

Geologic Resources Inventory Scoping Summary

Sleeping Bear Dunes National Lakeshore

Michigan

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Geologic Resources Division
National Park Service
U.S. Department of the Interior



The Geologic Resources Inventory (GRI) Program provides each of the 270 identified natural area National Park System units with a geologic scoping meeting and summary, a digital geologic map, and a geologic resources inventory report. Geologic scoping meetings generate an evaluation of the adequacy of existing geologic maps for resource management, provide an opportunity to discuss park-specific geologic management issues and, if possible, include a site visit with local experts. Meeting discussions also highlight distinctive geologic features and processes and identify potential mapping, monitoring, and research needs.

The National Park Service (NPS) Geologic Resources Division held a GRI scoping meeting for Sleeping Bear Dunes National Lakeshore on June 30, 2010, at the park headquarters in Empire, Michigan. Participants at the meeting included NPS staff from the national lakeshore and Geologic Resources Division, and cooperators from Colorado State University, Grand Traverse Band of Ottawa and Chippewa Indians, Indiana Geological Survey, Michigan Department of Natural Resources and Environment (MDNRE) Office of Geological Survey, Michigan State University, Northwestern Michigan College, and the U.S. Geological Survey (see table 6). Superintendent Dusty Shultz welcomed the group and expressed her support of the Geologic Resources Inventory, stating “geology is a critical component of our resources.” Chief of Natural Resources Steve Yanco provided background information on the natural resources of Sleeping Bear Dunes, and Facility Manager Lee Jameson covered cultural resources. During the “geologic overview” portion of the agenda, Kevin Kincare (U.S. Geological Survey) highlighted many of the glacial features and other landforms at the national lakeshore. Todd Thompson (Indiana Geological Survey) made a presentation about the evolution of the shoreline-dune system surrounding Lake Michigan and briefly discussed isostatic rebound and the vibracore method of taking sediment samples in the vicinity of Lake Michigan. Frank Snyder (Northwestern Michigan College) provided information about dune stabilization and the significance of paleosols within the dunes. Georgia Hybels (Geologic Resources Division) facilitated the group’s assessment of map coverage and needs, and Lisa Norby (Geologic Resources Division) led the discussion of geologic features, processes, and issues.

During the site visit on the afternoon of June 30, participants drove to Miller Hill, which serves as an overlook for Glen Lake, the Manistee moraine, beach ridges, dunes, Sleeping Bear Point, and Lake Michigan. This stop highlighted a combination of glacial and shoreline features. Miller Hill is composed of ice-marginal debris. The second stop was the Dune Climb, which the National Park Service manages as a “sacrifice dune,” allowing visitors to climb to the top. From the top of the dune, it appears an easy walk to Lake Michigan, but the lake’s waters are actually 3 km (2 mi) away. Baby’s breath (*Gypsophila paniculata* L.), a nonnative invasive species, covers much of this highly popular area. After visiting the Dune Climb, scoping participants drove the Pierce Stocking Scenic Drive, making stops at the Dune and Lake Michigan overlooks. These stops provided an opportunity to discuss shoaling at North Manitou Island, the creation of social trails on dunes, the “ghost forests” buried in sand, maintenance of windblown sand on anthropogenic structures (i.e.,

boardwalks and walkways), glacial till and paleosols in the dunes, ventifact surfaces on the dunes, and the Traverse Group (reef-forming coral). In addition, Steve Yancho showed some of the participants the restored gravel pit near Stormer Road, the beaver dams on Otter Creek, Loon Lake, the fish cleaning station at the Platte River Campground, and the dredge spoils/piping plover habitat at the mouth of the Platte River/Platte Point.

On July 1, participants left on a boat trip from Leland, Michigan. This site visit provided the opportunity to view from the water many of the overlooks visited on the land the previous afternoon (e.g., Dune and Lake Michigan overlooks). Participants also saw Sleeping Bear Dune from the vantage point of Lake Michigan. Of particular interest were the slope failures at Pyramid Point and Sleeping Bear Point, which participants discussed during the “features, processes, and issues” portion of the previous day’s meeting. In addition, participants made stops at South Manitou Island, where they toured the lighthouse and discussed shoaling at the dock, as well as North Manitou Island, where they discussed building of the dock and associated major shoaling, the zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussel invasion, stratification of sand and algae at the dock area, and dredging projects. Between South and North Manitou islands, participants passed the 1960 shipwreck of the Francisco Morazan, as well as potholes, debris flows, and erosional features along the shoreline and bluffs of the islands.

Park Setting

Established in 1970 with boundary changes in 1982 and 2004, Sleeping Bear Dunes National Lakeshore is one of five National Park System units in Michigan. Isle Royale National Park in Houghton, Keweenaw National Historical Park in Calumet, and Pictured Rocks National Lakeshore in Munising are in the Upper Peninsula; River Raisin National Battlefield Park in Monroe and Sleeping Bear Dunes in Empire are in the Lower Peninsula. Covering 29,000 ha (71,000 ac), Sleeping Bear Dunes National Lakeshore sets aside from future development 105 km (65 mi) of Lake Michigan’s shoreline between Crystal Lake and Good Harbor Bay, and two islands within Lake Michigan—North Manitou and South Manitou islands (fig. 1). In addition to its well-known sand dunes, the national lakeshore hosts rivers and riparian corridors, inland lakes and ponds, and numerous wetlands. Hence, Sleeping Bear Dunes is known for its water-related, recreational activities such as fishing, swimming, kayaking, canoeing, as well as its scenic overlooks on Lake Michigan.

The setting of Sleeping Bear Dunes National Lakeshore is dominated by three types of geologic features and processes: lacustrine, glacial, and eolian. Lake Michigan is the primary lacustrine feature. With a surface area of 57,700 km² (22,300 mi²), Lake Michigan is the largest lake entirely within the United States and the second largest of the Great Lakes (Vana-Miller 2002), which are the largest complex of freshwater lakes in the world. Lake Michigan contains 4,920 km³ (1,180 mi³) of water with a retention time of 99 years. Its average depth is 85 m (279 ft) and deepest point is 282 m (925 ft) (Vana-Miller 2002). The highest lake level in recorded history was 177.2 m (581.3 ft) in 1986 and the lowest was 175.4 m (575.5 ft) in 1964 (Vana-Miller 2002). Modern-day lake levels fluctuate naturally on a decadal scale, varying as much as 1.5 m (5 ft) within the last 15 years (National Park Service 2006a).



Figure 1. Location map of Sleeping Bear Dunes National Lakeshore. National Park Service graphic.

Although glaciers retreated from the area 13,000 radiocarbon (^{14}C) years before present (B.P.) (Fullerton 1980), evidence of their occupation abounds in surficial deposits. Larson et al. (2000) mapped these deposits, and Kincadeo and Larson (2008) highlighted many glacial landforms in the vicinity of Sleeping Bear Dunes National Lakeshore (see “Glacial Features and Processes”).

Glacial material comprises the bluffs that surround Lake Michigan, and these bluffs provide the sediment (sand) for eolian processes, namely dune formation. Some sand dunes form near modern-day lake level, occurring along beaches in the national lakeshore. These beach dunes occasionally grow to considerable heights such as the Aral dunes along Platte Bay, which rise over 30 m (100 ft) above Lake Michigan. However, it is the “perched dunes” for which the national lakeshore was named and is known. In particular, Sleeping Bear Dune is a landmark on the mainland. Perched dunes appear immense because they are situated atop high headlands composed of glacially transported and deposited material. The perched dunes at Sleeping Bear Bluffs, Pyramid Point, and Empire Bluffs tower 140 m (450 ft) above Lake Michigan and provided excellent vantage points for the millions of visitors drawn to the national lakeshore (1.2 million in 2009) (National Park Service 2010).

Geologic Mapping for Sleeping Bear Dunes National Lakeshore

During the scoping meeting, Georgia Hybels (Geologic Resources Division) showed some of the main features of the GRI Program’s digital geologic maps, which reproduce all aspects of paper maps, including notes, legend, and cross sections, with the added benefit of being GIS compatible. The NPS GRI Geology–GIS Geodatabase Data Model incorporates the standards of digital map creation for the GRI Program and allows for rigorous quality control. Staff members digitize maps or convert digital data to the GRI digital geologic map model using ESRI ArcGIS software. Final digital geologic map products include data in geodatabase and shapefile format, layer files complete with feature symbology, Federal Geographic Data Committee (FGDC)–compliant metadata, a help file that captures ancillary map data, and a map document that displays the map and provides a tool to directly access the help file. Final GRI products are available at http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed December 9, 2010).

When possible, the GRI Program provides large-scale (1:24,000) digital geologic map coverage for each unit’s area of interest, which is generally composed of the 7.5' quadrangles that contain NPS-managed lands. Maps of this scale (and larger) are useful to resource managers because they capture most of the geologic features of interest and are spatially accurate within 12 m (40 ft). The process of selecting maps for management begins with the identification of existing geologic maps in the vicinity of the National Park System unit. Scoping participants then discuss mapping needs and select appropriate source maps for the digital geologic data or, if necessary, develop a plan to obtain new mapping. In the lower 48 states, large-scale mapping is usually defined as “one inch to 2,000 feet” or quadrangles produced at a scale of 1:24,000 on a 7.5' $\times$ 7.5' base. There are thirty-two 7.5' quadrangles on a 30' $\times$ 60' (scale 1:100,000) sheet.

Prior to scoping, sixteen 7.5' quadrangles were of potential interest for Sleeping Bear Dunes National Lakeshore: North Manitou Island OE North, North Manitou Island OE Northeast, South Manitou Island, North Manitou Island, North Manitou Island OE East, Leland, Glen Haven, Glen Arbor, Good Harbor Bay, Maple City, Burdickville, Empire, Lake Ann, Platte River, Beulah, and Frankfort (fig. 2). However, since scoping, GRI staff realized that the quadrangles containing “OE”

in their titles are “over edge” maps. “OE” is a naming convention that indicates that the quadrangle for a particular area does not have an associated USGS quadrangle number, and the data are included on the adjoining map sheet, in this case, the North Manitou Island and South Manitou Island quadrangles. Moreover, the Leland quadrangle will only be included in the final map product if geologic units (surficial or bedrock) appear within the quadrangle once the problem with mapping projections is remedied (see fig. 2 and “Surficial Data”).

Bedrock Data

Milstein et al. (1987), *Bedrock Geology of Michigan* (scale 1:500,000), provides the best bedrock data available for the national lakeshore and is in a digital format (table 1 and fig. 3). Most of the original mapping was done on Mylar. During scoping, participants noted that the Traverse Group (Middle Devonian, 397 million to 385 million years ago) underlies the entire national lakeshore. However, a PowerPoint presentation by John Esch (MDNRE Office of Geological Survey), suggested that the Middle Devonian Dundee Formation (limestone), not the Traverse Group, likely underlies North Manitou and South Manitou islands (fig. 4). Post-scoping inquiries revealed that although the Traverse Group has long been assumed to underlie both the mainland portion of the national lakeshore and these islands, recent bathymetric mapping shows a distinct NE–SW trending valley that cuts across the N–S trending valley that becomes the East Arm and West Arm of Traverse Bay (see fig. 4). This NE–SW trending valley runs between mainland Leelanau County and the Manitou Islands and continues onshore where the Bell Shale, which underlies the Traverse Group, crops out on the mainland north of Little Traverse Bay. Therefore, based on geography and stratigraphy, a likely interpretation is that this NE–SW trending valley is formed in the Bell Shale and the bedrock of North Manitou and South Manitou islands is Dundee Limestone, which underlies the Bell Shale (figs. 3 and 4). According to Kevin Kincare (U.S. Geological Survey), this is a very reasonable hypothesis based on new information that was not available to Milstein et al. (1987). Hence, while John Esch’s new interpretation has not been published as a geologic map, the idea is gaining support (Kevin Kincare, U.S. Geological Survey, e-mail communication, September 15, 2010).

The final map product for Sleeping Bear Dunes National Lakeshore will either use data from Milstein et al. (1987) with an explanation of this new hypothesis in the help file (and report), or will incorporate updated geologic mapping based on the hypothesis noted above (see table 1).

Surficial Data

The Geologic Resources Inventory has already completed a surficial geologic map for Sleeping Bear Dunes National Lakeshore that covers all the quadrangles of interest except the Frankfort quadrangle (fig. 2). Larson et al. (2000), which is an unpublished dataset, provided the source data for this map. During the scoping meeting, participants discussed this dataset: Kevin Kincare (U.S. Geological Survey) stated that the source information was not mapped accurately relative to the surface features, and projection issues need to be addressed and corrected. The geologic dataset is a compilation of mapping by multiple authors, captured in different datums (base maps), at different scales. Kevin Kincare said the MDNRE Office of Geological Survey is working on fixing these projection issues and updating the surficial dataset. GRI staff could assist in this process. Presently, Kincare is available to complete mapping in the Frankfort quadrangle in summer 2011, and the National Park Service could provide housing at the national lakeshore. Completion of this quadrangle would give park managers a digital surficial geologic map for the entire national

lakeshore and surrounding areas (table 2). GRI staff members, Bruce Heise and Tim Connors, need to discuss a plan, including time frame and budget constraints, with Kevin Kincare and the U.S. Geological Survey.

Table 1. Source maps for bedrock geologic data at Sleeping Bear Dunes National Lakeshore

Quadrangle of interest (7.5' quadrangle)	Reference/source	GMAP ¹	Scale	Format
North Manitou Island	Milstein et al. (1987) ²	TBD	1:500,000	GIS
South Manitou Island	Milstein et al. (1987) ²	TBD	1:500,000	GIS
Leland ³	Milstein et al. (1987)	TBD	1:500,000	GIS
Glen Haven	Milstein et al. (1987)	TBD	1:500,000	GIS
Glen Arbor	Milstein et al. (1987)	TBD	1:500,000	GIS
Good Harbor Bay	Milstein et al. (1987)	TBD	1:500,000	GIS
Empire	Milstein et al. (1987)	TBD	1:500,000	GIS
Burdickville	Milstein et al. (1987)	TBD	1:500,000	GIS
Maple City	Milstein et al. (1987)	TBD	1:500,000	GIS
Frankfort	Milstein et al. (1987)	TBD	1:500,000	GIS
Beulah	Milstein et al. (1987)	TBD	1:500,000	GIS
Platte River	Milstein et al. (1987)	TBD	1:500,000	GIS
Lake Ann	Milstein et al. (1987)	TBD	1:500,000	GIS

¹GMAP numbers are identification codes for the GRI Program's database.

²The final GRI map product may suggest an alternative hypothesis for the bedrock underlying North Manitou and South Manitou islands based on new bathymetric data and interpretation since Milstein et al. (1987).

³Depending on the final map projection, the Leland quadrangle will only be included in the final map product if it contains surficial or bedrock geologic units.

Table 2. Source maps for surficial geologic data at Sleeping Bear Dunes National Lakeshore

Quadrangle of interest (7.5' quadrangle)	Reference/source	GMAP ¹	Scale	Format
North Manitou Island	Larson et al. (2000)	1012	1:24,000 (?)	GIS
South Manitou Island	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Leland ²	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Glen Haven	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Glen Arbor	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Good Harbor Bay	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Empire	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Burdickville	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Maple City	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Frankfort	Mapping by Kevin Kincare (USGS) in summer 2011 (?)	TBD	unmapped	unmapped
Beulah	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Platte River	Larson et al. (2000)	1012	1:24,000 (?)	GIS
Lake Ann	Larson et al. (2000)	1012	1:24,000 (?)	GIS

¹GMAP numbers are identification codes for the GRI Program's database.

²Depending on the final map projection, the Leland quadrangle will only be included in the final map product if it contains surficial or bedrock geologic units.

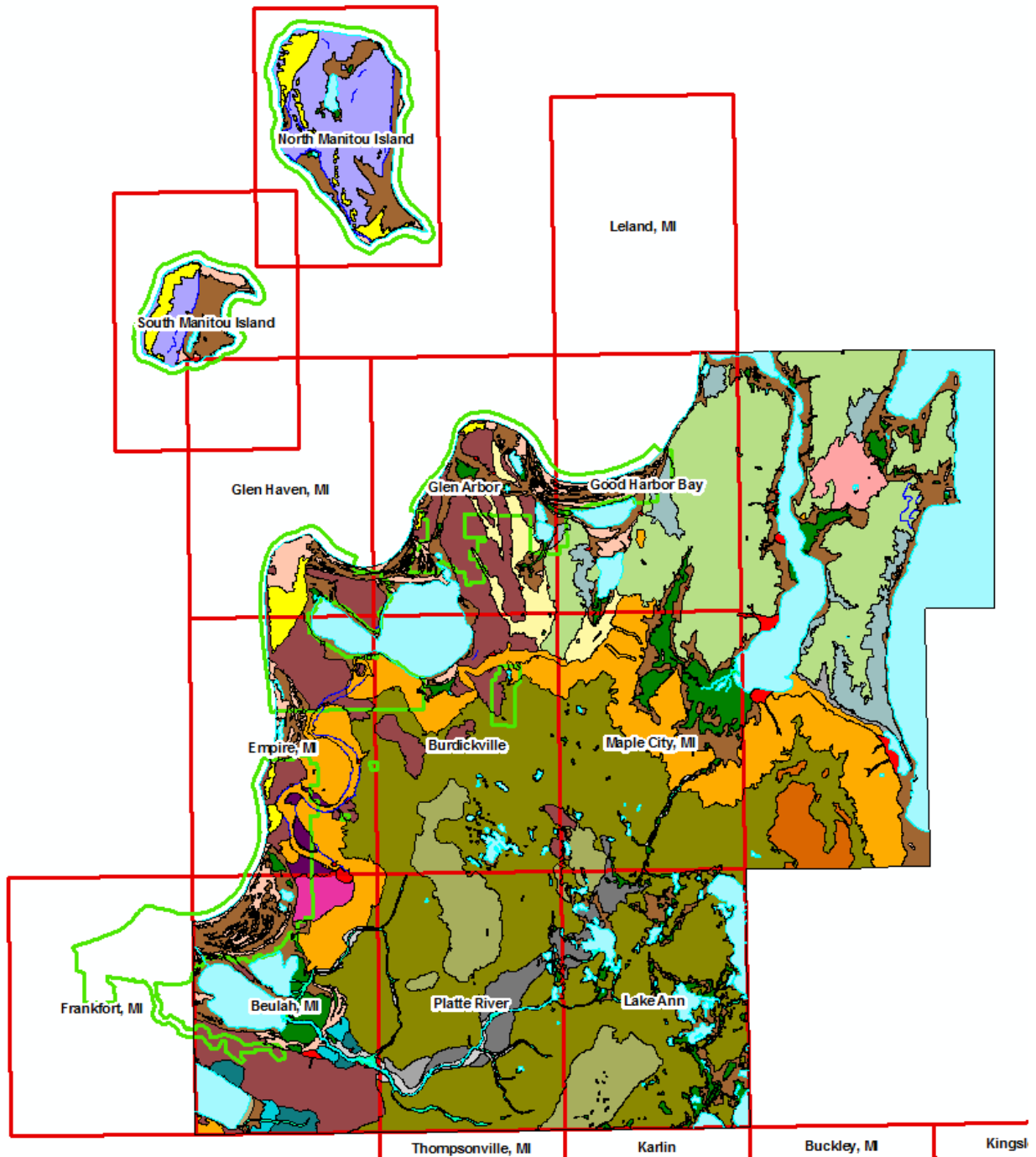


Figure 2. Quadrangles of interest for Sleeping Bear Dunes National Lakeshore. The various colors on the figure depict the surficial geologic map units of Larson et al. (2000). The 7.5' quadrangles surrounding the national lakeshore are labeled and outlined in red on the figure. USGS mapping in summer 2011 could provide the necessary data for the (unmapped) Frankfort quadrangle. The park boundary is shown in bright green on the figure. Graphic from Larson et al. (2000), modified by Georgia Hybels (Geologic Resources Division).

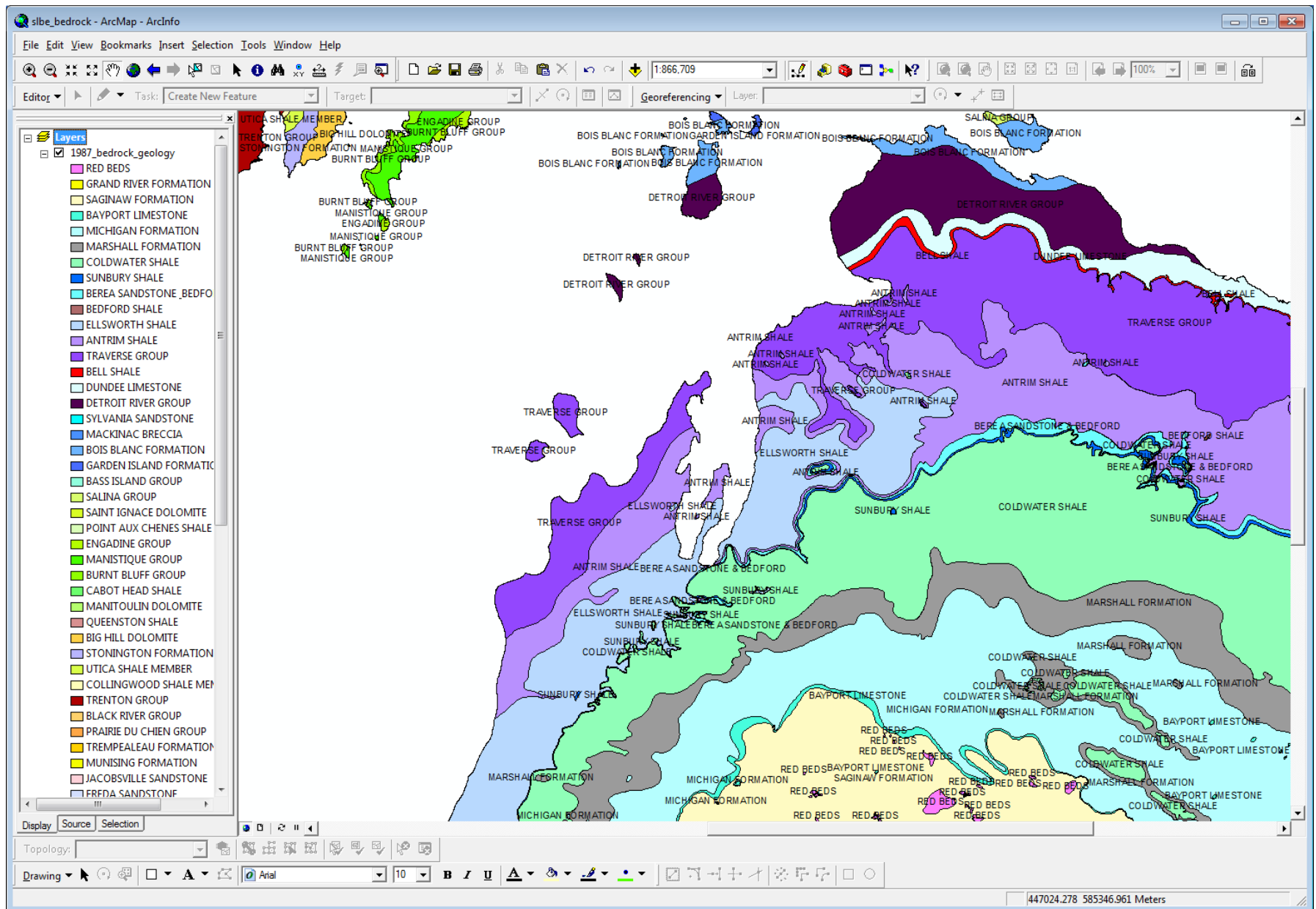


Figure 3. Bedrock geology of Michigan. Milstein et al. (1987) mapped the bedrock geology of Michigan at a scale of 1:500,000. Based on this mapping, the Traverse Group is the only bedrock unit underlying Sleeping Bear Dunes National Lakeshore. However, new bathymetric mapping and interpretation suggests that the Dundee Limestone may underlie North Manitou and South Manitou islands. Graphic from Milstein et al. (1987), modified by Georgia Hybels (Geologic Resources Division).

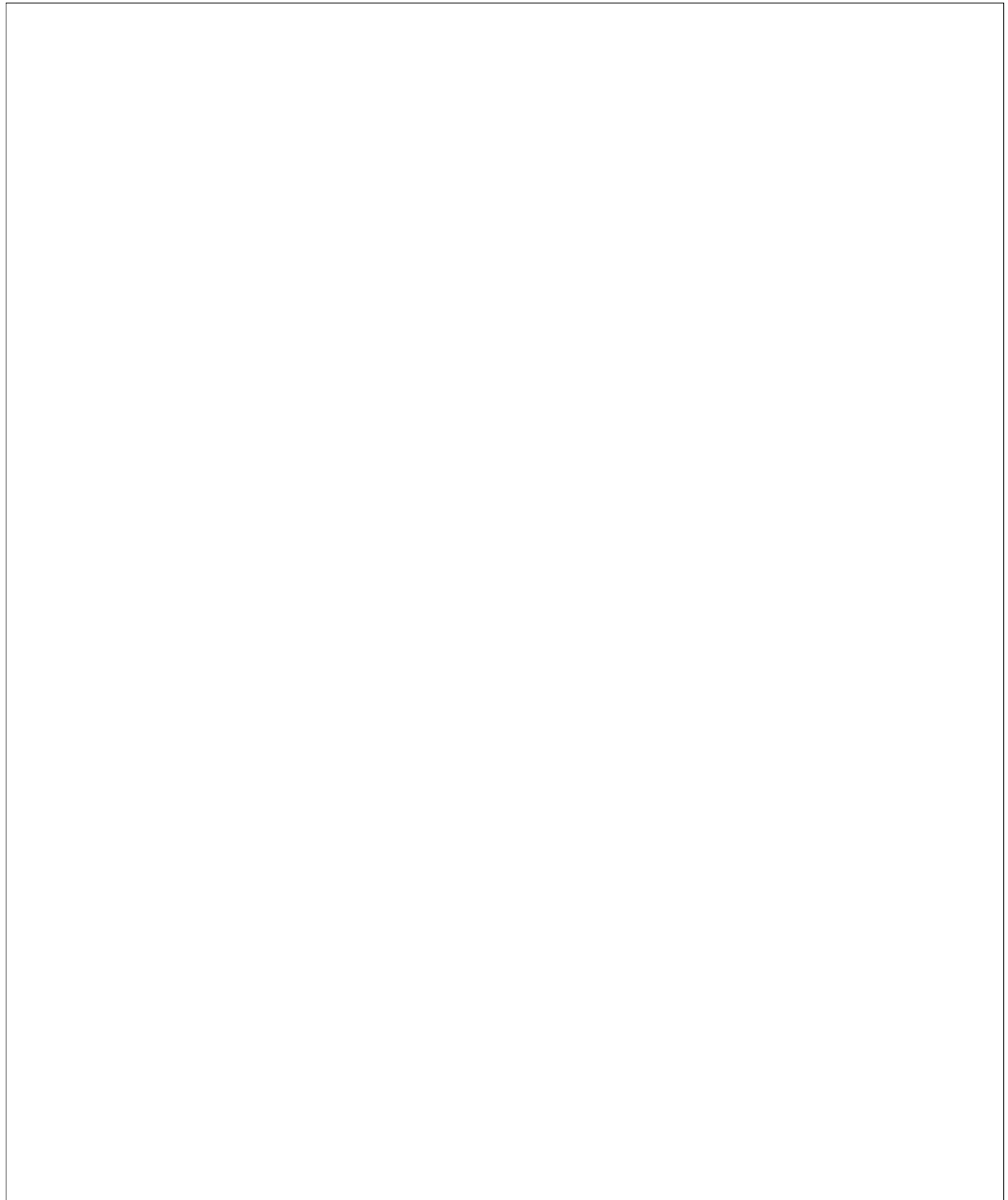


Figure 4. Bedrock geology and bathymetry in the vicinity of Sleeping Bear Dunes National Lakeshore. According to John Esch, (MDNRE Office of Geological Survey), the Dundee Limestone, not the Traverse Group, likely underlies the Manitou Islands. Note the pale blue Dundee Limestone mapped on the mainland north of Little Traverse Bay. The red unit at this same location is the overlying (younger) Bell Shale. The dark purple unit on the graphic is the Traverse Group. Graphic by John Esch (MDNRE Office of Geological Survey), extracted from PowerPoint presentation prepared for June 30, 2010, GRI scoping meeting for Sleeping Bear Dunes National Lakeshore.

Geologic Features, Processes, and Issues

The scoping meeting for Sleeping Bear Dunes National Lakeshore provided an opportunity to discuss geologic features and processes, many of which have associated issues of management concern. The highest priority issues are disturbed lands and restoration, shoreline features and processes, and hillslope features and processes. These are discussed first followed alphabetically by other features and processes at the national lakeshore.

Disturbed Lands and Restoration

With the creation of the national lakeshore in 1970, the National Park Service acquired, or scheduled for acquisition over the ensuing 40 years, more than 1,800 tracts of land, many of which were developed or disturbed. These sites were primarily residences, including foundations, outbuildings, driveways, septic systems, and wells, as well as docks, riprap, groins, and other engineering structures along waterways and shorelines. Acquired properties also included businesses (e.g., gas stations), abandoned power lines, railroad grades, logging roads, gravel pits, refuse dumps, agricultural fields, pine plantations, and impacted areas adjacent to popular attractions such as beaches and campsites. Today, about 90 inholdings (private lands within the administrative boundary) remain. At present, park managers do not have a thorough inventory of disturbed lands, including restored sites and those remaining to be restored. Having such an inventory would help in the identification of management priorities for long-term planning and the submission of funding requests (Steve Yancho, Sleeping Bear Dunes National Lakeshore, written communication, November 23, 2010).

The effort to restore natural conditions to acquired sites has been steady and very successful (National Park Service 2006b). Restoration has re-created large, contiguous areas of wildlife habitat; protected the shorelines of entire inland lakes; and returned former dump sites and agricultural areas to healthy northern-hardwood forests. In many cases, the disturbed sites are landscaped back to the original contours, which results in a natural appearance with restored hydrology. Some roads only require blocking at main intersections to inhibit further use and allow natural processes to regenerate the area. However, where clay and gravel was imported and used as road base, removal of these materials is necessary so that native tree seedlings can become established in the native sandy soils (National Park Service 2006b). An associated issue with imported road base is that this material created ideal habitat for the establishment of nonnative plants. The removed clay and gravel, along with concrete and dredge spoils, is used to fill former borrow pits, from which sand, gravel, or topsoil were mined. Most farms had a gravel pit of some size, with the average covering between 1.2 ha (3 ac) and 1.6 ha (4 ac). Eleven sites cover much larger areas, as much as 50 ha (125 ac). Among other uses, larger pits supplied sand and gravel for rebuilding Chicago after the Great Chicago Fire in 1871. Over the past 15 years, the NPS Geologic Resources Division has assisted with restoration of some of the larger gravel pits, for example, the Dorsey, Aral, and Scussel pits. A significant concern with disturbed lands is that nonnative species such as black locust (*Robinia pseudoacacia* L.) and poplar (*Populus*) often invade these areas, impeding natural geologic and hydrologic processes. Small invasions of black locust can also invade restored areas (e.g., Dorsey pit) (Pranger 2000).

Other disturbances have impacted the eolian, fluvial, and lacustrine resources at Sleeping Bear Dunes National Lakeshore (see these sections respectively). A few specific issues were highlighted during the scoping meeting:

Pig Farm

Otter Creek and Aral Springs have been impacted by nitrate (via groundwater discharge) possibly from a pig farm, which is up gradient from Otter Creek and Otter Springs. In addition to onsite nitrate accumulation of pig waste, the farm also accepts human waste for disposal from local sewage haulers. The National Park Service monitored nitrate levels in the Otter Creek Springs from the late 1990s to 2004, but questions still remain regarding natural vs. anthropogenic levels of nitrate. Staff from the NPS Water Resources Division (WRD) visited the site in August 2010 to address this issue (Pete Penoyer, Water Resources Division, e-mail communication, July 12, 2010). At that time, WRD staff also planned to take a look at the fish cleaning station (Pete Penoyer, Water Resources Division, e-mail communication, July 12, 2010). Park managers have not yet received the results of these investigations (Steve Yanchow, Sleeping Bear Dunes National Lakeshore, written communication, November 23, 2010), but any findings related to geology will be included in the final GRI report.

Fish Cleaning Station

As a courtesy to anglers, the National Park Service provides a fish cleaning station adjacent to the Platte River Campground near the mouth of the Platte River. In spring, this area is popular for steelhead (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) fishing, and for coho (*Oncorhynchus kisutch*) and king (*Oncorhynchus tshawytscha*) salmon fishing in the fall. The National Park Service replaced a previous fish cleaning station at the location because the design was inadequate for the actual capacity and resulted in environmental impacts to the Platte River. The new facility incorporates an artificially created wetland, which is part of a closed-loop system designed to be sampled at several points to ensure that the system is operating properly and not leaching nutrients into the Platte River or groundwater. Although evidence of breakthrough nutrients from the system has not been found, chemical testing has revealed that the artificial wetland is not adequately removing excess nutrients generated by the fish effluent. Park employees are in the process of reestablishing targeted wetland plant species for more effective removal of excess nutrients and correcting identified issues with the site design. Kevin Noon (NPS Water Resources Division) has been working with park staff on this issue.

Tucker Dump

Residents of Glen Arbor disposed of household waste, construction debris, some hazardous-materials containers (e.g., paint cans), small appliances, and car parts in a “town dump” near Tucker Lake. The site is roughly triangular in shape and covers approximately 2.4 ha (6 ac) (Vana-Miller 2002). The dump is currently proposed for site characterization and may be restored in the future. The Water Resources Division will handle any restoration and remediation deemed necessary after the site characterization is completed (Pete Penoyer, Water Resources Division, e-mail communication, July 12, 2010).

Shoreline Features and Processes

The shorelines along Lake Michigan and around North Manitou and South Manitou islands are a very dynamic component of the environment at Sleeping Bear Dunes National Lakeshore. The steep bluff faces are prone to slope failure, transporting enormous quantities of sand and gravel into Lake Michigan (see “Hillslope Features and Processes”). Even without such spectacular failures, the shoreline is continually changing, especially in years of above-average lake levels. Therefore, understanding changes of lake levels is important for resource managers at Sleeping Bear Dunes

because fluctuations are a major factor in the development of geomorphic features (e.g., sand dunes and beach ridges). Also, from the perspective of providing recreational resources, water level determines the area of beaches. Furthermore, high lake levels equate to periods of severe shoreline erosion, and erosion influences harbor depths, water depths along the shore, and the amount of suspended particles in offshore waters (Vana-Miller 2002). Other concerns associated with changes in lake levels are the expansion or retraction of vegetation near the shoreline and the contamination of shoreline areas by mercury with the associated impacts to wildlife habitat.

Final retreat of glacial ice from Michigan allowed fluctuations in lake levels to become the dominant agent of landform change (Kincare and Larson 2008). Investigators have identified nine lake-level phases within the Lake Michigan basin during the past 14,800 years, including the modern phase, which has not fluctuated significantly for the past 3,500 years (fig. 5). Starting with the Nipissing phase (6,500–3,500 years ago), Thompson and Baedke (1997) determined a relative lake-level curve at the Platte Lake embayment in the national lakeshore, finding that lake-level highs occurred at 4,600–4,400 (Nipissing II phase); 4,300–4,000; 3,200–2,300 (Algoma phase); and 2,000–1,200 calendar years before present at this location. Distinct shoreline features formed at the national lakeshore during these highs, most notably during the Nipissing phase (Barnhardt et al. 2004). For example, a cycle of eolian activity resulted in dune building and general sand-sheet accumulation at this time. Additionally, streams emerging from the drumlin-covered uplands deposited notable alluvial fans (Kincare and Larson 2008). Evidence of the Chippewa lake-level low (fig. 5) in the national lakeshore includes deep incision by rivers, forming paleochannels later filled with sediment (Foster and Coleman 1991).

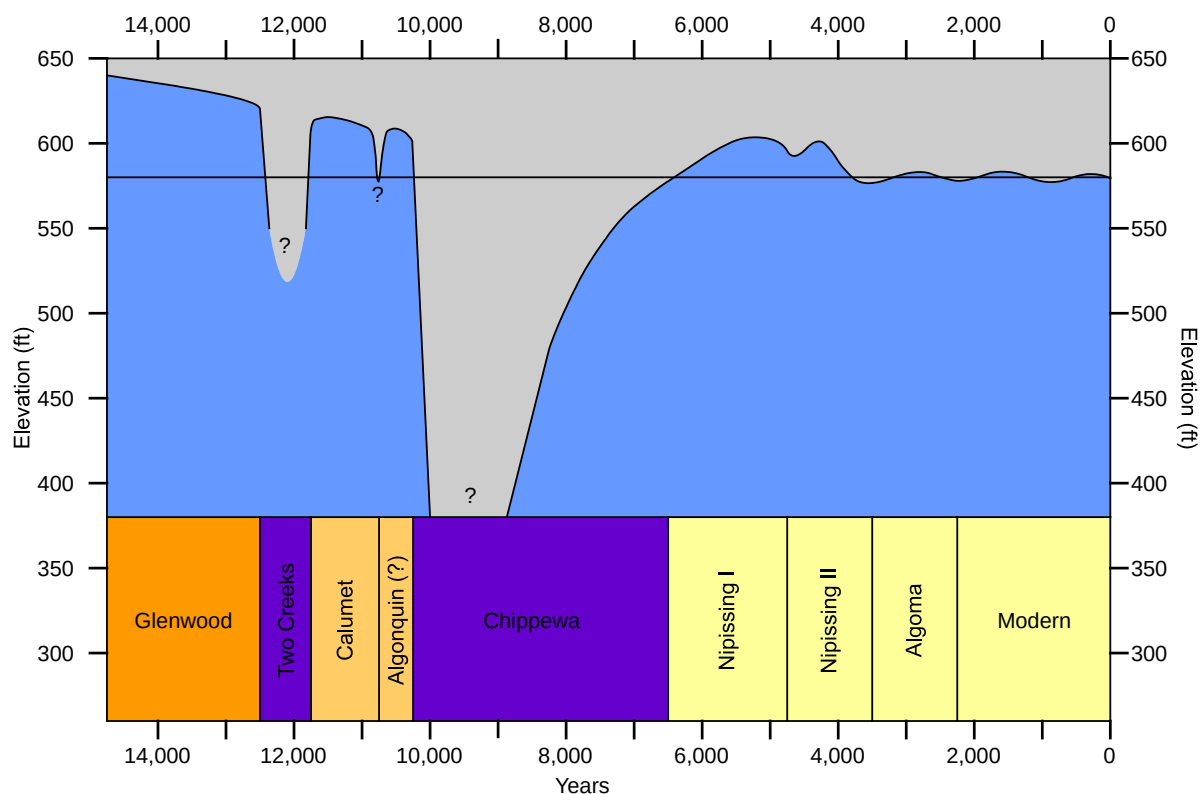


Figure 5. Lake levels. This hydrograph shows the fluctuating lake levels of ancestral and modern Lake Michigan for the past 14,800 years. The blocks at the bottom of the graph indicate named lake-level phases. Graphic by Todd Thompson (Indiana Geological Survey), extracted from GRI scoping PowerPoint presentation, June 28, 2010.

In many areas surrounding the Great Lakes, post-glacial isostatic rebound is a major factor in lake-level change. Isostatic rebound continues to affect water management and shoreline construction in many areas. However, at Sleeping Bear Dunes, the land surface has been isostatically stable (neither uplifting nor subsiding) for at least the past 4,000 years (fig. 6). Isostatic quiescence equates to relatively stable lake levels that have fluctuated only about 2 m (7 ft) between the highest and lowest levels during this period (Larsen 1985; Baedke et al. 2004). Over the short term, however, this amount of change can still cause severe shoreline erosion (Fraser et al. 1990).

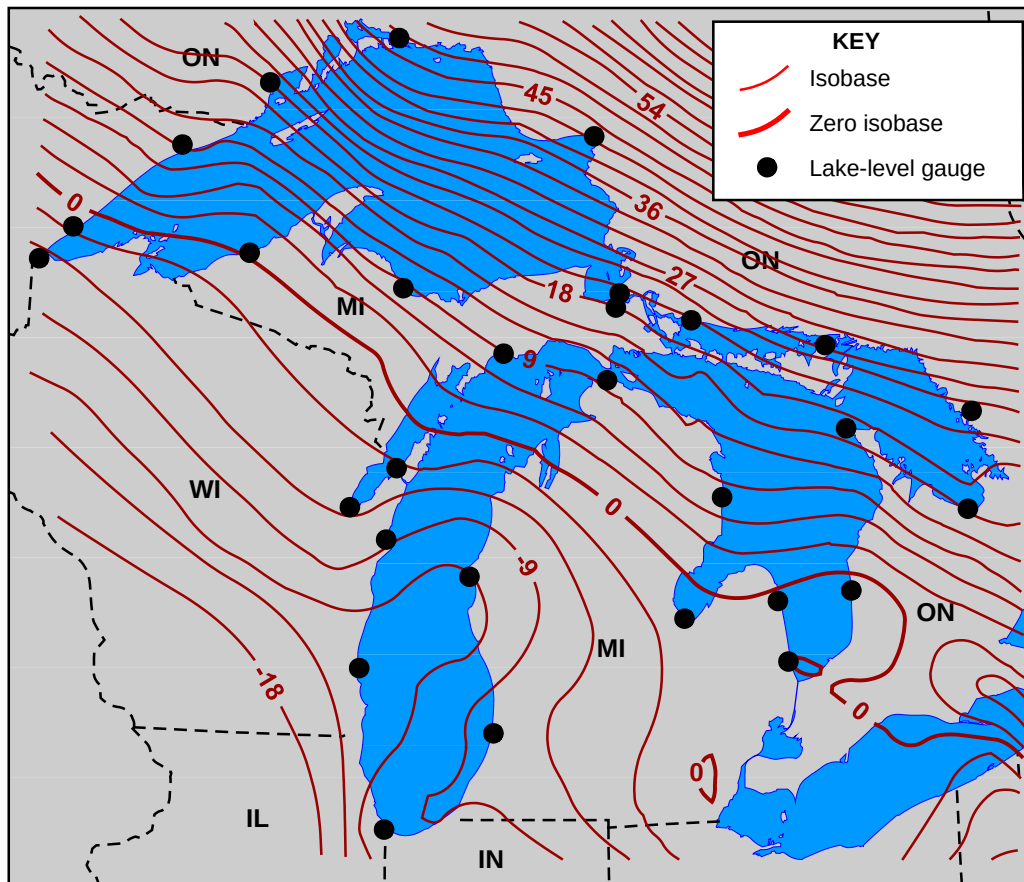


Figure 6. Rates of isostatic rebound in the Great Lakes area. Sleeping Bear Dunes National Lakeshore is situated in an area of isostatic quiescence as shown by the "0" isobase. Source: Mainville and Craymer (2005), extracted from GRI scoping presentation by Todd Thompson (Indiana Geological Survey).

Longshore drift at Sleeping Bear Dunes National Lakeshore moves large volumes of sand northward along the mainland. Easily eroded glacial headlands provide an abundant sediment supply (Kincare and Larson 2008). The tendency is for spits to form on the up-current side of an embayment. Over time, a spit can completely close off an embayment (Kincare and Larson 2008). For example, North Bar and South Bar lakes near Empire are embayment lakes (National Park Service 2007). On an even grander scale, longshore drift closed off Glen Lake and Crystal Lake from Lake Michigan (see fig. 1). These lakes were embayments during the Algonquin lake-level high (see fig. 5), but were cut off from the open waters of the lake by sand moving steadily along the shoreline (National Park Service 2007).

Another aspect of longshore drift is the tendency for the mouth of a stream to migrate downcurrent (Kincare and Larson 2008). A shift in wind direction (and longshore drift) causes a shift in the orientation of the stream. A conspicuous example is the Crystal River, which has changed course 12 times on its way to Lake Michigan (fig. 7). Each change in the river's course indicates a shift in the major wind direction (Kincare and Larson 2008).

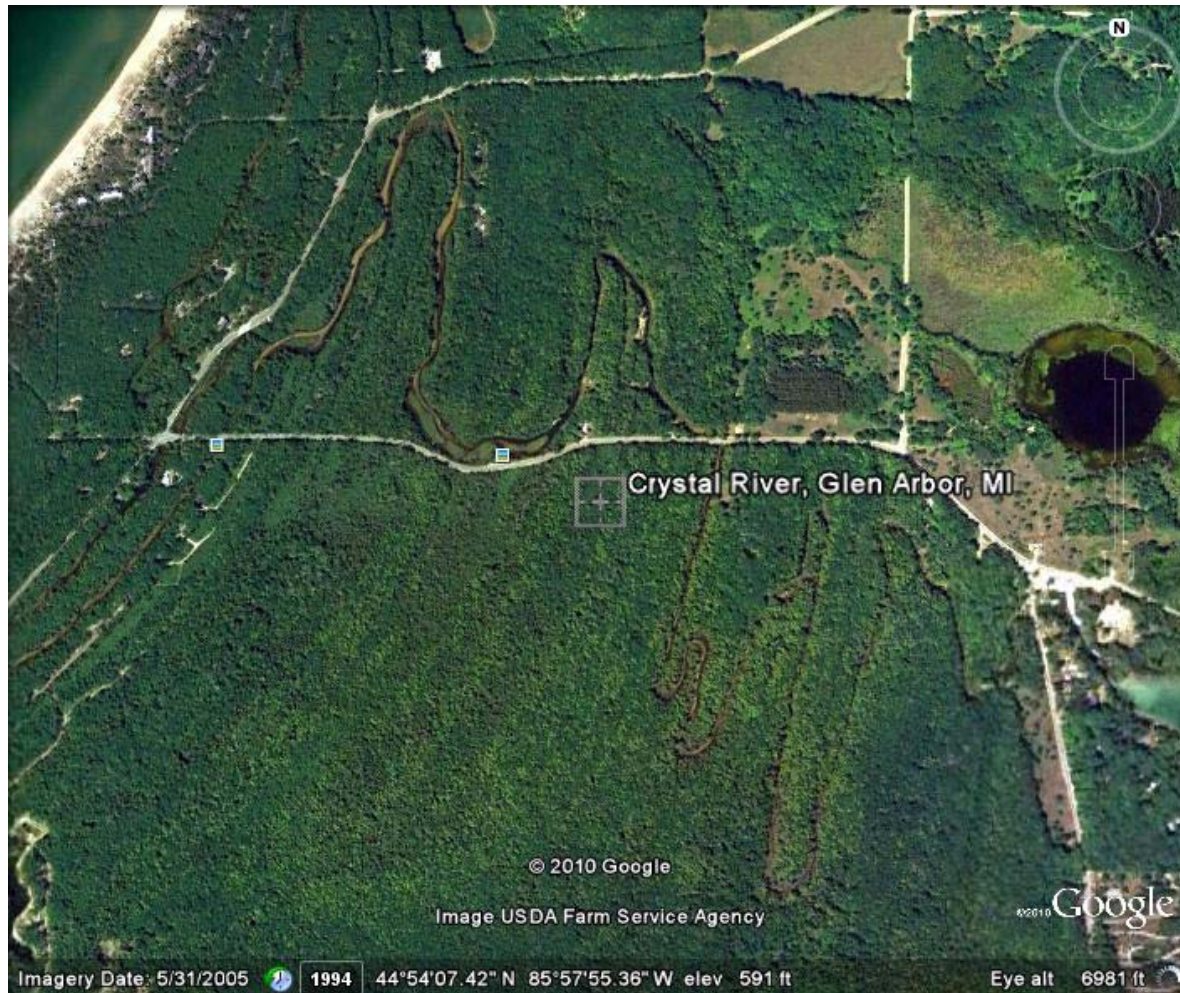


Figure 7. Crystal River. As a result of longshore drift, the course of the Crystal River has changed 12 times on its way to Lake Michigan. Image from Google Earth.

The shorelines of North Manitou and South Manitou islands are also subject to longshore drift, causing erosion in some areas and accretion of sediment in others. On South Manitou Island, the National Park Service added riprap and retaining walls to the southern shoreline to protect the lighthouse from erosion. By contrast, sand is accumulating in the vicinity of the docks on the eastern shoreline of the island. The historic dock was built in 1901 and the National Park Service added the extension in 1983–1984. During the site visit, scoping participants estimated that each year longshore drift is adding between 1.5 m (5 ft) and 3.5 m (10 ft) of sediment to the dock area. The majority of sediment appears to be added during storm events. Docks previously surrounded by open water are now engulfed in sediment (fig. 8). The National Park Service periodically dredges the dock area.



Figure 8. Dock area at South Manitou Island. In 1983–1984, the National Park Service extended the dock to reach open waters. Photo by Katie KellerLynn.

Much information is needed regarding the local effects of currents and sediment transport at South Manitou Island. This information is significant for managing the deposition of dredge spoils at the site. Coastal geomorphologists Rebecca Beavers and Jodi Eshleman (Geologic Resources Division) are currently assisting park staff with addressing shoaling and dredge disposal at South Manitou and North Manitou islands.

On North Manitou Island, the National Park Service built an open dock structure in the mid-1980s and a solid, enclosed extension in 1991–1992. The solid dock allows ferries to drop off and pick up passengers under poor weather conditions. However, major shoaling occurs around the structure, and dredging is required. The National Park Service conducts annual maintenance dredging, and the U.S. Army Corps of Engineers completes a major dredging project every three to five years. A primary concern is placement of the dredge spoils. In the past, spoils have been placed on the beach near the dock; however, the spoils are composed of material visibly different (e.g., larger grain size) from the native beach sand. Moreover, it appears, the dredge pile created a groundwater divide, raising the water table and flooding (and killing) the trees behind the spoils. Also, dredging activities have the potential to impact Pitcher's thistle (*Cirsium pitcher*), a state and federally listed threatened plant that inhabits this shoreline. Furthermore, when placed in the vicinity, dredge spoils have the potential to quickly refill around the dock. The National Park Service is looking into possible disposal in open waters.

Another concern at North Manitou is that *Cladophora* algae is washing up on shorelines, where it is buried by sand layers, forming mats that smell like sewage. Shoaling near the dock location appears to be concentrating the *Cladophora* deposition (fig. 9). *Cladophora* is natural to Lake Michigan, but not in these amounts. The reason for this increased growth is unknown but under investigation. Park staff suspect that the exotic mussels—zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*)—may be a factor. Water ballast of freight ships loading in European harbors and dumping in the Great Lakes imported these mussels. The mussels voraciously eat plankton that under natural conditions would have removed excess (waste) nutrients and clouded the water column. *Cladophora* thrives on the additional sunlight and extra nutrients. Another concern regarding *Cladophora* is that when it decays, it provides breeding grounds for the botulism bacteria. Birds contract botulism from eating invertebrates or fish that have ingested the bacteria. Knowing how and where the nearshore currents are transporting the botulism bacteria would help park managers better address this issue.



Figure 9. Dock area at North Manitou Island. Geologic issues at North Manitou Island include shoaling and the associated accumulation/stratification of *Cladophora* along the shore. Photo by Katie KellerLynn.

Hillslope Features Processes

In February 1995, a 488-m (1,600-ft) stretch of beach and bluff at Sleeping Bear Point suddenly slid into Lake Michigan. An estimated 1 million m³ (35 million ft³) of sand disappeared beneath the waters of the lake. The deposit, which was up to 18 m (60 ft) thick, extended more than 3.2 km (2 mi) offshore into water depths greater than 76 m (250 ft).

In order to protect the public and evaluate the hazard, the National Park Service requested assistance from the U.S. Geological Survey, whose investigators had been conducting surveys of the area from 1989 to 1993 as part of a shoreline-change study. Previous landslides had occurred at this location

in December 1914 and March 1971. All three slides occurred during unseasonably warm weather during the winter (Jaffe et al. 1998). Moreover, the landslides occurred at times of above-average lake levels (Barnhardt et al. 2004). Jaffe et al. (1998) concluded that coastal landsliding at Sleeping Bear Point is not the result of erosional undercutting of the offshore slope by water currents because sediment is actually accumulating in the nearshore zone in this area; rather sliding is related to increases in fluid pressure (in the spaces between the grains of sand) within the bluff. High pore pressure created by melting snow raised the water table, and the still-frozen, north-facing bluff acted like a dam to the groundwater flow. Increased fluid pressure reduced the intergranular friction allowing the slope to slide (Kincare and Larson 2008). Furthermore, Barnhardt et al. (2004) identified a buried channel oriented nearly perpendicular to the shoreline in the vicinity of Sleeping Bear Point. Investigators proposed that this paleochannel, which probably represents stream incision during a lake-level lowstand, serves as a conduit for groundwater from Glen Lake to Lake Michigan through Sleeping Bear Point (Barnhardt et al. 2004).

Although the landslides at Sleeping Bear Point are the most noteworthy, slope failures also have occurred along the shoreline at Pyramid Point. Additionally, the south shore of South Manitou Island is prone to failure, affecting the U.S. Coast Guard (previously called the U.S. Life Saving Service from 1848 to 1915) facilities and resulting in the loss of docks.

Climate Change Impacts

The primary impact from climate change to affect geologic resources at Sleeping Bear Dunes National Lakeshore is that Lake Michigan is no longer icing over during the winter. The lack of ice results in increased wave attack and erosion along beaches and bluffs. Furthermore, because beaches are no longer “frozen in place,” erosion is further exacerbated. Once protected by ice, now these areas are subjected to the more intense winds of winter. Biologically, the lack of ice scour along shorelines may be resulting in increased and more robust vegetation, which in turn decreases nesting habitat for piping plover (*Charadrius melodus*), a state and federally listed endangered species. Changing lake levels, which may result from climate change, also cause shifts in vegetation along shorelines, including exotic-species invasions. Another implication of Lake Michigan not icing over is that evaporation now occurs during the winter and spring when ice cover used to inhibit this process. Increased evaporation is a factor in fluctuating lake levels, which in turn affect erosion rates (see “Lacustrine Features and Processes”).

Eolian Features and Processes

Sleeping Bear Dunes National Lakeshore has some of the most significant wind resources in the state (Public Sector Consultants Inc. 2009) and is known for its eolian features, namely perched dunes.

Perched Dunes and Beach Dunes

The most notable windblown features at the national lakeshore are the immense perched dunes that sit atop the high bluffs that surround Lake Michigan. Relative to the thickness of the glacial deposits upon which they sit, the perched dunes have relatively little relief (Pranger 2006b). Their elevation primarily comes from the glacial material upon which the dunes formed. Empire Bluffs, Sleeping Bear Plateau, and Pyramid Point are examples of the towering headlands topped by perched dunes.

Thousands of years ago, these headlands protruded farther into Lake Michigan but have been eroded by wind and waves into the steep faces that are such prominent landmarks today. As waves cut away the bases of the bluffs, a continuous supply of sand and gravel is exposed; the wind continually transports the sand, blowing and depositing it on top, creating the perched dunes. Spreading behind the steep faces of the bluffs are dune fields such as Sleeping Bear Plateau, which is about 6.4 km (4 mi) long and 2.4 km (1.5 mi) wide.

According to Snyder (1985), the perched dunes are of two ages. Perched dunes that formed on the Manistee moraine, referred to as the “Sleeping Bear Highland” dunes, are 3,000 years old (before present, B.P.). Perched dunes that formed on ground moraine and lacustrine plains, referred to as “Sleeping Bear Lowland” dunes, are 2,000 years B.P. Perched dunes near the edges of bluffs are generally 3,500 years B.P. and younger. The predominance of eolian activity corresponds to after 1,000 years B.P. (Snyder 1985). Certain stabilized dunes located farther inland such as on the Platte River embayment may be as old as 11,000 years and might not be linked to the cyclical lake level-dependent processes of the past 3,500 years (Calver 1946; Taylor 1990).

Dunes also form at lake level along the shoreline of Lake Michigan. No beach dunes older than 670 years have been found (Pranger 2006b). Vegetation such as marram grass (*Ammophila*), Pitcher’s thistle (*Cirsium pitcheri*), sand cherry (*Prunus pumila*), wormwood (*Artemisia*), sand reed grass (*Calamovilfa longifolia*), and beach pea (*Lathyrus maritimus*), which can adapt to windy conditions, grow on these beach dunes and foredunes. Farther inland are higher backdunes with more mature trees such as jack pine (*Pinus banksiana*), cottonwood (*Populus balsamifera*), and oak (*Quercus*), and shrubs such as juniper (*Juniperus communis* L.) and buffalo berry (*Shepherdia* Nutt.) (National Park Service 2006c). Vegetation in eolian settings plays an integral role in the accumulation (via baffling) and stabilization of sand.

Other than relief and setting, the primary difference between perched and beach dunes is that perched dunes are almost exclusively parabolic dunes, whereas the beach-dune complex contains a combination of linear beach ridges, foredune ridges, and parabolic dunes (Pranger 2006b). These two types of dune deposits (i.e., perched and beach) cover 4,649 ha (11,488 ac) or 16.1% of the total park area (Pranger 2006b). The processes that activate dunes in these two settings are different but both are tied closely to the level of the lake’s water surface (Pranger 2006b).

The model of dune activation proposed by Loope and Arbogast (2000) illustrates that during high lake levels the bluffs retreat more rapidly and, thereby, produce more source material for the perched dunes. Conversely, during low lake stands, more beach surface area is exposed, creating the source material for the beach ridges and dunes along the shore. Loope and Arbogast (2000) linked periods of increased activity in the perched dunes with the 150-year high lake stands and periods of increased activity in beach dunes with 30-year low lake stands (see “Lacustrine Features and Processes”). In the modern environment, if high lake levels return, bluff erosion might increase and perched dunes might become more active. On the other hand, if lake levels fall, beach dunes might become more active and perched-dune movement might slow (Pranger 2006b). Significantly, Loope and Arbogast (2000) indicated that their model of dune activation is valid for dunes along the shore and near the bluffs, not dunes farther inland.

Impacts from Wind Erosion

Impacts from wind erosion at the national lakeshore include sandblasting of park signs, etching of trees near the shoreline and bluffs, blowing sand over walkways, and sand movement unearthing posts. Windblown sand periodically buries the boardwalk at the Lake Michigan Overlook (referred to as the “#9 overlook” on the Pierce Stocking Scenic Drive), at which point a higher level of boardwalk is constructed (fig. 10). Also at this site, sand movement has left support posts under the overlook hanging in midair. Park staff needs engineering suggestions for building boardwalks in this dynamic location.

Eolian sand periodically buries much of the paved walkway that leads from the parking lot to the Lake Michigan Overlook. As a result, park personnel have installed a moveable walkway/boardwalk, which requires regular maintenance to be a sustainable solution at this location. At the time of the site visit/scoping meeting, approximately 6 m (20 ft) of eolian sand had covered the paved walkway leading from the parking lot to the overlook. This amount of sand likely accumulated over a period of a week to 10 days (Ross Toles, Sleeping Bear Dunes National Lakeshore, e-mail communication, December 9, 2010).



Figure 10. Windblown sand. Blowing sand periodically covers the overlook structure, and moving sand exposes posts at the Lake Michigan Overlook. Photo by Katie KellerLynn.

In spring, staff of the Roads and Trails division at the national lakeshore removes sand that accumulated as a result of high winds during late fall and winter. The sand that is removed is stockpiled in a storage area to be used as clean fill in other parts of the lakeshore (Ross Toles, Sleeping Bear Dunes National Lakeshore, e-mail communication, December 9, 2010). After

attaining a manageable amount of sand via removal, crews push the remaining sand back over the face of the dune. The objective is to get the sand down close to the grade of the walkway and boardwalk to the overlook. The crews then set the grade for the boardwalk to go on (Ross Toles, Sleeping Bear Dunes National Lakeshore, e-mail communication, December 9, 2010).

After placing the boardwalk, staff monitors the sand accumulation at least three times a week, and crews shovel, sweep, and blow the boardwalk clean. Several times throughout the season, staff has to clear the boardwalk with a tractor. However during the 2010 season, the winds were so high throughout the summer that staff had to rent a tracked skid steer loader to try to keep the boardwalk clear. On the Friday before Labor Day crews had cleared the boardwalk but by the following Tuesday, 3 m (10 ft) of sand had covered the entire walkway (Ross Toles, Sleeping Bear Dunes National Lakeshore, e-mail communication, December 9, 2010). Such a high rate of sand accumulation is an issue at popular overlooks because of pedestrian traffic; during summer, crews can only get about four hours per day for clearing sand before visitor traffic is so heavy that they have to stop for safety reasons (Ross Toles, Sleeping Bear Dunes National Lakeshore, e-mail communication, December 9, 2010).

Disturbances

Over the past 200 years, and prior to establishment of the national lakeshore, “legacy disturbances” to the dunes included logging, farming (particularly on the older dunes farther inland), and the construction of hardened roads. Also, nonnative plant species have caused disruptions to natural dune processes. Starting in the 1940s and continuing into the 1960s, pine plantations were started for economic reasons but also to stabilize the dunes. Some areas of planted pine have become so dense as to render them wildlife “deserts.” In recent years, exotic plants such as white sweet clover (*Melilotus alba*), baby’s breath (*Gypsophila paniculata*), and spotted knapweed (*Centaurea stoebe* L. subsp. *micranthos* (Gugler) Hayek) have invaded parklands. In addition, common reed (*Phragmites*) has invaded shoreline, interdunal ponds, and other wetland habitats. This exotic reed commonly grows to 5.5 m (18 ft) tall. Frank Snyder (Northwestern Michigan College) has observed that the dunes are becoming more stabilized as a result of both native and nonnative vegetation, most noticeably in the southern part of the Sleeping Bear Dunes complex.

Although many of the dunes inland from the shoreline are stabilized by vegetation, dune blowouts are common. Trails and other disturbances through the dunes reactivate sand movement and develop into blowouts (National Park Service 2006c). Access points where roads intersect with dunes generally show signs of intense visitor use and resultant erosion. According to scoping participants, parties at these popular access areas can “kill a dune” in one evening. Trampling destroys dune vegetation and causes erosion which can be accelerated by wind events. Party goers often collect juniper (*Juniperus communis* L.) as firewood, which further exacerbates erosion at these locations.

Since creation of the national lakeshore, the greatest human disturbance to the dunes has been foot traffic. In 2005, Hal Pranger (Geologic Resources Division) addressed a technical assistance request from park managers regarding the sensitivity of dunes to foot traffic. The report described the geographic and geomorphic setting of the national lakeshore; evaluated, by park unit and by individual dune area, the sensitivity of the lakeshore’s vast dune resources; and made recommendations for long-term management and preservation of the dunes (Pranger 2006b). Areas with high levels of foot traffic are the Dune Climb and the Cottonwood Trail area, which has access

from the Pierce Stocking Scenic Drive. At these sites, major portions of entire dunes have been completely denuded, and the morphology of the parabolic dunes is now largely unrecognizable (Pranger 2006b). Abandoned dune buggy roads composed of clayey material have impacted the dunes near Cottonwood Trail by providing a growth medium suitable for nonnative species such as baby's breath and spotted knapweed, which have in turn unnaturally stabilized the dunes adjacent to abandoned roads and discouraged the growth of native species that rely on active sand movement for survival (Pranger 2000). Areas with more localized disturbance from foot traffic are Sleeping Bear Point, Lake Michigan Overlook, and the dune area just south and across the river from Platte River Point (Pranger 2006b).

Erosional Troughs

During the scoping meeting, park staff pointed out the “erosional troughs” formed as a result of foot traffic at Sleeping Bear Point and the Lake Michigan Overlook. These troughs extend from bluff tops down to the Lake Michigan beach. This disturbance is primarily aesthetic, particularly from the vantage point of Lake Michigan. Moreover, foot traffic has impacted the bluffs, rather than the dunes in these areas. As stated in Pranger (2006b), “while aesthetically objectionable, [these bluff impacts] do not substantially impact the overall processes or features in the adjacent dune fields” (Pranger 2006b, p. 23).

Fluvial Features and Processes

In 2002, the NPS Water Resources Division assisted park managers in completing a water resources management plan for Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002). Mechenich et al. (2009) completed an assessment of natural resources, including rivers and streams (table 3).

Scoping participants discussed the following rivers and streams as having particular resource-management issues related to geology:

Crystal River

The Crystal River flows through a rare dune and swale complex. Dune and swale complexes—also known as linear dunes, beach ridge complexes, or shore parallel dune ridges—are composed of past shorelines of ancient Lake Michigan. This terrain, which guides the flow of the Crystal River (see fig. 7), is unique to the Great Lakes region and known for its high concentration of biodiversity in a small area (The Nature Conservancy 2004). The U.S. Fish and Wildlife Service has described this portion of the Crystal River as globally significant. The Crystal River is serpentine, meandering its way to Lake Michigan; 10 km (6 mi) of river equates to 2.6 km (1.6 mi) across land.

Anthropogenic impacts are a concern for preserving this rare setting. Increased recreational use of this significant area, short cutting, foot traffic along the banks, removal of vegetation, shoreline engineering, and water release from the Glen Lake dam all have the potential to accelerate channel-bank erosion and cause unnatural levels of sedimentation within the channel. Boaters on the Crystal River typically put in at a launch at Fisher Road and float to takeouts at County Road 675 or liveries within the town of Glen Arbor. The serpentine nature of the river tempts boaters to short cut the river meanders, similar to the tendency for hikers to short cut a winding trail on land. Vegetation across the river is cut as a courtesy to ensure passage for recreational boaters. Shoreline-engineering structures fix the mouth of the river, which is located within a resort development outside of the national lakeshore. Finally, a dam upstream at Glen Lake, from which occasional pulses of high water flow, is another perturbation on the system.

Park managers have requested that staff from both the Geologic Resources Division (i.e., Hal Pranger) and Water Resources Division (i.e., Gary Smillie) evaluate the Crystal River corridor for impacts. Neither investigator found that recreational activities along the river were causing major changes; however, Smillie suggested that park managers try to influence dam release to the extent practicable (Gary Smillie, Water Resources Division, e-mail communication, July 12, 2010), and Pranger commented that if too much foot traffic or tree/debris removal were to occur, the stream could suffer some pretty quick, dramatic, and undesirable changes. Pranger does not see this happening soon, but if management of the river corridor changes, then this could be an issue (Hal Pranger, Geologic Resources Division, e-mail communication, July 12, 2010). Hal Pranger has numerous GPS-stamped photos of the Crystal River from September 2009, which could serve as point-in-time data from which to evaluate future changes.

Table 3. Rivers and streams within Sleeping Bear Dunes National Lakeshore

Name	Location	Headwaters	Length in kilometers	Length in miles
Unnamed stream	North Manitou Island	Lake Manitou	3.0	1.9
Unnamed stream	North Manitou Island	Spring near Lake Tamarack	0.5	0.3
Crystal River	Mainland (north)	Fisher Lake (outside Sleeping Bear Dunes National Lakeshore)	10 (4.1 within Sleeping Bear Dunes National Lakeshore)	6 (2.5 within Sleeping Bear Dunes National Lakeshore)
Good Harbor Creek	Mainland (north)	Groundwater seeps near Good Harbor Bay	1.2	0.7
Narada Creek	Mainland (north)	Narada Lake	0.9	0.6
Shalda Creek	Mainland (north)	Little Traverse Lake	4.3	2.7
Three unnamed tributaries to Shalda Creek	Mainland (north)	Unknown	0.8 total	0.5 total
Unnamed, intermittent stream above Narada Lake	Mainland (north)	Unknown	1.4	0.9
Unnamed stream connecting School and Bass lakes	Mainland (north)	School Lake	0.1	0.06
Unnamed, intermittent stream east of Shalda Creek and north of Bass Lake	Mainland (north)	Unknown	3.9	2.4
Unnamed stream connecting Tucker and Fisher lakes	Mainland (north)	Fisher Lake	0.3	0.2
Unnamed stream south of School Lake	Mainland (north)	Unknown	0.7	0.4
Unnamed, intermittent stream east of Tucker Lake	Mainland (north)	Unknown	2.9	1.8
Unnamed, intermittent stream south of Good Harbor Creek	Mainland (north)	Unknown	2.3	1.4
Otter Creek	Mainland (south)	Deer Lake, but main source is groundwater	3.7	2.3
Platte River	Mainland (south)	Lake Dubonnett (outside Sleeping Bear Dunes National Lakeshore)	97 (7.5 within Sleeping Bear Dunes National Lakeshore)	60 (4.7 within Sleeping Bear Dunes National Lakeshore)

Source: Mechenich et al. (2009).

Platte River

The Platte River corridor is a popular recreation destination, and park managers are developing potential indicators for monitoring and evaluating user capacity. Similar to the Crystal River, though much less sinuous, the Platte River flows through a dune and swale complex. Heavy use is causing erosion and the loss of dunes in the vicinity. Additionally, sand is filling the stream channel, which has become noticeably shallower in recent years. Although many residences have been removed,

some structures (e.g., concrete and wood walls along the bank) remain and affect geomorphic processes and riparian habitat. Of note is the Hwy M-22 bridge that crosses the river. A canoe rental service for trips down the Platte River is located near the bridge. Two former canoe liveries/gas stations used to be at this location, but restoration efforts removed them and cleaned up hydrocarbon contamination. Plans for upgrading the M-22 bridge could disturb channel processes and riparian habitat during construction and longer term, if not properly designed.

The use of the lower Platte River is mainly kayaking, canoeing, and tubing during the summer (Vana-Miller 2002). Segments of the Platte River are owned by the state, primarily from Loon Lake to the MDNRE harvest weir. Illegal fishing (snagging) activity has resulted in a portion of the river to be cleared of woody debris. Similar clearing of woody material occasionally takes place for canoe use of the river. Such clearing changes streamflow, sedimentation patterns, and the formation of riparian habitat. Additionally, pontoon and motor boats on the river affect riparian areas, with wakes and traffic around takeout areas promoting erosion.

Much activity is concentrated at the mouth of the Platte River. From Memorial Day to Labor Day, swimming is popular. Lake Township operates a park at this location, which is heavily used as a canoe takeout. A boat ramp, which is maintained by the Benzie County Road Commission, is located on Lake Michigan Road into the Platte River. Fishing is mainly concentrated in spring for steelhead, and in September and October for coho and king salmon (Vana-Miller 2002).

The issue of greatest concern on the Platte River is dredging at the mouth. In 1968, before establishment of the national lakeshore, the Michigan Department of Natural Resources began dredging the mouth to provide boating access between Lake Michigan and the Platte River during the fall salmon run. Dredging began in the wake of a storm that drowned seven Platte Bay anglers; it provided a way for boats to exit or enter the Platte River, eliminating the long and potentially dangerous open-water passage around Point Betsie (Karamanski 2000). The National Park Service took over this practice in 1979 and now dredges in September, starting the day after Labor Day and continuing for up to 30 days.

An estimated 13,460 m³ (17,600 yd³) of dredge spoils cover approximately 0.5 ha (1.3 ac) to 0.6 ha (1.5 ac) in up to 3.5 m (11 ft) of material (Pranger 2006a), which spreads from the terminus of Lake Michigan Road to approximately 0.4 km (0.25 mi) to the east. Dredging has impacted the natural shoreline processes at the mouth of the river, creating an unnatural headland, armoring the beach, anchoring the location of the river's mouth, and eliminating the formation of a sand spit or barrier. In short, dredging has transformed the flat sandy beach on either side of the Platte River's mouth into a coarse gravelly terrace. Moreover, the channel is narrower, deeper, and straighter than it would have been under natural conditions.

In 2006, the Geologic Resources Division provided technical assistance and completed a report addressing this issue (Pranger 2006a), which made the following recommendations:

- Take into account all of the various competing recreational, natural resource, and policy issues related to dredging and consider revising the Platte River management plan accordingly.

- Remove the accumulated dredged spoils from the lower Platte River area and either use the material for restoration or construction purposes (e.g., to fill open abandoned gravel pits or as a road base material) or dispose of properly.
- Discontinue dredging to preserve natural stream channel and coastal processes. If, however, dredging must continue because of other considerations, the Geologic Resources Division recommends that the spoil be removed and not stockpiled onsite.
- Allow the lower Platte River stream channel and coastal area to recover their physical characteristics on their own through natural geomorphic processes.

Because access to the fishing resources of Platte Bay is a complex issue there are no easy solutions to the dredging dilemma. It is likely that an environmental impact statement (EIS) will be needed to address access and dredging issues associated with the site, and it will be at no small cost to prepare such a document. This location has a number of unique issues that would need to be addressed to resolve the problem, including two federally listed species (endangered piping plover and threatened Pitcher's thistle), state-designated critical dunes, longshore currents and littoral drift, access road and parking developments, and impacts to park visitors. Because of potential sand deposition issues and critical dunes, engineering feasibility studies may be needed in the EIS. The current general management plan (GMP) for the lakeshore notes that the area is zoned to allow for the possibility of a new Lake Michigan boat ramp or dock in this area, but this is not proposed in the plan itself. The GMP goes on to further state that a separate study will be needed to determine whether any such facility would be appropriate in this area. An EIS would require that a range of reasonable alternatives be evaluated for such a proposal. The EIS would include a no-action option as well as other alternatives such as using the existing location with modifications, changing locations, or ceasing the activity entirely (NPS staff members, Sleeping Bear Dunes National Lakeshore, written review comments, November 23, 2010).

Otter Creek

Otter Creek is notable in that 85% of the discharge is supplied by groundwater; Otter Lake supplies the remainder. Groundwater flowing through the limestone-rich substrate results in a marl-lined streambed. Marl is a deposit composed of a mixture of clay and calcium carbonate (CaCO_3). Otter Creek is a unique niche for native brook trout (*Salvelinus fontinalis*) and is one of a very few small tributaries to Lake Michigan that contains a population of brook trout in close proximity to the mouth (Fessell 2007a). The Grand Traverse Band of Ottawa and Chippewa Indians is monitoring changes to stream morphology in Otter Creek as a means for protecting this rare habitat.

In summer 2009, multiple partners facilitated replacement of culverts in the Otter Creek corridor. These culverts used to back up then flush after storms, causing unnatural erosion patterns within the stream channel.

A primary concern for Otter Creek is that monitoring has detected high nitrate levels, potentially related to a commercial pig farm in the watershed (see "Disturbed Lands").

Another "unique" feature of Otter Creek is the town site of Aral. This ghost town was a booming lumber community in the 1800s. The culturally significant slab wood sluice, used for logging, still exists within the stream. Aral was located on Lake Michigan where Otter Creek empties into the

lake just south of Esch Road. Today this is one of the most popular swimming beaches in the national lakeshore (National Park Service 2008).

Shalda Creek

The headwaters of Shalda Creek are Little Traverse Lake, outside the national lakeshore, but significant parts of the creek flow within the national lakeshore. This low-gradient stream generally is not navigable. Many wetlands surround Shalda Creek, and in high-water years water from Lake Michigan enhances the wetlands and allows for limited boat travel. The primary issue on Shalda Creek is occasional flooding of residences on Little Traverse Lake. Potential causes of the flooding may be beaver (*Castor canadensis*) activity on NPS lands downstream from the lake or undersized culverts at the lake's outlet. Park staff would like assistance in trying to determine the cause of the flooding.

Glacial and Periglacial Features

Before lake-level change became the dominant geomorphic agent, glaciers and glacial meltwater created the landforms of Sleeping Bear Dunes National Lakeshore. The two types of glacial deposits at the national lakeshore are proglacial and subglacial; that is, formed in front of the glacier (proglacial) or beneath it (subglacial) (Lundstrom et al. 2003). Most of the glacial landforms are between 11,000 and 12,000 years old; Lundstrom et al. (2003) provided a carbon-14 date of 11,700 years B.P.

The dominant glacial deposits mapped in the vicinity of Sleeping Bear Dunes are the Pearl Lake deposit (sand and gravel) and the Duck Lake diamict (a terrigenous sedimentary rock that contains a wide range of particle sizes) (Larson et al. 2000; Kincare and Larson 2008). The proglacial Pearl Lake deposit is described as a "pitted outwash plain" and characterized by kettle depressions (Kincare and Larson 2008). When blocks of buried ice melted in the outwash plain, kettles formed. Many of these depressions now contain lakes. The subglacial Duck Lake diamict is characterized by drumlins, which have high relief generally 40 m (130 ft) or more. Drumlins are linear features molded by subglacial ice and, thereby, indicate the direction of a glacier's flow. The diamict overlies fluvial sand and gravel in the northern part of the map area and lacustrine sand toward the south (Larson et al. 2000; Kincare and Larson 2008). Good examples of the drumlinized landscape appear as part of the Good Harbor Bay quadrangle (see fig. 2).

During the scoping meeting and site visit, participants mentioned two other features of glacial origin—moraines and potholes. The moraines—referred to as "interlobate moraines" in park literature (e.g., National Park Service 2000)—were deposited between lobes of ice to form highlands such as the Empire Bluffs, Sleeping Bear Bluffs, and Pyramid Point. From the top of Miller Hill, participants noted the Manistee moraine during the site visit. From this vantage point, Kevin Kincare (U.S. Geological Survey) described the terrain as "ice marginal debris." The "moraines" at Sleeping Bear Dunes are likely a combination of glacial, fluvial, and lacustrine material. The other feature potentially of glacial origin is the "potholes" on North Manitou Island, which scoping participants observed from the waters of Lake Michigan (fig. 11). Verification that these features are indeed potholes is needed, but observations during the site visit seem to fit the standard definition of a pothole as it pertains to glacial geology: "a term applied in Michigan to a small pit depression (1–15 m deep), generally circular or elliptical, occurring in an outwash plain, a recessional moraine, or a till plain" (Neuendorf et al. 2005).

Although not glacial in origin, two features discussed during the scoping meeting are often associated with glacial periods—patterned ground and loess. The U.S. Geological Survey has recently discovered 12,000-year-old patterned ground in Lower Michigan, though none as far north as Sleeping Bear Dunes National Lakeshore. Investigators interpreted the patterned ground as a possible relict permafrost feature, forming proximal to the continental glaciers during the late Wisconsin glacial period (Lusch et al. 2009). In very cold climates, patterned ground is an effect of ice-crystal growth (ground ice) in soils, which moves rock fragments upward towards the surface. This process causes large, angular blocks of rock to accumulate in conspicuous displays of bands, circles, nets, and polygons.

Muhs (2006, p. 1405) defined loess as “sediment that has been entrained, transported, and deposited by the wind and is dominated by silt-sized (50–2 μm -diameter) particles.” In addition, it is recognized in the field as a distinctive sedimentary body (Muhs 2006). In Michigan, Schaetzl and Hook (2008) were the first to document and characterize an extensive loess sheet. They described the loess deposit as “a silt-rich mantle, generally 35–45 cm [14–18 in] thick, on a section of the Outer Port Huron outwash plain in northwest Lower Michigan, known locally as the Buckley Flats” (Schaetzl and Hook 2008, p. 140). During the latter phases of the glacial advance, silty sediment was probably transported by wind out of the Manistee floodplain and deposited on nearby uplands (Schaetzl and Hook 2008).



Figure 11. “Potholes” on North Manitou Island. Depressions in the island’s glacial material may be potholes, though verification by a glacial geomorphologist is needed. Photo by Katie KellerLynn.

Karst Features and Processes

Topographic maps of the area show depressions that are clearly rounded in shape. These features have been interpreted as sinkholes in drift karst, which is a different geomorphic feature than a glacial kettle. Although also a depression in the land surface, drift karst is produced by the collapse of bedrock that is covered by glacial drift, not the melting of ice. Among other features, drift karst is differentiated from kettles by (1) a steep, abrupt transition from the surrounding terrain to the upper wall, and (2) a generally round shape (T. Van Zoeren, Sleeping Bear Dunes National Lakeshore, case incident record 200117, April 8, 1994) (table 4).

A 1994 case incident record positively identified an area of drift karst in the vicinity of the national lakeshore. Park staff along with Tyrone J. Black (Michigan Department of Natural Resources, Geological Survey Division) investigated this drift karst just outside the lakeshore's boundary on the Dave Zeigler farm (T. Van Zoeren, Sleeping Bear Dunes National Lakeshore, case incident record 200117, April 8, 1994). During the scoping meeting, participants noted that the south side of Otter Creek and Echo Valley Road has well-defined sinkhole features. In October 2010 (i.e., since the scoping meeting), Ty Black led a field trip that highlighted drift karst in the vicinity of the national lakeshore; park staff and about 20 geologists participated in the trip (Steve Yancho, Sleeping Bear Dunes National Lakeshore, e-mail communication, November 23, 2010).

Table 4. Sinkholes vs. kettles

	Drift sinkholes	Kettles
Origin	Karst (i.e., dissolution of bedrock)	Glacial (i.e., erosion, transport, or deposition by glaciers)
Shape	Usually circular	Rarely circular, usually complicated irregular outline
Width	6 m (20 ft) to 366 m (1,200 ft)	Several feet to miles across
Depth	0.9 m (3 ft) to 15 m (50 ft)	3 m (10 ft) to 30 (100 ft)
Occurrence	Usually isolated, but can occur in random clusters or in a line	Rarely isolated; occur in ground moraine along old ice front in scattered, random patterns
Profile	Sharp crest break between sinkhole and sloping host terrain 26°–28° collapse slope Sloping transition to floor Sloping floor that usually grades into minor swallow or blind drainage	Gentle, rounded crest break between kettle and surrounding terrain Slope <24° Gentle transition to floor Flat to irregular floor
Features	Steep sides that may have steeper slump scars Floors of young sinks may be conical Tilted trees in vicinity indicate soil creep or slip No accumulation of water	Rarely has slump scars; slope scars are usually due to springs Temporary lakes and water saturation

Source: Black (2010).

Lacustrine Features and Processes

In 2002, the NPS Water Resources Division assisted park managers in completing a water resources management plan for Sleeping Bear Dunes National Lakeshore (Vana-Miller 2002). Mechenich et al. (2009) completed an assessment of natural resources, including inland water resources. These studies inventoried more than 20 permanent, named lakes in and adjacent to the national lakeshore (table 5); however, as many as 113 lakes, some less than 0.2 ha (0.5 ac) and ephemeral, occur within the boundaries of Sleeping Bear Dunes.

Table 5. Lakes within or adjacent to Sleeping Bear Dunes National Lakeshore

Name	Location	Area in hectares	Area in acres	Maximum depth in meters	Maximum depth in feet
Lake Manitou	North Manitou Island	104	256	14	45
Tamarack Lake	North Manitou Island	4	9	3	9
Florence Lake	South Manitou Island	32	78	8	26
*Bass Lake	Mainland (north)	38	93	7	24
Hatt Pond	Mainland (north)	<1	1	<1	3
Hidden Lake	Mainland (north)	<1	2	<1	<1
Narada Lake	Mainland (north)	13	31	12	39
School Lake	Mainland (north)	71	176	4	13
Shell Lake	Mainland (north)	41	102	4	13
Tucker Lake	Mainland (north)	7	17	3	9
Bow Lakes	Mainland (north)	5	13	–	–
Day Mill Pond	Mainland (central)	2	6	<1	3
Glen Lake	Mainland (central), partially within park boundaries	1,979	4,890	40	130
Little Glen Lake	Mainland (central), partially within park boundaries	574	1,419	4	14
North Bar Lake	Mainland (central)	12	30	9	31
Fisher Lake	Mainland (central)	23	58	4	14
*Bass Lake	Mainland (south)	11	27	8	26
Beck Pond	Mainland (south)	<1	2	–	–
Deer Lake	Mainland (south)	2	5	7	22
Platte Lake	Mainland (south), not within park boundaries	1,021	2,522	27	90
Little Platte Lake	Mainland (south), not within park boundaries	363	897	2	7
Long Lake	Mainland (south), partially within park boundaries	132	326	6	20
Loon Lake	Mainland (south)	37	92	20	64
Mud Lake	Mainland (south)	21	53	<1	<1
Otter Lake	Mainland (south)	26	64	6	21
Round Lake	Mainland (south)	6	15	8	26
Rush Lake	Mainland (south), not within park boundaries	49	121	<1	3
Taylor Lake	Mainland (south)	1	3	2	7

Sources: Vana-Miller (2002); Mechenich et al. (2009).

*There are two "Bass Lakes" in Sleeping Bear Dunes National Lakeshore, one in Leelanau County and one in Benzie County.

During the scoping meeting, participants discussed the following lakes as having particular resource-management issues related to geology:

Day Mill Pond

Day Mill Pond is a shallow pond near the base of the Dune Climb (see fig. 1). Historically, a canal connected the pond to Little Glen Lake on its east side near the public beach. After Hwy 109 was completed, the canal was replaced by a culvert that has become filled with sediment and debris, thereby, preventing fish passage between the pond and lake. The pond has also become filled with sediment and organic material. The pond was dry in summer 2007, but refilled after the connection with Little Glen Lake was reestablished following removal of a portion of the culvert. Park managers have submitted a proposal for funding from the Great Lakes Restoration Initiative, which if granted would extend the restoration efforts. An environmental assessment will be completed in 2011.

Florence Lake

Florence Lake, in the south-central part of South Manitou Island, is oblong in shape, has a surface area of about 32 ha (78 ac), and a maximum depth of 8 m (26 ft). The lake has no inlet or outlet, no groundwater input, and is primarily supported by surface runoff. As such, it is susceptible to drought. Scoping participants remarked that in 2010, "it was a shadow of what it used to be."

Glen Lake

A portion of the southern shoreline of Glen Lake is within Sleeping Bear Dunes National Lakeshore. The area surrounding the lake is highly developed with many residences and two marinas (Mechenich et al. 2009). Two court orders (1945 and 2003) regulate water levels in Glen Lake at a small dam approximately 0.4 km (0.2 mi) downstream of Fisher Lake. Since 1941, volunteers have maintained a manual gauge record, which indicates that lake levels have been generally maintained within a range of 15 cm (6 in) to 34 cm (13 in), and the lake elevation generally does not vary more than 3 mm (0.1 in) to 6 mm (0.2 in) from one day to the next (Mechenich et al. 2009). In order to prevent shoreline erosion during winter, water level is kept down until the lake is ice free.

Historically, the flow was controlled by adding or removing boards within the dam, but in June 2001, adjustable gates were installed that allowed for easier control. However, this upgrade resulted in a fish kill when river flow was reduced or shut down for approximately 18 hours (Vana-Miller 2002). As a result, a technical committee was formed, with members from the Glen Lake Association, Crystal River Preservation Association, Michigan Department of Environmental Quality, Leelanau County Drain Commissioner, and the U.S. Department of Interior. Lake and river levels were monitored several times a week. The U.S. Geological Survey determined that 23 cm (9 in) of water depth over a 3 m (10 ft) to 6 m (20 ft) width of channel was needed to float canoes, maintain submerged stream substrates, and protect aquatic organisms, which required a minimum of 0.85 m^3 (30 ft^3) per second of flow from the lake (Albright et al. 2002).

Little Glen Lake

Only areas along the north and northwest shoreline of Little Glen Lake are within park boundaries, and many private residences ring the rest of the lake shoreline. This lake has experienced high fecal coliform bacteria levels. Park staff created a green belt (vegetated strip) at the site of the former swimming beach to reduce surface runoff contaminated by waterfowl feces and associated bacteria (Mechenich et al. 2009). This lake directly connects to Glen Lake and maintains similar issues to those noted above.

Loon Lake

Loon Lake is very popular recreational destination. High levels of canoe, kayak, and tube users cause the greatest impact. However, Steve Yancho (Sleeping Bear Dunes National Lakeshore) noted that during fall salmon runs, when conditions do not allow easy boat access to Lake Michigan, fishermen launch boats at Loon Lake as an alternate fishing site. In the past when salmon numbers were higher, the number of boats could exceed 70 at a time. For instance, a run on perch (*Perca*) during the 2007 ice-fishing season brought more than 80 vehicles to Loon Lake on one day. Resource impacts from recreational use at Loon Lake include loss of vegetation, increased erosion, and sedimentation into the lake. Anthropogenic erosion and resultant sedimentation is causing a delta to form at the mouth of the river where it enters the lake.

Lake Manitou

Lake Manitou is the largest lake completely within Sleeping Bear Dunes National Lakeshore. The lake is primarily supported by surface runoff (Fessell 2007b), but has a small inlet at the southern end; a small intermittent outlet on the northern end drains into a wetland. During high water years the wetland drains into Lake Michigan (Hazlett 1988). The lake bottom is sandy (Handy and Stark 1984), and includes soft marl, with abundant gravel, rock, and cobble pockets throughout (Fessell

2007b). Scoping participants remarked that the lake is “aging” and becoming more eutrophic over time. Elias (2007) confirmed this observation and recommended that the lake be closely monitored in the near future. Elias (2007) also reported an anoxic layer below the thermocline.

North Bar Lake

Handy and Stark (1984) noted that the sand bar separating North Bar Lake from Lake Michigan occasionally washes out, for example at the end of June 1979, June and July 1980, and near the end of September 1982 during their study. Steve Yanco (Sleeping Bear Dunes National Lakeshore) commented that a breach in the “sand bridge” can flush North Bar Lake, resulting in a 0.9-m (3-ft) decrease in lake level. Park visitors with a small shovel can cause such a breach, and often have.

The channel between North Bar Lake and Lake Michigan is approximately 137 m (450 ft) long and 6 m (20 ft) wide and flows through a 46-m (150-ft) gap in active dunes (Pranger 2000). Human foot traffic likely destabilized the dunes, causing sand to migrate into the outlet area. A significant portion of North Bar Lake also has filled with sand. To mitigate the problem, in 1996–1997, the National Park Service erected fencing that enclosed the disturbed area of dunes, prohibiting public access. Four years later, the dunes appear to be rebuilding as a result. Park managers have good documentation via photo and vegetation monitoring transects of the site.

An accompanying problem is that the channel is eroding laterally towards a multi-story home on and adjacent land tract, which is owned by the National Park Service but maintained by the family under the terms of a life estate. According to Pranger (2000), the channel will probably migrate farther over time and be a recurrent problem for the landowner. Pranger (2000) suggested that park managers work cooperatively with the private landowner if the private landowner proposes measures to address the migration of the North Bar Lake channel. GRD staff is willing to review technical proposals that address the North Bar Lake channel migration to determine potential impacts to the national lakeshore’s resources.

Scoping participants also noted that the waters of North Bar Lake have high levels of nitrogen, with no obvious sources. Laura Loope (U.S. Geological Survey) and staffs from Sleeping Bear Dunes and Pictured Rocks national lakeshores have submitted a proposal for federal funding to investigate the cause.

Otter Lake

Otter Lake is the largest lake in the Otter Creek watershed. It is spring fed and has a soft, marl bottom. The largest spring has created a deep depression, which is seen as a “black hole” on aerial photographs. Also, sampling of spring waters has revealed very cold temperatures of 50°F (10°C). Both the inlet and outlet streams have intermittent beaver activity that affects the lake’s water levels.

Bow Lakes

Although not discussed during the scoping meeting, the Bow Lakes are in the vicinity of the national lakeshore and worthy of mention. The two Bow Lakes have individual surface areas of 3.3 ha (8.2 ac) and 1.4 ha (3.5 ac). Bow Valley Pond, 0.1 ha (0.2 ac), and an unnamed lake locally known as Kettle Pond, 0.6 ha (1.5 ac), also occur in the vicinity of the Bow Lakes. These are glacial kettles that are surrounded by bogs, fens, wet meadows, and marshes and positioned between two high wooded bluffs (Mechenich et al. 2009). These lakes are located primarily on private property

and have no public access. Little information is available on the Bow Lakes (Mechenich et al. 2009).

Oil and Gas (and Coal) Development

Centered on Michigan's Lower Peninsula, the Michigan Basin has been supplying oil and gas for decades. The basin also underlies portions of the Upper Peninsula, Wisconsin, Illinois, Indiana, Ohio, and Ontario, Canada. The basin covers an area of about 316,000 km² (122,000 mi²) and has an estimated 450,000 km³ (108,000 mi³) of sedimentary rocks of which 47% are carbonate, 23% are sandstone, 18% are shale, and 12% are evaporites. Precambrian rocks underlie the basin, which is 5,180 m (17,000 ft) deep at the center. The Paleozoic Era (542 million to 257 million years ago) in the Michigan Basin is represented by Cambrian, Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian rocks. Only the Cambrian (542 million to 488 million years ago) rocks have not produced oil and gas. During the 1930s and 1940s, the Mississippian (359 million to 299 million years ago) rocks were the target, while Devonian (416 million to 359 million years ago) rocks became the major producers in the 1950s. The Ordovician (488 million to 359 million years ago) reservoirs contributed most of the production during the 1960s. Discovery of the Silurian (443 million to 416 million years ago) Niagaran reef in southeastern Michigan in the 1970s resulted in development of the Niagaran Reef Belt, which has been a prolific producer (Aminian et al. 1986).

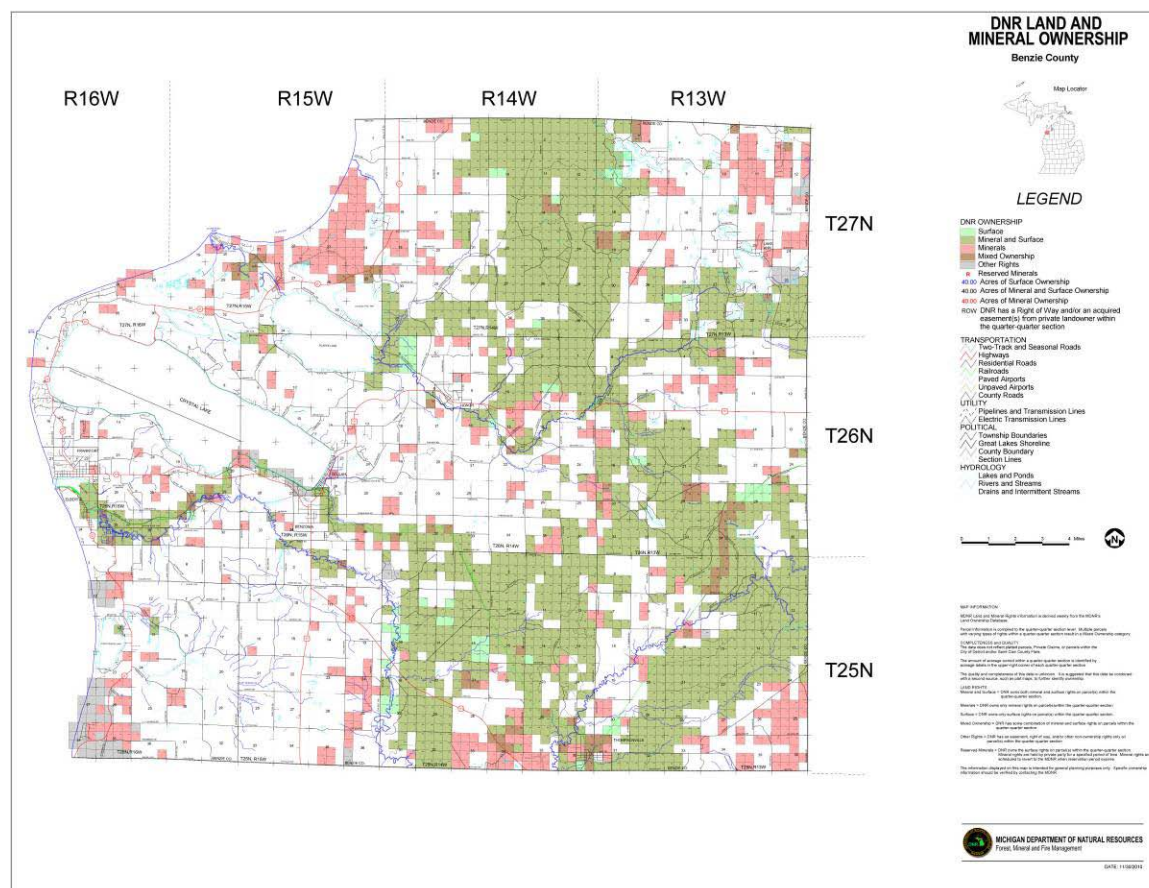


Figure 12. Mineral ownership in Benzie County, Michigan. Within Sleeping Bear Dunes National Lakeshore, 204 tracts of land have oil and gas encumbrances, and 14 tracts of land have private rights for coal. MDNRE image available at http://www.dnr.state.mi.us/spatialdatalibrary/pdf_maps/ownership_dnr/benzie_dnr_ownership.pdf (accessed December 3, 2010). Note: Viewers can manipulate and zoom in on this map at the website.

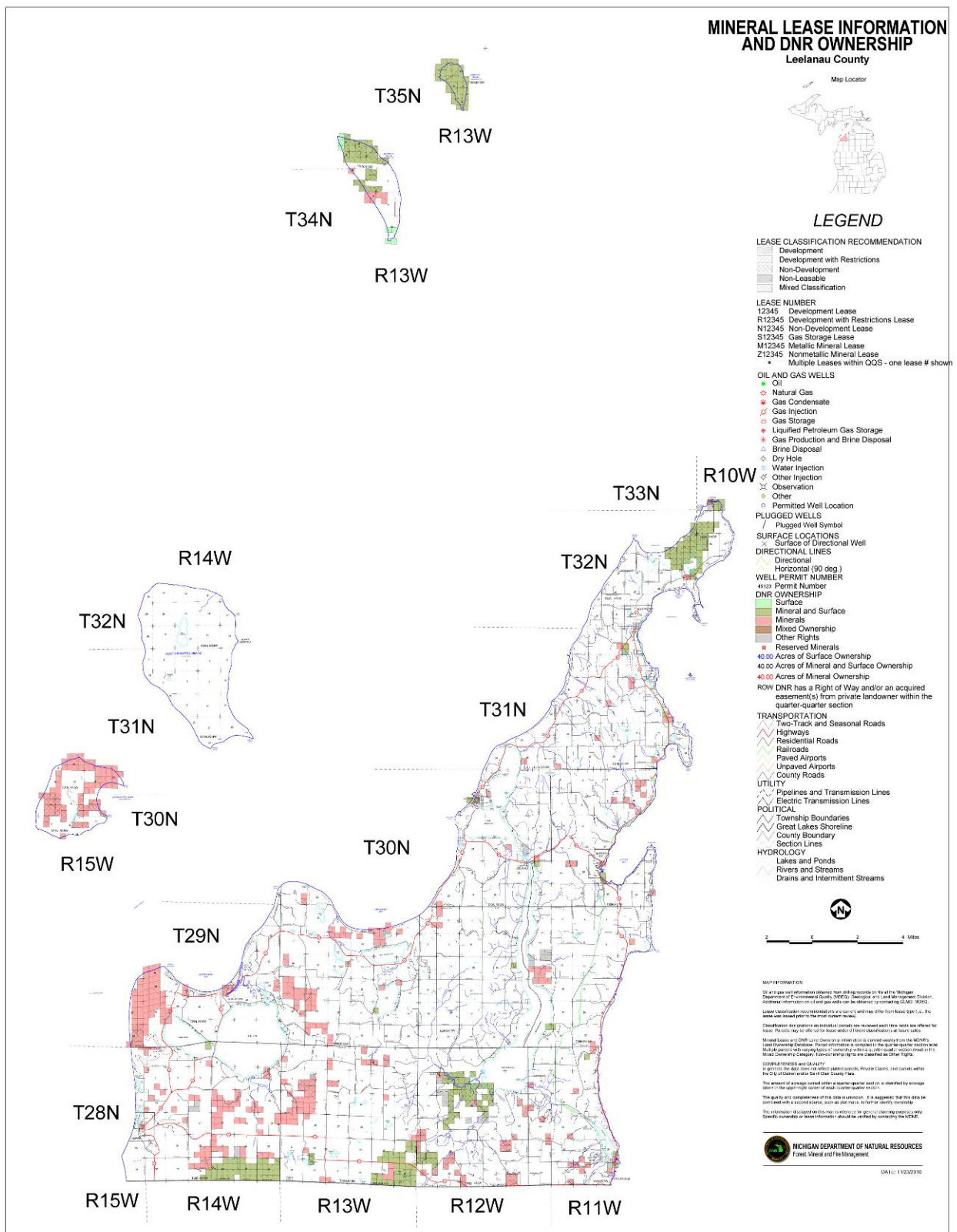


Figure 13. Mineral ownership in Leelanau County, Michigan. Within Sleeping Bear Dunes National Lakeshore, 204 tracts of land have oil and gas encumbrances, and 14 tracts of land have private rights for coal. MDNRE image available at http://www.dnr.state.mi.us/spatialdatalibrary/pdf_maps/mineral_lease_information/leelanau_lease_information.pdf (accessed December 3, 2010). Note: Viewers can manipulate and zoom in on this map at the website.

Future impacts from oil and gas production in the vicinity of Sleeping Bear Dunes would come from development of Devonian and Ordovician shales, primarily the Antrim and Collingwood shales (see fig. 3). In addition, scoping participants thought that park managers should be aware of the Silurian Niagaran pinnacle reefs, which are south of the national lakeshore and currently producing oil and gas. In the past, oil and gas companies have conducted seismic surveys on parklands. At present, however, there is a moratorium on directional drilling under Lake Michigan and a 460-m (1,500-ft) setback from the lake. Interested companies apply for permits through the state of Michigan, and the MDNRE Office of Geological Survey is funded with respect to the value of produced oil and gas in the state. Many leases for drilling are being issued north of the national lakeshore, and Sleeping Bear Dunes has a mix of mineral rights that could be developed in the future. According to records retained by the NPS Geologic Resources Division, 204 tracts of land covering 6,111.35 ha (15,100.93 ac) possess oil and gas encumbrances within the national lakeshore (figs. 12 and 13). All of these encumbrances are on land owned by the federal government, but nonfederal entities (in this case, both private and the state of Michigan) own the mineral rights on these tracts of land. In addition, the national lakeshore has 14 tracts of land covering 345.05 ha (852.61 ac) with private mineral rights for coal (Pat O'Dell, Geologic Resources Division, written communication, December 2, 2010). Moreover, there are 5,644 ha (13,947 ac) of land within Sleeping Bear Dunes National Lakeshore where the U.S. federal government has no ownership whatsoever, and that too might be available for mineral development (Pat O'Dell, Geologic Resources Division, e-mail communication, December 6, 2010).

Park managers are primarily concerned about how to position themselves for future development in or near the national lakeshore. Sue Jennings (Sleeping Bear Dunes National Lakeshore) and GRD staff worked together on oil and gas issues at Big South Fork National River and Recreation Area in Tennessee. The Geologic Resources Division can provide technical assistance and guidance; the MDNRE General Land Office has maps showing the land tracts in question. The National Park Service controls nonfederal oil and gas development in parks under the Code of Federal Regulations (CFR), namely 36 CFR, Part 9, Subpart B ("9B regulations"), which covers minerals management. The regulations require a prospective operator to demonstrate its right to the oil and gas, to submit and obtain NPS approval of a plan of operations, and to post a performance bond. The plan of operations is an operator's blueprint covering the scope of activities inside park boundaries including measures to protect park resources and values.

Paleontological Resources

Hunt et al. (2008) completed a baseline paleontological inventory for the Great Lakes Network, including Sleeping Bear Dunes National Lakeshore. This inventory found that paleontological resources are known from within the national lakeshore's collections, which are housed at the Museum of Paleontology at the University of Michigan in Ann Arbor, Michigan. Geologic units mapped within the national lakeshore also host fossils. Both the paleontological inventory and GRI scoping participants identified three sources of paleontological material: (1) Traverse Group (Middle Devonian, 397 million to 385 million years ago), (2) Antrim Shale (Upper Devonian, 385 million to 359 million years ago), and (3) glacial and post-glacial deposits (Pleistocene and Holocene, 2.5 million years ago to present).

Traverse Group

Formed in Middle-Devonian seas, the Traverse Group is the source of “Petoskey stones”—the well-known, Michigan state stone, sought by collectors and rock hounds. When polished by waves (or artificially), the colonial rugose coral *Hexagonaria*, which make up the stones, appear as shiny hexagons. The tabulate coral genus *Favosites* also makes Petoskey-like stones, in this case appearing as polished honeycomb. Petoskey stones are named from Petoskey, Michigan, where they occur in abundance. All Petoskey stones at the national lakeshore are allochthonous; that is, formed elsewhere but washed onto the beaches of the lakeshore. In addition, Devonian brachiopods (bivalves), bryozoans (colonial filter feeders), and stromatoporoids (sponge-like reef builders) occur in beach-washed gravels in the national lakeshore (Hunt et al. 2008).

Antrim Shale

Another source of paleontological material is the Antrim Shale, although no specimens have been found in the national lakeshore to date. Hunt et al. (2008) described the Antrim Shale as hosting “fossilized wood fragments,” but during the scoping meeting, Kevin Kincare (U.S. Geological Survey) clarified that this fossilized plant material is more likely fossilized fern fragments (*Calamites*), as opposed to “wood.”

Glacial and Post-Glacial Deposits

Various investigators have identified paleontological resources as occurring in the Pleistocene deposits at Sleeping Bear Dunes National Lakeshore (Gates 1939; Pruitt 1954; Wilson 1967). Identified taxa are six species of mollusk and 23 three species of mammals, including woodchuck, chipmunk, squirrels, beaver, mouse, muskrat (first record in Michigan), voles, raccoon, marten, fox, dog, and deer. Wilson (1967) lists a catfish from the Sleeping Bear Dunes locality as well.

Scoping participants mentioned one other possible paleontological resource at the national lakeshore—root casts, a type of trace fossil. Roots penetrate marl soils and become casts filled with calcite (a common rock-forming mineral composed of calcium carbonate, CaCO_3). The production of these soils is post-glacial but some root casts may be as old as 2,500 years. The source of the calcium carbonate is most likely the abundant limestone clasts in the glacial deposits. Root casts are a feature in paleosols (Frank Snyder, Northwestern Michigan College, telephone communication, December 1, 2010).

Another form of calcium carbonate, and potential source of paleontological material, is tufa, which forms at the mouth of springs. Organic material such as wood fragments, leaves, and even bones can become part of a tufa deposit, encrusted by calcium carbonate. Investigators have observed tufa precipitation in the Platte River near the Hwy M-22 bridge (Lundstrom 2001); however, no fossils have been documented.

Seismic Features and Processes

Seismic activity is minimal, faults are far away, and threats from ground shaking or other seismic hazards are seemingly nonexistent at Sleeping Bear Dunes National Lakeshore. Nevertheless, park staff mentioned that tremors were felt the week before the scoping meeting, possibly emanating from faults in the vicinity of Ontario, Canada.

Unique Geologic Features

“Unique geologic features” are often mentioned in a park’s enabling legislation; these features are of widespread geologic importance and may be of interest to visitors and worthy of interpretation. One such feature, perched dunes, is discussed in “Eolian Features and Processes.” Other unique geologic features at Sleeping Bear Dunes include the following:

Ghost Forests

Trees that have been killed by migrating sand but left standing are called “ghost forests.” These trees were buried alive during a period of active sand accumulation. Later, winds removed the sand, exposing the “skeletal remains” that now lack leaves, branches, and bark. Although the wood is not known to have been dated, the trees in the ghost forest on Sleeping Bear Dune, for example, formed on eolian deposits and are, therefore, less than 2,000 years old (Frank Snyder, Northwestern Michigan College, telephone communication, December 1, 2010). One of the most spectacular ghost forests at the national lakeshore occurs on Sleeping Bear Dune. At this site, trunks of individual trees are as large as 1 m (0.9 ft) in diameter. Unfortunately, mass wasting is causing the loss of these trees at this location, with trees sliding down the bluff (Frank Snyder, Northwestern Michigan College, telephone communication, December 1, 2010). Ghost forests also occur along the Old Indian Trail, Dunes Trail at Sleeping Bear Point, and on the west side of South Manitou Island.

Paleosols

Ancient soil horizons called “paleosols” are exposed in the perched dunes at the national lakeshore. The Sleeping Bear Dune has 79 discontinuous paleosols. Snyder (1985) sampled 69 of these paleosols; three of these were dated ($4,065 \pm 160$ years B.P.; $2,675 \pm 145$ years B.P.; and 925 ± 130 years B.P.) (Snyder 1985). Because paleosols retain water, modern cottonwoods often indicate the presence of these ancient soils (Frank Snyder, Northwestern Michigan College, telephone communication, December 1, 2010). Two-thirds of the paleosols in the Sleeping Bear Dunes complex contain charcoal and/or wood. Of these, 86% contain charcoal. Such a high percentage of charcoal indicates the consistent presence of fire on the landscape. Analysis of paleosols indicates that grassland was the primary habitat at the time of paleosol formation, but charcoal is evidence of shrubs or larger vegetation types (Frank Snyder, Northwestern Michigan College, telephone communication, December 1, 2010). Fire, as indicated by the presence of this charcoal, was one of the most important factors for remobilizing fixed sand (Snyder 1985).

Ventifacts

Stones that have been sandblasted by windblown sand are called “ventifacts.” Ventifacts can be worn, polished, and even faceted by the wind. Notable ventifacts occur at Dimmick’s Point on North Manitou Island. In addition, Sleeping Bear Dune has a massive layer of glacial drift (gravel), up to 5 m (16 ft) thick, which is covered by ventifacts. This gravel layer armors the dunes in various locations.

Fulgurite

When lightning hits sand, it can fuse the particles together, forming fulgurite. Likely places for lightning strike are points of highest elevation, which in the case of Sleeping Bear Dunes National Lakeshore are the tops of perched dunes. Lightning penetrates the ground and turns the sand into glass, which forms in the path of the strike, creating branches or rods below ground and crusts on

the surface. Fusion also can vaporize the center of fulgurite, resulting in a tube. Fulgurite typically is between 2 cm (1 in) and 5 cm (2 in) in diameter.

Notable Glacial Erratic

In many glaciated areas, large boulders end up stranded when glaciers recede. Called “erratics,” these out of place rocks have different lithologies than the rock surfaces upon which they have come to rest. Glacial erratics are scattered throughout the national lakeshore, but a dolomite boulder north of Sleeping Bear Dune is particularly notable, though not for the evidence it provides for past glacial activity. Rather, investigators have used this erratic as a marker of bluff retreat. In 1932, the Coast and Geodetic Survey placed a brass marker on this erratic, which at that point was situated 32 m (105 ft) from the edge of the bluff north of Sleeping Bear Dune. In 2002 that distance had been reduced to 6.6 m (21.5 ft), which is an average erosion rate of 0.36 m (1.19 ft) per year. Since then, park staff has measured the retreat rate at 0.3 m (1 ft) per year (Pranger 2006b).

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