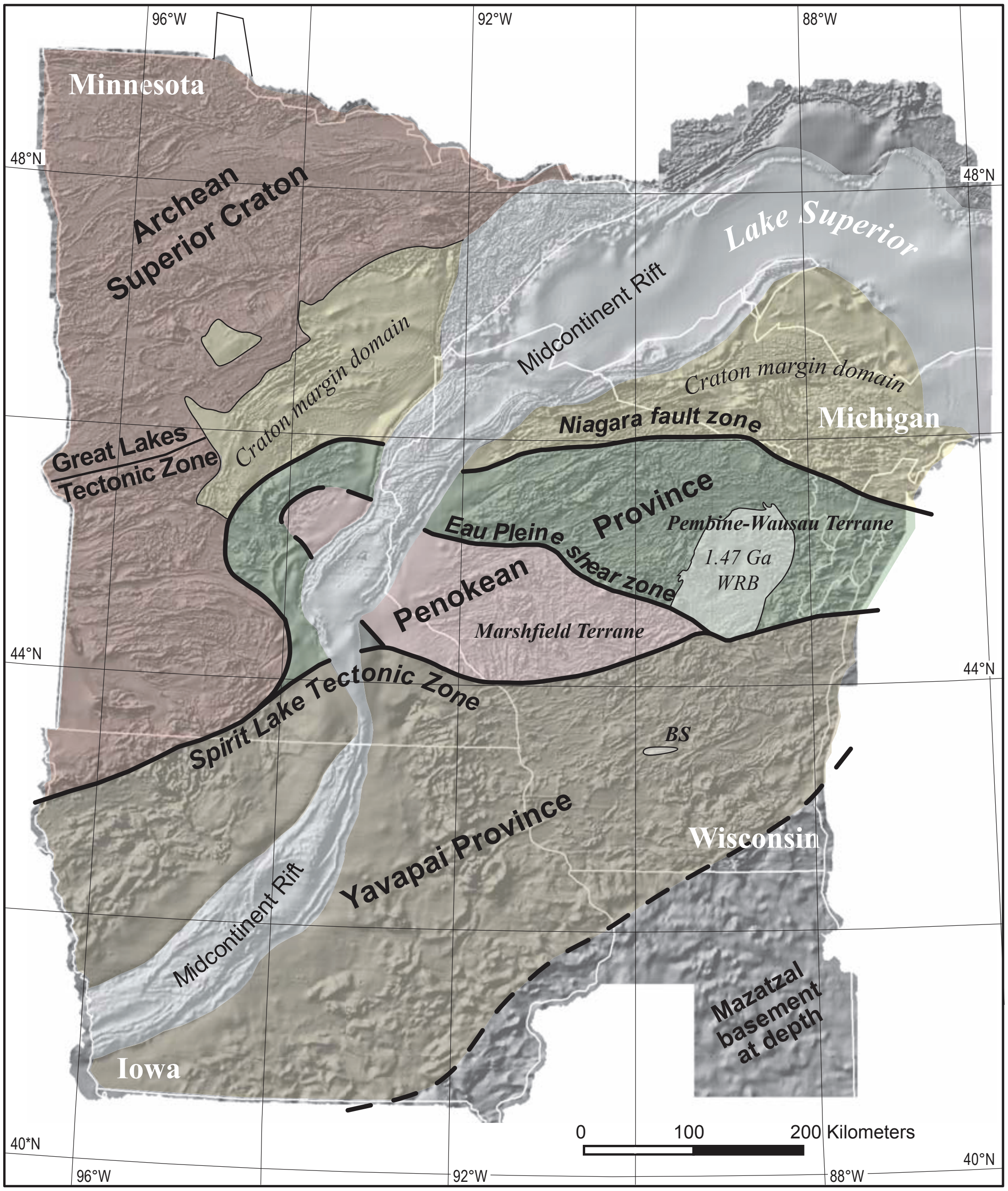

Figure 3. *Geologic terrane map of Precambrian basement rocks in the northern U.S. midcontinental interior. WRB = Wolf-River batholith, BS = Baraboo Syncline. Underlying gray shaded base map is the regional aeromagnetic anomaly map. The "craton margin domain," north of the Niagara fault zone, represents the portion of the Superior Craton with sedimentary and volcanic rocks deposited during the interval 2.3–1.77 billion years ago. Map modified after NICE Working Group (2007); courtesy of Daniel Holm.*

and 1,750 Ma granites and rhyolites, but before the subsequent Mazatzal Orogeny. The Baraboo interval quartzites and the underlying felsic rocks were metamorphosed and significantly folded and fractured about 1,630 Ma. The Mazatzal Orogeny was a significant regional orogeny stretching from the southwestern United States northeastward to Illinois, Michigan, and southeastern Wisconsin, and it was responsible for regional deformation of igneous rocks and quartzites on the Yavapai block (for example, NICE Working Group, 2007; Jones and others, 2009). The composition of the Precambrian bedrock in the vicinity of the Niagara Escarpment in eastern Wisconsin is poorly known, but is thought to include both Penokean and Yavapai age crustal blocks (NICE Working Group, 2007). In some areas near Fond du Lac, Wisconsin, apparent Baraboo interval quartzites are also preserved in the subsurface and have been retrieved in drill cores (Bill Batten, 2008, personal communication).

Even later episodes of granite and syenite igneous intrusions, which are not apparently related to mountain building events, occurred between 1,522 and 1,468 Ma in north-central Wisconsin, the largest of which is known as the Wolf River Batholith (fig. 3), about 60 mi (96 km) northwest of Green Bay, Wisconsin (Dewane and Van Schmus, 2007).

The final major Precambrian event in the Lake Superior region involves the formation of a 1,200 mi (2,000 km) long horseshoe-shaped rift known as the Midcontinent Rift System. This rift system formed between 1.1 and 1.0 billion years ago and stretches from eastern Kansas up through Lake Superior and down toward southeastern Michigan (fig. 3, gray area) (Ojakangas and others, 2001). The rift preserves a thick sequence of up to 12 mi (20 km) of volcanic rocks and as much as 6 mi (10 km) of post-rift sediments. The world famous native copper deposits in the Keweenaw peninsula of Michigan's upper peninsula were produced by hydrothermal solutions related to this aborted rift system.

A long period of erosion followed all of these Precambrian events, producing a great unconformity in eastern Wisconsin, for which no rock record was preserved over at least a 1-billion-year period in most areas. It was not until the Cambrian Period of the Paleozoic Era when oceans invaded the middle of the North American continent that a new record of deposition began in the region.

Paleozoic history

Rocks deposited during the Paleozoic Era (541 to 252 Ma) consist mainly of sandstone, dolostone, and shale, and these rocks form the bedrock of northeastern Wisconsin. Nearly all of these rocks are marine or marginal marine, deposited during some of the highest sea levels of the Paleozoic Era. These rocks range in age from Late Cambrian to Late Devonian, although the Devonian rocks are only preserved along the Lake Michigan shoreline south of Sheboygan (Kluessendorf and others, 1988). As much as 2,300 ft (700 m) of lower and middle Paleozoic quartz sandstone, dolostone, and shale are present in northeastern Wisconsin (fig. 4), and the strata thicken toward the

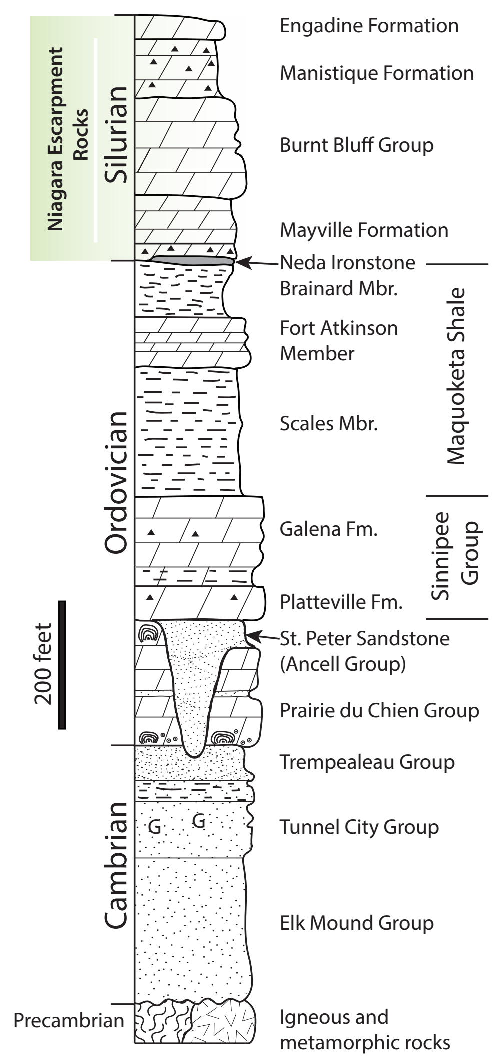

Figure 4. *Generalized stratigraphic column for northeastern Wisconsin.*

ancestral Michigan basin, where they are overlain by even younger Paleozoic and Mesozoic sedimentary rocks (Catacosinos and others, 1990; Luczaj, 2006). Subsidence of the Michigan basin began during the Late Cambrian and occurred simultaneously with sediment deposition throughout the Paleozoic Era. The subsidence of the ancestral Michigan basin is centered over a portion of the Proterozoic Midcontinent rift system (Catacosinos and others, 1990). This subsidence in the ancestral Michigan basin is the reason why the rocks in eastern Wisconsin are tilted toward the east-southeast (figs. 5 and 6). This part of the North American continent was situated 10° to 20° south of the equator during the early to middle parts of the Paleozoic Era. Evidence for this geographic position is based upon paleomagnetic evidence preserved in rocks throughout North America (for example, Scotese, 1984), and it is the principal reason why tropical marine fauna such as corals and stromatolites are abundant in these rocks (Stanley, 2009).

Early Paleozoic depositional history

The lowermost Paleozoic rocks in eastern Wisconsin are Upper Cambrian sandstones, which were deposited as sea level gradually rose to cover most of the North American craton. They are exposed about 25 mi (40 km) to the west of the Niagara Escarpment. These sandstones form the principal portion of the deep confined aquifer system in northeastern Wisconsin and are about 400 ft (120 m) thick on average (Krohelski, 1986; Luczaj and Hart, 2009; Maas, 2009). While these rocks have been extensively studied west of the Wisconsin arch (for example, Runkel and others, 2007), their deep burial has impeded research on these rocks in northeastern Wisconsin, despite their regional importance as aquifers.

The Ordovician Period (485 to 443 Ma) saw variable deposition of carbonate rocks, sandstones, and shales. Rocks of this age are intermittently exposed west of the Silurian bedrock that defines most of the Niagara Escarpment. The lower half of the Ordovician section includes dolostone of the Prairie du Chien Group, sandstones and minor shale of the Ancell Group, and dolostone from the Sinnipee Group. The upper half of the Ordovician section is dominated by shale.

The Prairie du Chien Group is composed of mixed carbonate-clastic sediments that were deposited on a restricted platform during two major highstands of sea level that covered the North American craton (Smith and Simo, 1997). The carbonate portions of this unit contain locally abundant ooids and stromatolites that can be found in quarries and road cuts. The Prairie du Chien Group is variable in thickness between 0 and 200 ft (0 and 61 m), mainly due to continent-wide subaerial exposure that followed a eustatic (global) sea level fall before deposition of the Ancell Group (Sloss, 1963; Mai and Dott, 1985).

The Ancell Group consists of the St. Peter Sandstone and the overlying Glenwood Shale. The St. Peter Sandstone is generally well-sorted white quartz sandstone, but local layers of red and gray shale and a basal conglomeratic layer are also present. Few fossils are found in the St. Peter, and it is the most variable unit in the region with regard to thickness. It ranges from 0 to at least 250 ft in northeastern Wisconsin, and it is not uncommon for this change to occur over the distance of less than 1 mile (Mai and Dott, 1985; Luczaj and Hart, 2009). The overlying Glenwood shale is generally a few feet thick of brown shale, with locally preserved pyritized trilobite fragments.

The Sinnipee Group consists of two formations in northeastern Wisconsin, which are a nearly uniform 200 ft (61 m) thick. The Platteville Formation and the overlying Galena Formation are mainly subtidal dolostone, with limited shale and shaly dolostone that were deposited on shallow to deep portions of a carbonate ramp. Sinnipee Group carbonates have locally abundant fossils, including nautiloid cephalopods, articulate brachiopods, trilobites, crinoids, graptolites, and a calcareous alga called *Fisherites*. The Decorah Formation, while reported in southern and southwestern Wisconsin, is not present in northeastern Wisconsin (Choi and others, 1999). The robust dolostones of the Sinnipee Group form the lowlands of the Fox River Valley region to the west of the Niagara Escarpment.

The upper half of the Ordovician section is comprised mainly of the Maquoketa Shale, along with a thin, rarely preserved ironstone unit called the Neda Formation. The Maquoketa Shale ranges in thickness from around 230 ft (70 m) to the south to at least 500 ft (152 m) thick to the northeast in Door County. Most of the Maquoketa Formation is green to brown shale that is easily eroded and not typically exposed at the surface. However, a thin (about 50 ft, 15 m, thick) but somewhat resistant dolostone layer known

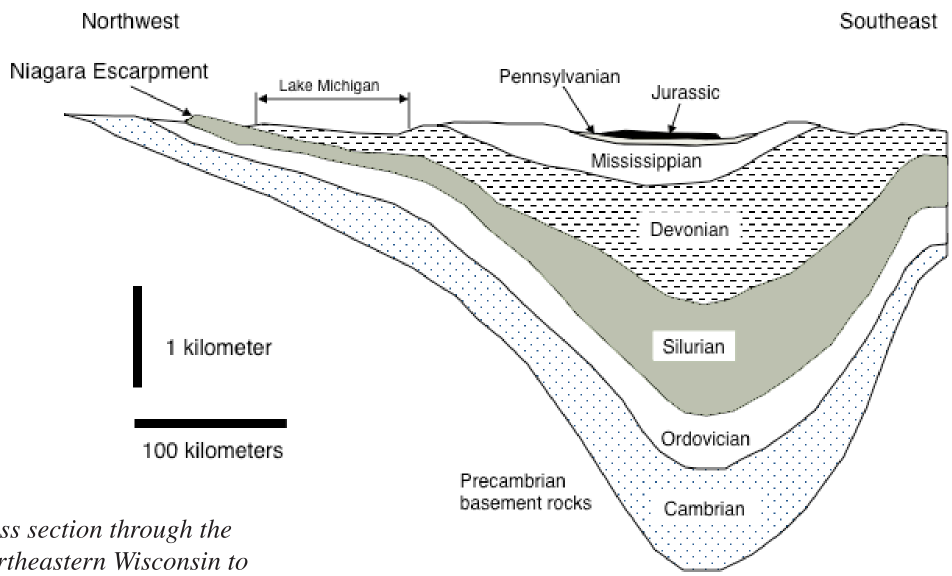

Figure 5. *Schematic cross section through the Michigan basin from northeastern Wisconsin to southeastern Michigan.*

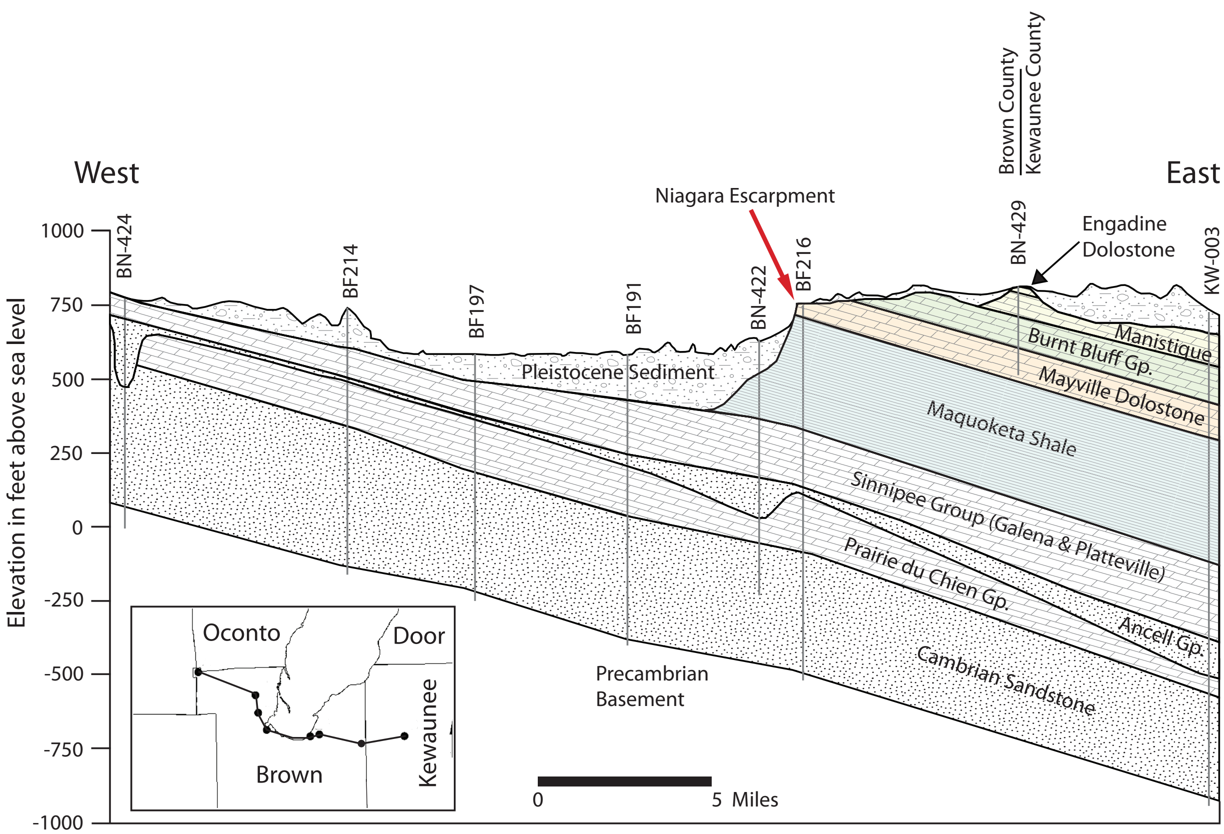

Figure 6. *Cross section through the midpoint of the Niagara Escarpment in Wisconsin. Rock strata dip eastward toward the ancestral Michigan basin. Note the relief on the bedrock surface west of the escarpment that is partially concealed by Pleistocene glacial sediments. Vertical exaggeration is 45 x. Wells (vertical lines) are BN-424 = McKeefry Borehole, Pulaski; BF214 = Village of Howard Well 2; BF197 = City of Green Bay Well 10; BF191 = City of Green Bay Well 4; BN-422 = Shorewood Golf Course Well at UW-Green Bay; BF216 = Town of Scott Well 1; BN-429 = Green Bay Water Treatment Plant Core; KW-003 = former Green Bay and Western Railroad Well, Luxemburg. (Modified after Maas, 2009)*

as the Fort Atkinson Member (fig. 4) is an important cliff-forming unit in places to the west of the Niagara Escarpment. This brachiopod and bryozoan-rich unit is commonly found as beach rubble along the Green Bay shoreline near UW–Green Bay. It also forms rapids, waterfalls, and ledges in several places in Brown County, including the lower falls along Wequiock Creek (Sivon, 1980), the falls of Baird Creek, and the northeast-trending ledge in the Town of Ledgeview.

Along the western shore of the Door Peninsula between Green Bay and Sturgeon Bay, the Maquoketa Formation changes character somewhat, and may include a southern extension of a unit equivalent to the Mormon Creek Formation in the Upper Peninsula of Michigan. This unit contains a poorly fossiliferous assemblage of shallow water carbonates and shales with mud cracks and wave ripple marks (Chamberlin, 1877; Kluessendorf and Mikulic, 1989). This unit is important because it is this resistant material of the Maquoketa Formation that forms a moderate bluff in Door County to the southwest of Little Sturgeon Bay, and which some have included with the Niagara Escarpment in this area.

The youngest Ordovician unit in some areas is the Neda Formation, which is present sporadically throughout eastern Wisconsin, and is considered a member of the Maquoketa Formation by some researchers. The Upper Ordovician Neda Formation is an enigmatic ironstone layer composed of hematite-goethite ooids and interbedded maroon shale that was deposited on local shoal areas as sea level fell during the Late Ordovician. The Neda is not typically observed in exposures or boreholes throughout most of the region, due either to nondeposition and/or subsequent erosion. However, where exposed or present in the subsurface, the Neda Formation ranges in thickness from a few feet to as much as 55 ft (16.7 m) thick. This layer was the source of iron ore for Wisconsin's first iron mines in Dodge County (Mikulic and Kluessendorf, 1983; Paull and Emerick, 1991).

In a few places in the region, such as at Gardner lime kilns, an Ordovician green carbonate unit occurs above the Neda Formation. This unit is known in Ontario as the Kagwong "beds", and a similar relationship exists in the type locality of the Maquoketa in Iowa (Pat McLaughlin, 2013 personal communication).

The end of the Ordovician is marked by a significant unconformity, which resulted from the global drawdown of sea level due to glaciation that drained vast epicontinental seaways (for example, Sheehan, 2001). The contact between the Ordovician and overlying Silurian rocks appears to have little relief in northeastern Wisconsin, although it has as much as 100 ft (30 m) of relief in parts of northern Illinois and Iowa (Kluessendorf and Mikulic, 2004).

Middle and Late Paleozoic depositional history

The Middle and Late Paleozoic Era was recorded in northeastern Wisconsin by a sequence of Silurian (443 to 419 Ma) dolostone units as much as 800 ft thick (240 m) that were deposited in both open and marginal marine environments. These rocks form the backbone of the Niagara cuesta in the Garden Peninsula in Upper Michigan, in the Door Peninsula in Wisconsin, and throughout the uplands of eastern Wisconsin.

The Silurian rocks in Wisconsin were first studied in detail by Chamberlin (1877) and were later modified by Shrock (1939, 1940). Subsequent stratigraphic and bedrock investigations have been conducted on northeast Wisconsin's Silurian rocks, with a main focus on Door County (for example, Sherrill, 1978; Kluessendorf and Mikulic, 1989; Harris and Waldhuetter, 1996; Watkins and Kuglitsch, 1997; Harris and others, 1998; Mikulic and others, 2010) and areas in southeastern Wisconsin (for example, Mikulic and Kluessendorf, 1988; Kluessendorf and Mikulic, 2004). Significant questions remain as to precisely how Silurian rocks in southeastern Wisconsin transition northward to those in Door County. This is due mainly to limited Silurian bedrock exposures in east-central Wisconsin, with the exception of areas near the Niagara Escarpment. Bedrock mapping projects sponsored by the Wisconsin Geological and Natural History Survey are presently being conducted for Brown, Sheboygan, and Manitowoc counties, and future work is planned for Kewaunee, Calumet and Door counties.

For the purpose of this article, Silurian rocks in northeastern Wisconsin were broadly subdivided into four general units (fig. 4). These include, in ascending stratigraphic order, the Mayville Formation, the Burnt Bluff Group, the Manistique Formation, and the Engadine Formation. Kluessendorf and Mikulic (1989, 2004), Mikulic and others (2010), and Harris and others (1998) provide more detailed descriptions for Door, Fond du Lac, and Calumet Counties.

The Mayville Formation is a light brownish gray, burrowed fine to medium grained dolostone. Silicified tabulate corals, stromatoporoids, crinoid debris, and brachiopods are sporadically preserved in this unit, with the upper contact usually designated as one of two regionally extensive beds of *Virgiana* brachiopods (Kluessendorf and Mikulic, 1989; Harris and Waldhuetter, 1996; Mikulic and Kluessendorf, 2009; Mikulic and others, 2010). The Mayville Formation is the principal cliff-forming unit over much of the Niagara Escarpment in Wisconsin, although the overlying Burnt Bluff Group is also present along portions of the escarpment with the highest relief in parts of Door and Brown Counties. The thickness of the Mayville formation reported in the literature varies dramatically, from 66 ft (20 m) in Fond du Lac County (Kluessendorf and Mikulic, 2004) to about 115 ft (35 m) thick in Brown County (Luczaj, 2011), to as much as 230 to 270 ft (70 to 82 m) in Door County (Sherrill, 1978; Harris and others, 1998).

The Burnt Bluff Group overlies the Mayville and consists of two formations: the Byron Dolostone and the overlying Hendricks Dolostone. To the north in Door County, these formations are better exposed and have a somewhat different lithologic character, so they are often treated as separate formations known as the Byron and Hendricks Formations. In Brown County and areas further south, these units are more difficult to distinguish, even in continuous drill cores. The Burnt Bluff Group is entirely dolostone and is dominated by two alternating lithologies (rock types). One lithology consists of medium to dark gray fine-grained dolostones, sometimes with a distinctive burrow mottled appearance. The contact between the Burnt Bluff Group and the underlying Mayville Formation is sharp, and defined by one of these fine grained burrowed layers in the Burnt Bluff Group. The other lithology is predominantly buff to light brown, coarse-grained, laminated to massively bedded intervals with maroon stylolites. Both lithologies in the Burnt Bluff Group have limited fauna with minor tabulate and rugose corals, gastropods, brachiopods, and rare trilobites. Mud cracks, cyanobacterial mats, and other evidence of a peritidal environment are well preserved, especially toward the northern half of the outcrop belt in Wisconsin. Chert is present, but not common in the Burnt Bluff Group. The upper contact of this unit is gradational with the overlying Manistique Formation. The Burnt Bluff Group also varies in thickness from about 130 ft (40 m) in Door County to about 240 ft (73 m) thick in Brown County (Harris and Waldhuetter, 1996; Watkins and Kuglitsch, 1997; Luczaj, 2011). The unit is often heavily fractured and exhibits some of the best-developed karst features in northeastern Wisconsin.

Because of its thickness and resistance to erosion, the Burnt Bluff Group tends to be a prominent cliff-forming unit, especially along the western shore of the Door Peninsula north of Little Sturgeon Bay where extensive cliffs are 100 to 200 ft (30 to 60 m) high. The most noteworthy examples of these cliffs occur at Quarry Point in Potawatomi State Park, at the Leatham D. Smith quarry across the mouth of Sturgeon Bay from Quarry Point, along the western shore of Eagle Harbor in Peninsula State Park, at Ellison Bluff in Ellison Bay Bluff County Park, at Door Bluff in Door Bluff County Park, at Boyer Bluff on Washinton Island, and at Pottawatomie Point on Rock Island. The Byron Dolomite of the Burnt Bluff Group is an important building stone that has been mined along the escarpment for over a century (Kluessendorf and Mikulic, 1989).

The Manistique Formation is generally white to buff, coarse-grained fossiliferous dolostone, which is very cherty and porous in the upper two-thirds of the unit. While separated into the Schoolcraft and Cordell Members, also known as the “coral beds” to the north in Door County, differentiation in Brown County and further south may not be possible with confidence due to limited exposures. Bedding is typically wedge-shaped and contains abundant large, white chert nodules and diverse open-marine fauna, particularly in the upper two-thirds of the unit. Both silicified and non-silicified tabulate corals (*Favosites, Halysites, Syringopora*, and *Cladopora*) are present, along with stromatoporoids, gastropods, pentamerid brachiopods (including a *Virgiana*-rich bed), and rugose corals. Some stromatoporoids and corals as large as 10 to 15 in (25 to 38 cm) across, and red and green stylolites are also common. The Manistique Formation is 90 to 100 ft (27 to 30 m) thick in Door and Brown counties and is generally not a prominent cliff-forming unit. Rather, it is more easily eroded and is often concealed beneath glacial sediments in buried bedrock valleys, especially in areas south of Door County.

The uppermost Silurian unit preserved in northeastern Wisconsin is the Engadine Formation. It is light to dark gray, fine-grained, burrowed and mottled dolostone that is often discolored buff to tan along joints, fractures, and bedding planes. It contains little chert with limited fauna preserved as both silicified and non-silicified tabulate corals and stromatoporoids present as thin plate-like growths. In parts of Kewaunee and Manitowoc counties, a second possible facies of the Engadine is found as a white, coarse-grained, fossil-rich grainstone to packstone. This facies has abundant corals (locally up to 1 meter wide), brachiopods, stromatoporoids, and crinoids. The Engadine Formation is exposed sporadically along the Lake Michigan shoreline and varies from at least 30 ft (9 m) in parts of eastern Brown and western Kewaunee counties (Luczaj, 2011; this study) to about 40 ft (12 m) thick on Washington Island in Door County (Kluessendorf and Mikulic, 1989). Although the Engadine is not particularly thick, the fact that it overlies the much weaker Manistique Formation has allowed for the development of topographic ridges that are roughly parallel to the main escarpment, such as in extreme eastern Brown County.

Deposition following the Engadine probably occurred in northeastern Wisconsin but has been subsequently eroded. Several younger Silurian units are recognized in southeastern Wisconsin and in the ancestral Michigan basin to the east (Mikulic and Kluessendorf, 1988; Harris and others, 1998) and their precise relationship to rocks in northeastern Wisconsin is still not well understood.

There are presently some disagreements regarding the lithostratigraphy and sequence stratigraphy of Silurian units in the region due to difficulties stemming from limited exposures, few drill cores, and limited biostratigraphically useful fossils (for example, Mikulic and others, 2010). One of these disagreements deals with the location of the contact between the Mayville Dolostone and the Byron Dolostone. Another deals with the stratigraphic position of the Byron Dolostone. Mikulic and others (2010) have summarized these disagreements and have proposed that both the Lime Island Dolostone and an unnamed unit should lie between the Byron Dolostone and the Hendricks Dolostone in Door County. A new era of research is being undertaken on the stratigraphy of Silurian rocks in eastern Wisconsin through research conducted by the Wisconsin Geological & Natural History Survey that should help resolve these issues. The new research involves mapping of bedrock units, an aggressive subsurface coring program, and the application of carbon-isotope stratigraphy to aid in regional correlation (see McLaughlin, Geoscience Wisconsin, in preparation).

From Sheboygan southward, Devonian limestone, dolostone, and shale up to 194 ft (59 m) thick are present in places along the Lake Michigan shoreline (Kluessendorf and others, 1988). These are generally best exposed in Milwaukee, and are not discussed further here.

Limited deposition during the Mississippian, Pennsylvanian, and possibly even the Permian Period and Mesozoic Era is expected to have occurred in Wisconsin as it did in Michigan, but those rocks must have been removed by erosion. Luczaj (2006) provides a synopsis and estimate of post Silurian burial in Wisconsin and the adjacent parts of the Michigan basin.

The ancestral Michigan sedimentary basin

A critical component in the development of the Niagara Escarpment is the east to southeast dip that has developed in the Paleozoic sedimentary section of eastern Wisconsin (figs. 5 and 6). This results from the fact that significant subsidence occurred throughout most of the Paleozoic Era in a region centered roughly in the middle of the Lower Peninsula of Michigan. Subsidence began during the Late Cambrian, reached a maximum rate of subsidence during the Silurian and Devonian, and had nearly ceased subsiding by the end of the Paleozoic Era (250 Ma) (Catacosinos and others, 1990; Luczaj, 2000). Catacosinos and others (1990) present a comprehensive description of the structure, stratigraphy, and petroleum geology of the ancestral Michigan basin. Swezey (2008) presents a modern stratigraphic compilation for the entire ancestral Michigan basin and surrounding areas.

The ancestral Michigan basin is the classic example of an intracratonic sedimentary basin. Intracratonic basins form over broad areas away from plate boundaries in the middle of otherwise stable continental areas. It is worth mentioning to those less familiar with the terminology that the ancestral Michigan basin is not the same as the much younger Lake Michigan basin occupied by Lake Michigan. Other than lithologic control on the location of Lake Michigan, the ancestral Michigan basin is hundreds of million years older and is generally unrelated to the present day Lake Michigan.

Within the ancestral Michigan basin, several kilometers of sediments are preserved, which results in a concentric "bull's-eye" pattern on bedrock geologic maps (fig. 2). While a maximum of about 2,300 ft (700 m) of Paleozoic sediments are present in northeastern Wisconsin, at least 15,700 ft (4,800 m) of Paleozoic rocks are present in the thickest parts of the Michigan basin (for example, Catacosinos and others, 1990). The youngest Paleozoic rocks in the basin are Middle Pennsylvanian, which are overlain by nonmarine Jurassic sediments in the center of the basin that reach thicknesses of 400 ft (130 m) (Velbel, 2009). Eastern Wisconsin, including the entire set of rock outcrops along the Niagara Escarpment, is located on the western portion of the ancestral Michigan basin. The southeastward dip that results from the development of this basin sets the stage for subsequent erosion and development of the Niagara Escarpment. Along the Niagara Escarpment in northeastern Wisconsin, Paleozoic strata typically dip southeastward between about 25 and 40 ft/mi (5 and 7.5 m/km).

Post-depositional chemical changes

There are several significant post-depositional changes that have been important in developing the character and surface morphology of rocks along the Niagara Escarpment. Although many of these changes have affected the entire Paleozoic section, attention here will focus on the Silurian part of the section and the effects that are readily observed in the escarpment corridor.

Dolomitization

Most carbonate rocks are initially deposited on the sea floor as biochemically and/or chemically precipitated calcium carbonate ($CaCO_3$) grains of varying size. After burial, this sediment becomes lithified, or turned into rock, when it is subjected to processes collectively known as diagenesis. Processes including compaction, cementation, recrystallization, and replacement modify the textures, fossils, and often the chemical compositions of sediments. Limestone is lithified calcium carbonate made of either the mineral aragonite or calcite (both are $CaCO_3$). However, one significant change that occurs is a process known as dolomitization, whereby the initial calcite is altered through precipitation and replacement by the mineral dolomite ($CaMg(CO_3)_2$). When a carbonate rock contains greater than 50% of the mineral dolomite, it is called a dolostone. Dolostone (a.k.a. dolomite) is quite common in Paleozoic strata, especially in eastern Wisconsin.

With the exception of some Devonian and upper Ordovician rocks, the entire Paleozoic carbonate section in eastern Wisconsin has been transformed from limestone to dolostone by one or more post-depositional processes. As a result, *there is no Silurian limestone in northeastern Wisconsin*. In fact, the majority of Silurian rocks along the entire Niagara Escarpment, from Wisconsin to New York, are composed of dolostone. Luczaj (2006) provides a detailed explanation for the possible mechanisms of dolomitization in Wisconsin, but a summary is provided here because of the significance to the Niagara Escarpment rocks.

It is possible that multiple processes operated at different times to cause the replacement of calcite by dolomite. For example, evaporite reflux dolomitization systems operating along the western edge of the Michigan Basin during the Silurian and/or Devonian periods might have been responsible for the formation of early dolomite in the study area. This would be consistent with the reflux dolomitization interpretations in other parts of the Silurian of the Michigan Basin and the evidence for Devonian arid tidal flat environments in eastern Wisconsin (for example, Mikulic and Kluessendorf, 1988; Luczaj, 2006).

During 2010–2011, oxygen isotopic analysis was conducted on 903 dolomite samples, spanning the entire stratigraphic range of Silurian carbonates along the Niagara Escarpment as part of an ongoing study to map the bedrock geology of Brown County. The $\partial^{18}O_{(PDB)}$ values for all 903 samples fall between –2.59‰ and –7.66‰, with most falling below –4‰. The strongly negative (light) character of this oxygen is inconsistent with an interpretation of low temperature reflux dolomitization by evaporated brines (Allan and Wiggins, 1994). Although it is possible that reflux dolomitization could have been the initial process responsible for converting these rocks from limestone to dolostone, oxygen isotopes and other evidence suggest that another process must have been involved to reset the isotopic signature.

Petrographic and geochemical analysis, along with evaluation of fluid inclusions trapped in dolomite and other minerals, has revealed that the Paleozoic sedimentary rocks of eastern Wisconsin were strongly affected by an incursion of hot (65 to 120°C) saline brines that were roughly four to eight times saltier than seawater. These brines migrated westward into Wisconsin from deeper parts of the ancestral Michigan basin, along the deeper sandstone aquifers that acted as conduits. Water-rock interaction in eastern Wisconsin's rocks was most dramatic in Ordovician carbonates and sandstones, which preserve a diverse assemblage of dolomite, quartz, metal sulfides, and potassium silicate minerals that are together known as Mississippi Valley-type (MVT) minerals. Subsurface weathering of these minerals has allowed for the release of arsenic, nickel, cobalt, and other metals into regional aquifers. Although the extent of sulfide mineralization is more sporadic in the Silurian portion of the section, strong evidence for this MVT overprint is found throughout the Silurian and Devonian section in eastern Wisconsin (Luczaj, 2006).

One of the most destructive results of dolomitization is the degradation of fossils and primary depositional textures in the precursor carbonate rock. Although some units, such as the Burnt Bluff Group, were not very fossiliferous to begin with because the depositional environments were not well suited to open marine fauna, other units like the Manistique Formation are quite fossiliferous. Most of these fossils in the Manistique Formation, however, are not finely preserved because of their replacement by coarsely crystalline dolomite. Unfortunately, this limits their use as biostratigraphic tools for determining the age of a particular unit.

Silicification

Another significant post-depositional change is the development of chert nodules and silicified fossils during diagenesis. Replacive chert nodules (SiO_2) are found throughout the Ordovician and Silurian carbonate section in eastern Wisconsin, but they are abundant in the Lower Mayville Formation and in the Manistique Formation. In the Mayville, this material is well exposed in various quarries and at outcrops such as Fonferek Glen County Park and Bayshore County Park in Brown County. White to gray chert nodules often form a network of interwoven nodules, which appear to follow large bedding plane burrows (fig. 7). This material is not desirable for the aggregate

Figure 7. *White chert nodules replacing burrows along a bedding plane in the Mayville Dolomite of Fonferek Glen County Park (Brown County). Geologic hammer for scale.*

industry, as it causes the premature breakdown of concrete due to weathering-induced fracturing. A similar result occurs in places along the Niagara Escarpment, with recessive chert-rich layers easily observed at Bayshore County Park and beneath the waterfall at Fonferek Glen County Park and other localities.

One benefit that has resulted from silicification of the Silurian rocks is the enhanced preservation of fossils compared to non-silicified portions of the dolostones. This occurs in two ways. First, very fine details of fossils, burrows, and original grain boundaries are preserved in the chert nodules, especially in the Manistique Formation. Second, replacement of tabulate corals, stromatoporoids, and pentamerid brachiopods by quartz often results in large, well preserved fossils that are resistant to weathering and glacial erosion. In both cases, some of the best fossil collecting in the region is associated with silicified fossil-bearing material from the Silurian Manistique Formation.

Stylolite formation

Another secondary change that has affected carbonate rocks in the region is the development of stylolites. Stylolites are extensive surfaces or thin seams resulting from pressure dissolution of mineral matter under directed pressure (McLane, 1995). In most cases, as in northeastern Wisconsin, they are subhorizontal and preserve thin films of insoluble residues, including clays, quartz grains, and other less soluble materials. Stylolites vary dramatically in appearance between different geologic units, but they are generally wispy, anastomosing dark brown to black in the Mayville Formation, and red/maroon to green in higher stratigraphic intervals, especially where closer to the surface.

The importance of stylolites to the weathered surface textures, bedding characteristics, and diagenetic history of the rocks in northeastern Wisconsin cannot be overstated. They can be observed in every carbonate unit in the region, and have been attributed to significant post-depositional volume reduction in carbonate systems, sometimes by as much as 25 to 30 percent (McLane, 1995). The dark, wispy insoluble residues preserved on the stylolites in the Silurian of northeastern Wisconsin are not immediately obvious to the untrained eye on weathered outcrops, but weathering is typically focused along these features in such a way that the surface texture on rock outcrops is often strongly controlled by these features (fig. 8a). Stylolites within individual layers and between sedimentary strata along bedding planes are often the most heavily weathered features that produce subhorizontal, recessively weathered features on the outcrop. The dark, wispy insoluble residues are quite obvious if samples are cut with a rock saw or observed in drill core (figs. 8b and c). Epikarst and other bedding plane-focused weathering appear to be focused on these features. Aside from major lithologic changes, weathered stylolite seams are one of the few major surface textures one observes on carbonate bedrock outcrops in the region, despite the fact that they are rarely mentioned, and sometimes confused with other features, such as wave and current ripples. It is the author's opinion and experience that these features are under-recognized, even by many trained geologists.

GEOMORPHOLOGY OF THE ESCARPMENT

Recognition of the Niagara Escarpment's importance in Wisconsin began a century and a half ago in 1851 when Milwaukee naturalist and scientist Increase A. Lapham observed that the Iron Ridge of Wisconsin was a continuation of the Mountain Ridge (Niagara Escarpment) of western New York (Kluessendorf and Mikulic, 1989). Early work by Chamberlin (1877) and Martin (1916) both recognized that differential erosion of the resistant Silurian dolostone and the underlying soft Ordovician shale was responsible for producing the escarpment.

To precisely understand the origin and extent of the Niagara Escarpment, it is important to consider the definition of two terms: escarpment and cuesta. One reasonable definition for an escarpment that applies in this case is: A long, semi-continuous bedrock cliff or steep slope facing in one direction resulting from differential erosion of a resistant layer in a series of gently dipping softer strata; specifically the steep face of a cuesta. A cuesta is an asymmetric ridge with a gentle face (dip slope) conforming to the dip of the resistant strata that forms it, and the opposite face (scarp

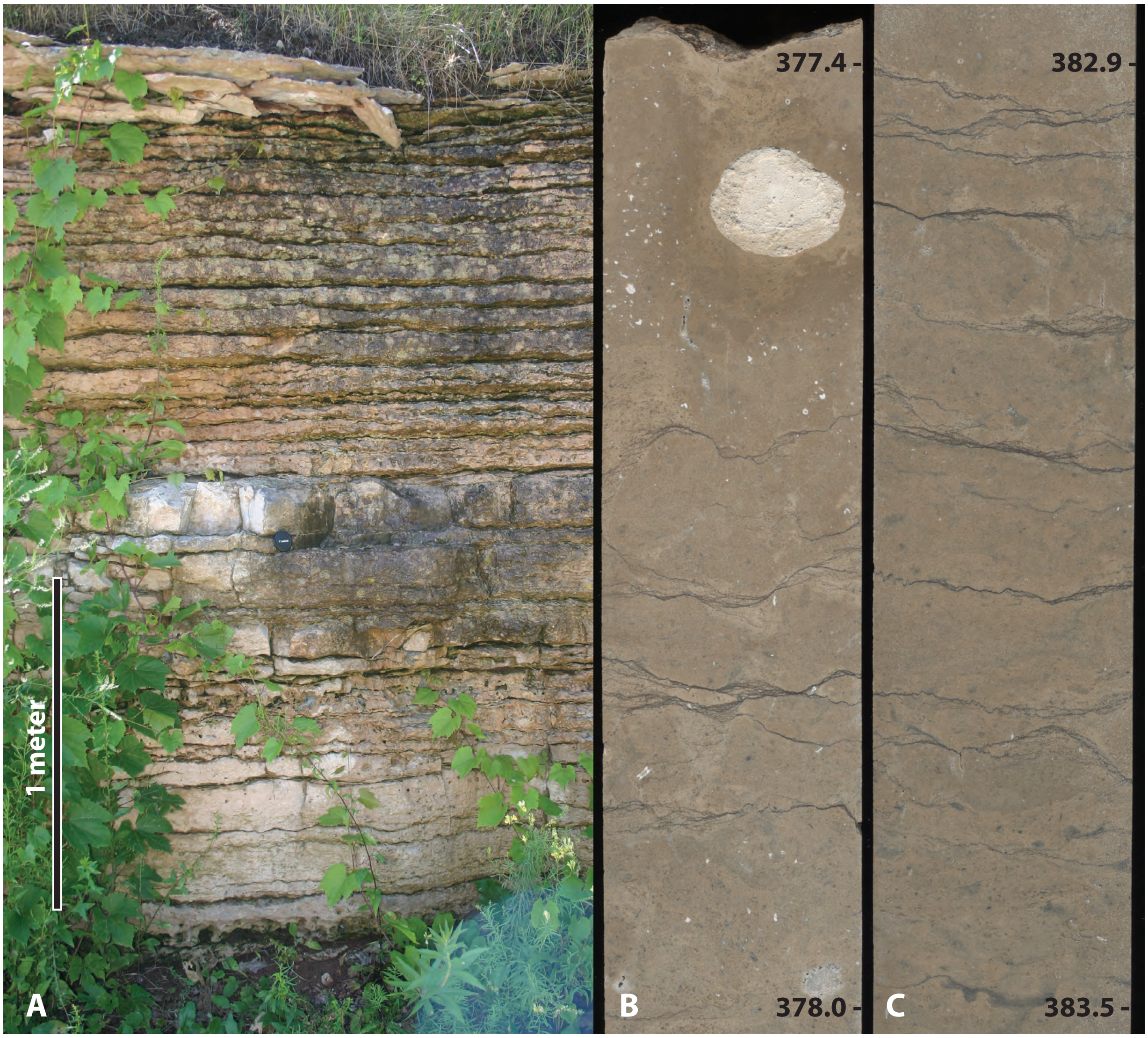

Figure 8. *(a) Weathered outcrop of Mayville Dolomite at Bayshore County Park in Brown County. Dissolution compaction was focused on horizontal stylolites, both within beds and along bedding planes. (b, c) Stylolites in cut and polished drill core from a similar stratigraphic position in the Mayville Dolomite from the D&J Gravel Pit Run #1 core in northwestern Manitowoc County. These stylolites do not appear to be related to bedding planes, as they occur in burrowed subtidal dolostone (wackestones). The large white circle is a chert nodule, and small white grains are silicified crinoid columnals. Numbers indicate depth below ground surface in feet.*

slope) that is controlled by the differential erosion of the gently inclined strata (modified from Bates and Jackson, 1987). Using these definitions, the Niagara Escarpment in Wisconsin is a semicontinuous ridge of resistant bedrock with generally west to northwest-facing steep slopes that result from differential erosion of eastward dipping Silurian dolostone that overlies the softer Maquoketa Shale to form an asymmetric landform known as the Niagara cuesta (fig. 9).

It is also important to recognize that the alternating section of Paleozoic dolostone, shale, and sandstone of eastern Wisconsin has been modified to exhibit three major cuestas with west-facing escarpments, with the Niagara Escarpment being the largest and best known (Schultz, 1986). A second example is the Ordovician Sinnipee escarpment (sometimes called the Trenton-Black River escarpment) where the durable Platteville Dolomite overlies the poorly cemented

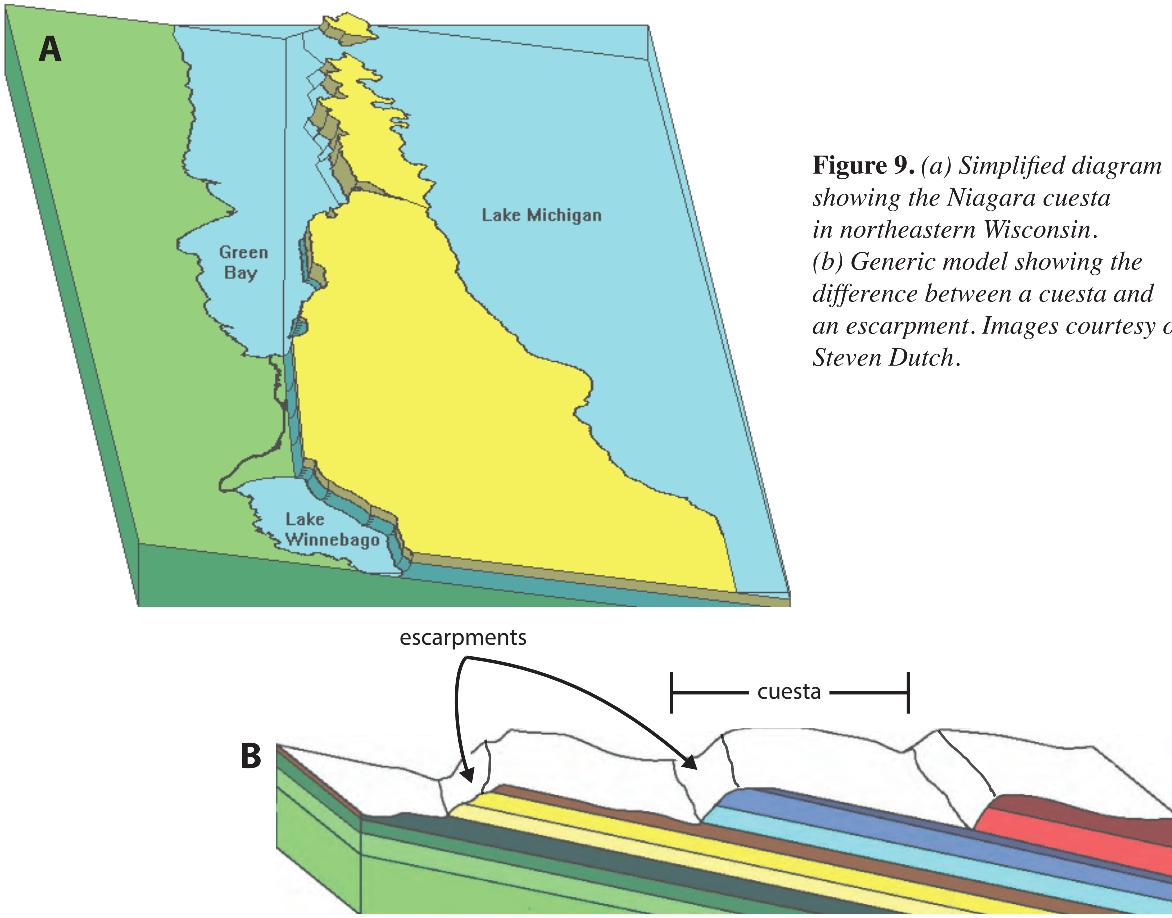

Figure 9. *(a) Simplified diagram showing the Niagara cuesta in northeastern Wisconsin. (b) Generic model showing the difference between a cuesta and an escarpment. Images courtesy of Steven Dutch.*

St. Peter Sandstone of the Ancell Group. This subdued escarpment extends from Marinette County south to Beloit and is about 18 to 20 mi (29 to 32 km) west of the Niagara Escarpment. The third escarpment is the Prairie du Chien Escarpment (sometimes called the Magnesian Escarpment) where dolostone overlies less resistant Cambrian sandstones approximately 25 mi (40 km) west of the Niagara Escarpment. The contrast in durability expressed by these older Ordovician and Cambrian units is also responsible for the cliffs and more extreme topography in southwestern Wisconsin along the Mississippi River and in the Driftless Area (Paull and Paull, 1977).

Several different geologic processes each played an important role in forming the Niagara Escarpment in Wisconsin as we see it today. The earliest geologic event critical to the development of the escarpment was the deposition of two distinctly different rock units during a 15 million year interval during the Late Ordovician and Early Silurian periods (approximately 445 to 430 Ma). Without the dramatic contrast in erosion resistance between the soft Maquoketa Shale and the overlying Silurian dolomite, there would not be a Niagara Escarpment. Likewise, the east-southeast tilting toward the center of the ancestral Michigan basin that took place throughout most of the Paleozoic Era was also necessary to allow for the later development of the Niagara cuesta.

While previous researchers concluded that faulting was definitely not responsible for producing the simple outline of the Niagara Escarpment in Wisconsin (for example, Martin, 1916, p. 234), it is clear that faulting must play a role in controlling the shape and presence of gaps in at least a few locations in Wisconsin (see below). Finally, one must recognize that erosion by rivers, glaciers, and mass wasting processes over at least the last several million years has contributed greatly to the character and appearance of the present day escarpment.

Post-depositional jointing

Joints (or fractures) in bedrock have a strong influence on the orientation and character of most of the Silurian rocks in the region, especially those along the Niagara Escarpment. Joints are found throughout the midcontinental United States in rocks of all ages. Joints in Door and Brown Counties follow two prominent sets with azimuths of about 72° and 155° (Schneider, 1989; Carson and others, 2013). In northeastern Wisconsin, many cliffs and buried bedrock valleys appear to be parallel to observed joint directions, although the case for joint control of the main escarpment in parts of Brown County was less obvious (Dutch, 1980). Nevertheless, Dutch (1980) concluded, and the author concurs, that many segments of the Niagara Escarpment are too straight for too great a distance to be explained solely by river or glacial erosion without structural control.

While the precise age for joints in the region is not well known, it is clear that most of these are extremely old. Evidence for a Middle to Late Paleozoic age for these joints and rarely observed faults includes the precipitation of Paleozoic MVT minerals along these planar surfaces, as well as a second, late episode of dolomitization, which is sometimes observed only along joints and bedding plane fractures (Luczaj, 2006). It is likely that many of the mineralized joints in northeastern Wisconsin formed during a period of significant regional stress during the Middle and Late Paleozoic Era along with faulting.

Faulting

Faults cutting the Paleozoic rocks of eastern Wisconsin were recognized very early by Chamberlin (1877). However, limited work has been done on understanding the distribution and significance of faulting in northeastern Wisconsin due to the extensive cover of Pleistocene glacial drift and lack of abundant data on the deep subsurface. Early work by Thwaites (1931, 1957) suggested the presence of several faults in the region, but the confidence of some of these structures was called into question later by Kuntz and Perry (1976) because of limited data and a new focus on generation of safety reports related to the Nuclear Regulatory Commission.

Recent bedrock mapping in Brown County (Luczaj, 2011), along with the careful preparation of cross sections, has revealed the existence of several regionally extensive dip-slip faults (fig. 10). While both dip-slip and strike-slip faults have been observed in quarry exposures in northeastern Wisconsin (for example, Luczaj, 2000, 2006), only dip-slip faults are able to be located with confidence using subsurface data from well construction reports. The presence and significance of strike-slip faults in the region is difficult to address in areas of nearly flat lying rocks with significant glacial sediment cover because little or no vertical offset would be produced that could be deduced from well construction reports.

Whereas early workers (for example, Martin, 1916, p. 216) attributed gaps in the Niagara Escarpment solely to river and/or glacial erosion, it appears that the presence of faults is sometimes the key to why river and glacial erosion was focused at these particular locations. It is important to recognize that the continuity, and in some cases the orientation, of the escarpment appear to be directly controlled by the orientation of these faults. This concept is illustrated below with examples from Brown County, but the likelihood of other gaps in the escarpment resulting from faulting seems possible. The exact timing of the faulting is not entirely clear, but multiple episodes of faulting along some of the structures are evident from examining the stratigraphy. For at least one fault in downtown Green Bay, some of the movement must have taken place during the Middle Ordovician because the thickness of the St. Peter Sandstone changes dramatically across the fault. However, it is clear that the majority of movement on these faults must have taken place after the Early Silurian because those rocks appear to have also been offset. There is no evidence for movement along these faults in recorded human history.

A major east-west fault zone is located approximately 3 mi (5 km) north of Greenleaf, Wisconsin and is one of the most significant regional faults that cuts the Paleozoic section with about 100 ft (30 m) of vertical displacement, dropped downward on the south side (fig. 11). Preliminary work suggests that this fault stretches from at least an area near Denmark, Wisconsin westward to as far west as Waupaca County. Its existence was first suggested in Outagamie County by Chamberlin (1877, p. 280–281) and later by Thwaites (1931) and Dutton and Bradley (1970). The precise location of the fault was recently determined in Brown County during an ongoing bedrock mapping investigation. Based on aeromagnetic maps, it appears likely that this fault is a once-reactivated

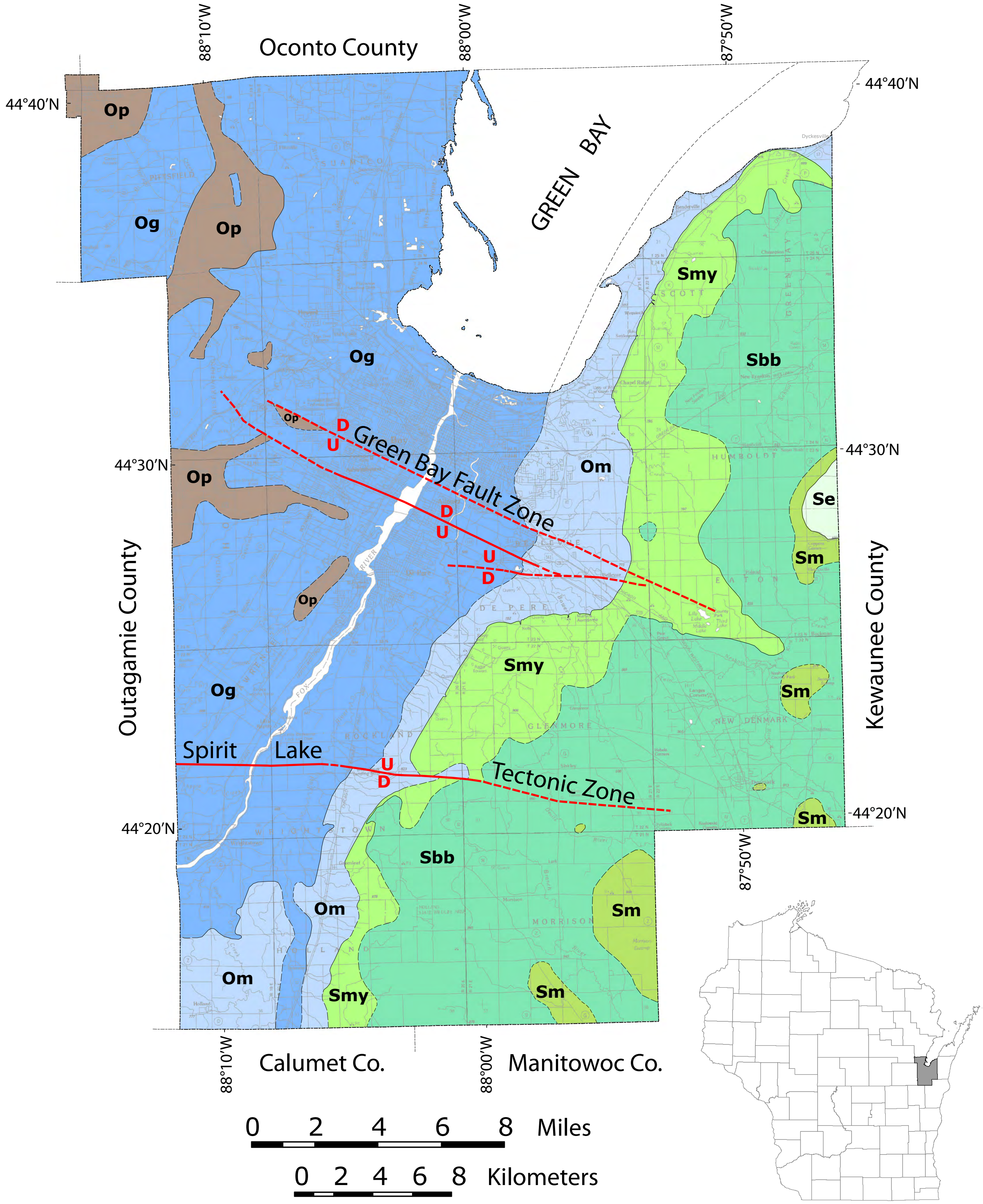

Figure 10. *Preliminary bedrock geologic map of Brown County, Wisconsin, showing the locations of major dip-slip faults (red lines) that influence the shape and position of parts of the Niagara Escarpment. Ordovician units: Op = Platteville Fm., Og = Galena Fm., and Om = Maquoketa Fm.; Silurian units: Smy = Mayville Fm., Sbb = Burnt Bluff Gp., Sm = Manistique Fm., Se = Engadine Fm.; fault sides: U = upthrown, D = downthrown. Map is modified after Luczaj (2011).*

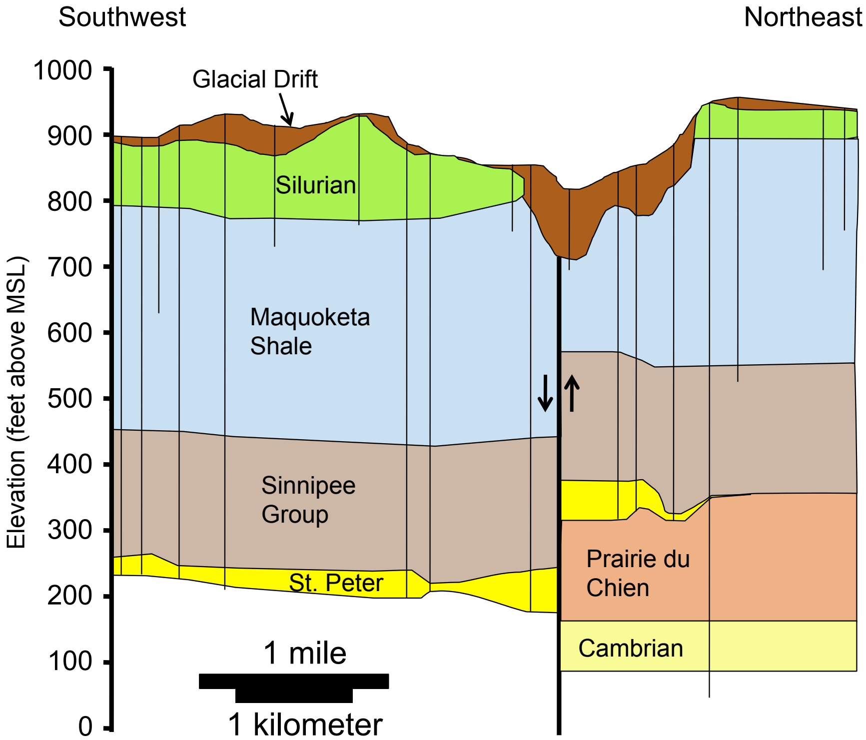

Figure 11. *South to north cross section along the top of the Niagara Escarpment north of Greenleaf, Wisconsin. Thin vertical lines indicate water well locations. Arrows indicate relative offset along the main fault at this location (thick line).*

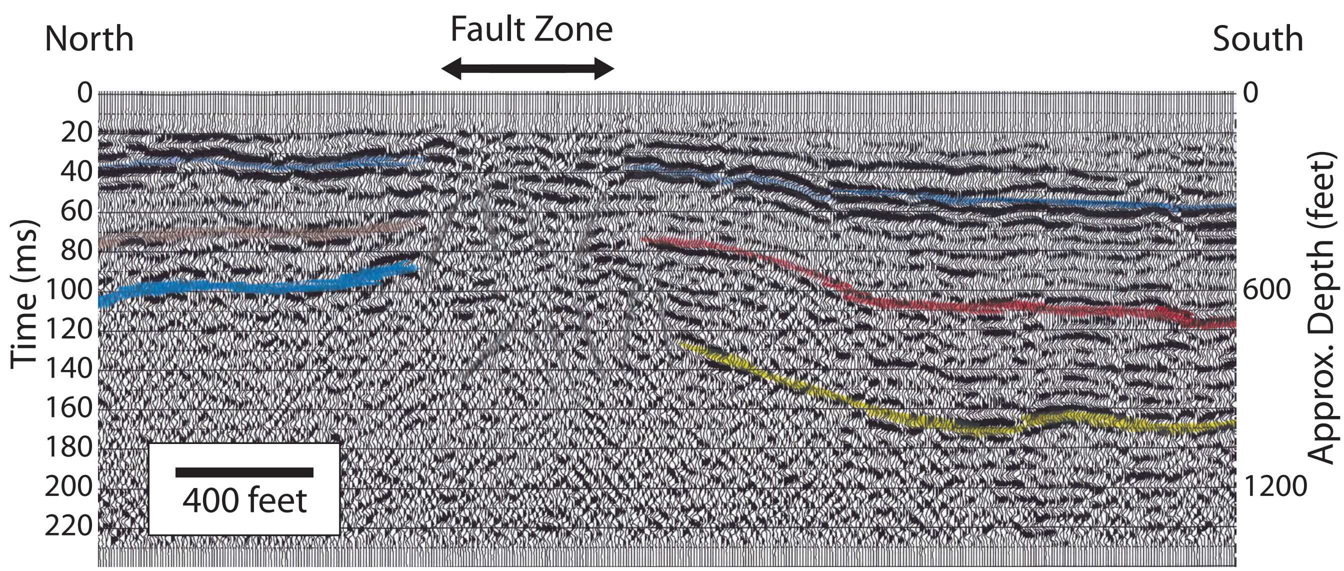

Figure 12. *A portion of a preliminary north-south reflection seismic line across the fault north of Greenleaf, Wisconsin (Spirit Lake Tectonic Zone?). Segment shown here is 3,300 ft (1 km) long and was taken along Tetzlaff Road, just east of the Fox River in the Towns of Rockland and Wrightstown (Brown County). Note the vertical offset with the southern block dropped downward. Yellow line (south side) may indicate the top of the Precambrian basement. Precise correlation of seismic reflectors across the fault is awaiting further processing. Acquisition and processing of seismic data performed by the Kansas Geological Survey.*

portion of the Spirit Lake Tectonic Zone (SLTZ), which is the Proterozoic suture between the Penokean orogen and the Yavapai orogen in the Precambrian basement that runs westward to Minnesota (see above; NICE Working Group, 2007; Schulz and Cannon, 2007). Preliminary results from an ongoing seismic reflection study confirm the location of the fault and suggest that there is a zone of breakage a couple of hundred feet wide along the fault (fig. 12) (Rick Miller, 2012, written communication). There is a significant erosional gap in the Niagara Escarpment just north of the Hilly Haven Golf Course in Brown County, where a distinct break occurs in an otherwise perfectly straight segment of the escarpment running from Greenleaf to Ledgeview. Pre-Pleistocene river erosion and subsequent glacial erosion during the Pleistocene were likely focused on the already broken rocks along this fault, which resulted in an east-west valley cutting into the escarpment and a beautiful waterfall where rocks crop out on the nearby Hilly Haven Golf Course. Vertical offset along the SLTZ preserved extra Silurian dolostone on the southern (downthrown) side of the fault, which may also have influenced the position of the recessional moraine north of the fault, near Shirley.

Another newly discovered example is a set of at least three unnamed east-west and southeast-northwest trending dip-slip faults in the Green Bay to Bellevue region that appear to converge along a southeast-trending buried bedrock valley located south of Bellevue, Wisconsin (fig. 10). Although the faults are unnamed at present, and their precise relationship to structures further to the west is not well known, it is possible that these faults indicate the eastern portion of the Eau Pleine Shear Zone on the eastern side of the Wolf River Batholith. For this paper, however, I will refer to these newly mapped faults in Brown County as the Green Bay fault zone. One of the blocks caught between two of these faults appears to be a horst, although the dip on the faults is unknown at present. The orientation of the Niagara Escarpment changes abruptly at Scray Hill from a southwest-northeast trending cliff to a nearly west-east trending cliff. The southern fault in this cluster is an east-west oriented fault that appears to have at least 60 ft (18 m) of vertical displacement (north side up). The east-west portion of the Niagara Escarpment south of this fault runs from Scray Hill near the Ledgeview Golf Course east for 3.8 mi (6.1 km) to Kittell Falls and Fonferek Glen County Park to the intersection of Shadow Lane and Interstate 43, where it becomes concealed by glacial drift. It seems sensible to conclude that the position and orientation of the east-west portion of the escarpment is due to erosion that began near the fault trace that caused the retreat of the escarpment southward away from the fault as erosion progressed. Together the three faults of the Green Bay fault zone appear to have had a strong influence on the bedrock geology a few miles further to the southeast. The northwest-southeast trending fault zone lines up with the central axis of a buried bedrock valley near the upper reaches of the present day Neshota-West Twin River (fig. 10). It is likely that preglacial and glacial erosion was focused along this preexisting structure, and a lack of detailed subsurface bedrock mapping prevented its discovery until 2010.

It was only recently, during 2008 and 2009 that renewed attention was given to bedrock mapping in the Silurian outcrop belt of northeastern Wisconsin. In addition, there has been a dramatic increase in the number of deep water wells in the region along the Niagara Escarpment over the past 25 years. These newer wells, many of which are 500 to 750 ft (150 to 230 m) deep, allow a much improved understanding of regional stratigraphy and faults.

It seems possible that many of the Niagara Escarpment reentrants and other bedrock-controlled river valleys in the Silurian of northeastern Wisconsin are structurally controlled. Preliminary subsurface investigation in northern Kewaunee County near the mouth of the Red River has revealed the possibility of another fault with dip-slip movement that appears to line up with a fault drawn by Thwaites (1931, 1957), but which was called into question by Kuntz and Perry (1976). It was only during the last few years when adequate subsurface information along the shore of Green Bay has become available that this fault can be drawn with some confidence. Other buried bedrock river valleys are present in Manitowoc, Calumet, and Sheboygan Counties that might also be structurally controlled (Stephen Mauel, 2010 personal communication) and as they appear to be in southeastern Wisconsin (for example, Evans and others, 2004). Future work will focus on gaining a better understanding of such bedrock structures, but an ambitious subsurface study involving drilling and seismic work may be required.

Preglacial history

Little is known about the period of time between deposition of Paleozoic rocks and the expansion of the Laurentide Ice Sheet over North America during the Pleistocene. The youngest known rocks preserved in eastern Wisconsin today are from the Devonian System and are located between Sheboygan and Milwaukee (Kluessendorf and others, 1988). There is a large gap in the geologic record of northeastern Wisconsin that stretches from about 400 million years ago until the Pleistocene Epoch during the last 2.6 million years. Other Late Devonian and Carboniferous rocks were likely once deposited in northeastern Wisconsin, and they are still preserved to the east in the ancestral Michigan basin. In addition, a limited amount of Jurassic sediment is also preserved in the central portions of the basin (Velbel, 2009). Marine and nonmarine rocks of the Cretaceous System are preserved in Minnesota, and limited outcrops of Cretaceous strata are preserved in parts of western and southern Wisconsin, but the extent and thickness of these rocks is unknown. After the Cretaceous, sea levels fell and never returned to the middle of the continent. As a result, the region was certainly exposed to long-term subaerial erosion for tens of millions of years or more.

This "lost interval" as described by Velbel (2009) was probably the most important interval of time in the geomorphic development of northeastern Wisconsin. While subsequent glacial erosion was certainly important at eroding and sculpting the bedrock, the predevelopment of deep-seated river valleys and some form of a precursor Niagara Escarpment must have formed during this time. Martin (1916) and Larson and Schaetzl (2001) have published suggested preglacial drainage patterns for northeastern Wisconsin. Figure 13 shows a possible preglacial hydrology. Major river valleys likely once occupied positions on either side of the Niagara Escarpment near the center of Lake Michigan and near the Fox River Valley before they joined and headed

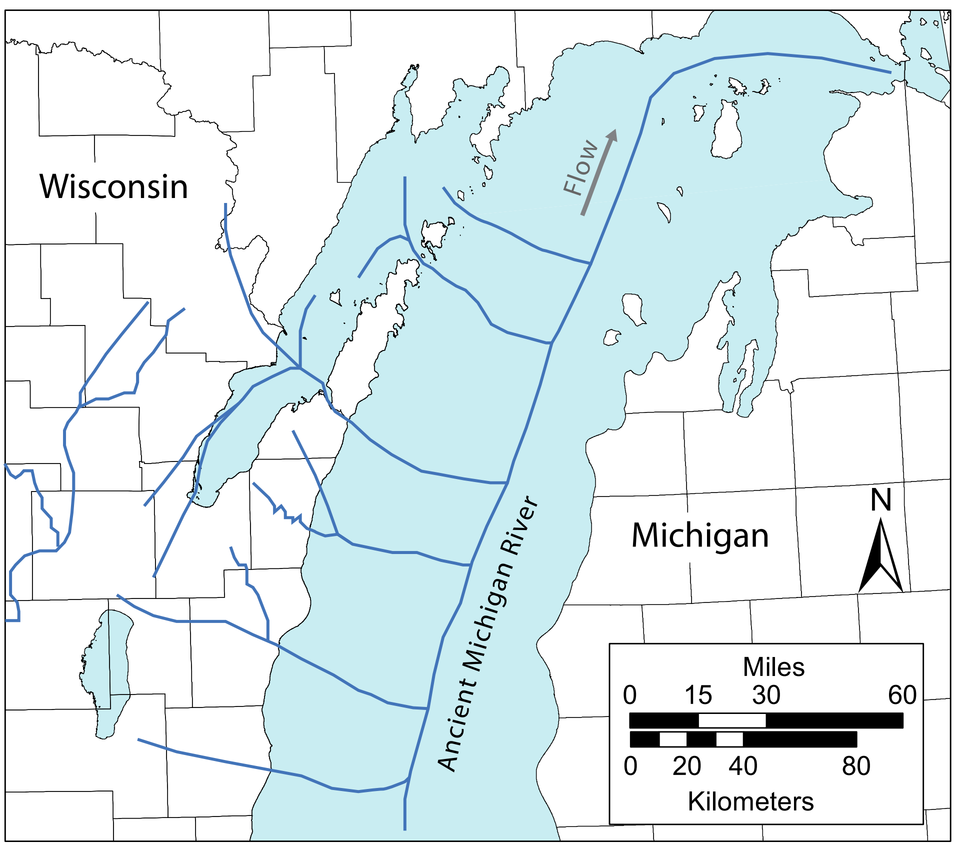

Figure 13. *Possible preglacial drainage pattern in northeastern Wisconsin. Modified from Martin (1916) and Larson and Schaetzl (2001).*

northeastward toward present day Lake Huron. The rivers were located there because they had a much easier time eroding the soft shales of the Upper Ordovician Maquoketa Formation to the west and the much thicker Upper Devonian Antrim Shale to the east.

Another signature characteristic of the Silurian dolostones along the Niagara cuesta in northeastern Wisconsin is the development of a karst landscape. One of the most difficult questions to address while unraveling the karst history of northeastern Wisconsin is the question of timing. Because the process of karst development is primarily one of bedrock dissolution, geologists are left with little evidence that records precisely when this took place. To establish an age range for a particular event, geologists must use either cross cutting relationships between rocks of known age or numerical age dates determined for special materials such as igneous rocks or other isotopically-datable materials. Examples of well-developed caves are present at Cherney-Maribel Caves County Park in Manitowoc County, Ledgeview Nature Center in Calumet County, and several places in Door County, including Horseshoe Bay Cave, Paradise Pit Cave, Dorchester Cave, and Brussels Hill Pit Cave. Some of these contain mammal bones that have been radiometrically dated to be several thousand years old (for example, Brozowski and Day, 1994; Luczaj and Stieglitz, 2008, ongoing research), indicating that cave formation and some of the sediments in these caves are even older.

It is likely that most of the karst developed in northeastern Wisconsin predates the Pleistocene glaciations, which took place within the last 2 million years in this part of North America. A wide variety of debris has been observed in sinkholes, caves, and solution enlarged joints of northeastern Wisconsin. Unfortunately, no isotopic age dates have been obtained from speleothems or cave decorations, and organic materials have yielded age dates that are too young to indicate much about the timing of cave development. The development of karst features such as caves, sinkholes, and solution-enlarged fractures in the Silurian rocks of northeast Wisconsin must have occurred during the last several tens of millions of years, but likely before the Pleistocene. This is because many caves in the region contain glacially derived materials and the upper portions of the karst landscape have been removed by glaciation. Although the Ordovician dolostones that crop out farther west are similar in composition and therefore susceptible to dissolution and karst, the Silurian dolostones appear to be the only carbonates in northeastern Wisconsin to have mature karst. While essentially the same from the perspective of chemical composition, the difference in development of karst features in each group of rocks (or lack thereof) is striking. The Maquoketa Shale likely extended much farther to the west over the Ordovician carbonates until the Pleistocene glacial episodes, which would have isolated those layers from aggressive surface waters capable of causing significant karst (Luczaj and Stieglitz, 2008).

Glacial history

Glaciation in Wisconsin took place during the Quaternary Period, which is divided into two units known as the Pleistocene Epoch (2.6 Ma to 11,700 years ago) and Holocene Epoch (11,700 years ago to present). Pleistocene glacial advances in Wisconsin are grouped into three general age ranges, from oldest to youngest, as the Pre-Illinoian, Illinoian, and Wisconsin glaciations. Only Wisconsin glacial events appear to be recorded in sediments in northeastern Wisconsin.

The earliest (Pre-Illinoian) record of glacial advance into Wisconsin is preserved as a thin till sheet in parts of central and northwestern Wisconsin and in limited areas in westernmost Grant County (Carson and Knox, 2011) and at the mouth of the Wisconsin River (Knox and Attig, 1988). Because some of the oldest glacial tills preserve a reversed remnant magnetic signature, they seem to have been deposited when the Earth's magnetic field was reversed. This suggests that the sediments are at least 780,000 years old (before the Matuyama-Brunhes magnetic reversal), and their presence in Iowa and Missouri suggests that the maximum ice extent during the Quaternary was reached prior to the Illinoian Glaciation. This early advance involved ice coming in from the northwest, as indicated by provenance studies of boulder trains in the glacial till (Larson and Schaetzl, 2001; Syverson and Colgan, 2004). At least two later advances occurred in the state during the Illinoian Glaciation, which lasted from about 300,000 to 130,000 years ago.

The last major episode of glaciation in Wisconsin occurred during the Late Pleistocene and is known as the Wisconsin Glaciation, which lasted between about

32,000 years ago and 13,000 years ago. In northeastern Wisconsin, three major advances of the Late Wisconsin Green Bay lobe left a good record of these sediments. The till sheets that record glacial advances in the region are interspersed with thick sequences of fine-grained sediments from Glacial Lake Oshkosh (Socha and others, 1999; Hooyer, 2007; WGNHS, 2011). It is these Late Wisconsin glacial deposits that rest directly upon freshly scoured bedrock and conceal much of the underlying geology of the region, including much of the Niagara cuesta.

Northeastern Wisconsin, and specifically the Niagara Escarpment corridor, lies at or near the boundary between two major lobes of the ice sheet that advanced into Wisconsin during the Late Wisconsin Glaciation (fig. 14). The much larger Lake Michigan lobe was centered to the east, along the present day axis of the Lake Michigan basin. To the west, the Green Bay lobe was centered along the axis of Green Bay and the Fox River lowland, west of the Niagara Escarpment. The relative size and position of these two ice lobes was not a random occurrence. Rather, it was controlled by both preexisting topography, as well as a dramatic difference in lithology. As mentioned above, preglacial river drainage likely followed the outcrop belts of softer Upper Ordovician and Upper Devonian shales. The importance of glaciation to the development of the Great Lakes cannot be overstated. They simply would not exist had there not been glaciation in the region during the Pleistocene.

Figure 14. *Position of Niagara Escarpment relative to glacial ice lobes from the Late Wisconsin Glaciation. Map courtesy of Wisconsin Geological and Natural History Survey.*

The extreme depths of lakes Superior, Michigan, and Huron occur hundreds of feet below sea level, and could not have been cut by rivers.

Reconstructions of glacial ice lobe thickness suggest that the ice that overrode the Niagara Escarpment was less than 500 ft (150 m) thick near its terminus, and that the Niagara Escarpment definitely impacted the position and shape of the Green Bay lobe (Socha and others, 1999). However, the Niagara Escarpment was also certainly modified by glacial erosion. One need only to look at a fresh exposure of the bedrock surface on top of the Niagara cuesta to see clear evidence of glacial erosion in the form of striations. A much larger example is a major gap in the escarpment between southern Brown County and High Cliff State Park in Calumet County. This region contains a major reentrant into the escarpment, which likely reflects preglacial drainage to some degree. The Brillion sublobe of the Green Bay lobe flowed through this breach in the escarpment and likely acted to widen and deepen any preexisting valley. The Green Bay lobe was interpreted by Socha and others (1999) to have been a surging glacier with high subglacial water pressure. Luczaj and Stieglitz (2008) described traction transported sediments and high pressure water escape structures in New Hope Cave that could be related to subglacial water flow in the karst bedrock of northern Manitowoc County. It is possible that other caves in the region have preserved similar records.

The Door Peninsula preserves a series of northwest-southeast trending linear bedrock valleys that exhibit smooth margined embayments on both sides of the Niagara cuesta (Schneider, 1989). The most prominent bedrock gaps are at Sturgeon Bay and at Deaths Door Passage between Washington Island and the mainland. Other major bedrock valleys identified by Sherrill (1978) that cross the Door Peninsula include a valley between Ellison Bay and Rowley Bay and another between Ephraim and Baileys Harbor. Smaller bedrock valleys are present between Sister Bay and North Bay, between Little Sister Bay and Moonlight Bay, between Fish Creek and Kangaroo Lake, and between Egg Harbor and Clark Lake (Sherrill, 1978; Schneider, 1989). These buried bedrock valleys end as smooth margined embayments on both sides of the peninsula, and are likely the product of significant glacial sculpting of the bedrock. Although less obvious away from the lake, other embayments in the Niagara Escarpment near Bellevue, Brillion, and Fond du Lac have almost certainly been produced in a similar way by glacial modification of preexisting river valleys.

The relief on the escarpment is often defined as the elevation difference between the top of the bluff and the level of Green Bay or the lowland of the Fox Valley. However, it is important to keep in mind that the true relief on the bedrock surface is sometimes much greater, and a large portion of the relief is hidden by glacial deposits or water in Lake Michigan (fig. 6). For example, a buried bedrock valley west of the escarpment in southern Brown County contains over 300 ft (90 m) of Pleistocene sediments. Off the coast of Peninsula State Park and Washington Island in Door County, the escarpment continues underwater.

Postglacial modifications to the escarpment

Over the past 13,000 years since northeastern Wisconsin has been free of glacial ice, there have been numerous modifications to the Niagara Escarpment including river erosion, wave erosion, and gravity-induced mass wasting.

Rivers and waterfalls along the escarpment

Despite its 230 mi (370 km) length in Wisconsin, the Niagara Escarpment has a limited number of westward flowing streams that carry water from the upland of the cuesta to the Green Bay/Fox River lowland. This is because the dip slope of the Niagara cuesta is to the east-southeast. As a result, the drainage divide between The Fox River watershed and the Lake Michigan watershed is close to the escarpment edge. There are, therefore, only a few places where water is prevented from flowing eastward by moraines or other topographic features. These few westward flowing streams have cut short, but dramatic gorges into the Niagara Escarpment. Some notable examples of these occur in Brown County, Wisconsin, at Wequiock Falls, Fonferek Falls, Kittell Falls, and the Hilly Haven Golf Course (fig. 15). In most cases, the waterfalls have formed due to the presence of relatively resistant Silurian dolostone overlying weak, incompetent Maquoketa Shale. One exception is at Fonferek

Falls along Bower Creek east of De Pere, Wisconsin where a hard dolostone cap rock overlies a weak, cherty layer in the lower Mayville Formation.

It is important to recognize that these small gorges with waterfalls may not have an entirely post-glacial origin. It is likely that streams have reoccupied these same locations numerous times. Evidence for this can be seen in a small gorge with a waterfall in Ordovician rocks in the Town of Ledgeview. Here, there appears to still be glacial till remaining along one of the walls of the gorge, suggesting that the gorge existed before the last advance of the ice at about 13,500 years ago.

Perhaps a more spectacular example of post-glacial erosion concerns the drainage of glacial Lake Oshkosh through a series of four progressively more northerly outlets that were occupied until Green Bay was free of glacial ice. These outlet valleys, named after the present day rivers that occupy them, were the Manitowoc, Neshota, Kewaunee, and Ahnapee outlets, each of which carried water along northwest-southeast trending bedrock controlled valleys that cut across the Niagara cuesta. Boulders transported by flowing water in at least one of these channels are up to 6 ft

Figure 15. *The Kittell and Wequiock Falls along the Niagara Escarpment in Brown County.*

(2 m) in diameter, and modeling suggests that catastrophic outflows of Glacial Lake Oshkosh occupied these valleys as it drained (Clark and others, 2008). These bedrock-controlled valleys are almost certainly preglacial features, as suggested by portions of buried bedrock valleys along portions of the Neshota River Valley, but the exact mechanism for how the valleys are reoccupied after concealment by glacial materials is poorly understood. Perhaps post-glacial compaction of Pleistocene sediments is greater where thick sequences of sediment occur in the valleys, compared to the bedrock valley walls, which could focus incipient stream erosion along those pathways and allow for reoccupation of the valleys at a later stage.

Ancient shorelines

Abandoned shorelines from several late-glacial and post-glacial lake phases can be found throughout the Door Peninsula, especially to the north. As many as a dozen different shorelines of higher lake levels can be seen in some areas, with good records of terraces, wave-cut cliffs, sea caves, dune ridges, and gravelly beach ridges (Schneider, 1989). These ancient shorelines are remnants of higher lake levels recorded during Algonquin and Nipissing stages, approximately 11,000 and 5,500 ^{14}C years ago, respectively. Schneider (1989) and Larson and Schaetzl (2001) provide more in depth descriptions of these features.

Mass wasting

Several examples of mass wasting can be seen along portions of the Niagara Escarpment. Stieglitz and others (1980) described a relict geomorphological terrace and talus slopes along the Niagara Escarpment in Brown County. They suggested that periglacial conditions including ice-wedging and shattering of dolomite contributed to erosion of the escarpment. In some cases, large joint-controlled blocks have slid partway down slope along the top of the Maquoketa Shale at Bayshore County Park. Erosion along the escarpment continues to this day. Fonferek Glen and Bayshore county parks in Brown County, for example, contain numerous examples of active and inactive mass wasting. For example, a few large blocks near the top of a metal staircase at Bayshore County Park appear ready to descend down the hill slope, as soon as the final few inches of weak, cherty Mayville Dolostone give way (fig. 16).

One of the most spectacular examples of post-glacial mass wasting along the entire escarpment in Wisconsin occurs at Fonferek Glen County Park (fig. 16). Here one of only a handful of large natural bridges in the State of Wisconsin towers 40 ft (12 m) above the Bower Creek below. The natural bridge has developed as the result of mechanical weathering of a weak porous, cherty dolostone layer beneath a cap rock of dense chert-free dolostone as was Fonferek Falls farther upstream, which descends over the same weak dolostone layer. In addition to a detailed description of Fonferek Glen, Paull (1992) describes other natural bridges in Wisconsin, including several at the Oakfield Ledges Scientific Area in Fond du Lac County.

MINERALOGY AND FOSSILS

Some stratigraphic units of the Niagara cuesta contain very attractive fossils and a few interesting mineral occurrences. Examples of paleontological studies on the Silurian of northeastern Wisconsin include work on corals and stromatoporoids (Allen, 1986; Watkins and Kuglitsch, 1997), brachiopods (Watkins, 1994; Kluessendorf and Mikulic, 1989; Mikulic and Kluessendorf, 2009; Mikulic and others 2010), thelodont fish scales (Turner and others, 1999), stromatolites (Soderman and Carozzi, 1963), and conodonts (Watkins and Kuglitsch, 1997). Kluessendorf and Mikulic (1989) and Mikulic and others (2010) present general summaries of macrofossils preserved in the Door Peninsula. In general, the Manistique Formation contains the most impressive assemblage of open marine invertebrate fossils, including corals, brachiopods, and stromatoporoids. These fossils are typically best preserved when replaced by silica (SiO_2) phases (fig. 17), but fine examples also exist where the fossils have been replaced by dolomite. Most of the Burnt Bluff Group contains limited fossils, probably due to the restricted marine environments present during much of the deposition, as is typical today in peritidal carbonates. The Mayville and Engadine dolostones contain some limited fossils that can be observed in places such as Fonferek Glen County Park in Brown County and Whitefish Dunes State Park in Door County.

Outside of Wisconsin, there are many examples of mineral and fossil finds along the Niagara Escarpment (for example, Dietrich, 1994). And although little has been written about the accessory minerals present in the Silurian of northeastern Wisconsin, there are some worthwhile mineral specimens that have been obtained here. The best collecting is generally in difficult to access quarries, but occasional outcrops along the escarpment can yield interesting material. It is not uncommon to find calcite, quartz, dolomite, and pyrite crystals in vugs and fossil molds in the region, and there is some rare fluorite in the Sturgeon Bay area. Unlike the more heavily mineralized Ordovician rocks in the region, there are fewer examples of Mississippi Valley-type sulfide mineralization in Silurian rocks of northeastern Wisconsin, although sporadic examples are found that are sometimes quite spectacular, especially near the base of the Mayville Formation.

TERMINOLOGY CHALLENGES

For geology experts, disagreement about the nuances of terminology might seem unimportant when communicating with the public about the Niagara Escarpment. What exactly people mean when they use the term "Niagara Escarpment" varies somewhat from person to person, even among geologists, and there is no universally accepted definition. A precise definition of what the Niagara Escarpment is—and what it is not—is important for several reasons, including land use planning of the escarpment and nearby areas.

The Niagara Escarpment was named for the region around Niagara Falls where the Niagara River plunges over the Silurian Lockport Dolostone into a gorge cut mainly through underlying mudstone and sandstone below. The Lockport Dolostone is the cap rock over the weaker shale and sandstones of Niagaran and Alexandrian age. Niagaran and Alexandrian are

Figure 16. *Examples of mass wasting controlled by a weak, recessive chert-rich layer in the lower Mayville Formation. (left) One of several large unstable blocks that are barely supported by a small amount of the cherty Mayville. (right) Natural bridge in the Mayville Dolomite at Fonferek Glen County Park in Brown County. Note the talus pile beneath the bridge.*

legacy series names for subdivisions of the Silurian System in North America that many researchers have abandoned in favor of the global stratigraphic term Llandovery. In Wisconsin, the Niagara Escarpment follows a similar stratigraphic contact, but the base of the escarpment here is actually well below the Niagaran stratigraphic level preserved in New York's Niagara Escarpment, although all these Silurian rocks in Wisconsin were once described as "Niagara Limestone" by Chamberlin (1877). This stratigraphic change, as well as the informal use of the term 'Niagaran,' has proven to be confusing for people who are not intimately familiar with these nuances. Books, journal articles, websites, and well construction reports commonly describe the Mayville Formation as "Niagara Dolomite," "Niagaran Dolomite," or "Niagara Limestone." However, much of the Niagara Escarpment in Wisconsin is actually not Niagaran in

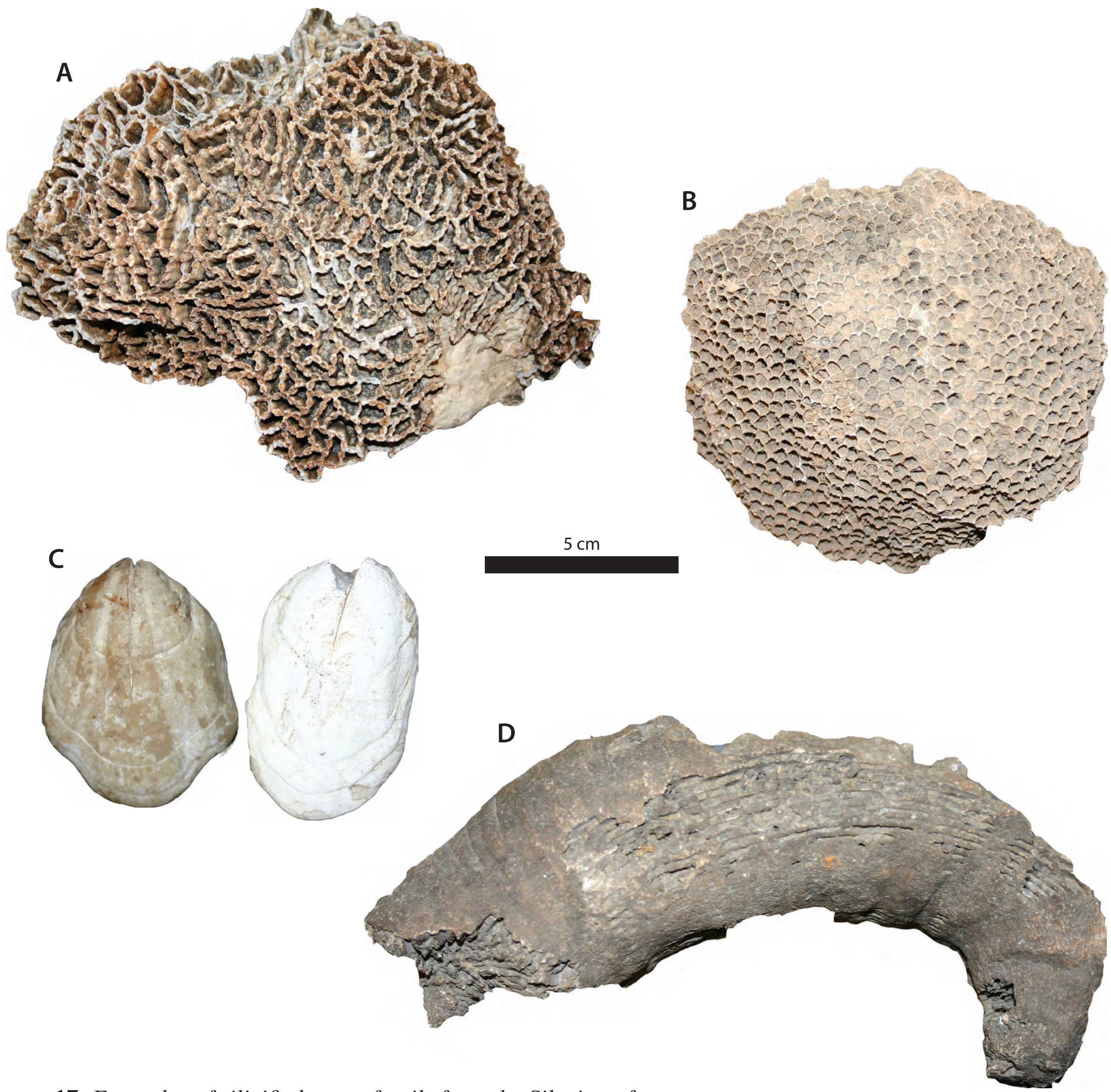

Figure 17. *Examples of silicified macrofossils from the Silurian of northeastern Wisconsin. A =* Halysites *(chain coral), B =* Favosites *(honeycomb coral), C = pentamerid brachiopods, D = large rugose coral.*

age, and it is dolostone, not limestone. Perhaps it is for this reason that some researchers have chosen to use the term “Silurian escarpment” in Wisconsin (for example, Dutch, 1980; Stieglitz and others, 1980; Paull, 1992; Socha and others, 1999; Hooyer, 2007). Recent peer-reviewed articles use the internationally accepted term “Llandovery” instead of “Niagaran” to describe the age of these rocks (for example, Cramer and others, 2011), but the older term still appears in a considerable amount of modern literature – both formal and informal (for example, Kasprzak and Walter, 2001; Dott and Attig, 2004). In fact, the improved global Silurian chronostratigraphic framework has forced so many changes in our ability to correlate North American units with confidence, that the Silurian stratigraphic nomenclature is “in a state of flux and needs further refinement” (Cramer and others, 2011). Use of the term “Niagara(n) Dolomite” should be discouraged in Wisconsin to avoid confusion with the time connotation implied by the formal North American stage name “Niagaran.” A more accurate and less confusing term to use for these rocks is “Silurian Dolostone.”

Even the escarpment’s length, both in Wisconsin and internationally, is reported inconsistently. Some describe the length of the Niagara Escarpment in Wisconsin as 150 mi (241 km) (e.g, Kasprzak and Walter, 2001), while others report a length of 230 mi (370 km) (for example, Martin, 1916; Anderson and others, 2002; 2009-2010 Wisconsin State Legislature). Some report the Niagara Escarpment’s entire length from Wisconsin to New York as 650 mi (1,046 km) (for example, Kasprzak and Walter, 2001; Anderson and others, 2002), while others describe it as an almost continuous feature that runs 900 mi (1,448 km) from New York to Wisconsin (Kluessendorf and Mikulic, 1989). While the starting and ending points seem to be the reason for at least some of these discrepancies, differences of opinion exist on the length of the escarpment.

The continuity of the escarpment has also been described differently. Some describe it as extending “almost continuously for 900 miles” (for example, Kluessendorf and Mikulic, 1989) and being “remarkable for the absence of transverse gaps” (Martin, 1916, p. 215). Others recognize that the escarpment is quite discontinuous (for example, Dietrich, 1994; Anderson and others, 2002). Wisconsin’s Niagara Escarpment is, in fact, discontinuous, with two of the most prominent gaps in Brown and Calumet counties that are at least 6 and 10 mi (10 and 16 km) long and represent buried bedrock valleys.

Another difference in the terminology relates to whether the Niagara Escarpment represents just the single escarpment near the Silurian-Ordovician contact or whether other nearby escarpments to the east or west should be included. Different maps of the Niagara Escarpment include some of these nearby escarpments, while others do not. To the east of the main escarpment, there are several additional ledges defined by changes in durability of various Silurian dolostones along the dip slope of the Niagara cuesta. One definition proposed by Joanne Kluessendorf and Don Mikulic includes “any and all outcrops that form a rock ridge or series of ridges at the bedrock surface along the ‘western’ edge of the Silurian (‘Niagaran’) outcrop belt” (Kasprzak and Walter, 2001, p. 9–10). This definition appears to be the most sensible because it includes the cliffs of Silurian dolostone both along and near the western edge of the Silurian outcrop belt. However, this definition does not strictly include ledges to the west that might be from resistant layers in older Ordovician units, and it also groups together multiple Silurian rock escarpments into a single geomorphic feature.

To the west of the main escarpment, there are occasional ledges produced by the resistant Fort Atkinson Member of the Maquoketa Shale (fig. 4). One of these is quite obvious on topographic maps and aerial photographs north of the escarpment in the Town of Ledgeview in Brown County. The spectacular view of the Fox River lowlands at Ledgeview is a product of the tall escarpment produced by the Silurian Mayville Dolostone. However, the Ledgeview Golf Course is built on a lower, and distinctly different ledge of Fort Atkinson dolostone. Although this Ordovician layer is not traditionally part of the series of rocks that define the Niagara Escarpment, it is erroneously labeled as Niagara Escarpment on many maps. This same ledge of Fort Atkinson dolomite also occurs in other areas of Brown County, but is not labeled as Niagara Escarpment in those cases. The Fort Atkinson dolomite forms recognizable ledges at Baird Creek east of Green Bay and along a two-mile long ledge near Crestview Road in southwestern Brown County about 5 mi (8 km) west of the Niagara Escarpment. Similar ledges of the Fort Atkinson Dolomite are present along Nicolet Drive near the UW–Green Bay campus and areas northward, but they too have not been labeled as part of the Niagara Escarpment. If the Fort Atkinson ledge in Ledgeview, Wisconsin is to be included in the “Niagara Escarpment” in Wisconsin, should these other areas also be included because of their identical geology? If not, why is the ledge on the Ledgeview Golf Course often included as part of the Niagara Escarpment? How far away from the main escarpment is “too far” to be included? One would certainly not include the genetically similar Sinnipee and Prairie du Chien escarpments that lie 18 to 25 mi (29 to 40 km) to the northwest and run roughly parallel to the Niagara Escarpment.

Another complication exists in southern Door County along the shoreline of Green Bay. There, the Ordovician rocks of the Maquoketa Formation have abundant carbonate material in their upper layers, and as a result, they form the main bluff in some places along Green Bay south of Little Sturgeon Bay. Although the presence of this escarpment is directly related to the same processes that formed the Niagara Escarpment elsewhere, it is important to recognize that here too, a strict definition of the Niagara Escarpment breaks down.

Places with rock outcrops in the region should not automatically be associated with the Niagara Escarpment. However, that is a common practice in the region. For example, Cherney Maribel Caves County Park in Manitowoc County and Cave Point County Park in Door County are not part of the Niagara Escarpment. Although they contain outcrops of the same Silurian rocks present within the cuesta, these localities would likely exist in a similar form if the Niagara Escarpment had not been formed at all. In a similar way, the Niagara Fault and the City of Niagara, Wisconsin have nothing to do with the Niagara Escarpment along the margin of the Michigan Basin. The Niagara Fault is part of a Precambrian east-west suture zone in igneous and metamorphic rocks along the southern margin of the Archean Superior Craton that is preserved near the town of Niagara Wisconsin (fig. 3). This is the place where the Superior Craton and the Pembine-Wausau Island Arc Terrane came together about 1,880 to 1,830 Ma (LaBerge, 1994; Schulz and Cannon, 2007).

In the end, the term “Niagara Escarpment” correctly applies to the same cliff face of Silurian dolostones overlying softer shale here in Wisconsin as it does in the Niagara Falls region. However, there are those who are looking to describe a broader geologic and ecologic region for purposes of interacting with the public, while at the same time are striving to use correct terminology (Bob Bultman, personal communication). If one is describing habitats or other features both along the escarpment and along the dip slope of the cuesta, then a more inclusive term such as “Niagara Escarpment corridor” or “Niagara cuesta” is probably the most appropriate.

SUMMARY

The Niagara Escarpment is the most prominent topographic and geomorphic feature in eastern Wisconsin. The Niagara Escarpment in Wisconsin includes outcrops that form a dolostone ridge or series of ridges at the bedrock surface along the western edge of the Silurian outcrop belt. It includes the mainly west and northwest-facing escarpments that have developed on resistant eastward-dipping Silurian dolostones that overlie the much softer Ordovician Maquoketa Shale. The exposed, but discontinuous escarpment runs from Rock Island on the tip of Door County all the way south to Ashippun in Dodge County and ranges in height from a few feet to over 200 ft. The escarpment controls the flow of rivers, such as the Fox River and others that flow eastward along the dip slope of the cuesta, and has produced some of the most spectacular overlooks in the region. This important geologic feature developed over hundreds of millions of years through a complex set of depositional, tectonic, and erosional processes.

Ongoing bedrock mapping projects and stratigraphic research on eastern Wisconsin Silurian rocks promise to yield substantial revisions to our understanding of these rocks in coming years. In addition, a consistent use of appropriate and modern terminology will benefit everyone who is interested in understanding and communicating about the Niagara Escarpment.

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REFERENCES CITED

2009–2010 Wisconsin State Legislature, 2009, 2009 Assembly Joint Resolution 1: Relating to: proclaiming Niagara Escarpment year and month. Wisconsin State Legislature, 3 p.

Allan, J.R., and W.D. Wiggins, 1993, Dolomite reservoirs, geochemical techniques for evaluating origin and distribution: AAPG Continuing Education Course Note Series 36, 129 p.

Allen, P.E., 1986, The petrology and paleoecology of a Silurian (Niagaran) coral-stromatoporoid association on the northwest margin of the Michigan Basin, Door County, Wisconsin: M.S. thesis, University of Wisconsin–Green Bay, 87 p.

Anderson, C., Epstein, E., Smith, W., and Merryfield, N., 2002, The Niagara Escarpment: Inventory findings 1999–2001 and considerations for management, final report: Natural Heritage Inventory Program, Bureau of Endangered Resources, Wisconsin Department of Natural Resources, PUBL ER-801 2002, 79 p.

Bates, R.L. and Jackson, J.A., 1987, Glossary of geology, 3rd edition: Alexandria, Va., American Geological Institute, 788 p.

Biggs, D.L., 1987, Centennial field guide, volume 3: Boulder, Co., North-Central Section of the Geological Society of America, 448 p.

Brozowski, J. and Day, M.J., 1994, Development of Brussels Hill pit cave, Door County, Wisconsin: Evidence from flowstone and sediment: Transactions of the Wisconsin Academy of Sciences, Arts, and Letters, v. 80, p. 1–16.

Carson, E.C., Brown, S.R., Mickelson, D.M., and Schneider, A.F., 2013, Quaternary geology of Door County, Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 109, 44 p.

Carson, E.C., and Knox, J.C., 2011, Quaternary landscape development in the Driftless Area of southwest Wisconsin: Geological Society of America, Abstracts with Programs, v. 43, no. 5, p. 508.

Catacosinos, P.A., Daniels, P.A., Jr., and Harrison, W.B., III, 1990, Structure, stratigraphy, and petroleum geology of the Michigan basin, in Leighton, M., Kolata, D., Oltz, D., and Eidel, J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir, v. 51, p. 561–601.

Chamberlin, T.C., 1877, Geology of Wisconsin: Survey of 1873-1877, Volume 2: Chief Geologist/ Commissioners of Public Printing, p. 91–405.

Choi, Y.S., Simo, J.A., and Saylor, B.Z., 1999, Sedimentologic and sequence stratigraphic interpretation of a mixed carbonate-siliciclastic ramp, mid-continent epeiric sea, Middle to Upper Ordovician Decorah and Galena Formations, Wisconsin, in Harris, P., Saller, A., and Simo, J.A., eds., Advances in carbonate sequence stratigraphy: Application to reservoirs, outcrops, and models: SEPM Special Publication No. 63, p. 275–289.

Clark, J.A., Befus, K.M., Hooyer, T.S., Stewart, P.W., Shipman, T.D., Gregory, C.T., and Zylstra, D.J., 2008, Numerical simulation of the paleohydrology of glacial Lake Oshkosh, eastern Wisconsin, USA: Quaternary Research, v. 69, p. 117–129.

Cramer, B.D., Brett, C.E., Melchin, M.J., Männik, P., Kleffner, M.A., McLaughlin, P.I., Loydell, D.K., Munnecke, A., Jeppsson, L., Corradini, C., Brunton, F.R., and Saltzman, M.R., 2011, Revised correlation of Silurian Provincial Series of North America with global and regional chronostratigraphic units and ∂13Ccarb chemostratigraphy: Lethaia, v. 44, p. 185–202, DOI 10.1111/j.1502-3931.2010.00234.x

Dewane, T.J., and Van Schmus, W.R., 2007, U-Pb geochronology of the Wolf River batholith, north-central Wisconsin: Evidence for successive magmatism between 1484 and 1468 Ma: Precambrian Research, v. 157, p. 215–234.

Dietrich, R.V., 1994, What is the Niagara Escarpment?: Rocks & Minerals, v. 69, May/June, p. 191–195.

Dott, R.H., Jr., and Attig, J.W., 2004, Roadside Geology of Wisconsin: Missoula, Mont., Mountain Press, 246 p.

Dutch, S.I., 1980, Trip 5: Structure and landform evolution in the Green Bay, Wisconsin, area, in Stieglitz, R.D., ed., Geology of eastern and northeastern Wisconsin: Annual Tri-State Geological Field Conference Guidebook, v. 44, p. 119–136.

DuMez, J., 2006, Brown County Wisconsin shaded-relief map: Brown County Land Information Office, (no scale given).

Dutton, C.E., and Bradley, R.E., 1970, Lithologic, geophysical, and mineral commodity maps of Precambrian rocks in Wisconsin: U.S. Geological Survey, Miscellaneous Geological Investigations Map I-631.

Evans, T.J., Massie-Ferch, K.M., and Peters, R.M., 2004, Preliminary bedrock geologic map of Walworth, Racine, Kenosha, Milwaukee, Waukesha, Ozaukee, and Washington Counties: Wisconsin Geological and Natural History Survey Open-File Report 2004-18, 1 plate, scale 1:100,000.

Harris, M.T., Kuglitsch, J.J., Watkins, R., Hegrenes, D.P., and Waldhuetter, K.R., 1998, Early Silurian stratigraphic sequences of eastern Wisconsin: New York State Museum Bulletin, v. 491, p. 39–49.

Harris, M.T., and Waldhuetter, K.R., 1996, Silurian of the Great Lakes region, part 3: Llandovery strata of the Door Peninsula, Wisconsin: Milwaukee Public Museum Contributions in Biology and Geology, no. 90, 162 p.

Hooyer, T.S., 2007, Evolution of glacial Lake Oshkosh and the Fox River lowland, in Hooyer, T.S., ed., Late-glacial history of east-central Wisconsin: Guide book for the 53rd Midwest Friends of the Pleistocene Field Conference, May 18–20, 2007, Oshkosh, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2007-1, 87 p.

Jones, J.V., III, Connelly, J.N., Karlstrom, K.E., Williams, M.L., and Doe, M.F., 2009, Age, provenance, and tectonic setting of Paleoproterozoic quartzite successions in the southwestern United States: Geological Society of America Bulletin, v. 121, p. 247–264.

Kasprzak, C.M., and Walter, M.A., 2001, An inventory and assessment of the Niagara Escarpment in Wisconsin: Bay-Lake Regional Planning Commission, Technical Report 77, 196 p.

Kluessendorf, J., and Mikulic, D.G., 1989, Bedrock geology of the Door Peninsula of Wisconsin, in Palmquist, J.C., ed., Wisconsin's Door Peninsula: A natural history: Appleton, Wis., Perlin Press, p. 12–31.

Kluessendorf, J., and Mikulic, D.G., 2004, The lake and the ledge: Geological links between the Niagara Escarpment and Lake Winnebago: 65th Annual Tri-State Geological Field Conference Guidebook, 64 p.

Kluessendorf, J., Mikulic, D.G., and Carman, M.R., 1988, Distribution and depositional environments of the westernmost Devonian rocks in the Michigan Basin, in McMillan, N.J., Embry, A.F., and Glan, D.J., eds., Devonian of the world: Proceedings of the Second International Symposium on the Devonian System, volume I: Regional syntheses: Canadian Society of Petroleum Geologists, Memoir 14, v. 1, p. 251–264.

Knox, J.C., and Attig, J.W., 1988, Geology of the pre-Illinoian sediment in the Bridgeport Terrace, lower Wisconsin River valley, Wisconsin: Journal of Geology, v. 96, p. 505–513.

Kox, N.H., 1985, Green Bay's wild caves: Wisconsin Natural Resources Magazine, September/October, p. 4–9.

Krohelski, J.T., 1986, Hydrogeology and ground-water use and quality, Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Information Circular Number 57, p. 1–42.

Kuntz, C.S., and Perry, A.O., 1976, History of reports on selected faults in southern and eastern Wisconsin: Geology, v. 4, p. 241–246.

LaBerge, G.L., 1994, Geology of the Lake Superior Region: Phoenix, Ariz., Geoscience Press, Inc., 313 p.

Larson, G., and Schaetzl, R., 2001, Origin and evolution of the Great Lakes: Journal of Great Lakes Research, v. 27, no. 4, p 518–546.

Luczaj, J.A., 2000, Epigenetic dolomitization and sulfide mineralization in Paleozoic rocks of eastern Wisconsin: Implications for fluid flow out of the Michigan Basin: Ph.D. dissertation, Baltimore, Md., Johns Hopkins University, 443 p.

Luczaj, J. A., 2006, Evidence against the Dorag (mixing-zone) model for dolomitization along the Wisconsin arch—a case for hydrothermal diagenesis: AAPG Bulletin, v. 90, p. 1719–1738.

Luczaj, J.A., 2011, Preliminary geologic map of the buried bedrock surface, Brown County, Wisconsin: Wisconsin Geological and Natural History Survey Open-File Report 2011-02, 1 plate, scale 1:100,000.

Luczaj, J.A., and Hart, D.J., 2009, Drawdown in the northeast groundwater management area (Brown, Outagamie, and Calumet Counties, Wisconsin): Wisconsin Geological and Natural History Survey Open-File Report 2009-04, 60 p.

Luczaj, J.A., and Stieglitz, R.D., 2008, Geologic history of New Hope Cave, Manitowoc County, Wisconsin: The Wisconsin Speleologist, June 2008, p. 7–17.

Maas, J.C., 2009, Drawdown, recovery, and hydrostratigraphy in Wisconsin's northeast groundwater management area (Brown, Outagamie, and Calumet Counties): M.S. thesis, University of Wisconsin–Green Bay, 196 p. plus CD-ROM.

Mai, H., and Dott, R.H., Jr., 1985, A subsurface study of the St. Peter sandstone in southern and eastern Wisconsin: Wisconsin Geological and Natural History Survey Information Circular 47, 26 p., with maps.

Martin, L., 1916, Physical geography of Wisconsin: Wisconsin Geological and Natural History Survey Bulletin 36, 549 p.

McLane, M., 1995, Sedimentology: New York, Oxford University Press, 423 p.

Mikulic, D.J., and Kluessendorf, J., 1983, The Oolitic Neda iron ore (Upper Ordovician?) of eastern Wisconsin: Field Trip Guidebook for the Seventeenth Annual Meeting of the North Central Section of the Geological Society of America, University of Wisconsin–Madison, April 28–May 1, 1983, 54 p.

Mikulic, D.G., and Kluessendorf, J., 1988, Subsurface stratigraphic relationships of the Upper Silurian and Devonian rock of Milwaukee County, Wisconsin: Geoscience Wisconsin, v. 12, p. 1–23.

Mikulic, D.J., and Kluessendorf, J., 2009, Pentamerid brachiopod intervals and their relationship to depositional sequences in the Silurian (Llandovery) of eastern Wisconsin and northeastern Illinois: Geological Society of America, Abstracts with Programs, North-Central Section, 42nd annual meeting, v. 41, no. 4, p. 61.

Mikulic, D.G., Kluessendorf, J., McLaughlin, P., and Luczaj, J., 2010, Bedrock geology of the Niagara Escarpment on the Door Peninsula of Wisconsin: Field Guidebook for the Joint Meeting of the Great Lakes Section SEPM Fall Field Conference and 65th Annual Tri-State Geological Field Conference, September 24–26, 2010, Sturgeon Bay, Wis., 79 p.

NICE (Northern Interior Continental Evolution) Working Group: Holm, D.K., Anderson, R., Boerboom, T.J., Cannon, W.F., Chandler, V., Jirsa, M., Miller, J., Schneider, D.A., Schulz, K.J., and Van Schmus, W.R., 2007, Reinterpretation of Peleoproterozoic accretionary boundaries of the north-central United States based on a new aeromagnetic-geologic compilation: Precambrian Research, v. 157, p. 71–79.

Ojakangas, R.W., Morey, G.B., and Green, J.C., 2001, The Mesoproterozoic Midcontinent Rift System, Lake Superior Region, USA: Sedimentary Geology, v. 141–142, p. 421–442.

Ontario Geological Survey, 1993, Bedrock geology, seamless coverage of the province of Ontario: Ontario Geological Survey, Data Set 6.

Paull, R.A., and Emerick, J.A., 1991, Genesis of the Upper Ordovician Neda Formation in eastern Wisconsin: Geoscience Wisconsin, v. 14, p. 23–52.

Paull, R.A., 1992, First report of natural bridges in eastern Wisconsin: Transactions of the Wisconsin Academy of Sciences, Arts, and Letters, v. 80, p. 139–148.

Runkel, A.C., Miller, J.F., McKay, R.M., Palmer, A.R., Taylor, J.F., 2007, High-resolution sequence stratigraphy of lower Paleozoic sheet sandstones in central North America: The role of special conditions of cratonic interiors in development of stratal architecture: GSA Bulletin, v. 119, no. 7/8, p. 860–881.

Schneider, A.F., 1989, Geomorphology and Quaternary geology of Wisconsin's Door Peninsula, in Palmquist, J.C., ed., Wisconsin's Door Peninsula: A natural history: Appleton, Wis., Perlin Press, p. 32–48.

Schruben, P.G., Arndt, R.E., and Bawiec, W.J., 1994, Geology of the conterminous United States at 1:2,500,000 scale—a digital representation of the 1974 P.B. King and H.M. Beikman map: U.S. Geological Survey Digital Data Series 11, release 2, http://pubs.usgs.gov/dds/dds11/.

Schultz, G.M, 1986, Wisconsin's foundations: A review of the state's geology and its influence on geography and human activity: Dubuque, Iowa, UW–Extension and Kendall/Hunt, 211 p.

Schulz, K.J. and Cannon, W.F., 2007, The Penokean orogeny in the Lake Superior region: Precambrian Research, v. 157, p. 4–25.

Scotese, C.R., 1984, An introduction to this volume: Paleozoic paleomagnetism and the assembly of Pangaea, in Van der Voo, R., Scotese, C.R., Bonhommet, N., eds., Plate reconstruction from Paleozoic paleomagnetism: International Lithosphere Program, Publication 0103, Geodynamics Series, v. 12, p. 1–10.

Sheehan, P.M., 2001, The Late Ordovician mass extinction: Annual Reviews of Earth and Planetary Sciences, v. 29, p. 331–364.

Sherrill, M.G., 1978, Geology and ground water in Door County, Wisconsin, with emphasis on contamination potential in the Silurian dolomite: U.S. Geological Survey Water-Supply Paper 2047, 38 p.

Shrock, R.R., 1939, Wisconsin bioherms: Geological Society of America Bulletin, v. 50, p. 529–562.

Shrock, R.R., 1940, Geology of Washington Island and its neighbors, Door County, Wisconsin: Transactions of the Wisconsin Academy of Sciences, Arts, and Letters, v. 32, p. 229–232.

Sivon, P.A., 1980, Stratigraphy and paleontology of the Maquoketa Group (Upper Ordovician) at Wequiock Creek, eastern Wisconsin: Milwaukee Public Museum, Contributions in Biology and Geology, no. 35, 45 p.

Sloss, L.L., 1963, Sequences in the Cratonic Interior of North America: Geological Society of America Bulletin, v. 74, p. 93–114.

Smith, G.L., and Simo, J.A., 1997, Carbonate diagenesis and dolomitization of the Lower Ordovician Prairie du Chien Group: Geoscience Wisconsin, v. 16, p. 1–16.

Socha, B.J., Colgan, P.M., and Mickelson, D.M., 1999, Ice-surface profiles and bed conditions of the Green Bay Lobe from 13,000 to 11,000 ^{14}C-years B.P., in Mickelson, D.M., and Attig, J.W., eds., Glacial processes past and present: Geological Society of America Special Paper, no. 337, p. 151–158.

Soderman, J.W., and Carozzi, A.V., 1963, Petrography of algal bioherms in Burnt Bluff Group (Silurian), Wisconsin: AAPG Bulletin, v. 47, no. 9, p. 1682–1708.

Stanley, S.M., 2009, Earth system history, 3rd edition: New York, W.H. Freeman and Company, 551 p.

Stieglitz, R.D., Moran, J.M., and Harris, J.D., 1980, A relict geomorphological feature adjacent to the Silurian escarpment in northeastern Wisconsin: Transactions of the Wisconsin Academy of Sciences, Arts, and Letters, v. 68, p. 202–207.

Swezey, C.S., 2008, Regional stratigraphy and petroleum systems of the Michigan Basin, North America: U.S. Geological Survey, Scientific Investigations Map 2978.

Syverson, K.M., and Colgan, P.M., 2004, The Quaternary of Wisconsin: A review of stratigraphy and glaciation history, in Ehlers, J., and Gibbard, P.L., eds., Quaternary Glaciations—Extent and Chronology, Part II: North America: Amsterdam, Elsevier Publishing, p. 295–311.

Thwaites, F.T., 1931, Buried Pre-Cambrian of Wisconsin: Geological Society of America Bulletin, v. 42, p. 719–750.

Thwaites, F.T., 1957, Buried Pre-Cambrian of Wisconsin: Wisconsin Geological and Natural History Survey Page-Size Map 10, 1 p.

Turner, S., Kuglitsch, J.J., and Clark, D.L., 1999, Llandoverian thelodont scales from the Burnt Bluff Group of Wisconsin and Michigan: Journal of Paleontology, v. 73, no. 4, p. 667–676.

Velbel, M., 2009, The “Lost Interval”: Geology from the Permian to the Pliocene, in Schaetzl, R., Darden, J., and Brant, D., eds., Michigan geography and geology: Pearson Custom Publishing, p. 60–68.

Watkins, R., 1994, Evolution of Silurian pentamerid communities in Wisconsin: PALAIOS, v. 9, p. 488–499.

Watkins, R., and Kuglitsch, J.J., 1997, Lower Silurian (Aeronian) megafaunal and conodont biofacies of the northwestern Michigan Basin: Canadian Journal of Earth Sciences, v. 34, p. 753–764.

WGNHS, 2011, Glaciation of Wisconsin: Wisconsin Geological and Natural History Survey Educational Series 36, 4 p.