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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

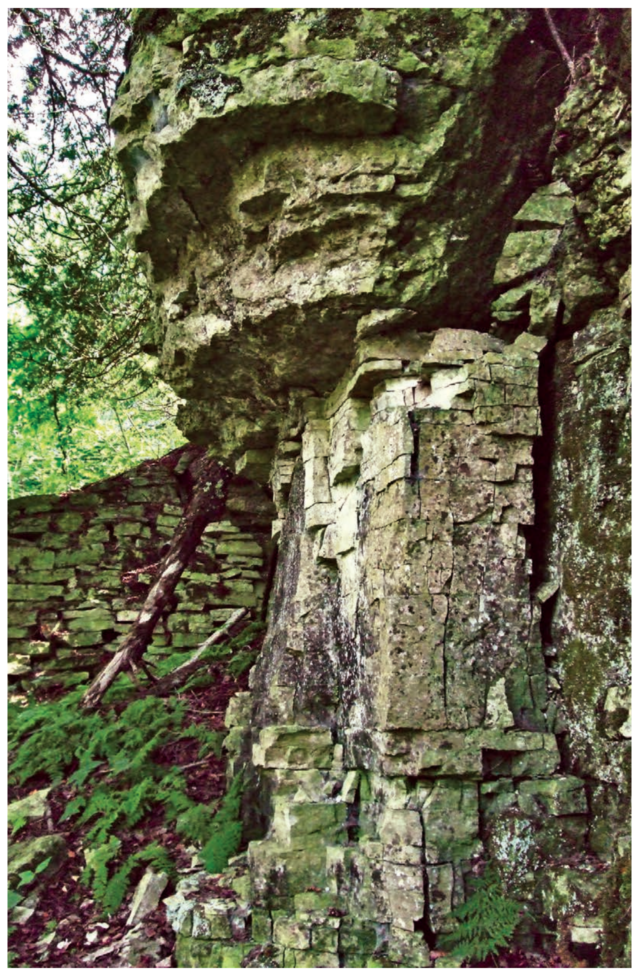

Figure 1. *Niagara Escarpment on Rock Island, Door County.*

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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.*

Ronald Stieglitz (all 4 photos)

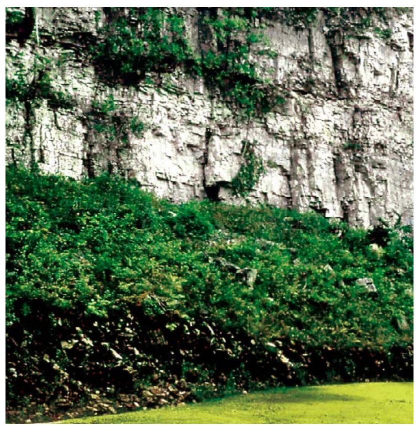


Figure 3a. *Thick-bedded dolostone at Alpine Resort Golf Course in Egg Harbor.*

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

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

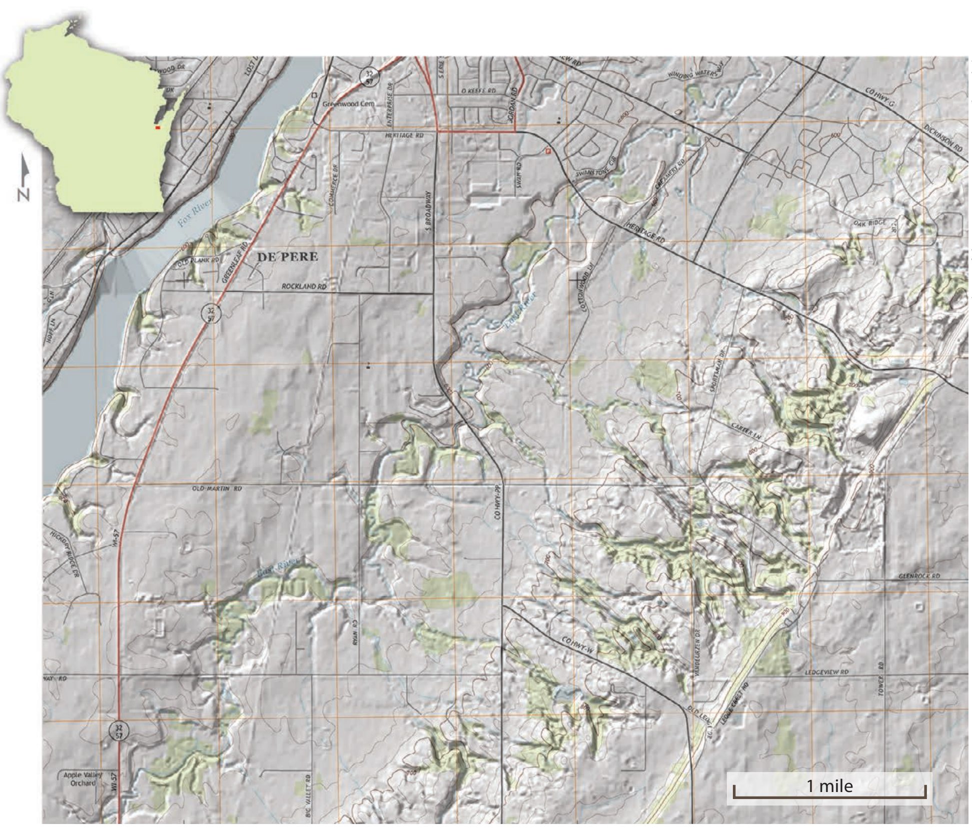
Following the deposition of the rocks that form the escarpment, an extended interval of continental weathering and erosion occurred long before the first glacial ice covered what is now Wisconsin. Pre-glacial erosion by now-disappeared stream systems was likely very significant. While it is difficult 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

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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),

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.

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