GEOSCIENCE WISCONSIN

Wisconsin's Niagara Escarpment


Eric Fowle

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

VOLUME 22 • 2016

University of Wisconsin-Extension

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Associate editor: Ronald D. Stieglitz

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Introduction to Wisconsin's Niagara Escarpment

Ronald D. Stieglitz[1]

The Niagara Escarpment is the steep, nearly vertical, face of the most prominent of a series of asymmetrical ridges, or cuestas, that form the Ridges and Lowlands Geographic Province of eastern Wisconsin (fig. 1). In places, it is a striking physiographic feature that appears picturesque from the land or water below (fig. 2 and 3) and which provides impressive vistas of the bay of Green Bay, the Fox River Valley, and Lake Winnebago. At other locations, it is rounded and subdued having been reduced by weathering and erosion. The escarpment has been long valued for its natural beauty, and the citizens of Wisconsin are fortunate that measures have been taken to protect segments from development. A number of state, county, and town parks are located on or adjacent to the escarpment, from Rock Island State Park in the north to at least Ledge County Park in Dodge County in the south. These public spaces are priceless: they preserve and provide public access to areas that could only be admired from distant points if they were in private ownership. In addition to

> "These public spaces are priceless: they preserve and provide public access to places that could only be admired from distant points…"

Figure 2. *Eagle Bluff from the water.*

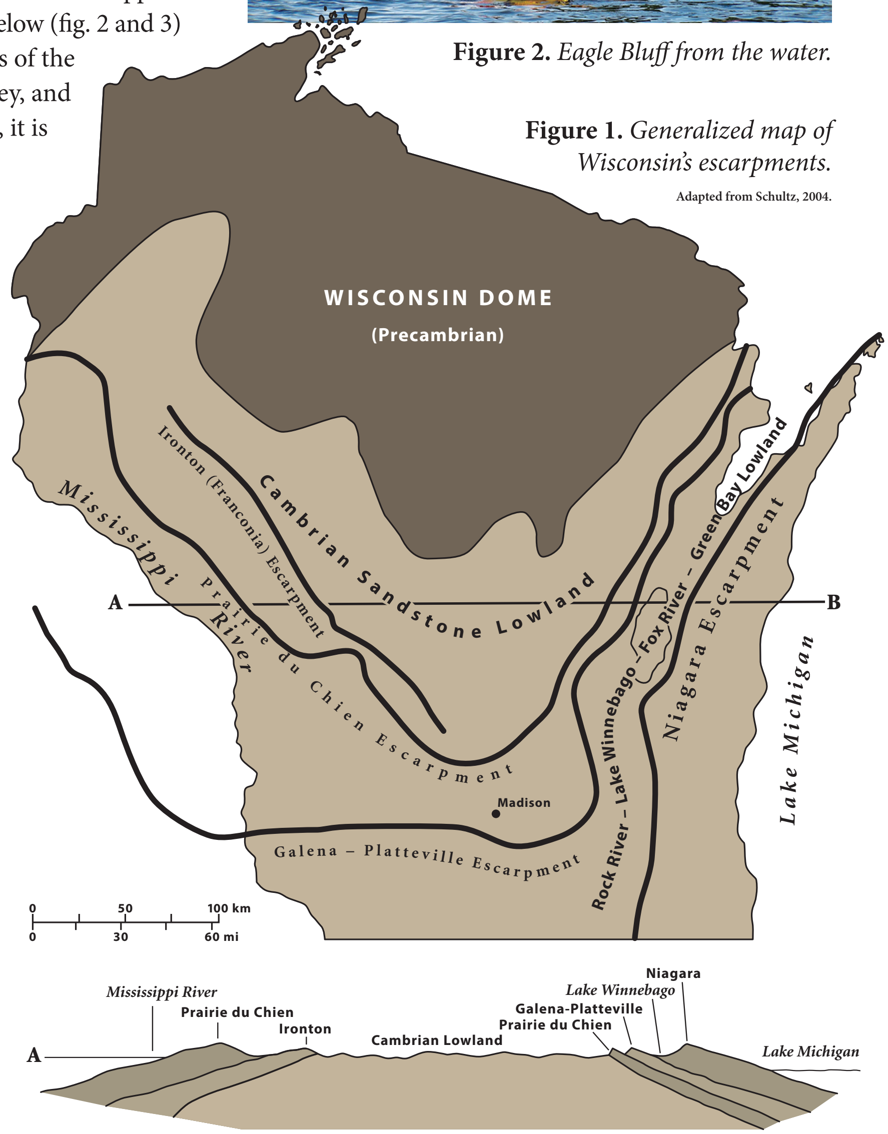

Figure 1. *Generalized map of Wisconsin's escarpments.*

Adapted from Schultz, 2004.

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Figure 3. *View of islands from the escarpment at Peninsula State Park. Door County.*

its scenic amenities, the escarpment or "the Ledge," as it is often called, is also biologically, economically, and hydrologically significant. The term escarpment, or cuesta, refers to a ridge that is steep on one side and gradually sloping on the other side. The Niagara Escarpment is arguably one of the premier landforms of our state (fig. 4).

A number of local and regional conference proceedings and reports focused on the escarpment have been published (for example, Hershbell, 1989; Palmquist, 1989; Schutte and Walter, 1997; Kasprzak and Walter, 2001; and Anderson and others, 2002). More recently, Mikulic and others (2010) reviewed the geology of the escarpment on the Door Peninsula. In January 2010, the Niagara Escarpment Resource Network sponsored a conference (The Niagara Escarpment: What Is It? And Why Should I Care?) on the University of Wisconsin-Green Bay campus. That event brought together a wide range of contributors and was well attended. This collection of papers was inspired by that conference and by the designation by the

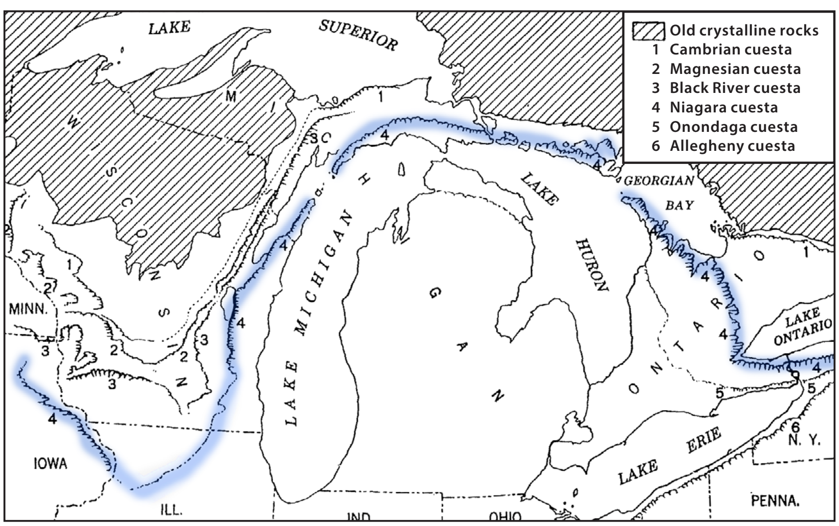

Figure 4. *The Niagara cuesta (highlighted in blue) and other less prominent cuestas in the sedimentary rocks of the Great Lakes region.*

From Trewartha and others, *Elements of Geography,* copyright McGraw-Hill Education.

Wisconsin legislature of 2010 as The Year of the Escarpment.

The origin of the escarpment is complex, and the appearance of the landform varies along its extent. The escarpment is frequently interrupted by valleys or re-entrants, with some segments dominated by high, nearly vertical cliffs and others formed by rounded low ridges (fig. 5). Those different and distinct aspects are the result of both long-standing geological relationships and past and present geomorphic processes.

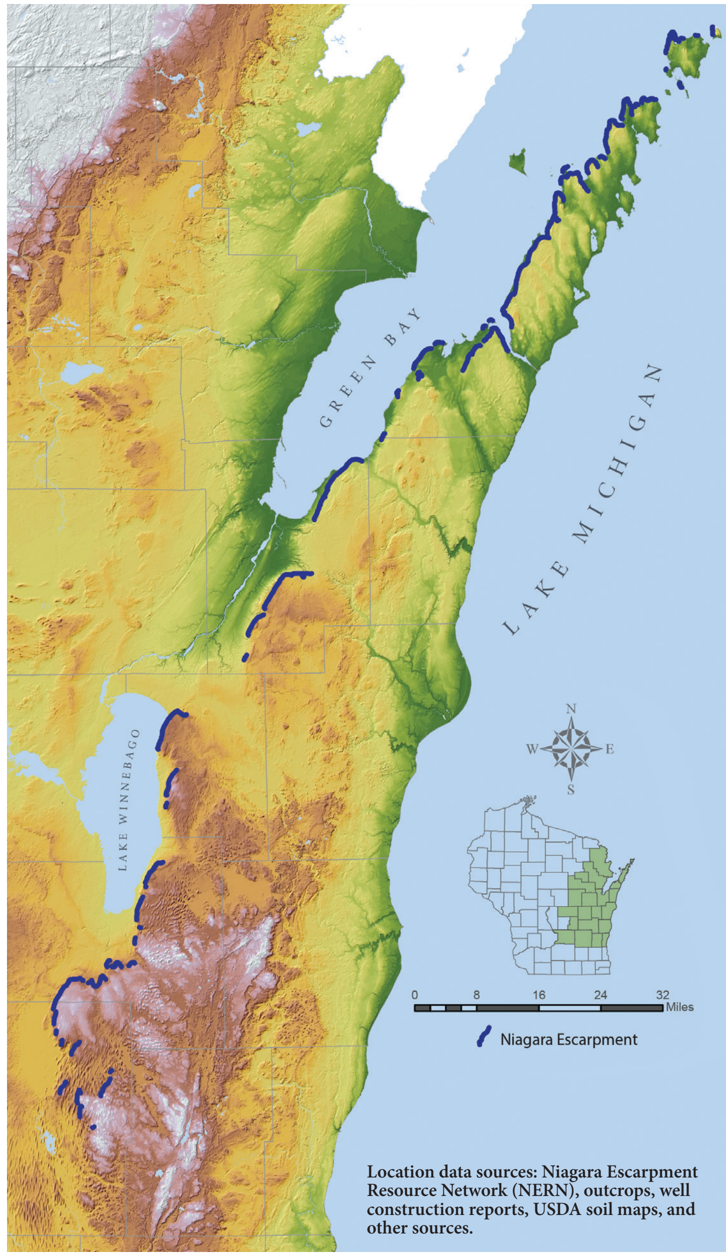

Figure 5. *Digital elevation model with hillshade showing the location of the Niagara Escarpment in Wisconsin.*

The papers in this volume cover the following topics:

- **Part 1 – Geology.** Luczaj (2013) summarizes the geologic history of the area and the stratigraphic and structural relationships that are basic to an understanding of the formation and modification of the escarpment. He also provides important new information on faults that cut the escarpment and touches on the issues of terminology that remain.

- **Part 2 – Processes that have shaped the escarpment.** Stieglitz (2016) reviews the many factors that have combined to shape the escarpment as it appears today. Some of the features result from processes presently modifying the landform, whereas others are relicts formed by processes and geological agents of the past. People have also affected the escarpment's attributes and appearance as we build on or near the feature. Because the stone is easily accessible, quarries have long operated on the escarpment and in several locations they have significantly changed its appearance. Examples abound, but two of the largest are the now-inactive quarries at High Cliff State Park in Calumet County and Olde Stone Quarry County Park near Sturgeon Bay.

- **Part 3 – Biota.** The escarpment is habitat for several rare flora and fauna species, such as ancient cedar trees and Pleistocene relict snails. The escarpment system is ecologically important at multiple scales but particularly at the small-to-micro scale that shelters those and perhaps other rare taxa (Howe, Wolf, and Fewless, 2016).

- **Part 4 – Bats.** The escarpment also has value as the site of hibernacula for bats, of particular importance in the face of the threat of white-nose syndrome (Novy, 2016). That disease has devastated bat populations in the eastern United States and Canada and is a major concern because of the importance of bats for insect control; the disease was confirmed in Wisconsin in 2014.

- **Part 5 – Caves and karst.** Zachariasen (2016) presents a caver's view of the types of caves in eastern Wisconsin and the efforts undertaken to ensure access for exploration and research while providing protection of fragile physical features and biological ecosystems.
- **Part 6 – Conservation geology ethic.** The international context of the Wisconsin escarpment and the concept of the Great Arc are discussed by Fowle (2016). The escarpment continues into Canada, and programs and policies in place in Ontario can serve to inform both promotional and preservation efforts in Wisconsin.

Collectively, the papers in this volume provide an overview of a major landscape feature of our state. The collection clearly establishes the concept that the Niagara Escarpment's ecosystem encompasses the cliff face as well as the areas behind and below. Individually, the papers address, explain, clarify, and highlight many aspects of the landform, its value, and the challenges that remain in its conservation and management. In sum, the Niagara Escarpment is a precious, fragile, and irreplaceable treasure that deserves to be preserved so that future generations may also enjoy its unique beauty and charm.

REFERENCES CITED

Anderson, C., Epstein, E., Smith, W., and Merryfield, N., 2002, The Niagara Escarpment inventory findings 1999–2001 and considerations for management: Bureau of Endangered Resources, Wisconsin Department of Natural Resources, PUBL ER-801 2002, 77 p.

Fowle, E.W., 2016, Building a conservation geology ethic along the Great Arc: *Geoscience Wisconsin,* v. 22, no. 6, 13 p.

Hershbell, K., 1989, Door County and the Niagara Escarpment: Foundations for the future: Madison, Wis., Wisconsin Academy of Sciences, Arts & Letters, 104 p.

Howe, R.W., Wolf, A.T., and Fewless, G.A., 2016, Biota of Wisconsin's Niagara Escarpment: *Geoscience Wisconsin,* v. 22, no. 3, 10 p.

Kasprzak, C.M., and Walter, M.A., 2001, An inventory and assessment of the resources of the Niagara Escarpment in Wisconsin: Green Bay, Wis., Bay-Lake Regional Planning Commission, Technical Report 77, 195 p.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin,* v. 22, 34 p.

Mikulic, D.G., Kluessendorf, J., McLaughlin, P.I., and Luczaj, J.A., 2010, Bedrock geology of the Niagara Escarpment on the Door Peninsula, *in* Joint Meeting of the Great Lakes Section Society for Sedimentary Geology (SEPM) Fall Field Conference and the 65th Annual Tri-State Geological Field Conference, Field Guide, 79 p.

Novy, R., 2016, Bats of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin,* v. 22, no. 4, 4 p.

Palmquist, J.C., ed., 1989, Wisconsin's Door Peninsula: A natural history: Appleton, Wis., Perin Press, 196 p.

Schultz, G.M., 2004, Wisconsin's foundations: A review of the state's geology and its influence on geography and human activity: Madison, Wis., The University of Wisconsin Press, 211 p.

Schutte, A., and Walter, M., 1997, Cumulative and secondary impacts of development along the Green Bay East Shore: Green Bay, Wis., Bay-Lake Regional Planning Commission, Technical Report 52, 133 p.

Stieglitz, R.D., 2016, Processes that have shaped the Niagara Escarpment: *Geoscience Wisconsin,* v. 22, no. 2, 12 p.

Trewartha, G.T., Robinson, A.H., and Hammond, E.H., 1967, Elements of geography (5th ed.): New York, McGraw-Hill Education, 660 p.

Zachariasen, G., 2016, Caves and karst of the Niagara Escarpment: A caver's perspective: *Geoscience Wisconsin,* v. 22, no. 5, 9 p.

GEOLOGY OF THE NIAGARA ESCARPMENT IN WISCONSIN

John A. Luczaj

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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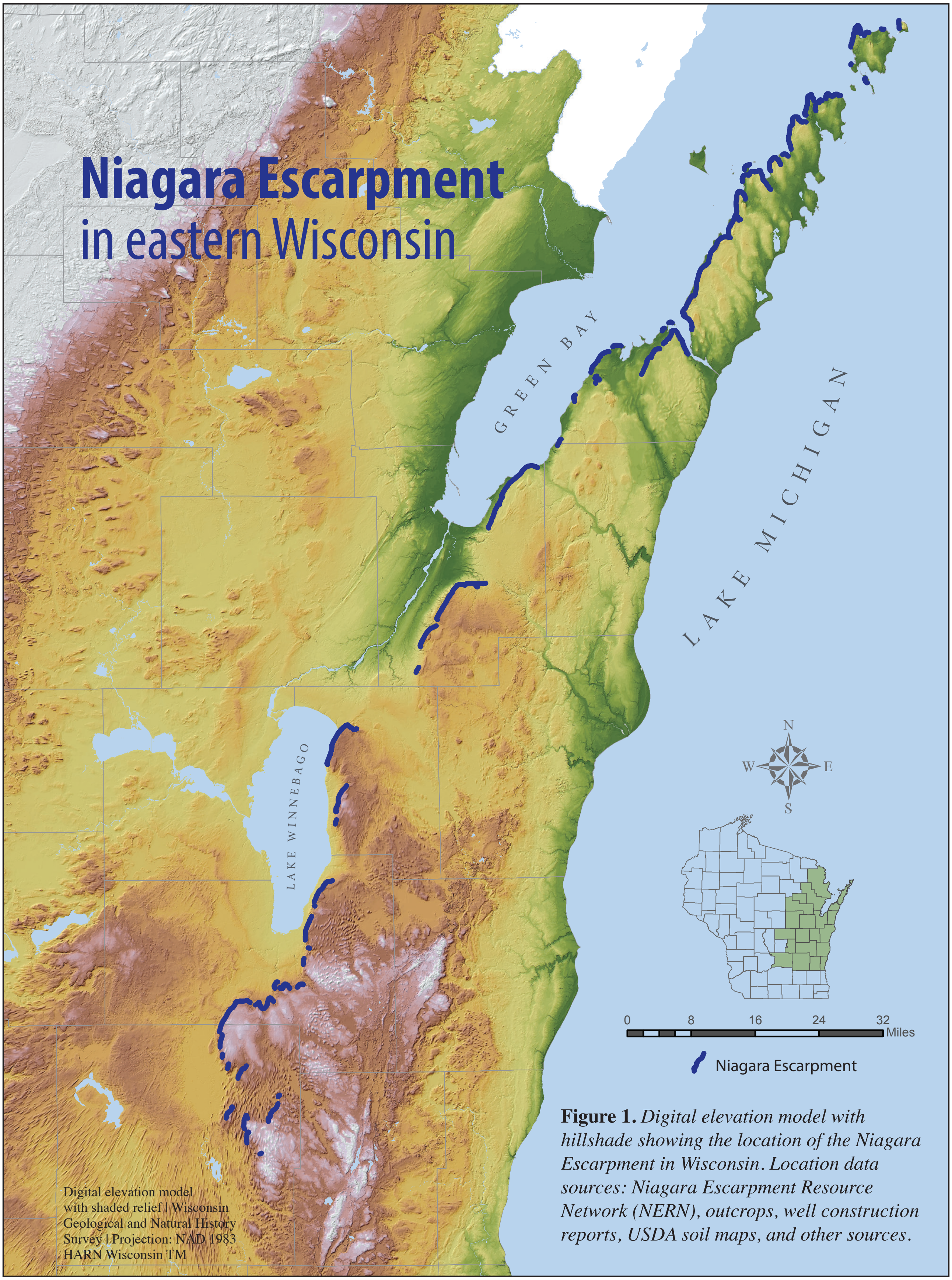

Figure 1. *Digital elevation model with hillshade showing the location of the Niagara Escarpment in Wisconsin. Location data sources: Niagara Escarpment Resource Network (NERN), outcrops, well construction reports, USDA soil maps, and other sources.*

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

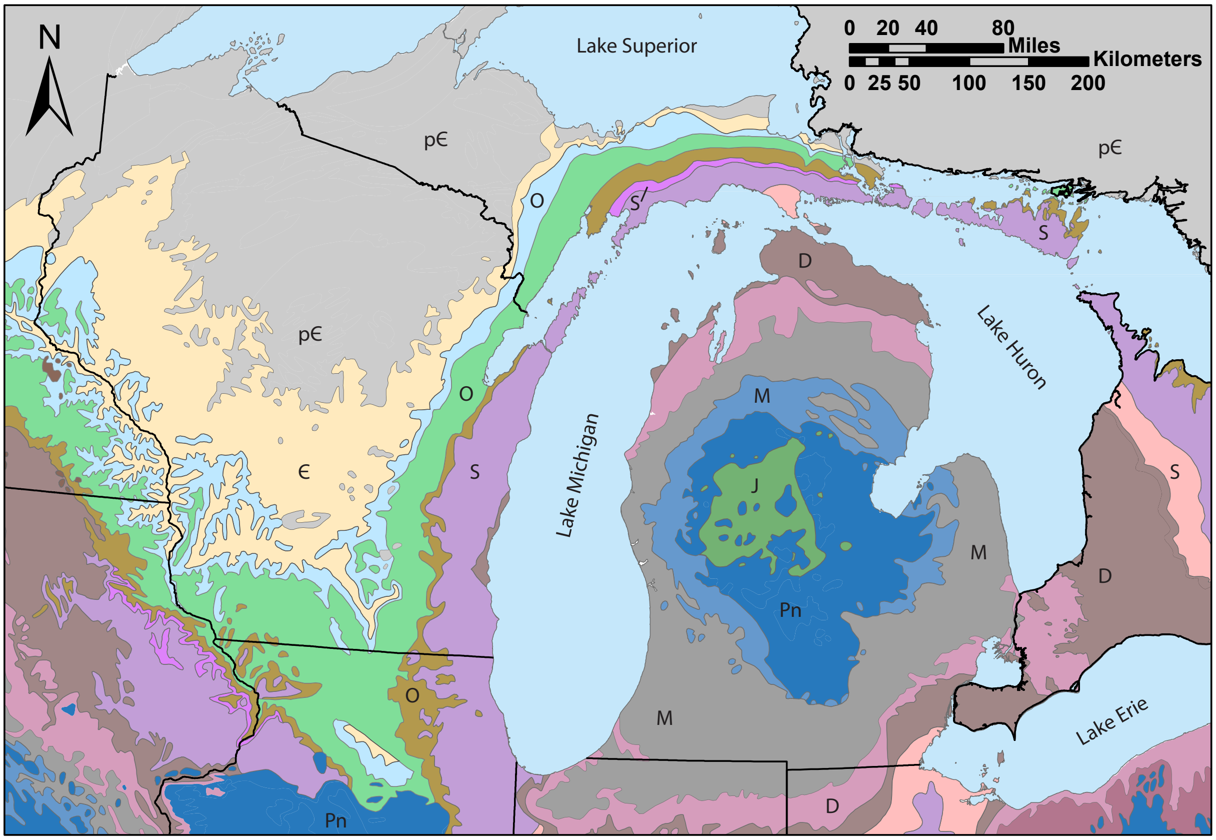

Figure 2. *Bedrock geologic map showing eastern Wisconsin and the ancestral Michigan basin (bullseye pattern). Geologic rock systems (periods): p€ = Precambrian, € = Cambrian, O = Ordovician, S = Silurian, D = Devonian, M = Mississippian, Pn = Pennsylvanian, J = Jurassic. Base map data modified after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

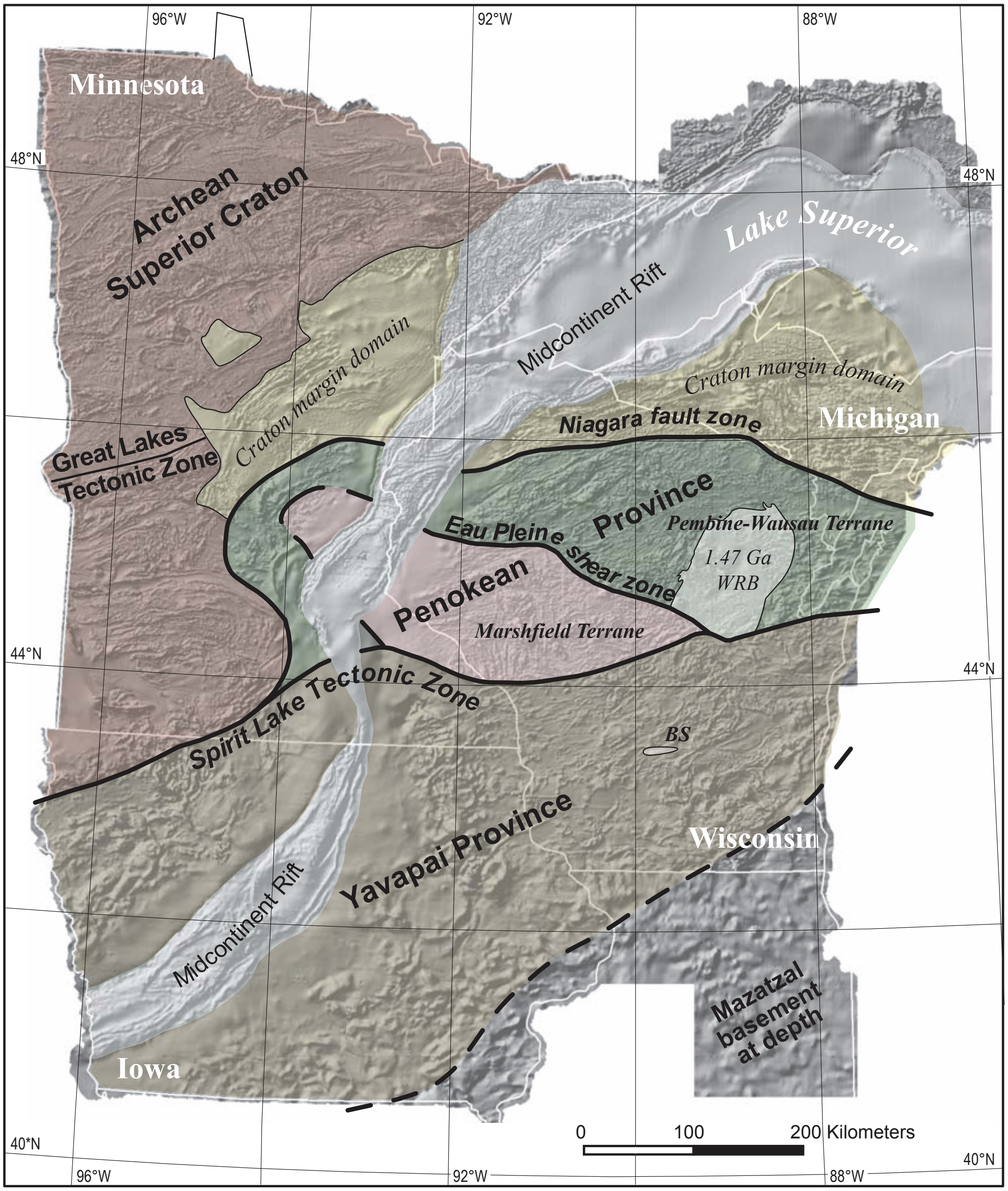

Figure 3. *Geologic terrane map of Precambrian basement rocks in the northern U.S. midcontinental interior. WRB = Wolf-River batholith, BS = Baraboo Syncline. Underlying gray shaded base map is the regional aeromagnetic anomaly map. The "craton margin domain," north of the Niagara fault zone, represents 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

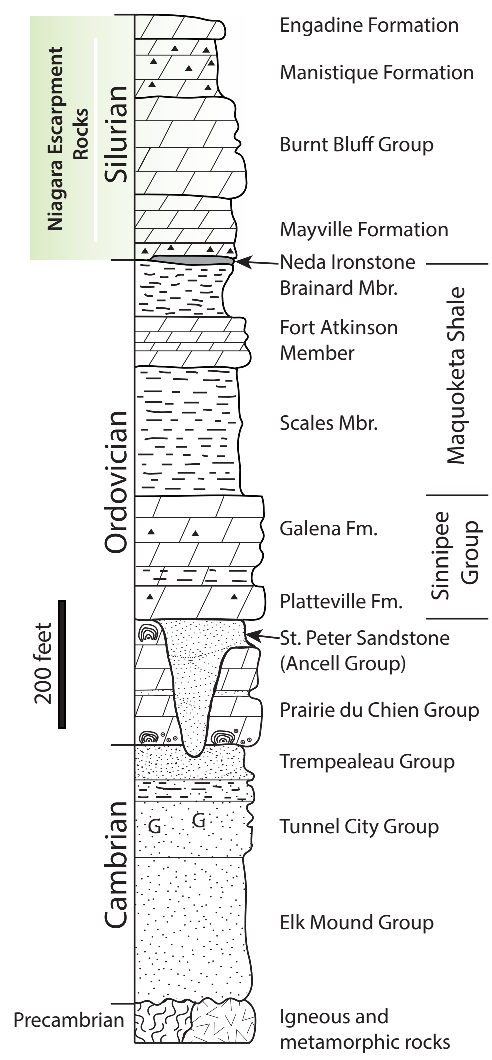

Figure 4. *Generalized stratigraphic column for northeastern Wisconsin.*

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

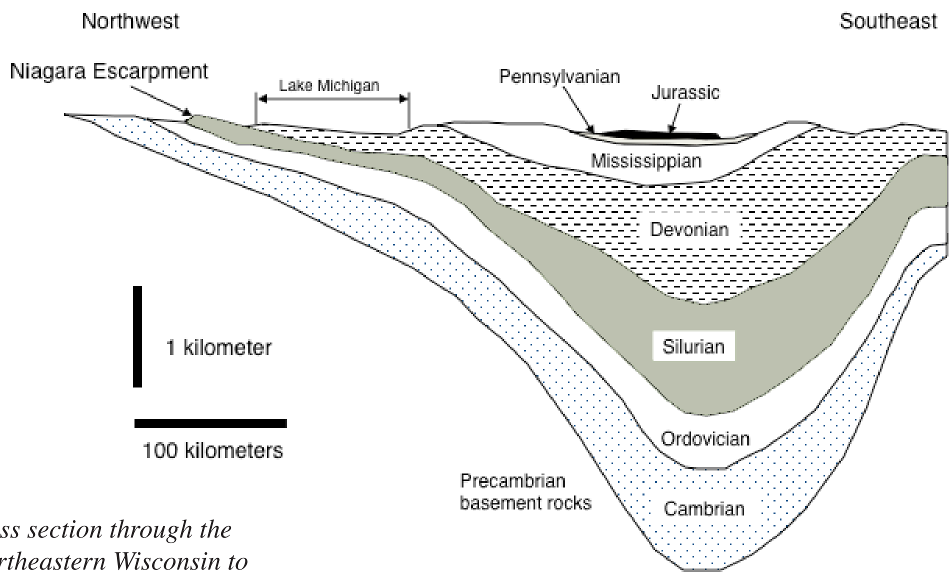

Figure 5. *Schematic cross section through the Michigan basin from northeastern Wisconsin to southeastern Michigan.*

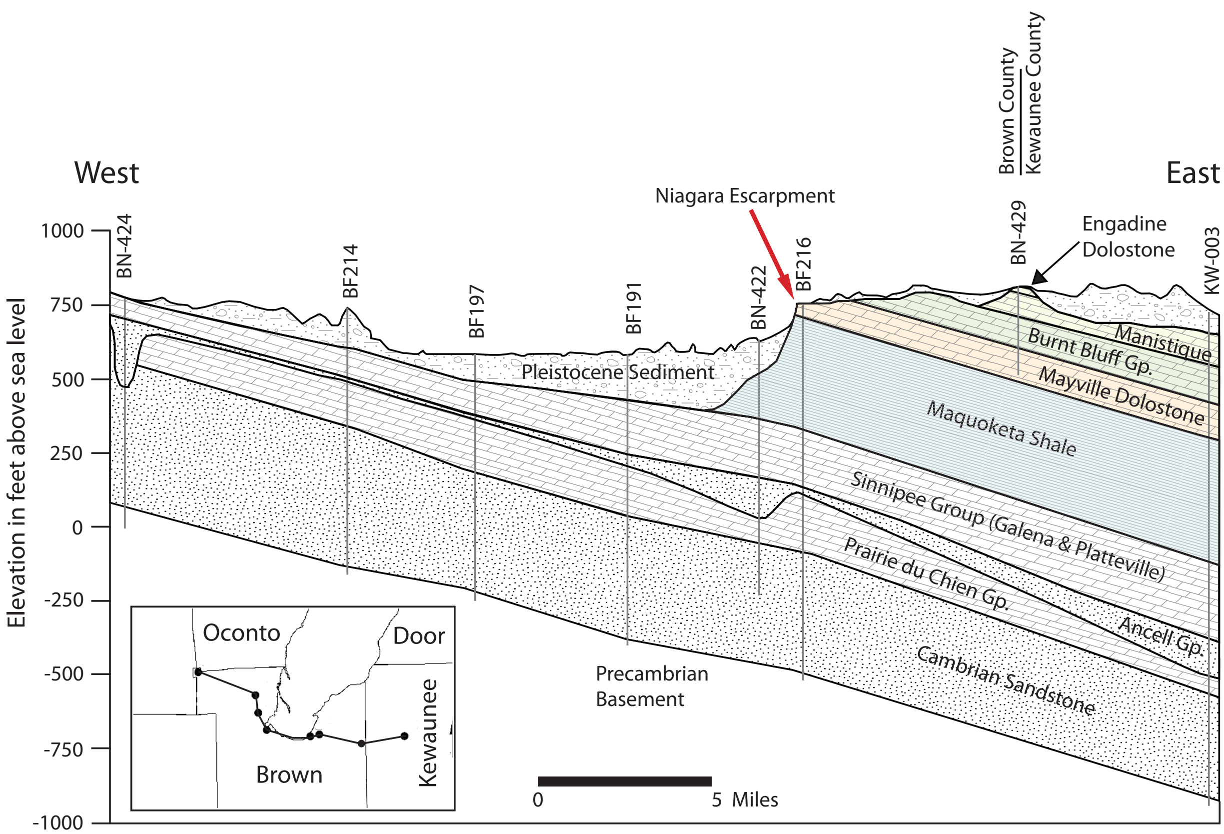

Figure 6. *Cross section through the midpoint of the Niagara Escarpment in Wisconsin. Rock strata dip eastward toward the ancestral Michigan basin. Note the relief on the bedrock surface west of the escarpment that is partially concealed by Pleistocene glacial sediments. Vertical exaggeration is 45 x. 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

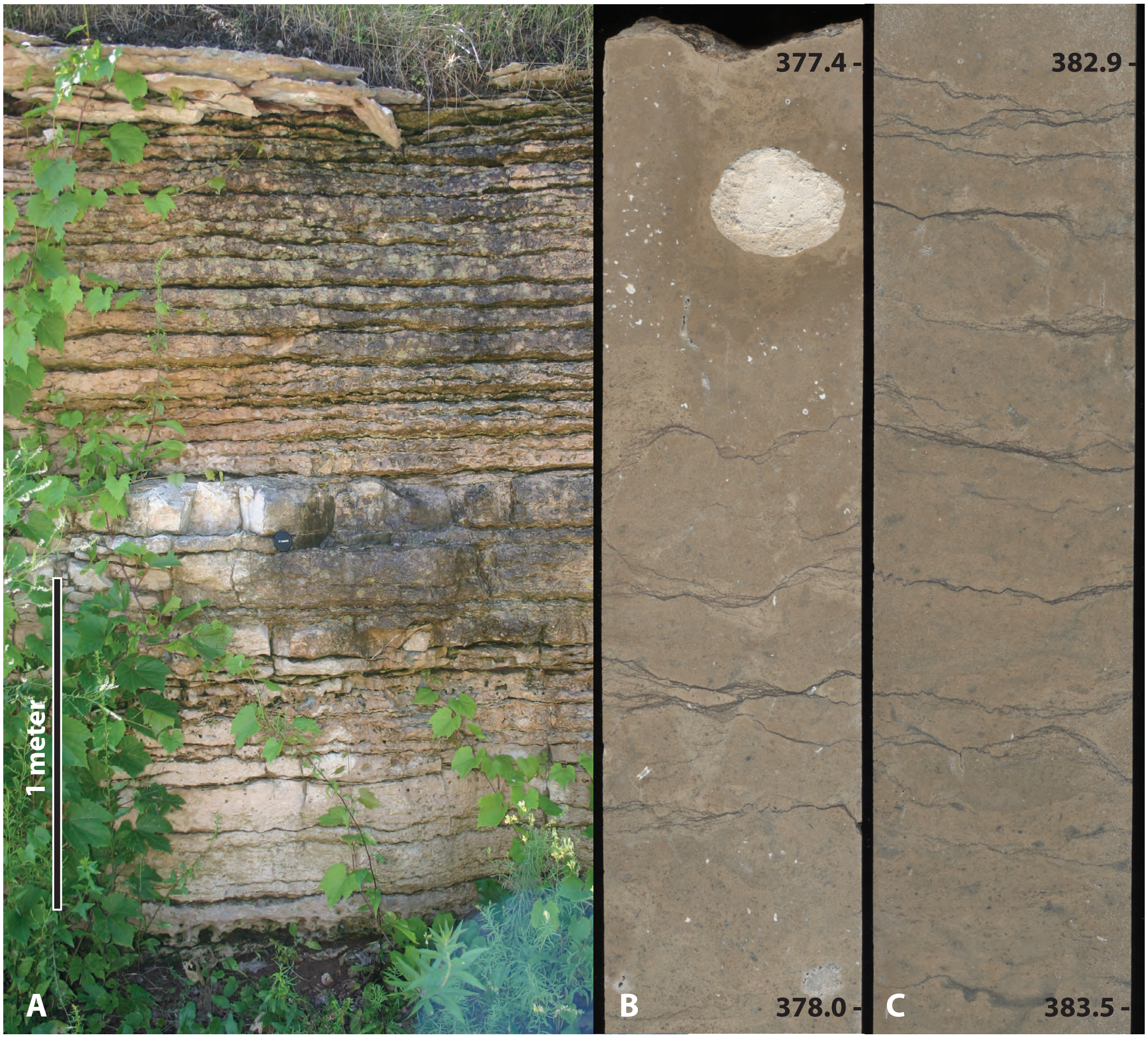

Figure 8. *(a) Weathered outcrop of Mayville Dolomite at Bayshore County Park in Brown County. Dissolution compaction was focused on horizontal stylolites, both within beds and along bedding planes. (b, c) Stylolites in cut and polished drill core from a similar stratigraphic position in the Mayville 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

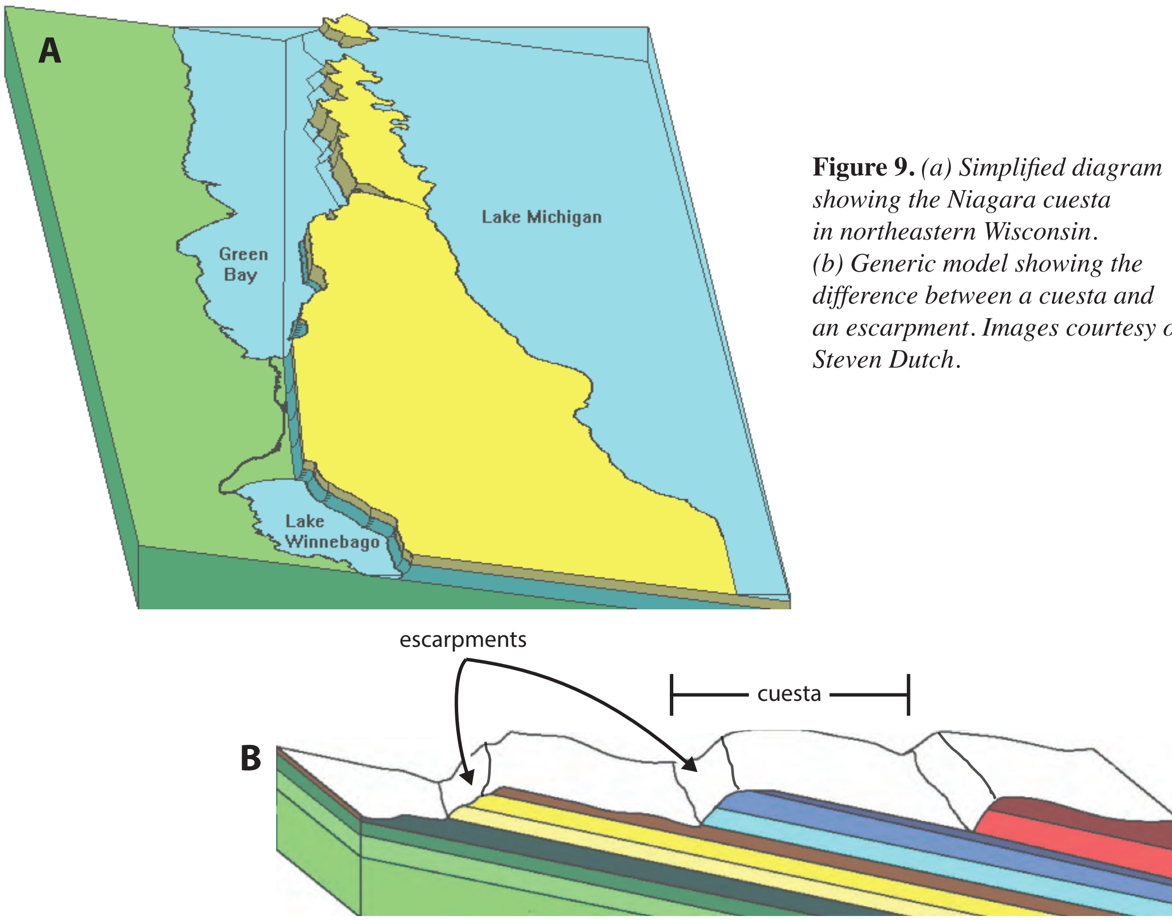

Figure 9. *(a) Simplified diagram showing the Niagara cuesta in northeastern Wisconsin. (b) Generic model showing the difference between a cuesta and an escarpment. Images courtesy of Steven Dutch.*

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

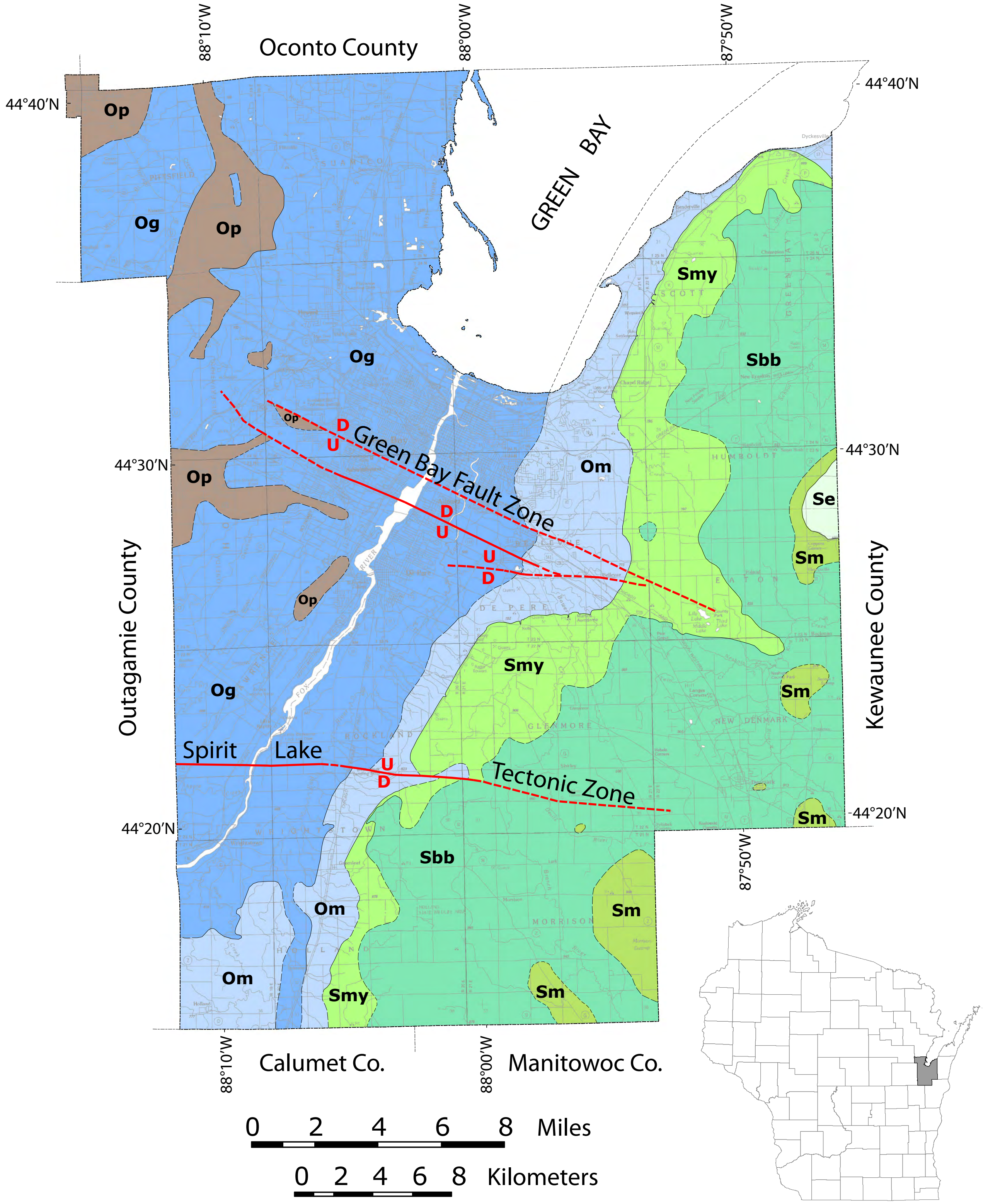

Figure 10. *Preliminary bedrock geologic map of Brown County, Wisconsin, showing the locations of major dip-slip faults (red lines) that influence the shape and position of parts of the Niagara Escarpment. Ordovician units: Op = Platteville Fm., Og = Galena Fm., and Om = Maquoketa Fm.; Silurian units: 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).*

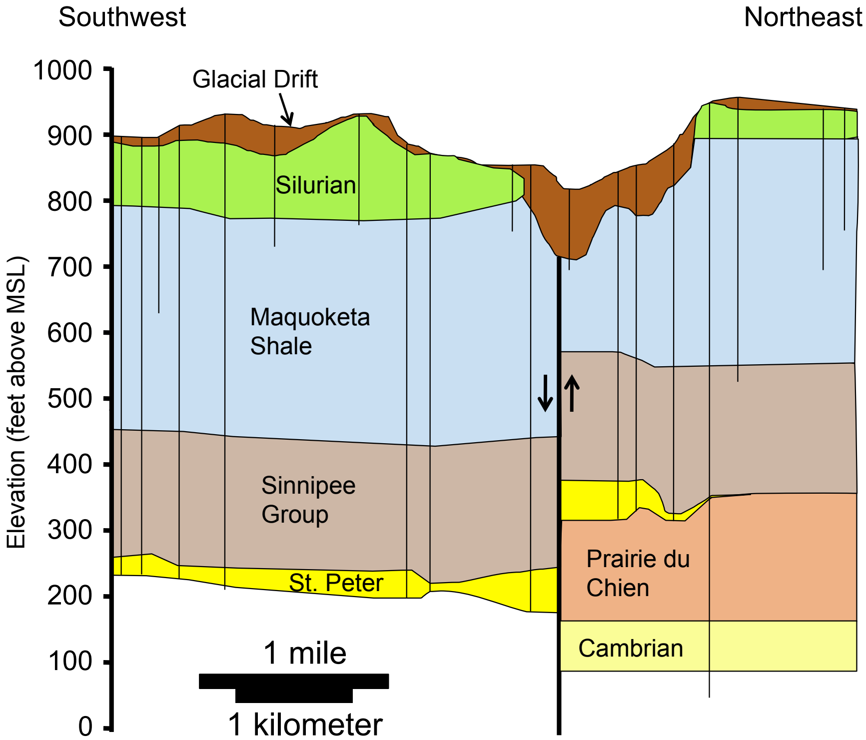

Figure 11. *South to north cross section along the top of the Niagara Escarpment north of Greenleaf, Wisconsin. Thin vertical lines indicate water well locations. Arrows indicate relative offset along the main fault at this location (thick line).*

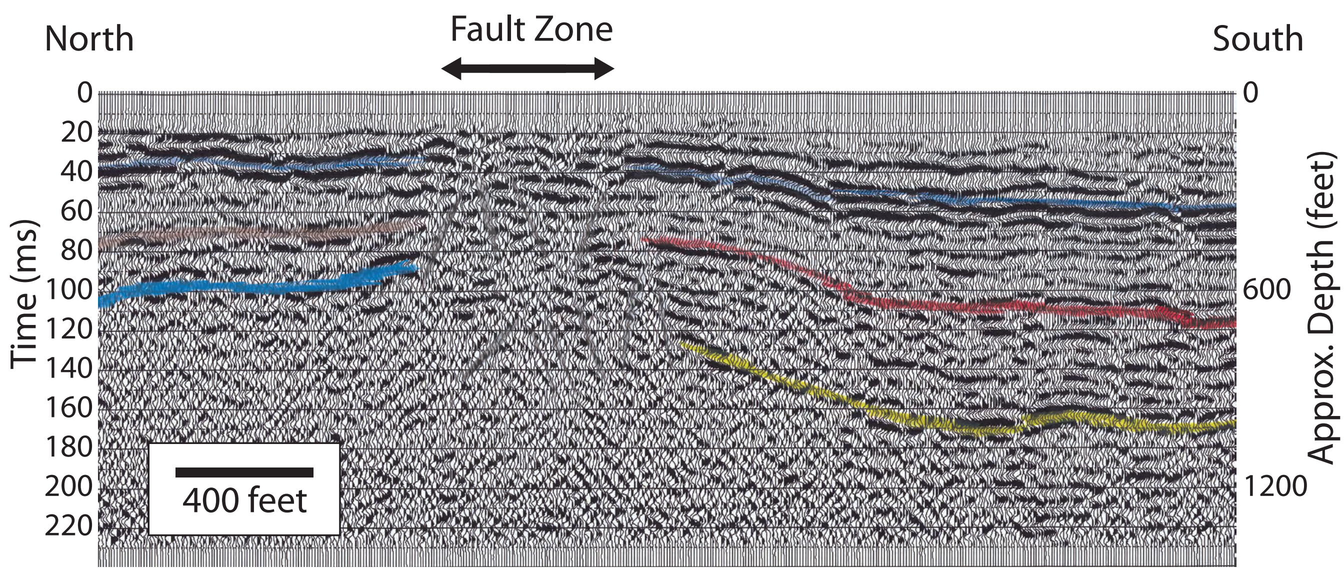

Figure 12. *A portion of a preliminary north-south reflection seismic line across the fault north of Greenleaf, Wisconsin (Spirit Lake Tectonic Zone?). Segment shown here is 3,300 ft (1 km) long and was taken along Tetzlaff Road, just east of the Fox River in the Towns of Rockland and Wrightstown (Brown 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

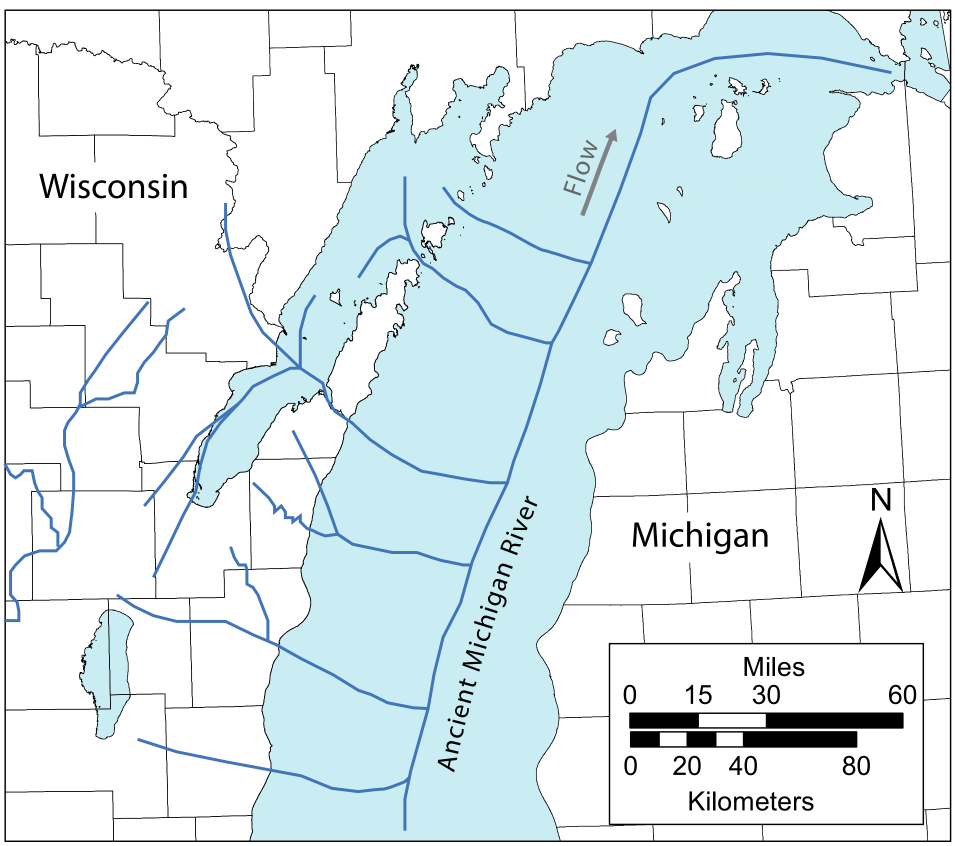

Figure 13. *Possible preglacial drainage pattern in northeastern Wisconsin. Modified from Martin (1916) and Larson and Schaetzl (2001).*

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

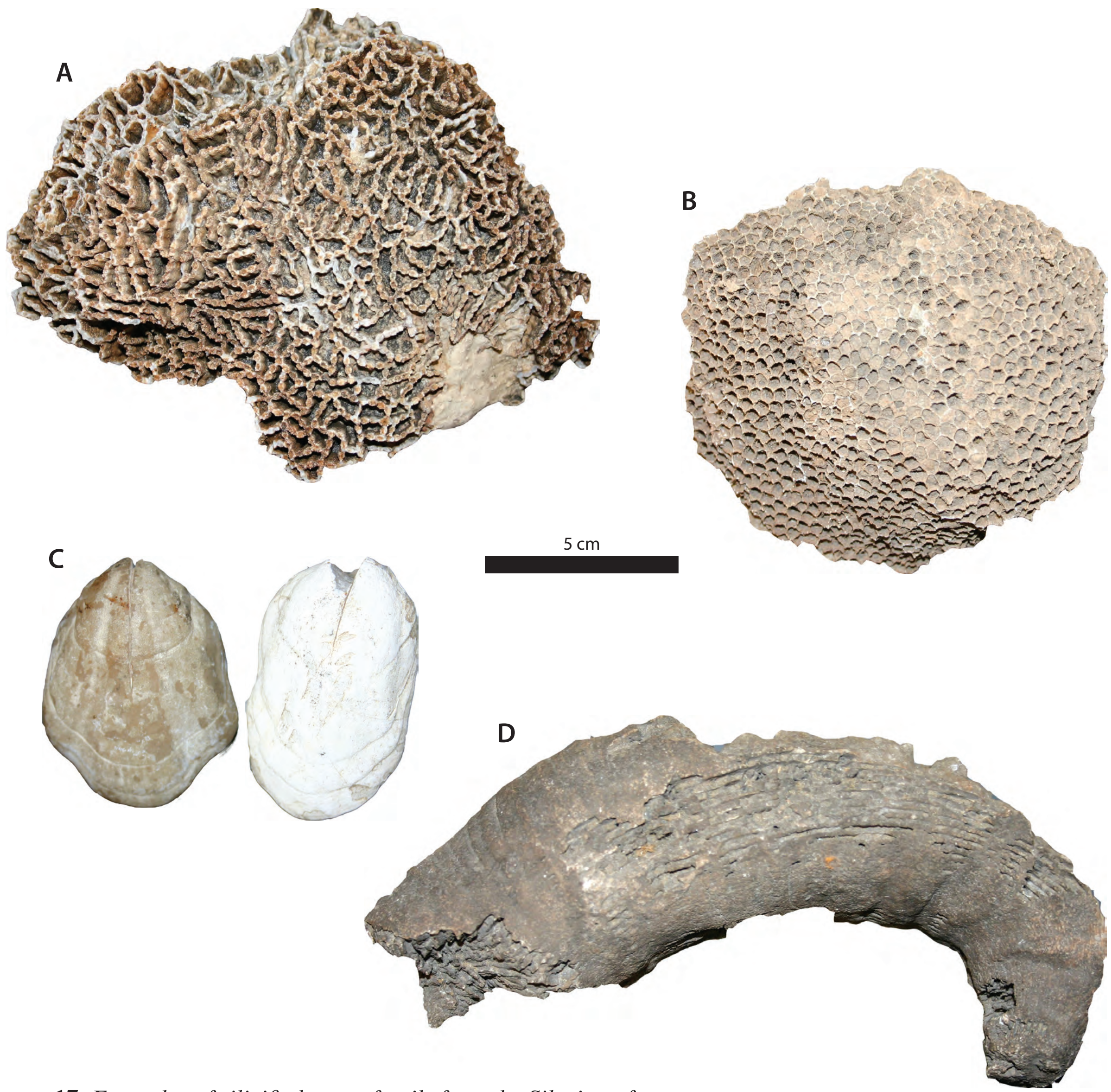

Figure 17. *Examples of silicified macrofossils from the Silurian of northeastern Wisconsin. A =* Halysites *(chain coral), B =* Favosites *(honeycomb coral), C = pentamerid brachiopods, D = large rugose coral.*

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.

ACKNOWLEDGEMENTS

Funding for a portion of the research presented here was provided by the U.S. Geologic Survey STATEMAP Program (grant numbers 09HQPA0003 and 10HQPA0003) and by the Wisconsin Geologic and Natural History Survey. I would like to thank the numerous quarry operators and land owners that allowed property access that has helped me better understand the rocks of the Niagara Escarpment corridor. Ron Stieglitz (editor), Eric Carson, Patrick McLaughlin, Esther Stewart, an anonymous reviewer, and Elizabeth Luczaj provided valuable comments on this manuscript. Daniel Holm, Eric Fowle, and Steven Dutch helped with additional information and graphics that have improved this manuscript. Peter Schoephoester, Mike Stiefvater, and Kevin Fermanich provided valuable help with GIS Imagery. UW-Green Bay students Andrea Duca, Lee Wilson, Lori Caelwaerts, Mike Rosinsky, Jena Winter, and Sarah Hunsicker assisted with field and lab work related to the Brown County bedrock mapping project, from which a part of this manuscript was derived. The Kansas Geological Survey was subcontracted to acquire seismic reflection data across the fault in southern Brown County.

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, midcontinent 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 groundwater 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.

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
GEOSCIENCE WISCONSIN • VOLUME 22, PART 2 • PUBLISHED ONLINE 2016

Processes that have shaped the Niagara Escarpment

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ABSTRACT

A diverse set of geomorphic or land-shaping processes acting on long-standing geologic and structural patterns have shaped the Niagara Escarpment. These processes vary in timescale, impact, and activity, and are frequently interrelated. The rocks of the landform were originally deposited in a subsiding basin in the Silurian sea and subsequently have been altered by climate and climate-dependent processes, such as running water, ice, groundwater, mass wasting, and the waves and currents of glacial and post-glacial lakes. The escarpment's form reflects the complex climatic and geological processes that have sculpted it over time.

INTRODUCTION

The Niagara Escarpment is the steep free-face portion of a larger physiographic feature known as a cuesta. That cliff-like landform owes its present form in Wisconsin to a wide range of geologic and land-shaping processes that are the subject of this paper. Some of the processes are still very much active and continue to modify the feature. Others are no longer operating but were important in the past. Many of the processes are gradational, that is they tend to break down and remove material and to cause retreat of the escarpment over time. A smaller number of processes are aggregational. That is, they tend to cause material to collect and thereby reduce the rate of cliff retreat.

INDEPENDENT VARIABLES

The shape and trend of the escarpment is broadly controlled by passive independent variables. These can be placed into two categories, regional geologic relationships, and the lithology and stratigraphic sequence of the rocks that form the escarpment. Luczaj (2013) has provided an excellent discussion of these elements. Regionally, the rock layers dip to the east and southeast into the Michigan geologic basin and their erosional edge is what we recognize as the escarpment (fig. 1). The properties of the rocks along the escarpment front influence the types and

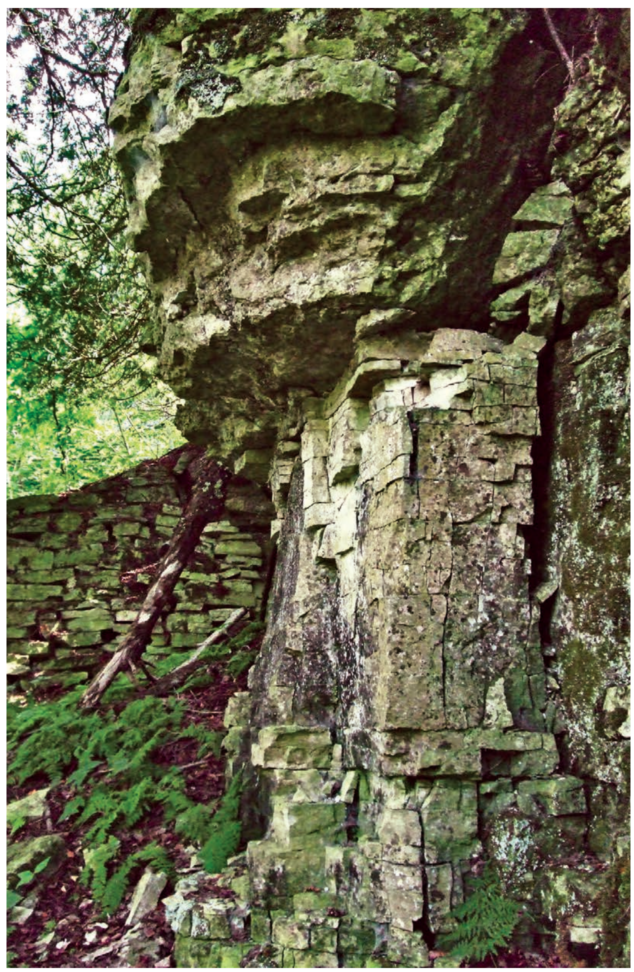

Figure 1. *Niagara Escarpment on Rock Island, Door County.*

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rates of the active processes that affect the landform. The soft weak shale of the Maquoketa Formation is easily erodible and under the proper conditions forms a slippage surface on which large blocks of the overlying dolostones slide away from the cliff face. Undercutting, an erosional process that removes the softer shale below the caprock, reduces support and increases instability. Thin-bedded and well-jointed dolostones are most unstable, and break down into thin flat blocks that fall to the base of the slope (fig. 2). More massive thick-bedded strata are more stable, yielding rectangular, sometimes large blocks (fig. 3).

A third independent, active variable is climate. Climate affects most, if not all, of the specific processes that result in the details of the escarpment in the landscape. Over geologic time, Wisconsin's climate has fluctuated dramatically. The region has experienced conditions ranging from the subtropical seas with coral reefs of the Silurian Period to the continental glaciers of the Pleistocene Epoch (Moran and Hopkins, 2002; Leavitt and others, 2006). Most important for the present appearance of the escarpment, however, are the shifts between humid temperate, glacial, and periglacial climates that have occurred multiple times over the most recent 2 million years known as the Quaternary Period.

Figure 2a. *Thin-bedded dolostone near Debroux Road in southern Door County.*

Figure 2b. *Platy talus from thin-bedded dolostone at Gardner Bluff in southern Door County.*

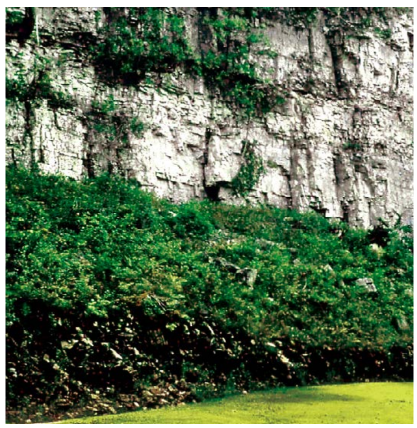


Figure 3a. *Thick-bedded dolostone at Alpine Resort Golf Course in Egg Harbor.*

Figure 3b. *Rectangular talus blocks at the Country House Resort in Sister Bay.*

Ronald Stieglitz (all 4 photos)

DEPENDENT VARIABLES

Many processes have played a role in shaping the escarpment's present form. Some of these processes were active in the distant past, some have been alternately active and inactive as conditions changed, and some remain active today. The specific magnitude and relative importance of each process is difficult to quantify, but they all played a part.

Inactive processes

Pre-glacial stream erosion

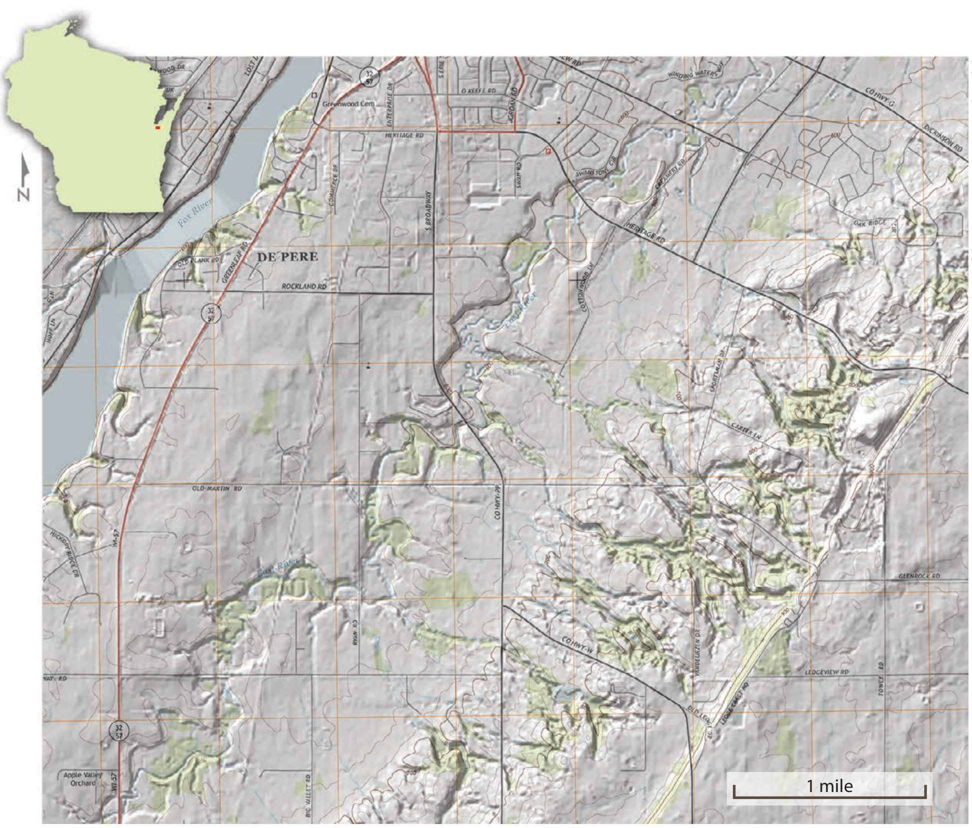
Following the deposition of the rocks that form the escarpment, an extended interval of continental weathering and erosion occurred long before the first glacial ice covered what is now Wisconsin. Pre-glacial erosion by now-disappeared stream systems was likely very significant. While it is difficult to assess how the effects of those events are preserved in the present landform, a number of geologists, including Martin ([1932] 1965), consider the northwest to southeast trending embayments or gaps known as re-entrants in the escarpment to reflect ancient drainage ways. If the re-entrants are remnants of pre-glacial drainage systems, they reflect significant modification of the escarpment by running water. Recently, Luczaj (2013) proposed that the drainage ways might be controlled by faults.

An interesting example of stream modification was reported by Stieglitz and Schuster (1993). In Egg Harbor Township in Door County, a dry channel can be traced toward the cliff where a series of bedrock steps mark its path across the escarpment. The feature occurs in a holokarst area—that is, an area where no surface drainage exists because water is quickly directed into the subsurface (Johnson and Stieglitz, 1990). When the channel formed, how long it carried water, and when it was abandoned is not clear.

Glaciers

Only deposits from the most recent glaciation occur in eastern Wisconsin. However, evidence from other locations indicates that ice repeatedly advanced over and retreated from the area between approximately 2 million and 10,000 years ago. The Pleistocene glaciers affected the escarpment primarily by erosion during advances, and appear to have been of major importance in shaping the outline of the feature. As the ice advanced along and over the escarpment, it incorporated loose material and plucked blocks of the bedrock by exploiting pre-existing lines of weakness such as joints and bedding planes. Straw (1968) discusses similar but more intense glacial erosion and re-entrant formation on the Niagara Escarpment in southern Ontario. Dutch (1980) suggested that Green Bay Lobe ice flowing southeastward into the re-entrants resulted in the noticeable curvature of the north side of some of the escarpment segments. The erosional effect of the ice might have been enhanced by differences in the dip direction of joints on opposite sides of the re-entrant. Dip inclinations of the high angle joints have not been mapped in detail along the escarpment, but Weissel and Seidl (1997) report that dip direction is important in shaping the walls of valleys in an Australian escarpment. Because it is impossible to document the former position of the escarpment, the amount of erosion cannot be quantified. However, it is reasonable to assume that glacial erosion shifted the face of the escarpment eastward.

Glacial deposition also occurred, primarily on the dip slope of the cuesta. Variable types and thicknesses of drift were deposited in the re-entrants, possibly during advances but certainly during retreats of the ice. Southeast of De Pere, Wisconsin, a strikingly straight stretch of the escarpment, some 6 to 7 miles long, was modified by glacial meltwater (fig. 4). Braided streams flowing between the escarpment and the melting ice in the Fox River lowland deposited a now-dissected apron of sand and gravel that contains talus near the escarpment and is mantled by younger colluvium. This segment has a form that is distinct from other reaches of the escarpment.



(Part of the De Pere 7.5-minute quadrangle.)

Figure 4. *Apron of sand and gravel near the escarpment, southeast of De Pere, Wisconsin (part of the De Pere 7.5-minute quadrangle).*

Late Pleistocene and Holocene lakes

Ronald Stieglitz

Figure 5. *Wave-cut platform clearly visible on Eagle Bluff, Peninsula State Park.*

Fluctuating water levels in the Lake Michigan basin helped shape the location of the escarpment. The history of the late Pleistocene and post-glacial lakes in the Lake Michigan basin is presented in detail by Larson and Schaetzl (2001). The water levels in those lakes were affected by the positions of the ice front, inlets to the system, the climate of the region, and the elevation of outlets controlled by erosion and the depression and rebound of the crust in response to loading and unloading by ice (Hansel and others, 1985; Hansel and Mickelson, 1988; Fraser, Larsen, and Hester, 1990; Clark and others, 1990, 1994).

While the specifics of the lake phases in the basin remain a subject of active research, several of them affected the escarpment. The highest and oldest shorelines in eastern Wisconsin are found in northern Door County (Schneider, 1989) and indicate that lake water encroached on the escarpment. Glacial rebound has raised the shoreline features of those lakes to their present positions with increasing elevations northward along a shoreline. The models put forth by Clark and others (1993) indicate that approximately 6,000 years ago the regional pattern shifted from uplift to subsidence, and that the relative changes of elevation result from slower subsidence to the north of the Door Peninsula. Those features might have been formed during either the Glenwood or Calumet lake phases as were those reported from Michigan by Taylor (1990) but their ages are uncertain.

When the most recent Wisconsin ice mass advanced down the Green Bay lowland and into what is now the Fox River Valley, ice blocked drainage to the north. As a result, water was impounded between the ice to the north, the escarpment to the east, and higher topography and older moraines to the west and south forming what is called Lake Oshkosh. Wielert (1980) describes the series of lake phases that stabilized as successively lower outlets were freed during the retreat of the ice. Water draining through the outlets across eastern Wisconsin into the Lake Michigan basin might have modified nearby escarpment reaches and increased local relief by removing some of the glacial sediments that filled the channels. Clark and others (2008) investigated the paleohydrology of Lake Oshkosh in response to post-glacial crustal adjustment.

About 11,000 years ago, as the ice retreated, glacial Lake Algonquin was formed by the confluence of what are now Lakes Superior, Michigan, and Huron (Hansel and others, 1985; Larsen, 1987). Wave-cut and wave-built shoreline features were formed on and along the escarpment on the Door Peninsula.

The subsequent deglaciation of the Lake Superior basin by about 9,000 years ago ended the glacial history of the Great Lakes Watershed (Larson and Schaetzl, 2001). With the ice gone, post-glacial crustal rebound raised the northeastern outlets of the Great Lakes system to elevations above those at the southern end of the basin resulting in another period of high lake levels (Hansel and others, 1985; Hansel and Mickelson, 1988). That body of water, called Lake Nipissing, reached its maximum extent about 5,000 to 4,000 years ago. Shoreline processes in Lake Nipissing modified the escarpment from northern Brown County to Washington Island. Waves cut into the cliff, forming platforms that can be clearly seen in profile across Eagle Harbor from the village of Ephraim (fig. 5) and at Sister Bay in Door County. Evidence of that lake can be closely viewed at Door Bluff and Ellison Bay Bluff County Parks, Peninsula State Park, and along the shoreline north of the Village of Sister Bay at the Country House resort (fig. 6). A remarkable series of about a dozen abandoned shorelines can be seen at Little Sister Bay inland from

Figure 6. *Second riser above present bay level from first wave-cut platform. Upper riser is visible through the trees.*

well-known Pebble Beach (Schneider, 1989). Each shoreline marks a period of stabilization as the system adjusted from the high stands of the Nipissing and Algoma levels, until essentially the present lake levels were established about 2,500 years ago. The maximum elevation reached during the Nipissing was approximately 7 m above that of the modern Lake Michigan. The shoreline features now occur at greater elevations, due to the post-glacial rebound of the crust.

Mass wasting during periglacial conditions

The face of the escarpment has always been affected by rock shattering and falls, except perhaps when it was mantled by ice. At other times, when the ice retreated but remained relatively nearby north and northwest of the escarpment, extremely cold conditions occurred with the formation of permanently frozen ground or permafrost. The term periglacial is used for those environmental conditions and the group of processes operating and features formed under those conditions. Periglacial features, apparently associated with the maximum of the Wisconsin Glaciation, have been long recognized in many places in Wisconsin (Black, 1964; Clayton and others, 2001).

Stieglitz and others (1980) present evidence for periglacial effects along the escarpment front in Brown County that might be associated with a limited readvance of ice about 9,000 years ago known as the Marquette advance. At several locations, thick accumulations of talus and colluvium mantle the escarpment forming a bench that fringes the feature. At Bay Shore Park, massive blocks of dolostone are tilted away from the cliff toward the shore (fig. 7). Movement of the blocks as units is called block glide and was initiated by the wedging of ice that formed in joints that parallel the cliff face. The blocks are now stable, but under periglacial

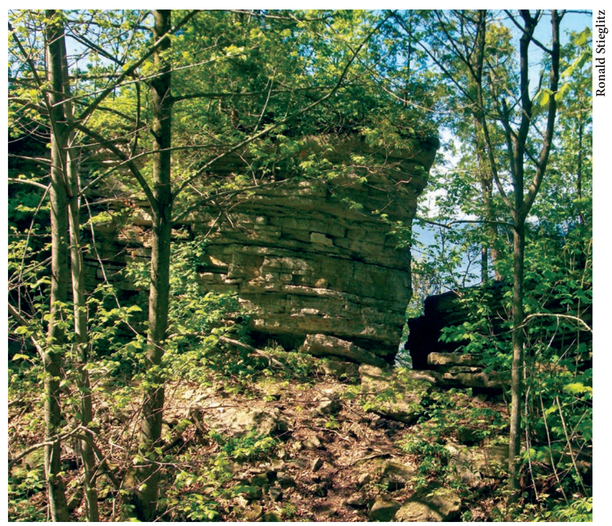


Figure 7. *View from escarpment of large isolated blocks with Green Bay in the background. Bay Shore Park, Brown County.*

conditions, movement took place along the contact with the underlying soft and less competent Maquoketa Formation. Gliding and tilting, perhaps aided by toe erosion and short periods of melting that produced water along the shale contact, continued until the blocks became unstable. Blocks overturned and disintegrated along bedding planes and joints to become part of the talus slope (fig. 8). Even back from the face of the cliff, several subparallel joints outline blocks that have shifted position relative to neighboring blocks. Straw (1966) and Hedges (1972) describe similar features from Ontario and Iowa, respectively. Hansel (1976) outlines a model of block gliding from a geologically and environmentally similar area in Iowa.

Another feature that apparently formed under periglacial conditions is a prominent trough-like low area between the escarpment and the talus called a protalus rampart (fig. 9). This landform can be observed at Bay Shore Park as well as in Section 4 T27N R25E in Nasewaupee Township in Door County. The feature cannot have formed directly by rock falls from the escarpment face because the fragments would have accumulated at the base of the cliff rather than meters away. The unusual feature suggests that rates of rock breakage and falls were much greater at some time in the past and that another factor or process affected the escarpment front. If rock breakdown operated at a rather constant rate, the talus slope should abut the cliff face at the angle of stability for the size and shape of the fragments rather than forming a trough and ridge pair. Demek (1969) suggested that such features would form where snow and ice collect against a cliff face for long periods of time. Rocks falling onto the snow and ice surface would slide away from the front and collect at some location lower on the slope. Such conditions would be expected during periglacial times.

"The unusual feature suggests that rates of rock breakage and falls were much greater at some time in the past…"

The trough and ridge features along the escarpment might also provide a clue to when block glide and talus production occurred. Stieglitz and others (1980) originally thought that the features originated after the most recent Greatlakean advance because they felt that an advance following the formation of talus would have removed the rocks. Subsequent work by Schneider (1993),

Ronald Stieglitz

Figure 8. *Tilted glide block separating along bedding planes at Bay Shore Park, Brown County.*

Figure 9a. *View from escarpment front across trough to protalus rampart. Bay Shore Park, Brown County.*

Figure 9b. *View along protalus rampart of talus. Note rounded appearance of some blocks from possible wave action in the past. Bay Shore Park, Brown County.*

Figure 10. *Faulted sand in pit along Scray Hill in Brown County.*

Clark and Ehlers (1993), and Clark and others (1994) suggests that Greatlakean ice was relatively thin and that it covered but did not significantly modify landforms. Periglacial conditions following the Port Huron retreat might have, in effect, frozen the talus in place, allowing thin ice to later override it with little alteration. Additional support for that possibility is found in Brown County where blocks of apparently frozen and faulted sands were exposed in aggregate pits in the escarpment apron along Scray Hill (fig. 10). It is also found in the Baird Creek valley where thin red till overlies undeformed outwash, suggesting that ice overrode the area while removing little, if any, sand and gravel.

Active processes

Weathering and erosive processes ranging from rock falls to groundwater solution are actively modifying the escarpment under current humid temperate climatic conditions. Similar processes certainly operated during the interglacial intervals in the past, but their rates and effects are impossible to quantify. For the most part, the roles that they had in shaping the escarpment as it appears today were secondary or overshadowed by glacial and periglacial processes. The processes active now, as in the past, are interrelated and interdependent: that is, the effects of one process often enhance or inhibit the rates and effects of others. In fact, often a variety of processes interact.

Chemical weathering

The most important chemical weathering agent is water. Rain and snow meltwater flows over, into, and through the dolostone caprock, exploiting and enlarging lines of weakness. Water flowing over the surface of exposed rock creates features of various scales and shapes that are collectively called karren. Infiltrating water produces interface features such as widened joints and sinkholes that connect the surface to the subsurface. Water flowing within the bedrock dissolves channels along bedding planes and caves. Small-scale runnels and pit karren occur on exposed rock faces. Solution-widened bedding planes and irregular tunnel-like features which result from focused discharge of groundwater are common along the escarpment front. While many appear to no longer transmit much water, some function as seasonal seeps and springs. Continued solution weakens the rock, making it more susceptible to mechanical breakdown and thereby enhancing escarpment retreat.

Figure 11. *Rock fall blocks along escarpment in Sister Bay.*

Mechanical weathering processes and mass wasting

Mechanical disintegration and mass wasting are closely associated. Freezing and thawing of water in joints and along bedding planes is an important breakdown process. Wedging by tree roots also plays a part in separating pieces from cliffs, although in some instances roots can also bind pieces in place. As the dolostone is broken into fragments and blocks, gravity drives the loosened material off of and away from the cliff face. Fragments fall to the base of the slope and remain there, or roll down the talus or colluvium slope until they attain a stable position (fig. 11). Rockfalls continue to occur along the cliff face, but the rate appears to be much reduced from that of the past as evidenced by thick accumulations of stable, tree-covered talus.

For the most part, the large blocks separated from, but adjacent to, the escarpment appear to be stable and not gliding; however, topples do occur. This type of movement takes place when a block of caprock separates from the cliff along a joint, pivots on its base, and falls as a unit. Undermining with loss of support can result from wave or stream action, or from the disintegration of a weak underlying layer due to weathering. A rather recent example can be found just west of the old bridge in Wequiock County Park in Brown County. Another even larger and more spectacular example is located along the Green Bay shore north of Fox Lane in Gardner Township in southwestern Door County (fig. 12).

Figure 12. *Disintegrated tumble block of thin-bedded strata along Gardner Bluff. Door County.*

Stream erosion

Luczaj (2013) notes that streams flowing westward across the escarpment to the Fox River lowland or Green Bay are rare, and he lists several in Brown County. Wequiock Creek in Brown County is an example of such a stream cutting a narrow valley into the escarpment. The caprock is being undermined as the underlying soft shale is weakened by groundwater seepage and eroded by the turbulence of the water in the plunge pool below a small waterfall.

A number of small westward-flowing streams occupy re-entrant lowlands in the escarpment. Examples are Ephraim Creek, Fish Creek, and Keys Creek in Door County. These are underfit streams that are too small for the valleys they are in and are not modifying the escarpment. South and east of DePere in Ledgeview and Rockland Townships, numerous small and often intermittent streams begin near the escarpment and continue westward to the East River. These streams do not affect the escarpment proper, but they have significantly dissected the outwash and colluvium apron or terrace at its base.

> "These are underfit streams that are too small for the valleys they are in…"

Wave erosion

There are only a few locations where waves and perhaps currents continue to affect the escarpment. Along most of its extent in eastern Wisconsin the escarpment is some distance from the shore of Green Bay and Lake Winnebago and therefore not under direct attack. The main effect of wave action, where it does occur, is to remove debris and prevent it from accumulating at the base of cliffs. The rock fragments are rounded as they are moved by waves and often concentrated in pebbles and cobblestone beaches. Some undercutting takes place along the shore of Green Bay in northern Door County, particularly during periods of high water in the Great Lakes system.

Human activities

Since the European settlement of Wisconsin, human activities have significantly altered the escarpment in many locations. Crushed stone is a commodity in high demand by the construction industry. The escarpment is attractive to quarry operators primarily because the rock is exposed at the surface and often there is little overburden to remove. Large abandoned quarries can be visited in High Cliff State Park in Calumet County, and at Old Stone Quarry Park near Sturgeon Bay in Door County. At both locations, multilevel excavations have changed the feature dramatically. At High Cliff most of the quarried stone was made into lime and shipped away by train, while stone of various sizes was produced at Old Stone Quarry Park for transport by ships and barges to other ports on the lake. Scray Hill in Brown County is the site of several large active crushed stone quarries. Additional active and abandoned quarries are located along the escarpment or nearby on the backslope of the cuesta.

Road construction also modifies the escarpment's topography. Many public roads and private driveways cross the escarpment to reach the Fox River Valley, the lowlands along Green Bay, or the shoreline. Examples abound, but an excellent one is at Bay Shore County Park in Brown County. There, a cut and fill through the escarpment and colluvium slope allows access to the bay for boat launching.

Finally, development along the extent of the Niagara Escarpment has greatly changed the character of the landscape. Houses, condominiums, resorts, golf courses, and wind turbines have been built on the top of or in front of the escarpment. Many of these can be seen not only from the top of the escarpment, but also from western lowlands and the waters of Lake Winnebago and Green Bay.

CONCLUSIONS

The Niagara Escarpment is an important component of the landscape of Wisconsin. The sweeping vistas visible from points on its crest and the magnificent views of cliffs seen from below are a much-loved part of Wisconsin's natural beauty. Much of what we see and experience today is the product of long-standing geologic patterns and past inactive processes as well as processes that are modifying it today. Some changes occur slowly, as frost and groundwater work on the rocks, while other changes are almost instantaneous, as when a dynamite blast brings down a quarry wall. As a result, the escarpment is dynamic and ever changing.

REFERENCES CITED

Black, R.F., 1964, Periglacial phenomena of Wisconsin, north-central United States: 6th International Congress on Quaternary Research, v. 4, p. 21–27.

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, U.S.A: *Quaternary Research*, v. 69, p. 117–129.

Clark, J.A., and Ehlers, T.A., 1993, Glacial isostasy of the Door Peninsula, Wisconsin, *in* Schneider, A.F., ed., Pleistocene geomorphology and stratigraphy of the Door Peninsula, Wisconsin: 40th Annual Meeting, Midwest Friends of the Pleistocene, p. 31–36.

Clark, J.A., Hendriks, M., Timmerman, T.J., Struck, C., and Hilverda, K.J., 1994, Glacial isostatic deformation of the Great Lakes region: *Geological Society of America Bulletin*, v. 106, p. 19–31.

Clark, J.A., Pranger, H.S., II, Walsh, J.K., and Primus, J.A., 1990, A numerical model of glacial isostasy in the Lake Michigan basin, *in* Schneider, A.F., and Fraser, G.S., eds., Late Quaternary history of the Lake Michigan basin: Geological Society of America Special Paper 251, p.111–123.

Clayton, L., Attig, J.W., and Mickelson, D.M., 2001, Effects of late Pleistocene permafrost on the landscape of Wisconsin, USA: *Boreas*, v. 30, p. 173–188.

Demek, J., 1969, Importance of slope deposits in the study of landscape development, *in* Wright, H.E., ed., Quaternary geology and climate: Washington, D.C., Proceedings of the VII Congress of the International Association for Quaternary Research, National Academy of Science, v. 16, p. 130–133.

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.

Fraser, G.S., Larsen, C.E., and Hester, N.C., 1990, Climate control of lake levels in the Lake Michigan and Lake Huron basins, *in* Schneider, A.F., and Fraser, G.S., eds., Late Quaternary history of the Lake Michigan basin: Geological Society of America Special Paper 251, p. 75–90.

Hansel, A.K., 1976, Mechanically induced karst development along the Silurian Escarpment in northeastern Iowa: Cedar Falls, Iowa, University of Northern Iowa, M.S. thesis, 102 p.

Hansel, A.K., and Mickelson, D.M., 1988, A reevaluation of the timing and causes of high lake phases in the Lake Michigan basin: *Quaternary Research*, v. 29, p. 113–128.

Hansel, A.K., Mickelson, D.M., Schneider, A.F., and Larsen, C.E., 1985, Late Wisconsinan and Holocene history of the Lake Michigan Basin, *in* Karrow, P.F., and Calkin, P.E., eds., Quaternary evolution of the Great Lakes: Geological Association of Canada Special Paper 30, p. 39–53.

Hedges, J., 1972, Expanded joints and other periglacial phenomena along the Niagara Escarpment: *Biuletyn Peryglacjalny*, no. 21, p. 87–126.

Johnson, S.B., and Stieglitz, R.D., 1990, Karst features of a glaciated dolomite peninsula, Door County, Wisconsin: *Geomorphology*, v. 4, p. 37–54.

Larsen, C.E., 1987, Geological history of glacial Lake Algonquin and the Upper Great Lakes: U.S. Geological Survey Bulletin 1801, 36 p.

Larson, G., and Schaetzl, R., 2001, Origin and evolution of the Great Lakes: *Journal of Great Lakes Research*, v. 27, p. 518–526.

Leavitt, S.W., Panyushkina, I.R., Lange, T., Wiedenhoeft, A., Cheng, L., Hunter, R.D., Houghes, J., Pranschke, F., Schneider, A.F., Moran, J., and Stieglitz, R., 2006, Climate in the Great Lakes region between 14,000 and 4,000 years ago from isotopic composition of conifer wood: *Radiocarbon*, v. 48, no. 2, p. 205–217.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin*, v. 22, no. 1, 34 p.

Martin, L., 1965, The physical geography of Wisconsin (3rd ed.): Madison, Wis., University of Wisconsin Press, 636 p.

Moran, J., and Hopkins, E., 2002, Wisconsin's weather and climate: Madison, Wis., University of Wisconsin Press, 321 p.

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

Schneider, A.F., 1993, Till stratigraphy and late glacial sequence of the northern Door Peninsula, Wisconsin, *in* Schneider, A.F., ed., Pleistocene geomorphology and stratigraphy of the Door Peninsula, Wisconsin: 40th Annual Meeting, Midwest Friends of the Pleistocene, p. 37–46.

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

Stieglitz, R.D., and Schuster, W.E., 1993, Glaciation and karst features of the Door Peninsula, Wisconsin, *in* Schneider, A.F., ed., Pleistocene geomorphology and stratigraphy of the Door Peninsula, Wisconsin: 40th Annual Meeting, Midwest Friends of the Pleistocene, p. 47–52.

Straw, A., 1966, Periglacial mass-movement on the Niagara Escarpment near Meaford, Grey County, Ontario: *Geographical Bulletin*, v. VIII, no. 4, p. 369-376.

Straw, A., 1968, Late-Pleistocene glacial erosion along the Niagara Escarpment of southern Ontario: *Geological Society of America Bulletin*, v. 79, p. 889–910.

Taylor, L.D., 1990, Evidence for high glacial-lake levels in the northeastern Lake Michigan basin and their relation to Glenwood and Calumet phases of glacial Lake Chicago, *in* Schneider, A.F., and Fraser, G.S., eds., Late Quaternary history of the Lake Michigan basin: Geological Society of America Special Paper 251, p. 91–110.

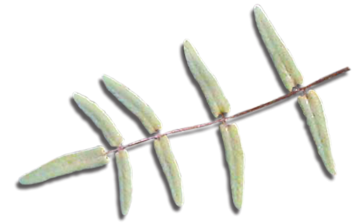
Weissel, J.K., and Seidl, M.A., 1997, Influence of rock strength properties on escarpment retreat across passive continental margins: *Geology*, v. 25, p. 631–634.

Wielert, J.S., 1980, The Late Wisconsinan glacial lakes of the Fox River watershed, Wisconsin: *Wisconsin Academy of Sciences, Arts, and Letters*, v. 68, p. 188–201.

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

GEOSCIENCE WISCONSIN • VOLUME 22, PART 3 • PUBLISHED ONLINE 2016

Biota of Wisconsin’s Niagara Escarpment



Robert W. Howe,[1] Amy T. Wolf,[1] and Gary A. Fewless[1]

ABSTRACT

The physical attributes of the Niagara Escarpment provide unique microhabitats for animals and plants, contributing to Wisconsin’s biological diversity at multiple scales. Within the predominantly forested landscape that existed before European settlement, dens and caves provided shelter for wide-ranging animals like reptiles, bats, and terrestrial mammals. Changes in the surrounding landscape have led to the regional loss of many of these species, but ecologically significant caves and denning habitats still exist in protected areas along the escarpment. On a more local scale, rock cliffs and associated features of the escarpment provide home for rare plants, ancient trees, and a rich assemblage of land snails, including relicts of post-glacial environments that have otherwise long disappeared from the region. Despite its obvious prominence as a geologic feature, the ecological significance of the Niagara Escarpment has only recently been demonstrated. Few of these studies of the escarpment’s biota have been conducted in Wisconsin. However, careful studies of land snails during the 1990s suggest that future investigations of other taxa (especially invertebrates) will lead to new discoveries about the ecology and conservation value of the Wisconsin’s Niagara Escarpment.

Recent studies have revealed a unique biota that deserves wider attention and increased conservation efforts, and our goal is to evaluate the biological significance of the Niagara Escarpment in Wisconsin and to help identify conservation needs and gaps in our current knowledge.

INTRODUCTION

In addition to its geologic and cultural significance, the Niagara Escarpment has helped sustain some of Wisconsin’s most interesting and mysterious plants and animals. In several cases, significant populations have been discovered only recently, suggesting that future research might reveal additional species or ecological interactions that are linked to the escarpment’s unique geology and microclimate. Destruction and degradation of native habitats, in addition to other factors, have led to the disappearance of wider-ranging species that once used the escarpment regularly. Nevertheless, the escarpment remains a significant ecological element in eastern Wisconsin; in fact, some of the little-known species found on the Niagara Escarpment are regionally and even globally significant.

Paleoecological studies from Ontario (Yu, 2003) and Wisconsin (Rech and others, 2012) have shown that after Pleistocene glaciation the region encompassing the Niagara Escarpment was characterized by a tundra-taiga landscape. By about 12,000 to 10,000 years ago, shrubby boreal habitats dominated by alder (*Alnus*), willow (*Salix*), and cedar (*Juniperus*) had given way to forests dominated by spruce (*Picea*) and, later, pine (*Pinus*). Mixed forests of eastern hemlock (*Tsuga*) and hardwoods such as beech (*Fagus*) and elm (*Ulmus*) became prominent by about 7,500 years ago and have persisted until modern times. Plants and animals of the escarpment have been drawn from these varying regional biotas, in some cases forming unique combinations of species

“…some of the little-known species found on the Niagara Escarpment are regionally and even globally significant.”

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from ancient environments and more recent landscapes. In this paper we describe some of the most prominent and special species that can be found in and near the Niagara Escarpment.

THE NIAGARA ESCARPMENT AS A LANDSCAPE FEATURE

Except for dramatic cliffs along the Green Bay shoreline in Door County and several other places such as High Cliff State Park in Calumet County, the Niagara Escarpment in Wisconsin is a narrow and relatively inconspicuous geologic feature embedded in a glacially derived landscape of till plains, moraines, and lake basins.

Before settlement, most of this landscape was forested, supporting a typical eastern North American flora and fauna of mesic deciduous forests and oak savannas. Any discussion of the animals and plants of the escarpment must consider the influence of this surrounding landscape. Biotic influences include the day-to-day movements of individual animals as well as the large-scale population dynamics of species that occur on both the escarpment and in the surrounding landscape.

Today, many of the forests and savannas of eastern Wisconsin have been fragmented or replaced by agricultural and urban land uses (Flader, 1983; Waller and Rooney, 2008). Unsurprisingly, these changes have influenced the composition of animal and plant populations on the Niagara Escarpment itself. Likewise, the ecological features associated with the escarpment (den sites, forest corridor, etc.) influence animal and perhaps plant populations in the surrounding landscape.

PLANTS OF THE NIAGARA ESCARPMENT

Several hundred species of vascular plants are clearly associated with the Niagara Escarpment in Wisconsin, and the number grows quickly if we include habitats that are influenced locally by the escarpment. The most consistently conspicuous species of the Wisconsin escarpment is northern white cedar (*Thuja occidentalis*), which often occurs above the cliffs as well as in cracks and ledges on the cliffs and at the base of the cliffs below the talus slope. In some cases, tall individuals of white pine (*Pinus strobus*) and red pine (*Pinus resinosa*) are present along the top of cliffs; a variety of somewhat dry forest habitats also may occur near the upper part of the escarpment. Paper birch (*Betula papyrifera*) is often conspicuous above and below the cliffs. In a very few locations, the rapidly disappearing Canada yew (*Taxus canadensis*) is abundant. On shaded cliff faces and especially on the talus slopes below, dense growths of bulblet fern (*Cystopteris bulbifera*) and the shrubs mountain maple (*Acer spicatum*) and red elderberry (*Sambucus racemosa*) are often prominent. A substantial number of native ferns can be found on cliff faces and associated boulders and talus slopes.

Studies of the Niagara Escarpment in southern Ontario have described the fascinating old-growth vegetation of cliffs (Larson and others, 1989; Larson and Kelly, 1991). Plant communities associated with the escarpment cover a physical gradient ranging from the exposed plateau at the top of the cliff to shady talus deposits at the base. The rocky cliffs themselves harbor ancient trees of wide-ranging species like northern white cedar and eastern red cedar (*Juniperus virginiana*), as well as locally rare or uncommon plant species like the maidenhair spleenwort (*Asplenium trichomanes*), dwarf cliff brake (*Pellaea glabella*, fig. 1), and bird's-eye primula (*Primula mistassinica*) (Larson and others, 1999b). Other more familiar plant species like Canada columbine (*Aquilegia canadensis*, fig. 2) and the fern *Polypodium virginianum* (fig. 3) thrive along the rocky cliff faces and outcrops associated with the Niagara Escarpment. Distinct assemblages of bryophytes, epilithic (rock-attached) lichens, and endolithic (within rock) algae and cyanobacteria have also been documented from cliffs of the Niagara Escarpment in Canada (Cox and Larson, 1992; Gerrath and others, 2000; and Matthes and others, 2000).

Trees and shrubs along Niagara Escarpment cliffs represent an often-overlooked old growth community type associated with rugged rock faces throughout the world (Larson and others, 1999, 2000). In the steepest cliffs of Wisconsin's Niagara Escarpment, stunted, slow-growing northern white cedar, eastern red cedar, and other tree species can persist for hundreds, sometimes thousands, of years. Cliff height, aspect, and rock type are not significantly correlated with the presence of ancient cliff woodlands; the primary factor in maintaining these unique communities appears to be simply imperviousness to human disturbance and fire (Larson and others, 2000). Likewise, uncommon Wisconsin plants like Canada yew are able to grow locally along Niagara Escarpment despite widespread range reductions elsewhere due to browsing by white-tailed deer (*Odocoileus virginianus*) and domestic animals. Larson, Matthes-Sears, and Kelly (1999), whose studies began at the Niagara Escarpment of Ontario, maintain that extensive cliff outcrops, including portions

> "In the steepest cliffs of Wisconsin's Niagara Escarpment…tree species can persist for hundreds, sometimes thousands, of years."

of the escarpment in eastern Wisconsin, support some of the most ancient and least-disturbed wooded habitats on Earth.

In Wisconsin, several rare or uncommon forbs are known primarily from the Niagara Escarpment, including two rare members of the Brassicaceae (mustard family), rock whitlow-grass, *Draba arabisans*, and hoary whitlow-cress, *D. cana*. Rock whitlow-grass occurs on exposed dolomite cliffs, especially in shady forests dominated by northern white cedar. This small perennial is native from eastern Canada to New York, westward to Minnesota (Voss, 1985; Penskar and Crispin, 2008). It has been designated a species of special concern by the state. Hoary whitlow-cress is a plant of the North American arctic and alpine habitats in western North America, occasionally found in northern states of the eastern U.S. (Al-Shehbaz, 2010). In Wisconsin, this species is found only in Door County and has been designated endangered by the state. Other Wisconsin rare species occurring on the Niagara Escarpment include limestone oak fern (*Gymnocarpium robertianum*) and Allegheny-vine (*Adlumia fungosa*). If we include wet and dry habitats of shallow soil over the Niagaran rocks, we can add to this list species such as elk sedge (*Carex garberi*), small-flowered grass-of-parnassus (*Parnassia parviflora*) and spoon-leaf moonwort (*Botrychium spathulatum*), a species known in Wisconsin from only a

Figure 1. *Dwarf cliff brake (*Pellaea glabella*) is characteristic of rocky habitats along the Niagara Escarpment in eastern Wisconsin.*

Figure 2. *Flower of Canada columbine (*Aquilegia canadensis*), a widespread plant that is common in slopes and forest openings of the Niagara Escarpment.*

Figure 3. *The fern,* Polypodium virginianum*, is tolerant of periodic drying (Reynolds and Bewley, 1993) making it well adapted to rock outcrops associated with the Niagara Escarpment.*

single location in Door County. Other uncommon but more widely distributed species such as small white lady's slipper (*Cypripedium candidum*), snow trillium (*Trillium nivale*), and low calamint (*Calamintha arkansana*) also occur on the calcareous substrates associated with the Niagara Escarpment (Anderson and others, 2002).

ANIMALS OF THE NIAGARA ESCARPMENT

Animals associated with the escarpment can be grouped into two general categories: (1) wide-ranging species that use the escarpment seasonally or temporarily for shelter or feeding and (2) small animals or micro-organisms that are permanent residents in the unique microhabitats of the escarpment. Not surprisingly, species in the latter category are relatively unnoticed by the general public and some may even await discovery.

Bats are probably the clearest examples of animals that use the Niagara Escarpment for part of their daily or seasonal activity schedule. At least four of Wisconsin's bats (little brown myotis, *Myotis lucifigus*; northern long-eared myotis, *Myotis septentrionalis*; big brown bat, *Eptesicus fuscus*; and tri-colored bat, *Perimyotis subflavus*) inhabit caves as roost sites or winter hibernacula (Barbour and Davis, 1969; Kurta, 1995; Tuttle and Taylor, 1998). At the Neda Mine in Dodge County, an estimated 150,000 to 200,000 individuals of these four species use the mine as an overwintering refuge, making it one of the largest (if not the single largest) bat hibernacula in the Midwest. The mine opens on an exposure of the Niagara Escarpment that is today a designated Wisconsin State Natural Area. Although this feature was created by human excavation of the Iron Ridge/Neda iron formation in the late 1800s and early 1900s (Frederick, 1993), the concentration of bats demonstrates the regional significance of caves for bat populations (Tuttle and Taylor, 1998). The Niagara Escarpment supports the largest number of underground caves in Wisconsin (Kluessendorf, 2010), and bats undoubtedly use many of these caves for roosting and overwintering. Along its entire length, the Niagara Escarpment is likely a major contributor to bat populations in Wisconsin and nearby states. The emergence of white-nose syndrome in bats of eastern North America (Blehert and others, 2009) underscores the importance of multiple bat roosting sites for conserving bat populations.

Other Wisconsin mammals use caves and crevices for shelter (for example, Fitch and Shirer, 1970; Weller and Pelton, 1987; Endres and Smith, 1993; Kurta, 1995). Bobcats (*Lynx rufus*), for example, frequently use rock outcrops as den or resting sites (Bailey, 1974; Anderson, 1990), although rocky habitats like those associated with the Niagara Escarpment are only used temporarily and individuals are able to survive and reproduce in the absences of rocky shelters (Kolowski and Woolf, 2002). Mammal species that have been shown to use rock crevices and caves when available include Virginia opossum (*Didelphis virginiana*), eastern chipmunk (*Tamias striatus*), porcupine (*Erethizon dorsatum*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), gray fox (*Urocyon cinereoargenteus*), and black bear (*Ursus americanus*). Like bobcats, these species undoubtedly use or have used caves and crevices of the Niagara Escarpment. Indeed, rocky crevices and small caves of the Niagara Escarpment might be more important than ever because alternative denning sites like hollow logs, large stumps, and tree cavities are less common than they were before the replacement of old growth forest by agricultural land and secondary forests (Frelich, 1995). No comprehensive study has explored the importance of the Niagara Escarpment as a refuge for non-flying mammals. Nevertheless, use of denning sites along the escarpment is dependent on the availability of other habitats nearby. The rugged terrain of the escarpment has largely prohibited certain land uses like farming, but the width of the natural corridor and land use in the adjacent landscape might be the most important factor in determining the mammal fauna associated with the Niagara Escarpment today.

The availability of nearby habitats is likely even more important for birds, which can easily fly to and from distant feeding or roosting areas. Two bird species, turkey vulture (*Cathartes aura*) and peregrine falcon (*Falco peregrinus*), use the Niagara Escarpment for nesting. Mossman (2006) noted that about half of the turkey vulture nests reported during the Wisconsin Breeding Bird Atlas survey were located in rock outcroppings, including sites along the Niagara Escarpment. Turkey vultures fly great distances from their nests for feeding, so the importance of places like the Niagara Escarpment for this species can be easily overlooked. Peregrine falcons no longer nest on cliffs of the Niagara Escarpment in Wisconsin, although historical records document peregrine nesting on the steep cliffs in Door County (Septon, 2006). As populations of this

Figure 4. *Red-backed salamander (*Plethodon cinereus*), a common inhabitant of forested habitats along the Niagara Escarpment in Wisconsin.*

species continue to recover in eastern North America, re-establishment of nesting sites in Door County cliffs are possible, if not likely.

Specialized cliff-nesting species like cliff swallow (*Petrochelidon pyrrhonata*) now make extensive use of human-made structures for nesting, although even today 11 percent of the cliff swallow nests reported in the Wisconsin Breeding Bird Atlas were located on natural cliffs (Davis and Davis, 2006). Common raven (*Corvus corax*), red-tailed hawk (*Buteo jamaicensis*), and great horned owl (*Bubo virginianus*) occasionally use cliffs for nesting (Watts, 2006), but the large majority of the nests of these species are located in trees.

Matheson and Larson (1998) conducted a community-level analysis of bird assemblages along the Niagara Escarpment in Ontario, Canada. The escarpment provides natural edge-related habitats and microhabitats that are atypical in continuous forest landscapes of the region. Consequently, species like eastern phoebe (*Sayornis phoebe*), warbling vireo (*Vireo gilvus*), cliff swallow, winter wren (*Troglodytes hiemalis*), and dark-eyed junco (*Junco hyemalis*) are present, leading to higher species richness than in typical forests of Ontario. Matheson and Larson recognized four habitat zones associated with the escarpment: plateau, cliff edge, cliff face, and talus slope, the last three occurring on the escarpment itself. Overall, the three escarpment zones yielded higher species richness than the adjacent plateau forest. At the same time, birds of forest interior were present in the vicinity of cliffs, suggesting that the negative effects of forest edge (Yahner, 1988) do not necessarily apply to openings associated with Niagara Escarpment cliff faces. Matheson and Larson concluded that the Niagara Escarpment provides habitat qualities that are not found in adjacent closed-canopy forests, while at the same time causing no significant negative effects on forest interior species.

Whereas birds and mammals typically include the Niagara Escarpment as only a small (but often important) portion of their home range, less mobile animals like reptiles, amphibians, and invertebrates rely more continuously on the rocky habitats for day-to-day activities. Several species of snakes use rocky crevices and talus along the escarpment for winter hibernacula and for temporary shelter throughout the year, especially in the vicinity of open habitats. Eastern garter snake (*Thamnophis sirtalis*), eastern milk snake (*Lampropeltis triangulum*), northern ring-necked snake (*Diadophis punctatus edwardsii*), northern red-bellied snake (*Storeria occipitomaculata*), DeKay's brown snake (*Storeria dekayi*), and western fox snake (*Elaphe vulpina*) have been observed by us or reported by others in rocky habitats along the Niagara Escarpment. The venomous timber rattlesnake (*Crotalus horridus*) once occurred on the Niagara Escarpment in Ontario (Environment Canada, 2010) and probably also lived along the Escarpment in Wisconsin, although no documentation exists.

Forested talus slopes along the Niagara Escarpment provide ideal habitat for red-backed salamanders (*Plethodon cinereus*, fig. 4) and other animals that live in moist soil under leaf litter, rocks, and debris. A large population of red-backed salamanders lives in the vicinity of the Niagara Escarpment in Brown County and probably along the entire length of the escarpment in Wisconsin. Ongoing studies by students at the University of Wisconsin-Green Bay have shown that salamander populations are much higher in the vicinity of rocky outcrops along the escarpment than in the surrounding forest. Perhaps like many other escarpment-associated animal species, salamander numbers vary seasonally and respond to local weather conditions.

Spring-fed ponds at the base of the Niagara Escarpment in eastern Wisconsin support isolated populations of blue-spotted salamander (*Ambystoma laterale*) and other species of interest such as fairy shrimp (*Eubranchipus* sp.) and frogs (spring peeper, *Pseudacris crucifer*, for example). Relatively undisturbed vernal ponds have become rare in Wisconsin (Reinartz, 2003; Jass and Klausmeier, 2006), so these habitats, fairly common below some segments of the Niagara Escarpment, deserve future research and protection efforts.

Perhaps the most interesting element of Wisconsin's Niagara Escarpment biota is the unique assemblage of land snails that have been described in a number of papers, including Nekola, Smith, and Frest (1996), Nekola and Smith (1999), and Nekola (2003). Initially reported in unpublished reports and conservation assessments, Frest and later Nekola led surveys to document extant populations of rare Upper Midwest land snails, some of which were known previously only as Pleistocene fossils or from widely disjunct montane/boreal regions (Nekola 1999a; Ostlie, unpub. report). Like relict snails of northern Eurasia (Horsák and others, 2010), a unique assemblage of land snails in North America once inhabited cool, moist environments near the margins of Pleistocene glaciers (Kuchta, 2009). Since the retreat of the glaciers, beginning approximately 18,000 years ago (Pielou, 1991), many Midwestern snail populations became extinct or retreated to highly localized microhabitats. For example, in the Paleozoic Plateau of northeastern Iowa and adjacent parts of Minnesota, Wisconsin, and Illinois, algific (cold-producing) talus slopes provide cold airflow from subterranean ice that persists throughout the year (Howe, 1984; Nekola, 1999b). These slopes provide microenvironments for otherwise out-of-place plants and animals such as the boreal plant, *Chrysosplenium iowense* (Levsen and Mort, 2008), and the federally endangered land snail, *Discus macclintocki* (Ross, 1999).

During the 1990s Nekola and students from the University of Wisconsin–Green Bay discovered populations of Pleistocene relict land snails and a wide variety of other snail species (fig. 5) along the Niagara Escarpment in Brown and Door Counties of northeastern Wisconsin (Nekola and others, 1996; Nekola and Smith, 1999). In their initial report, Nekola and others (1996) documented 12 notable land snail taxa (subspecies, species, or species groups) at study sites associated with the Niagara Escarpment (table 1). Subsequent studies (Nekola, 2003; Nekola and Coles, 2010; Ostlie, unpub. report) have re-interpreted these findings based on new field data and more detailed taxonomic analyses, but the significance of the Niagara Escarpment for land snails has not been diminished. In fact, the disjunct distribution of rare snail populations along the Niagara Escarpment in northeastern Wisconsin suggests that they have experienced a unique postglacial history that is mostly, if not entirely, independent of land snail populations in the Paleozoic Plateau of southwestern Wisconsin and nearby states.

Figure 5. Zonitoides arboreus*, a common land snail found along the Niagara Escarpment in northeastern Wisconsin. Rarer species, typically smaller than this snail, were documented along Wisconsin's Niagara Escarpment by Jeffrey Nekola and students in the 1990s.*

"…Nekola and students from the University of Wisconsin–Green Bay discovered populations of Pleistocene relict land snails…"

Land snail distributions (Hubricht, 1985, Nekola, 2003) underscore the ecological importance of the Niagara Escarpment. Nekola and Smith (1999) reported extremely high species richness of snails along the Niagara Escarpment, reaching 21 species per square meter at one site (Nekola and Smith, 1999). Richness was significantly greater near the base of the cliff, especially at undisturbed, forested localities. Cliffs of the Niagara Escarpment in Wisconsin lack the cold-air circulation patterns of algific

Table 1. Unique or relict land snails along the Niagara Escarpment of the Door Peninsula in northeastern Wisconsin.

Scientific name	Habitat and range	Notes
Carychium exile canadense	Present in cliff communities in Brown and Door Counties. This subspecies is locally distributed in northern states (Hubricht, 1985); *C. exile* species is considered common in deciduous forest leaf litter in much of eastern North America (Lewis, 2002).	
Catinella gelida	Dry areas of algific talus slopes and cold cliff micro-habitats. Found at a single Brown County study site, where it is common. Also present in northeastern Iowa and Black Hills of South Dakota.	State status:[a] special concern. Rare glacial relict. Shell characteristics are distinctive. Discovered by Frest in northeastern Iowa in 1983.
Gastrocopta corticaria	Limited to rock outcrops. Found locally on ledges and wooded calcareous outcrops across much of eastern North America, including eastern Wisconsin south from Door Peninsula.	
Hendersonia occulta	Found in algific talus slopes or cool, forested rock outcrops and cliffs. Known from numerous localities near western Lake Michigan shore.	State status:[a] threatened. Glacial relict. Common as a fossil in central U.S.
Paravitrea multidentata	Limited to rock outcrops and upland forests. Rare in Wisconsin but fairly widespread in eastern North America.	State status:[a] special concern. Reported from 68 sites by Nekola (2003), primarily in Door County.
Striatura exigua	Mesic forest species. Fairly widespread in northeastern North America.	State status:[a] special concern. Reported from 70 sites by Nekola (2003).
Striatura ferrea	Found in forests, especially in lowlands. Widespread in northeastern Wisconsin and eastern Upper Peninsula of Michigan.	State status:[a] special concern.
Succinea bakeri	Habitat and range uncertain (see note).	Glacial relict. Taxonomy of this group is notoriously problematic. Early identifications from Niagara Escarpment might have been incorrect (Ostlie, unpub. report)—specimens probably not *S. bakeri*, which is otherwise known only from Pleistocene fossils.
Vallonia cyclophorella	Primarily found in dry conifer forests of western U.S. (Hendricks, 2012).	Glacial relict.
Vertigo bollesiana	Found in rock outcrops in moist forests of Door Peninsula. Nekola (2003) reported this species from 73 stations in Door County and eastern Wisconsin and the eastern Upper Peninsula of Michigan. Also found locally but widely in northeastern North America.	
Vertigo hubrichti group	Found in cool microclimates in leaf litter, especially in northern white cedar forests. Found widely on rock outcrops of Door Peninsula and at about 50 sites on Paleozoic Plateau of southwestern Wisconsin and adjacent states. Also reported from scattered localities in eastern Canada along Niagara Escarpment.	State status:[a] endangered. Originally described as a Pleistocene fossil.
Vertigo pygmaea	Found in a variety of habitats including roadsides and disturbed grasslands (Nekola, 2003). Fairly widespread in northeastern North America.	Some populations may have been introduced from Europe (Nekola and Coles, 2010).

[a]State status (protection categories designated by the Wisconsin DNR): **Endangered** = species whose continued existence in Wisconsin is in jeopardy; **threatened** = species which appears likely to become endangered within the foreseeable future; **special concern** = species about which some problem of abundance or distribution is suspected but not yet proven.

talus slopes from the Paleozoic Plateau of northeastern Iowa and nearby parts of Minnesota, Wisconsin, and Illinois (Howe, 1984; Nekola, 1999b), but the effects of shade, aspect, and climate amelioration by Lake Michigan might combine to favor the persistence of relict land snails and other small organisms (Nekola, 1999b). Frest and Johannes (unpub. report) attributed the biological significance of the Niagara Escarpment and nearby habitats to special microclimatic conditions of soil, temperature, and relative humidity, influenced significantly by proximity to a large lake (Ostlie, unpub. report). The importance of these local microclimate conditions to other organisms deserves further study.

CONCLUSION

The Niagara Escarpment is important to plants and animals at multiple scales. The rugged topography and shallow soils have helped protect forest and natural habitats from intense development, benefitting both wide-ranging and local species. On a smaller scale, microhabitats associated with north- or northwest-facing rock outcrops along the escarpment, perhaps further influenced by the climatic effects of Lake Michigan, have created cool, moist conditions that harbor unique species like Pleistocene relict land snails and perhaps undiscovered populations of other rare taxa. Efforts to protect these habitats and microhabitats are important. The cliff faces, in particular, are sensitive to disturbance and should be a high priority for careful management. Hiking and rock climbing activities concentrated at the base of the cliffs can be particularly damaging (McMillan and others, 2003). Other priorities that will help sustain populations of unique Niagara Escarpment plants and animals include maintenance of an intact forest canopy, establishment of minimally disturbed buffer zones, and protection or restoration of natural biophysical processes such as hydrologic drainage patterns (Moss and Milne, 1998; Niagara Escarpment Commission, 2005).

Viable populations of large or wide-ranging animals that use the Niagara Escarpment require large areas of suitable habitat. Due to the narrow geographic region occupied by the Niagara Escarpment, protection of remnant natural areas along this corridor will make a modest contribution, at best, toward conservation of these species. However, viable populations of small species like land snails and salamanders require much less area, and formal protection of remnant natural or semi-natural areas along the Niagara Escarpment can have an extremely high benefit-cost ratio. Conservation of critical habitats for these species might literally involve the enlightened management of a single landowner's backyard.

Studies by Larson, Nekola, and others have demonstrated that careful research along the Niagara Escarpment reveals a unique but fragile biota (Haig and others, 2000). The composition of this biota and the ecological interactions on which they depend are just beginning to be appreciated. Finally, given the sensitivity of many escarpment species to unusual microclimate conditions, identification and regular monitoring of local populations can play a major role in understanding and mitigating the impacts of climate change on native plants and animals in the western Great Lakes region.

REFERENCES

Al-Shehbaz, I.A., 2010, Brassicaceae, *in* Flora of North America Editorial Committee, eds., Flora of North America North of Mexico, 18+ vols.: Oxford and New York, Oxford University Press, v. 7, p. 298.

Anderson, E.M., 1990, Bobcat diurnal loafing sites in southeastern Colorado: *Journal of Wildlife Management*, v. 54, p. 600–602.

Anderson, C., Epstein, E. Smith, W., and Merryfield, N., 2002, The Niagara Escarpment: Inventory findings 1999–2001 and considerations for management: Wisconsin Department of Natural Resources, PUBL ER-801-02, 79 p.

Bailey, T.N., 1974, Social organization in a bobcat population: *Journal of Wildlife Management*, v. 38, p. 435–446.

Barbour, R.W., and Davis, W.H., 1969, Bats of America: Lexington, Ky., University of Kentucky Press, 286 p.

Blehert, D.S., Hicks, A.C., Behr, M., Meteyer, C.U., Berlowski-Zier, B.M., Buckles, E.L., Coleman, J.T.H., Darling, S.R., Gargas, A., Niver, R., Okoniewski, J.C., Rudd, R.J., and Stone, W.B., 2009, Bat white-nose syndrome: An emerging fungal pathogen?: *Science*, v. 323, p. 227.

Cox, J.E., and Larson, D.W., 1992, Environmental relations of the bryophytic and vascular components of a talus slope plant community: *Journal of Vegetation Science*, v. 4, p. 553–560.

Davis, G., and Davis, J., 2006, Cliff swallow, *in* Cutright, N., and others, eds., The atlas of Wisconsin breeding birds: Milwaukee, Wis., Wisconsin Society for Ornithology, p. 314–315.

Endres, K.M., and Smith, W.P., 1993, Influence of age, sex, season, and availability on den selection by raccoons within the central basin of Tennessee: *American Midland Naturalist*, v. 129, p. 116–131.

Environment Canada, 2010, Recovery strategy for the timber rattlesnake (*Crotalus horridus*) in Canada: Environment Canada, Species at Risk Act, Recovery Strategy Series, 17 p.

Fitch, H.S., and Shirer, H.W., 1970, A radiotelemetric study of spatial relationships in the opossum: *American Midland Naturalist*, v. 84, p. 170–186.

Flader, S., 1983, The Great Lakes forest: An environmental and social history: Minneapolis, Minn., University of Minnesota Press, 336 p.

Frederick, G.G, 1993, When iron was king in Dodge County, Wisconsin: Mayville, Wis., Mayville Historical Society, 735 p.

Frelich, L.E., 1995, Old forest in the Lake States today and before European settlement: *Natural Areas Journal*, v. 15, p. 157–167.

Gerrath, J.F., Gerrath, J.A., Matthes, U., and Larson, D.W., 2000, Endolithic algae and cyanobacteria from cliffs of the Niagara Escarpment, Ontario, Canada: *Canadian Journal of Botany*, v. 78, p. 807–815.

Haig, A.R., Matthes, U., and Larson, D.W., 2000, Effects of natural habitat fragmentation on the species richness, diversity, and composition of cliff vegetation: *Canadian Journal of Botany*, v. 78, p. 786–797.

Hendricks, P., 2012, A guide to the land snails and slugs of Montana: A report to the U.S. Forest Service - Region 1: Helena, Mont., Montana Natural Heritage Program, 187 p. plus appendices.

Horsák, M., Chytrý, M., Pokryszko, B.M., Danihelka, J., Ermakov, N., Hájek, M., Hájková, P., Kintrová, K., Kočí, M., Kubešová, S., Lustyk, P., Otýpková, Z., Pelánková, B., and Valachovič, M., 2010, Habitats of relict terrestrial snails in southern Siberia: Lessons for the reconstruction of palaeoenvironments of full-glacial Europe: *Journal of Biogeography*, v. 37, p. 1450–1462.

Howe, R.W., 1984, Zoogeography of Iowa's Paleozoic plateau: *Proceedings of the Iowa Academy of Science*, v. 91, p. 32–36.

Hubricht, L., 1985, The distributions of the native land mollusks of the eastern United States: *Fieldiana Zoology*, v. 24, p. 1–191.

Jass, J., and Klausmeier, B., 2006, Determining the presence of fairy shrimps (Crustacea: Anostraca) at ephemeral pond sites in Wisconsin: Wisconsin Department of Natural Resources Research Report 188 (PUB-SS-588 2006), 4 p.

Kluessendorf, J., 2010, A look at the ledge: *Wisconsin Natural Resources Magazine*, October 2010, http://dnr.wi.gov/wnrmag/2010/10/ledge.htm.

Kolowski, J.M., and Woolf, A., 2002, Microhabitat use by bobcats in southern Illinois: *Journal of Wildlife Management*, v. 66, p. 822–832.

Kuchta, M.A., 2009, The paleoenvironmental significance of terrestrial gastropod fossils from the Upper Mississippi Valley in Minnesota and Wisconsin: University of Wisconsin–Madison, Ph.D. thesis, 259 p.

Kurta, A., 1995, Mammals of the Great Lakes Region: Ann Arbor, Mich., University of Michigan Press, 392 p.

Larson, D.W., and Kelly, P.E., 1991, The extent of old-growth *Thuja occidentalis* on cliffs of the Niagara Escarpment: *Canadian Journal of Botany*, v. 69, p. 1628–1636.

Larson, D.W., Matthes, U., Gerrath, J.A., Gerrath, J.M., Nekola, J.C., Porembski, S., Charlton, A., and Larson, N.W.K., 1999a, Ancient stunted trees on cliffs: *Nature*, v. 398, p. 382–383.

Larson, D.W., Matthes, U., Gerrath, J.A., Larson, N.W.K., Gerrath, J.M., Nekola, J.C., Walker, G.L., Porembski, S., and Charlton, A., 2000, Evidence for the wide-spread occurrence of ancient forests on cliffs: *Journal of Biogeography*, v. 27, p. 319–331.

Larson, D.W., Matthes-Sears, U., and Kelly, P.E., 1999b, The cliff ecosystem of the Niagara Escarpment, *in* Anderson, R.C., and others, eds., Savannas, barrens, and rock outcrop plant communities of North America: West Nyack, N.Y., Cambridge University Press, p. 362–374.

Larson, D.W., Spring, S.H., Matthes-Sears, U., and Bartlett, R.M., 1989, Organization of the Niagara Escarpment cliff community: *Canadian Journal of Botany*, v. 67, p. 2731–2742.

Levsen, N.D., and Mort, M.E., 2008, Determining patterns of genetic diversity and post-glacial recolonization of western Canada in the Iowa golden saxifrage, *Chrysosplenium iowense* (Saxifragaceae), using inter-simple sequence repeats: *Biological Journal of the Linnean Society*, v. 95, p. 815–823.

Lewis, J.J., 2002, Conservation assessment for ice thorn (*Carychium exile*): USDA Forest Service, Eastern Region, 11 p.

Matheson, J.D., and Larson, D.W., 1998, Influence of cliffs on bird community diversity: *Canadian Journal of Zoology*, v. 76, p. 278–287.

Matthes, U., Ryan, B.D., and Larson, D.W., 2000, Community structure of epilithic lichens on the cliffs of the Niagara Escarpment, Ontario, Canada: *Plant Ecology*, v. 148, p. 233–244.

McMillan, M., Nekola, J.C., and Larson, D.W., 2003, Impact of recreational rock climbing on land snail communities of the Niagara Escarpment, southern Ontario, Canada: *Conservation Biology*, v. 17, p. 616–621.

Moss, M.R., and Milne, R.J., 1998, Biophysical processes and bioregional planning: The Niagara Escarpment of southern Ontario, Canada: *Landscape and Urban Planning*, v. 40, p. 251–268.

Mossman, M.J., 2006, Turkey vulture, *in* Cutright, N., and others, eds., The atlas of Wisconsin breeding birds: Milwaukee, Wis., Wisconsin Society for Ornithology, p. 152–153.

Nekola, J.C, 1999a, Paleorefugia and neorefugia: The influence of colonization history on community pattern and process: *Ecology*, v. 80, p. 2459–2473.

Nekola, J.C., 1999b, Terrestrial gastropod richness of carbonate cliff and associated habitats in the Great Lakes region of North America: *Malacologia*, v. 41, p. 231–252.

Nekola, J.C., 2003, Large-scale terrestrial gastropod community composition patterns in the Great Lakes region of North America: *Diversity and Distribution*, v. 9, p. 55-71.

Nekola, J.C., and Coles, B.F., 2010, Pupillid land snails of eastern North America: *American Malacological Bulletin*, v. 28, p. 29–57.

Nekola, J.C., and Smith, T.A., 1999, Terrestrial gastropod richness patterns in Wisconsin carbonate cliff communities: *Malacologia*, v. 41, p. 253–269.

Nekola, J.C., Smith, T.A., and Frest, T.J., 1996, Land snails of Door Peninsula natural habitats: Final report: Madison, Wis., The Nature Conservancy, Wisconsin Chapter, 55 p.

Niagara Escarpment Commission, 2005, The Niagara Escarpment plan (website): http://www.escarpment.org/planreview/.

Penskar, M.R., and Crispin, S.R., 2008, Special plant abstract for *Draba arabisans* (rock whitlow-grass): Lansing, Mich., Michigan Natural Features Inventory, 3 p., http://mnfi.anr.msu.edu/abstracts/botany/Draba_arabisans.pdf.

Pielou, E.E., 1991, After the Ice Age: The return of life to glaciated North America: Chicago, Ill., University of Chicago Press, 366 p.

Rech, J.A., Nekola, J.C., and Pigati, J.S., 2012, Radiocarbon ages of terrestrial gastropods extend duration of ice-free conditions at the Two Creeks forest bed, Wisconsin, USA: *Quaternary Research*, v. 77, p. 289–292.

Reinartz, J.A., 2003, Vegetation of spring ephemeral ponds in the mesic forests of southeastern Wisconsin, *in* 2003 Field Station annual report: University of Wisconsin–Milwaukee Field Station, p. 20.

Reynolds, T.L., and Bewley, J.D., 1993, Characterization of protein synthetic changes in a desiccation-tolerant fern, *Polypodium virginianum*: Comparison of the effects of drying, rehydration and abscisic acid: *Journal of Experimental Botany*, v. 44, p. 921–928.

Ross, T.K., 1999, Phylogeography and conservation genetics of the Iowa Pleistocene snail: *Molecular Ecology*, v. 8, p. 1363–1373.

Septon, G., 2006, Peregrine falcon, *in* Cutright, N., and others, eds., The atlas of Wisconsin breeding birds: Milwaukee, Wisc., Wisconsin Society for Ornithology, p. 176–177.

Tuttle, M.D., and Taylor, D.A.R., 1998, Bats and mines [revised edition]: Austin, Tex., Bat Conservation International Resource Publication No. 3, 50 p.

Voss, E.G., 1985, Michigan flora part II, Dicots (Saururaceae-Cornaceae): Cranbrook Institute of Science Bulletin and University of Michigan Herbarium, v. 59, 724 p.

Waller, D.M., and Rooney, T.P., 2008, The vanishing present: Wisconsin's changing lands, waters, and wildlife: Chicago, Ill., University of Chicago Press, 507 p.

Watts, B.D., 2006, An investigation of cliffs and cliff-nesting birds in the southern Appalachians with an emphasis on the peregrine falcon: Williamsburg, Va., College of William and Mary, Center for Conservation Biology Technical Report Series, CCBTR-06-14, 43 p.

Weller, M.G., and Pelton, M.R., 1987, Denning characteristics of striped skunks in Great Smoky Mountains National Park: *Journal of Mammalogy*, v. 68, p. 177–179.

Yahner, R.H., 1988, Changes in wildlife communities near edges: *Conservation Biology*, v. 2, p. 333–339.

Yu, Z., 2003, Late Quaternary dynamics of tundra and forest vegetation in the southern Niagara Escarpment, Canada: *New Phytologist*, v. 157, p. 365–390.

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

GEOSCIENCE WISCONSIN • VOLUME 22, PART 4 • PUBLISHED ONLINE 2016

Bats of the Niagara Escarpment in Wisconsin

Richard Novy[1]

Tri-colored bat

Cindie Brunner illustration

ABSTRACT

The caves and rock crevices of the Niagara Escarpment provide habitat for four of Wisconsin's seven species of bats: the little brown myotis, the northern myotis, the big brown bat, and the tri-colored bat. All four of these species are currently listed in Wisconsin as threatened. In addition, the forests above the escarpment provide summer homes for the migrating bat species, including the silver-haired, eastern red, and hoary bats. All of the bat species found in the escarpment are insectivores. They reduce insect pests and are the only significant predators of nocturnal insects. Because of the spread of white-nose syndrome, a deadly fungus affecting bats, and the negative effects of wind turbines on bat populations, habitat provided by the caves in the escarpment has become even more critical.

INTRODUCTION

Bats are one of the most abundant and misunderstood mammals. Seven species of bats inhabit Wisconsin. Four of those species use the caves along the entire length of the Niagara Escarpment in Wisconsin. Habitat destruction, wind turbines, and white-nose syndrome have caused bat fatalities to rapidly increase in recent years, and all four of the cave-dwelling species are listed as threatened. Due to their important ecological roles, knowledge about these species is invaluable.

All the bat species in Wisconsin are members of the mammalian family Vespertilionidae. These bats travel and hunt using echolocation, emitting high frequency calls that bounce off objects near them and travel back to the bat, allowing them to gauge distance, size, shape, surface texture, and movement of their surroundings (Kurta, 1995; Feldhamer and others, 2007). The frequency range of bat calls is usually between 12 and 160 kHz, with most species' calls being greater than 20 kHz (Feldhamer and others, 2007). The average human can hear up to 18 kHz, so it is possible to hear some species' echolocation calls, but it is not common.

The benefits of bats are numerous and diverse. Around the world, bats are seed dispersers and pollinators for plant species important for food, timber, medicines, or fiber (Fujita and Tuttle, 1991). In Wisconsin, all the bats are insectivorous, and they are the only significant predator of nocturnal insects (Feldhamer and others, 2007). Depending on the size of the individual, season, and air temperature, a single bat will consume between 1.8 and 3.7 grams, which translates to hundreds of insects per night (Anthony and Kunz, 1977). By eating such enormous amounts of insects, bats reduce insect species populations that are common vectors for agricultural plant diseases, as well as those that are general pests (Whitaker, 1995).

> "…bats reduce insect species populations that are common vectors for agricultural plant diseases…"

Bats are often viewed negatively as creatures filled with disease. While the Centers for Disease Control and Prevention (2011) reported about 6 percent of cat-killed bats had rabies, researchers at the University of Calgary (2011) calculated that fewer than 1 percent of healthy bats killed by wind turbines were rabid. However, rabies has been reported in several bat species, and bats are rabies vectors, along with raccoons, skunks, and coyotes (CDC, 2011). In the case of bats, bites are usually due to improper handling by people attempting to pick bats up off the ground or from a wall.

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NIAGARA ESCARPMENT BACKGROUND AND LANDSCAPE DATA

The Niagara Escarpment is a 650-mile-long bedrock ridge filled with caves, cliffs, and ledges that extends from eastern Wisconsin to southern New York. The rocks of the escarpment were formed in ancient marine sedimentary environments and later eroded by glaciers and rivers (Luczaj, 2013). These rock openings throughout the escarpment provide ideal habitat for the four cave bat species found in Wisconsin. Although the cave bats mainly inhabit the escarpment during winter, some species will use caves as habitat periodically throughout the year.

CAVE BATS OF WISCONSIN

There are seven species of bats in Wisconsin, but only four of these are cave dwelling and inhabit the escarpment. The other three species are known as tree bats because they roost in trees. These bats, the silver-haired, eastern red, and hoary, migrate south in the fall and, depending on the species, may fly as far as Central America. The hibernating species, also known as cave bats, enter their hibernacula after the migratory species have begun flying south for the year.

The most common bat in Wisconsin, the little brown myotis (*Myotis lucifugus*) (fig. 1), is found nearly everywhere across the United States, and hibernates mostly in caves over winter (Kurta, 1995). Their summer roosting sites are anywhere from underneath tree bark to attics.

The northern myotis or northern long-eared bat (*Myotis septentrionalis*) (fig. 2) is found across the eastern United States and throughout Canada. They hibernate over winter in caves or abandoned mines, but during summer, can be found in groups with other myotis near their hibernacula (Kurta, 1995). They prefer to forage below the canopy within forests.

Big brown bats (*Eptesicus fuscus*) (fig. 3) live throughout the United States, mainly in cities, towns, and agricultural areas (Kurta, 1995). Unlike most other species, *E. fuscus* is less likely to be found in densely forested areas, but is a very common species overall (Jackson, 1961; Kurta, 1995). This species mainly hibernates in caves and mines over winter, but can also be found in building roofs or walls where the temperature stays above freezing (Kurta, 1995; Rancourt and others, 2007).

The tri-colored bat (*Perimyotis subflavus*) (fig. 4), formerly known as the eastern pipistrelle prior to a genera change (*Pipistrellus subflavus*), inhabits most of the eastern United States, from southern Canada to Central America, although it is quite rare in northeastern Wisconsin due to a lack of suitable hibernacula. *P. subflavus* is usually the first of the four species to enter into torpor, the bat's form of hibernation, in fall, and the last to emerge in spring (Kurta, 1995).

Figure 1. *Little brown myotis* (Myotis lucifugus).

Figure 2. *Northern myotis* (Myotis septentrionalis).

Figure 3. *Big brown bat* (Eptesicus fuscus).

Figure 4. *Tri-colored bat* (Perimyotis subflavus).

CAVES IN THE WISCONSIN NIAGARA ESCARPMENT

Although bats can be found in many caves within the Niagara Escarpment, there are four main hibernacula (shelters used for winter dormancy) that house large numbers of bats. New Hope Cave, Ledge View Cave, Horseshoe Bay Cave, and Neda Mine comprise the only large bat hibernacula in eastern Wisconsin. In fact, Neda Mine is the largest bat hibernaculum in Wisconsin. Many caves in the escarpment are not suitable for winter torpor, due to the small size and exposure of most of the caves. However, these smaller caves are useful for bat use during the summer months for daily torpor. Although an exact number of bats in the caves is unknown, Wisconsin has some of the largest numbers of cave-hibernating bat species remaining in the Midwest.

Conservation concerns

Habitat destruction is a concern for mammals around the world, and bats are no exception. Bats like the Indiana bat, *Myotis sodalist*, are endangered because about 85 percent of the population winter in a total of seven caves or mines in the Midwest (Kurta, 1995). With the rapid spread of white-nose syndrome (WNS), a fungal disease that has killed more than 90 percent of bat populations within infected caves, habitat concerns are particularly great. An up-to-date map of North America showing the occurrence of WNS by county or district can be found online at: www.whitenosesyndrome.org/resources/map.

The causal fungus, *Pseudogymnoascus destructans*, makes infected bat hibernacula a deadly place for bats to reside. The fungus can grow within caves at temperatures between about 39°F and 59°F (Verant and others, 2012). Bats can pick up the fungus directly from the cave, or from contact with other infected bats. The U.S. Fish and Wildlife Service (2011) reports that bats in a cave or mine that has been infected by WNS usually start showing symptoms during winter torpor. These symptoms include white fungus on the bats' snouts and wings. Dead and dying bats at affected hibernacula have low body weight and become dehydrated, especially over winter. Other symptoms of WNS are unusual behavior, including frequent arousals when they should be in torpor, flying in winter, and roosting near the hibernacula entrance, where temperatures may fall below freezing. Because their food source is not available during winter, they either starve or freeze to death, resulting in large piles of dead bats at the entrances to infected caves.

Scientists are still trying to find viable ways to stop or eliminate the fungus. It is estimated that millions of bats have been killed in the United States by WNS since its discovery in 2007. *P. destructans* was identified in Wisconsin in 2014. If you find a large number of dead bats outside a cave, or see numerous bats acting strangely (flying during the day, or crawling around the ground outside of a cave), alert the state Department of Natural Resources or the U.S. Fish and Wildlife Service immediately.

The U.S. Fish and Wildlife Service has established decontamination protocols for entering and exiting caves around the United States in hopes of preventing human transmission of the fungus from one cave to another. The Wisconsin Department of Natural Resources (WDNR) has expanded on these protocols to help control the human-assisted spread of the fungus into Wisconsin. No clothing or gear previously worn or brought in any cave may then be worn into a Wisconsin cave without it first being disinfected. Tourist cavers are exempt from this policy, but they should still be cautious not to wear clothes into a cave that they have worn in a previous cave in Wisconsin or another state. If you can avoid entering a non-tourist cave known to house bats, it would be better to do so. For more detailed information on the WDNR decontamination protocols, visit the WDNR website (http://dnr.wi.gov/topic/WildlifeHabitat/bats.html).

Wind turbines present another threat to bats. Although wind power facilities represent a great source of renewable energy, scientists estimate that they kill tens of thousands of bats in North America each year, leading researchers to wonder why (USGS, 2015). Bats are killed in one of two ways: they fly directly into a spinning turbine or, in some cases, fly between spinning turbines and are killed by the extreme pressure change from one side to the other (Baerwald and others, 2008). In the Midwest, on average, approximately 8 bats are killed per megawatt produced from the wind turbines (Arnett and others, 2008). Recent studies estimate that Wisconsin alone has a bat mortality rate as high as 32 bats per megawatt produced from wind turbines, which is among the highest mortality rates in the

"If you can avoid entering a non-tourist cave known to house bats, it would be better to do so."

United States (Strickland and others, 2011). A specific reason for the high mortality rates in Wisconsin is not known, but it may be that the area surrounding the turbines resides in a stretch of land popular for migratory species and may potentially be near a winter hibernaculum utilized by common cave bats. The Niagara Escarpment is such an area. Researchers are currently working on ways to decrease bat mortality, such as reducing turbine speed or installing acoustic deterrents (Horn and others, 2008).

CONCLUSION

The caves and mines in the Niagara Escarpment are very important for bats of eastern Wisconsin. The farming communities of eastern Wisconsin rely on bats for insect control, and without them, would require more pesticides to protect their crops. A few conservation efforts could greatly assist bat species: (1) With the developing threat of WNS, cavers should be extremely cautious when entering caves anywhere on the east coast or in the Midwestern states, including in Wisconsin. (2) Wind farm projects should have pre-construction surveys performed, to avoid placement in a bat migratory pathway. (3) If you have large hibernacula of summer or winter roosting bats on or near your property, inform the WDNR and help monitor our bat population.

REFERENCES CITED

Anthony, E.L.P., and Kunz, T.H., 1977, Feeding strategies of the little brown bat, *Myotis lucifugus*, in southern New Hampshire: *Ecology*, v. 58, p. 775–786.

Arnett, E.B., Brown, W.K., Erickson, W.P., Fiedler, J.K., Hamilton, B.L., Henry, T.H., Jain, A., Johnson, G.D., Kerns, J., Koford, R.R., Nicholson, C.P., O'Connell, T.J., Piorkowski, M.D., and Tankersley, R.D., Jr., 2008, Patterns of bat fatalities at wind energy facilities in North America: *The Journal of Wildlife Management*. v. 72, no. 1, p. 61–78.

Baerwald, E.F., D'Amours, G.H., Klug, B.J., and Barclay, R.M.R., 2008, Barotrauma is a significant cause of bat fatalities at wind turbines: *Current Biology*, v. 18, no. 16, p. R695–R696.

Centers for Disease Control and Prevention (CDC), 2011, Learning about bats and rabies: http://www.cdc.gov/rabies/bats/education, accessed June 2013.

Feldhamer, G.A., Drickamer, L.C., Vessey, S.H., Merritt, J.F., and Krajewski, C., 2007, Mammalogy: Adaptation, diversity, ecology (3d ed.): Baltimore, Md., The Johns Hopkins University Press, 672 p.

Fujita, M.S., and Tuttle, M.D., 1991, Flying foxes (Chiroptera: Pteropodidae): Threatened animals of key ecological and economic importance: *Conservation Biology*, v. 5, p. 455–463.

Horn, J.W., Arnett, E.B., and Kunz, T.H., 2008, Behavioral responses of bats to operating wind turbines: *The Journal of Wildlife Management*, v. 72, no. 1, p. 123–132.

Jackson, H.H.T., 1961, Mammals of Wisconsin: Madison, Wis., University of Wisconsin Press, 520 p.

Kurta, A., 1995, Mammals of the Great Lakes Region: Ann Arbor, Mich., University of Michigan Press, 392 p.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin*, v. 22, p. 1–34.

Rancourt, S.J., Rule, M.I., and O'Connell, M.A., 2007, Maternity roost site selection of big brown bats in ponderosa pine forests of the Channeled Scablands of northeastern Washington State, USA: *Forest Ecology and Management*, v. 248, p.183–192.

Strickland, D., Arnett, E., Erickson, W., Johnson, D., Johnson, G., Morrison, M., Shaffer, J., and Warren-Hicks, W., 2011, Comprehensive guide to studying wind energy/wildlife interactions: Prepared for the National Wind Coordinating Collaborative, Washington, D.C., 281 p.

U.S. Fish and Wildlife Service (USFWS), 2011, White-nose syndrome: The devastating disease of hibernating bats in North America: U.S. Fish and Wildlife Service, 2 p.

U.S. Geological Survey (USGS), 2015, Bat fatalities at wind turbines: Investigating the causes and consequences: USGS, Fort Collins Science Center, https://www.fort.usgs.gov/science-feature/96, accessed June 4, 2015.

University of Calgary, 2011, Fewer bats carry rabies than thought: *Science Daily*, March 22, 2011, http://www.sciencedaily.com/releases/2011/01/110131133323.htm.

Verant, M.L., Boyles, J.G., Waldrep, W., Jr., Wibbelt, G., Blehert, D.S., 2012, Temperature-dependent growth of *Geomyces destructans*, the fungus that causes bat white-nose syndrome: PLOS ONE, http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0046280.

Whitaker, J.O., Jr., 1995, Food of the big brown bat *Eptesicus fuscus* from maternity colonies in Indiana and Illinois: *American Midland Naturalist*, v. 134, p. 346–360.

Thank you to David Redell and Jennifer Schehr of the WDNR, and Dr. Ron Stieglitz.

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

GEOSCIENCE WISCONSIN • VOLUME 22, PART 5 • PUBLISHED ONLINE 2016

Caves and karst of the Niagara Escarpment: A caver's perspective

George Zachariasen[1]

Carolyn's Caverns

ABSTRACT

The Silurian bedrock of northeastern Wisconsin has been modified by glaciers, erosion, and dissolution over a long period of time. Three classes or types of caves—littoral (sea), block creep, and solutional—are found along the Niagara Escarpment, and this article describes examples of each. Other karst features such as enlarged joints and sinkholes are of interest for study and a potential cause for concern because of the pollution danger that they pose for groundwater. Caves in the area are not large or long by national or international standards, but are important to wildlife and to our health and safety.

GEOLOGY

The Niagara Escarpment is formed of dolostone bedrock. This sedimentary rock layer is mostly flat, but is slightly higher in elevation in the west than the east. In some areas along the western edge of its extent, the rock appears as a bluff or escarpment, while in other places it is covered by soil and rocks deposited by the glaciers that covered this part of the state, the last of which melted away roughly 10,000 years ago. In some places in eastern Wisconsin, as little as 6 to 12 inches of glacial debris covers the bedrock; elsewhere, more than 100 feet of material was deposited.

The dolostone bedrock was formed in the Silurian Period, between 443 and 417 million years ago, when this area was covered by shallow, tropical oceans (Dott and Attig, 2004). The limey sediment was deposited on the sea floor by algae, corals, and other marine organisms, and became limestone over time and with pressure and recrystallization. Historically, this type of rock was called limestone, even though it is not truly limestone: pure limestone is calcium carbonate. Scientists are not sure how or when, but magnesium replaced some of the calcium in the limestone here, possibly when mineral-rich water migrated upward through the rock (Dott and Attig, 2004). More recently and accurately it is now called dolomite or dolostone. The exact chemistry of the rock likely varies from place to place—in some localities, the rock seems to dissolve more readily in the weak acids found in nature, leading to enlarged joints, sinkholes, and caves. The Silurian-age formations lie above the Ordovician Maquoketa Formation, which can be seen in some areas at the base of the western bluff and along the Green Bay shore.

Karst terrain

Solution-formed features such as enlarged joints, sinkholes, and caves are typical of a karst terrain (Luczaj, 2013). In areas with karst, there are few surface streams because water easily drains through openings in the bedrock, and surface streams may lose water to underground drainage. For example, Logan Creek in Door County connects spring-fed Lost Lake to Clark Lake. In spring or during a wet fall, water typically flows along the entire length of the creek. During a dry summer, water seeps into the creek bed before it reaches Clark Lake. This is known as a "losing" stream.

With surface drainage rapidly reaching the water table, there is a significant risk of well pollution in a karst terrain. In rural areas, septic systems and barnyards as well as field-spreading of manure and septic wastes can and do pollute groundwater that supplies drinking water.

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Glaciers

Continental glaciers covered much of Wisconsin during the Pleistocene Epoch. While the southwestern corner of Wisconsin (known as the Driftless Area) escaped glaciation, its topography has been altered by precipitation and erosion. There have been a number of advances of glaciers into northeastern Wisconsin, but the Late Wisconsin glaciation, which started about 26,000 years ago, erased most evidence of previous advances (Dott and Attig, 2004). Ice flowed southward from central Canada as far as the Ohio River. The concept of ice flowing may be difficult to imagine, but over time very thick ice can flow over and around obstacles much like water in a river. A hill that is composed of harder stone may resist the ice, or a sharp point may deflect the moving glacier. An example of a hill that resisted the glacier's advance is one just south of Chilton, home to the Carolyn's Caverns System (described later).

Scientists have estimated that the glaciers were as much as 1 mile thick. Computer modeling estimates that the sheer weight of the glacier tilted eastern Wisconsin downward at least 100 m (330 ft) (Dutch, 2009). This weight fractured the bedrock or modified pre-existing fractures, and these joints contribute to the presence of caves in the Niagara Escarpment. Careful measurements have shown that the area is still rising as the land rebounds from the loss of the glacier's weight. That upward movement likely opens cracks that were produced by the weight of the glaciers.

As the climate warmed, the glaciers began to melt away faster than they had advanced. This melting process began about 16,000 years ago, but there were colder periods where they advanced again. The glaciers did not completely retreat from the area until 10,000 years ago. As they melted, Glacial Lake Oshkosh was formed. This glacial lake was an enormous body of water that encompassed the current Fox River Valley and Lake Winnebago. Drainage to the north was blocked by the retreating glacier. Over time, water found varying outlets to Lake Michigan. One outlet was the path of the Neshota and West Twin Rivers near Maribel, Wisconsin. The water from this drainage greatly affected the

Eric Fowle

Figure 1. *Eagle Cave, a littoral cave in Peninsula State Park.*

formation of caves that were in the area, first enlarging the caves and, later, partially filling them with water-washed sediment.

CAVES

Caves of the Niagara Escarpment fall into three classes: solution, littoral (sea), and block creep. Solution caves are the most common type, but they are not evenly distributed across the landscape. Glaciers likely crushed some caves, scraped the top off others, and filled still more with sediment and stones. Much of northeastern Wisconsin is covered by many feet of glacial drift and likely contains buried caves.

Littoral (sea) caves

Littoral, or sea, caves are formed by wave action. Well-known examples occur at Cave Point County Park in Door County along the Lake Michigan shore. Most of these are best seen from the water. These types of caves are formed as wave action erodes and loosens stone along joints; frost action probably also help to enlarge caves. Generally, sea caves follow the direction of joints or faults in the bedrock. At Cave Point most of the entrances are at water level and are roughly perpendicular to the shoreline, although there are examples of other entrance formations: one cave has three entrances and runs about 100 ft (30 m) parallel to the shore. Peninsula State Park on Green Bay has a number of sea caves in the Eagle Bluff area. All are well above current water level and were formed before glacial rebound, when water level was much higher relative to the land. **Eagle Cave** at Peninsula Park (fig. 1) is tens of feet above current water level. Potawatomi State Park near Sturgeon Bay also has some small sea caves.

Littoral caves are not common or widely distributed in Wisconsin. A rocky bluff must be near the shore of a sufficiently large body of water (Lake Michigan) for wave action to be violent enough to erode and loosen rock from the bluff.

Block creep caves

Block creep caves are usually found very near the edge of a bluff where the dolostone has a major joint or fault parallel to the bluff edge. These caves form when a sizable block of bedrock slides outward from the bluff, possibly helped by slipping on the underlying Maquoketa shale and by frost wedging. Many of these widened joints are open to the surface and may fill with soil, boulders, and organic matter. If a top layer of rock does not split off the bluff, a cave remains and is less likely to fill with debris.

On the bluff above Oakfield, Wisconsin, there is a block creep cave several hundred feet long. **Oakfield Crevice Cave** (fig. 2) is generally 2 to 6 ft (0.6 to 1.8 m) wide and varies in height from barely crawling height to 20 ft (6 m) tall in places. The cave is just a few feet

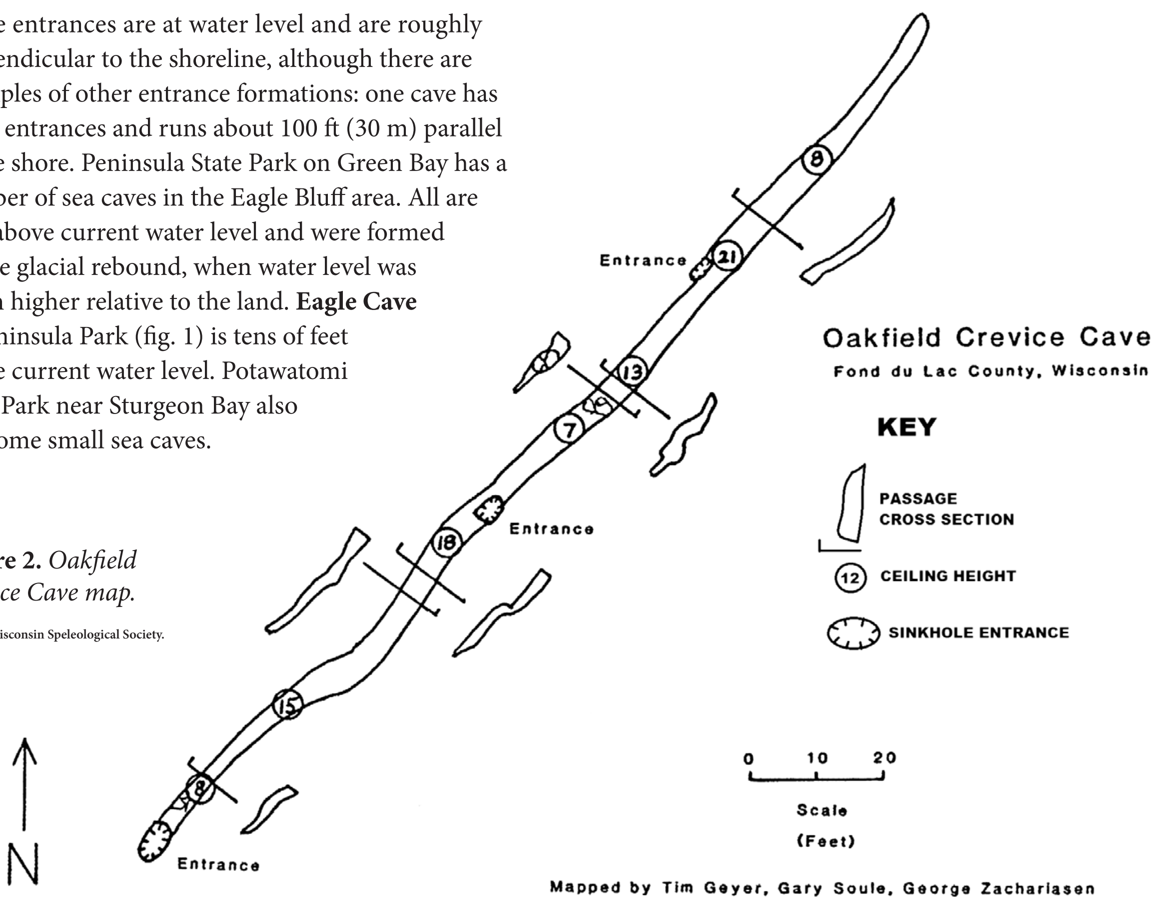

Figure 2. *Oakfield Crevice Cave map.*

Source: Wisconsin Speleological Society.

from the edge of the bluff and the bluff-side wall of the cave matches the contour of the other side very well in many places. Some stones have broken from the covering layer of bedrock, leaving four entrances and some keystones bridging the passage.

> "One end of this cave extends under the original part of the nursing home which had no basement."

In Sturgeon Bay, Wisconsin, basement excavation for an addition to a nursing home encountered a cave that appears to be of block creep origin. Excavation had destroyed the middle part of the cave, but local caver Gary K. Soule was able to convince the builders to modify the foundation of the addition to preserve access to the remaining two portions of the cave.

One end of this cave extends under the original part of the nursing home which had no basement. This portion is very dry. It contains walking-height passage several feet wide. In some areas, fossils have been eroded out of the walls. The other end of the cave tends to be wetter, and extends under a busy street. This cave is located on the side of a gently sloping hill. There is no obvious reason for the block to have moved downhill, leaving a solid roof over the cave. The distance from the cave ceiling to the surface is likely not more than about 10 ft (3 m), but there was no evidence of the cave's existence before the basement excavation.

Solution caves

Solution caves are formed by the slow dissolution of the bedrock by water. The dolostone of the Niagara Escarpment is not very soluble in pure water, but when carbon dioxide is dissolved in water, carbonic acid is formed that more easily dissolves the rock. Acidic water running through joints and bedding plane surfaces enlarges the opening. Over long periods of time this can create passages large enough for people to fit through. Caves that have been formed by relatively still water below the water table are considered to be phreatic, meaning the limestone has dissolved in all directions, while those caused by flowing water are formed by vadose action, creating a trench in the floor. There are examples of both types in northeastern Wisconsin. The dolostone is less soluble than the limestones found in other parts of the country where caves can be much larger.

Once a cave has formed it might be filled by sediment such as sand, breakdown rocks, and sometimes dripstone formations. As a cave drains of water, loose rocks may fall from the ceiling because they weigh more in air than when under water. Frost action may also loosen rocks near the entrance to a cave. Flowing water may carry silt, sand, and gravel into a cave, building up impressive deposits that can fill or nearly fill cave passages.

Al Schema

Figure 3. *Sediment profile of Maribel New Hope Cave. Samples were obtained at numbered locations for age dating. Note the cut-off layers at sample location 2.*

George Zachariasen

Figure 4. *Hikers in an un-roofed cave passage, Maribel Area.*

Glaciers traveling over northeastern Wisconsin collapsed some caves, and filled others with large amounts of sediment. Melting glaciers supplied large amounts of water that flowed through and enlarged some caves.

Members of the Wisconsin Speleological Society have excavated fill from several caves over a period of years. At Cherney Maribel Caves County Park in northern Manitowoc County, sandy sediments several feet deep in **Maribel New Hope Cave** show cross-bedding from many different depositional events (fig. 3). Sediment filled cave passages nearly to the ceiling in many places (Luczaj and Stieglitz, 2008). Soil samples were taken in the hope of age-dating the sediment layers. Water continues to seep through the fill. A short distance from this cave is a perennial spring which, years ago, was used as a source of mineral drinking water. Sinkholes in the surrounding farmland to the west may be the source of this water.

Also at Cherney Maribel Caves County Park, a recent excavation project connected two separate nearby crawlway caves into one cave, the **Tartarus Cave System**. This project was completed in 2012 and received a considerable amount of press coverage. Digging continues at both Tartarus and Maribel New Hope Cave attempting to find more unknown passages. Public tours are held on schedule during summer weekends.

The caves at Cherney Maribel Caves County Park are located on a bluff overlooking the valley of the West Twin River, which carried meltwater as the glaciers wasted. As mentioned previously, Glacial Lake Oshkosh formed in the Green Bay-Fox Valley lowland and drained through several different routes as the ice retreated. At some point, the water escaped through the Neshota and West Twin Rivers. This large flow of water excavated the valley, exposing the existing caves (Dott and Attig, 2004).

There are numerous small cave remnants and a large un-roofed cave segment or canyon on private land nearby (fig. 4). This canyon is some tens of feet wide in places, and lower portions of the wall show scallops, indicating this was a cave passage with a significant flow of water in the past. It appears that 3 to 4 ft (0.9 to 1.2 m) of ceiling rock collapsed, partially filling the canyon with broken stone. A few small sections of cave remain off the canyon. Other small sections of cave can be found in the woods nearby, showing that this was once an extensive cave system.

Ledge View Nature Center is located a few miles south of Chilton in Calumet County, and was established on a hill of dolostone where a small cave in the woods had been known for many years. The small cave, called **Montgomery Cave,** had been used as a dumpsite for refuse from a nearby rendering plant, but has since been cleaned up. In 1986, cavers from the Wisconsin Speleological Society exploring the nearby woods found a shallow sinkhole and began excavating dirt, stones, and cattle bones. They unearthed a small, shallow cave room which led to a lower shallow room. They called these caves **Carolyn's Caverns**. Over many years, more fill has been removed, and the now-extensive cave network is called the Carolyn's Caverns System (fig. 5). There are easy walking passages where only low crawlways or completely filled passages previously existed (fig. 6). Because the entrances to the cave system are near the top of the hill, it is clear that glacial meltwater provided most, if not all, of the fill. The excavation project is continuing, so it is yet unknown how large the full system is. Tours of the cave system are available through the Nature Center, which also houses excellent educational exhibits.

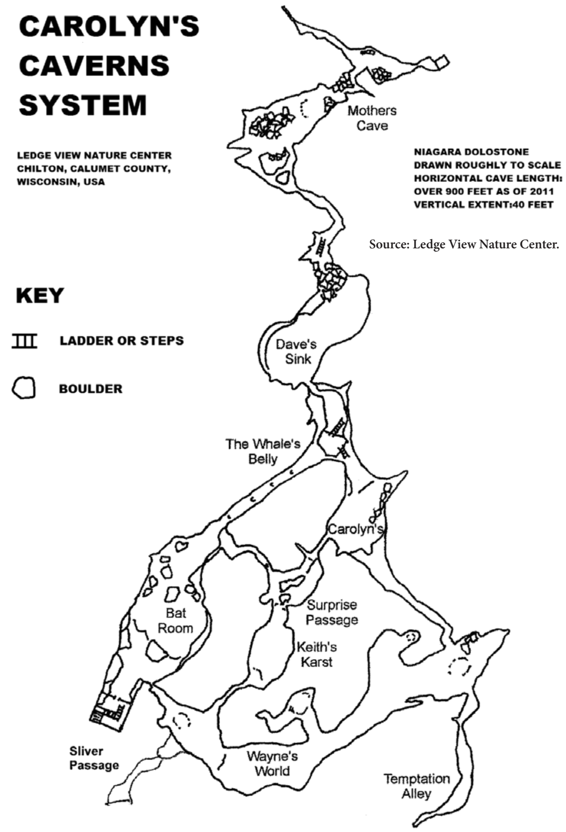

Figure 5. *Carolyn's Caverns System map.*

Ledge View Nature Center

Figure 6. *Passage in Carolyn's Caverns.*

Horseshoe Bay Cave is one of the longest caves in northeastern Wisconsin, and is located near the shore of Green Bay in Door County. This cave's existence has been known since at least 1896, when two hunters noticed water emerging from the bluff. From 1959 to 1963, cavers explored and mapped 1,740 ft (530 m) of passage, much of it low, wet, and cold. In 1978 cavers dug through a sand and gravel filled crawlway at the end of the mapped passage and entered a watery stream crawlway leading to about another thousand feet of passage. Cave divers have gone even farther.

The cave is unusual in Wisconsin for containing flowing water—most Wisconsin caves are high above the current water table and developed before valleys were formed by erosion. The Horseshoe Bay Cave map looks like a sinuous river and the cave was likely formed by flowing water (fig. 7). Many "rooms" are formed along the passage by solutionally enlarged joints. Occasionally water flows out of the cave, when snow melts rapidly enough. In 1986 water flowed out of the entrance for several days, and in September 2014 heavy rain again caused the entrance to flood (fig. 8). In the 1920s, Plum Bottom, a large, shallow closed valley just inland from the cave, flooded with water up to 6 ft (1.8 m) deep (Door County Advocate, 1982). Children attending


Eric Aleson

Figure 8. *Water flooding from the entrance of Horseshoe Bay Cave in 2014.*

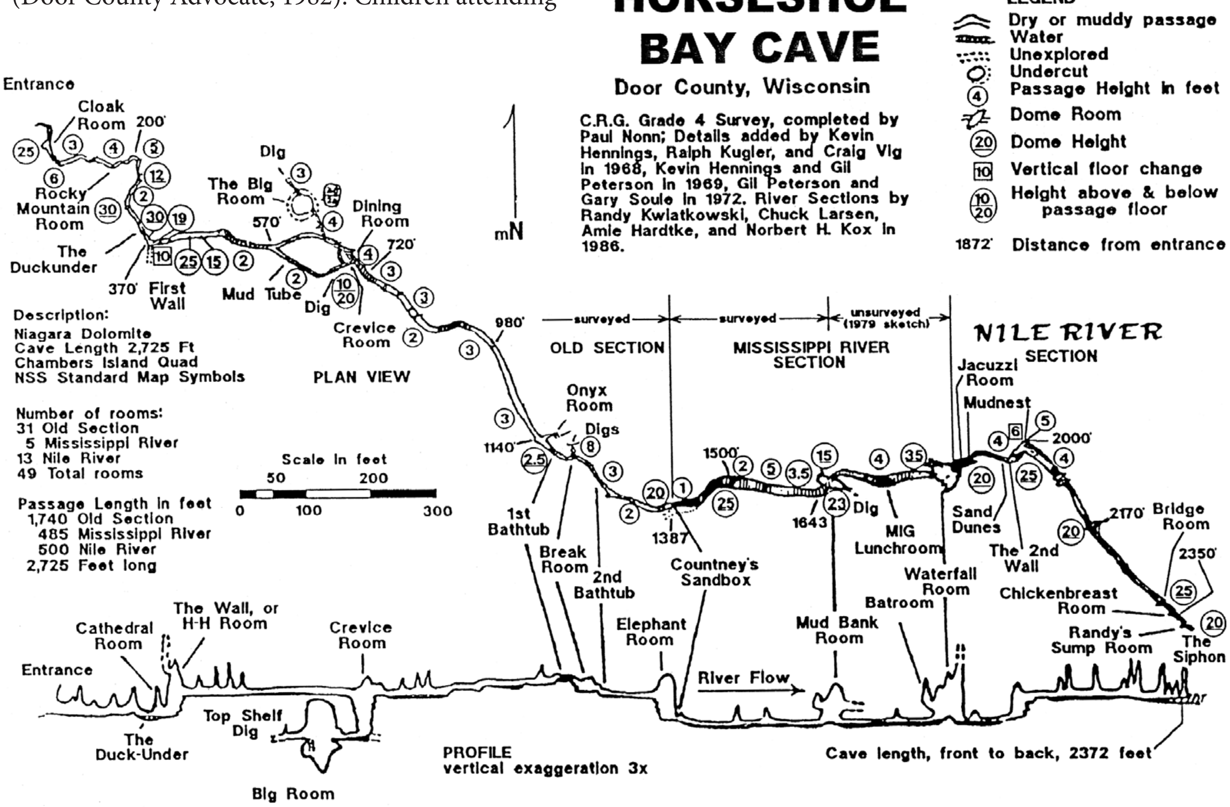

Figure 7. *Horseshoe Bay Cave map. Source: Wisconsin Speleological Society.*

school on the other side of the valley were rowed across the pond. One day a sinkhole opened up, taking water in, and a few hours later water was observed flowing out of Horseshoe Bay Cave. The whole valley drained during the day, according to witnesses at the time (G.K. Soule, personal communication). This is an unusual event, but during many years, snowmelt water flows through Plum Bottom and disappears into the ground in a farm field with no visible sinkhole. Whether that water flows directly to Horseshoe Bay Cave or to other discharge points along the escarpment to the west has not been documented. Many other small sinkholes are known in the area.

The entrance portion of Horseshoe Bay Cave has been obtained by Door County as a part of a larger county parks expansion project. Use of the cave for educational visits by school groups and the public is included as a desired function of a cave management plan. Much of the rest of the cave, not under county ownership, extends under an adjacent golf course. The cave entrance now has a bat-friendly gate, and access policies are being formulated with the Door County Parks Department.

THE IMPORTANCE OF CAVES AND KARST

Caves and karst play an extremely important role in the quality of the region's groundwater. In northeastern Wisconsin, the majority of the population gets their drinking water from wells. Many people think that the earth filters their well water adequately and they don't have to worry about its safety; however, the many fractures and joints in the bedrock and occasional cave passages allow water to travel into the water table rapidly without the filtering of harmful bacteria and chemicals that would naturally occur as water percolates slowly through soil, sand, and organic matter.

A testing project by the Wisconsin Geological and Natural History Survey in northern Door County from 1986 to 1990 (Bradbury and Muldoon, 1992) had some interesting results. A series of test wells were drilled in a pattern and tested for many parameters. A camera lowered into one bore hole showed fractures and areas that had been dissolved at different levels. At about 150 ft (45 m) below the surface, the rock had a dissolved or "Swiss cheese" appearance rather than discrete fractures. In drilling the wells, voids or holes were encountered and drilling fluids were lost at several levels. In one case, water was "forcefully rejected" at a well drilled 200 ft (60 m) away, showing a very open underground connection.

A test which introduced a tracer element at one test well and measured its arrival at a neighboring test well showed a groundwater flow rate of 55 ft (16.8 m) per day, which certainly allows little chance for filtering of contaminants. In September of 1987, contamination occurred that suggested an even faster flow rate: construction at a farm about a half mile from the test site caused farm wastes and blasting residue to flush into an exposed fracture system, and high nitrate levels were measured in a down-gradient test well the next time samples were obtained. There were 2 weeks between tests, so the precise flow rate cannot be determined, but it was at least 210 ft (64 m) per day. To a different test well farther away, the flow rate was at least 380 ft (116 m) per day. There are no previously known cave passages in this area, only the intersecting network of vertical and horizontal fractures revealed by the research of Bradbury and Muldoon (1992).

> "A test…showed a groundwater flow rate of 55 ft (16.8 m) per day, which certainly allows little chance for filtering of contaminants."

The author's personal experience also highlights this rapid flow of groundwater pollution. Several years ago manure was spread on a snow-covered farm field about ⅛ mi (200 m) from our well in the Plum Bottom area of Door County. Shortly after the snow rapidly melted, our tap water turned brown and tested positive for coliform bacteria for months afterward. The well had been recently drilled over 300 ft (91 m) deep and was properly cased, but was polluted anyway. Neighbors reported that their well water regularly turned brown in spring and they were in the habit of using bottled water during that time. About a year later a small sinkhole opened up at the low end of the farm field and a narrow crack was open at least 20 ft (6 m) deep. This may have been the source of well pollution. Later that summer the sinkhole was filled in again with soil.

CONCLUSION

Caves and their associated features are interesting and important features of the landscape on the Niagara Escarpment. Caves at Ledge View Nature Center near Chilton and Cherney Maribel Caves County Park have interpretive tours for the public and school groups. Caves provide habitat for animals large and small, from raccoons and bats to microscopic organisms. Caves, sinkholes, and underground water drainage are important to drinking water safety and public health.

REFERENCES CITED

Bradbury, K.R., and Muldoon, M.A., 1992, Hydrogeology and groundwater monitoring of fractured dolomite in the Upper Door Priority Watershed, Door County, Wisconsin: Final report to the Wisconsin Department of Natural Resources: Wisconsin Geological and Natural History Survey Open-File Report 1992-02, 70 p., 2 appendices.

Door County Advocate, April 21, 1982, "News of 60 years ago, April 21, 1922," p. 2.

Dott, R.H., Jr., and Attig, J.W., 2004, Roadside geology of Wisconsin: Missoula, Mont., Mountain Press Publishing Company, 346 p.

Dutch, S., 2009, Lake Oshkosh drainage (12Ka): http:www.uwgb.edu/dutchs/GeologyWisconsin/geohist/wi12ka.htm, accessed September 20, 2012.

Luczaj, J.A., 2013, Geology of the Niagara Escarpment in Wisconsin: *Geoscience Wisconsin,* vol. 22, no. 1, 34 p.

Luczaj, J.A., and Stieglitz, R.D., 2008, Geologic history of New Hope Cave, Manitowoc County, Wisconsin, *in* The Wisconsin Speleologist: The science of caves: Franklin, Wis., Wisconsin Speleological Society, p. 7–17.

Note: For more information on the caves mentioned, visit the following websites:
Wisconsin Speleological Society (wisconsincaves.org),
Ledge View Nature Center (ledgeviewnaturecenter.org),
and Maribel Caves (maribelcaves.com).

Caves are a delicate and potentially dangerous environment and it is not recommended to visit them without trained leadership.

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY

GEOSCIENCE WISCONSIN • VOLUME 22, PART 6 • PUBLISHED ONLINE 2016

Building a conservation geology ethic along the Great Arc

Eric W. Fowle[1]

ABSTRACT

The Niagara Escarpment and its adjacent cuesta formation form an approximate 650-mile-long corridor that traces the outer edge of the ancient Michigan Basin. While this geomorphologic feature straddles numerous political divides, it ties together the entire Great Lakes system, as no single lake is more than 50 mi (80 km) away from the escarpment's majestic cliff faces. This "Great Arc" creates and influences a terrestrial environment like no other feature of similar size in the world. This international-scale corridor contains a variety of geologic and biotic resources along its extent that expresses its uniqueness—and generates intrigue—like no other geologic feature in the Midwest.

This paper provides the reader with an overview of the Niagara Escarpment resource under the context of the Great Arc and discusses past and current education and protection efforts by both government and non-government entities as components of a broader "conservation geology" concept. The discussion surveys the potential for developing a formal conservation geology program (a Geopark) that spans the Great Arc, combining existing efforts into a more cohesive program for conservation awareness and action.

INTRODUCTION

Formation and description of the Niagara Escarpment

The Niagara Escarpment is comprised of dolomitic rock that was originally deposited as sediment on an ancient salt water sea floor about 420 million years ago. Its cliff faces represent the outer edge of the circular Michigan Basin. The present-day cliffs of the escarpment were formed by millions of years of weathering and erosion, and further enhanced by the actions of glaciers during the last several ice ages. In Wisconsin, the Niagara Escarpment spans over 230 mi (370 km) and reaches from Waukesha County in the south, to the tip of the Door Peninsula in the north. Internationally, the Niagara Escarpment is an approximate 650-mile-long sickle-shaped geomorphologic landform that spans the Great Lakes region in both the United States and Canada (fig. 1).

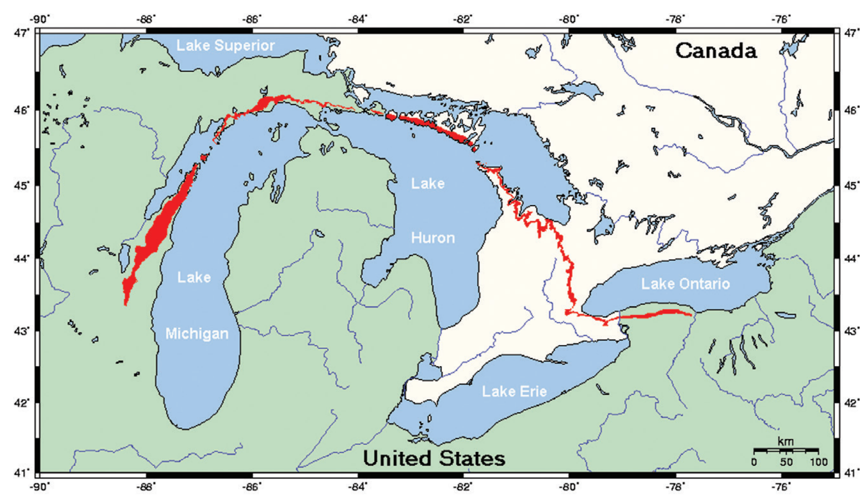

Figure 1. *Location of the Niagara Escarpment.* Source: http://commons.wikimedia.org

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Unique aspects of the Niagara Escarpment

The Niagara Escarpment's exposed cliff faces are the most widely known feature of this corridor's landscape. Unique in and of themselves, the craggy walls tower hundreds of feet above the adjacent landscape in some places. Many native and present-day cultures have been impressed by the escarpment's scenery and vistas and have held them in high regard.

Repeated glaciation and the fluctuating waters of the Great Lakes system have shaped the escarpment's landscape into a variety of large waterfall-scoured gorges, glacial re-entrant valleys (valleys cut through the escarpment by flowing ice), ancient beach ridges, low hills, steep slopes, and broad benches. These varied features create a unique natural setting and a productive agricultural environment. Glaciers and other erosional forces carved out distinctive formations and features including waterfalls, sea-stacks, sea caves, talus slopes, crevice caves, canyons, natural arches, glacial scrapes, scours, and potholes (fig. 2). Over time, water has dissolved the landscape behind its brow into a variable karst terrain. Furthermore, the highly fractured bedrock is covered with relatively thin soils, thereby greatly influencing the corridor's surface water and groundwater.

> "…the escarpment's cliff faces and rock formations harbor truly unique and extreme environments."

From a habitat perspective, the escarpment's cliff faces and rock formations harbor truly unique and extreme environments. The corridor is home to such rare and unique habitats such as algific talus slopes (creating cool, humid microclimates), moist cliff faces, dry cliff faces, alvars (grasslands on thinly soiled limestone plains) and savanna (fig. 2). The cliff faces are home to gnarled and twisted ancient cedar trees which cling to the rock and, in some cases, are over 1,500 years old. The escarpment landscape is often forested, providing habitat and migratory corridors for birds, while its caves contain major bat hibernacula. In Wisconsin over 241 rare and endangered species, both plant and animals, have been documented to exist in the corridor's unique environs (Anderson and others, 2002).

The Niagara Escarpment corridor has been used by mankind since Paleo-Indian times over 12,000 years ago (10,000–9,200 B.C.). Evidence of settlement and use of the landscape by later Woodland period (A.D. 300–1,000) cultures is well documented. Numerous archeological finds, including ancient petroforms, petroglyphs, and effigy mounds, are present throughout the corridor. Furthermore, written and oral histories of native tribes describe the escarpment as a significant and revered feature of the ancient landscape, and sacred sites abound. As settlement by French explorers occurred, the Niagara Escarpment's resources were used for hunting, trapping, agriculture, forestry, and mineral extraction. These uses were repeated by the numerous eastern European immigrant cultures during the 1700s and 1800s and exist through the present day. They continue to be the mainstay of the rural economy within the Great Arc corridor. Over the last 50 years, additional advancements in conservation activities have boosted the tourism/geotourism portion of the economy along the Great Arc. Urban and rural development interests have also greatly benefited from the natural beauty and aesthetic qualities of the Niagara Escarpment.

The combination of the escarpment's unique natural systems, along with its important role in culture and heritage, is what led to portions of Ontario's escarpment corridor being designated as a United Nations Educational, Scientific, and Cultural Organization (UNESCO) Biosphere Reserve in 1990. This noteworthy designation makes the Ontario portion of the Niagara Escarpment part of a global network of 631 biosphere sites (UNESCO, 2014).

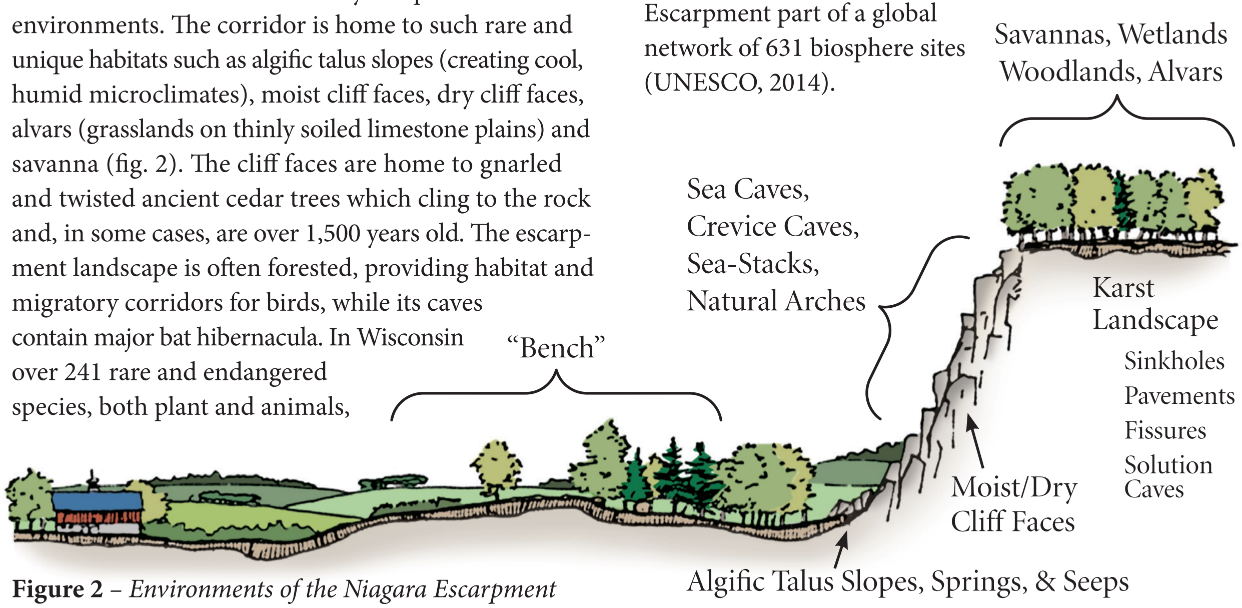


Figure 2 – *Environments of the Niagara Escarpment*

Source: Adapted from Kasprzak, C.M., and Walter, M.A., 2001.

The 'Great Arc' context

In recent years, the idea of the Great Arc has emerged as a tool for building cross-boundary conservation and sustainable development activities in Ontario and adjoining states in the U.S. The Great Arc refers to the entire Niagara Escarpment landform, from central New York, north through Ontario and south along the west side of Lake Michigan. The Great Arc is a special landscape of considerable natural, cultural, economic, aesthetic, recreational, touristic, and symbolic importance in Canada and the U.S. At its core, the Great Arc is a corridor for migratory birds and wildlife and also for people who hike and move along it through the seasons (Nelson and others, 2005).

In 2002 the Great Arc Initiative was launched and has involved many individuals and groups, although in recent years, no significant activity has occurred. The Initiative is loosely organized and participation levels of its partners vary based on time availability and level of interest. To generally describe the makeup of the effort, the following groups, entities, and individuals are noted as having some significant past level of involvement in the Great Arc Initiative:

1. University of Waterloo, Ontario
2. University of Toledo, Ohio
3. Ontario's Niagara Escarpment Commission
4. Niagara Escarpment Resource Network (NERN)
5. Western New York Land Conservancy
6. Michigan Karst Conservancy
7. Nature Conservancy of Michigan
8. U.S. Forest Service (Hiawatha, MI Unit)
9. Parks Research Forum of Ontario

Five separate conferences and symposiums were held in Wisconsin, Ontario, and the Upper Peninsula of Michigan between 2001 and 2006 in an effort to draw interest and attention to the development of the Great Arc concept. While no significant activity occurred with this group between 2007 and 2014, a surge of recent activities in Wisconsin regarding awareness of the Niagara Escarpment prompted the rekindling of this effort through the development of an international symposium in Tobermory, Ontario, in 2015. The Bruce Peninsula-based Sources of Knowledge (SOK) organization collaborated with seven Wisconsin experts to speak to various commonalities and differences of communities situated on the escarpment. Subjects such as geology, karst, biology, sustainability, tourism, economic development, and Geoparks have prompted additional dialogue and interest to formalize this effort with the goal of developing programs for information exchange and the development of a cross-border Geopark.

A DEFINITION FOR CONSERVATION GEOLOGY

Global examples

Conservation geology takes cues from the more well-known and widely adopted concept of conservation biology. The term *conservation biology* was introduced as the title of a conference held at the University of California, San Diego in 1978, and was defined as "the scientific study of the nature and status of Earth's biodiversity with the aim of protecting species, their habitats, and ecosystems from excessive rates of extinction" (Wikipedia contributors, 2010). Much like conservation biology, conservation geology is an interdisciplinary subject drawing on sciences, economics, and the practice of natural resource management—with the obvious emphasis on geology.

Geology encompasses scientific studies of evolution, history, structure, and composition of the earth. This field has explored the formation and evolution of the earth's history over the past billion years. Until recently, the field of geology emphasized exploration of earth resources for human need with limited focus on conservation (Suratman, 2008).

Conservation geology provides a means of protecting a geological formation or phenomenon that has special scientific value, representing different stages of the earth's geological history and its transformation through various geological processes (Suratman, 2008). The new field of conservation geology requires the input of all traditional fields of geology. A successful research and development program for advancement of this field requires expertise from disciplines outside of geology such as planning, law, tourism and management. Geologists should lead the development efforts and harness multidisciplinary networking to ensure that conservation geology contributes to the aspiration of achieving sustainable development (Komoo, 2008).

An outstanding example of conservation geology can be found in the Langkawi Geopark in Malaysia. This site is made up of 99 tropical islands which provide a rich example of geodiversity. Many of the islands have scientific value as well as national and regional significance. This particular site is mostly protected within the Malaysian holistic nature conservation concept of a Geoforest Park, wherein rock conservation is equally treated as biological conservation and other nature conservation components (Leman and others, 2008).

Other examples of conservation geology are known by different names. In the United Kingdom, formal policies and regulations for consideration of geologic sites are not in place; however, the notion of Regionally Important Geological and Geomorphological Sites (RIGS) are included in a non-statutory manner. RIGS are designated and protected sites of regional and local importance for geodiversity (geology and geomorphology) and are noted for their value to Earth science, and to Earth heritage in general. RIGS may include cultural, educational, historical, and aesthetic resources (RSNC, 1999).

The concept was introduced by the Nature Conservancy Council in their publication, *Earth Science Conservation in Great Britain – A Strategy* (1990). RIGS are locally designated with a scheme that relies almost entirely on volunteer efforts (DEFRA, 2006). In some cases, local action plans have also been prepared which aim to set local objectives to deliver and promote geological conservation based on knowledge of a broader existing network of nationally important geological Sites of Special Scientific Interest (SSSIs).

There are a number of similarities between geotourism, geoheritage, and conservation geology. While individual approaches may vary, four common themes exist across the range of definition:

1. **Education and awareness:** Encompasses activities that are critical to an individual's understanding of the geologic processes, and the resulting implications as they relate to human activity on the affected landscape. Knowledge can be powerful in terms of building conservation values and an improved land ethic. Education and Awareness can be delivered in a variety of ways to target diverse audiences at all age levels. From a tourism perspective, such information provides a context or a setting to help visitors understand what they are seeing on the landscape.

2. **Planning and regulation:** A key component to the long-term protection of any geologic resource. Most conservation-based plans and regulations are based on the concept of "community good" and the overall protection of the public's health, safety, and welfare with respect to the environment and its functions and values. They typically restrict certain uses, or the intensity of uses, for private landowners. Many plans and regulations have been successfully implemented along the Great Arc over the decades, often as a result of the increase in awareness by elected officials and regulatory agencies.

3. **Land conservation and stewardship:** Consists of both short- and long-term actions taken across the landscape to directly enhance, maintain or protect features or systems of the natural environment. In addition to outright land purchases by government and non-government entities, voluntary transferrals of property rights (conservation easements sold, donated, or partially donated by the landowner) are becoming an increasingly popular tool for protection. Along the Great Arc corridor, this includes agency-driven agricultural protection and land management programs, and the stewardship actions of individual property owners.

4. **Recreation and geotourism:** Public access to the land is critical to furthering the notion of conservation geology. Using lands for both active and passive recreation activities helps to bolster local and regional economies with businesses linked to the needs of tourists. In addition, when private businesses become involved in conservation activities, they help to promote a broader awareness of conservation geology. A system of publicly owned lands linked by various trails and paths has begun to form along the corridor.

While each of these components can exist independently, the inter-relationships are evident. Collaboration and communication at all levels will be required to integrate the four themes of conservation geology into an effective program that spans the Great Arc.

A CROSS-SECTION OF CONSERVATION GEOLOGY ALONG THE GREAT ARC

The application and practice of conservation geology exists throughout the Great Arc corridor in many different forms. Using the context of the definition and framework elements in the previous section, this discussion focuses on describing several of the most established and relevant activities occurring in the Great Arc which advance the creation of a conservation geology ethic.

Some of the earliest efforts began in Ontario over 50 years ago, while other efforts are much more recent. Nonetheless, they all comprise an important foundation for a coordinated international-scale conservation geology program for the Niagara Escarpment. These 'stand-alone' initiatives are inextricably linked to the underlying resource and therefore to one another.

ONTARIO'S NIAGARA ESCARPMENT

Education and awareness

One of the major grassroots entities in Ontario involved in education and awareness (as well as direct activism) is the Coalition on the Niagara Escarpment, or CONE. CONE is a nonprofit alliance of environmental groups, conservation organizations, and concerned citizens and businesses founded in 1978 and dedicated to the protection of Ontario's Niagara Escarpment. The group's origins began in the public discontent of a nonmetallic mining company's 1962 blast through the face of the Niagara Escarpment in Milton, Ontario (CONE, 2010).

During the mid- to late 1960s, CONE organized, consulted, and leveraged support for the eventual development of the draft Niagara Escarpment Plan. The creation of the Niagara Escarpment Commission (NEC) occurred in 1973 and, as a regulatory entity, it assumed development control within a defined corridor in 1975. In 1978, CONE formalized and succeeded in opening NEC meetings to the public, and it further monitored and participated in the two plus years of public hearings associated with the development of the NEC's Niagara Escarpment Plan. In 1985, CONE received formal recognition by NEC with an appointment to the land use decision-making body so as to provide a single voice representing concerned conservation organizations. Since that time, CONE has continually monitored the NEC's meetings and has actively participated in the NEC's 5-Year Plan Review processes (CONE, 2010).

CONE's organization consists of a seven-member volunteer board representing 27 separate organizations. Their role in planning is to assist in identifying sensitive areas and help incorporate environmental issues into management plans, thereby avoiding damage to endangered species of plants and animals living on the Niagara Escarpment. CONE also adopts formal positions on issues and publishes policy statements in four main focus areas: aggregates (mining), aboriginal peoples, wind turbines, and water. For example, in 2002 CONE released its water policy paper, a technical assessment of the need to change and upgrade the water science of the Niagara Escarpment Plan. Over the years, CONE has played an instrumental provincial leadership role in influencing and improving government decisions on water, aggregate, land use, transportation, economic, and other sustainability issues along Ontario's Niagara Escarpment corridor (CONE, 2010).

CONE's efforts have gone far beyond its formal role in the provincial government's Niagara Escarpment Commission. CONE created an Escarpment Enterprise Club, which highlights private corporations and their leaders who are doing the "right things" environmentally and finds ways to partner with them to show positive examples of the way to move forward and protect the Niagara Escarpment. In 2001, CONE created a sister organization called the Niagara Escarpment Foundation, a registered charity established to undertake research and education initiatives. They also lead research initiatives to learn more about the escarpment and best practices for protecting it, undertake educational programs to foster public appreciation for the escarpment and the issues that impact its integrity, and build awareness through their road signage program announcing that the Niagara Escarpment's countryside is part of this exclusive UNESCO Biosphere Reserve designation (CONE, 2010).

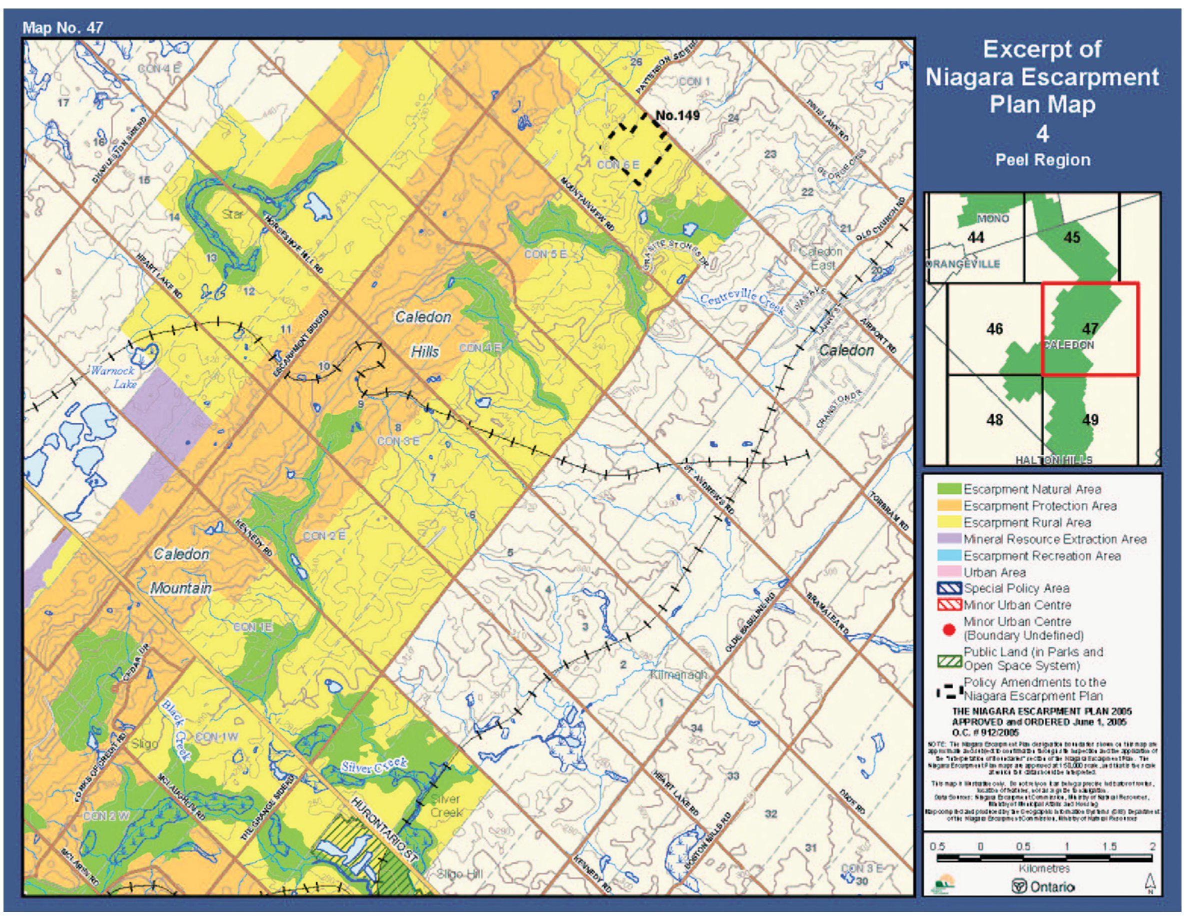
Planning and regulation

The Niagara Escarpment Plan, administered by the Niagara Escarpment Commission (NEC), serves as the primary mechanism for planning and regulation of the escarpment corridor in Ontario. This official plan guides provincial objectives for resource protection and land use control within the Niagara Escarpment corridor. Often noted as Canada's first "green plan," this visionary environmental land-use document was approved by the Ontario government in 1973 through adopting the Niagara Escarpment Planning and Development Act (NEC, 2010).

As a regulatory agency, the NEC conducts itself according to the management principles of the Government of Ontario, but its decisions are made independently and impartially. The commission has 17 members appointed by Order-in-Council (a type of legislative process). Nine members, including the chair, represent the public-at-large, and eight members represent counties and regions within the escarpment area. The NEC meets monthly to make decisions on development permit applications; consider recommendations on Plan amendments; comment on official plans, development proposals, consent applications, environmental assessments; and review Niagara Escarpment Plan policy issues (NEC, 2010).

The Niagara Escarpment Plan consists of a series of maps indicating six separate districts (fig. 3). Similar to a typical zoning ordinance, each district is accompanied by its own set of rules regarding allowable land uses and development controls. The districts range in intensity from strongly protected escarpment natural areas to intensely developed urban areas with a separate district designation existing for mineral extraction activities (aggregate). Map amendments and boundary changes to these districts are permitted on occasion, but follow a strict set of application and review standards. Similarly, a set of development standards (Regulation 828-90) apply to all development projects within the corridor's districts that allow such uses. An established process for the application and filing of development permits was created to accurately assess proposed projects and their conformance with policies and regulations. Separate and distinct policy documents have also been developed to cover topics such as "significant woodlands" and "visual assessment guidelines" (NEC, 2010).

> "The districts range in intensity from strongly protected escarpment natural areas to intensely developed urban areas…"



Source: Niagara Escarpment Commission, 2010.

Figure 3. *Niagara Escarpment plan map.*

Land conservation and stewardship

Numerous non-government organizations and provincial ministries (agencies) exist to monitor and protect the resources of the Niagara Escarpment. None, however, have been more effective than the use of land trusts to directly preserve, protect, and enhance the Niagara Escarpment corridor permanently.

According to the Ontario Land Trust (2010), of the five existing registered land trusts along Ontario's portion of the Niagara Escarpment corridor, none has been more successful than the Escarpment Biosphere Conservancy (EBC). The Escarpment Biosphere Conservancy was formed in 1998 and is now one of the most prominent and active organizations involved in the protection of private lands throughout the corridor. Land protection efforts are funded through a variety of means, including traditional landowner donations and the use of tax incentives, member donations, and charitable foundations.

Several unique and nontraditional fundraising methods have been developed using a variety of partnership arrangements. Examples include: (1) "Avalon Funds," which are offered to members as a new way to donate using secured endowment bonds which are backed by life insurance policies; and (2) partnering with Ag Energy, a farmers' co-op, which allows the EBC to offer competitive special usage rates that include a $75 average annual donation, plus one-half of that on income tax savings (EBC, 2010).

As of 2015, the EBC has successfully protected 145 reserves covering over 11,000 acres. Within these reserves lie over 18 km (11 mi) of Great Lakes shoreline and the habitats of 72 rare and endangered species (EBC, 2015). The EBC's ability to reach out to prospective landowners with their suite of conservation tools and products have increased protection, awareness, and tourist revenue generation for the Niagara Escarpment in Ontario.

Recreation and geotourism

While the Niagara Escarpment is used for many recreational activities in Ontario, including downhill skiing and rock-climbing, no activity is more prevalent than hiking or walking the Bruce Trail, Canada's oldest and longest marked footpath (fig. 4).

Source: The Bruce Trail Conservancy, 2014.

Figure 4. *Bruce Trail map.*

In 1960 the idea of a public footpath spanning the entire Niagara Escarpment was born by naturalist Raymond Lowes. He expressed his vision of a footpath at a meeting of the Federation of Ontario Naturalists and the subsequent first meeting of the Bruce Trail Committee (now four members strong) was held. The committee recognized that gaining access to the Niagara Escarpment was the critical first step in building the Bruce Trail, as a majority of its corridor lay on privately held lands. Understanding that building relationships was essential, then Trail Director Philip Gosling visited major towns along the proposed trail route to solicit help and a team of volunteers went door-to-door to discuss the vision for the trail with residents (BTC, 2015).

The Bruce Trail Conservancy (BTC), as it is now known, is a charitable organization committed to establishing a conservation corridor containing a public footpath along the Niagara Escarpment, to protect its natural ecosystems and to promote environmentally responsible public access. A formal Board of Directors governs the BTC and volunteers from the nine separate Bruce Trail Clubs are responsible for maintaining, stewarding, and promoting the trail. The BTC is now supported by more than 1,000 volunteers and 8,500 members (BTC, 2015).

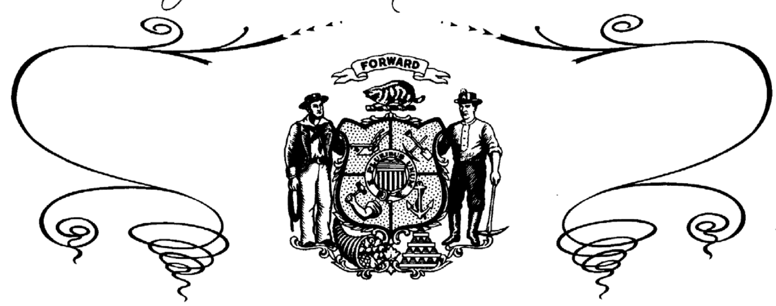
The economic impacts of the Bruce Trail's existence have been documented over the years. A 1997 study determined that direct recreational expenditures associated with visitors to the Bruce Trail contributed more than 4.4 million dollars (CAN) annually to the local economy. Multipliers which illustrate the indirect broader effect to regional economies raise this figure to as much as 10 million dollars (CAN) annually (Schutt, 1997). The trail's overall importance as a tourist attraction and economic generator has helped foster the idea that providing public access to the escarpment also supports and solidifies conservation values.

WISCONSIN'S NIAGARA ESCARPMENT

Education and awareness

The education and awareness efforts surrounding Wisconsin's Niagara Escarpment began in 1998. The Niagara Escarpment Resource Network (NERN) has been the leading organization behind enhancing the public's knowledge of the Niagara Escarpment through its many coordinated, partnership-style efforts.

State of Wisconsin



2009 Assembly Joint Resolution 1

ENROLLED JOINT RESOLUTION

Relating to: proclaiming Niagara Escarpment year and month.

Whereas, the Niagara Escarpment is a 650 mile long geologic feature of international scale and global importance that reaches across Wisconsin, Michigan, Ontario, and New York; and

Whereas, in Wisconsin, the Niagara Escarpment extends for a distance of over 230 miles and runs though Door, Kewaunee, Brown, Manitowoc, Calumet, Fond du Lac, Dodge, and Waukesha counties; and

Whereas, the Niagara Escarpment's cliff faces and high elevation on the landscape provide numerous important vistas and viewsheds, several of which are as much as 200 feet above the surrounding landscape; and

Whereas, the Niagara Escarpment corridor is home to high levels of biodiversity and unique plant and animal species, and over 240 different rare, threatened, or endangered plant and animal species have been identified along the Niagara Escarpment; and

Whereas, the Niagara Escarpment is known to have highly sensitive groundwater resources due to its composition of highly fractured bedrock and karst features; and

Whereas, the Niagara Escarpment contains numerous high–value passive recreation areas and contributes significantly to the tourism–based economy of many of the corridor's communities, and two of Wisconsin's most visited State Parks — Peninsula and High Cliff — lie along the Niagara Escarpment; and

Whereas, the Niagara Escarpment corridor has significant historical and cultural features which equate with both past and present uses of its resources. The Niagara Escarpment has been used since Paleo–Indian times for ceremonial purposes, has a long tradition of being a top agricultural area, is home to a rapidly growing viticulture industry and wine producing region, and is known as a present day source for quality building materials such as cut stone and crushed rock; and

Whereas, past and present landowners have used the Niagara Escarpment landscape as a resource for which to build communities, sustain their livelihoods, and promote a strong stewardship ethic; and

Whereas, the Niagara Escarpment has been recognized by the Wisconsin Department of Natural Resources as a highly ranked "Land Legacy Place"; now, therefore, be it

Resolved by the assembly, the senate concurring, That the members of the Wisconsin state legislature proclaim the year 2010 as the "Year of the Niagara Escarpment" in the State of Wisconsin so as to foster awareness and education on this important and unique landscape feature; and, be it further

Resolved, That the month of May 2010 be proclaimed as the "Month of the Niagara Escarpment" in the State of Wisconsin in order to promote efforts to recognize the Niagara Escarpment's significance as a statewide geologic and natural resource.

Figure 5. *State of Wisconsin Joint Assembly Resolution proclaiming 2010 as the "Year of the Niagara Escarpment."*

The Network's creation dates back to a conference that was held to inform people of the unique attributes of the Niagara Escarpment. Over 100 attendees provided the feedback and the motivation to create an informal organization that fostered education, awareness, research, planning, and ultimately conservation efforts at the community level, which would begin to protect the critical resources of the Niagara Escarpment in Wisconsin. The group started as a series of regular meetings amongst three key stakeholders who were eventually chosen by the group to co-lead the effort: the East Central Wisconsin Regional Planning Commission, the Bay-Lake Regional Planning Commission, and the Wisconsin Department of Natural Resources.

NERN's activities began to gain attention from local legislators, and in early 2009 the Network's crowning achievement was made: the formal recognition by the state legislature of the Niagara Escarpment as a unique and highly valued landscape within northeastern Wisconsin. Joint Assembly Resolution AJR-1 (fig. 5), sponsored by Rep. Al Ott (R-3rd Assembly District), officially designated 2010 the "Year of the Niagara Escarpment." This accomplishment motivated many of NERN's partners to celebrate by developing and dedicating numerous events, tours, educational programs, and promotional projects to further elevate the public's knowledge of this truly remarkable landscape.

The momentum built over the last few years fostered an opportunity to advance the efforts of the informal organization and a decision was made to join forces with an existing nonprofit conservation organization, the Lakeshore Natural Resource Partnership (LNRP). In early 2010 the Niagara Escarpment Resource Network officially became a dedicated program area of LNRP, joining the ranks of other successful efforts which focus on the health of the entire Lakeshore Basin—of which the Niagara Escarpment essentially forms the basin's western boundary.

As its name suggests, the Network exists mainly to link people with information in hopes that it will effect positive change in both individual stewardship and community-level conservation of this unique landscape's natural and cultural resources. NERN now serves to build a stronger foundation for conservation by continuing its awareness campaign and developing projects and plans which focus on maintaining or improving the corridor's ecology and economy.

Planning and regulation

Wisconsin has no equivalent to Ontario's Niagara Escarpment Plan either in scope or as a basis for state land use management and regulation. Rather, long-term plans for the Niagara Escarpment are fragmented and dispersed throughout numerous connected and disconnected documents, which were developed at all levels of government throughout the state. WDNR State Natural Area (SNA) plans, trail plans, recreation plans, and wildlife plans acknowledge the existence of the broad Niagara Escarpment corridor and recognize its uniqueness; however, they do little to form official policy that is implemented consistently. Most recently, the WDNR's *Land Legacy Report* has done the most to acknowledge and support the recognition of Wisconsin's Niagara Escarpment as one of the most special and valued landscapes in all of Wisconsin. The purpose of the *Wisconsin Land Legacy Report* is to identify the places believed to be most important to meet the state's conservation and recreation needs over the next 50 years. This report specifically identified the Niagara Escarpment corridor as being one of Wisconsin's top three specific sites/areas for future conservation efforts (WDNR, 2006).

Regional plans have been developed by both of the Regional Planning Commissions (RPCs) that cover portions of the escarpment's landscape; however, they too are not in-depth enough to provide sufficient guidance to the local units of government. *The Niagara Escarpment Greenway Plan,* an ongoing planning initiative (slated for completion in 2016), is being prepared under the guidance of the Niagara Escarpment Resource Network and will serve as an initial step for identifying policy issues and program opportunities which are more closely tied to community values, as well as opportunities for trail development and geotourism. Long-term, this plan could foster a more comprehensive approach to regulatory consistency issues along the numerous governments responsible for the management of this feature.

County and community level "smart growth" comprehensive land use plans do a fair job of recognizing the Niagara Escarpment; however, community values associated with the escarpment are difficult to measure, and political pressures easily restrict the ability of

"Wisconsin has no equivalent to Ontario's Niagara Escarpment Plan…"

communities to increase regulation and protection along its cliff faces and environs. Some communities, however, have had a great degree of success in improving the levels of protection for this resource.

From a regulation standpoint, most of the existing land-use provisions that apply to the Niagara Escarpment occur at a county or community level and are very dependent upon the communities' knowledge of and support for protection of the escarpment and its associated features (with the exception of the broad provisions offered through the federal Endangered Species Act, state authorized shoreland zoning, or state/county implemented farmland preservation programs). Few, if any, regional or statewide regulations exist that are specific to the Niagara Escarpment in Wisconsin.

In 2009, the escarpment's groundwater resources were the subject of a state Senate Bill (SB 632) that was proposed but never adopted. The rules were developed in response to historic well contamination issues stemming from both human wastewater treatment systems and the management of livestock manure within the corridor. They would have applied only to areas where carbonate bedrock is within 50 feet of the surface (fig. 6) and attempted to instill additional precautionary rules that would protect the aquifers sensitive resources. Justification for the proposed legislation was derived in part from the work of the Northeast Wisconsin Karst Task Force that convened for several years to discuss knowledge of human impacts and gaps in that knowledge base, best management methods for agriculture, and prioritized implementation of available technologies to better deal with karst environments.

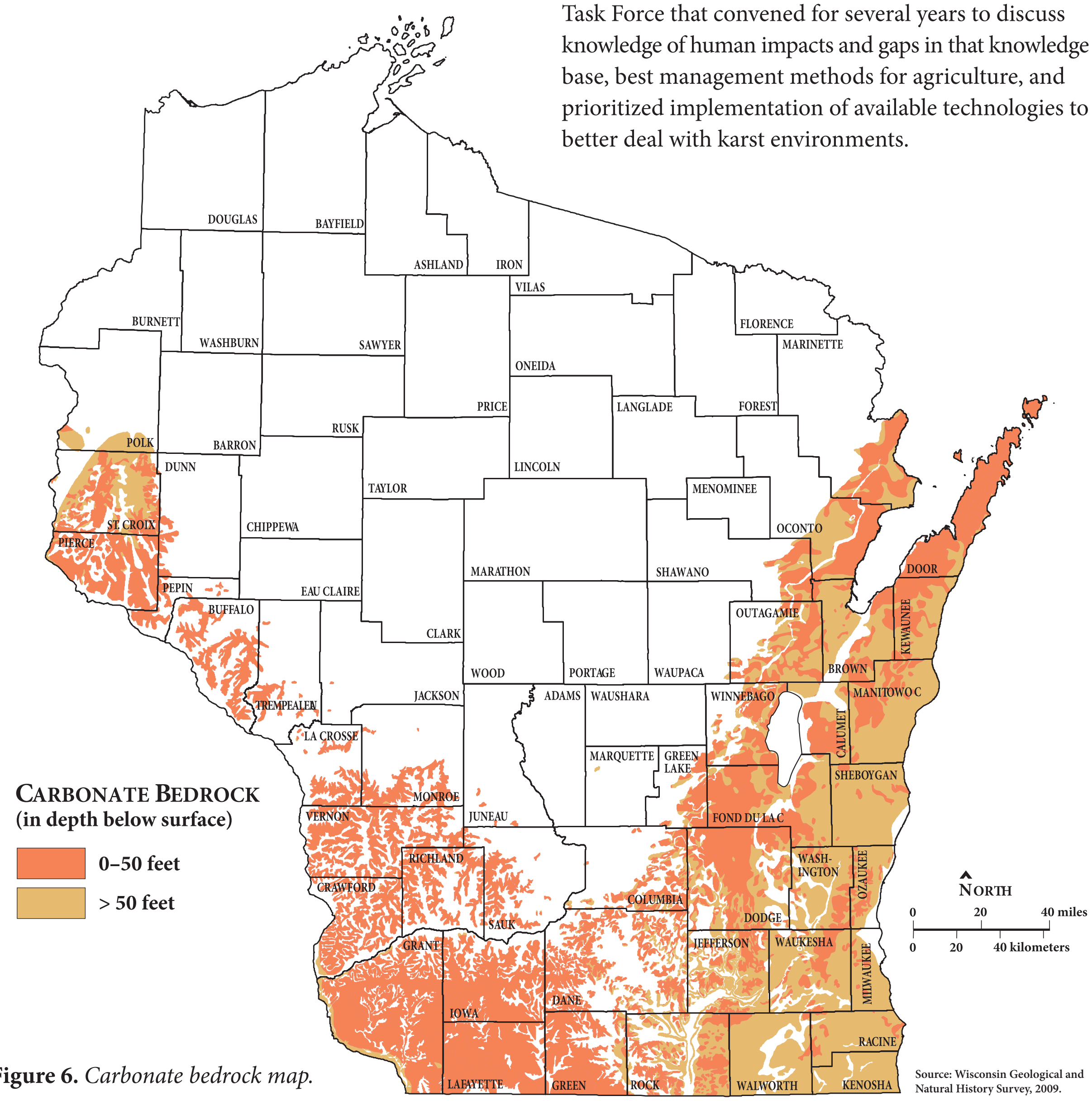


Figure 6. *Carbonate bedrock map.*

Land conservation and stewardship

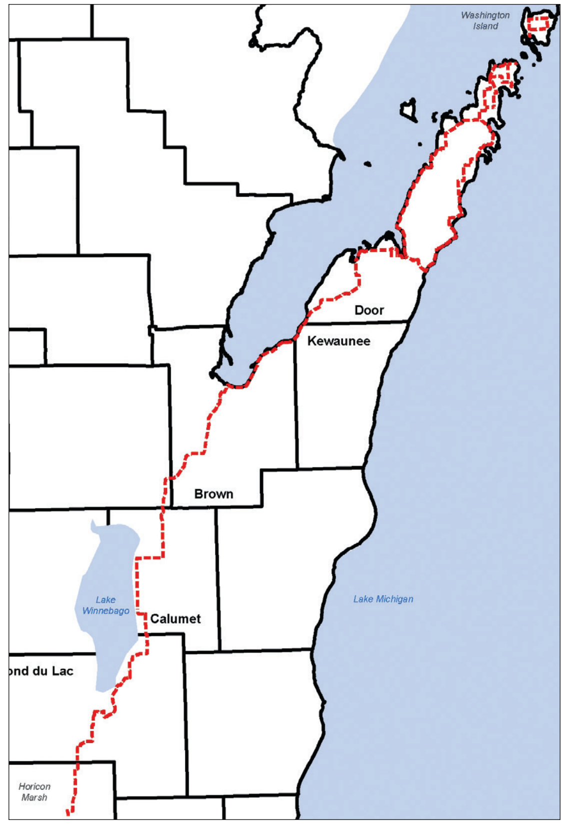
Like Ontario, many public and private conservation and stewardship activities are taking place in Wisconsin's Niagara Escarpment corridor. Effective efforts in land protection have been implemented by entities such as the Glacial Lakes Conservancy, Door County Land Trust, and the North Eastern Wisconsin Land Trust. Other efforts for conservation and stewardship focus on the underground, as the escarpment's fragile Niagaran aquifer is the source for much of the drinking water in eastern Wisconsin.

Leading the way in on-the-ground actions to improve groundwater conservation and stewardship efforts is the local implementation of the national Groundwater Guardians program. Groundwater Guardians is sponsored by the Groundwater Foundation in Lincoln, Nebraska, and connects and recognizes communities that take action to protect and educate the public about groundwater (Wisconsin Ground Water Association, 2010). Much of the program's work is overseen by local chapters such as the Calumet County Groundwater Guardians. Calumet County's chapter has implemented programs in partnership with local governments and other conservation organizations to increase awareness of the groundwater resource and to demonstrate how homeowners can adopt best practices for groundwater conservation and protection. The group promotes groundwater education through well testing programs, water conservation through rain barrels and rain gardens, and pollution prevention awareness through agricultural and medical "clean sweep" programs.

Many additional land stewardship activities occur throughout the corridor, ranging from private woodland management to strategic land acquisitions designed to strengthen wildlife corridors. While funding for such protection and management is becoming sparse, in 2011, the Wisconsin State Legislature added the Niagara Escarpment to the Warren Knowles–Gaylord Nelson Stewardship Program's list of priorities for project funding consideration.

Recreation and geotourism

Wisconsin has an extensive system of public lands along the Niagara Escarpment corridor. State-, county-, and locally owned parks within 1 mile of its cliff face account for over 37,290 acres of land that is accessible by the general public (Kasprzak and Walter, 2001). If one factors in the shoreline areas of the bay of Green Bay and Lake Winnebago, tens of thousands of additional



Source: East Central Wisconsin Regional Planning Commission, 2014.

Figure 7. *The Great Arc bike route.*

acres are made available for recreational purposes. These public lands not only provide for outdoor opportunities, but "underground" ones as well, since numerous caves exist along the corridor.

Similar to the hiking trail planning efforts mentioned above, the Great Arc Bike Trail (fig. 7) was created to help generate awareness through geotourism. This route was developed under the auspices of the NERN as part of the "Year of the Niagara Escarpment" celebration. A 204-mile-long route connects the escarpment from the Horicon Marsh in the south to Washington Island in the north. It is hoped that improved bicycle access to the escarpment will lead to increased awareness and revenue.

Another geotourism program recognizes the corridor's uniqueness and suitability for growing cold climate grape varietals. In 2012, the federal American Viticultural Area (AVA) formally created the "Wisconsin Ledge AVA" designation for a 2.4 million acre area. This area, the 12th largest wine region in the U.S., places Wisconsin's escarpment corridor on the national map for winery tour destinations and further promotes the connections between the natural landscape and agricultural and tourism economies.

A GREAT ARC GEOPARK?

Many of the resources reviewed for this paper suggested the notion of a Geopark as a way to collectively implement the components of conservation geology. A significant opportunity exists to collaborate between the U.S. and Canada on the possible development of the first bi-national Geopark in North America.

A Geopark is defined by UNESCO as "a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological or cultural value." The program aims to enhance the value of such sites while creating employment and promoting regional economic development in parallel with the protection of its ecological value. The program's goal is to designate a network of up to 500 Geoparks worldwide." (UNESCO, 2010). Today, UNESCO provides only ad hoc support to national Geopark initiatives which are coordinated through the Global Geoparks Network (GGN). The GGN helps to ensure that national geological heritage initiatives benefit fully from information exchange and cooperation through the network (UNESCO, 2015). When the program was first established in 1998, the following qualifications were developed in order to consider a site for designation as a Geopark. According to UNESCO's website, a Geopark needs to:

1. Have a management plan designed to foster socio-economic development that is sustainable (most likely to be based on agri-tourism and geotourism);
2. Demonstrate methods for conserving and enhancing geological heritage and provide means for teaching geo-scientific disciplines and broader environmental issues;
3. Have joint proposals submitted by public authorities, local communities and private interests acting together, which demonstrate the best practices with respect to Earth heritage conservation and its integration into sustainable development strategies.

The Niagara Escarpment, or Great Arc, is a prime example of a geologic feature that could qualify for a Geopark designation. The themes discussed above fit naturally with the numerous legislative efforts and localized conservation programs that have taken shape across the escarpment corridor over the decades. All of these efforts have been raised to their current status by the vision and hard work of concerned communities and their citizens who recognized that the Niagara Escarpment is a special place that is worthy of recognition and protection. Combining and integrating the many programs along the corridor, along with filling gaps in planning and management in some areas, could allow for the eventual creation of a Great Arc Geopark. A designation can be awarded to recognize "sites representing an interest for the earth sciences" (UNESCO, 2010). What better place than the Great Arc to implement such an idea?

> "The Niagara Escarpment, or Great Arc, is a prime example of a geologic feature that could qualify for a Geopark designation."

Such an effort would require the cooperation and coordination of dozens of organizations and agencies along the corridor in order to create a cohesive Geopark program that fosters conservation awareness and action. Integrating the components of *conservation geology* into these programs, and subsequently a Geopark could help to broaden the public's view of what the Niagara Escarpment is, particularly at an international scale.

And why not a Geopark for the Niagara Escarpment? The Niagara Escarpment corridor has long been known as a unique natural feature which contains rare geological, ecological and cultural landscapes. These natural and cultural features need to be placed in context within both the narrowly defined Niagara Escarpment and its broader surrounding landscape in order to establish a better definition for, and awareness of, the Niagara Escarpment as a true corridor system. The amount and variety of geoheritage sites which are recognized by the existing systems and programs may lend themselves well to efforts which seek formal recognition as a Geopark.

By applying national and trans-national planning concepts such as a Geopark, the individual resources of the Niagara Escarpment can be enhanced as a system that defines the current and future social and economic well-being of its owners and caretakers. Achieving the Geopark designation would certainly give people a reason to celebrate the Niagara Escarpment.

REFERENCES CITED

Anderson, C., Epstein, E., Smith, W., and Merryfield, N., 2002, The Niagara Escarpment inventory findings 1999–2001 and considerations for management: Natural Heritage Inventory Program, Bureau of Endangered Resources, Wisconsin Department of Natural Resources, PUBL ER-801-02, 79 p.

Bruce Trail Conservancy (BTC), 2015, History of the trail (web page): brucetrail.org/pages/about-us/history-of-the-trail.

Coalition on the Niagara Escarpment (CONE), Coalition on the Niagara Escarpment (website): www.niagaraescarpment.org.

Department for Environment, Food and Rural Affairs (DEFRA), 2006, Local sites: Guidance on their identification, selection, and management: Department for Environment, Food and Rural Affairs, 36 p.

Erb, K., and Stieglitz, R., eds., 2007, Final report of the Northeast Wisconsin Karst Task Force: Madison, Wis., University of Wisconsin–Extension Publications, G3836, 46 p.

Escarpment Biosphere Conservancy (EBC), 2015, Escarpment Biosphere Conservancy (website): www.escarpment.ca. Accessed December 14, 2015.

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

Komoo, I., 2008, Conservation geology: multidisciplinary approach in utilization of earth resources without destruction [abs.]: Institute for Environment and Development (LESTARI), Universiti Kebangsaan Malaysia.

Leman, M.S., Komoo, I., Mohamed, K.R., Ali, C.A., Unjah, T., Othman, K., and Yasin, M., 2008, Geology and geoheritage conservation within Langkawi Geopark: UNESCO Global Geoparks Network, 8 p.

Nature Conservancy Council, 1990, Earth science conservation in Great Britain: A strategy: Nature Conservancy Council, 84 p.

Nelson, J.G., and Peter, J., 2005, Building the Great Arc: An international heritage corridor in the Great Lakes Region: Waterloo, Ontario, Environments Publications, University of Waterloo, proceedings of Leading Edge Conference and Great Arc Workshop, 122 p.

Niagara Escarpment Commission (NEC), Niagara Escarpment Commission (website): www.escarpment.org.

Ontario Land Trust Alliance (OLTA), Ontario Land Trust Alliance (website): www.olta.ca.

Royal Society for Nature Conservation (RSNC), 1999, Regionally important geological and geomorphological site (RIGS) handbook: Royal Society for Nature Conservation, wiki.geoconservationuk.org.uk/index.php5?title=RIGS_Handbook_Contents

Schutt, A.M., 1997, Thirty years in the making: A comprehensive economic impact and user study of the Bruce Trail, Ontario, Canada: Hamilton, Ontario, The Bruce Trail Association, 148 p.

Suratman, S., 2008, Geological sensitive areas: Proposal for regulation and conservation [abs.]: Universiti Kabangsaan Malaysia, Department of Mineral and Geoscience, p. 4.

United Nations Educational, Scientific and Cultural Organization (UNESCO), 2010, Man and the Biosphere Programme (web page): www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/man-and-biosphere-programme/.

Wikipedia contributors, 2010, Conservation biology: en.wikipedia.org/wiki/Conservation_biology.

Wisconsin Department of Natural Resources (WDNR), 2006, Wisconsin land legacy report: An inventory of places to meet Wisconsin's future conservation and recreation needs: Wisconsin Department of Natural Resources LF-040-2006, 250 p.

Wisconsin Ground Water Association (WGWA), 2015, Wisconsin Ground Water Association (website): www.wgwa.org